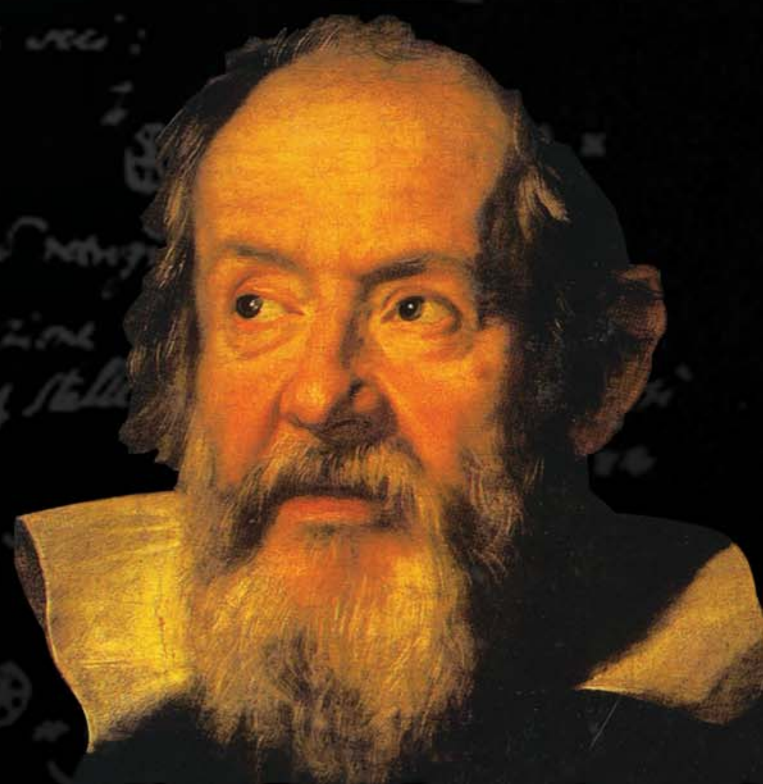
Challenging the Paradigm: The Legacy of Galileo

Symposium

November 19, 2009
California Institute of Technology
Pasadena, California



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Challenging the Paradigm: The Legacy of Galileo

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Introduction

In the year when the world celebrates the 400th anniversary of Galileo Galilei's discoveries through the use of the telescope, this one-day symposium reflected upon the significance of his discoveries to the development of our culture and to science. His discovery of the moons' motion around Jupiter challenged the notion of an Earth-centric universe, and catalyzed discoveries which centuries later are continuously challenging the premises of our understanding.

In our generation, the Galileo spacecraft's discoveries like an icy ocean underneath Europa's surface, the possibility of life on Europa, the widespread volcanism on Io, and the detection of a magnetic field around Ganymede, challenged our understanding of outer planet satellites.

Modern astronomical observatories have changed our understanding of the cosmos, from determining the age and shape of the universe to studying the origins and composition of planets and the evolution of stars. Most recently, the discovery of Earth-like planets and the questions surrounding their abundance close the loop on that assumption of the uniqueness of Earth embodied in the Ptolemaic system that Galileo's proceeded to shatter.

The symposium examined the questions of where the current challenges and frontiers are in the scientific knowledge, and what paradigms might be ripe for "revision."

The symposium also highlighted the contributions of Italian scientists to Space Science, and celebrated the vibrant collaborations between the California Institute of Technology, the Jet Propulsion Laboratory and the Italian scientific community.

Galileo's New Paradigm: The Ultimate Inconvenient Truth

PROFESSOR ALBERTO RIGHINI
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Galileo is considered to be the man that changed the paradigms of interpretation of nature[1], but perhaps it would be more accurate to say that he gave voice to the changes taking place at that time in his culture, but he was unable to understand that he was not permitted to do so[2].

Indeed the theocratic power sitting in Rome after the dramatic experience of the Protestant reformation would have not allowed anyone to independently fathom the work of God through the study of Nature, because the universe was considered as having been fully described in the Bible, and therefore, any new notion obtained as a result of experiments on natural phenomena might have lead to refute the Word of the Holy Spirit, or, even worse, might have shown that the interpretation of the Bible by the Church was wrong or incomplete, or, most probably, irrelevant.

The Council of Trent[3], which was the dramatic reaction of the Church of Rome to the Protestant heresy, had reserved the right to interpret the Bible exclusively to theologians[4], rebutting the Lutheran reformation's premise of independent interpretation of the Scripture, which had resulted in the Church of Rome, and all those who lived off its endowments, being deprived of the financial contribution from the German population. The idea that experimentation might be used to understand the mechanism of natural phenomena is heretical in its essence because it leads to different conclusions from those presented in the Scriptures without theological mediation.

The idea of investing the experiment of the role of a sort of discriminator to separate false from true in the study of nature is generally considered the new paradigm established by Galileo. However the idea that the study of nature could lead to grasp the mind of God was not at all new. The idea that God expressed Himself both through Scriptures and through the conception and the creation of nature had been already formulated by Calvin, who considered the Scriptures and the physical world as the two books written by the Supreme

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[1] For a rough account of Galileo's life which had a very significant role in shaping the common feeling of American culture about Galileo and the Church of Rome see John William Draper, *History of the conflict between religion and Science* (New York: D. Appleton and Co., 1890), and especially chapter six. A much better insight of high scientific value about the life of Galileo can be found in Stillman Drake *Galileo at work* (The University of Chicago Press 1978) or in Righini, A. *Galileo tra scienza Fede e Politica* (Editrice Compositori, Bologna 2008).
[2] See for example the letter written by Galileo to the Secretary of State in Florence on February 20, 1616 few days before the precept by Cardinal Bellarmino do not teach and do not write about Copernican theory in Antonio Favaro *Le Opere di Galileo Galilei* (G. Barbera Editore, Firenze 1968) vol. XII p. 238 (hereinafter quoted as GG, X, p. 238) and also the Letter to Mons. Piero Dini written on March 23, 1615 (GG, V, p. 293)
[3] Prosperi, A. *Dalla Peste Nera alla Guerra dei Trent'anni* (Einaudi, Torino 2000)
[4] This was stated in the session IV of the Council, see also the paper by George Coyne in this meeting.

Creator[5]. Consequently, the results obtained from the observation of the physical world, which was designed to work perfectly regardless of whether it could be easily comprehended by humans, in case of conflict must override, if properly validated by sensible experience, the literal explanation of the Scriptures, which had been conceived taking into account the limitations of the human mind. Galileo expresses this concept in a famous letter to Duchess Madama Cristina of Lorraine, wife of his sponsor the Duke of Florence, while defending himself from the accusation of heresy in affirming that the Earth was revolving around the Sun:

> Being then that the Bible in many instances must be interpreted differently from the apparent literal meaning of the words, I believe that in debates about Nature the Bible's explanation should be the last resort… Being Nature inexorable and immutable and not caring whether its inner laws and methods of operation are understandable to men, for this reason it never transgresses its governing rules… Hence, it appears that no physical manifestation which the experience of sense sets before our eyes, or which necessary demonstrations prove to us, ought to be questioned (much less condemned) based upon biblical references whose words might appear to be leading to a different conclusion. For the Bible is not constrained in every expression to conditions as strict as those governing all natural effects.[6]

Paradigms were changing In medicine also; anticipating the changes occurring in physics, the great Andreas von Wesel (Vesalius), had demonstrated at the beginning of the second half of the 16th century that the human anatomical structure was very different from that described by the Greek authors of medical treatises, and before him, although with different intentions, Leonardo Da Vinci had faithfully represented the details of the human body by observing and dissecting corpses in the morgue of the Florentine hospitals, against the rules of piety imposed by the Church. In Pisa, the great naturalist Andrea Cesalpino, some years before William Harvey, performed experiments on the blood circulation, being able to demonstrate that venous blood was moving back to the heart, contradicting what Aristotle had affirmed. Galileo describes this conflict between experience and the Aristotelian doctrine in the *Dialogue Concerning the Two Chief World Systems,* narrating an episode that he would have witnessed in Venice:

> One day I was in Venice at the house of a famous physician, where some flocked for their studies, while others sometimes went out of curiosity to witness anatomical dissections… By chance that day, when I was there, he was in search of the origin and stem of the nerves…The anatomist showed how the great bundle of nerves, departing from the brain, their root, passed by the nape of the neck, further extending… while only a very small filament, as fine as a thread, arrived at the heart. Then he turned to a gentleman in the audience whom he knew to be a Peripatetic philosopher… and asked if he was satisfied and persuaded that the origin of the nerves was in the brain and not in the heart. The philosopher answered: "You have

[5] Kenneth J. Howell *God's Two Books* (University of Notre Dame Press, Notre Dame 2002)

[6] Galilei, G. *Lettera a madama Cristina di Lorena* GG, V, p 316 (translation by Cinzia Zuffada)

> shown me this matter so clearly and perceptibly that had not the text of Aristotle asserted the contrary, by positively affirming the nerves to stem from the heart, I should be bound to confess your opinion to be true."[7]

This was the point, the philosopher and the theologian would have not agreed to change their views based on the experiment if the experimental evidence was against Aristotle's teachings.

The thinking of Galileo, like that of other great scientists such as Ptolemy, Copernicus, Newton, Einstein, is never completely original. The paradigms of interpretation in Science, but also in fine arts and philosophy, very seldom change abruptly, but rather changes are consequences of a complex cultural and political evolution.

Little more than seventy years before the birth of Galileo a new continent had been discovered west of Europe, and the great wealth coming from South America had inexorably changed the balance of power in Europe, Italy and on the seas where navigation along the new courses needed new technologies that required a new attitude in the study of nature.

The Protestant reformation had broken up the Christian world and its established transnational power system had been shattered together with the revenue stream of the Roman Catholic Church. This had been made possible thanks to the invention of printing with mobile characters and the availability of books and glasses, and aided by the power of printed images which could convey a message even to illiterate people: the power of icons was then equally effective then as television is today.

The idea that the authority of the ancients had to be challenged if one wanted to obtain significant results had grabbed the minds in medicine, music and also in the teaching of the peripatetic philosophy. Galileo's father was an outstanding composer and was very critical of the music of the ancients proposing a new way to play the lute, and advocating the freedom of the composer to choose the harmonies[8].

Galileo's philosophy Professor, in his lectures at the University of Pisa at the end of the 16th century, was teaching a forgotten aspect of the Aristotelian physics, often stating: *standum esse iudicio sensus,*[9] which means that the natural philosopher must first follow sensible experience. This concept, called the *Aristotelian empiricism,* had been lost in centuries of fossilized teaching of the subset of Aristotelian ideas functional to the temporal and spiritual power of the Holy and Apostolic Church of Rome. We should note that not all the ideas of Aristotle were taught in theological colleges and universities: for example the concept of temporal infinity of the universe, typical of the peripatetic school, was considered heretical

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[7] Galilei, G. *Dialogo sopra i due massimi sistemi del mondo* (Florence 1632) GG, VII, p. 134 (translation by Cinzia Zuffada) see also: S. Drake *Dialogue concerning the two chief world systems* (Berkeley, 1967)

[8] Vincentio Galilei, *Dialogo della Musica antica e della moderna* (Marescotti, Firenze, 1581)

[9] This, following Francesco Buonamici, Galileo's professor of Philosophy in Pisa, is the first rule to be observed while discussing about motion: literally *we should cling to experience of the senses.* Quoted in Mario O. Helbing *La filosofia di Francesco Buonamici* (Nistri-Lischi, Pisa 1989)

and heretics were those who taught those concepts like Cremonini, colleague of Galileo in Padua (and for this reason condemned by the Holy Inquisition, but free to teach since protected by the Senate in Venice), and, likewise, the Aristotelian empiricism was considered inappropriate.

But the great Galileo is not at all satisfied by a generic empiricism (which is already a significant change of paradigm in physical studies) like that of Francis Bacon or Bernardino Telesio (which is not *quantitative*): the new Galilean paradigm is presented in *the Assayer* where Galileo states that the great book of nature is written in mathematical and geometrical language and those who do not know these tools when speaking of the physical world are talking nonsense[10].

> I thought… I sensed in Sarsi (Orazio Grassi[11]) the firm belief that philosophical arguments must be based on the opinion of some established author, so that when our mind is not in agreement with someone else's opinion it should remain un-inquisitive… Mister Sarsi, the fact is rather different. Philosophy is written in this grand book—I mean the universe—which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is impossible to understand a single word of it, and one would be left wandering through a dark labyrinth…[12]

Galileo's assumption that mathematics and geometry are the fabric of the natural philosophy suddenly excluded from the physical debate all theologians and philosophers who were accustomed to explaining phenomena by establishing analogies but not quantitative relations between physical quantities.

The use of the telescope to explore nature is in itself a rejection of an old paradigm and the introduction of a new one: traditionally, sight was considered the least reliable of the five senses, the natural philosophers being well aware of the existence of optical illusions, such as the anamorphosis and the refraction effects. Galileo instead assigns to the observation the dignity of physical measurement, and to its graphic rendering that of a reliable record, as is clearly evident in the engraved figures of the *Sidereus Nuncius* representing the different faces

[10] In our opinion, Galileo should have been condemned by The Holy Inquisition for this statement, which was really revolutionary for those times, but the book examined by the censors was found free of heretical statements

[11] The Assayer is the conclusion of a long polemic with the Jesuit Orazio Grassi Astronomer at the Collegio Romano in Rome, a learned person, as all Jesuits usually are, architect and and astronomer. In those times the antagonists in a philosophical fight were designated with aliases: Lotario Sarsi Sigensano is the alias of Oratio Grassi Savonensis (from Savona).

[12] Galilei, G. Il *Saggiatore [The Assayer]* GG, VI, 232 (translation by Cinzia Zuffada) see also S. Drake *Discoveries and opinions of Galileo* (New York 1957) (including *Sidereus Nuncius* and *Il Saggiatore*)

of the Moon, where the average position's absolute error does not exceed 2% of the diameter of the Moon.[13]

Galileo's discoveries between 1609 and 1610 reinforce the Copernican cosmology demonstrating that the descriptions of the universe given by Aristotelian philosophers were wrong, just as the anatomical dissections in medicine proved that the description given at that time of the human body was incorrect. However, critics of the new Copernican cosmology objected that the Moon in motion around the Earth was a notable exception that destroyed the harmony of the system but:

> We therefore have a robust and excellent argument to remove any doubt amongst those who accept easily the revolution of the planets around the Sun in the Copernican system, but are much disturbed by the motion of the Moon around the Earth, while both make their annual revolution around the Sun, leading them to consider rejecting as impossible such structure of the Universe. Now, in fact, we not only have one planet that revolves around another, while both move on the great orbit around the Sun, but the observational experience shows four stars moving around Jupiter, just like the Moon around the Earth, while all together with Jupiter, describe a twelve-year orbit around the Sun.[14]

Again the change of paradigm is not as simple as it appears: it is not true that all the moving bodies in the sky revolve around the Sun, however the observations show new phenomena like the earth-like features of the Moon and the four Jupiter's satellites, the phases of Venus suggesting an unnecessary complexity which however will be explained by forthcoming paradigms, like the principle of dynamics, which were forethought by Galileo, but correctly enunciated by Newton.

In peripatetic (Aristotelian) Cosmology, the Earth has the special place of center of the universe but it is nevertheless imperfect due to the changes taking place on its surface and especially it hides inside the absolute evil and hell, while the planets and, in particular the sphere of the fixed stars, are made up of a perfect and immutable substance. Saint Thomas's philosophy, which is Aristotle's heritage embedded in the Roman Catholic Church's doctrine, represents the universe as the transition between the divine perfection located outside of the universe and the evil that is located inside the Earth; mankind is closer to evil than to the holy Perfection. In trying to demolish the Aristotelian edifice, showing its inconsistencies, Galileo wants to show that it is not true that the objects in the sky are like ethereal spheres. Thanks to the "*sensible experience*" offered by the telescope, Galileo, watching the mountains, valleys and craters on the moon obtains the required proof, and his intuition will be definitively proven by stellar spectroscopy at the end of the XIX century.

Simplicius, the voice of Aristotle in the *Dialogue* concludes a chapter of the book on the earth-like nature of the Moon, saying, horrified, that Salviati (Galileo's alter ego in the book) wants

[13] Righini, A. *Sulle date delle prime osservazioni lunari di Galileo* Giornale di Astronomia, 35, 3 2009

[14] Galilei, G. *Sidereus Nuncius* (Venice 1610) GG, III, p. 95 (translation by Cinzia Zuffada)

to put the Earth amongst the stars when he affirms that the Moon and the Earth are made of the same matter.

Salviati also claims that a place in transformation such as the Earth is more appealing than an immutable and sterile planet.

> I cannot without great admiration, and great repugnance to my intellect, listen to be attributed to natural bodies making up the Universe, nobility and perfection for being impassible, immutable, inalterable, etc. and on the contrary, a great imperfection to things for being alterable, transformable, mutable, etc. It is my opinion that the Earth is very noble and admirable, for the very reason of having so many and so different transformations, mutations, generations, etc. which are incessantly taking place; and if it were not subject to any alteration, and instead it were all one lonely sea of sand, or a mass of Jasper, or that at the time of the Deluge the waters had frozen and it had stayed an immense globe of crystal, in which nothing had ever grown, transformed, or changed, I should have thought it an ugly and useless body, boring, and in one word superfluous, and not part of nature; and I would see the same difference in it as I see between a living and dead creature: and I say the same of the Moon, Jupiter, and all the other celestial globes. But the closer I look at the vanity of popular opinions, the more empty and simplistic I find them. And what greater folly can there be than to call gems, silver and gold precious, and Earth and dirt vile? For do these people not consider that if there were as great a scarcity of Earth, as there is of jewels and precious metals, there would be no prince that would gladly not give a heap of diamonds and rubies, and many bullions of gold, only to purchase as much Earth as would be enough to plant a jasmine in a little pot, or the seed of a China Little Orange, that he might see it sprout, grow, and produce such beautiful leaves, such perfumed flowers, and such delicate fruit? [15]

Not always outstanding scientists understand clearly the consequences of their genial ideas, some changes perhaps are too complex for a single mind to fully understand. This is the case for the principle of relativity enunciated by Galileo, which was not completely understood by the scientist. As a matter of fact in the most important part of the dialogue, Galileo wants to show that with experiments of mechanics it is impossible to determine whether the reference frame is in uniform rectilinear motion or at rest relative to the absolute reference frame of God. To explain this physical principle Galileo describes several simple mechanical experiments carried out on the lower deck of a large vessel either moored at the quay or quietly sailing in the Adriatic sea; this example had been already used by Copernicus, and also by Giordano Bruno in the *Ash Wednesday Supper*.

> Shut yourself up with some friends in the main cabin below deck on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some small fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it. With the ship standing still, observe carefully how

[15] Galilei, G. *Dialogo*… (Florence, 1632) GG, VII, p. 83 (translation by Cinzia Zuffada)

> the little animals fly with equal speed towards all sides of the cabin. The fish swims indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something at your friends, you need to throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction. When you have observed all of these things carefully (though there is no doubt that when the ship is standing still everything must happen this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way or that. You will detect not the least change in all the effects described, nor could you tell from any of them whether the ship was moving or standing still.[16]

For the philosophers of Galileo's times, this page is definitely revolutionary and heretical; it really establishes a new physical principle, depriving God of the fundamental property to be at absolute rest, but it does not introduce, as is generally believed erroneously, in Galileo's mind, the principle of relativity, fully enunciated by Newton, about 60 years later, and correctly attributed to Galileo by him. This is a new fundamental paradigm, which however is not yet considered as such by the scientist who is describing it so well and clearly. On the other hand, Galileo considers the manifestation of tides as the consequence of the diurnal variation of the velocity vector on the Earth's surface relative to a reference centered in the Sun which results by adding the centripetal motion to the tangential motion, (The resulting motion being highest at midnight and smallest a noon). For this reason the ocean's basins, in Galileo's mind, behave as a shaken pail in which the water moves. Thus Galileo unknowingly devises an ideal experiment that would allow an observer to establish state of rest or motion of a reference system, negating in fact the principle of relativity he had just expressed. Galileo is convinced that the manifestation of tides is the long-searched physical proof of the Earth's own motion substituting for the one he was never able to find, i.e. the stellar parallaxes, and derides Kepler's hypothesis of the lunar influence on tides:

> But amongst all the great men who have thought about such admirable natural phenomenon, I am most surprised in Kepler, who, gifted with an independent and acute intellect, and who had originally grasped the Earth's laws of motion, subsequently listened to and agreed with the idea of the influence of the Moon on the tides, and superstitions and other childish fads.[17]

We may conclude that the trail of scientific discovery is not at all simple but as Kepler affirms *Per Aspera ad Astra*, i.e., it is possible to reach the stars passing through difficulties, and Galileo made a remarkable step forward.

ACKNOWLEDGEMENTS: THE AUTHOR WISHES TO THANK DR. CINZIA ZUFFADA FOR HER HELP AND SUGGESTION AND FOR TRANSLATING THE GALILEO INSERTS.

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[16] Galilei, G. *Dialogo*…. (Florence 1632) GG, VII, 212 (Translation by Cinzia Zuffada)
[17] Galilei, G. *Dialogo*……. (Florence 1632) GG, VII, p. 486 (translation by Cinzia Zuffada)

Galileo and His Times

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HISTORICAL PRECEDENTS

During the very last year of what he himself described "as the best [eighteen] years of his life" spent at the University of Padua Galileo first observed the heavens with a telescope. In order to appreciate the marvel and the true significance of those observations we must appreciate the historical precedents that will have important repercussions on the intellectual climate in Europe at the time of Galileo and, therefore, on the critical intellectual period through which Galileo himself was passing at the time those observations were made.

The natural philosophy of Aristotle (384 -321 BC) was an attempt to understand the true nature of the world and it was not just a mathematical expedient, as it had been for the Pythagoreans. Ptolemy's (130 AD) *Almagest*, one of the greatest astronomical works of antiquity, presents, however, a pure mathematical reconstruction of the universe with the earth at the center. Moreover, Aristotle proposed that everything in the sub-lunar universe was made of a combination of four elements: earth, air, fire and water and that the heavenly bodies, as compared to sub-lunar bodies, were perfect in shape and in their motions. Galileo's telescopic observations will challenge both Aristotle and Ptolemy as they present the first truly new data about the universe in about 2,000 years. To explain them a new physics would be necessary. The Aristotelian view of the universe was crumbling. Contrary to the Pythagorean inheritance of Ptolemy the word hypothesis would no longer signify a mere mathematical expedient. It would come to mean primarily, as it did for Galileo, the best available scientific explanation of how the universe really worked from an interpretation of observations of that same universe. His accusers would claim that he did not accept Copernicanism, a sun centered universe, as hypothetical. He did, but not in the Pythagorean sense. He would become one of the first modern scientists as he observed the universe and tried to interpret what he observed in an attempt to understand how the universe really worked. Copernicus in his *De Revolutionibus Orbum Coelestium* (1543) had, of course, already proposed a sun-centered universe, as had Aristarchus (310-230 BC) long before him, but he did not have at hand the telescopic observations which Galileo presented to the world in his *Sidereus Nuncius*.

Martin Luther's break with Rome in 1519 set the stage for one of the principal controversies to surface in the conflict of the Church with Galileo, the interpretation of Sacred Scripture. In the 4th Session of the Council of Trent, the reformation council, the Catholic Church in opposition to Luther solemnly declared that Scripture could not be interpreted privately but only by the official Church:

> Furthermore, to control petulant spirits, the Council decrees that. . . no one, relying on his own judgment and distorting the Sacred Scriptures according to his own

> conceptions, shall dare to interpret them according to his own conceptions, shall dare to interpret them contrary to that sense which Holy Mother Church. . . has held and does.
>
> As we shall see, Galileo interpreted Sacred Scripture privately which contributed to his condemnation, even though he essentially anticipated by some 300 years the official teachings of the Church on the interpretation of Scripture.[1]

From this brief review of historical precedents we can identify several issues which are lurking in the wings and which will come on stage as the confrontation of the Church with Galileo goes forward. A sun-centered universe in the eyes of the Church threatened both Sacred Scripture and Aristotelian natural philosophy. As to Scripture the conflict was obvious, since to the Church of those days Scripture taught in many verses that the Sun moved. As to Aristotle the earth had to be at the center since it was the heaviest of the elements. Furthermore, the philosophy of Aristotle was fundamental to Catholic theology at that time. If his natural philosophy was wrong was all of his philosophy, and therefore Catholic theology, menaced? Another lurking issue was the ambiguous meaning of hypothesis, the contrast between the view inherited from the Pythagoreans and that which was coming to light at the birth of modern science. Galileo will be accused of not accepting Copernicanism as a hypothesis. While he did not in the first sense, as a pioneer in the birth of modern science he certainly did in the second sense.

THE VIEWS OF ARISTOTLE AND PTOLEMY

For Aristotle all sub-lunar bodies were made of a combination of four elements: earth, water, fire and air. Since earth was the heaviest and water the next heaviest element, the planet Earth which consisted principally of these two elements had to be at the center as its natural place. Furthermore, there was a distinction between earthly elements and heavenly elements. Heavenly bodies by their nature were perfect in shape and in appearance: spheres, therefore, and smooth. They had to move in perfect geometrical trajectories, i.e., circles. There were at increasing distances from the Earth a series of real transparent rotating spheres on which were fixed all of the then known celestial objects. This natural philosophy, based on pure theoretical considerations, dominated the view of the universe for about 2,000 years. It presented a natural philosophy, a depiction of the universe as it truly was. It would eventually collapse under the weight of observations, especially those of Galileo.

Ptolemy, on the other hand, in his *Almagest* some five hundred years after Aristotle presented not a natural philosophy but a purely geometrical construction to explain the distances and the movements of the celestial bodies. His earth-centered universe with circles upon circles (technically called deferents and epicycles) to explain the motions of the planets against the background of the fixed stars would be considered today a much too complex explanation as

[1] On 18 November 1893, Pope Leo XIII issued his encyclical *Providentissimus Deus* which called for the study of the languages, literary forms, historical settings, etc. of Scripture so that a fundamentalist approach to Scripture could be avoided. On 7 May 1909, Pope Pius X founded the Pontifical Biblical Institute which is dedicated to such studies.

compared to any sun-centered system. But Ptolemy's system, proposed as a mere mathematical construct but sustained by the natural philosophy of Aristotle, will dominate thinking on the universe up until the 16th century.

THE INTERPRETATION OF SACRED SCRIPTURE

One of the first indications that Scripture was to play an important role in the Galileo affair occurred over lunch in 1613 at the palace of the Grand Duke of Tuscany when the Duke's mother, Christina, became alarmed by the possibility that the Scriptures might be contradicted by observations such as those of Galileo which might support an earth-centered universe. Since Galileo was supported by the Grand Duke and Duchess and in general by the Medici family, this episode was of acute interest to him. Although he was not present, it was reported to him by his friend, Benedetto Castelli. Galileo hastened to write a long letter to Castelli in which he treats of the relationship between science and the Bible.[2] In it Galileo stated what has become a cornerstone of the Catholic Church's teaching:

> I would believe that the authority of Holy Writ had only the aim of persuading men of those articles and propositions which, being necessary for our salvation and overriding all human reason, could not be made credible by any other science, or by other means than the mouth of the Holy Ghost itself. But I do not think it necessary that the same God who has given us our senses, reason, and intelligence wished us to abandon their use, giving us by some other means the information that we could gain through them—and especially in matters of which only a minimal part, and in partial conclusions, is to be read in Scripture.

Galileo was encouraged and supported in his thinking about Scripture by the publication of a letter by the Carmelite theologian, Antonio Foscarini, which favored Copernicanism and introduced detailed principles of the interpretation of Scripture that removed any possible conflict.[3] The renowned Jesuit Cardinal, Robert Bellarmine, who will play an important role in the Galileo affair, responded to arguments of Foscarini by stating that:

> . . . I say that if there were a true demonstration that the sun is at the center of the world and the earth in the third heaven, and that the sun does not circle the earth but the earth circles the sun, then one would have to proceed with great care in explaining the Scriptures that appear contrary; and say rather that we do not understand them than that what is demonstrated is false. But I will not believe that there is such a demonstration, until it is shown me.

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[2] A. Favaro, *Edizione Nazionale delle Opere di Galileo Galilei* (Florence: Giunti Barbera, 1968) V, 282-288.

[3] See an English translation of this letter in R. Blackwell, *Galileo, Bellarmine and the Bible* (Notre Dame: University of Notre Dame Press, 1991).

However, in the end, Bellarmine was convinced that there would never be a demonstration of Copernicanism and that the Scriptures taught an earth-centered universe.[4]

Finally in June 1615, Galileo completed his masterful Letter to Christina of Lorraine[5] (the same Christina, Duchess of Tuscany of the Medici family) in which he essentially proposes what the Catholic Church will begin to teach only about three centuries later, i.e., that the Books of Scripture must be interpreted by scholars according to the literary form, language and culture of each book and author. His treatment can be summed up by his statement that:

> . . . I heard from an ecclesiastical person in a very eminent position [Cardinal Baronio], namely that the intention of the Holy Spirit is to teach us how one goes to heaven and not how heaven goes.[6]

In the end, however, the Church's Congregation of the Holy Office will declare that putting the sun at the center of the world is "foolish and absurd in philosophy, and formally heretical since it explicitly contradicts in many places the sense of Holy Scripture."[7] The Church had declared that Copernicanism contradicted both Aristotelian natural philosophy and Scripture. This sentence will over time come home to roost!

GALILEO, THE FIRST OBSERVATIONAL ASTRONOMER

Galileo was the first true observational astronomer,[8] but he was also an experimentalist. It is impressive, indeed, to visit the *Istituto e Museo di Storia della Scienza* in Florence where one sees the many broken lenses from Galileo's attempts to make ever better telescopes. He himself stated that "of the more than 60 telescopes made at great effort and expense [in his home here in Borgo de' Vignali] I have been able to choose only a very small number ... which are apt to show all of the observations." In that museum one also sees a display showing Galileo's application of the pendulum to a clock and his experiments with an inclined plane in search of the law of falling bodies. Before he pointed his finest telescope to the heavens he had done his best to show experimentally that there were no serious "instrumental effects."

[4] See an English translation of Bellarmine's letter in M. Finocchiaro, *The Galileo Affair* (Berkeley: University of California Press,1989).
[5] A. Favaro, *Edizione Nazionale delle Opere di Galileo Galilei* (Florence: Giunti Barbera, 1968) V, 309-348.
[6] A. Favaro, *Edizione Nazionale delle Opere di Galileo Galilei* (Florence: Giunti Barbera, 1968) V,319.
[7] A. Favaro, *Edizione Nazionale delle Opere di Galileo Galilei* (Florence: Giunti Barbera, 1968) XIX, 321.
[8] My claim that Galileo was the first true observational astronomer requires some justification. Galileo did not invent the telescope; he improved it for the precise purpose of astronomical observations. Nor, it seems, was he the first to use the telescope to observe the heavens. There is evidence that Thomas Digges of England, using a rudimentary reflecting telescopic invented by his brother Leonard, saw myriads of stars about thirty years before Galileo's first observations. Even if this is true, the observations of Digges did not become known and had no scientific impact. Galileo not only observed; he intuited the great importance of his observations and he communicated them rapidly to the whole cultured world of his day. It is for that reason that I feel justified in naming him the first true observational astronomer.

Again, in his own words:

> In so far as I can truthfully state it, during the infinite, or, better said, innumerable times that I have looked with this instrument I have never noticed any variation in its functioning and, therefore, I see that it always functions in the same way.

In fact, it was precisely through his dedication as an experimentalist, and in particular through his studies on motion, that he had come to have serious doubts about the Aristotelian concept of nature. What he sensed was lacking was a true physics. The world models inherited from the Greeks were purely geometrical and the geometry was based upon preconceived philosophical notions about the nature of objects in the universe: all objects had a natural place in the universe and consequently they had a natural motion. But there was no experimental justification for these preconceptions. They were simply based upon a philosophical idea of the degree of perfection of various objects.

In addition to his attachment to experiment and the sense for physics that derived from it, Galileo also nourished the idea that the true physical explanation of things must be simple in the richest meaning of that word. To be more specific, among several possible geometrical models the nature of the physical world would see to it that the simplest was the truest. Thus, as early as 1597, at the age of thirty-three and only five years after the beginning of his teaching career in Padua, he was able to state in a letter to Kepler:

> ...already for many years I have come to the same opinion as Copernicus[9] and from that point of view the *causes of many natural effects*, which undoubtedly cannot be explained by the common hypothesis, have been revealed by me. (Emphasis mine.)

One senses in such statements as this by Galileo that, although he did not yet have the physical explanation, he realized that it must be a simple and unifying one. For Galileo, the motion of falling bodies and the motion of the planets had something in common and geometrical explanations were not sufficient. Physics was required.

Let us now turn our gaze upon Galileo with his perfected telescope pointed to the heavens. Obviously not everything happened in the first hours or even the first nights of observing. The vault of the heavens is vast and varied. It is difficult to reconstruct in any detail the progress of Galileo's observations; but from October 1609 through January 1610 there is every indication that he was absorbed in his telescopic observations. From his correspondence we learn that he had spent “the greater part of the winter nights under a peaceful open sky rather than in the warmth of his bedroom.” They were obviously months of intense activity, not just at the telescope but also in his attempt to absorb and understand the significance of what he saw. His usual copious correspondence becomes significantly reduced during these months but we do learn from it that he continued in his attempts to improve his

[9] Historians debate endlessly as to when Galileo first became personally convinced of the correctness of Copernicanism. Judging from his statement of “already for many years” and from other indications he must have certainly been leaning towards Copernicanism during the first years of his teaching at Pisa, which began in 1589.

telescope and even to introduce "some other invention." He finally succeeded in November of 1609 to make a telescope that magnified twenty times.

At times his emotional state breaks through in his correspondence. He makes a climatic statement in this regard in a letter of 20 January 1610, some weeks after his observations of the Medicean moons of Jupiter, when he states: "I am infinitely grateful to God who has deigned to choose me alone to be the first to observe such marvelous things which have lain hidden for all ages past." For Galileo these must have been the most exhilarating moments of his entire life. The observations will be carefully recorded in the *Sidereus Nuncius* but denuded for the most part, and by necessity, of their emotional content. What must have been, for instance, the state of mind of Galileo when for the first time he viewed the Milky Way in all of its splendor: innumerable stars resolved for the first time, splotches of light and darkness intertwined in an intriguing mosaic? He will actually say little about this of any scientific significance; and rightly so, since his observations had gone far beyond the capacity to understand. He could, nonetheless, be ignorant and still marvel.

But he will be very acute and intuitive when it comes to sensing the significance of his observations of the moon, of the phases of Venus, and, most of all, of the moons of Jupiter. The preconceptions of the Aristotelians were crumbling before his eyes. He had remained silent long enough, over a three month period, in his contemplations of the heavens. It was time to organize his thoughts and tell what he had seen and what he thought it meant. It was time to publish! It happened quickly. The date of publication of the *Sidereus Nuncius* can be put at 1 March 1610, less than two months after his discovery of Jupiter's brightest moons and not more than five months after he had first pointed his telescope to the heavens. With this publication both science and the scientific view of the universe were forever changed, although Galileo would suffer much before this was realized. For the first time in over 2,000 years new significant observational data had been put at the disposition of anyone who cared to think, not in abstract preconceptions but in obedience to what the universe had to say about itself. Modern science was aborning and the birth pangs were already being felt. We know all too well how much Galileo suffered in that birth process. That story has been told quite well even into most recent times.[10]

Did Galileo's telescopic discoveries prove the Copernican system? Did Galileo himself think that they had so proven? There is no simple answer to these questions, since there is no simple definition of what one might mean by proof. Let us limit ourselves to asking whether, with all the information available to a contemporary of Galileo's, it was more reasonable to consider the Earth as the center of the known universe or that there was some other center. The observation of at least one other center of motion, the clear evidence that at least some heavenly bodies were "corrupt", measurements of the sun's rotation and the inclination of its axis to the ecliptic and most of all the immensity and density of the number of stars which populated the Milky Way left little doubt that the Earth could no longer be reasonably

[10] An excellent up-to-date study of the Galileo affair up until the most recent statements of John Paul II is: A. Fantoli, *Galileo: For Copernicanism and for the Church* (Vatican Observatory Publications: Vatican City State, 1996) Second English Edition; distributed by the University of Notre Dame Press.

considered the center of it all. Of course, a more definitive conclusion will be possible in the coming centuries with the measurement of light aberration, of stellar parallaxes and of the rotation of the Foucault pendulum. As to Galileo, his telescopic discoveries, presented in a booklet of fifty pages, the *Sidereus Nuncius*, will become the substance of his Copernican convictions lucidly presented in his *Dialogue on the Two Chief World Systems*, a work which he promised would appear "in a short while" but which actually appeared only twenty-two years later. His own convictions are clear, for instance, from his own statement in the *Dialogue*:

> ...if we consider only the immense mass of the sphere of the stars in comparison to the smallness of the Earth's globe, which could be contained in the former many millions of times, and if furthermore we think upon the immense velocity required for that sphere to go around in the course of a night and a day, I cannot convince myself that anyone could be found who would consider it more reasonable and believable that the celestial sphere would be the one that is turning and that the globe would be at rest.

But Galileo was also wise enough to know that not everyone could be easily convinced. In a letter to Benedetto Castelli he wrote:

> ...to convince the obstinate and those who care about nothing more than the vain applause of the most stupid and silly populace, the witness of the stars themselves would not be enough, even if they came down to the Earth to tell their own story.

While he could not bring the stars to Earth, he had, with his telescope, taken the Earth towards the stars and he would spend the rest of his life drawing out the significance of those discoveries.

THE FUTURE

Could the Galileo affair, interpreted with historical accuracy, provide an opportunity to come to understand the relationship of contemporary scientific culture and inherited religious culture? In the Catholic tradition there is what Blackwell calls a "logic of centralized authority" required by the fact that revelation is derived from Scripture and tradition that are officially interpreted only by the Church.[11] In contrast, authority in science is essentially derived from empirical evidence, which is the ultimate criterion of the veracity of scientific theory. In the trial of 1616 Blackwell sees the defendant to be a scientific idea and the authority that condemned that idea to be derived from the decree of the Council of Trent on the interpretation of Scripture. What would have been the consequences if, instead of exercising its authority in this case, the Church had suspended judgment? But, having already exercised that authority over a scientific idea, the Church then applied that authority in the admonition

[11] Blackwell, "Could there be another Galileo case?" in *The Cambridge Companion to Galileo*, ed. P.Machamer. (Cambridge: Cambridge University Press, 1998), 348-66.

given by Bellarmine to Galileo in 1616. That admonition would go on later to play a key role in the condemnation of Galileo in 1633 as "vehemently suspect" of heresy.[12]

There is a clear distinction here between authority exercised over the intellectual content of a scientific idea and that exercised over a person in the enforcement of the former. This results in the fact that, as Blackwell so clearly puts it, the abjuration forced on Galileo in 1633 "was intended to bend—or break—his will rather than his reason." Could this contrast between the two authorities result in other conflicts? It is of some interest to note that in the third part of the same discourse whereby he received the final report of the Galileo Commission John Paul II says:

> And the purpose of your Academy [the Pontifical Academy of Sciences] is precisely to discern and to make known, in the present state of science and within its proper limits, what can be regarded as an acquired truth or at least as enjoying such a *degree of probability that it would be imprudent and unreasonable to reject it*. In this way unnecessary conflicts can be avoided.[13]

Would that the Congregation of the Index in 1616 had displayed such wisdom regarding the degree of probability for Copernicanism! Would that this wisdom may guide the Church's action in times to come!

[12] Fantoli, "The disputed injunction," in this volume.

[13] John Paul II, "Discourse to the Pontifical Academy of Sciences," *Origins* 22 (12 Nov. 1992): 370–75, English trans.; original in *Discorsi dei Papi alla Pontificia Accademia delle Scienze (1936-1993)* (Vatican: Pontificia Academia Scientiarum, 1994), 271 ff.

The Galileo Mission: Exploring the Jovian System

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My task is to take us from the era of Galileo's original discoveries, described in the first two presentations, to the era of modern exploration. I will start with my personal perspectives, as a modern planetary scientist using spacecraft technology, on the impact that Galileo's discoveries have had on the last 400 years of science and exploration and then describe briefly the mission to Jupiter that we named after him.

The publication of *Sidereus Nuncius* in 1610, discussed by George Coyne and Alberto Righini in the first presentations, was truly a watershed event in the history of science. What strikes me in looking at the history of the observations and publication of this great work is not so much the difficulties that Galileo later had with the Church's opposition to the Copernican system—although this was important to Galileo's history and to society—but rather the astonishing rapidity with which Galileo got the word of his observations out to virtually everyone in the Western world who had an interest in astronomy and what's more, got his views generally accepted by his peers. The observations were mostly made in January of 1610; by the end of February Galileo already had the printing almost complete and had received the approval of the censors. Within three to four months, five hundred copies were sold out and in the hands of anyone in Western society who cared about natural philosophy. There followed debate and flurries of letters across Europe, criticizing, asking questions, praising Galileo. In the words of translator and commentator Albert van Helden of Rice University[1], "*Sidereus Nuncius* made Galileo into an international celebrity almost overnight." Here is the real paradigm shift—from observation to publication to verification and acceptance in a few short months! We would be hard-pressed to match this performance today, even in the Internet Age, with perhaps the closest recent example being the views of comet Shoemaker-Levy 9 impacting Jupiter in 1994, which flashed around the world in near real time from every available observing platform on Earth or in space, including the Galileo spacecraft as it approached Jupiter.

Figure 1 shows some of the reproductions in *Sidereus Nuncius* of Galileo's highly accurate drawings of the positions of Jupiter's moons, which led to his discovery of an entire system of worlds circling another planet. These satellites figure prominently in recent spacecraft exploration of Jupiter of course. But *Sidereus Nuncius* also reported other major observational results—the phases of Venus and craters and valleys on the Moon. It does not contain, however, the 'erroneous' discovery of seas or "maria" on the Moon, as I had been led to believe during my early schooling. Rather, Galileo performed what today we would call a "thought experiment," imagining what the Earth would look like if viewed from a distance: "Indeed, for me there has never been any doubt that when the terrestrial globe, bathed in

[1] Galilei, G., Van Helden, A., 1610 (trans. 1989). Sidereus Nuncius. The University of Chicago Press, Chicago

sunlight, is observed from a distance, the land surface will present itself brighter to the view and the water surface darker." Just prior to this statement, he attributes to the Pythagoreans the opinion that "the Moon is, as it were, another Earth…," which he appears to find quite reasonable.[2] Thus, he combines two very modern approaches to science—reporting accurately what his experiment revealed (i.e., mountains and valleys on the Moon), and discussing them in the context that the celestial bodies were *worlds* just like the Earth (and incidentally—not over-interpreting his observations—his telescope could not determine if the dark regions of the Moon were seas or not, and he did not claim that it could).

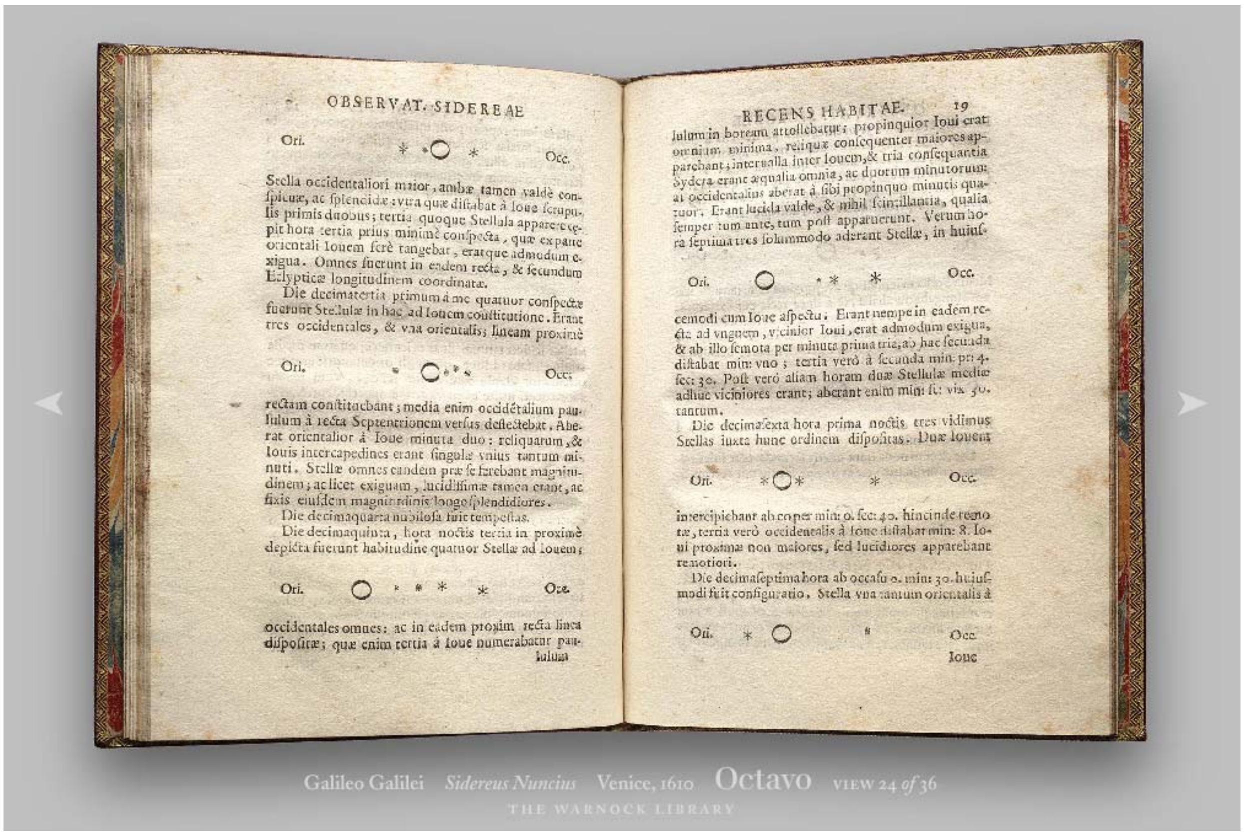

Figure 1: Reproductions in *Sidereus Nuncius* of Galileo's drawings of Jupiter's moons.

The impact of Galileo's observations, as reported in the *Sidereus Nuncius* affected not just scientific thought but art and civilization as well during the intervening four centuries. Soon after Galileo reported his observations, his friend, the artist known as Cigoli, painted the *Assumption of the Virgin* in the Pauline chapel of Santa Maria Maggiore in Rome. In the painting, Mary stands atop the Moon, in accord with earlier depictions and traditional iconography. However, Cigoli's Moon is not the traditional pure, crystalline sphere of earlier

[2] (Galilei and Helden, 1610 (trans. 1989))

paintings, but rather a spotted and scarred orb modeled after his friend's drawings made with aid of the telescope[3]

The regular motions of Jupiter's moons around the giant planet were quickly recognized as providing an invaluable celestial clock. The speed of light (which Galileo tried unsuccessfully to measure) was determined from Ole Roemer's measurements of satellite eclipse timings in 1676. Use of Galilean satellite eclipses became a standard way of determining longitudes by the eighteenth century. A planisphere from the collection of a French nobleman dating from 1745-1749 illustrates the impact of these astronomical advances on general culture of the era. Now part of the decorative arts collection of the Getty Museum in Malibu, California[4], this work of art includes a dial for predicting the "Eclipses du Ier Satellite de Jupiter"—that is, an "Io dial" with 42.5 divisions around it's circumference (Io orbital period in hours)(Wilson et al., 1996). Galileo's "Medicean stars" also helped advance the understanding of celestial mechanics, with Laplace studying their orbital resonances, now known to be a major source of energy for heating some of the satellites.

It was not until the early twentieth century, however, that we began to get an idea of these moons as *worlds*, in Galileo's sense. By the time of the launch of the Voyager spacecraft in 1977, telescopic observations of ever-increasing sophistication and data from the Pioneer 10 and 11 spacecrafts provided the information illustrated in **Figure 2**, which comes from a briefing package used to explain Voyager's scientific goals during launch preparations. At that time, the satellites individual characters were beginning to emerge. We knew, for instance, that Io was red (although not why) and was surrounded by a tenuous cloud of atomic sodium atoms escaping into Jupiter's magnetosphere. By contrast, spectra showed that Europa, Ganymede and Callisto had water ice on their surfaces. We had reasonably accurate densities, showing that Io and Europa were mostly rocky in composition while Ganymede and Callisto were mixtures of rock and ice. Theoretical models for the satellites' thermal evolution suggested the possibility of global liquid water oceans beneath the icy surfaces of at least the larger satellites. The state of knowledge prior to the Voyager mission is reviewed in *Planetary Satellite*.[5]

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[3] Ostrow, S. F., 1996. Cigoli's Immacolata and Galileo's Moon: Astronomy and the Virgin in the Early Seicento. Art Bulletin. 78, 219-235
[4] Wilson, G., et al., 1996. European Clocks in the J. Paul Getty Museum. The J. Paul Getty Museum, Los Angeles
[5] In: J. A. Burns, (Ed.), *Planetary Satellites*. University of Arizona Press, Tucson, 1977

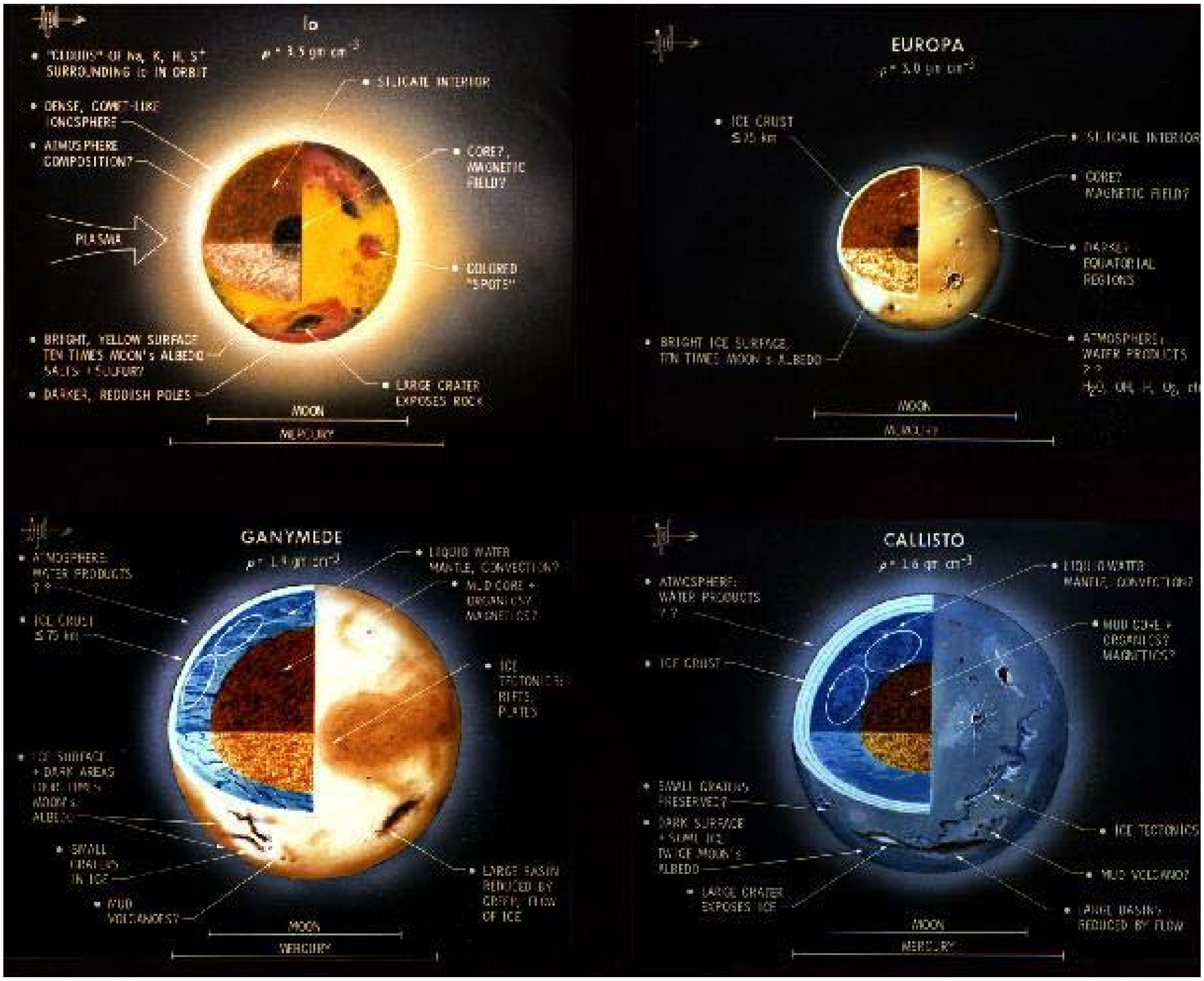

Figure 2: Data from the Pioneer 10 and 11 spacecrafts.

Even given these high expectations, the results of the Voyager flybys in 1979 surpassed our most optimistic projections, and completely revolutionized our view of Galileo's moons, completing their transformation from points of light seen through a telescope to complex worlds, each with its individual properties and geologic history. **Figure 3** shows a composite of the four Galilean satellites as seen by Voyager. Voyager's data revealed that Io is an active, volcanic world, heated by tidal forces and emitting sulfurous gases that explain its yellow-reddish hue. Callisto's dark, ancient cratered surface was seen in stark contrast to Ganymede's more geologically youthful surface, with older regions cut by smooth, resurfaced lanes. And Europa appearance defied easy explanation, with its bright, smooth icy planes almost free of large impact scars but crisscrossed by ridges and fracture patterns of global extent. Europa was immediately added to the list of moons suspected of harboring liquid water oceans. Voyager results for the satellites are reviewed in *Satellites of Jupiter*[6] and *Satellites*.[7]

[6] In: D. Morrision, (Ed.), *Satellites of Jupiter*. University of Arizona Press, Tucson, 1982
[7] In: J. A. Burns, M. S. Matthews, (Eds.), *Satellites*. University of Arizona Press, Tucson, 1986

Figure 3: Composite of Four Galilean satellites.

Even before Voyager was launched, however, plans were being laid to return to Jupiter to follow up on whatever Voyager discovered. The rationale for a new mission to the Jupiter system was based on the limitations of even well-instrumented flyby spacecraft such as Voyager for studying the dynamic magnetosphere, the composition of Jupiter's atmosphere beneath the clouds, and, significantly, exploring the Galilean moons in more detail. Thus a committee of scientists, chaired by the late James Van Allen, recommended to NASA in 1976 that the next major outer planet mission should be a Jupiter orbiter spacecraft which would also carry an atmospheric entry probe[8]. The mission would be designed to study the entire Jupiter system, sampling Jupiter's atmosphere, spending at least two years mapping out Jupiter's immense magnetosphere and making multiple close passes by each of the Galilean satellites. It was the goal of studying Jupiter and its environs as a *system* that made changing

[8] (VanAlle Van Allen, J. A., et al., *A Science Rationale for Jupiter Orbiter Probe 1981/1982 Mission*. Doc 660-26, National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology, Ames Research Center, 1976

the mission's name from its study designation of *Jupiter Orbiter Probe* (JOP) to *Galileo*, the obvious choice.

The launch of Galileo was delayed for some years from its original target of January 1982, first by delays in the development of the Space Transportation System, or Space Shuttle, which was to carry Galileo and its upper stage rocket into space, and then by the tragic loss of the Challenger and its crew in 1986. During this time, the stunning discoveries from the Voyager flybys were being analyzed in depth and Galileo's mission plans and experiment strategies modified to respond to the new information. Finally, on 18 October, 1989, Galileo was successfully launched aboard STS-34 Atlantis. Using a gravity assist trajectory that took it by Venus and the Earth twice, Galileo arrived at Jupiter a little over six years after launch, on 7 December, 1995. After using its propulsion system to enter orbit about Jupiter, Galileo spent seven years studying the system in three phases: the two year primary mission, and two extended missions, the Galileo Europa Mission and the Galileo Millennium mission, ending with a planned impact in 2003 into Jupiter to avoid any possibility of contamination of Europa by a future inadvertent impact. During each orbit, the Galileo was targeted to make a close flyby of one of the Galilean moons, to make high-resolution observations and to modify the orbit, while making observations of Jupiter and the other moons as well. **Figure 4** shows Galileo's trajectory and the time of each of these targeted satellite flybys as Jupiter and its new artificial moon journeyed around the Sun.

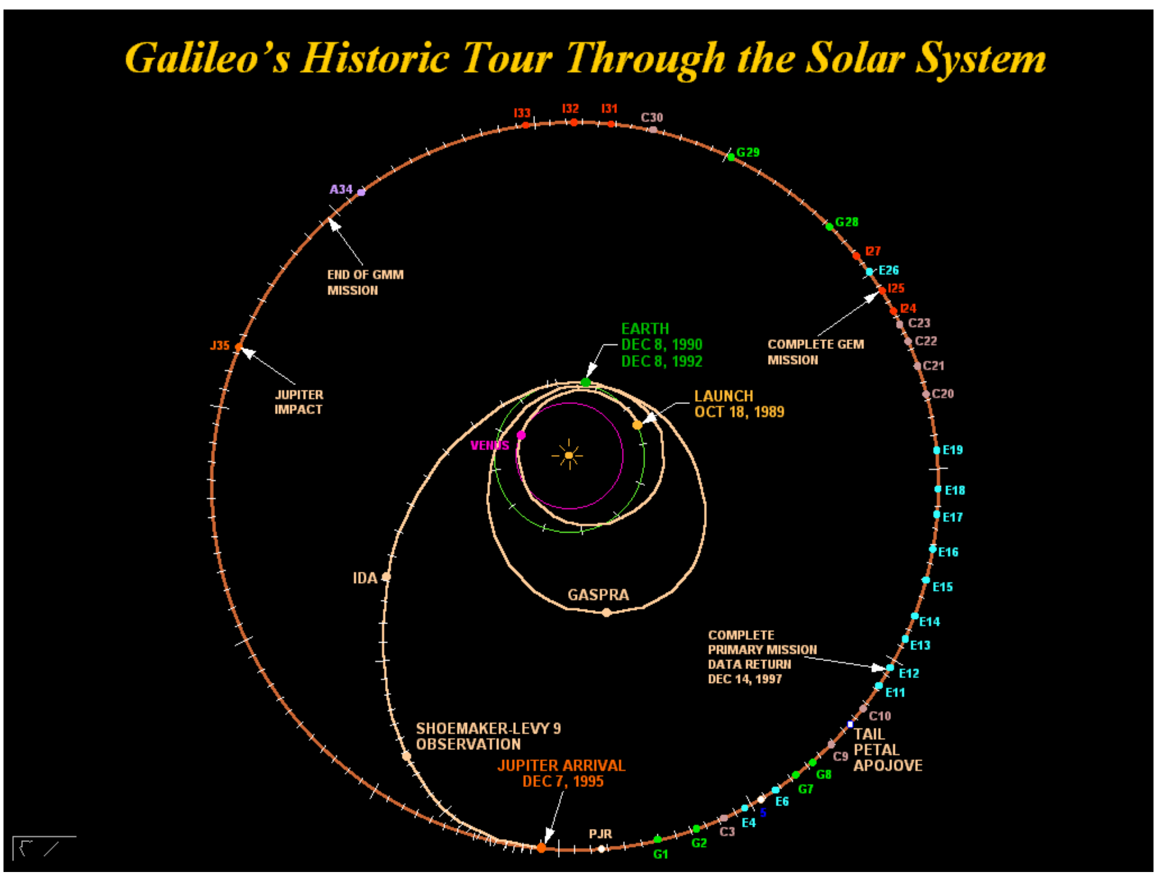

Figure 4: Galileo's trajectory.

Galileo's first scientific data from the Jupiter system was collected even before the spacecraft had achieved orbit. The Galileo atmospheric Probe had been targeted and released about one hundred and fifty days prior to encounter. As Galileo approached its injection burn altitude above Jupiter's clouds, the Probe slammed into the atmosphere at almost 48 km/s-1. Protected by its heat shield, it slowed to subsonic speeds in less than 3 minutes, deployed a large parachute and began transmitting its observations to the orbiter speeding overhead as it descended into the depths of the gas giant's atmosphere. The Probe measured the atmospheric temperature and pressure and wind speed as it descended in addition to collecting data on cloud properties and lightning. A major goal of the Probe experimenters was to measure the composition of the atmosphere with unprecedented accuracy. Jupiter was generally thought to have been built of material from the solar nebular with solar composition. The compositional results, summarized in **Figure 5**, show that key condensable atomic species, such as carbon, nitrogen and sulfur as well as the noble gases argon, krypton and xenon are all enhanced over expected solar abundances by a factor of about three. This suggests significant enrichment of the solar nebular gas by accretion of cold icy planetesimals early in Jupiter's history and represents a key constraint on the conditions and timing of gas giant formation in the solar system.

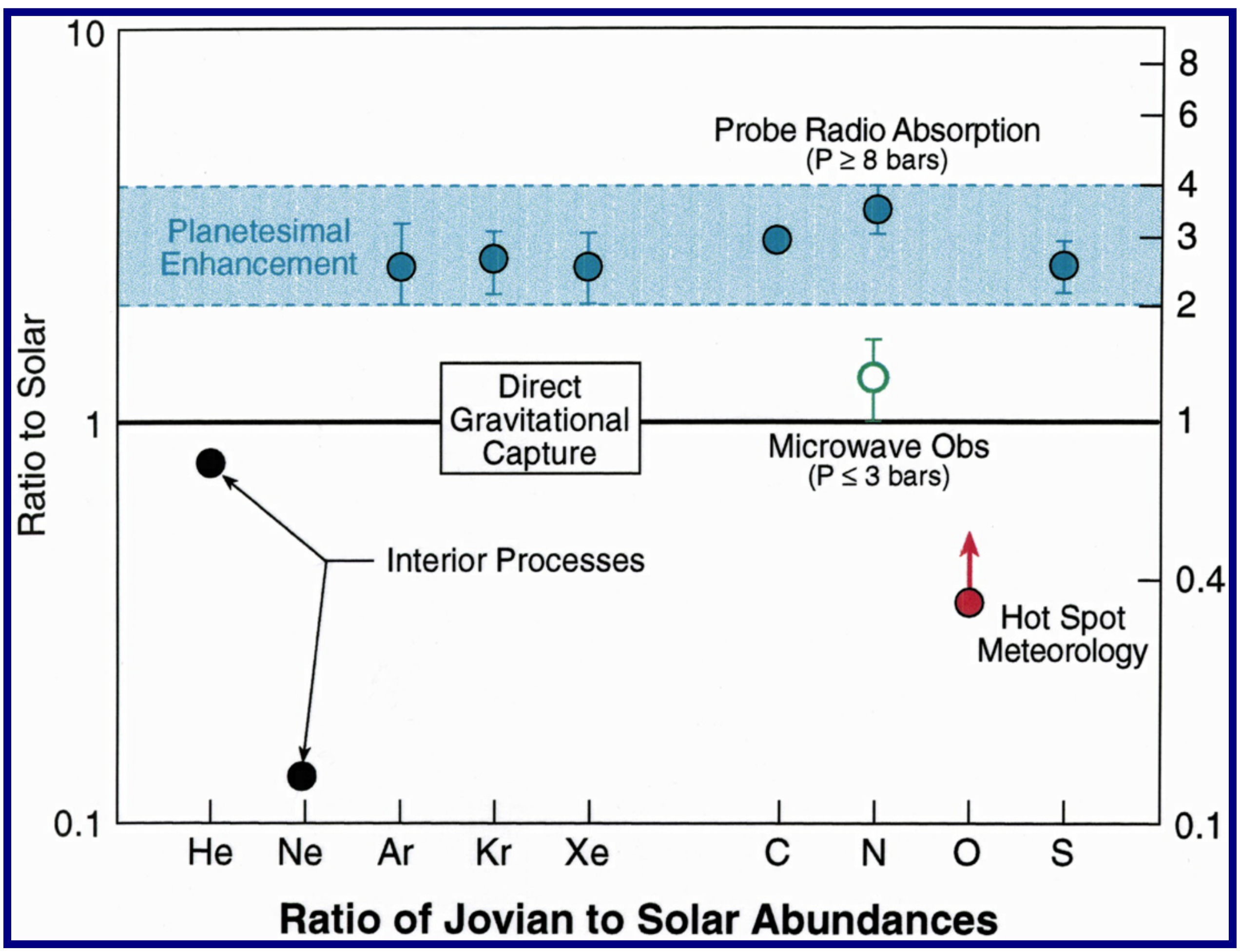

Figure 5: Ratio of Jovian to solar abundances.

As it swung back through the inner part of the Jovian system, Galileo's first close encounter with a Galilean satellite was, appropriately enough, a fly-over of Galileo Regio, a dark region named for the moon's discoverer. High-resolution images of nearby Uruk Sulcus, more than ten times better than Voyager pictures, quickly resolved the origin of the bright, apparently smooth lanes that Voyager had seen. Galileo's images revealed that, seen close up, they were not smooth frozen flows of icy "lava," as had been suggested after Voyager, but rather a tectonically reworked region where dark material had slumped off the steep slopes of a set of faulted and fractured ridges, shown in **Figure 6**.

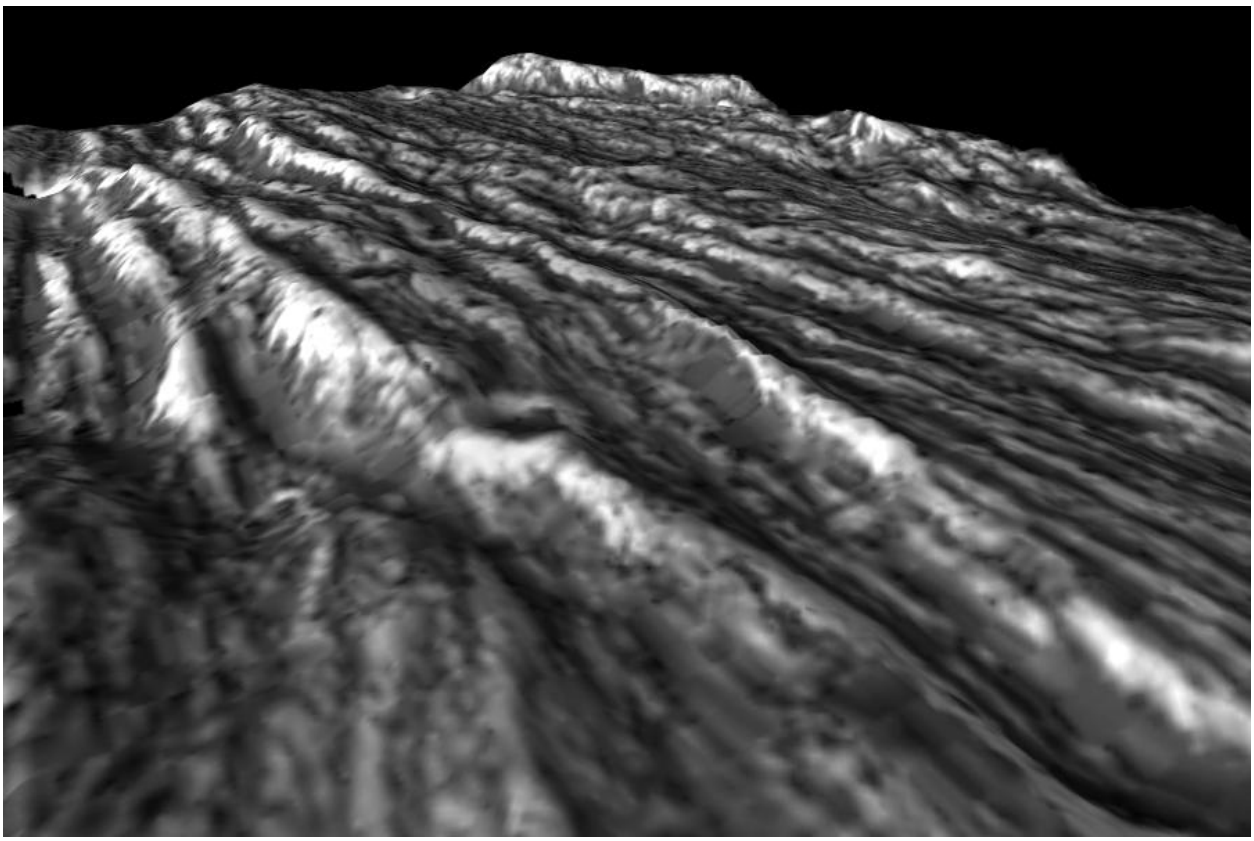

Figure 6: Faulted and fractured ridges.

While Galileo's cameras and spectrometers were probing the surface of Ganymede, space physics instruments were providing startling evidence about the moon's deep interior. The spacecraft's magnetometer recorded a strong deflection of the magnetic field while Galileo was passing close to the moon. At the same time the plasma wave analyzer recorded bursts of radio noise indicative of electrons interacting with a magnetosphere. Taken together the data suggested that Ganymede was a "moon with magnetism" and possessed its own internal, dipole, magnetic field strong enough to counteract the local field from Jupiter, creating a magnetic "bubble" in Jupiter's magnetic environment—a magnetosphere-within-a-magnetosphere. This result makes Ganymede the only planetary satellite known to have an actively generated internal field at the present time (the Earth's Moon may have had such a field very early in its history). Prior to Galileo's arrival at Jupiter, Io was believed to be the most likely satellite to have a magnetic field, with its strong tidal heating and rocky, iron rich composition. However, no strong magnetic signature had been seen when Galileo flew past volcanic Io. The Ganymede magnetic results, supported by gravity data suggesting it has a dense core, imply that the icy moon's interior has a rock mantle and a molten, electrically conducting iron or iron sulfide core capable of generating a dynamo field. **Figure 7** shows the configuration of Ganymede's magnetosphere based on data from multiple flybys.[9]

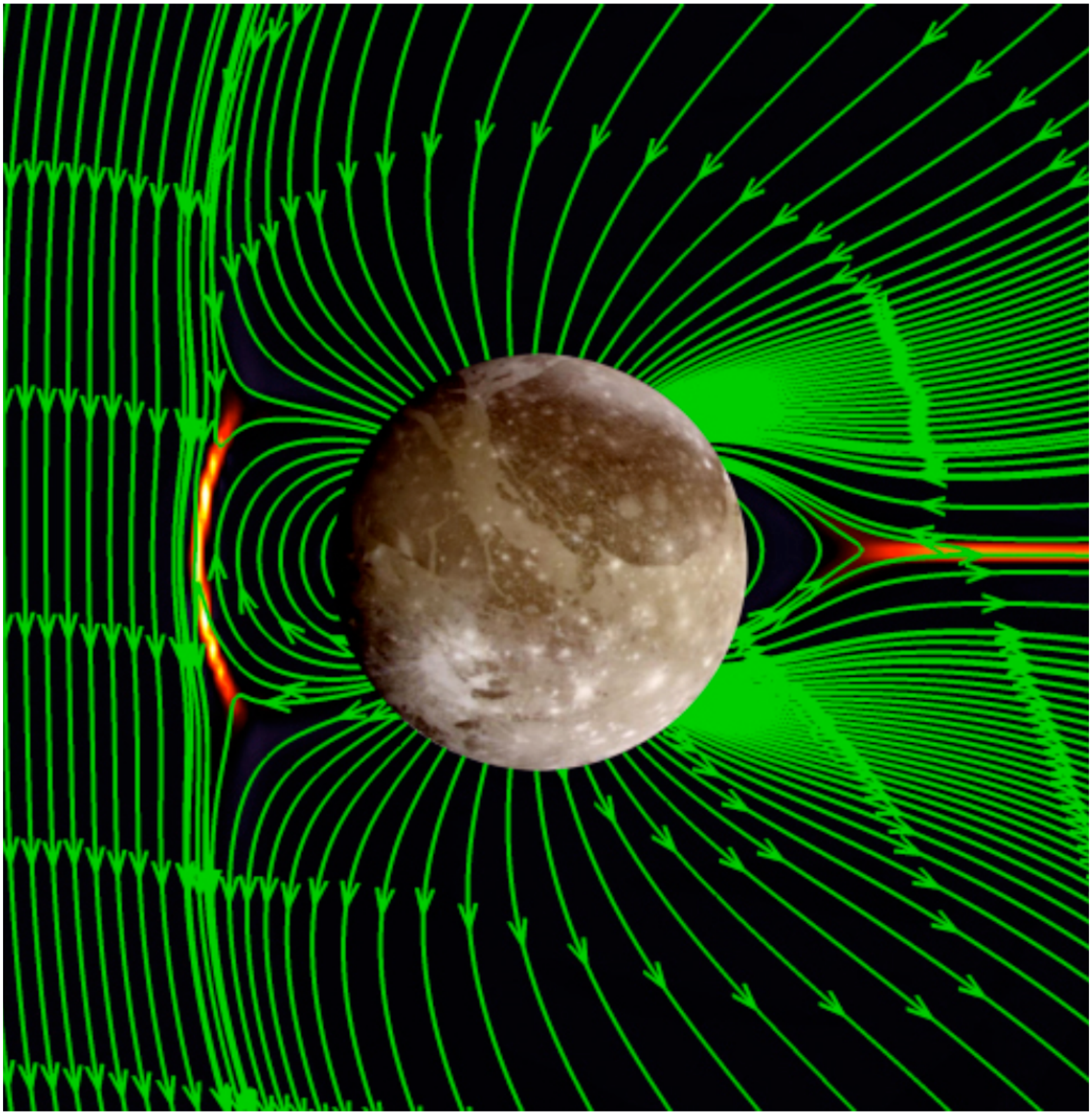

Figure 7: Configuration of Ganymede's magnetosphere.

[9]Kivelson, M. G., et al., 1997. The magnetic field and magnetosphere of Ganymede. Geophysical Research Letters. 24, 2155-2158

One of Voyager's important results in 1979 was the discovery of Jupiter's extremely tenuous ring system, so different from Saturn's bright, magnificent rings. Galileo observations were able to identify the origin of the rings at Jupiter. Images taken with the rings back-lit by the sun showed that the rings are associated with the tiny satellites, also discovered by Voyager, with the vertical extent of each ring segment matching the range of inclination of the orbit of its associated satellite (**Figure 8**). The rings are formed from dust particles ejected from the satellites' surfaces by micrometeoroid impacts, which then drift inward toward Jupiter under the influence of gravitational, radiation and electromagnetic forces to produce the diffuse ring bands seen in the images.

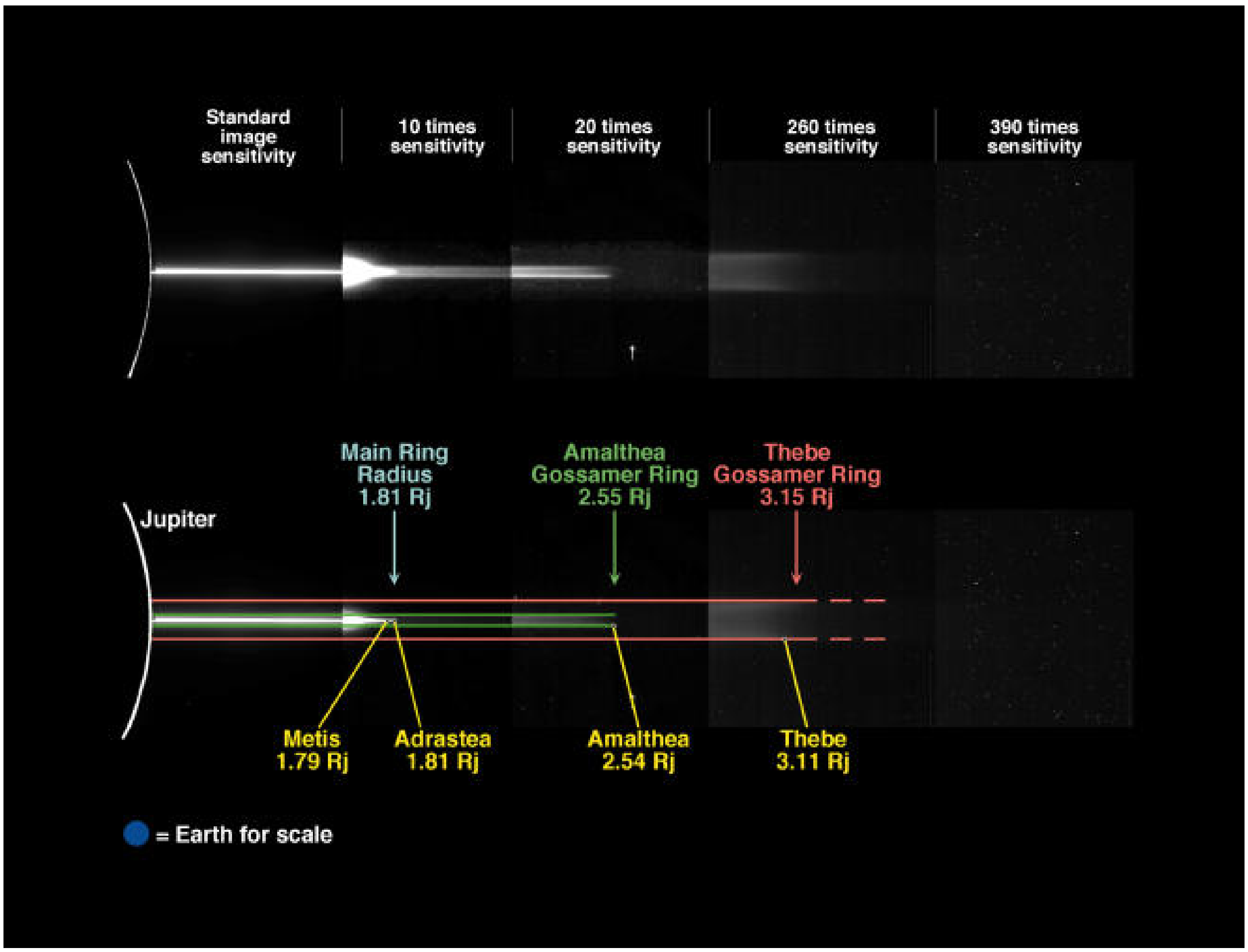

Figure 8: Rings associated with satellites.

Fiery Io was a high priority target for Galileo investigators. The intensity of radiation in Jupiter's magnetosphere is much higher at Io's distance from Jupiter than at the more distant moons, and engineering considerations severely limited close flyby of Io early in the mission. However, even distant observations showed the volcanic activity discovered by Voyager was continuing unabated. In the extended mission phase, Galileo's better than expected resistance to radiation damage permitted a series of close flyby to complement the more distant monitoring. These observations allowed a detailed characterization of Io's activity and spectacular views of eruptions in progress. Estimates from images and spectra of the temperatures associated with eruptions confirmed that the majority of Io's volcanic flows are molten rock at very high temperatures, similar to basaltic lavas on Earth. **Figure 9** shows such an eruption in progress in Io's northern region, within Tvashtar Catena. Sulfur and sulfur dioxide are abundant in the gases and surface deposits around vents but are not the primary component of lava flows, as had been suggested in some models analyzing Voyager data.

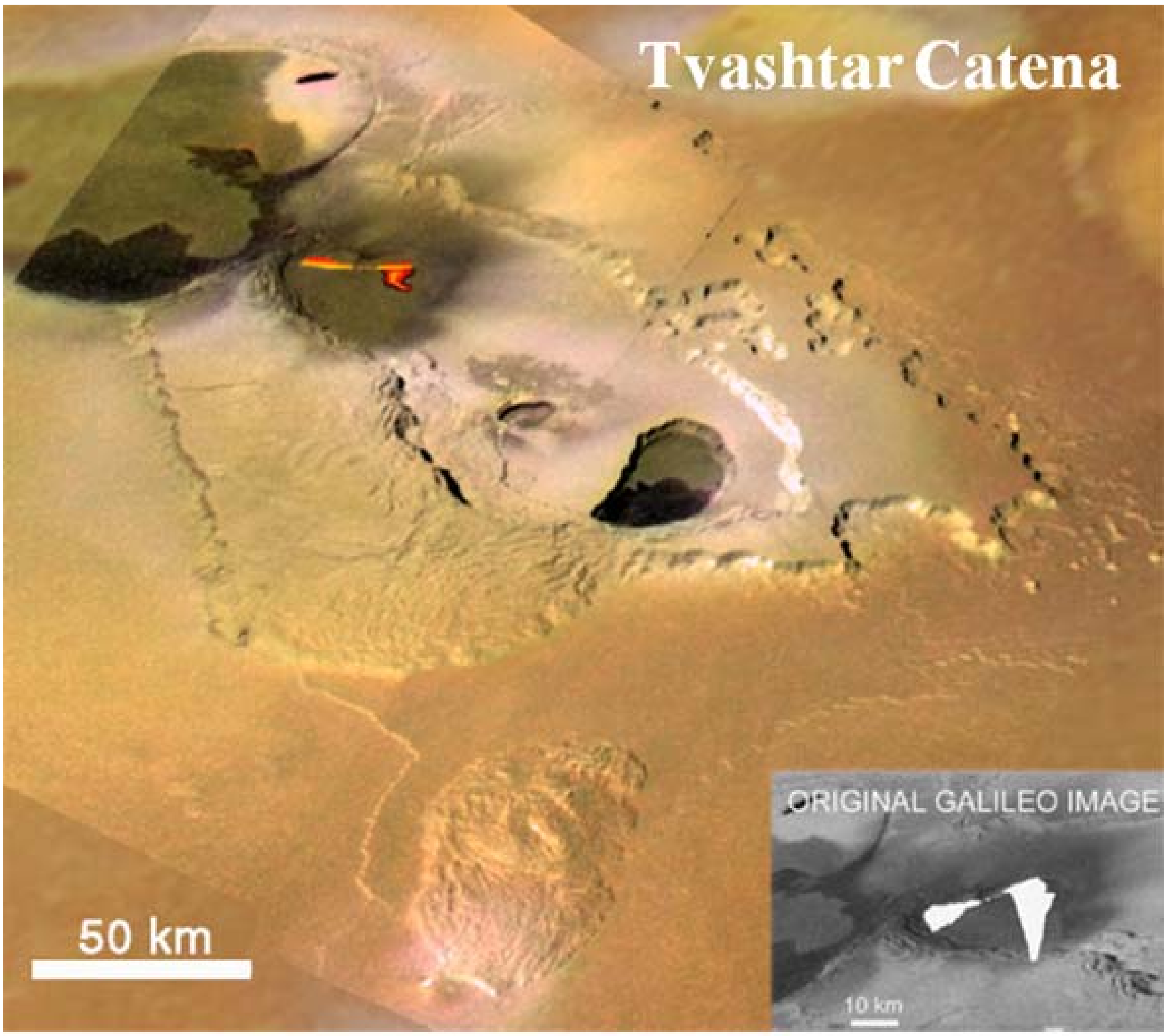

Figure 9: Eruption in progress.

Spectacular as the other moons turned out to be, enigmatic Europa was for many Galileo experimenters the star of the satellite show. Galileo's pictures of Europa's icy ridges and plains had up to one thousand times higher resolution than Voyager images. These confirmed the paucity of both large and small impact craters on the surface, leading to estimates of the surface age of 50-100 million years. Images of chaotic regions showed broken, disrupted blocks of ice, rotated and tilted, very reminiscent of ice floes in arctic sea ice on the Earth

(**Figure 10**). Gravity data taken during the close flybys also indicated a low density (i.e., ~1000 kg/m-3) layer about 100 km deep overlying a denser rock and iron interior. These observations were all consistent with models showing that a liquid water ocean, with a volume twice that of all Earth's oceans, could be maintained under an icy crust by tidal dissipation.

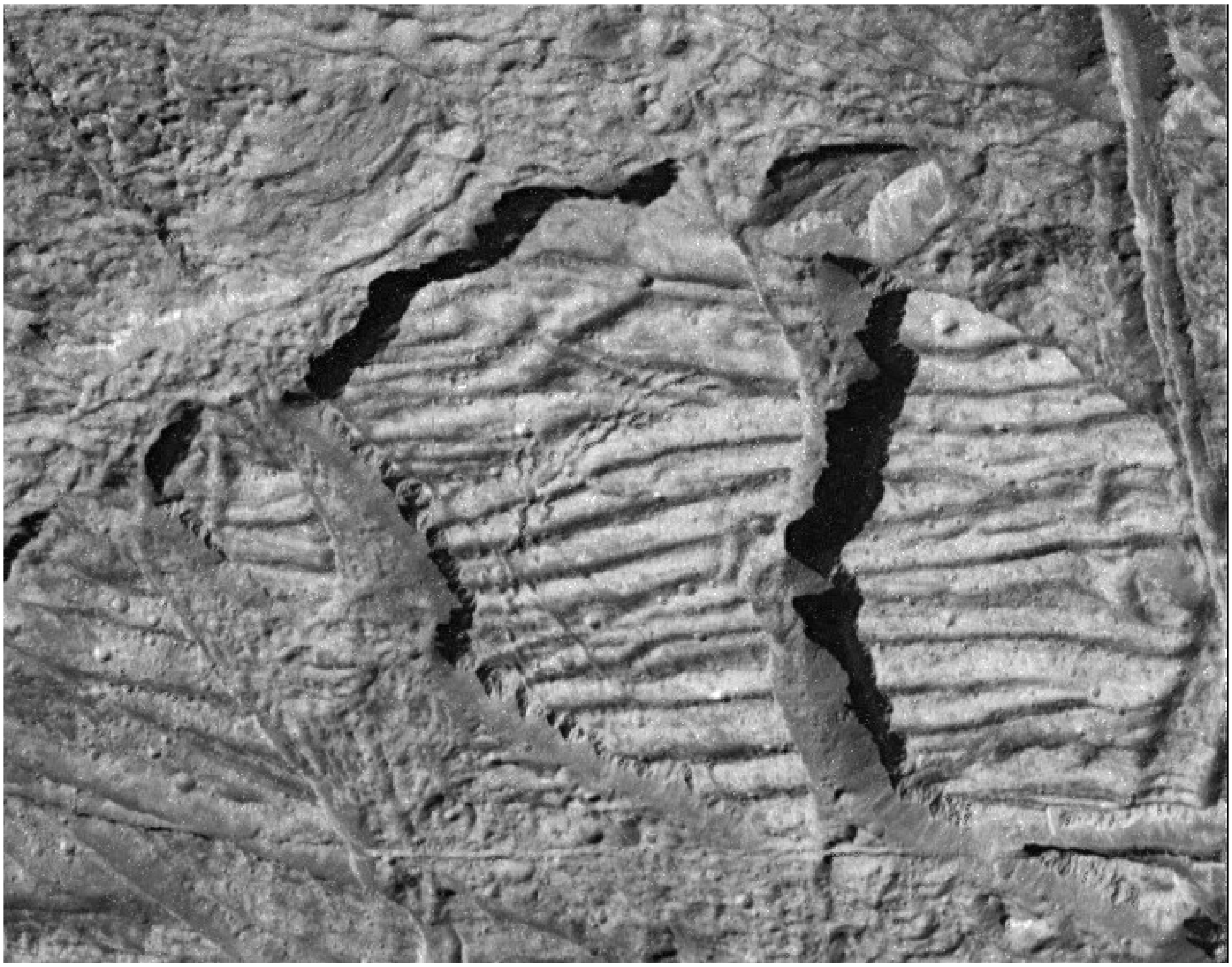

Figure 10: Europa's blocks of ice.

Crucial evidence for a subsurface ocean at not only Europa, but also Ganymede and Callisto came from magnetic field data. Only Ganymede, as described earlier, exhibits a strong, fixed, dipole-like magnetic field indicative of an internal dynamo. However, significant magnetic deflections were observed during close flybys of each of the icy satellites, with the pattern of the deflection changing from encounter to encounter. Correlating these magnetic perturbations with the direction and timing of Jupiter's magnetic field, the magnetometer investigators found that the perturbations exactly matched calculations for an *induced* magnetic field produced by changes in Jupiter's field as the planet rotates. The satellites are embedded in the magnetosphere, and Jupiter's dipole field is tilted about ten degrees to the planet's rotation axis. Thus, the magnetic field seen by each satellite rocks back and forth, causing the radial component of the field to vary periodically. An electrically conducting body placed in such a time varying magnetic field will produce an induced magnetic field. It appeared that the icy moons were acting as if they were large electrically conducting spheres. Rock and ice are not sufficiently conductive to produce the effect seen, but a global ocean of modest salinity could produce such an effect. Galileo results are discussed in detail in *Jupiter: The Planet, Satellites and Magnetosphere*[10].

Taking all the Galileo mission data into account we can visualize the likely internal structure of these distant worlds first glimpsed by Galileo the man in his telescope four hundred years ago. **Figure 11** (from Robert Pappalardo) shows such models for a number of planetary bodies now believed or suspected of having liquid water oceans.

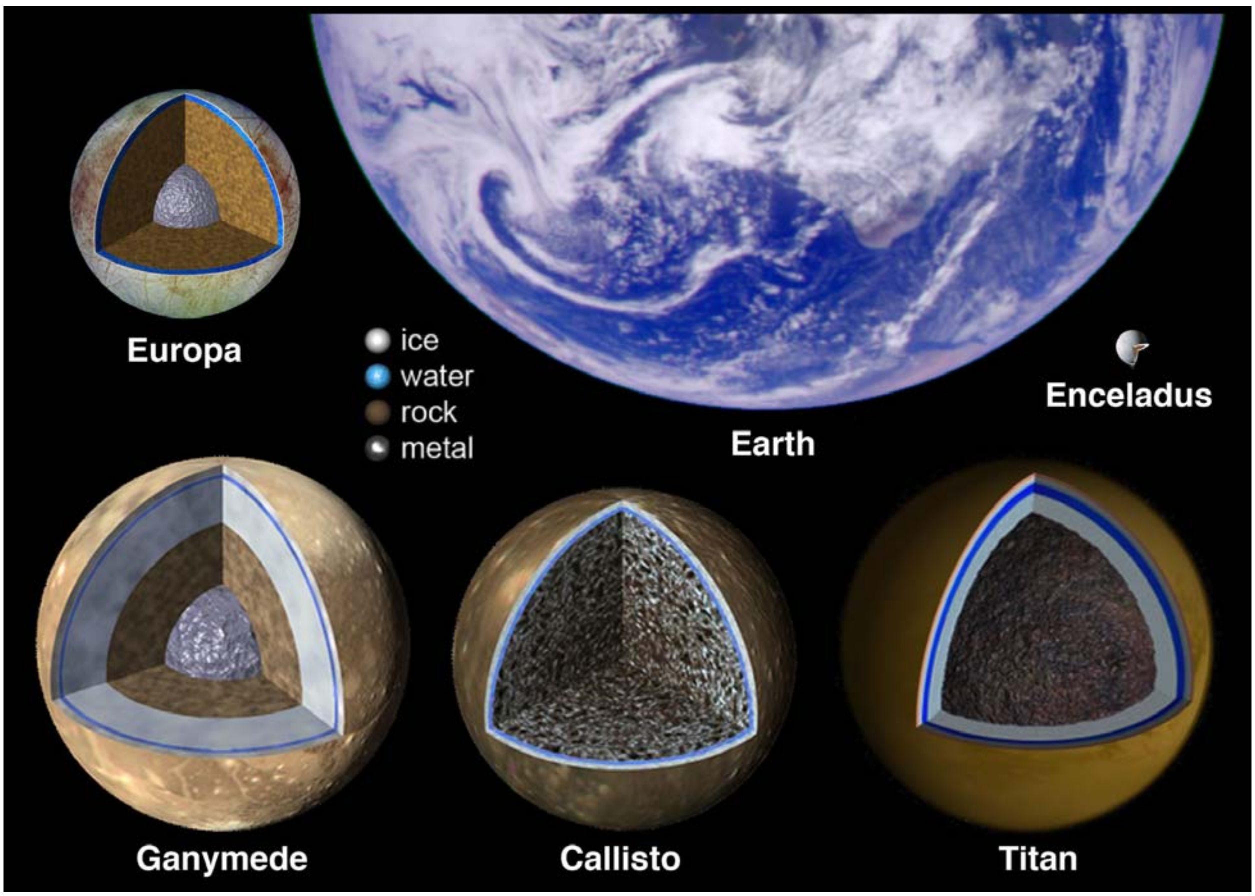

Figure 11: Bodies believed to have liquid water oceans.

Following the end of Galileo' prime mission, a conference was held in Padua, Italy to commemorate *The Three Galileo's: The Man, The Spacecraft, The Telescope*. At the close of the meeting, Pope John Paul II received the participants and guests in Rome on January 11, 1997.

[10] In: F. Bagenal, et al., (Eds.), *Jupiter: The Planet, Satellites and Magnetosphere.* Cambridge University Press, New York, 2004

His Holiness's succinct reaction on viewing one of Galileo's pictures of Europa is hard to better as a summary of Galileo's mission: "Wow!"

What We Don't Know About Europa

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In our understanding of Europa's geology today, we are arguably about where the understanding of Earth geology was prior to the plate tectonic revolution. We have catalogued Europa's feature types, and we have some ideas of how they formed; we have some ideas of Europa's composition and its geophysics. However, we do not yet have a unified vision for how the satellite works overall and where and how its surface is linked to the interior.

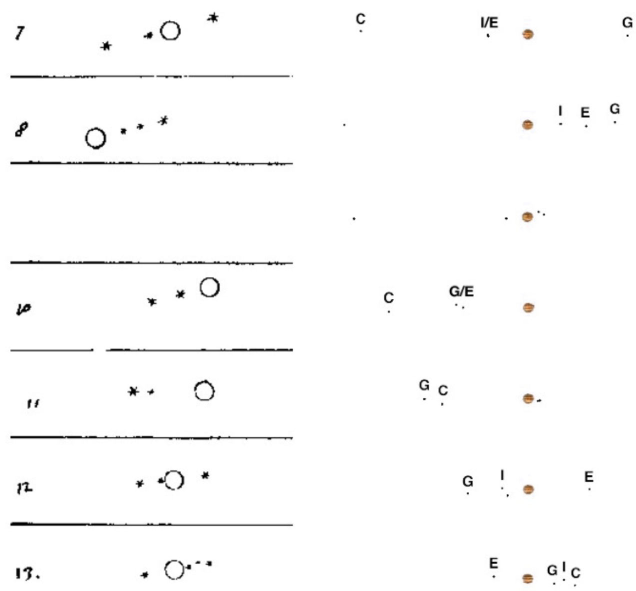

Figure 1: Galileo's sketches of Jupiter and its four large moons, from January 7–13, 1610 (with the exception of Jan. 9, which was cloudy), compared to a simulated view on the same nights from the Jet Propulsion Laboratory's Solar System Simulator (space.jpl.nasa.gov) as seen from Padua, Italy at about 1 hr past sunset. The labels indicate the positions of the satellites identified by Galileo: Io (I), Europa (E), Ganymede (G), and Callisto (C). Europa and Io apparently blended together into one point in the discovery sketch of January 7.

It is reasonable to expect that when we investigate Europa more closely in the future with an orbiting spacecraft,[1] many things that we think we know today we will find we did not know so well. There will also be new questions that will arise, which today we can hardly imagine to ask.

[1] Greeley, R., R. T. Pappalardo, L. M. Prockter, and A. Hendrix (2009). Future exploration of Europa. In *Europa* (R.T. Pappalardo et al., eds.), pp. 655–695, Univ. of Arizona, Tucson.

Four hundred years ago, Galileo's observations of Europa and the other large Jovian satellites that bear his name helped to bring about the Copernican revolution. We can put Galileo's sketches side-by-side with modern depictions from the JPL Solar System Simulator, which simulate the view from Padua at about 7 p.m. each evening, to try to match the satellites' positions to his observations (**Figure 1**). We see that on the historic night of January 7, 1610, Galileo apparently saw light from all four Galilean satellites, with Io and Europa merged into one. It took several days before it was apparent to Galileo that these were four distinct objects that travel about Jupiter.

Figure 2: Global map of Europa. Lineaments arc across the bright plains, and darker mottled terrain pockmarks the surface. Very few large craters are apparent, testifying to the youth of the surface. Simple cylindrical projection centered at (0°, 180°W); data from U.S. Geological Survey Map I-2757. [2]

Four hundred years later, the Galileo spacecraft has explored these large satellites, giving us a much better understanding of the processes that have shaped them. Jupiter and its Galilean satellites are somewhat like a miniature solar system, where Europa holds a position analogous to Earth in the inner solar system: not too warm (from tidal heating, discussed below) as Io is, and not too cold (with too little tidal heating) as Ganymede is. Europa appears to be just right, holding a position where it includes a patina of H_2O, while receiving sufficient tidal heating (it seems) to maintain a subsurface ocean within.

Viewing Europa's surface stretched out into map projection (**Figure 2**) shows it is unlike a typical satellite. Instead of being covered with craters (as is our Moon), there are very few. The 25 km diameter crater Pwyll stands out, thanks to bright rays which surround the crater (**Figure 2,** right center), and which stretch over 1000 km across the trailing hemisphere. There

[2] Becker, T., 2009. Appendix Europa Galileo and Voyager image mosaic maps. In *Europa* (R.T. Pappalardo et al., eds.), pp. 711–718, Univ. of Arizona, Tucson.

are many small craters on Europa (<1 km), but most are identified as "secondary" craters, formed from debris tossed from the few large "primary" craters. In fact, there are so few large craters on Europa that the surface age is estimated as just 40 to 90 million years old,[3] which is just a blink of an eye geologically. In the last 1% of solar system history, Europa's surface has been somehow completely repaved, either continuously or perhaps in a rapid spurt, destroying craters and other features that must have been there previously.

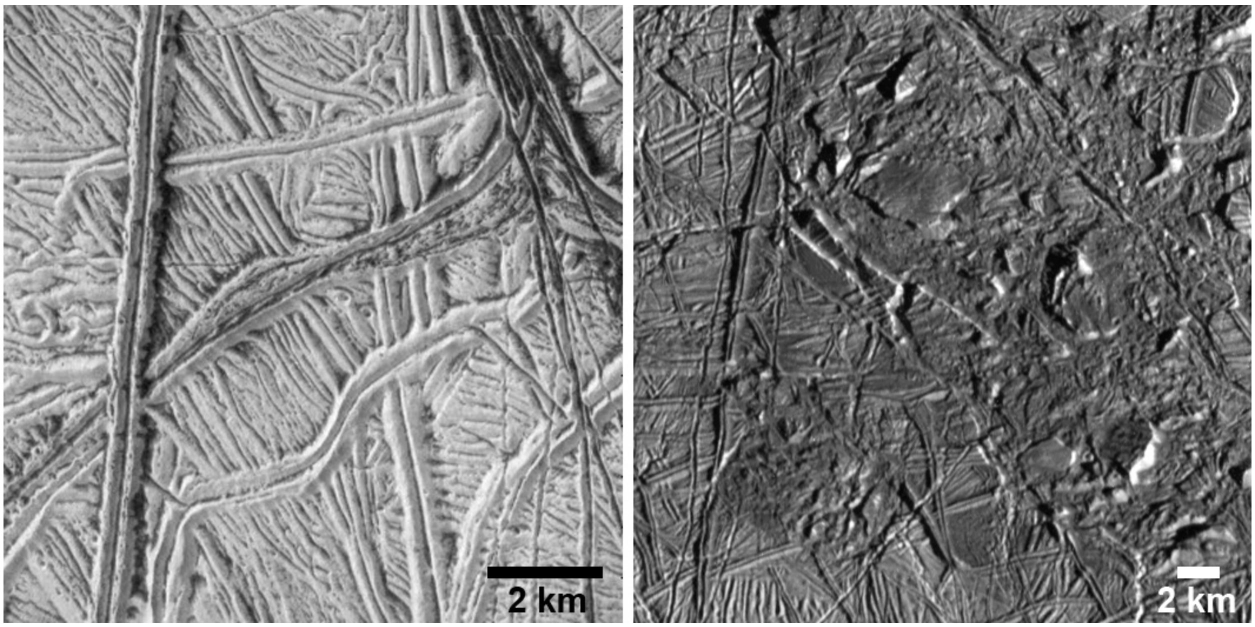

Figure 3: Samples of the bright "ridged plains" (left) and the darker and mottled "chaotic terrain," as imaged at high resolution from the Galileo spacecraft.

Many other dark spots are not impact sites, but instead are mottled terrain formed by internal processes. Overall Europa's surface can be divided into bright ridged plains and darker mottled terrain. At high resolution (**Figure 3,** left), the bright ridged plains are seen to be crisscrossed by a myriad of features, many of them double ridges with an axial valley, and broader bands of dark or gray material. It appears that generations of ridges, troughs, and bands crisscross the surface. The mottled terrain (**Figure 3,** right) has formed at the expense of the ridged plains, which have disintegrated in place to form a jumble of chaotic material and smooth patches.

There is strong reason to infer that Europa contains a globe-girdling ocean within it today.[4] Theoretical models say that enough heat is generated as Europa orbits Jupiter, its ice shell flexing as it does, as to maintain an ocean today. Europa's distinctive geological features hint of the existence of an internal ocean. And most compelling, magnetometer data from the

[3] Zahnle K., P. Schenk, H. F. Levison., L. Dones (2003) Cratering rates in the outer solar system. *Icarus*, 163, 263–289.; Bierhaus, E.B., K. Zahnle, and C.R. Chapman (2009). Europa's crater distributions and surface ages. In *Europa*, (R.T. Pappalardo et al., eds.), pp. 161–180. Univ. of Arizona Press, Tucson.
[4] McKinnon, W.B., R.T. Pappalardo, and K.K. Khurana (2009). Europa: Perspectives on an ocean world. In *Europa* (R.T. Pappalardo et al., eds.), pp. 697–709, Univ. of Arizona, Tucson.

Galileo spacecraft indicate an induced magnetic field at Europa, betraying the presence of subsurface saltwater.

The magnetic dipole of Jupiter is tilted by 10 degrees, and Europa and the other satellites are orbiting slowly about Jupiter compared to the 10 hour rotation rate of Jupiter. Because of the dipole's tilt, the satellites find themselves alternating above and then below the Jovian magnetic equator. Thus, Europa feels a changing Jovian field with an 11.2 hr period. The Galileo spacecraft measured that Europa creates its own induced magnetic field to counter that effectively alternating external Jovian field.[5] This implies that Europa's subsurface is behaving as a conductor, presumed a salty ocean, as shallow as ~15 to a few tens of kilometers below the surface.[6]

As it orbits around Jupiter, Europa "breathes" in and out, flexing in its slightly elliptical 3.55-day orbit about Jupiter. Europa is tidally stretched more as it gets closer to Jupiter and contracts as it moves further away. If there is indeed a decoupling ocean between the outer icy shell and the deeper interior, then the radial tide should allow the surface to rise and fall by a total of 30 m with each orbit.[7] From Europa's perspective, Jupiter also seems to move back-and-forth in the sky, which means that Europa's Jupiter-facing tidal bulge shifts back-and-forth across the satellite's surface.[8] This is a straightforward consequence of Kepler's laws of planetary motion, because Europa's spin rate is constant but its orbital velocity is not as it revolves about Jupiter.

The stretching and shrinking of Europa's tidal bulge, along with its back-and-forth motion, generates the heat that is thought to maintain its internal ocean.[9] Most of the heat is probably dissipated where Europa's ice is warmest, near the base of ice shell. It is also possible that heat is dissipated in the mantle,[10] but in a chicken-and-egg conundrum of planetary proportions, only if that mantle is already warm and deformable.

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[5] Kivelson M. G., K. K. Khurana, C. T. Russell, M. Volwerk, R. J. Walker, and C. Zimmer (2000). Galileo magnetometer measurements strengthen the case for a subsurface ocean at Europa. *Science*, 289, 1340.
[6] Khurana, K. K., M. G. Kivelson, K. P. Hand, and C. T. Russell (2009). Electromagnetic induction from Europa's ocean and the deep interior. In *Europa* (R.T. Pappalardo et al., eds.), pp. 571–587. Univ. of Arizona Press, Tucson
[7] Moore W. B. and G. Schubert (2000). The tidal response of Europa. *Icarus*, 147, 317–319.
[8] Greenberg, R., P. E. Geissler, G. Hoppa, B. R. Tufts, D. D. Durda, R. Pappalardo, J. W. Head, R. Greeley, R. Sullivan, and M. H. Carr, Tectonic processes on Europa: Tidal stresses, mechanical response, and visible features, *Icarus*, 135, 64–78, 1998 .
[9] Sotin, C., G. Tobie, J. Wahr, and W.B McKinnon (2009). Tides and tidal heating on Europa. In *Europa* (R.T. Pappalardo et al., eds.), pp. 85–117, Univ. of Arizona, Tucson.
[10] Moore, W.B., and H. Hussmann (2009). Thermal evolution of Europa's silicate interior. In *Europa* (R.T. Pappalardo et al., eds.), pp. 369–380. Univ. of Arizona Press, Tucson.

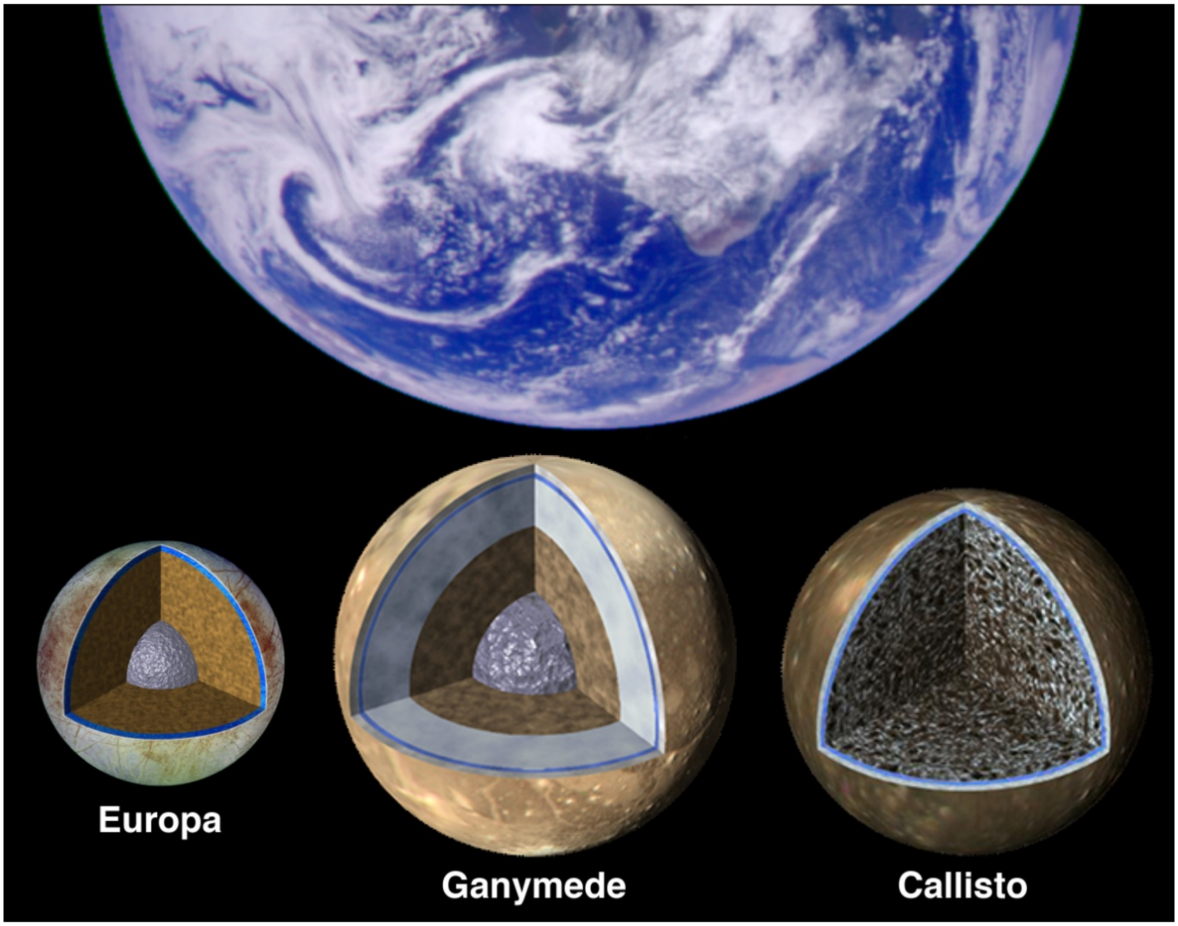

Figure 4: Possible oceans exist within the three ice-rich Galilean satellites, shown to scale with Earth. Europa's ocean has high potential for chemical nutrients that could permit life, making it very attractive in the search for life beyond Earth.

Planetary scientists are now coming to understand that oceans may exist in several of the solar system's icy satellites (**Figure 4**). The Galileo spacecraft also found an induced magnetic field at Callisto, suggesting a salty subsurface ocean even in this geologically rather "dead" world.[11] Ganymede hints at an induced field, in addition to its intrinsic dipole field.[12] Based on its obliquity Titan hints of a subsurface ocean,[13] likely a water-ammonia mixture, some 50 or so km beneath its surface lakes of ethane and methane.[14] Some middle-sized icy satellites might harbor oceans, if they contain ammonia, which lowers the melting temperature of ice.[15]

[11] Kivelson, M.G., F. Bagenal, W.S. Kurth, F.M. Neubauer, C. Paranicas, and J. Saur (2004). Magnetospheric interactions with satellites. In *Jupiter: The Planet, Satellites & Magnetosphere* (F. Bagenal et al., eds.), Cambridge Univ. Press, pp. 513–536.
[12] Kivelson et al., 2004.
[13] Bills, B.G., F. Nimmo (2008). Forced obliquity and moments of inertia of Titan. *Icarus*, 196, 293–297.
[14] Lorenz, R., and C. Sotin (2010). The moon that would be a planet. *Sci. Am*., 302, 20–27.
[15] Hussmann, F. Sohl, and T. Spohn (2006). Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-neptunian objects. *Icarus*, 185, 258–273.

Surprisingly, tiny Enceladus at Saturn hints of a watery ocean within, based on its chemistry and high thermal output.[16]

In comparing the probable watery oceans of the solar system, Earth's is the most unusual in being on the surface. Europa and the other icy satellites are teaching us that internal oceans may be the most common type of ocean, not just in our solar system, but throughout the universe. If these internal oceans are potentially habitable environments, then they may be the most common habitable environments that exist, probably much more common than Earth-like planets with surface oceans.

Of the extraterrestrial oceans of our solar system, Europa's is the most astrobiologically compelling, for four reasons. 1) Europa's ocean is probably in direct contact with its rocky mantle, permitting chemical nutrients to enter the ocean directly from below, especially if there is hydrothermal activity at the interface. 2) Europa is embedded within the harsh Jovian radiation belts, which create plentiful oxidants on the surface from radiolysis of ice, and which might permit metabolism of organisms if the oxidants can reach the ocean below. 3) Europa's icy shell is inferred to be thinner than the ice shells that hide deeper oceans within other large icy satellites, permitting more direct exchange between the surface and oceanic material at Europa, and potentially allowing surface oxidants to reach the ocean. 4) Europa is probably globally geologically active today, promoting surface-ocean exchange of materials including oxidants, and potentially promoting mantle heating and hydrothermal activity.

Given Europa's high astrobiological potential and intriguing geology and geophysical processes, twelve questions can be posed which, once answered, would contribute to changing our paradigm regarding Europa. Most of the answers will have to await future spacecraft exploration, but the answers to these questions will alter the way we think about Europa, other icy satellites, and possibly ourselves.

WHAT IS THE THREE DIMENSIONAL CHARACTER OF THE ICY SHELL?

Two end-member models have been argued based on the geology of Europa (**Figure 5**). In the "thin ice" model,[17] the ice shell is just a few kilometers thick, so thin that it can: crack all the way through to create outbursts; build ridges by slushy material coming up to the surface along cracks; build bands by opening of the ice shell to expose sea water that rapidly freezes; and create regions of chaotic terrain through direct melting of the ice shell. This model would imply a very high heat output from that rocky mantle, thus extreme tidal heating of the mantle, and little tidal heating in the ice shell.

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[16] Spencer, J.R., A.C. Barr, L.W. Esposito, P. Helfenstein, A.P. Ingersoll, R. Jaumann, C.P. McKay, F. Nimmo, and J.H. Waite (2009). Enceladus: An active cryovolcanic satellite. In *Saturn from Cassini-Huygens* (M.K. Dougherty et al., eds.), pp. 683–724, Springer.
[17] Greenberg, R., P. Geissler, G. Hoppa, and B.R. Tufts (2002). Tidal tectonic processes and their implications for the character of Europa's icy crust, *Rev. Geophysics*, 40, 1004, doi:10.1029/2000RG000096.

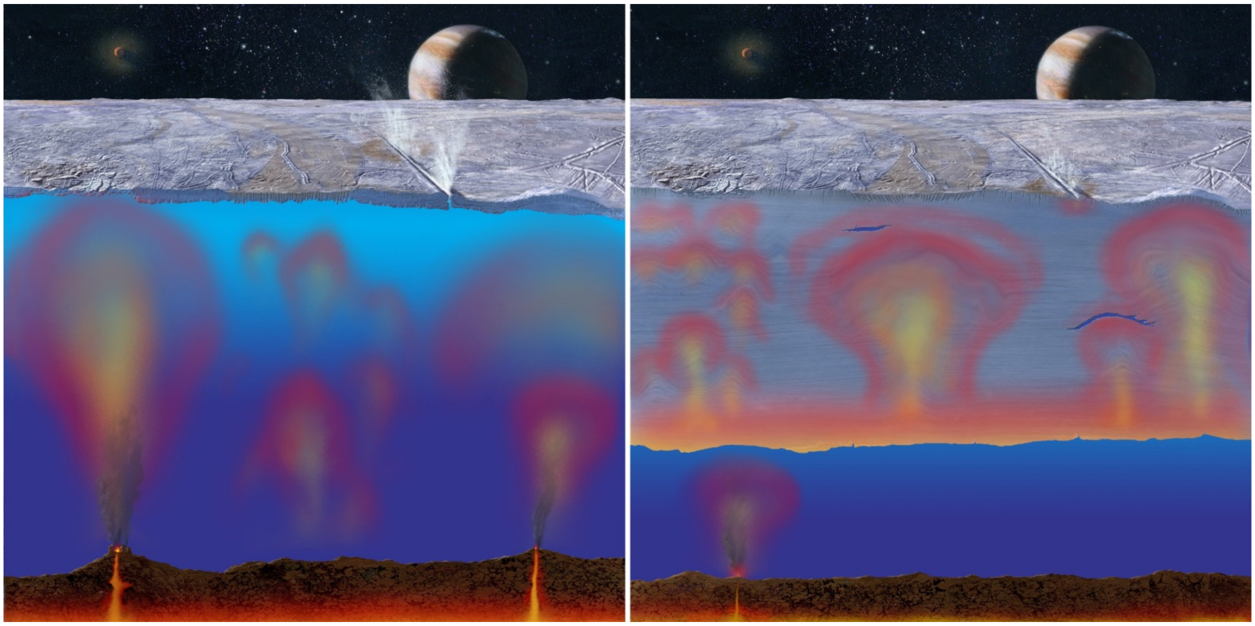


Figure 5: Schematic depiction of the "thin shell" (left) and "thick shell" (right) interpretations of Europa's geology. In the thin ice model, the ocean can be in direct contact with the surface through melting and venting. In the thick ice model, the contact between the surface and ocean is indirect, through convection of warm ice. Art by M. Carroll.

In contrast, the "thick ice" model[18] suggests an ice shell tens of kilometers thick, in which: ridges form from largely solid-state processes such as shear heating; bands form through an icy analog to plate-tectonic-like spreading; solid-state convection transports warm icy material from the bottom of the ice shell toward the surface; tidal heating can trigger partial melting within the ice shell, especially if low melting-point contaminants are present; and tidal heating in the rocky mantle is small or negligible.

These end-member models have different implications for habitability, especially for whether an ocean can be in direct contact with the surface (such as through melting), or in indirect contact with the surface (through ice shell convection). As discussed below, the processes by which the ocean and the surface can exchange materials are key to understanding Europa's potential habitability.

[18] Pappalardo, R.T., M.J.S. Belton, H.H. Breneman, M.H. Carr, C.R. Chapman, G.C. Collins, T. Denk, S. Fagents, P.E. Geissler, B. Giese, R. Greeley, R. Greenberg, J.W. Head, P. Helfenstein, G. Hoppa, S.D. Kadel, K.P. Klaasen, J.E. Klemaszewski, K. Magee, A.S. McEwen, J.M. Moore, W.B. Moore, G. Neukum, C.B. Phillips, L.M. Prockter, G. Schubert, D.A. Senske, R.J. Sullivan, B.R. Tufts, E.P. Turtle, R. Wagner, and K.K. Williams (1999). Does Europa have a subsurface ocean? Evaluation of the geological evidence. *J. Geophys. Res.*, 104, 24015–24055; Pappalardo, R.T. (2010). Seeking Europa's ocean. In *Galileo's Medicean Moons: Their Impact on 400 Years of Discovery*, Proceedings IAU Symposium No. 269 (C. Barbieri et al., eds.), pp. 101–114.

WHAT ARE THE MECHANISMS OF ICY SHELL CRACKING?

There are many troughs that cut across Europa's surface, and evidence that troughs build into ridges. Understanding the stressing mechanisms that can crack the ice shell will help to elucidate its history and relationship to an ocean beneath. An important contribution comes from modeling of cycloidal features on Europa's surface. These bizarre chains of arcs were first observed on Europa by Voyager 2, and were observed with wider spatial distribution, and with much greater imaging resolution with Galileo spacecraft imaging.

Randy Tufts and Greg Hoppa first realized that "diurnal" (orbital) stresses on Europa, generated from the combination of a radial tide and libration tide, rotate over the course of each Europa orbit (**Figure 6**).

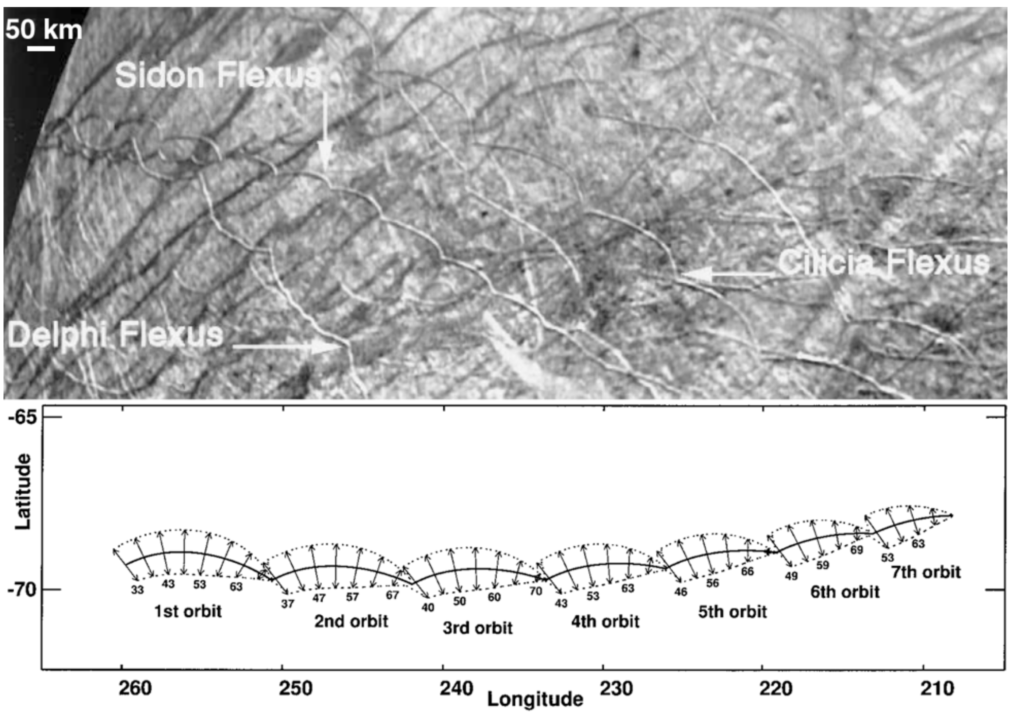


Figure 6: (top) Cycloidal ridges, here imaged by the Voyager 2 spacecraft in 1979. (bottom) Model trajectory of a fracture propagating eastward across Europa. Arrows indicate the direction of least compressive (maximum tensile) diurnal stress. The magnitude and direction of the stress vary, permitting the fracture to propagate in a cycloidal path, with one arc traced each Europan orbit (small numbers indicate hours after perijove, i.e. after Europa's closest point in its orbit to Jupiter). At cusps, stress magnitude diminishes and crack propagation wanes, until sufficient stress builds during the next orbit to permit further propagation. After Hoppa et al.[19]

[19] Hoppa G. V., B. R. Tufts, R. Greenberg, and P.E. Geissler (1999). Formation of cycloidal features on Europa. *Science*, 285, 1899–1902.

Thus, if a fracture propagates at just the right speed across the surface (about 1 m/s), it can follow the changing direction and magnitude of stress to create an arc.[20] Most portions of Europa's surface see a stress that rotates and changes in magnitude during each Europan day, i.e. with each orbit around Jupiter. If this model is correct, it raises many questions.[21] Why is the effective speed of fracture propagation across the surface so slow? Can such fractures penetrate deeply enough to significantly affect the geology? How do fractures transition to ridges? There are many questions related to the mechanisms of ice shell cracking, but this elegant model for cycloid formation is a start toward the answers.

WHAT IS THE ROTATION HISTORY RECORDED IN THE ICY SHELL?

Dynamical modeling suggests that the ice shell will get a slight extra torque near perijove, when it is closest to Jupiter, which should spin up the ice shell if it is decoupled from the interior by an ocean, promoting rotation that is slightly faster than synchronous.[22] However, other effects may prevent NSR from happening.[23] Observations of Europa's surface provide clues as to whether nonsynchronous rotation has actually occurred.

Unlike the diurnal stresses which act on the 3.5 orbital day period of Europa, nonsynchronous rotation is predicted to act on a timescale of something like 10^7 years per rotation. Nonetheless, such can build significant stresses in Europa's ice shell, significantly more than the orbital stresses.[24] Previous work has shown that the global-scale pattern of Europa's lineaments is a good match to the tensile stresses predicted if the ice shell is slowly slipping relative to the interior.[25]

[20] Hoppa G. V., B.R. Tufts, R. Greenberg, and P.E. Geissler (1999). Formation of cycloidal features on Europa. *Science*, 285, 1899–1902.

[21] Lee, S., R. T. Pappalardo, and N. C. Makris (2005). Mechanics of tidally driven fractures in Europa's ice shell. Icarus, 177, 367–379; Kattenhorn, S.A. and T. Hurford (2009). Tectonics of Europa. In *Europa* (R.T. Pappalardo et al., eds.), pp. 199–236. Univ. of Arizona Press, Tucson.

[22] Greenberg, R., and S.J. Weidenschilling (1984). How fast do Galilean satellites spin? *Icarus*, 58, 186–196; Ojakangas G. W. and D. J. Stevenson (1989a). Thermal state of an ice shell on Europa. *Icarus*, 81, 220–241.

[23] Bills, B.G., F. Nimmo, O. Karatekin, T. Van Hoolst, N. Rambaux, B. Levrard, and J. Laskar (2009). Rotational dynamics of Europa. In *Europa* (R.T. Pappalardo et al., eds.), pp. 119–136, Univ. of Arizona, Tucson; Goldreich, P.M. and J.L. Mitchell (2010). Elastic ice shells of synchronous moons: Implications for cracks on Europa and non-synchronous rotation of Titan. *Icarus*, 209, 631-638.

[24] Wahr, J., Z.A. Selvans, M.E. Mullen, A.C. Barr, G.C. Collins, M.M. Selvans, and R.T. Pappalardo (2009). Modeling stresses on satellites due to nonsynchronous rotation and orbital eccentricity using gravitational potential theory. *Icarus*, 200, 188–206.

[25] Kattenhorn and Hurford, 2009, and references therein.

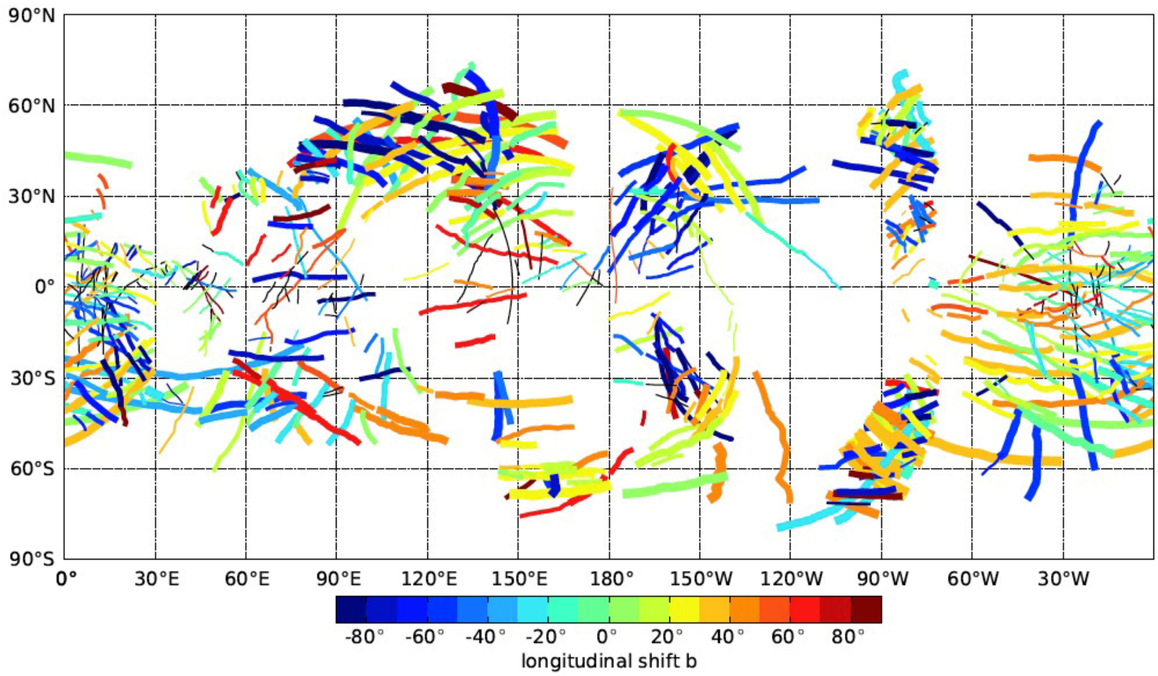


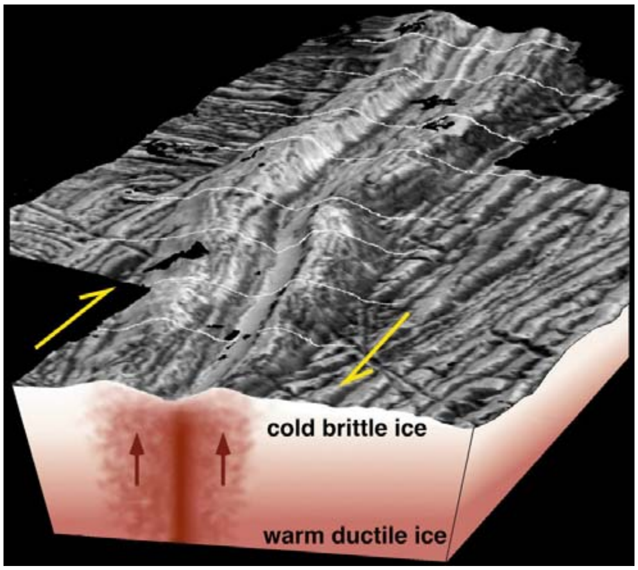
Figure 7: Global-scale lineaments on Europa (compare to Figure 2). Color corresponds to the backrotation **b** resulting in the lineament's best fit to the stress predictions of nonsynchronous rotation. Wider lines imply a better fit to the stress predictions, while thin black lineaments fit poorly and were excluded from the fit. Most lineaments fit well at some degree of backrotation; more important is the concentration of lineament fits near 30° of backrotation (light blue). [26]

Selvans [27] notes that nearly any lineament on Europa's surface can fit the nonsynchronous stress pattern, if one allows for an arbitrary longitudinal displacement of Europa's shell by nonsynchronous rotation; in fact, he finds that a random set of great circles fits the nonsynchronous stress pattern better than do Europa's actual global scale lineaments. Thus, it is not so much the goodness of fit of individual lineaments to the global stress pattern of nonsynchronous rotation which matters, but that backrotation of Europa's ice shell shows a spike in the lineament formation history, suggesting past lineament formation was concentrated in backrotation (**Figure 7**). This provides the strongest evidence for nonsynchronous rotation of Europa's ice shell, and indirect evidence for an internal ocean.

There are other processes that can also induce reorientation of Europa's ice shell. Simply because it is much colder at the poles, Europa's ice shell is predicted to be thicker at the poles. This can induce true polar wander, causing the ice shell to flip by 90° to place the thickest ice at the equator.[28] Schenk et al.[29] have argued that rare arcuate depressions on Europa fit the predictions of stresses generated from true polar wander. Putting together the rotation history of Europa from its crisscrossing lineaments is a task in its infancy. To date, only about

[26] Selvans, Z.A. (2010). *Time, Tides, and Tectonics on Icy Satellites*. Ph.D. thesis, University of Colorado, Boulder.
[27] Selvans, 2010.
[28] Ojakangas G. W. and D.J. Stevenson (1989b). Polar wander of an ice shell on Europa. *Icarus* 81, 242–270.
[29] Schenk P., I. Matsuyama, and F. Nimmo (2008). True polar wander on Europa from global-scale small-circle depressions. *Nature*, 453, 368–371.

15% of Europa's surface is imaged at a resolution of 200 m/pixel of better,[30] which is necessary to identify its regional-scale landforms and their cross-cutting relationships. Once a future mission provides global high resolution coverage, the full story of Europa's "pick-up-sticks" history could be assembled. Then we will be able to disentangle the complicated rotational history of Europa's ice shell.



How do ridges form, and is liquid water involved?

Ridges are the most ubiquitous feature on Europa's surface, yet we do not understand how they form. There has been a range of models suggested: volcanism, tidal pumping, diapirism, compression, diking, shear heating, and volumetric strain.[31] Some of these models directly involve liquid water, others operate with warm ice alone, and others require the indirect tidal effects enabled by an ocean.

Figure 8: Schematic description of the shear heating model applied to Europa's ridges. Tidal kneading induces strike-slip motion and fractures, inducing frictional warming of ice to either side of the fracture. Warm ice may upwell buoyantly or serve as a plane of weakness that permits local compression to form a ridge; some ice might even be able to melt.

A quite comprehensive model is one of shear heating (**Figure 8**).[32] If fractures penetrate through the cold, brittle near-surface ice to warmer ductile ice below, then the diurnal stresses that are rotating through Europa's day in the presence of a subsurface ocean will cause each side of the fracture to slide back and forth. Imagine if the San Andreas fault, instead of moving in one direction, moved back and forth by tens of centimeters on the time scale of 3.5 days. That is what may be happening along Europa's fractures, generating sufficient frictional heat as to warm the ice on either side, allowing the ice to rise buoyantly just slightly (sufficient to push the surface up into a ridge), or creating a weak axial zone that allows for compression to concentrate there to form a ridge. Heating might be intensive enough to melt ice along the ridge axis. Shear heating provides an elegant model that combines predictions of tidal stressing, cracking, strike-slip motion, and frictional heating.

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[30] Doggett, T., R. Greeley. P. Figueredo, and K. Tanaka, Geologic stratigraphy and evolution of Europa's surface. In *Europa (* R. T. Pappalardo et al., eds.), pp. 137–160. Univ. of Arizona Press, Tucson.
[31] Prockter, L.M. and G.W. Patterson (2009). Morphology and evolution of Europa's ridges and bands. In *Europa* (R.T. Pappalardo et al., eds.), pp. 237–258, Univ. of Arizona, Tucson.
[32] Nimmo F. and E. Gaidos (2002) Strike-slip motion and double ridge formation on Europa. *J. Geophys. Res.*, 107, 1–8 .

A future orbiter could map out the three-dimensional morphology of Europa's ridges, potentially coupled with ice-penetrating radar observations to understand their subsurface "plumbing."[33] In this way, we will be able to understand ridge formation, and whether and how liquid water is involved.

HOW ARE CHAOTIC REGIONS FORMED, AND IS LIQUID WATER INVOLVED?

Europa's aptly named regions of chaotic terrain are places where blocks of the ridged terrain have broken, translated, rotated, and tilted within a matrix of hummocky material.[34] The two end-member "thin shell" and "thick shell" models apply here as well (**Figure 9**).

In a thin shell model, locally complete melting of the ice shell might form zones of chaotic terrain, if sufficient heat could be concentrated for sufficient time for melting. Indeed, chaotic terrain does look a lot like Arctic sea ice; however, the amount of energy needed for melting is large. If the ice shell is greater than several kilometers thick, it will tend to flow to fill in a hole faster than it can melt.

In the thick ice shell model, a field of individual diapirs (perhaps coupled with concentrated tidal heating in the warm ice) causes partial melting to create chaos zones. This would permit blocks to translate, rotate, and tip, like crowd surfing on the upstretched hands of an exuberant concert audience.

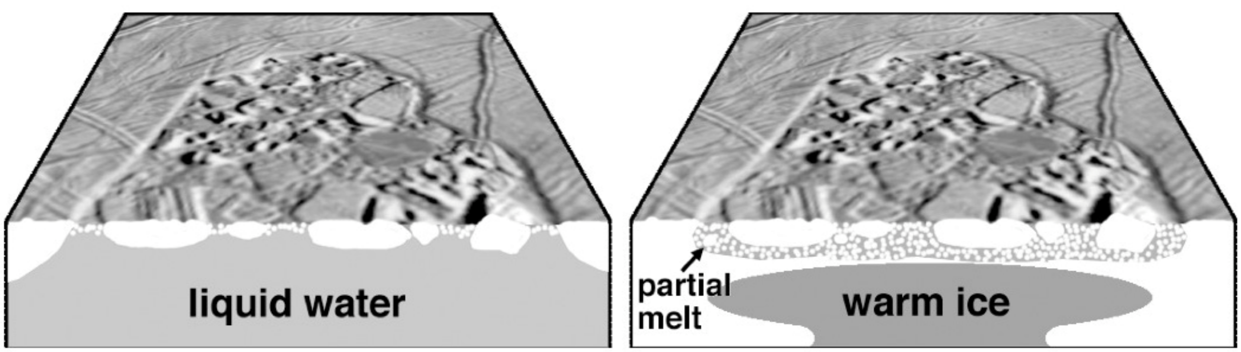

Figure 9: Chaotic terrain might form through direct melting of a thin ice shell, or through partial melting of a thick ice shell above a convecting interior.[35]

Which of these models better applies has implications for Europa's habitability, because it is important to understand whether and how surface oxidants can reach the subsurface ocean (as discussed below). It also has implications for whether oceanic materials can directly reach the surface, or whether transport to the surface is indirect through convection.

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[33] Blankenship, D.D., D. A. Young, W. B. Moore, and J. C. Moore (2009). Radar sounding of Europa's subsurface properties and processes: The view from Earth. In *Europa* (R.T. Pappalardo et al., eds.), pp. 631–654. Univ. of Arizona Press, Tucson.
[34] Collins, G., and F. Nimmo (2009). Chaos on Europa. In *Europa* (R.T. Pappalardo et al., eds.), pp. 259–282. Univ. of Arizona Press, Tucson.
[35] Collins and Nimmo, 2009.

IS THE ICY SHELL CONVECTING?

Pits, spots, and domes pepper Europa's surface, composing much of its mottled terrain.[36] Domes are areas where the surface has been pushed up from below, and are morphologically related to small zones of chaotic terrain. These features have been related to the rise of warm ice diapirs toward the surface (**Figure 10**), the expression of solid-state convection of Europa's ice shell.[37]

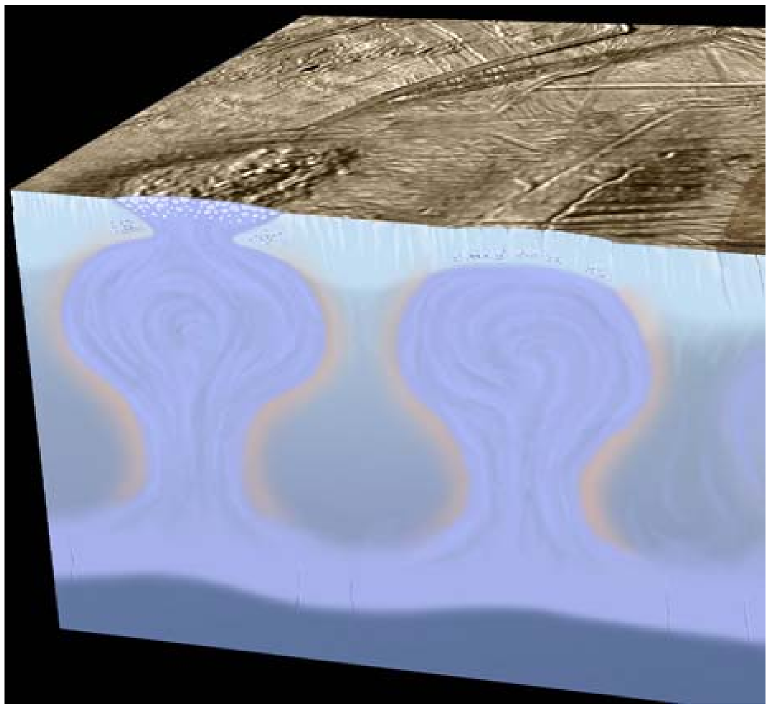

Figure 10: Surface spots and small chaotic zones (left) and uplifted domes (right) may be the expression of warm ice diapirs that rise through the ice shell due to convection.

Convection models[38] suggest that Europa's ice shell must be >15 km or so thick for convection to initiate, depending on the ice grain size. Diapiric plumes can rise from the ice-ocean interface towards the surface in ~10^5 yr. However, in pure ice, it is very difficult for a warm ice diapir to break through the very cold near-surface "stagnant lid" that caps the convective zone, which forms the top ~30% of the ice shell. It may take compositional variations or concentrated tidal heating to permit diapirs to rise all the way to the surface and extrude.

[36] Pappalardo, R. T., J. W., Head, R. Greeley, R. J. Sullivan, C. Pilcher, G. Schubert, W. Moore, M. H. Carr, J. M. Moore, M. J. S. Belton, and D. L. Goldsby (1998). Geological evidence for solid-state convection in Europa's ice shell. *Nature*, 391, 365–368.

[37] Barr, A.C. and A.P. Showman (2009). Heat transfer in Europa's icy shell. In *Europa* (R.T. Pappalardo et al., eds.), pp. 405–430. Univ. of Arizona Press, Tucson.

[38] Barr and Showman, 2009, and references therein.

Multiple feedbacks of ice temperature, strain rate, and grain size are relevant to ice shell convection, making it a geophysically complex issue. Important issues are whether Europa's ice shell is in fact convecting, how convection is related to surface features, and whether ice shell convection is isolated or widespread in space and time.

WHAT ARE THE NON-ICE COMPONENTS OF THE ICY SHELL?

Based on near infra-red spectroscopy from the Galileo spacecraft, we know that non-ice materials on Europa are concentrated in the satellite's visibly darker and redder regions.[39] Asymmetric and relatively shallow absorption bands are observed at 1.5 and 2 µm. Comparison of these spectra to various candidate salts (**Figure 11**) suggests that hydrated salts, such as magnesium sulfate hydrate and sulfuric acid hydrate, may be present.[40] Magnesium sulfate hydrate and other salts may be a significant component of the ocean, perhaps indicating that oceanic materials are observable on the surface. Sulfuric acid hydrate may be produced on the surface through radiolysis,[41] processed by irradiation of surface materials; the reddish color of Europa's endogenic materials could be similarly explained if radiolysis forms chains of sulfur through high-energy particle bombardment of sulfur-bearing compounds.

Future observations using improved techniques,[42] including higher spatial and spectral resolution remote spectroscopy, could help to identify the make-up of Europa's surface materials, perhaps revealing the composition of its ocean. Moreover, a mass spectrometer in orbit could reveal Europa's surface composition, because energetic particles sputter surface materials to create a tenuous atmosphere, which could be sampled directly by a spacecraft from a ~100 km orbital altitude.

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[39] Carlson, R. W., W. M. Calvin, J. B. Dalton, G. B. Hansen, R. L. Hudson, R. E. Johnson, T. B. McCord, and M. H. Moore (2009). Europa's surface composition. In *Europa* (R.T. Pappalardo et al., eds.), pp. 283–328. Univ. of Arizona Press, Tucson.

[40] McCord T. B., G. B. Hansen, D. L. Matson., T. V. Johnson, J. K. Crowley, F. P. Fanale, R. W. Carlson, W. D. Smythe, P.D. Martin, C. A. Hibbitts, J. C. Granahan, A. Ocampo, and the NIMS Team (1999). Hydrated salt minerals on Europa's surface from the Galileo NIMS investigation. *J. Geophys Res*., 104, 11827–11851; Dalton J. B. (2007) Linear mixture modeling of Europa's nonice material using cryogenic laboratory spectroscopy. *Geophys. Res. Lett*., 34, L21205, doi: 10.1029/2007GL031497.

[41] Carlson, R. W., R. E. Johnson, and M. S. Anderson (1999). Sulfuric acid on Europa and the radiolytic sulfur cycle. *Science*, 286, 97–99.

[42] Greeley et al., 2009.

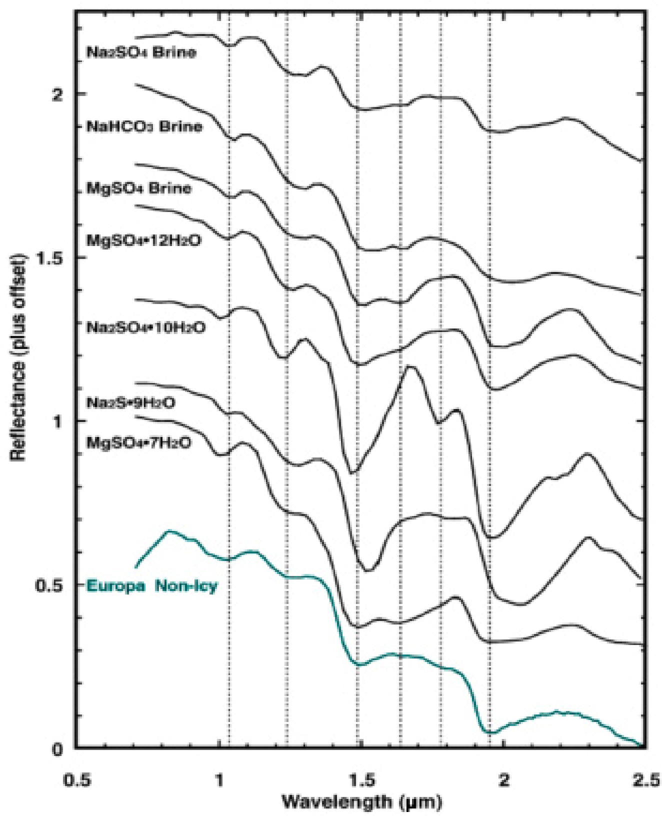

Figure 11: The infra-red spectral fingerprint of non-ice material on Europa's surface (bottom curve) shows characteristics similar to some salts measured at cryogenic temperatures. After Dalton.[43]

HOW ACTIVE IS EUROPA TODAY?

Given the youthful age of Europa's surface, it is expected that tidal kneading of Europa probably still causes cracking and shifting of the icy surface today. However, current-day activity has not been confirmed at Europa, and the kind of dramatic heat flow and jetting activity observed at Enceladus by the Cassini spacecraft have not (yet) been observed at Europa.

Resolution and areal coverage limitations mean that comparisons between Voyager and Galileo data have not revealed any visible changes.[44] A lack of change at 2 km/pixel scale in the nearly 20 years between Voyager and Galileo images **(Figure 12)** is consistent with a tens of millions of years surface age. If Enceladus-like activity occurs at Europa today, it might not have been observed by Galileo, which was limited in its thermal observations and high-phase imaging.

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[43] Dalton, 2007.

[44] Phillips, C.B., A.S. McEwen, G.V. Hoppa, S.A. Fagents, R. Greeley, J.E. Klemaszewski, R.T. Pappalardo, K.K. Klaasen, and H.H. Breneman (2000). The search for current geologic activity on Europa. *J. Geophys. Res.*, 105, 22,579–22,598.

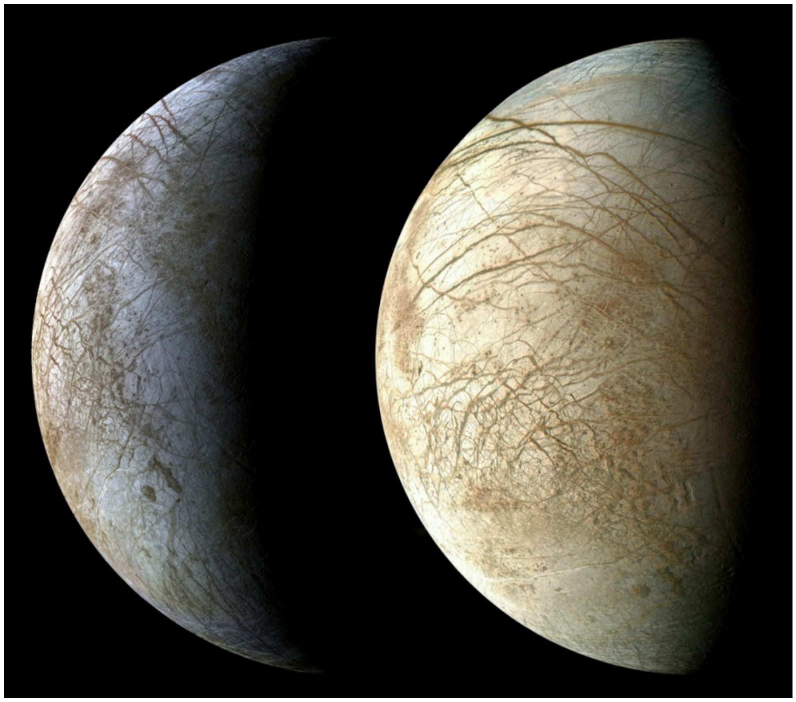

Figure 12: Voyager 2 mosaic (left) of Europa's anti-Jovian hemisphere (1.9 km/pixel), compared to a Galileo mosaic (right) of similar territory and resolution (1.4–1.6 km/pixel) obtained nearly 20 years later. Voyager mosaic courtesy Paul Schenk; Galileo mosaic courtesy Ted Stryke.

Whether a future orbiter mission could detect current-day activity is uncertain. The rate and level of current-day activity is not known, and indeed Europa could be in a relatively inactive phase of its history today (as discussed below). Ultimately, being certain of whether Europa is an active world today may require placing a seismometer on the surface using a simple surface element, such as a lander or penetrator.

IS THE ROCKY MANTLE HOT?

As mentioned above, the thermal state of Europa's rocky mantle is relevant to issues of ice shell thickness, geological style, and habitability. Models of heat transport in Io[45] have been applied to Europa,[46] suggesting that Europa's mantle should be in one of two stable states of temperature and heat flux (**Figure 13**). In one stable state, radiogenic heating alone maintains the heat flux from the mantle, as balanced by cooling by convection, in which case the mantle is cold and Moon-like. In the other stable state, Europa's mantle is hot and tidally heated, with tidal heating reaching equilibrium with cooling by convection and volcanism at temperatures so high as to initiate melting, and the mantle is Io-like. An unstable equilibrium exists in between, where convective cooling balances modest tidal heating, but the system is generally driven away from this state, toward one of the stable equilibriums.

[45] Moore W. B. (2003). Tidal heating and convection in Io. *J. Geophys. Res*., 108, 5096, doi: 10.1029/2002JE001,943
[46] Moore and Hussmann, 2009.

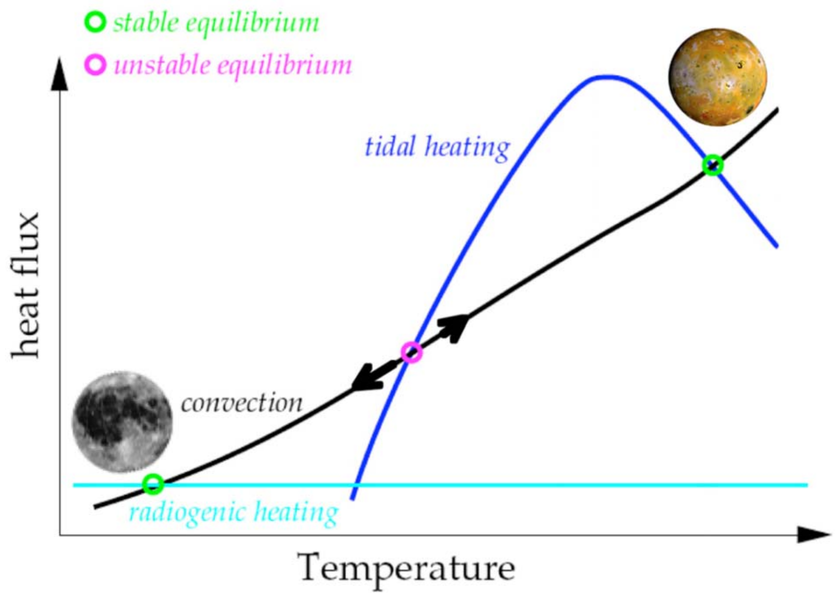

Figure 13: Schematic representation of the balance between heat flux and temperature within a tidally heated rocky satellite like Io, or within Europa's rocky mantle. In a low-temperature (Moon-like) equilibrium state, tidal heat is insignificant and radiogenic heat production (light blue horizontal line) is balanced by convective heat loss (black curve). [47, 48] In a high-temperature (Io-like) equilibrium state, tidal heat production (dark blue curve) is high and is balanced by convective and volcanic heat loss (black curve). The intermediate point where modest tidal heating balances solid-state convective heat loss is an unstable equilibrium. It is plausible that Europa's mantle oscillates as its and Io's orbit and tidal heating vary. Figure courtesy William Moore.

The Io-like stable state is much more attractive for hydrothermal vents and life within Europa, but of course this desire by humans cannot affect the actuality of the thermal state Europa is in. It might be possible that Europa's mantle oscillates about a constantly moving stable point, due to orbital evolution driven largely by Io, shifting its heat flux and temperature in response to cyclical changes in its orbital eccentricity (discussed below).

HAS EUROPA'S ACTIVITY CHANGED OVER TIME?

Geological mapping suggests that chaos regions are generally newer than the ridged plains.[49] However, it would be strange for Europa's youthful surface to have gone through a transition in its geological style, in only the last 1% of geological time. It is plausibly a coincidence that Europa recently went through a chaos forming event, for example if heating has decreased and the ice shell thickened to trigger convection, or if Europa warmed up to increase the vigor of convection.

[47] Moore W. B. (2003). Tidal heating and convection in Io. *J. Geophys. Res*., 108, 5096, doi: 10.1029/2002JE001,943
[48] Moore and Hussmann, 2009.
[49] Pappalardo et al., 1999; P. H. Figueredo and R. Greeley (2004). Resurfacing history of Europa from pole-to-pole geological mapping. *Icarus*, 167, 287–312; Doggett et al., 2009, and references therein.

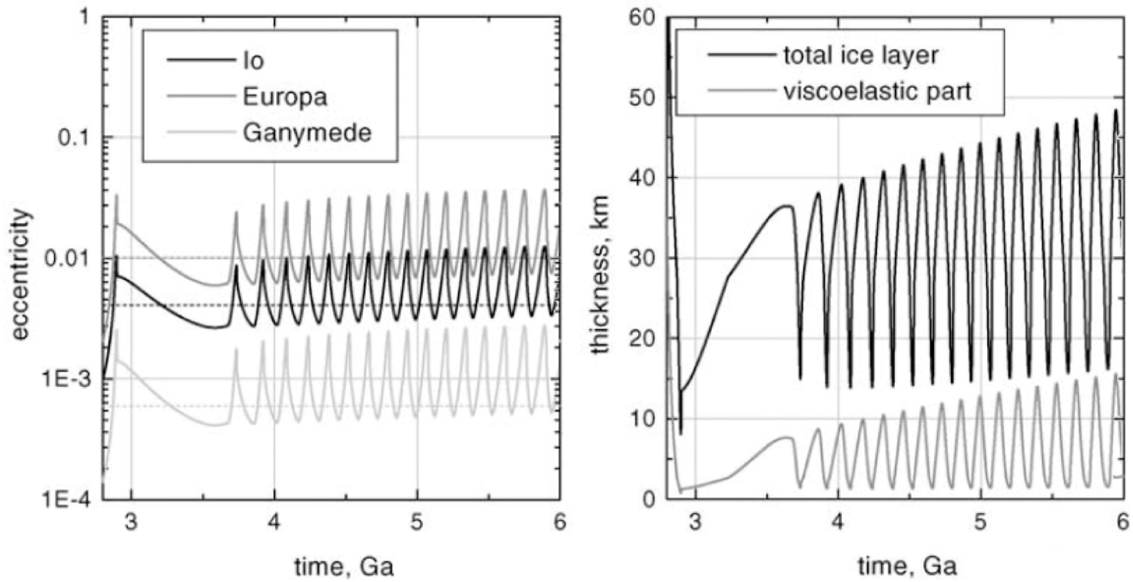

Figure 14: The inner three Galilean satellites are locked in the Laplace resonance, such that variation in the orbital eccentricity of Io will affect the eccentricity of Europa and Ganymede. Change in Europa's orbital eccentricity is predicted to affect the thickness of Europa's ice shell through time.

An attractive possibility arises from the coupling of Europa's orbit to the orbits of Io and Ganymede.[50] Io's orbit is predicted to go through periodic changes in eccentricity, driven by changes in the rate of tidal heating and heat transfer, on time scales of ~100 Myr.[51] Maintenance of the Laplace resonance between the three inner Galilean satellites means that Io would pull Europa along with it, similarly altering Europa's eccentricity **(Figure 14)**. Such would alter the tidal heating rate, which could change the predicted thickness of Europa's ice shell from ~15 to 35–45 km through time. Thus, it is plausible that Europa's shell may have thickened over the geologically recent past, allowing convection to commence or intensify, and triggering formation of mottled and chaotic terrain.

If the ocean is inhabited by organisms which rely on geological activity to supply their chemical nutrients, from hydrothermal activity of the mantle below and/or from down-stirring of oxidants from the ice shell above, we might consider whether such organisms could survive through fallow periods of nearly 100 Myr in length. If so, what evolutionary adaptations might result? The implications of such long-period variations in activity are unknown on our own planet, but ponderable at Europa.

HOW DOES EUROPA COUPLE TO THE EXTERNAL ENVIRONMENT?

Europa is immersed in and coupled to the powerful radiation belts of Jupiter (**Figure 15**). Particle bombardment is key to modifying Europa's surface composition through radiolysis

[50] Hussmann and Spohn, 2004.

[51] Ojakangas G. W. and D. J. Stevenson (1986). Episodic volcanism of tidally heated satellites with application to Io. *Icarus*, 66, 341–358.

and implantation of ions, such as from Io.[52] Sputtering generates Europa's tenuous atmosphere and may modify the surface through slow redistribution of water molecules.[53] Europa's relative motion through Jupiter's magnetic field generates the induced magnetic field that betrays its ocean.[54] Understanding the composition and potential habitability of Europa's ocean is inherently linked to understanding the satellite's external environment, including the energy spectrum and composition of bombarding particles. In fact, the potential habitability of Europa is tied to its particle environment (as discussed below), and our understanding of it.

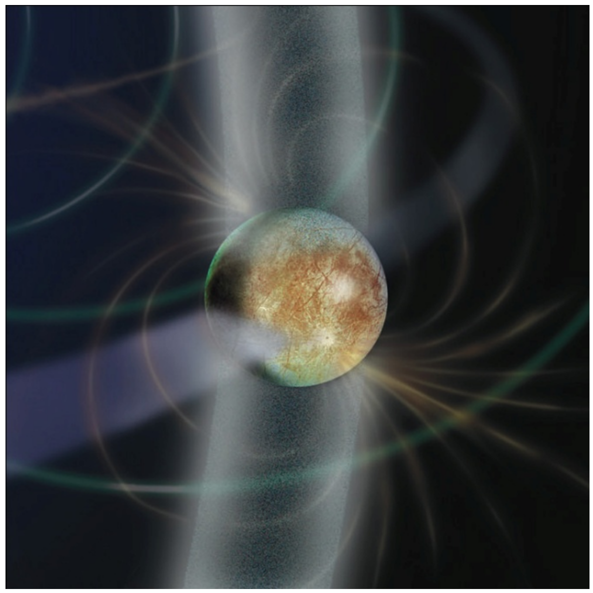

Figure 15: Europa is immersed in and coupled to the powerful radiation belts of Jupiter. Figure courtesy Michael Carroll.

IS EUROPA'S OCEAN HABITABLE AND INHABITED?

Whether Europa's ocean is inhabited is one of the most significant questions of modern planetary exploration. However, it is not a question that can be readily answered with today's technology, as such would require going to Europa's surface and analyzing samples *in situ*.[55] But the first step toward an answer is to assess from an orbiting spacecraft whether Europa is

[52] Carlson et al., 2009; C. Paranicas, J. F. Cooper, H. B. Garrett, R. E. Johnson, and S. J. Sturner (2009). Europa's radiation environment and its effects on the surface. In *Europa* (R.T. Pappalardo et al., eds.), pp. 529–544. Univ. of Arizona Press, Tucson.

[53] Johnson, R.E., M. H. Burger, T. A. Cassidy, F. Leblanc, M. Marconi, and W. H. Smyth (2009). Composition and detection of Europa's sputter-induced atmosphere. In *Europa* (R.T. Pappalardo et al., eds.), pp. 507–528. Univ. of Arizona Press, Tucson; McGrath, M. A. , C. J. Hansen, and A. R. Hendrix (2009). Observations of Europa's Tenuous Atmosphere. In *Europa* (R.T. Pappalardo et al., eds.), pp. 485–506, Univ. of Arizona, Tucson.

[54] Khurana et al., 2009.

[54.] Hand, K.P., C. F. Chyba, J. C. Priscu, R. W. Carlson, and K. H. Nealson (2009). Astrobiology and the potential for life on Europa. In *Europa* (R.T. Pappalardo et al., eds.), pp. 589–630. Univ. of Arizona Press, Tucson.

a habitable environment today.[56] This requires identification of the three necessary "ingredients" for life: liquid water, bioessential elements, and chemical energy for life.

The first ingredient can be readily confirmed by an orbiting spacecraft, which could directly measure the tidal signature of a subsurface ocean.[57] Chemical measurements would be required[58] to confirm the existence at Europa of the second ingredient, the "bioessential" elements from which organic molecules are built, including carbon, nitrogen, phosphorous, sulfur, and various metals. Such are presumed to be present in any world with a significant rock fraction.

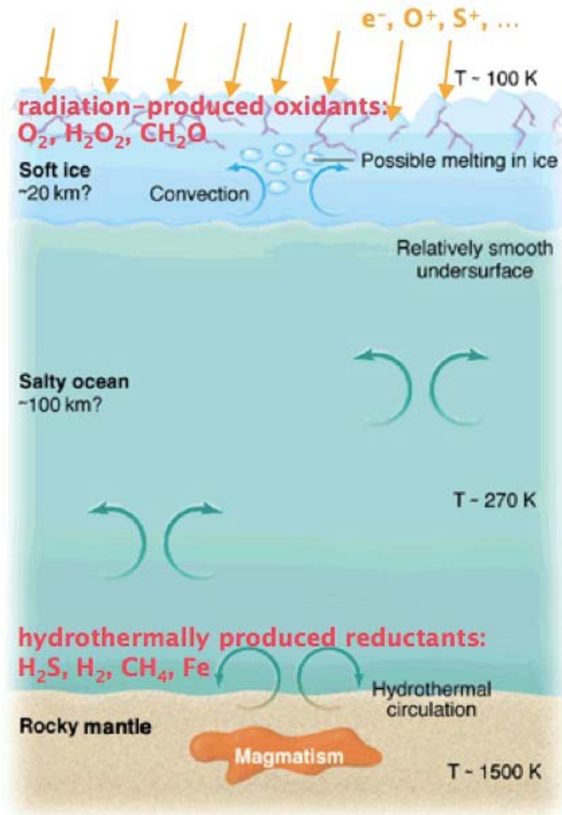

Figure 16: Representation of Europa's ice shell, ocean, and rocky mantle. Oxidants are produced at Europa's surface by ion irradiation (arrows), and might be stirred into Europa's interior by geological processes. Reductants might be produced at the ocean floor if the mantle rock is hot, promoting hydrothermal circulation. Such oxidants and reductants could serve to fuel life in Europa's ocean.[59]

The third ingredient is the least certain. In the certain absence of photosynthesis beneath Europa's ice cover, chemical energy is required to power metabolism within Europa's ocean. Such implies chemical disequilibrium, i.e., a redox potential, within the ocean. Can radiation-induced oxidants get into the surface ocean? Such depends on the resurfacing mechanisms

[56] Greeley et al., 2009.
[57] Moore and Schubert, 2000.
[58] Hand et al., 2009.
[59] After Stevenson, 2000.

and ocean-surface exchange processes,[60] which we do not yet understand. Is the mantle hot enough that there is hydrothermal circulation and production of reductants at the ocean floor? If oxidants and reductants can combine within Europa's watery depths, there is great potential for life (**Figure 16**).

These issues are key to the objectives of the planned Jupiter Europa Orbiter, currently in the development stage.[61] Its objectives relate to the ocean, ice shell, composition, geology, and local particle environment of Europa, as well as Europa's relation to the Jupiter system as a whole. Success of this mission would change our current paradigm of Europa in particular and of icy satellites in general.

Certainly any spacecraft mission leaves some questions unanswered, and presents a myriad of new ones. As we better understand Europa's ocean and its potential habitability, and ultimately whether Europa actually contains life, then like 400 years ago, Europa may contribute to changing a scientific paradigm: "Are we alone in the Universe?"

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[60] Hand, K. P., R. W. Carlson, and C. F. Chyba (2007). Energy, chemical disequilibrium, and geological constraints on Europa. *Astrobiology*, 7, 1–18.

[61] Greeley et al., 2009; Clark, K., J. Boldt, R. Greeley, K. Hand, I. Jun, R. Lock, R. Pappalardo, T. Van Houten, and T. Yan. Return to Europa: Overview of the Jupiter Europa Orbiter mission. *Adv. Space Res.,* in press.

The Saturn System as Seen from the Cassini Mission

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INTRODUCTION

The Cassini Orbiter is one of the most complex spacecraft ever developed: all together, the spacecraft and its ensemble of instruments can be considered as a complex experiment, aimed at studying the Saturn system, unveiling a new world. In this sense, the Cassini mission isn't so different from the much simpler instruments that our ancestors used. Galileo, with a very simple telescope, was the first to discover that the Solar System, as an ensemble of bodies orbiting around a central object, was not unique, but in fact the Jovian system had similar characteristics: what is remarkable is that he was able to defend his idea against conformism and prejudice. In our times we can express our scientific ideas more freely, having only to be afraid of the perception and approval of our work by the group of scientist expert in our field. However, even now, new ideas are slowly accepted by the scientific communities, that tend to have—as in Galileo's times—a certain "inertia," and that hardly change their minds about what is considered an acquired knowledge.

New experiments have a double role: in fact they not only provide new data, but also, often, they challenge the current theories, thus causing to revise our views and to formulate new hypotheses. The Cassini mission is a good example of this: the data collected by the different sensors have flooded our "Planetary Science" community: the analysis and interpretation of these data is still evolving, so that a final scheme of the Saturn System and its evolution is not yet available. In any case, there were some currently accepted ideas that turned out to be inadequate to describe the reality observed by the Cassini mission. As an example, it was thought that Titan was covered—partially or totally by an ocean of ethane or by a mixture of ethane and methane. This idea was based on the consideration that Titan's atmosphere, rich in methane, couldn't be maintained from the time of its formation to the present, since methane would be gradually lost in the atmosphere by photo-dissociation. So an ocean or lakes could have been a reasonable source from which the atmosphere was replenished. This ocean has not been seen: there are large polar lakes on Titan, but probably the source that replenishes the atmosphere has to be searched elsewhere. Another inadequate idea was that a small satellite, made mainly of ice, can possibly—even if seldom—have a tectonic activity, like Europa (Jupiter's satellite) but cannot sustain an extended volcanic emission: as we will see, this is disproved in the case of Enceladus, where a kind of volcanic activity has been identified. In all cases, we have now a much better knowledge of the complex mechanisms characterizing the Saturn system.

The spectacular launch of the Cassini mission took place in October 1997 on a Titan IV-Centaur rocket from Cape Canaveral. The Spacecraft was not injected into a direct trajectory to Saturn, but its orbit was modified by making use of gravity-assist maneuvers at Venus, Earth and Jupiter. These maneuvers increased the duration of the voyage, which lasted about 6.7 years. The bodies encountered during the trip to Saturn were observed, and the data collected by the instruments allowed to verify their performance and to improve their calibration.

I had the privilege to be present at the launch and this was one of the most exciting and scary moments of my scientific career. In fact, after several years of personal involvement in the development of the Visible Channel of the VIS-IR imagining spectrometer on Cassini, named VIMS, any problem in the launch would have wiped out a lot of the efforts and dreams that I shared with a large number of colleagues and friends. Moreover, the Cassini mission was always at risk of cancellation during its development but was saved many times thanks to the great international involvement. The Cassini mission is in fact a NASA-ESA-ASI project. The main effort was made by NASA, which provided the launch facilities, the integration and several instruments; ESA provided the Huygens probe and ASI some of the key elements of the mission such as the high-gain antenna, most of the radio system and important instruments of the Orbiter, such as the Cassini Radar and the visible channel of the VIMS experiment. ASI contributed also to the development of the HASI experiment on the Huygens probe. The Cassini mission was the first case where the Italian Planetary community was directly involved, developing state of the art hardware for a NASA mission.

An exhaustive description of the Cassini results is almost impossible, given the long duration of the mission and the complexity of the payload onboard Cassini, and it is also beyond the scope of this paper. Instead, we will describe some selected examples of the most important results. We will also put these examples in the context of the overall evolution of the system, stressing why the selected examples are representative of the overall evolution of the Saturn system. In that, again, we will follow Galileo's legacy, since he was always trying to interpret the data that he collected.

THE CASSINI MISSION PAYLOAD

Cassini-Huygens, as we already stated, is a joint NASA/ESA/ASI mission to explore Saturn's system, and in particular Titan and the icy moons surrounding the planet, as well as the Saturn rings. On July 1st 2004 the Cassini-Huygens spacecraft entered the Saturnian system starting the nominal mission, that lasted four years and that is now concluded. On 25th December 2004, the Cassini Orbiter released the Huygens probe, which started its 20-days long trip to Titan. Despite the worries, the probe was not destroyed on impacting the solid surface and survived for about one extra hour.

The first four years of the Cassini-Huygens measurements were fundamental to understand the complexity and the diversity of Saturn's system. During the next two years, the Cassini mission will be named Cassini Equinox Mission. The name stresses the fact that the Cassini Orbiter will observe seasonal changes in the atmosphere at Saturn and Titan.

TABLE 1: CASSINI ORBITER PAYLOAD

Instrument	Investigation
Imaging science subsystem	Imaging in visible, near-ultraviolet, and NIR
Visual and infrared mapping spectrometer	Identifies the chemical composition of the surfaces, atmospheres, and rings of Saturn
Composite infrared spectrometer	Measures infrared energy from the surfaces, atmospheres, and rings
Ultraviolet imaging spectrograph	Measures ultraviolet energy from atmospheres and rings to study their structure, chemistry, and composition.
Cassini radar	Maps surface of Titan
Radio science subsystem	Searches for gravitational waves; studies the atmosphere, rings, and gravity fields of Saturn and its moons.
Magnetospheric imaging instrument	Images Saturn's magnetosphere and measures interactions between the magnetosphere and the solar wind
Cassini plasma spectrometer	Explores plasma within and near Saturn's magnetic field.
Ion and neutral mass spectrometer	Examines neutral and charged particles
Radio and plasma wave science	Investigates plasma waves natural emissions of radio energy, and dust.
Cosmic dust analyzer	Studies ice and dust grains in and near the Saturn system.

The Cassini Orbiter Payload is reported in **Table 1**, with the instruments grouped into suites. The *Optical instruments* are mounted on the remote sensing pallet and are aligned together: their goal is to study Saturn and its rings and moons in the largest electromagnetic spectrum, from UV to radio-frequency. These instruments are: the Composite Infrared Spectrometer (CIRS), the Imaging Science Subsystem (ISS), the Ultraviolet Imaging Spectrograph (UVIS) and the Visible and Infrared Mapping Spectrometer (VIMS). The microwave instruments, using radio wavelengths, were included to map the atmosphere and the surface of Titan despite its dense atmosphere. Radio Science experiments are used to determine the mass of moons and collect data on the size distribution of ring particles.

The *Fields, Particles and Waves instruments* study the dust, plasma and magnetic fields around Saturn. While most don't produce actual "pictures," the information they collect is critical to understand the Saturnian environment. They are considered "in situ" instruments.

The *Microwave Remote Sensing instruments*, using radio waves, map atmospheres, determine the mass of moons, collect data on the size distribution of ring particles and unveil the surface of Titan. They are the Radar and Radio Science (RSS) suite.

It should be noted that the instruments can be grouped in terms of their scientific goals: the Imaging suite of instruments is mainly devoted to the study of the overall geological/geophysical history of the central body and of the satellites. In particular, of great geophysical significance is the knowledge of the figure (namely the geometrical structure of the planet), whose knowledge - coupled with the analysis of gravitational fields, obtained thanks to the radio-science experiment-permits to infer the internal structure of the observed objects. As far as the satellites are concerned, the imaging suite and the radar, allow to study the large scale geological processes characterizing the surface, such as tectonic activity, volcanic activity, if present, and crater history. The spectroscopy instruments give information on the composition and on the mineralogy of the observed surfaces and on the composition of the atmospheres, when present. The radar data can be also used to gather some knowledge of the composition of different surfaces—through the determination of the surfaces materials' dielectric constant. The Cassini radar has been mainly developed to study the Titan surface, passing through the atmosphere and revealing the nature and the characteristics of the surface. The Magnetometer and Plasma analyzers give a description of the intrinsic magnetic fields generated inside the different objects, and also are used to study the interaction between the internal and induced magnetic fields and the particles trapped in the Saturn magnetosphere.

CASSINI RESULTS: SATURN

The first high quality observations of Saturn were done by Galileo Galilei, who, unfortunately misunderstood his observation: to Galilei the planet appeared as a "triplet," in which a central body was surrounded by two large moons (**Figure 1**). A few years after, in 1655, Christiaan Huygens understood that the two "moons" were a ring—probably flat—surrounding the planet, and he saw the largest moon, Titan, as well. Later the Italian astronomer Gian Domenico Cassini discovered four moons (Iapetus, Rhea, Thetis, and Dione) and correctly understood that Iapetus has two hemispheres of different color. He discovered in 1675 that the "ring" consisted of an outer ring and an inner ring, separated by a darker band, now known as the "Cassini Division."

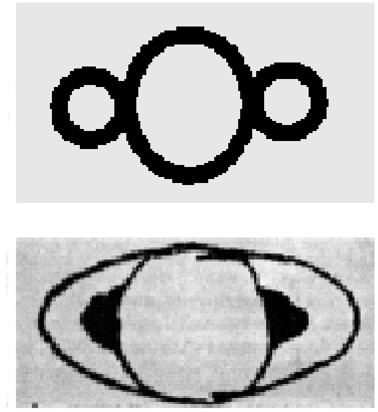

Figure 1: Saturn Illustrations made by Galileo: the top one was made in the year 1610, while the bottom one in the year 1616 (“Saturno tricorporeo” drown by Galileo in a letter to Belisario Vinta 30 July 1610 BNCF, Ms. Gal. 86, c. 42v).

Galileo Galilei was the first to observe Saturn with a telescope in 1610. The quality of his telescope was insufficient to understand what he was seeing, however he was able to accurately and minutely report his result. This correctness in reporting the observations is really apparent in the observations of the Galilean satellites.

These discoveries were made when he moved from Bologna, where he was a professor to Paris, where, being Luis XV’ s royal astronomer, he had the possibility to build and use more accurate telescopes. Also for Giandomenico Cassini, the technical ability to build new instruments and the scientific understanding of the observed reality proceed together.

Since that time, Saturn has been observed from the ground and from spacecraft missions, particularly the two Voyagers. So when the Cassini mission reached Saturn a general idea of Saturn’s atmospheric composition and internal structure existed in the planetary community. It was believed that Saturn’s atmosphere was more quiescent than Jupiter’s. Saturn. When Cassini arrived in 2004, Saturn's north pole looked different from what was expected based on the Voyager images. The north pole of Saturn is characterized by a high-speed cyclonic vortex, that has been identified by the visible-infrared mapping spectrometer (VIMS) onboard the Cassini–Huygens Orbiter[1] Thanks to these observations, Baines et al[2] showed that the troposphere at both poles of Saturn is occupied by cyclonic vortices with winds exceeding 135 m/s. High-speed winds, exceeding 125 m/s, were also measured for cloud features at depth near 76° (planetocentric) latitude within the polar hexagon, consistent with the idea that the hexagon itself, which remains nearly stationary, is a westward (retrograde) propagating Rossby wave (ibid). The polar cyclone is similar in size and shape to its counterpart at the south pole; a primary difference is the presence of a small (<600 km in diameter) nearly pole-centered cloud, perhaps indicative of localized upwelling. Many dozens

[1] Baines, Kevin H.; Kim, J. H.2009, Momary, T. W.; Buratti, B. J.; Delitsky, M. L.; Clark, R. N.; Brown, R. H.; Nicholson, P. D.; Cassini/VIMS Science Team, The Thunderstorm-related Clouds of Saturn: Composition, Structure, and Origin as Constrained from Cassini/VIMS Spectral Imagery, American Astronomical Society, DPS meeting #41, #28.07
[2] Baines et al. 2009

of discrete, circular cloud features dot the polar region, with typical diameters of 300–700 km. The existence of cyclones at both poles of Saturn indicates that cyclonic circulation may be an important dynamical feature in planets with significant atmospheres.

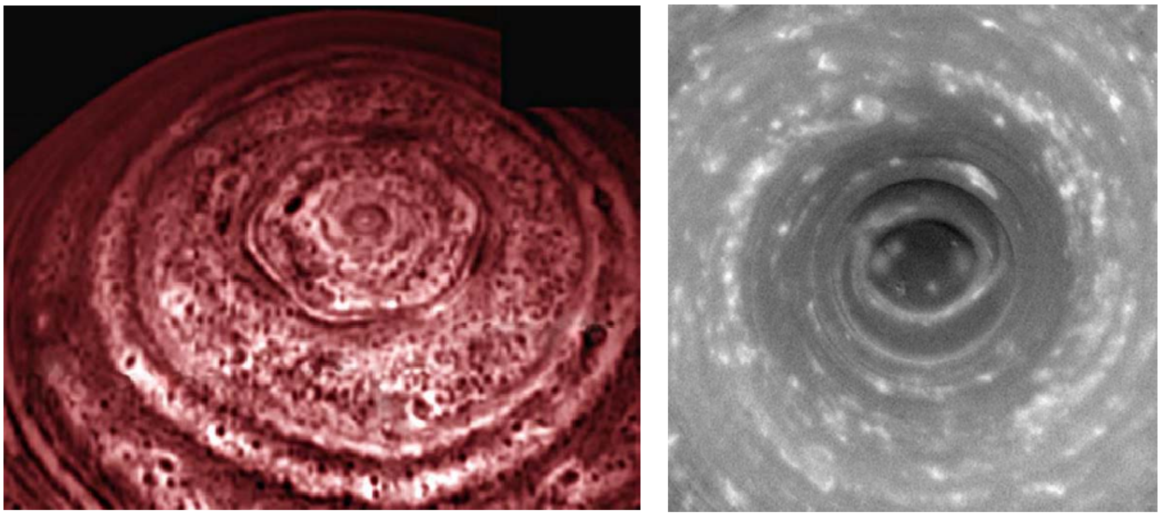

Figure 2: North Pole (left). VIMS image taken at 5 μm.

In the 5 μm spectral range infrared photons that originate from the deep troposphere are measured. Storm systems which provide enough opacity will block these photons creating the dark features observed; right South Pole: A hurricane-like storm two-thirds as wide as the Earth is raging on Saturn's south pole, new images from the Cassini spacecraft reveal. Such clear hurricane-like features have never before been seen on any other planet.

Why is it so important to study the Saturn atmosphere, and how is its knowledge related to the global structure of the planet? Saturn, as the other giants, is surrounded by a large fluid molecular envelope, which extends down the layers where the phase transition to liquid metallic hydrogen occurs. The depth at which this phase transition occurs can affect the latitudinal extent of the so called "zonal jets.[3]" In fact, the interior of Saturn is in convection due to the high hydrogen opacity, that doesn't allow energy transport by radiative transfer. The convective cells rise and sink slowly. Because of the continuous nature of the atmosphere, the wind pattern seen in the belts and zones of Saturn may originate in the deep convective interior of the planet, near the liquid-metallic hydrogen transition. Winds in all the giant planets are predominantly in east-west (zonal) directions, and this can be tracked through the observations of clouds. Theoretical models of the thermodynamics of the Saturn atmosphere haven't yet explained completely the observed dynamics of the atmosphere and how the winds distribution is related to the known sources of energy available and to the

[3] West, R. A., 2007, Atmospheres of Giant planets, in "Enciclopedia of the Solar System", Mc Faddem Wiessman and Johnson Edr, Elsevier

interior of Saturn.[4] However, with Cassini, a better knowledge of the Saturn atmosphere has been achieved.

THE SATELLITES

The satellite systems of Jupiter, Saturn and Uranus have been considered as small planetary systems for a long time, in fact regular satellites, which experience negligible solar perturbations, display dynamical properties similar to those of the planets. The Galilean satellites are a key example of a satellite system that is believed to have co-formed with its parent planet, with satellites accumulating within a circumplanetary accretion disk that existed during the final stages of the planetary formation process. However, while the Jupiter system exhibits a noticeable regularity, the Saturn system doesn't: in fact the large part of the mass of the Saturn system resides in the largest satellite, Titan, which contains more than 96 percent of the mass in orbit around Saturn. The other icy moons constitute roughly four percent, while the remaining 54 together with the rings only comprise 0.01 percent of the mass. Therefore, we will describe first Titan and, as the paramount example of the icy satellites, we will describe Enceladus, a small moon characterized by a strong and peculiar activity. However, some common characteristics can be identified that can be modeled as in the case of Jupiter.

TITAN

Before the Cassini-Huygens spacecraft arrived at the Saturnian system, very little was known about Saturn's largest moon Titan. After the Voyager 1 encounter it was clear that nitrogen (N2) and methane (CH4) were the major constituents of the Titan thick atmosphere: small percentage of methane and higher order hydrocarbons were also revealed. This atmosphere is completely opaque at visible wavelengths, due to the absorption of aerosols and gas and the scattering by aerosols. In fact in the upper atmosphere (up to at least ~1100 km), photochemistry driven by ultraviolet light and the chemistry of the charged particles produce suites of complex heavy hydrocarbons and nitriles, affecting the thermal balance and chemistry of the whole atmosphere. Already in the eighties[5] it was suggested that the composition, climatology, and evolution of the Titan atmosphere are controlled by five major processes: CH_4 photolysis and photosensitized dissociation, H-to-H_2 conversion and hydrogen escape, higher hydrocarbon synthesis, nitrogen and hydrocarbon coupling, and oxygen and hydrocarbon coupling. The effect of these complex phenomena lead to a gradual erosion of the atmosphere, both toward the space, due to photodissociation and toward the surface. In fact chemical elements can form aerosols and these the aerosols tend to accumulate on the surface, being removed from the atmosphere. This suggested that the atmosphere should be

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[4] See for example the basic paper on the subject by Stevenson and Salpeter, 1977. Stevenson, D. J., and E. E. Salpeter 1977. The phase diagram and transport properties for hydrogen-helium fluid planets. Astrophys. J. Suppl. 35,221-237

[5] Yung, Y. L., Allen, M., & Pinto, J. P., 1984, Photochemistry of the atmosphere of Titan - Comparison between model and observations, Astrophysical Journal Supplement Series (ISSN 0067-0049), vol. 55, July 1984, p. 465-506.

replenished by a source present on the surface of Titan,[6] and that this source was an extended ethane ocean. Because the surface is obscured by hydrocarbon smog at the visible wavelengths, the Titan Radar Mapper was included in the scientific payload of the Cassini spacecraft to study the surface of Titan. Titan fly-by observations and ground-based observations rule out the presence of extensive bodies of liquid hydrocarbons at present, which means that methane must be derived from another source over Titan's history. Moreover the Huygens probe showed a surface almost void of liquid materials. Only later, the discovery of numerous lakes near Titan's north pole by the Cassini radar instrument has confirmed that several possible sources are present on Titan,[7] and indicates an apparent preference during the current season for liquids to be located near the north pole (**Figure 3**).

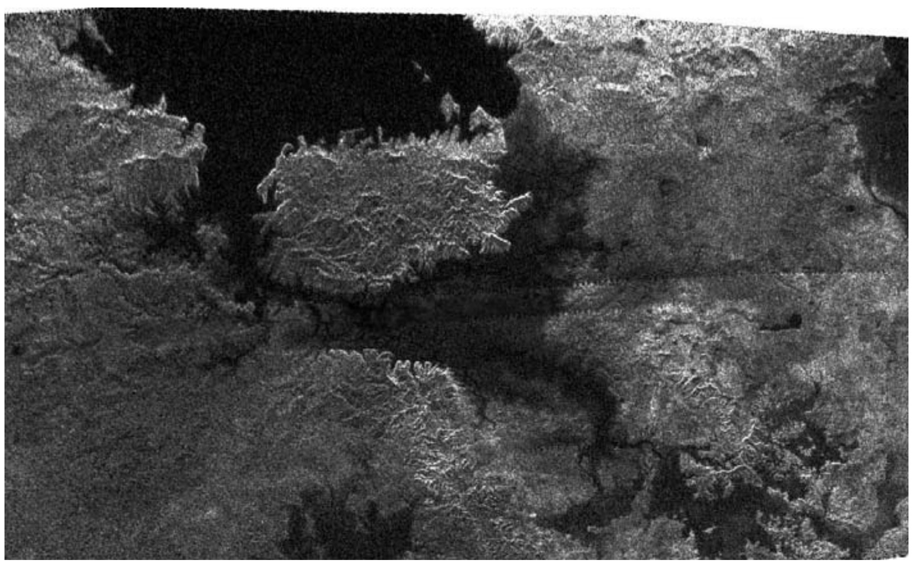

Figure 3: Island on Titan. Image credit: NASA/JPL.

This radar image, obtained by Cassini's radar instrument during a near-polar flyby on Feb. 22, 2007, shows a big island in the middle of one of the larger lakes imaged on Titan. The island is about 90 kilometers by 150 kilometers across. This image was taken in synthetic aperture mode at 700 meters resolution. North is toward the left-hand side. The image is centered at about 79 north degrees north and 310 degrees west.

However, the lakes are insufficient reservoirs to replenish the Titan atmosphere. Recently Tobie et al[8] suggested that episodic outgassing of methane stored as clathrate hydrates within an icy shell above an ammonia-enriched water ocean is the most likely explanation for Titan's atmospheric methane. What is the geological evolution revealed by the Cassini radar? The radar images revealed a complex world with diverse geophysical and atmospheric processes. However the radar alone wasn't insufficient to identify the main geological

[6] Lunine, J. I., Stevenson, D. J. & Yung, Y. L., 1983, Ethane Ocean On Titan *Science* 222, 1229–1230
[7] Stofan, E. R., and 37 colleagues 2007. The lakes of Titan. *Nature* 445, 61-64
[8] G Tobie, JI Lunine, C Sotin, 2006, Episodic outgassing as the origin of atmospheric methane on Titan, *Nature*, Vol 440, 61

features present on the Titan surface. In exploring the surface of Titan, an extremely powerful combination of data from the Cassini Orbiter instruments is the joint coverage by the multi-mode RADAR Investigation and the Visible and Infrared Mapping Spectrometer (VIMS). The Cassini Titan RADAR Mapper operates at Ku-band (13.78 GHz frequency or 2.17 cm wavelength) and collects low-resolution (several to tens of km) scatterometer, altimeter, and radiometer data as well as very high-resolution (down to ~350 m) synthetic aperture radar (SAR) images covering large strips of Titan's surface.[9] VIMS collects spectral cubes that are more limited in spatial coverage, at best usually a few km in resolution (and rarely a few hundred meters in resolution), but covers a large spectral range from 0.35 to 5.2 μm.[10] VIMS provides information about the morphology of the surface thanks to seven infrared windows, where the atmospheric methane is not effective as an absorber. In particular, very sharp images are acquired at 2 μm, where the scattering by aerosols is much reduced compared to the shorter wavelengths. Finally, the ISS camera[11] provides images of the surface in the 0.93 μm filter, once the strong scattering by aerosols has been corrected by image enhancement techniques.[12] Cassini has discovered features such as seas of dunes, lakes in the polar regions, and a young surface marked by few craters. Images from the Titan Radar Mapper in its Synthetic Aperture Radar (SAR) mode, together with those from the Imaging Science Subsystem (ISS) and the Visual and Infrared Mapping Spectrometer (VIMS), revealed a complex surface that has been shaped by all major planetary geologic processes—volcanism, tectonism, impact cratering and erosional/depositional processes, both from fluvial and aeolian activity.[13]

ENCELADUS

Enceladus is a small moon, only 504 km in diameter. On Enceladus old cratered terrains are interlaced with newly resurfaced smooth ice flows. Several authors[14] believed that Enceladus is too small to be active. Cassini measurements showed that this satellite is one of the most geologically dynamic objects in the Solar System. From a compositional point of view

[9] Elachi, C., Allison, M.D., Borgarelli, L., Encrenaz, P., Im, E., Janssen, M.A., Johnson, W.T.K., Kirk, R.L., Lorenz, R.D., Lunine, J.I., Muhleman, D.O., Ostro, S.J., Picardi, G., Posa, F., Rapley, C.G., Roth, L.E., Seu, R., Soderblom, L.A., Vetrella, S., Wall, S.D., Wood, C.A., Zebker, H.A., 2004. RADAR, the Cassini Titan RADAR

[10] Brown, R.H., Baines, K.H., Bellucci, G., Bibring, J.-P., Buratti, B.J., Capaccioni, F., Cerroni, P., Clark, R.N., Coradini, A., Cruikshank, D.P., Drossart, P., Formisano, V., Jaumann, R., Langevin, Y., Matson, D.L., McCord, T.B., Mennella, V., Miller, E., Nelson, R.M., Nicholson, D., Sicardy, B., Sotin, C., 2004. The Cassini Visual and Infrared Mapping Spectrometer (VIMS) investigation. *Space Sci. Rev*. 115 (1–4), 111–168

[11] Porco, C.C., Baker, E., Barbara, J., Beurle, K., Brahic, A., Burns, J.A., Charnoz, S., Cooper, N., Dawson, D.D., Del Genio, A.D., Denk, T., Dones, L., Dyudina, U., Evans, M.W., Fussner, S., Giese, B., Grazier, K., Helfenstein, P., Ingersoll, A.P., Jacobson, R.A., Johnson, T.V., McEwen, A., Murray, C.D., Neukum, G., Owen, W.M., Perry, J., Roatsch, T., Spitale, J., Squyres, S., Thomas, P., Tiscareno, M., Turtle, E.P., Vasavada, A.R., Veverka, J., Wagner, R., West, R., 2005. Imaging of Titan from the Cassini spacecraft. *Nature* 434 (7030), 159–168

[12] Perry, J. E., A. S. McEwen, S. Fussner, E. P. Turtle, R. A.West, C. C. Porco, B. Knowles, and D. D. Dawson (2005), The Cassini ISS team, processing ISS images of Titan's surface, *36th Annual Lunar and Planetary Science Conference*, March 14– 18, 2005, League City, Texas, abstract 2312

[13] Lopes, R. M. C., and 43 colleagues 2007. Cryovolcanic features on Titan's surface as revealed by the Cassini Titan Radar Mapper. Icarus 186, 395-412

[14] See, for example, Jeffrey S. Kargel, Enceladus: Cosmic Gymnast, Volatile Miniworld, 2006, Science 311 (5766), 1389

Enceladus' surface is composed mostly of nearly pure water ice except near its south pole, where there are light organics, CO2, and amorphous and crystalline water ice. CO is also present in the atmospheric column above Enceladus.[15] Cassini identified a geologically active region at the south pole of Saturn's moon Enceladus. In the images acquired by the Imaging Science Subsystem (ISS)[16] this region is surrounded by a chain of folded ridges (named "Tiger Stripes"). Cassini's Composite Infrared Spectrometer (CIRS) detected a strong thermal emission (3 to 7 Gigawatts).[17] The region of Tiger Stripes is emitting jets of organic-laden water vapor and dust-sized icy particles. Thanks to these measures performed by different instruments, it was confirmed that the source of E-ring's dust and gas was Enceladus.[18] Cassini magnetometer detected as well the interaction of the magnetospheric plasma of Saturn with an atmospheric plume.[19]

The investigation of Enceladus is a typical example of how all the instruments must be used in order to achieve a new understanding of the evolution of the icy moons, since each of them represents a new world by itself and a new challenge. However, little is known today about the mechanisms generating the intense activity of Enceladus' south pole. The Cassini Ion Neutral Mass Spectrometer (Cassini INMS)[20] continues to return a wealth of information about the Saturn satellites, Titan and Enceladus. Earlier data from Titan shows an unanticipated organic complexity in the upper atmosphere and the isotopic ratios of H, C, and N harbor important clues about the evolution of the atmosphere over geological time. Recent results from Enceladus indicate an unanticipated organic complexity in the plume that is quite different from that at Titan.

WHAT SATELLITES TELL

Let's summarize the large scale characteristics of the satellites of the Saturn system. First of all they don't have atmospheres with the exception of Titan and we can try to guess why Titan has an atmosphere while the other satellites don't. It seems to be a combination of different factors: the first is that the local nebular temperatures are sufficiently cold that a substantial atmosphere was able to form; moreover the Titan's mass was sufficiently high to allow to

[15] Robert H. Brown, Roger N. Clark, Bonnie J. Buratti, Dale P. Cruikshank, Jason W. Barnes, Rachel M. E. Mastrapa, J. Bauer, S. Newman, T. Momary, K. H. Baines, G. Bellucci, F. Capaccioni, P. Cerroni, M. Combes, A. Coradini, P. Drossart, V. Formisano, R. Jaumann, Y. Langevin, D. L. Matson, T. B. McCord, R. M. Nelson, P. D. Nicholson, B. Sicardy, and C. Sotin, 2006. Composition and Physical Properties of Enceladus' Surface, *Science*, 311, 5766, 1425 - 1428

[16] Porco et al. 2006

[17] Porco et al. 2006

[18] Frank Spahn, Jürgen Schmidt, Nicole Albers, Marcel Hörning, Martin Makuch, Martin Seiß, Sascha Kempf, Ralf Srama, Valeri Dikarev, Stefan Helfert, Georg MoragasKlostermeyer, Alexander V. Krivov, Miodrag Sremevi,Anthony J. Tuzzolino, Thanasis Economou,2009. Eberhard Grün, Cassini Dust Measurements at Enceladus and Implications for the Origin of the E Ring, *Science* 10 March 2006:Vol. 311. no. 5766, pp. 1416 – 1418, DOI: 10.1126/science.1121375

[19] Dougherty, M. K , K. K. Khurana, F. M. Neubauer, C. T. Russell, J. Saur, J. S. Leisner, and M. E. Burton (10 March 2006) Identification of a Dynamic Atmosphere at Enceladus with the Cassini Magnetometer *Science* 311 (5766), 1406.

[20] Waite, J. Hunter; Magee, B. 2009,Titan and Enceladus Composition From Cassini INMS: Implications for the Formation and Evolution of the Saturn System, American Astronomical Society, DPS meeting #41, #64.04

retain a large fraction of this original atmosphere (Jeans escape) and finally, the surface temperature was warm enough to prevent some volatiles (e.g., N_2) from freezing out (c.f. Pluto, Triton), even if large part of the complex hydrocarbons formed in the atmosphere was able to sink toward the surface of Titan.

The surface structures are also very variable, as they go from being heavily cratered to totally resurfaced: in the Saturn system the two extremes are Enceladus, almost devoid of craters and Mimas, totally coved by craters.

At the same time, we can clearly identify signs of tectonic activity that is the surface expression of the internal activity. This is in turn related to the amount of heat that is available in the interior to generate internal motion, as convection. The main sources hypothesized are, tidal heating, that is one of the most important sources, and the decay of long and short lived radioactive elements. These lasts, were effective at the beginning of the history of satellites: in fact Al26 has a decay time with a half-life of ~0.7 Ma. Moreover, if this source has been active, as many authors assume, then this pose a limit in the formation time of satellites that should have taken place before the overall decay of this element.[21]

The internal structure is also very complex, going from differentiated satellites, to probably undifferentiated ones. In some cases the internal structure is not only differentiated, but is accompanied by the presence of liquid subsurface layers. This is again not only strongly related to the existence of heat sources, able to trigger the differentiation, but also to the chemical composition of the body. In fact the presence of high volatility materials, that have a low melting point, can allow the melting and differentiation of the satellite also in the presence of energy sources weaker than those needed for silicatic bodies. This could be the case for Enceladus, where the presence of ice grains of ammonia—reducing the melting point of the ice mixture—has been identified in the plumes.

The different chemical composition of satellites can be strongly relates to their original composition, namely to the composition of the satellites' subnebula, that could have been characterized by radial and lateral gradients in chemical composition.[22] Organic chemistry has surely played an important role, given the importance of carbon compounds in the Saturn nebula.

If we ask ourselves how we have achieved this quite extensive knowledge of these dark, small, cold, and far objects, obviously the answer is the big experiment of the Cassini mission. Only the combination of the complex experiments present on Cassini have allowed us to understand what we have briefly summarized. We must be ready to interpret the new data with an open mind and be prepared to change our theories accordingly when they don't explain the data. We can accept what Galileo said, about Aristotle, in *Il Saggiatore*:

[21] Castillo-Rogez, T. J., V. Johnson, Man Hoi Lee, N. J. Turner, D. L. Matson and J. Lunine, 2009, 26Al decay: Heat production and a revised age for Iapetus, *Icarus*
Volume 204, Pages 658-662

[22] Coradini A., Magni G., Turrini D., "From gas to satellitesimals: disk formation and evolution", 2010, *Space Science Reviews*, DOI:10.1007/s11214-009-9611-9

> Avete voi forse dubbio che, quando Aristotele vedesse le novità scoperte in cielo, e' non fusse per mutar opinione e per emendar I suoi libri , e per accostarsi a più sensate dottrine discacciando da se quei poveretti di cervello che troppo pusillanimemente s'inducono a voler sostenere ogni suo detto.[23]

(Do you think that if Aristotle could have seen all the new things discovered in the sky, would he not have changed opinion and accepted more reasonable theories, and distanced himself from those people who too pusillanimously want to support any of his positions?)

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Tosi, F., Orosei, R., Seu, R., Filacchione, G., Coradini, A., Lunine, J.I., Gavrishin, AI., Capaccioni, F., Cerroni, P., Adriani, A., Moriconi, M.L., Negrão, A., Flamini, E., Brown, R.H., Wye, L.C., Janssen, M., West, R., Barnes, J.W., Clark, R.N., Cruikshank, D.P., McCord, T.B., Nicholson, P.D., Soderblom, J., 2009. Analysis of selected VIMS and RADAR data over the surface of Titan through a multivariate statistical method. Submitted to Icarus.

[23] (Saggiatore, VII, 133).

Solar Activity: From Galileo's Sunspots to the Heliosphere

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INTRODUCTION

Four hundred years ago Galileo described the intellectual road along which to pursue the physical sciences. Four centuries of pursuit have uncovered the basic laws of classical (non quantum mechanical) physics and initiated many successful applications of those basic laws to understanding the diverse macroscopic phenomena of the Universe. In space science and solar physics we apply Newton's equation as well as the basic principles of Ampere and Maxwell and Lorentz, along with the twentieth century developments in atomic physics and nuclear physics. We have exploited the technological advances in instrumentation, in telescopes, and in the transporting of instruments and telescopes throughout the solar system. Surely Galileo would be pleased, and perhaps a little amazed, to see how far the science has come. He might also be amused to find that the sunspot—one of his first discoveries—is still without an explanation in terms of the basic laws of physics. Why must the Sun have spots?

Yet for all the changes and advances, there are some obvious parallels between the destructive human attitudes that beset Galileo and certain difficult aspects of modern day science. Galileo's persecution, prosecuting, and incarceration were a direct outgrowth of the success of his two guiding principles: (a) experiment and observation are the only road to understanding the world around us and (b) "The book of Nature is written in mathematical characters." To step outside these two principles is to wander off into the infinite universe of fantasy.

Following principle (a) Galileo developed a workable telescope and soon discovered sunspots and the four major satellites of Jupiter. He publicized the Copernican form of the Jovian satellites and emphasized that one can arrive at scientific truth only by direct study of Nature, in contrast with the classical verbal logic of Aristotle. That was a direct threat to the supremacy of the Aristotelian professors of the day, so they persuaded the Church of Rome that Galileo's work was heretical, supporting Copernicus and demanding suppression and imprisonment. After Galileo's pro forma conviction and sentencing on these charges, Pope Urban VIII was sympathetic enough to commute Galileo's life sentence from prison to house arrest.

Four hundred years later this level of persecution does not occur in the more advanced nations of the world, but we are still encumbered by ancient attitudes. Given that human nature is the fundamental invariant of human history, this should come as no surprise, of course. In particular, the spirit of the suppression by the Inquisition still lurks in a small but potent way among some of the anonymous "eminent" scientists who act as referees of the research papers submitted to scientific journals. Not uncommonly the referee deals with a scientific paper felt to be trespassing on his turf (particularly if the author is young and unknown) simply by assuring the editor in suitably vague language that the paper "is not suitable for publication." This destructive rejection for publication is too often confused with maintaining high scientific standards. Unfortunately scientific advances are slowed and young careers are sometimes blighted.

The other ghost from the past is the application of Aristotelian logic, based on verbal analogies, in place of the basic laws of physics. Indeed, we all use some form of Aristotelian analogies in dealing with the vicissitudes of everyday life. However, where the basic laws of physics can be applied, the result, however attained, must comply with those laws. Of concern to the physics of solar activity and the heliosphere is the manner in which the flowing, swirling plasma interacts with the magnetic field, and vice versa. For it is the magnetic field and the swirling plasma that combine to provide the heliosphere. Of concern to the physics of the heliosphere is an Aristotelian conviction, commonly held in the magnetospheric and ionospheric communities and sometimes urged upon solar physics. The verbal logic has come round to the conviction that the large-scale dynamical behavior of the magnetic field ***B*** embedded in a large-scale plasma is driven by the electric current ***j***, with the current ***j*** driven by the electric field ***E***—the (***E***,***j***) paradigm. Then it is has been declared that the dynamical behavior of ***j*** is described by an equivalent laboratory electric circuit. This point of view overlooks the fact that in a highly conducting plasma it is the energy from the magnetic field ***B*** that drives ***j*** via a very weak electric field $\boldsymbol{E}'$ in the moving frame of reference of the electrically conducting plasma. It also overlooks the fact that the laboratory electric circuit involves conductors (wires) electrically isolated by the surrounding air and permanently fixed in the laboratory frame of reference. In contrast, the electric current in the plasma moves with the plasma and experiences only the weak electric field $\boldsymbol{E}'$, and the swirling magnetized plasma in space is an amorphous, simply connected, highly conducting medium, in which the topology of the current varies freely according to the dictates of Ampere's law in the continually deforming magnetic field. It is also imagined that the electric field $\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B}/c$ in the laboratory reference frame (because $\boldsymbol{E}'$ is negligible) is a dynamical force in itself, affecting the bulk flow velocity ***v*** of the plasma. This fails to note that the electric stress $E^2/8\pi$ are small to second order in *v/c* compared to the magnetic stress $B^2/8\pi$ and, therefore, quite negligible.

To set the record straight before turning to the heliosphere itself, we note that the equations of Newton and Maxwell and Lorentz are simply expressed in terms of ***B*** and ***v*** - the (***B***,***v***) paradigm - displaying the direct large-scale *mechanical* interaction between the magnetic stresses and the pressure and momentum of the moving plasma. The moving plasma does work as it deforms and extends the infinitely elastic magnetic field.

To elaborate, the electric current ***j*** is prescribed by the curl of the existing ***B*** (Ampere's law), and is correspondingly limited to small values by the large scale of ***B***. So in view of the high electrical conductivity of the plasma and the limited current, the electric field $\boldsymbol{E}'$ in the moving frame of reference of the plasma is very small. It follows from the Lorentz transformation between the laboratory and the plasma that there is the electric field

$\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B} / c$ in the laboratory reference frame. This can be understood from the fact that the laboratory is moving with velocity -***v*** relative to the electric field-free ($\boldsymbol{E}' = 0$) plasma. It follows that the flux of electromagnetic energy in the laboratory, given by the Poynting vector $\boldsymbol{P} = c\boldsymbol{E} \times \boldsymbol{B} / 4\pi = \boldsymbol{v}_{\perp} B^2 / 4\pi$, represents the bulk transport of the magnetic enthalpy density with the plasma velocity component $\boldsymbol{v}_{\perp}$ perpendicular to ***B***. That is to say, the magnetic fields and the ionized gases in space are constrained to swirl around together. That is the basic concept known as magnetohydrodynamics (MHD). Fortunately most theoretical research in space physics and solar physics is treated correctly with MHD, so that progress has been substantial over the past several decades.

THE HELIOSPHERE

Turning to the physics of the heliosphere, we recall that, except for the cold planetary atmospheres, all the gas in the heliosphere, including the Sun itself, is ionized to a sufficient degree that the electrical conductivity is large and MHD is applicable. So the electric currents associated with the magnetic fields are pushed along by very weak electric fields $\boldsymbol{E}'$ in the plasma, and MHD describes the large-scale bulk dynamics of the plasma and magnetic field. The magnetic field is tightly constrained to move with the swirling large-scale ionized gases, or plasma.

The heliosphere begins at the Sun with the hydrodynamic expansion of the million degree outer atmosphere of the Sun—the corona—and the weak magnetic fields embedded in the corona. The expansion, creating the solar wind, reaches supersonic velocities of 300–700 km/sec and stretches out the weak magnetic fields (5–10 Gauss) at the Sun for as far as the solar wind can push aside the interstellar gas and magnetic fields. That proves to be a long way, with the supersonic wind exhibiting a standing terminal shock wave at 94 AU, located by the Voyager I spacecraft after traveling for 28 years in the direction toward the impacting interstellar wind. To get a feeling for the immense distance of 94 AU note that the most distant planet, Neptune, orbits out there at 30 AU, with the heliosphere extending three times farther. Sunlight at 94 AU is hardly more than one ten thousandth the intensity we find here at Earth. The Sun subtends an angle of only 20”. It takes about 13 hours for sunlight to travel out to the end of the heliosphere. A radio signal to the Voyager I spacecraft requires the same 13 hours to make the trip, and an immediate Voyager reply to Earth arrives back another 13 hours later—the day after the original signal was sent. A solar observer located at 94 AU sees the Sun as it was 13 hours earlier. On the other hand, the travel time of the solar wind from the Sun to the termination shock in the wind is about one year.

As already noted, Voyager I took 28 years to make the outward trip, and, like the solar wind gases, it will never turn around and come back. The nearest stars, e.g., Proxima Centauri, are three thousand times farther than the 94 AU to the termination shock, from which it is evident that the heliospheres of ordinary stars like the Sun, occupy a very small fraction of space, about 3×10^{-11} . We note that it would take some 70,000 years for Voyager I to get to the nearest star at its present pace. To appreciate the time span of 70,000 years, ask what we humans were doing 70,000 years ago. Our ancestors had begun their migration out of the human cradle—Africa. The Neanderthals were thriving in Europe and the Middle East, having earlier developed the means to make fire, warm clothing, and the hunting tools adequate to face the ice age. Our Homo Sapiens line was flourishing but seemingly of limited numbers, not yet taking over the European scene.

Then we may ask what our little world will be like 70,000 years from now, when Voyager I will be as far away as the nearest stars.

It is interesting to reflect that the 94 AU dimension of the heliosphere at the present time is by no means an eternal condition. The distance to the termination shock depends on the impact pressure of the interstellar wind blowing against the heliosphere, together with the pressure of the interstellar magnetic field. The solar wind spreads out as it flows away from the Sun, with the density falling off inversely with the square of the distance, $1/r^2$, just like sunlight. So there is always a distance at which the solar wind falls to the impact level of the external interstellar wind and is brought to a stop.

It is clear that in the 4.6×10^9 years since our Sun and solar system were formed the Sun has passed through a variety of external interstellar conditions, from an occasional dense interstellar gas cloud to a rarified interstellar region, even sparser than the 0.2 hydrogen atoms/cm^3 experienced today. The termination shock may at times have been farther than 94 AU, or very much closer, as on the rare occasion that the Sun passed at 10–20 km/sec through a cold (100° K) dense (10^5 atoms/cm^3) neutral gas cloud. The flood of neutral atoms would fall freely into the heliosphere before ionization by solar UV or charge exchange with the solar wind ions and would swamp the tenuous solar wind. The heliosphere might have been squeezed down to 1 AU or less. In fact today, with the local tenuous (0.2 neutral atoms/cm^3 and 0.1 ions/cm^3) interstellar gas, the infalling neutral atoms play a remarkable dynamical role, becoming ionized somewhere in the vicinity of Jupiter at 5 AU. The newly created ions are picked up by the magnetic field in the wind, relative to which they have a speed equal and opposite to the wind velocity, giving them a thermal energy of the order of one KeV in the wind. These hot pickup ions are transported back out to the terminal shock where some of them are evidently accelerated to energies of many MeV. Some of these accelerated particles find their way back into the heliosphere and are picked up in space-borne cosmic ray detectors under the label of *anomalous cosmic rays*, because the nuclear abundances among them reflect the abundances in the interstellar gas, rather than the abundances found among the galactic cosmic rays or the energetic particles from the Sun. So the solar wind is significantly impeded in the outer heliosphere by the mass of the newly created ions.

Physical Origin of the Heliosphere

Consider how it comes about that the Sun has a million degree corona, a solar wind, and a heliosphere. The process begins in the thermonuclear core at the center of the Sun, where the temperature is 15 million K and the density of the gas is 115 times the density of water. In spite of the huge density, the medium is a gas because the particles—electrons and ions—do not stick to each other. To appreciate the significance of the 15 million degree temperature, note that the associated thermal electromagnetic radiation is mostly X-rays. The temperature is 2500 times the 6000 K temperature at the visible surface of the Sun. The intensity of the radiation is proportional to the fourth power of the temperature, from which it follows that the radiation is approximately 40 trillion times more intense than the dazzling sunlight at the visible surface. So the Sun has an incredible fireball at its center, and it follows that the Sun is basically a dark shroud enclosing that fireball. The shroud is so opaque that the nuclear energy released in the core requires about a million years to work its way out to the visible surface, from which it escapes freely into space as the familiar 6000 K yellow radiation we call sunlight. It is the slow outflow of energy through the solar shroud that provides the activity of the Sun.

The energy from the fireball core of the Sun is transported outward by the intense electromagnetic radiation, with the temperature falling to two million degrees at about 5/7, or 70%, of the solar radius. The radiation intensity has fallen by about a factor of 3000 and can no longer handle the entire energy outflow. So the gas below that level becomes hotter, making it lighter so that it rises upward, pushing its way toward the surface. A compensating downflow around the rising plume of hotter gas carries an equal amount of cooler gas downward where it is heated and rises. This ongoing convective overturning is a familiar phenomenon in a pot of water on a hot stove, and it mixes the hotter gas upward, gradually taking over the heat transport from the dwindling radiative transport. The energy arriving at the visible surface is almost entirely transported by the convective overturning. Given that the radius of the Sun is 0.7 million km, the average heat transport velocity is about 0.7 km/yr to make the trip from the core to the surface in a million years. In fact the heat transport velocity starts from zero at the center of the Sun, increasing gradually to about 0.5 km/sec approaching the visible surface. Radiative transport increases upon approaching the visible surface, where it takes over from the convection in the clear space outside.

The convection represents a heat-driven engine diverting a small fraction of the outward energy flow into mechanical motion. Several things happen then. For instance, the turbulent convection produces sound waves in the solar interior with periods from a minute to an hour. The solar interior becomes an echo chamber with the sound waves bouncing around inside. The waves are reflected and confined to the Sun by the steep density gradient at the surface. Trapped in this way, the acoustic waves set up standing modes that can be detected at the visible surface. The frequency of each mode can be determined with great precision and the path of the wave within the Sun can be computed. This activity is referred to as helioseismology, in analogy to seismology here at Earth. Combining the result for hundreds of modes penetrating to various depths, it becomes possible to work out the speed of sound as a function of distance from the center of the Sun. This provides a direct check on the standard theoretical model of the solar interior, testing the basic assumption that the atomic abundances throughout the interior were initially the same as observed at the surface today. That was the simplest hypothesis, of course, and helioseismology confirms it with substantial precision.

Another important aspect of helioseismology arises from the slight splitting of the frequency of a mode into two separate modes, for the eastward and westward propagating waves in the rotating Sun, caused by the different Coriolis force for the two. Using the observed splitting of hundreds of modes allows computation of a map of the angular velocity throughout the solar interior.

Now it is well known that the surface of the Sun rotates non-uniformly, with a 25 day period at the equator, increasing to more than 30 days at the poles. Hydrodynamic considerations would suggest that the rotation extends along cylindrical shells through the interior. The convection may alter this simple pattern to some degree, of course. In fact the internal rotation is nothing like cylindrical shells. The radiative zone—the inner 5/7 of the solar radius—rotates rigidly, while the angular velocity observed at the surface projects radially downward (approximately) across the convective zone to the top of the radiative zone. The sharp break in the angular velocity at the bottom of the convective zone is called the tachocline. No one has been able to construct a theoretical numerical hydrodynamic model that gets very far from the shells, in spite of some very smart people working hard on the problem. Something is missing from our picture of the solar interior. The theoretical computation is difficult because of the enormous difference in density across the convective zone. One wonders if unknown magnetic forces are involved, but it not obvious what those forces might be if they are to produce a rotation profile resembling the observed pattern.

This brings us to the magnetic fields generated in the convective zone by the non-uniform rotation and convective mixing, and observed on all scales over the surface of the Sun. The principles of MHD tell us that the non-uniform rotation, with the more rapid rotation at low latitudes, shears a north pointing field, stretching it out to form a strong (solar) westward pointing field with the passage of time. A southward field is sheared to provide a strong eastward magnetic field component. The stretching is in opposition to the tension in the magnetic field, so the non-uniform rotation does work on the magnetic field, greatly increasing the magnetic energy. Then the rising convective cells in the convective zone poke up through the east-west magnetic fields, to form what is sometimes called an Ω-loop. The Coriolis force causes each rising convective cell to revolve about a vertical axis, rotating the Ω-loop into the meridional plane so that the loop provides a circulation of magnetic flux in the meridional plane. Collectively the rotated Ω-loops represent a net large-scale circulation of north-south magnetic field, which is then sheared by the non-uniform rotation as already described. Putting these two steps together provides a net amplification of the magnetic field, and the process is called an $\alpha\omega$-dynamo, where α represents the cyclonic strength of the convection and the ω stands for the shearing by the non-uniform rotation. In particular, the combination of the two effects provides growing dynamo waves first appearing in middle latitudes and propagating toward the equator from each hemisphere. The east-west fields have opposite signs in the northern and southern hemisphere, and the fields reverse with each successive wave. The east-west fields are much the strongest, and the theoretical magnetic wave form is confirmed by the observed emergence of bipolar magnetic field regions at the visible surface—the apexes of Ω-loops. So it is generally believed that the magnetic field of the Sun is the product of an $\alpha\omega$-dynamo operating somewhere in the convective zone. It should be noted that the geomagnetic field also appears to be produced by an $\alpha\omega$-dynamo in the convecting liquid iron-nickel core of Earth. The terrestrial dynamo produces a non-cyclic magnetic field because of the different geometry of the convecting region.

The fluid motions in the convective zone, which include a meridional circulation, are sufficiently complex and vigorous that it has not yet been possible to construct a unique and final theoretical model, as already noted in connection with the puzzling rotation profile. There are several mysteries waiting to be resolved. An obvious example is the remarkable fibril structure of the magnetic fields where they emerge through the visible surface and perhaps throughout the subsurface convection as well. Another mystery is the essential large-scale diffusion and dissipation of the magnetic field over the dimensions of the convective zone during each 11-year magnetic half cycle. The essential diffusion of the magnetic field over the decade of a magnetic cycle is commonly attributed to "turbulent diffusion," but it remains to be shown how such strong fields can be mixed and diffused by the relatively weak convection. Then, of course, there is the question of the remarkable forcible compression of the magnetic field at the surface to 2–4 kilogauss to produce one of Galileo's sunspots.

Moving on, it is important to note that magnetic fields are buoyant, because a magnetic field exerts an isotropic pressure, slightly expanding the gas within the field. The magnetic fields appearing at the surface of the Sun have all floated up to the surface at least in part because of their buoyancy. The Ω-loop carried up in a rising convective cell is a case in point, along with the myriads of tiny loops of individual fibers emerging through the visible surface. The net effect at the surface is a carpet of chaotic upward arching magnetic fibrils in which there are ongoing micro-explosions of magnetic dissipation, called microflares. Each microflare provides a burst of million degree plasma, along with intense plasma waves and probably suprathermal particles. An individual flare, or microflare, is created where oppositely directed magnetic field components are pressed together by the magnetic stresses. Then, according to Ampere's law, an intense current sheet is created in the plasma, and magnetic energy is rapidly dissipated with the energy going into heating the ambient plasma and into plasma waves which may propagate elsewhere before dissipating... When this happens in a highly strained large-scale magnetic field, the total dissipation may be as much as 10^{32} ergs over a period of 30 minutes. Such occasional large flares sometimes produce enormous quantities of fast protons and electrons (up to 25 Gev on rare occasions) representing as much as 20 percent of the total flare energy. These accelerated particles come bursting out into interplanetary space, bathing Earth in intense deadly particle radiation.

The ongoing microflaring over the surface of the Sun is of particular interest for the heliosphere; because it appears that the plasma waves produced by the microflares dissipate in the corona and represent the principal heat source for the million degree corona. It must be appreciated that the corona, with a density of the order of 10^8 ions/cm^3 is too tenuous to radiate efficiently. That is to say, the optical depth of the corona is very small, so that the million degree temperature is maintained by a heat input of only 0.1 Watts/cm^2.

Turning, then to the corona, it should be noted that the corona close to the Sun is essentially static, strongly bound to the Sun by the gravitational field. The gravitational binding energy is typically five or more times the thermal energy. However, the corona is actively heated for large distances out into space. Thermal conductivity alone would extend the temperature outward in proportion to $1/r^{2/7}$, while the plasma waves from the microflaring may propagate for large distances out into the surrounding space, with substantial heating of the plasma. In contrast, the gravitational binding energy declines in proportion to $1/r$. So one way or another, the thermal energy exceeds the binding energy at a distance of a few solar radii, and the coronal plasma is free to expand away from the Sun. The temperature extends far out into space, so the expansion accelerates to supersonic velocity, becoming the solar wind that we observe here at 1 AU. The wind has enough force to sweep away the interstellar gas and magnetic field out to 94 AU, thereby creating the heliosphere.

MAGNETIC FIELDS

The corona near the Sun is filled with magnetic field extending up from the photosphere. In the vicinity of magnetic active regions, where the magnetic field at the visible surface is observed to be 50 Gauss or more, the arching field is strong enough to confine the corona, preventing escape from the Sun. On the other hand, as already noted, in the regions of weaker magnetic fields of 5–10 Gauss outside the active regions the corona overpowers the magnetic field and stretches it out through the heliosphere to 94 AU. The magnetic field remains connected at the Sun as the wind runs away, so the heliosphere would be filled with radial magnetic field were it not for the fact that the Sun rotates. During the one year that it takes the wind to reach 94 AU the equatorial region of the solar surface rotates about 14 times. It follows that the field extends in a spiral pattern, winding approximately 14 times around the Sun in its path out through the heliosphere. At 1 AU the magnetic field is still approximately radial, falling off as $1/r^2$, and beyond the asteroid belt the field is approximately azimuthal, declining outward in proportion to $1/r$.

Note, then, that the solar corona is not uniform around the Sun, with the result that the solar wind velocity and density vary substantially over the range of 300–700 km/sec and 1–20 ions /cm^3. Curiously, the ion flux (ions/cm^2 sec) given by the product of the velocity and density, varies much less than either the velocity or density alone. Note, then, that the coronal gas stream from a location rotating with the Sun lies along the same spiral path as the magnetic field. It follows that the extended path of a faster wind rams into the rear of the tighter spiral of a stream of slower wind, creating turbulence and a shock wave, often accelerating ambient thermal particles to high energies.

The most vigorous feature in the solar wind is the gigantic coronal mass ejection (CME), in which coronal gas is expelled from the Sun at speeds up to 1000 km/sec by the accumulating stress and energy in a deformed magnetic field. The magnetic field springs away from the Sun, carrying something of the order of 10^{16} gm of plasma with it. An essential part of the ejection is the severing of the magnetic field connection to the Sun, evidently by some form of rapid reconnection. Without that cutting of the field, the CME would be unable to escape to infinity. Very approximately there are one or two CME's per 24 hours, with more during the years of high magnetic activity (sunspot maximum) and less when the Sun is inactive (sunspot minimum). The CMEs punch out through the solar wind to distances far beyond Earth. Their impact against the terrestrial magnetosphere is the cause of the magnetic storm.

In summary, the solar wind is an active phenomenon, with the dynamics of the wind throughout the heliosphere a source of many diverse effects. We have made no attempt here to provide an exhaustive list. But it is worth noting that the interaction of the outward sweeping magnetic fields in the wind and the galactic cosmic rays has been a major subject of study from the beginning, when, prior to the space age, it provided direct evidence that interplanetary space is filled with magnetic fields embedded in moving plasma. Another ongoing field of study is the fascinating diversity of the magnetic activity of planetary magnetospheres driven by the impacting solar wind. The giant magnetosphere of Jupiter with the active moon Io is the most exotic case, but the magnetic field of Earth has proved to be complex enough to be challenging and is certainly more accessible. Finally, we should mention again that the sunspot phenomenon merits its contemporary extensive observational study with the highest telescopic resolution available, because the spot represents a compact collection of very thin active magnetic filaments that may play an essential role in the formation of the spot. And Galileo is still waiting for an explanation for the formation of sunspots. Then we note that the universal intense filamentary structure of all the magnetic fields emerging through the visible surface of the Sun poses a fundamental challenge to the astrophysics of stars, and we must remember the violent interactions among the individual magnetic filaments (microflaring), providing the corona, the solar wind, and the heliosphere. So we can understand the physics of the heliosphere only as well as we understand the physics of the magnetic activity at the Sun.

From Galileo to Hubble and Beyond - The Contributions and Future of the Telescope: The Galactic Perspective

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INTRODUCTION

We live in an era of telescopic renaissance. Ground based optical telescopes with 8-to-10 meter apertures operate regularly on mountain tops around the world. In space, NASA has fulfilled a long-standing dream by completing its family of Great Observatories: together, the Fermi Gamma Ray Observatory, the Chandra X-Ray Observatory, the Hubble Space Telescope, and the Spitzer Space Telescope provide powerful observational capabilities which blanket most of the electromagnetic spectrum which is either inaccessible from the Earth's surface or adversely affected by the Earth's atmosphere. The power of multiple observatories used together across the spectrum can be seen, for example, in the joint Hubble/Chandra/Spitzer image of the galactic center released to commemorate the International Year of Astronomy (http://gallery.spitzer.caltech.edu/Imagegallery/image.php?image_name=ssc2009-20a). Both the European Space Agency, for example with its recently launched Herschel Space Observatory, and the Japanese Space Agency, through the successful AKARI all-sky infrared survey, participate fully in this telescopic renaissance. A number of smaller, more specialized telescopes are operating with great success in space or on the ground as well.

The scientific grasp and the technical complexity of these telescopes far exceed not only anything Galileo could have conceived but also, I suspect, the expectations of all but the most imaginative astronomers as recently as the middle of the 20th century.

The technical complexity of these telescopes is reflected in their costs, which range upward of $1B for the larger space observatories such as Hubble and Chandra. Because a venture of this scale necessarily involves large numbers of people, one might assume that the contributions of individual scientists would be difficult to discern. I wish to argue, however, that even in this era of megaprojects, one can often see that the drive, ability, vision, and initiative of a single person has been critical to the development of a new instrument. I do this by identifying and discussing a number of people whose individual contributions have been of great significance in the development of modern telescopes which have led, in turn, to advances in our understanding of galactic astronomy. I refer to these people as modern Galileos. This may be a bit presumptuous: It is unlikely that too many of them will be remembered 400 years from now, and they have been rewarded by their contemporaries with research grants, tenure, MacArthur prizes—and even Nobel and Crafoord prizes—rather than house arrest. Nevertheless, like Galileo, they have broken paradigms and taken us to new places.

I hasten to add that this is my personal list and apologize for the fact that entire fields of study, most notably radio, neutrino and gamma ray astronomy, have been omitted. Colleagues making similar lists might well come up with an entirely different cast of characters; however, I hope that all would agree on the importance of key individuals to the development of astronomy as we know it today.

GEORGE ELLERY HALE (1868-1938)[1]

Hale was an astronomer and a scientific entrepreneur with a staggering set of accomplishments. He saw early on that astronomy could develop only if more powerful telescopes were constructed, and he was the driving force behind four major telescopes: The Yerkes Observatory 40-inch refractor (1897); the Mt. Wilson Observatory 60-inch and 100-inch reflectors; and the Palomar Observatory 200-inch reflector, now appropriately called the Hale telescope. Each of these was, in its day, the largest telescope of its kind in the world, and the Hale telescope held that position from its completion in 1948 for more than 40 years, until the arrival on the scene of the much larger reflectors described below. In addition, Hale was the founder or co-founder of The Astrophysical Journal (1895), the American Astronomical Society (1899), the National Research Council (1916) and the California Institute of Technology (1920).

Hale was also a pioneering solar astronomer who invented the spectroheliograph and discovered that the sun has a strong magnetic field. Appropriately for the Italian-American flavor of this meeting, Hale was also a strong supporter and contributor to the development of a solar tower with modern instrumentation at the Arcetri Observatory in the 1920s.

The telescopes which Hale masterminded have made many, many contributions to the study of our Milky Way galaxy. Here I cite only two: In 1968, Becklin and Neugebauer used the 200-inch telescope to make the first high resolution map of the center of our Galaxy at an infrared wavelength of 2.2um. The image showed the dense stellar cluster at the core of the Galaxy. It also spawned an active line of research which has culminated in the identification of a massive black hole coincident with the peculiar radio source Sgr A* at the galactic center. Becklin and Neugbauer made this image with a single detector and an aperture or spatial resolution of 2.7 arcsec, corresponding to about 0.3 light years at the galactic center. As discussed further below, more recent observations have produced detailed images of the central 0.1 light years of the galaxy!

A second noteworthy result was the discovery by Nakajima, Kulkarni et al of the first bona fide brown dwarf, found as a companion to a nearby low-mass main sequence star. The discovery observations were actually made at the 60-inch telescope of the Palomar Observatory, but confirmation required use of the neighboring 200-inch. Brown dwarfs are failed stars—objects less massive than ~0.08 solar masses that never became dense or hot enough at their centers to ignite nuclear burning and become truly self-luminous. Although generally fainter than stars—except when very young—brown dwarfs can be seen at wavelengths beyond the visible; they glow in the infrared as the heat generated in their formation diffuses outward and is radiated away. Subsequent observations have shown that brown dwarfs are

[1] *Explorer of the Universe*, biography by Helen Wright, 1994; *Pauper and Prince*: Ritchey, Hale, and *Big American Telescopes*, by Donald Osterbrock, 1993

about as abundant locally as are all other types of stars put together; in fact, the latest results from the Spitzer Space Telescope suggest that there is about a 50% chance of a brown dwarf being closer to the sun than is the nearest presently known star, Proxima Centauri. Identifying this celestial neighbor is an important objective of the recently launched Wide Field Infrared Survey Explorer (WISE) mission.

ROGER ANGEL (B1941)[2], JERRY NELSON (B1944)[2], AND ANDREA GHEZ (B1965)

Angel and Nelson have independently developed new approaches to making large visible-and-infrared wavelength telescopes which break the paradigm for mirror fabrication used for the 200-inch and other telescopes of its generation, while Ghez has been among the most effective users of these new telescopes. Nelson developed and demonstrated a technique which greatly eased the task of making a segmented primary mirror (which may have mechanical and cost advantages over a monolith of similar size). The easiest figure for an optician to grind onto a mirror blank is a sphere or an on-axis parabola, but the off-axis segments of a non-spherical segmented primary are considerably more challenging. Nelson showed that by gluing weights to the perimeter of a circular blank it was possible to deform it elastically. A spherical surface could be polished into the surface of the distorted blank so that, when the stress was relieved by removing the weights, the blank relaxed to the shape appropriate for an off-axis segment of a larger primary mirror. By trimming the polished segments to hexagonal shape and using edge sensors and other means of figure control, astronomers and engineers have assembled ~1.8-m-sized segments manufactured in this way into the twin 10-m diameter reflectors of the Keck Observatory in Hawaii.

Angel developed a new method for fabrication of a large monolithic primary mirror, casting the mirror out of lightweighted Pyrex blocks placed in a large, rotatable oven. The glass melts as the mirror rotates, and the surface of the viscous molten glass assumes a parabolic figure. Mirrors up to 8.4 m in diameter have been made in this fashion, with the size being set by the spacing of the pillars holding up the University of Arizona football stadium, beneath which Angel's mirror laboratory is located. The primary mirrors produced in this fashion are relatively lightweight and inexpensive and can be thermally controlled to reduce temperature gradients and the resulting air currents which can degrade image quality in an observatory dome. Two of Angel's 8.4-m diameter primary mirrors are mounted side-by-side—and co-aligned—in the Large Binocular Telescope (LBT) at Mt. Graham in Arizona. Both approaches, stressed mirror polishing and spin casting, are being advocated for the ~30m diameter telescope recommended by the National Academy of Sciences' Astro2010 decadal review committee.

It is no accident that both the Keck observatory and the LBT feature two large apertures which are close together. In each case, it was envisioned that the two apertures could be used together as an interferometer to achieve higher resolution than would be possible with a single telescope. This has already been done successfully at the Keck Observatory, where the

[2] "Race for the Heavens" by Yudhijit Bhattacharjee, *Science* 23 October 2009 326: 512-515 [DOI: 10.1126/science.326_512]

separation of the two primary mirrors is ~85m, and is being actively pursued at the LBT, where the maximum baseline achievable will be ~25m. (To be complete, I should mention that the European Southern Observatory (ESO) includes four 8.2-m diameter telescopes with thin meniscus primary mirrors—a third successful approach to building a large mirror that was also used for the Gemini telescopes—and that the ESO telescopes can also be paired up and used interferometrically).

One of the best examples of the galactic astronomy enabled by these large ground-based telescopes is the work of Andrea Ghez and her UCLA colleagues on the motions of stars at the galactic center. (A similar investigation has been carried out by Reinhard Genzel and colleagues at ESO.) Ghez' work relies as well on another recent technological advance, adaptive optics (AO), which provides a means of correcting telescopic images for the distortion or "seeing" produced by the Earth's atmosphere. In Ghez' case, the AO system now in use is built around a "laser guide star:" a sodium laser beam is projected through the telescope and scatters off a layer of sodium atoms high in the atmosphere. The returned beam is imprinted with the effects of atmospheric distortion, which can be measured by comparison with the undistorted laser beam. The difference is fed to a deformable mirror which continually corrects the wavefront of the light arriving from celestial targets to sharpen the image. (Ghez began work on the galactic center using a "natural guide star," a star within the region being studied which is bright enough to allow rapid wavefront updates using the deformable mirror).

Adaptive optics allows a single 10m aperture Keck telescope to produce images smaller than 0.05 arcsec at 2.2um; this is about 50 times better than the angular resolution used in the original Becklin/Neugebauer map of the galactic center and has allowed Ghez and her team to examine the central 1", or 0.1 light years, of the dense central stellar cluster in great detail. Over the past 10 years, their repeated measurements of stellar positions have shown that the stars in this central region are orbiting a compact central mass at velocities up to several thousand km/s. This central mass is identified with great confidence as a black hole with mass $\sim 4 \times 10^6$ solar masses; a variety of previous observations had suggested that a black hole of about this mass was lurking at the center of the galaxy.

The precision achievable in Ghez' measurements is currently limited by systematic uncertainties due to possible blending of the background stars used to establish the reference grid against which the stellar motions are measured. When the coming generation of ~30m telescopes arrives, it will be possible to push these measurements to the point where general relativistic effects due to the curvature of space-time in the vicinity of the black hole become observable.

Lyman Spitzer, Jr. (1914-1997)

Lyman Spitzer was a versatile and scientifically influential astrophysicist, as witnessed by his receipt of the Crafoord Prize in astrophysics (1985). His research and books on the interstellar medium have challenged and informed generations of graduate students, and he worked as well on stellar dynamics and plasma physics. Perhaps less well known is his unquestioned position as the father of space astronomy, which he occupied in 1946 with an extraordinarily prescient report, entitled "Astronomical Advantages of an Extra-Terrestrial Observatory". In this paper, written at a time when the German V2 rocket had only recently demonstrated the feasibility of rocket flight, he foresaw the development and power of space observatories across the spectrum from infrared to ultraviolet, as well as the importance of the entire electromagnetic spectrum for the study of astrophysical phenomena. The paper is replete with statements like "…new phenomena not yet imagined…" and "…open up completely new vistas of astronomical research…" which predict with uncanny accuracy the scientific bounty of space astronomy. Later in his career Spitzer became the Principal Investigator of the Copernicus ultraviolet satellite (1972), which was one of the first truly powerful telescopes in space; later still, he and his Princeton colleague John Bahcall (1934-2005) tirelessly and successfully walked the halls of Congress, advocating what we now know as the Hubble Space Telescope (HST).

The telescopes most directly identified with Spitzer, Copernicus and HST, have made numerous contributions to our understanding of the Galaxy. By providing access to ultraviolet wavelengths not accessible from the ground, Copernicus has provided marvelous data on the atomic, ionic, and molecular constituents of interstellar matter—the stuff between the stars. As many as 27 different chemical species have been identified in these spectra, which provide new insights into the physical, chemical, and dynamic processes in the space between the stars. These studies are confined to the low density phase of the interstellar medium because the interstellar dust in the denser regions becomes opaque in the ultraviolet.

Spitzer's magnum opus, the Hubble Space Telescope, has contributed greatly to our understanding of the formation of stars and planetary systems in the galaxy. The iconic image of the Pillars of Creation in the Eagle Nebula highlights the dynamic sculpting of dense clouds which can trigger the formation of new stars. Perhaps more fundamentally, Hubble has also returned direct, dramatic images of circumstellar disks around young stars. The basic model for the formation of stars and planetary systems starts with the collapse of a dense interstellar cloud under its own gravity. The angular momentum of the collapsing cloud—perhaps accumulated stochastically as the cloud formed—goes into a disk rotating around the forming star. Some of the material of this disk loses its angular momentum and accretes on to the star, while the remaining disk in many cases gives birth to a planetary system. Although this picture is supported by a great deal of indirect data and calculation, the images of disks from Hubble, particularly the so-called proplyds seen in silhouette against the bright Orion nebulae, provide dramatic and direct confirmation.

RICCARDO GIACCONI (B1931)[3]

Giacconi first became known in the astronomical community as the pioneer of [non-solar] x-ray astronomy, which he initiated in 1962 with a rocket flight aimed at detecting x-rays from the moon. X-rays were detected, not from the moon, but from the galactic binary star system now known as Sco X-1. Subsequent investigations by Giacconi and his colleagues—including Uhuru, the first x-ray satellite, which was launched in 1970—rapidly demonstrated the power of x-ray observations to probe a very wide range of astrophysical phenomena. Giacconi was intimately involved in many subsequent x-ray missions, including the two major observatories now operating, NASA's Chandra X-ray Observatory (CXO) and ESA's XMM-Newton satellite. Going far beyond his work in X-ray astronomy, Giacconi was the first director of the (Hubble) Space Telescope Science Institute and later Director General of the European Southern Observatory. He was awarded the Nobel Prize in Physics in 2002 for the development and exploitation of X-ray astronomy.

X-ray studies have contributed immeasurably to our understanding of galactic astronomy. An early and perhaps surprising result was the discovery of strong x-ray emission from young and forming solar-type stars, which results from enhanced coronal activity in the magnetically and convectively active young stars. Because x-ray and infrared radiation readily penetrate clouds of interstellar dust, x-ray and infrared images can show embedded clusters of stars in regions which appear inactive or uninteresting in the less penetrating visible and ultraviolet bands. In addition, x-rays incident on the planet-forming disk may influence its chemistry in interesting ways because of their ionizing and penetrating power.

A truly remarkable galactic astronomy result is the Chandra x-ray observatory image of the Crab Nebula, which is a supernova remnant—the debris left behind by a star which exploded in 1054, as noted by Chinese astronomers at the time. It has been known for some time that the Crab Nebula houses a pulsar—a rotating neutron star which is the collapsed core of the exploded star. A neutron star is, quite literally, a giant atomic nucleus, perhaps 1.5 solar masses of material compressed to the density of an atomic nucleus, so that its radius is only some 10km. The Crab Nebula pulsar was discovered by the pulsed radio emission it emits with a period of ~33msec, and subsequently pulses have been observed at infrared, visible, and x-rays. The pulse period is identified with the neutron star's rotation period, and—although the details are very uncertain—it appears that the pulsed emission is due to directional beams of radiation which sweep across the Earth as the pulsar rotates. Soon after the discovery of the pulsar, it was pointed out that the rotation was slowing and that the rate at which the pulsar loses kinetic energy is about the same as the rate at which the Crab nebula radiates energy when integrated across all wavelengths. The Chandra image of the Crab shows not only the neutron star itself—which is very hot due to matter falling into the

[3] *Revealing the Universe*, by Wallace and Karen Tucker, Harvard, 2001, is a book dedicated to the story of xRAY astronomy and Giacconi's work on the Chandra XRay Observatory; *Cosmic Inquirers*, by the same authors, talks about people like Low, Neugebauer, and Giacconi who made early space observatories possible. There is almost certainly quite a bit in it about Spitzer as well. It was published in 1986 by Princeton University Press; "An Education in Astronomy", by R. Giacconi. *Annual Reviews of Astronomy and Astrophysics*, v43, p1, 2005 is an autobiographical memoir.

deep gravitational well it produces—but also a concentric series of wisps and knots which are moving outward at very high speed. It is thought that these features delineate regions where a high-speed wind from the pulsar interacts with the surrounding nebula, transferring the energy required to sustain the nebula's radiation. This is truly astrophysics in action!

ROBERT LEIGHTON (1919-1997)[4]

Leighton was a remarkably versatile experimental physicist who—following a successful career in particle physics—pioneered an astonishing number of techniques and instruments for exploring both the Solar System and the Universe. His career amply demonstrates the essential role of technical innovation in advancing astrophysics. Leighton began his remarkable career in astrophysics with the discovery of the 5 minute oscillations of the sun, ushering in the use of solar seismology to probe the solar interior. Later on he led the imaging teams which built and operated the cameras on the Mariner 4, 6, and 7 spacecraft, returning our first close-up images of Mars. But it is Leighton's work as a builder of innovative telescopes which commands our attention here.

In the early 1960's, Leighton and Gerry Neugebauer carried out the 2-Micron survey on Mt. Wilson, using a 62-inch telescope which Leighton spun out of curing epoxy, using the same principles adopted years later by Roger Angel to produce 8.4m diameter mirror blanks for large optical telescopes. The 2-Micron survey covered nearly the entire sky visible from Mt. Wilson and resulted in a catalog of some 5600 infrared sources, mostly dusty, mass-losing stars throughout our Milky Way galaxy. During the phase recorded by the 2-Micron survey, red giant stars of roughly solar mass can be shrouded in warm, infrared-emitting dust which condenses in their expanding outer atmospheres. Dynamical effects and radiation pressure drive the dust and any residual gas away from the star into the interstellar medium, thereby seeding the space between the stars with new material—atoms heavier than hydrogen and helium—to be incorporated into succeeding stellar generations. Analysis of the 2-Micron catalog and follow-up studies of individual objects within it have contributed much to our understanding of the later stages of a star's life.

Leighton's telescope building adventures went from the 2-Micron survey telescope to a much larger scale—the design and construction of high precision radio dishes for the study of millimeter and submillimeter radiation. Leighton's telescopes are 10.4-m diameter dishes constructed from 1-m-sized aluminum panels mounted on a carefully designed and constructed backup structure fabricated from lightweight steel tubes. The panels, constructed of aluminum faceplates on a honeycomb aluminum core, were actually machined in place on the telescope, which was mounted on a large, rotating horizontal bearing. As the bearing rotated, a cutting tool moved radially along a parabolic track which approximated the desired telescope surface. Most of this work was done by Leighton himself with the help of Dave Vail, a very capable technician. Appropriately enough, this work was done in the same large laboratory at Caltech where the 200-inch mirror had been figured and

[4] Biographical Memoir by Jesse Greenstein appears in "Biographical Memoirs of the National Academy of Sciences", v.75, p.164, 1997

polished in years past. Using this technique, Leighton fabricated three telescopes which were used as an interferometer at the Owens Valley Radio Observatory and are now part of the CARMA array located on White Mountain above the Owens Valley.

The (literally) crowning jewel of Leighton's radio telescope construction is the high precision dish he built for the Caltech Submillimeter Observatory, which is located atop Mauna Kea in Hawaii. This high, dry site sits well above most of the water vapor in the Earth's atmosphere; so that the atmosphere is relatively transparent to the highest frequency radio waves [wavelength ~350um; frequency ~100 THz] accessible from the ground.

The CSO dish is adjusted to a surface precision of about 10 microns [about 5/10,000 of an inch] which allows it to achieve excellent performance at these high frequencies. The submillimeter spectral band is rich in emission lines of the molecules now known to abound in both interstellar and circumstellar clouds. These range from simple, familiar substances such as water, carbon monoxide, and ammonia to large and exotic species such as $H_3COC_2H_5$ [trans-ethyl methyl ether] and $HC_{10}CN$ [cyanodecapentayne]. These molecules are evidence of complex chemical processes in space. Because of the preponderance of organic species amongst them, they may hold clues to the pathways which produced the chemical environment in which life arose on Earth. Leighton's CSO dish has been used very effectively to survey the molecular content of various astronomical environments. Instructively, the molecular inventory of typical interstellar material, such as the center of the Orion nebula, differs greatly from that of the circumstellar shells around many of the stars recorded in the 2-Micron survey. This can be understood simply from the variation of the ratio of carbon to oxygen [C/O]. In Orion, C/O<1, and regions with C/O<1 are dominated by oxygen-rich molecules, because much of the carbon is bound into CO. However, material ejected from a mass-losing star can have C/O>1 if the ejecta contain material from within the star which was processed in the nuclear reactions which powered the star. In this case, the ejected material will be rich in carbon-bearing molecules, such as HCN and C_2H. The most famous such carbon star with a molecular envelope is the very well-studied object known as IRC+10216, a designation derived from the 2-Micron survey in which it was first identified. Thus, one of Leighton's telescopes is used to explore the discoveries of another.

GERRY NEUGEBAUER (B1932)

Neugebauer began his scientific career as a particle physicist (as did Leighton) but quickly took advantage of other opportunities. He worked with Leighton on the 2 Micron survey described above, and went on to become a leader in the rapidly-developing field of infrared astronomy. He started the "infrared army," the name give to, or adopted by, the dynamic infrared group at the California Institute of Technology. He and his students and collaborators, most notably Eric Becklin, made use of the telescopes of the Mt. Wilson and Mt. Palomar Observatories to make numerous pioneering discoveries, including the discovery of the dense stellar cluster at the center of the Galaxy discussed earlier. Earlier, Neugebauer had contributed to the development and flight of the infrared radiometer on Mariner 2, the first successful interplanetary spacecraft, which was launched in 1962.

In the mid-1970's, Neugebauer was selected as the co-chair—and US lead—of the international science team for IRAS, the Infrared Astronomical Satellite. IRAS, the first liquid-helium cooled observatory for space infrared astronomy, was a joint effort of the United States, the Netherlands, and the United Kingdom. IRAS pioneered the use in space of number of technologies—most notably long-lived cryogenics—which led to a tumultuous and rocky, but ultimately highly successful, development. The principal objective of IRAS was to survey the entire sky with ~arcmin resolution, using 62 discrete detectors in four broadbands at12, 25, 60, and 100um. IRAS was launched in January of 2003 and its helium cryogen lasted until November. IRAS achieved sensitivity over the entire sky which had previously been achieved, if at all, only through very long observations at a few specific points. The scientific output of IRAS is contained in numerous data products, including catalogs of over 250,000 infrared sources, most of which had never before been measured in these wavelengths. Its scientific discoveries are too numerous to detail here, but include, in the field of galactic astronomy, the following: detection of emission from nearby, solar-type stars which signals that solar systems have formed and evolved around them; and identification of numerous very young stars—seen at a much earlier stage—which are embedded in the clouds of dust and gas within which they have only recently formed, and which show evidence for harboring circumstellar disks within which planets may form.

In addition to its scientific bounty, IRAS was the first space observatory for which a very rich data set was made easily available to the entire scientific community, first in the form of hard copy or microfiche, but soon in machine readable form which can be interrogated over the Internet. IRAS' data are particularly appropriate for this type of treatment, because, as an all-sky survey, they can be used in comprehensive statistical studies. To be truly useful to a number of relatively untrained users, such a catalog has to be highly reliable, of known completeness, and also very well-documented. Above and beyond his contributions to the technical success of the mission, Neugebauer's greatest contribution to IRAS may have been his insistence that the catalog and data bases meet very strict and very well documented standards of reliability and completeness. The catalogs were implemented at the Infrared Processing and Analysis Center [IPAC] at Caltech, a data center established for this purpose which has supported IRAS data users from all countries. The quality and lasting importance of the IRAS archive can be seen from the fact that even today, almost 30 years after the end of the mission; dozens of research papers every year make use of IRAS data. The IRAS data were also among the first data sets for which NASA provided funding—through what is now known as the Astrophysics Data Program—to users competitively selected to carry out what is now known as archival research using the data.

Neugebauer was thus a leader in establishing what is now a well-accepted paradigm for large astronomical data sets, from both space and ground telescopes, which is that the data are made publicly and electronically available in a well-documented and supported archive. Many important projects, such as Princeton's Sloan Digital Sky Survey or NASA's recently-launched Wide Field Infrared Survey Explorer (WISE) have been designed and executed largely or entirely for the purpose of creating such a multi-user, multi-purpose archive. These archives have enabled an entirely new approach to astrophysics, based on multi-wavelength, multi-facility exploration of pressing astrophysical problems.

FRANK LOW (1933-2009)[5]

Low's contributions produced major steps in ground-based, airborne, and space infrared astronomy. They began with his invention, while working as a low temperature physicist at Texas Instruments in the early 1960s, of the germanium bolometer, the first really sensitive detector for radiation in the thermal infrared. Not long thereafter, Low began a long career in astronomy, first as a staff member at the National Radio Astronomy Observatory, and then on the faculty at the University of Arizona and Rice University. Low realized the importance of optimized low-background telescopes for infrared observations, and built and used several telescopes of this type in the mountains around Tucson. He also realized the utility of getting above as much as possible of the water vapor which makes the Earth's atmosphere opaque over much of the infrared. While others used balloon-borne telescopes for this purpose, Low pioneered the use of high altitude aircraft, mounting a 12-inch diameter reflecting telescope in the escape hatch of a Lear Jet. In this configuration, the telescope itself produced a re-entrant cavity in the aircraft fuselage; the telescope optics were In equilibrium with the ambient environment at altitude, so that the incoming radiation saw no window other than the small, thin one which preserved the vacuum in the cryostat which held the detector. (The cryostat, or dewar, was another of Low's innovations; he successfully used metal cryostats which are much more appropriate for use in the field than are the glass cryostats used for laboratory work.) The scientific program which Low and his students carried out from the Lear Jet was highly successful, leading, for example, to the discovery that Jupiter has an internal heat source, and identifying for the first time the infrared luminous galaxies later studied in greater depth by IRAS. The success of the Lear Jet encouraged NASA to field a larger airborne telescope, the Kuiper Airborne Observatory (KAO). The KAO featured a 91-cm diameter telescope carried into the heavens by a converted C-141 military transport, and it operated very successfully from 1974 to 1995. A still larger airborne telescope, the Stratospheric Observatory for Infrared Astronomy (SOFIA), had its first scientific flights in 2010. SOFIA incorporates a 2.7-m diameter telescope into a 747-SP aircraft. It is a joint project of NASA and the German Space Agency.

Infrared investigations are challenged by the fact that the foreground emission from either a warm telescope or the atmosphere is many orders of magnitude brighter than a typical astronomical source. Thus even small (<<1%) fluctuations in this foreground emission—which is far from stable—can produce spurious signals. The effects of the foreground can be minimized by looking on and off the target more rapidly (say 5Hz or greater) than the bulk of the fluctuations. This modulation of the signal is called "chopping". Typically a large telescope cannot be moved this rapidly, and placing chopping mirrors or blades close to the detector at the focus of the telescope encounters a number of problems. Among Low's many contributions to the progress of infrared astronomy was his introduction

[5] "The Beginning of Modern Infrared Astronomy," Frank J. Low, G.H.Rieke, and R.D.Gehrz, *Annual Reviews of Astronomy and Astrophysics*, v.45, p.43 (2007).

of the chopping secondary mirror—articulating the relatively small secondary mirror of the telescope so that it can be oscillated at an appropriate frequency, moving the target rapidly on and off the detector. This approach dramatically improved the performance of both ground-based and airborne telescopes in the infrared.

Low, like several other leading infrared astronomers, served with Neugebauer as a member of the IRAS science team. His physical intuition and insistence on technically correct decisions contributed greatly to the success of IRAS. Most notably, he invented a new type of pre-amplifier, based on the use of cryogenic field effect transistors, or JFETS, which boosted the small signals from the detectors to a level at which they could be routed out of the cryostat without degrading the sensitivity of the observations. These devices were built by Low at a small company, Infrared Laboratories, which he had started in the late 1960s to provide the community of infrared astronomers with access to the detectors and cryostats which he developed.

As did the author of this article, Low served as a member of the Science Working Group (SWG) for what became known as the Spitzer Space Telescope, named for Lyman Spitzer, Jr.[6] Spitzer, launched in 2003, is the infrared member of NASA's family of Great Observatories, which also includes the Hubble and Chandra observatories mentioned earlier. Low was named to the SWG as Facility Scientist, and he made numerous contributions to the technical development of what has been a very successful and exciting mission. Chief among these was his insight—which came to him during a sleepless night at a SWG retreat in 1993—that we could implement Spitzer's cryo-thermal system in what has become known as the Warm Launch Architecture. In this configuration the Spitzer telescope was launched warm and cooled down on orbit through the combination of radiative cooling, by which most of the heat energy in the telescope was radiated into space, and conduction to the evaporating liquid helium, which brought the telescope down to its final operating temperature of ~5K. This approach is well-suited to Spitzer's solar orbit, which takes the observatory far from the heat of the Earth. It saves the mass and volume penalty which previous infrared space observatories, such as IRAS, paid for enclosing the entire telescope in a cryostat so that it could be launched at operating temperature. The power of the radiative cooling can be seen from the fact that at present, following the depletion of Spitzer's liquid helium cryogen, the telescope is maintained at a temperature below 30K entirely by radiative cooling. At this temperature, Spitzer continues to operate at its shortest wavelength bands without loss of sensitivity.

The contributions to galactic astronomy of the telescopes and innovations that Low pioneered are innumerable. To cite just a few, the inherent mobility of an airborne telescope allowed the KAO to discover the rings of Uranus in an observation of a stellar occultation made off the coast of Australia in 1977. Spitzer has contributed higher sensitivity, improved

[6] "Lyman Spitzer, Jr. 1914-199," by Jeremiah P. Ostriker, Biographical Memoirs of the NAS", 2007; "Dreams, Stars, and Electrons", selected writings of Lyman Spitzer, Jr. Compiled by Lyman Spitzer, Jr., and Jeremiah P. Ostriker. Princeton University Press (1997); "Dreams, Stars, and Electrons," by Lyman Spitzer, Jr. Annual Reviews of Astronomy and Astrophysics, v27, p1 (1989). Autobiographical memoir; "The Astronomical Advantages of an Extraterrestrial Observatory", L.Spitzer, Jr., Astronomical Quarterly, v.7, p.129 (1990) – Spitzer's seminal paper on telescopes in space.

spatial resolution, and spectroscopy to the study of star and planetary system formation initiated by IRAS. Most notably, however, Spitzer has also made the first measurements of light from planets around other stars, or exoplanets. Since the mid-1990s astronomers have discovered over 400 planets orbiting solar type stars in our corner of the Milky Way galaxy. In almost every case, the planets have been discovered indirectly through their influence on the position, radial velocity, or brightness of the parent star. Many of these planets are large enough [~Jupiter-sized] and hot enough, by virtue of being closer to the star than Venus is to the sun, that they would be readily visible to Spitzer in the infrared if not for the much, much brighter infrared glare of the very nearby star. What saves the day is that some fraction of the discovered planets are in orbits which are edge on as seen from Earth, so that the planet alternately passes in front of or behind the star. (The first of these so-called transiting planets were identified on the basis of the orbit inferred from radial velocity studies, but, more recently, targeted ground-based searches and the CoRoT and Kepler satellites have been optimized for the discovery of many more examples.) However discovered, transiting planets are a goldmine for exoplanet studies. When the planet passes in front of the star, the fraction by which the starlight dims [generally a percent or smaller] provides a direct measure of the size of the star. When the planet passes behind, the infrared signal from the system drops by a small amount (generally 0.1% or less) providing a measure of the infrared light of the planet relative to that of the star. Because the size of the planet is known, its infrared brightness can be easily related to its temperature. More sophisticated variants of this approach using several spectral bands or a spectrograph, or following the planet over an entire orbit, have revealed amazing details about the composition of exoplanets, and about the structure and dynamics of their atmospheres.

A Scientific Summary

If we sort the scientific studies alluded to in the forgoing in a slightly different way, we come up with the following list, where the scientists' names refer back to the sections in which these topics are cited:

1. The diffuse interstellar medium (*Spitzer*)
2. Dense interstellar clouds (*Leighton*)
    a. Young and forming stars (*Spitzer, Giacconi, Neugebauer, Low*)
    b. Protoplanetary disks (*Spitzer, Neugebauer, Low*)
    c. Exoplanet systems (*Low, Neugebauer*)
3. Brown dwarfs (*Hale*)
4. Evolved stars undergoing mass loss (*Leighton*)
5. Supernova remnants and neutron stars (*Giacconi*)
6. The center of the Galaxy (*Hale, Angel, Nelson, Ghez, Neugebauer*)
7. Massive black holes (*Ghez*)

Viewed as an evolutionary sequence, the first five items in this list summarize a great cyclical process in which the chemical elements are produced in evolved stars and supernovae and returned to the interstellar medium for incorporation into future generations of stars, planets, and eventually into Galileo's telescope and into Galileo himself. This cycle, which leads to both the enrichment and the depletion of the interstellar medium as more and more if it is locked up in stellar remnants and brown dwarfs, drives the evolution of our galaxy and of others like it. Observation of these phenomena locally thus illuminates some of the fundamental processes of astrophysics. Identification of this cycle is surely one of the major triumphs of 20th century astronomy.

The final two items on the list, the Galactic Center and massive black holes, lie outside this cycle but provide yet another instance where local studies illuminate universal phenomena. Every galaxy has a center, of course, and in many cases, as in our own Milky Way, it is the position of highest stellar density and home to an intriguing mixture of physical processes. Less obviously, we now know that essentially every spheroidal stellar population, whether an elliptical galaxy or the central bulge of a spiral galaxy, hosts a black hole with mass proportional to the mass of the stars. The implied (but not yet understood) universality of black hole formation and activity highlights the importance of the opportunity which the black hole at the center of our galaxy provides for detailed study of these intriguing bodies.

SOME COMMON CHARACTERISTICS

The scientists described earlier, from Hale to Low, worked on a disparate set of problems using a variety of techniques—observational, experimental, instrumental and theoretical. Their accomplishments have rewritten the astronomy textbooks of the 20th century and set the stage for great discoveries yet to come. It is instructive to search for common characteristics amongst this group which have contributed to their success and may inform others who wish to follow in their footsteps. In the author's opinion, these common characteristics, shared in each instance by most if not all of our 20th Century Galileos include (in addition to the obvious one of being smart, or very smart, or even a genius):

1. Technical Expertise and Mastery
2. Ingenuity and Opportunism
3. Vision and Leadership
4. Ambition and Drive
5. Daring and Self-Confidence
6. Uncompromising Insistence on Excellence

Although the tools, theories, and techniques—as well as the underlying knowledge base—evolve with time, there is universality to the scientific method. One can imagine that Galileo shared may of the characteristics listed above, and that they account for his success and persistence in the face of great adversity. Moreover, the continuation of the telescopic renaissance and scientific progress highlighted in this article is assured if—but perhaps only if—we continue to recognize and reward those unusual individuals who share these rare attributes.

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Beyond Galileo's Wildest Dreams: Telescope Observations of the Early Universe and Modern Cosmology

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ABSTRACT

Galileo Galilei was the first archaeologist of the Universe. He was convinced of the finite speed of propagation of light, and detected for the first time light produced from distant stars in our Galaxy, emitted thousands of years before his observations.

Today's microwave telescopes explore regions of the Universe so distant that light was emitted about 13.7 billion years ago. These telescopes, exploring the Cosmic Microwave Background (CMB), are now producing detailed images of the early universe, measuring both the CMB brightness and polarization distribution. These observations, combined with measurements of distant supernovae and of other cosmological observables, support the model of an inflationary universe, composed of radiation, ordinary matter, dark matter and dark energy.

Current observations include extremely sensitive surveys of the polarization of the CMB, and sensitive observations of the fine-scale anisotropy of the CMB. We will focus on a few new experiments, opening new vistas on the early universe, like the proposed SAGACE mission to measure the spectrum (in wavelength) of CMB anisotropy.

INTRODUCTION

In *Discorsi e dimostrazioni matematiche intorno a due nuove scienze*, Galileo discusses the speed of light, and describes his attempt to measure it. Galileo and his assistant went to the top of two hills, each of them equipped with a lantern and a black cloth. The assistant was instructed to uncover his lantern only after seeing light from Galileo's one. Galileo would uncover his lantern and start a water-stopwatch, stopping it after receiving light from his assistant's lantern, thus measuring the time elapsed in the round trip of light.

The experiment was conceptually correct, but failed due to human reaction times and to the poor performance of the water stopwatch: my third-year-physics students reproduce Galileo's experiment using a laser diode, a mirror on the other side of the lab, a photodiode and a digital oscilloscope. They measure the speed of light to a few %. Galileo admits that he failed:

> …In fact I have tried the experiment only at a short distance, less than a mile, from which I have not been able to establish with certainty whether the appearance of the opposite light was instantaneous or not; but if not instantaneous it is extraordinarily rapid — I should call it momentary…

but remains convinced of the finite value of the speed of light.

Having failed at his experiment, he tries to use the laboratory of Nature. His argument is based on the observation of distant lightning spreading between clouds:

> …for the present I should compare it to motion which we see in the lightning flash between clouds eight or ten miles away from us. We see the beginning of this light — I might say its head and source—located at a particular place among the clouds; but it immediately spreads to the surrounding ones, which seems to be an argument that at least some time is required for propagation; for if the illumination were instantaneous and not gradual, we should not be able to distinguish its origin—its center, so to speak—from its outlying portions.

Today we know that this argument is wrong, but at least it demonstrates that Galileo was convinced of the finite speed of light, measured by experiments rather than believing the paradigm (which stated, from Aristotle, the instantaneous propagation of light).

We should also remember that Galileo's discovery of Jupiter's moons opened up the possibility to measure the speed of light with good accuracy, later in the same century, by Ole RØmer in 1676.

In 1610 Galileo pointed his new telescope to the sky, and observed stars. He saw well known stars (the Pleiades, Orion, Presepae…) but also resolved the Milky Way, recognizing a large number of dimmer stars. He wrote:

> …the Galaxy is nothing else than a countless set of stars clustered in groups, because wherever one points his telescope, he sees a crowd of stars. Several of them are large and well visible, while the largest part of the small ones is completely unexplorable. He clearly understood he was the first human being to see stars never observed before. These stars are thousands of light years away, so Galileo was the first human being seeing light emitted many millennia before the observation.

I don't know if he ever dreamed about himself being the first archaeologist of the Universe. He certainly had all the necessary qualitative elements to think so, but he did not know quantitatively the speed of light, nor had he a method to measure the distances of stars.

The possibility to study the past of the Universe observing light coming from far away was clearly stated almost three centuries later, by Camille Flammarion (*l' Univers Anterieur*).

Nowadays we measure light emitted in remote regions of the universe, billions years ago. In the following I'll focus about observations of the earliest light in the Universe, the Cosmic Microwave Background (CMB).

THE COSMIC MICROWAVE BACKGROUND

The discovery of cosmological red-shift (elongation of wavelengths) of light from distant galaxies was the proof of the expansion of the Universe. In an expanding universe, where the distance of any two points increases with time, the wavelengths of light also increase by exactly the same factor. The longer light travels through an expanding universe, the more its wavelength is elongated. For this reason the redshift increases with the distance of the source, as Hubble and Wirtz and others discovered in the 20s.

Since the Universe expands, it was hotter in the past. If we consider sources very far away, their light, that we receive today, was emitted when the universe was much denser and hotter than today. This fact limits the maximum distance of a source we can actually observe today. Beyond a certain distance, we would receive light produced at such an early epoch that the temperature of the universe was hotter than the surface of the sun (a few thousand degrees Kelvin). This distance is about 13.7 Gly. In fact, 13.7 Gy ago (and 380000 years after the Big Bang) the universe cooled below 3000K, thus allowing for the first time the combination of protons and electrons into hydrogen atoms, and thus becoming transparent to electromagnetic waves (this process is misleadingly called recombination). Before recombination, the temperature was so high that electrons and protons could not form atoms: the universe was ionized. As a result, it was opaque, not transparent to light (as is, for the same reason, the interior of the sun). For this reason, the farthest distance we can receive light from is 13.7 Gly. Radiation coming from recombination is redshifted by a factor as large as 1100. Visible light (with wavelength < 1 m) produced at that epoch has been converted by the expansion of the universe into microwaves with wavelength of the order of 1 m x 1100 = 1.1 mm today. Light coming from recombination should have a thermal (blackbody) spectrum, as a blackbody is the spectrum of light coming from the surface of the sun. Being a 3000K blackbody at recombination, radiation is redshifted and diluted into a 2.725 K blackbody today: this is the Cosmic Microwave Background (CMB), which was observed for the first time in 1965 by Penzias and Wilson, and whose spectrum has been accurately measured by the FIRAS spectrometer aboard the COBE satellite in 1992.

The perfect blackbody spectrum[1] of the CMB, together with the measured primordial abundances of light elements, represents strong evidence of a hot early phase of a homogeneous Universe, confirming the hot big bang hypothesis introduced by George Gamow in 1946.[2]

The CMB is to first approximation isotropic, i.e., we receive quite accurately the same brightness from any direction we look at. This strongly confirms that the universe is and was in the past homogeneous and isotropic, at large (cosmological) scales.

However, we do expect at least small inhomogeneities to be present in the early universe, at redshift 1100, as the starting phase of the long process producing the structures we see in the inhomogeneous Universe today (galaxies, clusters of galaxies, superclusters). This should be visible as a faint anisotropy in the otherwise isotropic CMB.

[1] Mather J. et al., 1999, Ap.J., 512, 511
[2] Gamow G., 1946, Phys. Rev. 70, 572

An experimental activity lasting decades has finally produced resolved images and precise angular power spectra of the CMB anisotropy.[3] As for gases or any other large physical system, our theoretical description of inhomogeneities in the early Universe is entirely statistical. The statistical quantity describing the anisotropy of the CMB is the power spectrum of its image. This describes how large are the fluctuations in the brightness of the CMB at different angular scales.

This quantity is sensitive to the physics of the primeval fireball (including acoustic oscillations of the photon-baryon plasma, baryonic and dark matter content, dark energy content), to the initial conditions of the structure formation process, and to the overall geometry of the universe.

Using well known physics, theorists are able to predict very accurately the power spectrum of the CMB expected for different values of the cosmological parameters. Today we have accurate measurements of the power spectrum, so we can constrain quite precisely the cosmological parameters. Specialists find that an adiabatic inflationary cosmological model with cold dark matter and a cosmological constant fits extremely well the measured data.[4]

CMB Polarization

At recombination CMB photons interacted with matter for the last time. This interaction was a scattering against free electrons (the last ones present, just before neutral atoms formed), i.e., Thomson scattering. Let us consider a single electron at recombination, and the incoming CMB photons. Classically we see that if their distribution is isotropic, the resulting motion of the electron will not have any preferred direction, and the scattered radiation will not be polarized. If, instead, the incoming distribution has a quadrupole anisotropy, i.e. there is excess emission from two antipodal directions, this will result in a wider motion of the electron along the directions orthogonal to the quadrupole axis. This will result, in turn, in a degree of linear polarization of the scattered radiation.[5] The small density fluctuations which are believed to have originated CMB anisotropy (and the large scale structure of the present universe) were present at recombination, so the distribution of incoming photons will be slightly anisotropic, and will include, among others, a small quadrupole component. For this

[3] de Bernardis P., et al., 2000, Nature, 404, 955; Lee A.T., et al. 2001, Ap.J.Lett., 561, L1; de Bernardis P., et al., 2002, Ap.J., 564, 559; Halverson, N.W., 2002, Ap.J., 568, 38; Ruhl, W.J., et al., 2003, Ap.J., 599, 786; Grainge K., et al., 2003, MNRAS, 341, L23; Jones, W.J., et al., 2006, Ap.J., 647, 823; Kuo, C.L., et al., 2007, Ap.J., 664, 687; Hinshaw, G., et al., 2003, Ap.J.Suppl.Ser., 148, 135; Hinshaw, G. et al., 2007, Ap.J.Suppl.Ser., 170, 288

[4] Reichardt, C. L, et al., 2009, Ap.J., 694, 1200;de Bernardis, P., et al., 1994, Ap.J.Letters, 433, L1;Bond, J. R., et al., 1998, D57, 2117; Bond, J. R., et al., 2000, Astrophys.J., 533, 19; Dodelson, S., Knox, L., 2000, Phys. Rev.Lett., 84, 3523; Tegmark, M., Zaldarriaga, M., 2000, ApJ, 544, 30; Tegmark, M., Zaldarriaga, M., 2000, Phys. Rev. Lett., 85, 2240; Bridle, S.L. et al., 2001, MNRAS, 321, 333; Douspis, M., et al., 2001, A&A, 368, 1; Lange A.E., et al., 2001, Phys.Rev., D63, 042001; Jaffe A.H., et al., 2001, Phys. Rev.Letters, 86, 3475; Lewis, A., Bridle, S., 2002, Phys.Rev., D66, 103511; Netterfield C.B., et al., 2002, Ap.J., 571, 604; Spergel D.N., 2003, et al., Ap.J.Suppl., 148, 175; Bennett, C. Et al., 2003, Ap.J.Suppl., 148, 1; Tegmark, M., et al., 2004, Phys.Rev.D, 69, 103501; Spergel, D.N., et al., 2007, Ap.J.Suppl., 170, 377

[5] Rees M., 1968, Ap.J.,153, L1

reason the expected polarization of the CMB is quite small.[6] The statistical properties of the pattern of polarization vectors of the CMB can be computed together with the statistical properties of the anisotropy pattern. It is thus possible to compute the power spectra of the polarization expected for a given cosmological scenario. Being generated by scalar (density) perturbations, this component of the CMB polarization is expected to be curl-free, and is named the **E** component of the polarization pattern. A cross correlation spectrum **ET** is expected as well,[7] with amplitude larger than the pure polarization spectrum.

In the inflationary scenario (a hypothetical and extremely fast exponential expansion of the very early universe) gravitational waves (tensor fluctuations) are generated. These also produce quadrupole anisotropy in the photons at the last scattering, resulting in an additional (and different) pattern of polarization of the CMB. These fluctuations introduce both curl-free and curl (labeled **B**) components in the polarization pattern. The **B** component is not generated by density fluctuations, so its detection at large angular scales would be a confirmation of the inflation hypothesis.

A small fraction of the CMB photons are re-scattered at the epoch of reionization (redshift around 10) when the first large stars, producing a huge flux of UV photons) ionize the intergalactic medium.

So at reionization there is an additional likelihood (around 10%) to produce Thomson scattering and thus polarization in CMB photons. These rescattered photons come all the way from recombination, so the level of induced polarization depends on much larger scales than in the scattering happening at recombination. For this reason we expect two peaks in the angular power spectrum of B-modes: one at the scale of tens of degrees, corresponding to scattering at reionization, and one at a scale of a couple of degrees, corresponding to scattering at recombination.

B-modes produced by inflationary gravitational waves have an amplitude related to the amplitude of the primordial gravity waves, which depends on the energy-scale of inflation (estimated to be around 10^{16} GeV). Detecting them represents a way to study physics at energies which cannot be reached in Earth laboratories. Once again, following Galileo's method, we are using Nature as the most powerful physics laboratory.

In addition to these two components, there is a calculable lensed contaminant component, arising from the gravitational lensing of scalar E mode polarization by intervening structures, around z=2.

Using proper analysis methods, the B-mode inflationary component can be disentangled from the dominant E-mode, opening a unique window to probe the very early universe and the physics of extremely high energies.[8]

[6] Kaiser N., 1983, MNRAS, 202, 1169; Hu W., White M., 1997, New A., 2, 323
[7] Kamionkowsky M., Kosowsky A., 1999, Ann.Rev.Nucl.Part.Sci., 49, 77-123
[8] Dodelson S. 2003, "Modern Cosmology: Anisotropies and Inhomogeneities in the Universe" Academic Press

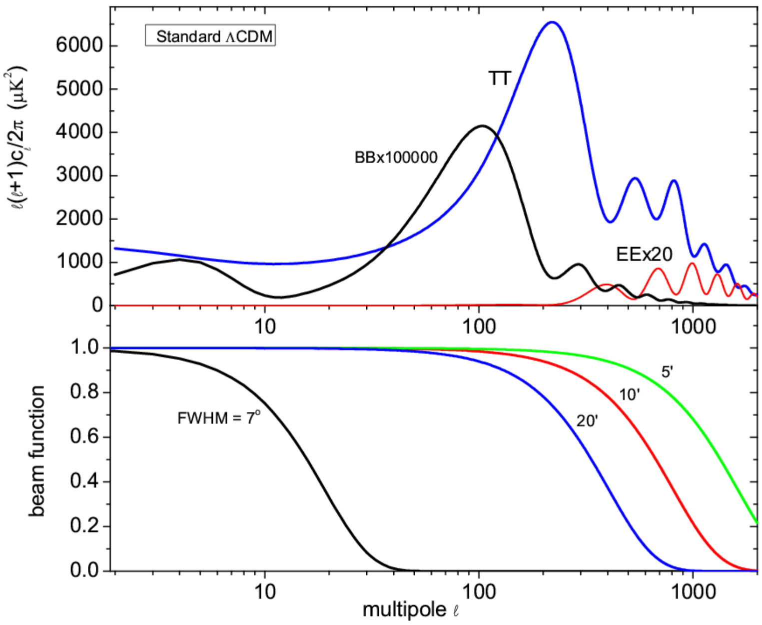

Figure 1: Angular power spectrum for CMB anisotropy (TT) and polarization (EE and BB). Polarization power spectra have been amplified to make them visible in the same plot of TT (top). Filter functions of absolute instruments with different angular resolutions (bottom).

A FWHM smaller than 1° is needed to be sensitive to the "acoustic peaks" due to photon-baryon oscillations in the early universe. The curves are labeled with the beam FWHM in arcmin.

In addition, polarization measurements will provide essential information on the reionization process itself. There are thus several good reasons to search for such small polarization signatures in the CMB sky.

In **Figure 1**, we plot the power spectra best fitting current anisotropy data, and, for the same cosmological parameters, the power spectrum of the **E** and **B** polarization (for a tensor to scalar ratio of the order of 0.05).

CMB fluctuations are extremely weak; as a rule of thumb the rms anisotropy is of the order of 30-100 K. The polarization signal generated by scalar (density) perturbations at recombination is of the order of a few K. The polarization signal generated by tensor perturbations during the inflation phase (if inflation really happened) depends on the energy scale of inflation, but is even weaker, in the range of 100nK or lower.[9]

Measuring the weak anisotropy of the CMB at the 1% level seemed science fiction 20 years ago. Now it is reality, and even the scalar polarization signal is currently being measured. This gives us confidence that the weaker B-mode polarization measurements can be measured in the future. To do this, however, observation methods need to be significantly improved.

[9] Copeland E.J., et al., 1993, Phys.Rev.Lett., 71, 219; Turner M.S., 1993, Phys.Rev.Lett., 71, 3502

CMB MEASUREMENT METHODS

Observing the CMB is not an easy task. The spectrum of the CMB, a 2.725K blackbody, is very weak compared to the emission of the local environment. For this reason, only a space mission like COBE-FIRAS has been able to measure it precisely. The anisotropy and polarization of the CMB offer a more difficult challenge. Their level is $<10^{-5}$ of the absolute intensity: extremely sensitive detectors, excellent sites, and differential methods are needed to measure it.

Of course the best way to avoid atmospheric emission is to carry the instrument above the atmosphere. The extremely successful WMAP mission of NASA has been operated at 1.5 million km of altitude, in the Lagrangian point L2 of the earth-sun system. The currently operating Planck mission of ESA operates from the same vantage point, and a third generation experiment, called CMB-pol in the proposal to NASA and B-Pol in the proposal to ESA is currently being studied.

In the case of polarization measurements, the small linear polarization degree must be extracted from the larger temperature anisotropy by means of a polarization modulator.

Most of the detections of CMB polarization to date have been made using coherent detectors at frequencies lower than 100 GHz.[10] In these instruments the detector is intrinsically sensitive to one polarization of the incoming signal, and two orthogonal polarizations can be switched on the detector by means of a ferrite modulator in a circular waveguide, either in a direct or in a correlation receiver.

Other instruments have used thermal detectors instead,[11] using either polarization sensitive bolometers[12] or a rotating waveplate modulator.[13] In the first case, the signal from two different bolometers, each sensitive to one of the two orthogonal polarizations, is compared, while the telescope scans the sky. This approach requires a good matching of the characteristics of the two detectors. In fact, selected thermistors are mounted on two independent orthogonal wire grids, which are placed inside the same groove of a corrugated waveguide. This approach offers the same mapping speed of anisotropy measurements, but is prone to significant cross-polarization and poor common mode rejection. These have to be properly characterized and calibrated.[14] This is the methodology selected for the HFI instrument on Planck, after validation on the BOOMERanG-03 balloon flight. The other

[10] Turner M.S., 1993, Phys.Rev.Lett., 71, 3502; Kovac J.M., et al, 2002, Nature, 420, 772; Barkats, D., et al, 1005, Ap.J.Letters, 619, 127; Barkats, D., et al, 2005, Ap.J.Suppl., 159, 1; Readhead, A.C.S., et al., 2004, Science, 306, 836; Kogut A., et al., 2003, Ap.J.Suppl., 148, 161; Page, L., et al., 2007, Ap.J.Suppl., 170, 335; Bischoff C., et al., 2008, Ap.J., 684, 771

[11] Masi, S., et al., 2006, A&A, 458, 687; Montroy T.E., et al., 2006, Ap.J., 647, 813; Piacentini F., et al., 2006, Ap.J., 647, 833; Wu J.H.P., et al., 2007, Ap.J., 665, 55; Ade P.A.R., et al., 2008, Ap.J., 674, 22; Pryke C., et al., 2009, Ap.J., 692, 1247; Hinderks J.R., et al., 2009, ApJ, 692, 1221; Chiang H. C., et al., 2009, astro-ph/ 0906.1181; Brown M. L., et al., 2009, Ap.J., 705, 978

[12] Jones B., et al., 2003, SPIE, 4855, 227

[13] Johnson B. R., et al., 2007, Ap.J., 665, 42

[14] Masi, S., et al., 2006, A&A, 458, 687

approach modulates on the same bolometer the two orthogonal polarizations of the incoming radiation, by means of a rotating waveplate. The method is a dynamic implementation of the original measurement method by Stokes, which analyzes the polarization of the incoming radiation by means of a waveplate followed by a polarizer. With a half-wave plate a modulated signal at 4 times the rotation frequency is produced. Suitable materials for efficient waveplates at mm wavelengths are quartz or sapphire, and using a stack of waveplates a wide bandwidth can be covered with the same modulator;[15] moreover, metal-mesh waveplates are also being developed.[16] The main problem with this approach is the necessity of a uniform waveplate, with its optical axis perfectly aligned to the spin axis. Moreover, the waveplate must spin at cryogenic temperature, without introducing vibrations and microphonics in the detectors. The mapping speed of this method is limited by the necessity of integrating on each sky pixel for several rotations of the waveplate. To solve this problem, fast spinning levitating waveplates are being developed:[17] this technology is required for balloon and space-borne missions devoted to CMB polarization currently under study.[18]

HIGH ANGULAR RESOLUTION IMAGES AND SPECTRA OF THE CMB

Our knowledge of the distribution of visible matter in the universe has improved significantly, thanks to the 3D galaxy surveys like 2DF and SDSS. Galaxy filaments form a sort of "cosmic web" with clusters and voids. From X-ray images of the clusters we have evidence that the potential wells of clusters of galaxies are full of hot (around 10keV), ionized and diluted gas.

Can CMB observations help us with understanding the formation and evolution of structures?

The photons of the Cosmic Microwave Background can interact with the hot gas, receiving a small boost in energy from its electrons (Inverse Compton Effect): this is the so called Sunyaev-Zeldovich (S-Z) effect. There is a 1% likelihood that a CMB photon crossing the cluster is scattered by an electron of the hot gas. To first order, the energy gain of the photon is about 1%, because the energy of the electrons is of the order of 1% of their rest mass. So the total energy gain of CMB photons (and the resulting CMB anisotropy) is of the order of 10^{-4}. Since all photons get a positive boost in energy, and the number of photons is conserved, there is a shift towards higher energies of the spectrum of the CMB anisotropy. This results in a decrement of the brightness at frequencies below 217 GHz, where the CMB anisotropy spectrum is increasing, and an increment at frequencies above 217 GHz. This behavior is peculiar and can be measured by comparing the signal from the cluster to the signal from a reference region outside the cluster (see **Figure 2**). The S-Z effect is one of the three main sources of small-scale anisotropy in the microwave sky at high galactic latitudes and

[15] Pisano G., et al., 2006, Appl.Opt., 45, 6982; Savini G., et al., 2006, Appl.Opt., 45, 8907
[16] Pisano G., et al., 2008, Appl.Opt., in press
[17] Hanany S., et al., IEEE Trans. Appl. Supercond., 13, 2128
[18] Crill B., et al., Proceedings of SPIE Volume 7010, arXiv:0807.1548; Oxley P., et al., 2004, Proc. SPIE Int. Soc. Opt. Eng., 5543, 320-331; Bock J., et al., astro-ph/0604101; de Bernardis P., et al., 2009, Experimental Astronomy, 23, 5, astro-ph/0808.1881

millimeter wavelengths. The primary anisotropy of the CMB and the anisotropy of the Extragalactic Far Infrared Background (FIRB) are the other main contributors.

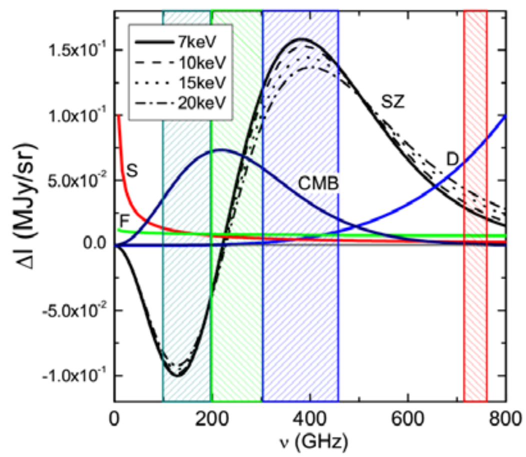

Figure 2: The differential spectrum of the Sunyaev-Zeldovich effect (SZ) in a cluster of galaxies, for different electron temperatures.

The SZ is compared to the spectra of competing effects: primordial CMB anisotropy (CMB) and local emission from synchrotron (S), free-free (F) and interstellar dust (D). Due to the peculiar positive-negative spectrum, the SZ effect can be easily separated by local effects if a multiband instrument (like OLIMPO) or a spectrometer (like SAGACE) is used. The bands explored by the SAGACE spectrometer are also shown as dashed regions.

The "cosmological window" where these components are dominant extends roughly from 90 to 600 GHz: at lower frequencies interstellar emission of spinning dust grains, free-free and synchrotron dominate over the cosmological background; at higher frequencies the clumpy foreground from cirrus dust dominates the sky brightness even at high Galactic latitudes.

The intensity of the S-Z effect is proportional to the density of the intergalactic electrons, while the X-ray brightness of the same cluster is proportional to the density squared. So the S-Z measurements are sensitive to the intracluster gas in the peripheral regions of the cluster, while X-ray measurements are not. Moreover, by combining measurements of the two quantities it is possible to derive the angular diameter distance of the clusters of galaxies.[19] Observations of many clusters would allow to build a Hubble diagram, and from this to measure the Hubble constant. These measurements are being carried out,[20] but the error in the determination of H_o is still quite large. To improve these measurements we need to collect a larger sample of clusters (and forthcoming experiments like SPT[21] and ACT[22] will do a wonderful job in this respect), and also to improve our knowledge of the details of the S-Z effect (cooling flows, inhomogeneities, relativistic corrections and so on): a survey of nearby

[19] Silk J., White S., 1978, Ap.J.Lett., 226, L103; Cavaliere A., et al., 1979, A&A, 75, 322
[20] Bonamente M., et al., 2006, Ap. J., 647, 25B
[21] Ruhl J. et al., 2004. Proc. SPIE, 5498,11
[22] Fowler J.W., et al., 2007, Appl.Optics, 46, 3444

clusters with excellent inter-channel calibration and wide frequency coverage, will be instrumental in this. The S-Z effect depends on the optical depth, but it does not depend on the distance of the clusters (it is like an opacity effect). So we can see clusters that are too faint to be visible in the optical or in the X-rays bands. The number of clusters seen at different distances is a strong function of the Dark Energy density: clusters can in principle be used as probes of the history of Dark Energy.[23] Observing selected clusters where dark matter is separated from baryons it is possible to study the SZ effect generated by annihilation products of the Dark Matter, thus testing the nature of Dark Matter.[24] This requires arcmin resolution to resolve the clouds of dark and baryonic matter. The best frequency to operate at is around 220 GHz, where the baryonic SZ signal is nearly null, and only the DM signal and the kinetic SZ are present. This high frequency represents a challenge for ground based telescopes. OLIMPO,[25] a 2.6 m stratospheric balloon borne telescope, will carry out its survey in four frequency bands centered at 140, 220, 410 and 540 GHz, in order to be optimally sensitive to the S-Z effect and to efficiently reject competing sources of emission.

Figure 3: The OLIMPO balloon-borne telescope (the ground and sun shields are not present, revealing the 2.6m mm-wave telescope with steerable primary mirror.

A satellite version of this telescope has been recently proposed to the Italian Space Agency. The payload, named SAGACE (Spectroscopic Active Galaxies And Clusters Explorer)[26] (see **Figure 4**) is able to perform spectral measurements in the range 100 to 760 GHz, using a

[23] Nunes N.J., et al., 2006, A&A, 450, 899
[24] Colafrancesco S., et al., 2007, A&A, 467, L1
[25] Masi S., et al., 2003, Mem.S.A.It., 74, 96
[26] de Bernardis P., et al., Proc. of the 12th Marcel Grossmann Meeting (2009)

differential imaging Fourier Transform Spectrometer (FTS) in the focus of an OLIMPO-like telescope. Four medium size arrays of bolometers improve the mapping speed of the instrument, which can produce spectral maps of diffuse mm emission with a resolution of a few arcmin. The result will be a catalog of spectra of a few thousand AGNs and Clusters. The high S/N of the measurement (see **Figure 5**) allows a very detailed study of the thermal, non thermal and kinematic SZ effect, the Hubble diagram, the study of $T_{CMB}(z)$ and the identification of the physical mechanisms of emission in AGNs. In addition, the high frequency band (720-260 GHz) will provide tomography of early galaxies using the C^+ line in the "redshift desert," thus complementing optical surveys of galaxies.

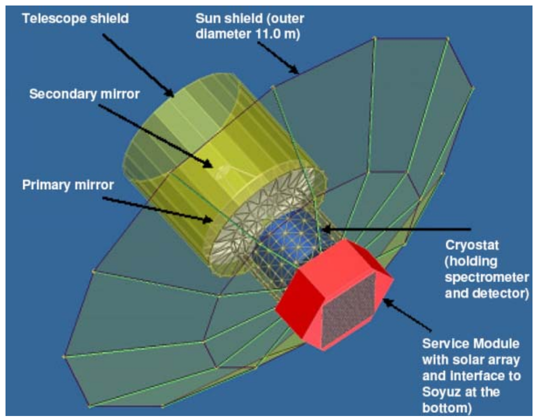

Figure 4: The SAGACE satellite, a phase-A study in the framework of the small missions call of the Italian Space Agency in 2007 (courtesy of Kayser Italia).

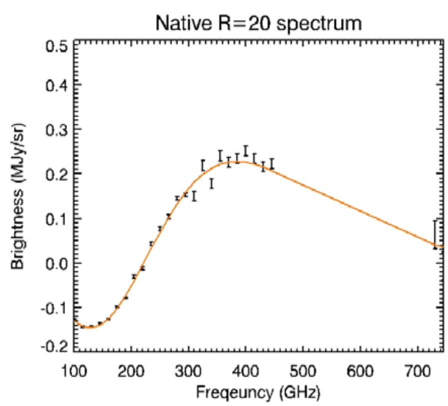

Figure 5: Simulated measurement of the SZ effect using SAGACE. The cluster is Coma, the total exposure time is 10 minutes.

The CMB is differentially absorbed/scattered by atoms. In particular, it is believed that, during reionization, the first metals are produced by population-III stars, enriching the IGM. In principle, a tomography of the abundance of particular metals can be carried out by precisely calibrated, high resolution, multi-band CMB anisotropy experiment.[27] This kind of

[27] Hernandez-Monteagudo C., et al., 2006, Ap.J., 653, 1

observations requires very high angular resolution, very accurate spectroscopy, and the absence of atmospheric contamination of the measurements. A large space telescope mission coupled to FTS analyzers or other forms of advanced spectrometers is probably the only way to carry out such demanding observations (SAGACE could be a perfect pathfinder for this mission). In turn, these observations can provide essential information on reionization, complementary to other probes like Ly Emitters, 21 cm and IR surveys, CMB polarization. The path of the photons, from the last scattering surface to the observer, traverses the large-scale structure of the universe: these density inhomogeneities produce mainly two effects. Gravitational lensing by intervening mass distorts the anisotropy and the polarization of the CMB. Photons are deflected typically by a few arcmin, with a coherence scale of a few degrees[28]. The main effect is a smoothing of the acoustic peaks of anisotropy and polarization power spectra, and the production of B-mode polarization at high multipoles. The former will be detected by the high accuracy anisotropy measurement of Planck. The latter will be measured by current polarization experiments. These measurements have the potential to measure the growth of structure and the properties of dark matter, including massive neutrinos.[29] And, of course, they are needed to remove this contaminant in searches of primordial B-modes.

Gravitational redshift produced by large scale structures also produces CMB anisotropy, via the Integrated Sachs-Wolfe (ISW) effect,[30] observable at large angular scales because at small scales the effect is averaged out on the line of sight through many structures. Since density perturbations stop their growth when dark energy starts to dominate the expansion, the ISW is very sensitive to dark energy and its equation of state. However, being a large scale effect, cosmic variance prevents an accurate measurement. A possible solution is the correlation of the ISW with lensing maps of the CMB: this requires extremely accurate anisotropy and polarization measurements.

CONCLUSIONS

Since the first telescopic observations of stars by Galileo, technology and methods for looking at the distant universe have evolved exponentially. We now have space telescopes devoted to studying the finest details of the CMB, directly imaging the deepest observable sky fields. Precise CMB measurements promise crucial data to solve the outstanding enigmas of current cosmology (Inflation, Dark Matter, Dark Energy). Using the Universe as an extremely powerful laboratory, these activities complement direct fundamental physics measurements.

ACKNOWLEDGEMENTS: THE ACTIVITIES DESCRIBED IN THIS PAPER HAVE BEEN SUPPORTED BY THE ITALIAN SPACE AGENCY CONTRACTS "STUDIES ON THEMES AND MODELS IN COSMOLOGY AND FUNDAMENTAL PHYSICS" AND "SAGACE". THE INVITATION AND GENEROUS SUPPORT OF KISS (KECK INSTITUTE FOR SPACE STUDIES) ARE GRATEFULLY ACKNOWLEDGED.

[28] Blanchard A. Schneider J., 1987,A&A, 184, 1
[29] Hu W., 2003, Phys. Rev. D., 65, 023003
[30] Sachs R.K., Wolfe A.M., 1967, ApJ, 147, 73; Kofman L.A., Starobinskij A.A., 1985, Sov.Astron., 11, 27

The Human and Scientific Tale of Galileo

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THE HISTORICAL AND CULTURAL CONTEXT

The year 2009 has been declared by the United Nations the International Year of Astronomy, to celebrate the four hundredth anniversary of the publications of two of Kepler's laws in Prague, the 40 years since the landing on the Moon, and finally another four hundredth anniversary: the first time that an optical instrument, widely considered almost a toy, was aimed at the sky by Galileo Galilei, Florentine nobleman, professor of Mathematics at Padua University[1]. The instrument was greatly improved by professor Galilei[2] until it became a useful tool for warfare and scientific research. We are of course talking about the telescope[3] which was, at that time, known in western Europe, but probably also in the Islamic world, as no more than an optical curiosity and was probably a casual offspring of the flourishing optical industry producing spectacles, to meet the large demand arising as a consequence of the protestant reformation leading to an increasing number of readers. Galileo was able to increase the number of enlargements of this instrument, realizing that it could be useful to the Venetian navy; he submitted his new instrument to the Doge of Venice (the elected Venice "chief magistrate") who, with the Senate, rewarded the scientist by increasing his salary and by giving him a lifelong tenure at Padua University.

Galileo, at the first opportunity aimed his *occhiale*[4] (this was at that time the name of the telescope) with *informed curiosity* to the skies; not with the eye of an astronomer, but with that of a physicist willing to expand his investigations of the nature of the universe. We may say that four hundred years ago Astrophysics was born.

Paradoxically, the enemies of Galileo were the first to notice that he was not an astronomer (astronomers at that time limited themselves to describing the position of the celestial bodies in the sky, in particular making predictions of future positions, a subject important to decision makers), and his effort to investigate natural philosophy (i.e. physics) made him a dangerous opponent, an *heretic*, in the literal sense (from the Greek word *airesis,* which means choice) claiming his freedom of investigation in any field of natural science where his intelligence and his curiosity were drawing his attention. Many were the authoritative suggestions to him to confine his interests to astronomy, the *philosophia naturalis* (i.e., physics) was a matter for

[1] Alberto Righini *The telescope in the making, the Galileo first telescopic observations* in *Galileo's Medicean Moons* IAU Symp. 269 (in press).
[2] Stillman Drake *Galileo studies* (The University of Michigan Press, Ann Arbor 1970), William R. Shea *Galileo's intellectual revolution* (The Macmillan press, Toronto 1972), Stillman Drake *Galileo at work* (The University of Chicago Press 1978), Michele Camerota *Galileo Galilei* (Salerno editrice, Roma 2004), Alberto Righini *Galileo tra Scienza Fede e Politica* (Compositori, Bologna 2008).
[3] Albert van Helden *The invention of the telescope* Trans. American Philosophical Society vol. 67, part 4, 1977.
[4] The word *occhiale* in Italian means *spectacle*.

philosophers and even for experts in theology, not for a mathematician like he was considered.

It was clear to everyone that with Galileo a new discipline was born that would be based on completely different paradigms of interpretation of Nature and not compatible with the *principle of authority*. The human and scientific tale of Galileo, is paradigmatic to understand the never ending conflict between those who want to understand by applying their own reason to explain observed phenomena and those who claim to find the laws of Nature in the books of the ancients, or worse, in the dogmas of their faith or superstition. This topic is particularly relevant now that at the scene of the intellectual debate there appears an attitude of denial of the results of science (in particular of the theory of evolution), in favor of *creationism* and the theory of *intelligent design*.

In the story of Galileo we may find very clear reflections of that complex historical period in which many paradigms and habits were evolving very rapidly, in science and social life. In Tuscany, in the years preceding the birth of Galileo, the Italian Protestantism, which had won over many consciences, was very strong.[5] However, the Duke of Florence Cosimo I decided in 1567 to suppress the Protestant heresy (obtaining in exchange from the Pope the title of Grand Duke) and suddenly the cultural environment, which was relatively free, became close and dominated by the Roman Inquisition. However Galileo received an education where intellectual freedom was appreciated, perhaps through the teaching of his father and his friends and some professors at Pisa University.

Copernicus died in 1543, the same year his book *De Revolutionibus Orbium Coelestiun* was published with the *exculpatory* introduction of Andreas Osiander.[6] His theory came across as very difficult and in the collective imagination of even the most cultivated scholars, only the heliocentric structure of the planetary system survived, originally devised by Aristarchus[7] and partly by Pythagoras. We note that the copy of the *De Revolutionibus* owned by Galileo is virtually free of annotations, which shows that Galileo himself did not appreciate the mathematical details of the book.[8]

At the universities only the Aristotelian physics was taught at the time of Galileo. In this construct, functional to the counter-reformation, an immovable Earth sits at the center of the universe being the focal point of the Cosmos, which is made up of concentric spheres and enclosed by the sphere of the fixed stars, beyond which was the Creator. The *special place* of the Earth at the center of the universe supported the *special place* of the Holy Roman Catholic Church.

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[5] Delio Cantimori *Eretici italiani del Cinquecento* (edited by Adriano Prosperi, Einaudi, Turin 1991), Massimo Firpo *Riforma protestante ed eresie nell'Italia del Cinquecento* (Laterza, Bari 2006).

[6] Andreas Osiander was responsible for the editing and printing of the Copernicus *De Revolutionibus*, while its author lay helpless and dying in far-off Frombork. Many scholars think that the Osiander's introduction to the *Revolutionibus* would have been refused by Copernicus if he could have decided.

[7] Aristarchus (310 B.C. – 230 B.C.) was a Greek astronomer born in the island of Samos.

[8] Owen Gingerich *The book nobody read* (Walker & Company, New York 2004).

Galileo's father, Vincenzio, was a great scholar of music and a composer. He and his colleagues, meeting within the *Camerata de'Bardi*[9] developed a new approach to the study of music. Vincenzio was definitely a revolutionary composer for his times; reading now his works we recognize the argumentative pages written by Galileo, almost forty years later against an honest but traditional Jesuit.[10] The young Galileo, who was very interested in music, was breathing that air of cultural freedom typical of the artistic *avant garde,* which as often happens in history, indicate a forthcoming political and cultural change.

THE YOUNG GALILEO

In the year 1581 Galileo was enrolled at the University of Pisa in the School of Artists (part of the Medical School). The course of studies, chosen by his father, was not particularly interesting and Galileo was a very critical student who was unable to refrain from expressing his strong doubts about the obsolete teaching based on the Physics of Aristotle, mandatory in the medical curriculum, acquiring the reputation, amongst his teachers, of an *argumentative and contrarian* student[11]. Galileo was not really interested in the university teaching, no doubt he would have skipped several lectures, preferring to spend his time in one of the several wine bars in Pisa, La Malvagia, il Chiassolino or Le Bertucce,[12] or staying with his young cousin Bartolommea,[13] who was the house keeper of Messer Muzio Tedaldi, his host in Pisa, but perhaps he did not skip those of Professor Francesco Buonamici who was teaching that the Aristotelian empiricism formed the basis of Physics. This concept, about two thousand years old, had been forgotten and omitted in the peripatetic (i.e., Aristotelian) philosophy, since it obviously leads to a continuous challenge of the established paradigms by those who take the trouble to interpret new experimental evidence,[14] as professor Andrea Cesalpino was doing in teaching anatomy and blood circulation in that University.[15] We can find a loud echo of these lessons in the Galileo' masterpiece *Dialogo intorno ai due massimi sistemi (Dialogue concerning the two chief systems of the world)* when Sagredo, one of the interlocutors, describes an anatomical dissection he witnessed in Venice, the results of which clearly contradicted the then prevailing theories that the nerves were spreading from the heart.

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[9] To have an idea of the music composed by Vincenzio Galilei in the *Camerata dei Bardi* we suggest to the reader to visit the home page of the Lute Society of America http://www.cs.dartmouth.edu/~lsa/ and to download some music from their *Fronimo* project. See also the CD AG 137 by M.Leonardi and U. Nastrucci who play Vincenzio Galilei's music.

[10]Vincentio Galilei, *Dialogo della Musica antica e della moderna* (Marescotti, Firenze, 1581).

[11] Vincenzio Viviani *Racconto istorico della vita di Galileo* in Antonio Favaro *Le Opere di Galileo Galilei* vol. XIX p. 603 (G. Barbera Editore, Firenze 1968) (hereinafter quoted as GG XIX 603).

[12] Galileo Galilei *Capitolo contro il portare la toga* GG IX 213-223.

[13] Galileo's father was hesitating to send the young Galileo in Pisa in the house of Muzio Tedaldi due to presence of the young cousin Bartolommea, but, since he had not been able to obtain for his son a grant in the university college where forty young Tuscan were hosted free of charge every year he was obliged to put aside all his scruples.

[14] This, following Francesco Buonamici, Galileo's professor of Philosophy in Pisa, is the first rule to be observed while discussing about motion, he was used to affirm: *standum esse iudicio sensus* literally *we should cling to experience of the senses.* Quoted in Mario O. Helbing *La filosofia di Francesco Buonamici* (Nistri-Lischi, Pisa 1989).

[15] H.P. Bayon, *The significance of the Demonstration of the Harveyan Circulation by Experimental Tests* ISIS 33, 4, 1941 pp. 443-453.

> One day I was in Venice at the house of a famous physician, where some flocked for their studies, while others sometimes went out of curiosity to witness anatomical dissections… By chance that day, when I was there, he was in search of the origin and stem of the nerves… The anatomist showed how the great bundle of nerves, departing from the brain, their root, passed by the nape of the neck, further extending … while only a very small filament, as fine as a thread, arrived at the heart. Then he turned to a gentleman in the audience whom he knew to be a Peripatetic philosopher… and asked if he was satisfied and persuaded that the origin of the nerves was in the brain and not in the heart. The philosopher answered, "You have shown me this matter so clearly and perceptibly that had not the text of Aristotle asserted the contrary, by positively affirming the nerves to stem from the heart, I should be bound to confess your opinion to be true."[16]

At the end of the university courses Galileo returned to Florence without graduating in medicine, we may imagine the fights in the Galilei's house, but for at least four years he was allowed to stay in Florence, studying geometry and the books by Archimedes on hydrostatics; he gave several private lessons of mathematics, we know that he was in Rome and there he met Christopher Clavius, astronomer and professor at the Jesuit University (*Collegio Romano*) and cardinal Enrico Caetani**.**

Galileo Professor in Pisa and Padua

In 1589, at the age of twenty-five, Galileo was appointed Professor of mathematics at the University of Pisa thanks to the recommendation of the mathematician Guidobaldo del Monte. In modern terms he had a one-year contract requiring to give 60 lessons (lasting half an hour each), possibly renewable for the following year. The salary was 60 *scudi*[17] at a time when the minimum a family of four needed to survive in Rome was 90 *scudi.*[18]

Just as Galileo had not been happy in Pisa as a student, so he was not at ease as a Professor, and perhaps for the same reason: the presumptuous ignorance of some of his colleagues, who merely repeated in their teaching what they had learned from their teachers without any critical assessment. Anyhow, in Pisa Galileo forms his scientific foundation in the physics' of motion, discussing and arguing with colleagues, at least with those who accepted the scientific debate.

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[16] Galilei, G. *Dialogo sopra i due massimi sistemi del mondo* (Landini, Florence 1632) GG VII 134 (translation by Cinzia Zuffada) see also: S. Drake *Dialogue concerning the two chief world Systems* (Berkeley, 1967).

[17] The *Scudo* (*Escudo* in Spanish) was the monetary unit of that time, and was accepted in all the countries under the Spanish economical influence. In Venice the unit was the *Venetian Florin*. However both had about the same value. The *Scudo* and the *Venetian Florin* were gold coins, their weight was between 3.5 and 3.0 gr. We may roughly evaluate that one *Scudo* was worth about 280 USD (2010).

[18] Richard E. Spear *Scrambling for Scudi: Notes on Painters' Earnings in Early Baroque Rome* The Art Bulletin, Vol. 85, No. 2. (Jun., 2003), pp. 310-320.

Figure 1: Giovanni Paolo Lasinio (Lasinio Jr.) (1789-1855) (private collection): Galileo Galilei. Etching derived by the traditional Galilean iconography.

Galileo could not survive for a long time at such a university. Professors were invited to wear the academic robe, also when walking outside the *Sapienza* (the University palace), and they were proud of the many devout students who followed them. Galileo wrote a satirical poem against his colleagues, while drinking with his students or young collaborators at one of the many wine bars. The poem is interesting since it states a fundamental methodological paradigm he was going to establish in experimental Physics:

> Of great aggravation to me are those people
> Who are intent on investigating the ultimate truth
> And yet are totally clueless

Because in my opinion
Those who want to discover something
Must be inquisitive
And play with inventiveness, and guesswork
And accept that if there isn't a straight path
A thousand other avenues might be helpful[19]

In 1592 Galileo moves to Padua with an annual salary of 180 florins. The University of Padua was a thriving economic resource for the city and the Venetian Republic itself, both through student tuition fees and ancillary expenses. For this reason the University encouraged its professors to engage in private activity which, on the one hand drew more students to town, and on the other allowed the university to maintain low salaries: professors had the freedom to teach private lessons and could sell syllabuses and mathematical tools. Virtually every private student made Galileo another 180 florins. In Padua and Venice the freedom to teach was generally guaranteed, even though occasionally some heretic condemned by the Holy Inquisition would be executed by drowning at dawn, or arrested and sent to Rome, as happened to Giordano Bruno[20]. Soon the reputation of the new Tuscan Professor spread amongst the students and many rushed to hear his lectures, so that the University authorities were compelled to give Galileo the largest room available: the *Aula Magna*. In Padua Galileo rented a large home, where he could run a sort of boarding school for rich students. At another house he supported his mistress Marina Gamba, a charming Venetian young lady, who bore him two daughters and one son. We may note that in this behavior Galileo was very typical for his times, and... also for ours.

GALILEO ENTREPRENEUR AND THE DISCOVERIES WITH THE OCCHIALE

Galileo was always in need of money, due to the requests coming from the relatives in Florence, and to his expensive life in Venice and Padua, and therefore he was always in search of new opportunities to make extra money. In addition to hosting paying students, Galileo increased his earnings by building mathematical instruments in his small workshop, which he then sold. One of this, the *Compasso Geometrico e Militare*, an instrument used in the battlefield to calculate the size and mass of cannon projectiles, became at that time as popular as pocket calculators are now. Such was the success of the instrument that Galileo invented the practice of *franchising* and *outsourcing* to satisfy all the requests. New paradigms also in business!

[19] Galileo Galilei *Capitolo contro il portare la toga* GG IX, 213. (translation by Cinzia Zuffada).
[20] Luigi Firpo *Il processo a Giordano Bruno* (Edited by Diego Quaglioni, Salerno Editrice, Roma 1998).

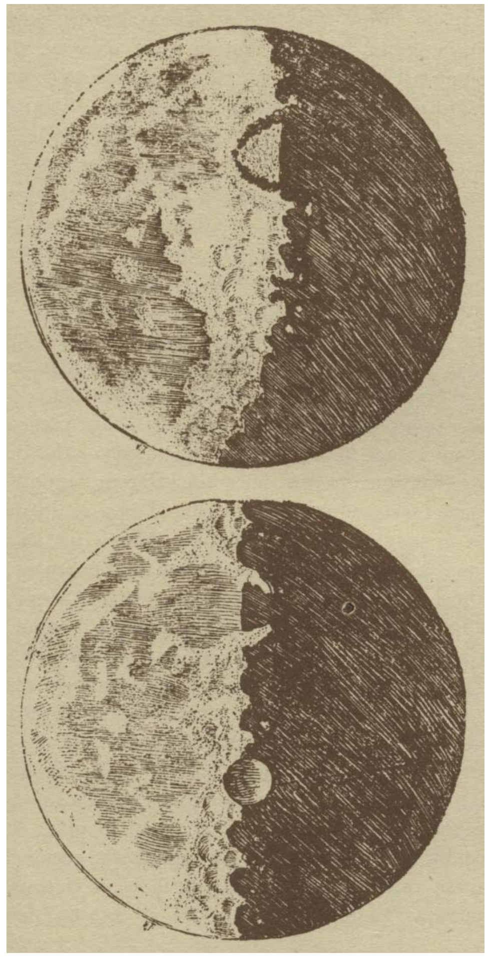

Figure 2: *Sidereus Nuncius*, etchings of the Moon derived by watermarks prepared by Galileo.

The *Nuncius* is the prototype of the modern scientific communication in which graphic resources are fundamental. These two images refer to observations performed Padua in the nights Dec, 18, 1609 (upper) and Dec, 17, 1609 (better Jan, 16, 1610). The etchings are dimensionally faithful, the position of the indentified structures suffer of a mean absolute error of less that 3% of the lunar diameter.

In 1609 the news reached Venice that a certain Flemish optician had built a special spyglass through which it was possible to see distant objects closer with a magnification of about 4 times. As we alluded to at the beginning, Galileo was able to quickly push the magnification first to 10 times and then to 20 times and even to 30 times.

After having sold the instrument to the political and military establishment, he aimed it at the sky. In quick succession Galileo discovered that the clouds of the Milky Way were large clusters of stars, the Moon had valleys and mountains like the Earth, Jupiter had four satellites (Moons), Venus had phases like the Moon, Saturn had some sort of ears (the ears were actually rings seen in a projection, but Galileo was unable to interpret that strange figure) and finally sunspots. The first results were published in the space of about two months in a booklet entitled *Sidereus Nuncius* (*Celestial Messenger*). For his concise and direct Latin prose, and the full use of the graphics, it can be considered very close to the modern scientific reports than to the astronomical literature of those times. The Nuncius concludes with the statement:

> We therefore have a robust and excellent argument to remove any doubt amongst those who accept easily the revolution of the planets around the Sun in the Copernican system, but are much disturbed by the motion of the Moon around the Earth, while both make their annual revolution around the Sun, leading them to consider rejecting as impossible such structure of the Universe. Now, in fact, we not only have one planet that revolves around another, while both move on the great orbit around the Sun, but the observational experience shows four stars moving around Jupiter, just like the Moon around the Earth, while all together with Jupiter, describe a twelve-year orbit around the Sun.[21]

Galileo, through the political use of his discoveries, succeeded in obtaining from the Tuscan Court a generous salary and the lifelong appointment as *Philosopher and First Mathematician* of the Grand Duke and quickly left Padua and moved to Florence, trading freedom of teaching, provided by the Republic of Venice, with the weak protection of the Grand Duke of Tuscany, not realizing that, while the first was guaranteed by a robust political order, the second was depending on the will (or caprice) of an individual. Galileo was a courtier, not understanding that his new science was incompatible with the courts,[22] especially with those prone to the will of the Holy See.

BACK IN FLORENCE, THE START OF THE PROBLEMS WITH THE CHURCH

In Florence he is a wealthy man; he is often invited to court, participates in erudite discussions, publishes a booklet dealing with the phenomenon of buoyancy, discovers the phases of Venus and, in 1612, travels to Rome to present his findings to the Pope and to the Jesuits. Cardinal Bellarmine,[23] who at that time was the president of the Holy Inquisition, asked his brothers in the Collegio Romano if Galileo's findings were real discoveries, and with some marginal doubts the Jesuits honestly confirmed.[24]

Back in Florence, he soon entered into harsh conflicts with some philosophical and religious circles, specifically the Dominicans, who proclaimed the heresy of the Copernican theory which affirmed the centrality of the *motionless* Sun, since this theory contradicted the Holy Scripture where it says that God, to help the Jews exterminate their enemies by extending the

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[21] Galilei, G. *Sidereus Nuncius* (Baglioni, Venice 1610) GG III 95 (translation by Cinzia Zuffada)

[22] For a detailed analysis of this complex aspect of Galileo see Mario Biagioli *Galileo Courtier* The University of Chicago Press 1994.

[23] Roberto Romolo Bellarmine (Bellarmino in Italian) was an outstanding catholic theologian. His teaching, was very controversial. He was canonized in 1930.

[24] The Jesuits at the *Collegio Romano* represented the highest instance of the scientific knowledge in Rome and we must acknowledge that they fully confirmed to their brother Roberto cardinal Bellarmino Galileo's discoveries which, therefore, become *fully certified*. The astronomer in chief, Christopher Clavius however had some doubts about lunar mountains. (see GG XI 68).

length of the day, stopped the Sun and the Moon.[25] Galileo reacted by writing two letters one of which was addressed to Grand Duchess Madama Cristina of Lorraine, mother of the young Grand Duke Cosimo II, very aware of the pressure of the circle of friars against Galileo.

> Being then that the Bible in many instances must be interpreted differently from the apparent literal meaning of the words, I believe that in debates about Nature the Bible's explanation should be the last resort… Being Nature inexorable and immutable and not caring whether its inner laws and methods of operation are understandable to men, for this reason it never transgresses its governing rules… Hence, it appears that no physical manifestation which the experience of sense sets before our eyes, or which necessary demonstrations prove to us, ought to be questioned (much less condemned) based upon biblical references whose words might appear to be leading to a different conclusion. For the Bible is not constrained in every expression to conditions as strict as those governing all natural effects.[26]

We can see a kind of Neo-Platonism in these words: God speaks through the Scriptures but the texts are metaphoric and adapted to the lack of understanding of people (myth of the cave), however the phenomena occurring in Nature strictly obey God's will; and therefore when we measure and we understand the physics we comprehend the Design of the Creator of the Universe (the platonic world of ideas), and, since two versions of one truth cannot contradict each other, it follows that in case of conflict between Physics and the Holy Bible, the Bible should be re-interpreted.

We may consider this new paradigm as a sort of Galileo's crypto-Protestantism, since he affirms that all of us, provided that we are good physicists, may understand God's Design without the aid of any intermediary (priest or Church) like Luther and Valdes[27] who declared that all of us are able to read and interpret the Holy Book. We should note that the idea that we may understand God by reading the Holy Book of Nature is not new; Calvin in Geneva was teaching, before Galileo's birth, the theory of the "two books:" the Bible and the Nature.[28]

We should note that Galileo, all his life, considered himself a good and faithful member of the Holy Roman Catholic and Apostolic Church; he was a man of his time, accustomed to seek protection and benefits from those who held the power and the money, were they Popes or Cardinals, and hence he would have found abhorrent any behavior that could cut him off from that world. A world that was however inhomogeneous: on one side the doctrinal closures of the Dominicans, on the other the almost revolutionary social ideas of the Jesuits. Despite all of Galileo's efforts, in February of 1616 Pope Camillo Borghese (Paul V) issues a

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[25] Old Testament Book X (Joshua), 12, 13, 14.

[26] Galilei, G. *Lettera a madama Cristina di Lorena* (GG V 316) (translation by Cinzia Zuffada). Galileo, in this letter explains the hidden sense of the Bible by affirming that God stopped all the motion of the Copernican System by stopping the Solar rotation (just discovered by Galileo) which might be considered as the source of all the planetary motions and also of the Earth's rotation.

[27] Juan de Valdes (Cuenca, Spain 1505, Naples, Italy 1541) is the founder of the Italian Protestantism which was cancelled in the blood and with the fire of the stakes by the Holy Roman Inquisition.

[28] Kenneth J. Howell *God's Two Books* (University of Notre Dame Press, Notre Dame 2002).

precept, to abstain from spreading Copernican concepts, affirming that the idea of the motion of the Earth is heretical and that it should not be defended in writings and should not be taught; Bellarmine, was charged by the Pope to notify Galileo of the precept and to arrest him if he had objected. The precept was mainly, but not solely, directed to Galileo; in the Catholic world other voices had spoken in favor of Galileo and Copernican ideas, such as that of Tommaso Campanella and abbot Foscarini.[29] Galileo does not understand the dangerous situation he is in, believing that the admonition was just a formality, perhaps because the politeness of the words used by Cardinal Bellarmine, probably embarrassed by the obvious nonsense of what he was obliged to say, had convinced him that the precept was merely a formality issued to satisfy the Dominicans and the intransigent wing of the Church.

THE LEGACY

After the 1616 admonition Galileo's life in Florence continued to be that of a wealthy person. He was among the ten highest paid officials of the Grand Duchy of Tuscany. In the meantime a Jesuit, Thomas Scheiner, was affirming that he was the first to have discovered sunspots and to have the proof that they aren't on the solar surface but instead they are the shadow of inner planets, thus rescuing the concept of incorruptibility of the solar matter. These allegations are contained in three letters addressed to Marco Welser, Governor of Augsburg and banker of the Jesuits. The letters were forwarded to Galileo by Welser, almost as an invitation to the controversy. Galileo responded by writing a booklet on sunspots, thus knowingly creating a conflict with the powerful order of the Jesuits that up to that time had been supportive of him. Later, to reinforce the clash with the order founded by Saint Ignatius a controversy involving Orazio Grassi arose on the nature of the comets. Grassi was professor of Mathematics at the *Collegio Romano*. The controversy was very complex, and interestingly it ended with Galileo writing a seminal book relevant to modern Physics: *The Assayer*. The book is full of errors of physics but it establishes unequivocally the foundations of the method of modern physics; its writing contains real jewels, of both polemical and epistemological high value. In its pages it is stated that in physical investigations the sources of knowledge are not the books of the ancient philosophers (the world of paper) but the Book of Nature whose characters are mathematical and geometric, and consequently, only those who know how to read that alphabet are able to read it and to understand its laws.

> I thought… I sensed in Sarsi [Orazio Grassi, Jesuit] the firm belief that philosophical arguments must be based on the opinion of some established author, so that when our mind is not in agreement with someone else's opinion it should remain uninquisitive… Mister Sarsi, the fact is rather different. Philosophy is written in this grand book—I mean the universe—which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of

[29] Foscarini was a carmelite friar born in Montalto di Calabria named Scarini, the name Foscarini is the corruption of Fra' (brother) Scarini. He wrote a booklet in favor of the Copernican theory; for more details see GG XX, p.443. Bellarmino, answering to Foscarini writes a famous letter in which he outlines the relationship between Science and the Catholic Faith (GG XII 171).

> mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is impossible to understand a single word of it.[30]

The new paradigm of Galileo is revolutionary, and in short, it means that the philosophers and theologians can say nothing about the physical world, because they are mathematically illiterate.

Galileo at about 60 decided to write a sort of spiritual testament to summarize the proofs of the motion of the Earth around the Sun, or at least to demonstrate that Aristotelian conclusions on motion and on matter were wrong. Of course it was not simple for Galileo to obtain permission to print a Copernican book after the 1616's admonition. After various and complex events and a lot of diplomatic work, the book gained the *imprimatur*[31] of the bureaucracy of the Church guided by Pope Maffeo Barberini (Urban VIII) who had been, in his youth, an admirer of Galileo's discoveries. The book was published in Italian, or rather *Volgare*, with the title: *Dialogue concerning the two chief systems of the world*. The *Dialogue* is written on the model of Plato's dialogues and takes place among a strict Aristotelian philosopher called Simplicio[32] espousing the views of the classical philosophical school, often using the same arguments used by Pope Maffeo Barberini when debating with Galileo about Earth's motion, Sagredo, who represents and intelligent, un-biased and thoughtful person, and Salviati who is Galileo himself.

In the peripatetic Cosmology the Earth, made of four substances, has the distinctive place at the Center of the universe but is imperfect, due to all the changes that take place on its surface and in its sky, and in particular it contains Hell. In contrast the planets and the sphere of the fixed stars are made of Ether, the fifth perfect and immutable substance. The Universe in Saint Thomas' philosophy represents the transition from the divine perfection located outside of the skies to the evil that is located inside the Earth; man, guilty of the Original Sin, is close to evil but is defended by the Pope and the Church. In trying to demolish the Aristotelian edifice, showing its inconsistencies, Galileo wants to overthrow this point of view, thanks to the "experience of sense" enabled by the telescope, watching the mountains and valleys and craters on the moon that ought to be a perfect ethereal sphere. Simplicio, the voice of Aristotle in the dialogue, concludes the discussion on the terrestrial nature of the Moon, horrified that Salviati (Galileo) wants to put *the Earth amongst the stars* since the Moon and the Earth are made of the same substance and they have the same appearance. Here Galileo, with poetic language introduces the beginning of a revolution that will be completed in the 19th century, when spectroscopy will show that the stars' and galaxies' chemical composition is very similar to that of the Earth, declaring that Earth and Moon are made of the

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[30] Galilei, G. Il *Saggiatore [The Essayer]* GG VI 232 (translation by Cinzia Zuffada) see also S. Drake *Discoveries and opinions of Galileo* (New York 1957) (including *Sidereus Nuncius* and *Il Saggiatore*).
[31] Literally "*should be printed."*
[32] Simplicius (6th century A. D.), was a Greek philosopher, born in Cilicia. He wrote commentaries on Aristotles's *de Coelo* and *Physica*. In Italian the name *Simplicio* is very close to the word *semplice* which means *simple* but may also mean *simple minded*. And since *Simplicio* in the *Dialogue* argues following the arguments used by the Pope Urban VIII in his debates with Galileo, it may be understood why *simple minded* scholars considered this a valid reason for the Pope to be upset against Galileo.

same matter and that a place where changes do occur is more attractive than immutable planets.

> I cannot without great admiration, and great repugnance to my intellect, listen to be attributed to natural bodies making up the Universe, nobility and perfection for being impassible, immutable, inalterable, etc. and on the contrary, a great imperfection to things for being alterable, transformable, mutable, etc. It is my opinion that the Earth is very noble and admirable, for the very reason of having so many and so different transformations, mutations, generations, etc. which are incessantly taking place; and if it were not subject to any alteration, and instead it were all one lonely sea of sand, or a mass of Jasper, or that at the time of the Deluge the waters had frozen and it had stayed an immense globe of crystal, in which nothing had ever grown, transformed, or changed, I should have thought it an ugly and useless body, boring, and in one word superfluous, and not part of nature; and I would see the same difference in it as I see between a living and dead creature: and I say the same of the Moon, Jupiter, and all the other celestial globes. But the closer I look at the vanity of popular opinions, the more empty and simplistic I find them. And what greater folly can there be than to call gems, silver and gold precious, and Earth and dirt vile? For do these people not consider that if there were as great a scarcity of Earth, as there is of jewels and precious metals, there would be no prince that would gladly not give a heap of diamonds and rubies, and many bullions of gold, only to purchase as much Earth as would be enough to plant a jasmine in a little pot, or the seed of a China Orange, that he might see it sprout, grow, and produce such beautiful leaves, such perfumed flowers, and such delicate fruit? [33]

The *Dialogue* is written in beautiful Italian, sometimes we find clear geometrical demonstrations, it is easy to understand and without mathematical complications; the purpose is to show the plausibility of the natural motion of the Earth around the Sun, and this objective is reached first by showing that the experiment often produces results in contradiction with the Aristotelian theory, like for example in the case of the dissection of corpses, and then by enunciating a fundamental principle (*the principle of Galilean relativity* in modern physics) that however Galileo shows to have not fully understood. In one of the most beautiful pages of the book he writes:

> Shut yourself up with some friends in the main cabin below deck on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some small fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed towards all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something at your friends, you need to throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction.

[33] Galilei, G. *Dialogo…* (Landini, Florence, 1632) GG VII 83 (translation by Cinzia Zuffada).

> When you have observed all of these things carefully (though there is no doubt that when the ship is standing still everything must happen this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way or that. You will detect not the least change in all the effects described, nor could you tell from any of them whether the ship was moving or standing still.[34]

Galileo says simply that some mechanical phenomena manifested in the same way on a ship at anchor or sailing at uniform velocity. The example of the ship, admirably described by Galileo, was not new; it is mentioned in the *De Revolutionibus* by Copernicus and in the *The Ash Wednesday Supper* by Giordano Bruno, practically with the same words used by Galileo. In the dialogue Galileo, after having discussed various astronomical phenomena that are trivially explained assuming the motion of the Earth, invokes the phenomenon which he considers crucial to demonstrating the motion of the Earth around the Sun and its rotation, i.e., the tides. Now we know that the tides are due to lunar gravitational force and to the motion of the Earth-Moon system around the common center of mass, but Galileo did not grasp this and instead regarded the role of the moon on the tide to be a superstition, not different from that which prevents transferring wine from one vessel to another at certain times of the lunar month. He was so sure of his explanation of tides that he criticized Kepler, who correctly considered the tides connected to the “influence” of the moon:

> But amongst all the great men who have thought about such admirable natural phenomenon, I am most surprised in Kepler, who, gifted with an independent and acute intellect, and who had originally grasped the Earth’s laws of motion, subsequently listened to and agreed with the idea of the influence of the Moon on the tides, and superstitions and other childish fads.[35]

The Trial and the Last Years

Despite these errors, the Dialogue is a powerful new book on *natural philosophy* (Physics), clearly Copernican, making Galileo a *relapso,* i.e., a *returning heretic*. This was a particularly hideous crime for the Church of the counter-reformation, often prepared to forgive the first offense but almost never the second. The Inquisition of Pope Urban VIII confiscated the book, forced Galileo to go to Rome, arrested him and, after several hearings it condemned him for violation of the 1616 precept, imposed the abjuration and life imprisonment at the discretion of the Holy Office. The imprisonment was changed into house arrest, after only one day, at the villa that Galileo had rented from Esaù Martellini at *Jesters Flat* (Pian dei Giullari) in the hill named Arcetri close to Florence. Galileo was forced to pronounce an abjuration prepared by the Tribunal…

> …after receiving an injunction by this Holy Office intimating to me that I must altogether abandon the false opinion that the sun is the center of the world and immovable, and that the earth is not the center of the world, and moves… and after I

[34] Galilei, G. *Dialogo*... (Landini, Florence 1632) GG VII 212 (translation by Cinzia Zuffada).
[35] Galilei, G. *Dialogo*… (Landini, Florence 1632) GG VII 486 (translation by Cinzia Zuffada).

> was notified that the said doctrine was contrary to the Holy Scripture—I wrote and printed a book in which I discuss this new doctrine already condemned, and present convincing arguments in its favor… with sincere heart and unfeigned faith I abjure, curse, and detest the aforementioned errors and heresies…[36]

The abjuration, written by the Inquisition, admits that the *Dialogue* was written so well to be very effective in persuading the reader of the veracity of the Copernican theory.

Galileo's trial was the result of one or more compromises. In the trial papers there are documents accusing Galileo of heresies (concerning the structure of matter) much more serious than the affirmation of the centrality of the Sun.[37] Those heresies if pursued, would have led Galileo to the stake; it seems that the Pope (or his nephew, Cardinal Francesco Barberini, Secretary of State) asked the judges not to pursue them. On the other hand the Church, providing the Catholic response to the Protestantism of Luther and Valdes, strongly needed to reaffirm its role as sole authority to interpret the Holy Scriptures,[38] since one of the major instances of the Protestant Reformation was the affirmed freedom of each person to interpret the Holy Books: this statement implicitly destroys the Church authority, its political influence and its capacity to raise money.

On his part Galileo could do very little, the Grand Duke of Tuscany, Ferdinand II could not protect him, he did not have the strength to oppose the Pope, most Europeans scholars were on Galileo's side, but these were largely Protestant and had no influence on the policy of the Church.

Figure 3: Inner court of the Galileo's country house called *Il Gioiello* in which he was obliged to live being at house arrest. Galileo calls this typical Tuscan house *my jail in Arcetri*. (Photo A. Righini, courtesy University of Florence).

[36] GG XIX 406-407.

[37] Pietro Redondi, *Galileo eretico* (Laterza Editori, Bari 2009).

[38] This statement was clearly affirmed in the Session IV of the *Council of Trent*.

Back in Arcetri in 1632, a prisoner in his house, Galileo wrote another great treaty entitled "*Discorso intorno a due nuove scienze*" in which he discusses statics, mechanics and local movements. This book is just as fundamental for affirming the Copernican theory as the *Dialogue*, but the theologians were so ignorant that they did not realize the revolutionary impetus of his last work. All of us teaching mechanics to our students today, practically read to them this book. Galileo died in 1642 at the age of 78 while under house arrest. The funerals were held in a very quiet manner and the corpse was buried in the wall of a room adjacent to the Church of Santa Croce. It took about one century to transport Galileo's mortal remains on the marble tomb on the left side of the Church. The Holy Roman Church canceled the prohibition to read Copernican books and Galileo's *Dialogue* only in the XIX century.

Figure 4: Galileo's room in the house *Il gioiello*. From the window, Galileo could see the nunnery where he segregated his daughters Virginia and Livia. In this room Galileo died in 1642 assisted by Evangelista Torricelli and Vincenzio Viviani (Photo A. Righini, courtesy University of Florence).

EPILOGUE

Galileo lived in a difficult period of transition; after him the world of science will no longer be the same, his character did not help him to cope with the political environment, educated in the 16th century courtier's cultural freedom he did not realize that the new paradigms that he was teaching were in violent conflict with the effort of the Holy Catholic and Apostolic Church of Rome to maintain its political power by means of the use of the "*Keys*" the Church *claims* to have obtained from Christ. For this reason we should consider that Galileo' trial was not a clash between science and faith, but was a political trial, a *disciplinary* trial,[39] made in order to reaffirm the political control of thought through the monopoly of the interpretation of the Scriptures.

Figure 5: Gian Lorenzo Bernini (1598-1680), Pope Urbano VIII, Rome, Galleria Nazionale d'arte antica.

It is possible also to give another reading of the ultimate causes of Galileo's second trial. Maffeo Barberini (Pope Urban VIII) was very well connected with the French court that at the time was fighting against Spain, and allied with the protestant Swedish army in the context of the Thirty Years War. The Spanish cardinals, by reaction, threatened the Pope of impeachment for heresy. As a matter of fact Urban VIII was very careful in managing the interests of the Barberini family but was not equally attentive to Holy Matters and it was very well known that Galileo, at least in the past, was a Pope's favorite. In this political conundrum, the simplest escape route for Urban VIII might have been to demonstrate that he was very severe with a former friend of his, accused of heresy. This, and the strong and continuous effort of the Tuscan ambassador in Rome in favor of Galileo, would explain the formal severity of the trial, but the substantial clemency used towards our beloved Scientist; we should remember that the trial was decided by the Pope and not by an independent college of judges and that the Inquisition trials were not *fair trials* in the modern sense. There are no proofs of this reading of

[39] Mariano Artigas, Melchor Sanchez de Toca *Galileo e il Vaticano. Storia della Pontificia Commissione di Studio sul Caso Galileo (1981-1992)* (Marcianum Press Roma 2009).

Galileo's vicissitudes, this is just an informed guess but history is made on the documents, and it is very unlikely that on this matter new documents will come out.

We should remark that the Church we are speaking about, dealing with the conflict with Galileo, is the Church of the political power, in which the Pope behaves as any other sovereign, not caring to mix large amounts of "*esprit Florentin*" with the Holy Principles of the Religion (used as *political tools*) whenever it is politically convenient. Beside this Church of Popes and Cardinals dressed in rich golden robes living in beautiful palaces, there was a Church of Men and Women, often very poor but sincere believers. Many of them were good friends of Galileo's. Even some outstanding personalities of the Church tried to help him, like Claude Fabri de Peiresc or Gassendi in France, or Clemente Settimi, a Calasantian friar who, for a while, was Galileo's secretary when he returned, after the trial, in Arcetri. Settimi was even allowed to stay in Arcetri during the night; in a letter his chief Saint Joseph Calasanzio (then simply Joseph Calasanzio) recommended that he learn as much as possible from Galileo. [40]

We want to close remembering Galileo with his own words written in a letter to his friend Elia Diodati in Paris. It is the year 1638, Galileo is now old and tired, completely blind, and confined to his villa in Arcetri.

> But unfortunately, Mr. Diodati, your dear friend and servant Galileo, has gone in the last month almost completely blind. You should imagine my pain as I think of that sky, that world and that universe that I, with my wonderful observations and clear explanations, had expanded by one hundred or one thousand times over what had been seen and known by all the learned men of the past, now for myself it has shrunk and it is no larger than the space occupied by my own body.[41]

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[40] GG, XVIII 41.
[41] GG XVII 247 (translation by Cinzia Zuffada).

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