New Approaches to Lunar Ice Detection and Mapping

Keck Institute for Space Studies
Caltech, Pasadena, CA
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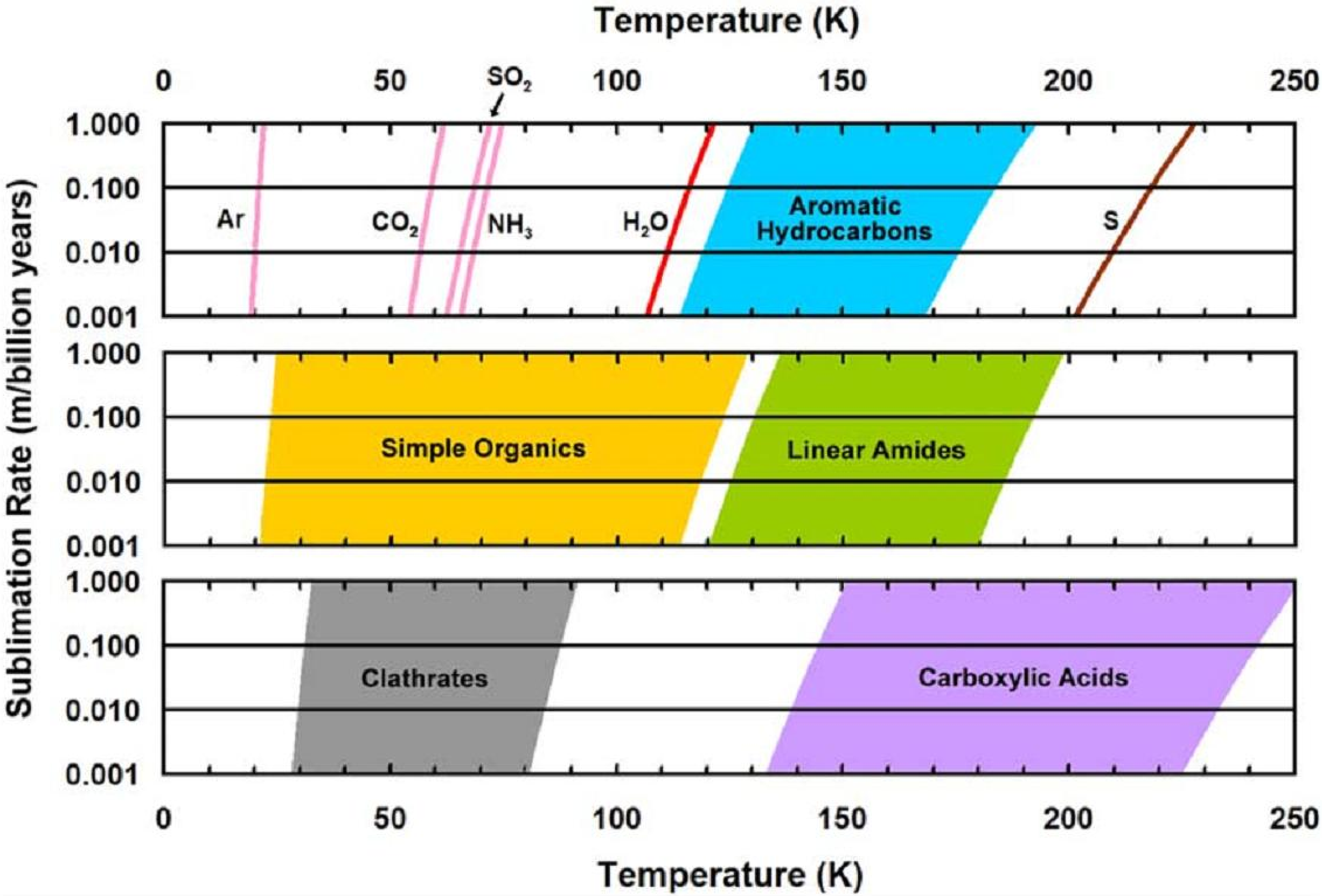
Recent Results: Thermal

David A. Paige
Dept. of Earth, Planetary and Space Sciences
UCLA

Temperature - The Master Variable

- Thermal Stability of Volatiles
- Spatial Distribution of Cold Traps
- Thermal Evolution of Cold Traps
- Correlations with Other Datasets and Models
  - Radar
  - Neutrons
  - Surface Reflectance
  - In-Situ
  - Future….

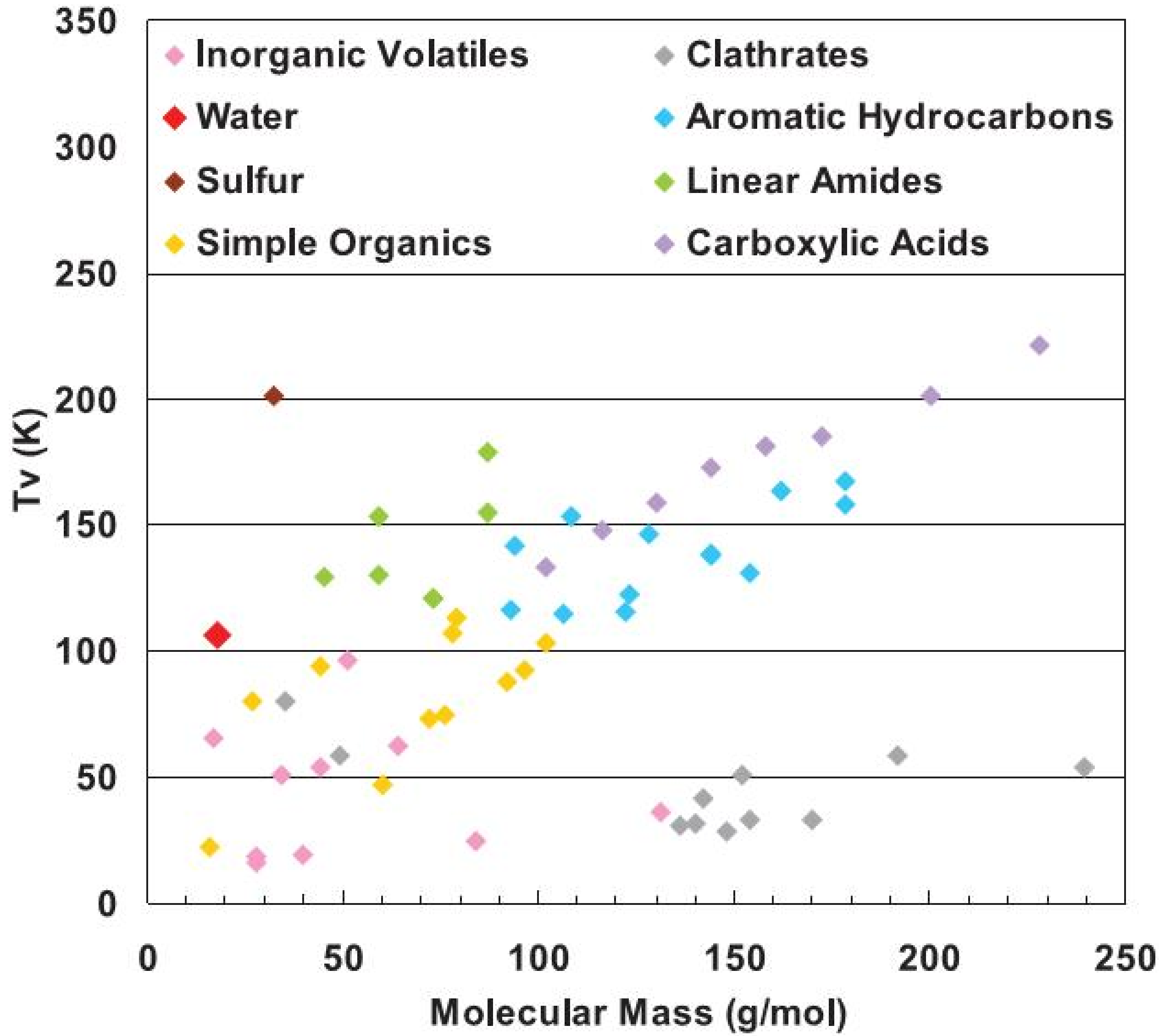


Zhang and Paige, Geophysical Research Letters 36, L16203, 2009.

Category	Chemical Formula	Name	M (g/mol)	T_v (K)
Inorganics	N_2	Nitrogen	28.02	16.2
	CO	Carbon monoxide	28.01	18.2
	Ar	Argon	39.95	19.5
	Kr	Krypton	83.80	24.5
	Xe	Xeon	131.30	36.1
	H_2S	Hydrogen sulfide	34.09	50.6
	CO_2	Carbon dioxide	44.01	54.3
	NH_3	Ammonia	17.03	65.5
	NH_4SH	Ammonium hydrosulfide	51.12	96.1
	SO_2	Sulfur dioxide	64.07	62.3
	H_2O	**Water**	18.02	106.6
	S	**Sulfur**	32.07	201.5
Simple Organics	CH_4	Methane	16.04	22.0
	OCS	Carbonyl sulfide	60.08	46.8
	C_5H_{12}	Pentane	72.15	73.6
	CS_2	Carbon disulfide	76.15	74.4
	HCN	Hydrogen cyanide	27.03	80.5
	C_7H_8	Toluene	92.13	87.6
	$C_5H_{10}O$	3-Pentanone	96.21	92.8
	NH_4CN	Ammonium cyanide	44.06	93.8
	$C_5H_{10}O_2$	Ethyl propanoate	102.13	103.6
	$NH_4CO_2NH_2$	Ammonium carbonate	78.08	107.4
	NH_4HCO_3	Ammonium bicarbonate	79.06	113.3
Clathrates	$Ar{\cdot}6H_2O$	Argon clathrate	148.05	28.9
	$N_2{\cdot}6H_2O$	Nitrogen clathrate	136.12	30.5
	$O_2{\cdot}6H_2O$	Oxygen clathrate	140.10	31.9
	$CO_2{\cdot}7H_2O$	Carbon dioxide clathrate	170.12	33.4
	$N_2{\cdot}7H_2O$	Nitrogen clathrate	154.13	33.4
	$CH_4{\cdot}7H_2O$	Methane clathrate	142.15	41.8
	$CO_2{\cdot}6H_2O$	Carbon dioxide clathrate	152.12	50.9
	$Xe{\cdot}6H_2O$	Xeon clathrate	239.40	53.9
	$2NH_3{\cdot}H_2O$	Ammonia clathrate	191.90	58.4
	$Kr{\cdot}6H_2O$	Krypton clathrate	49.06	58.6
	$NH_3{\cdot}H_2O$	Ammonia clathrate	35.05	80.3

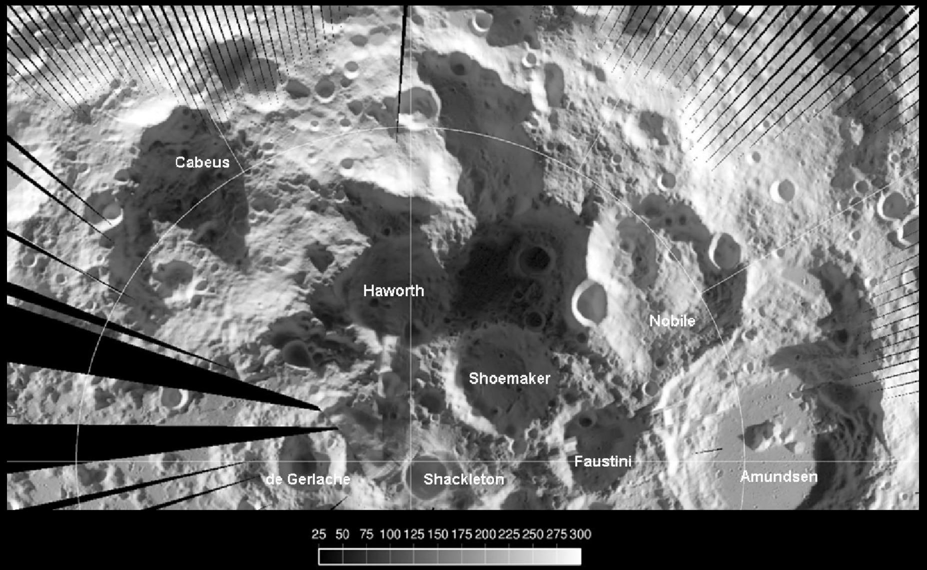
Category	Chemical Formula	Name	M (g/mol)	T_v (K)
Aromatic Hydrocarbons	C_7H_6O	Benzaldehyde	106.13	114.6
	$C_7H_6O_2$	Salicylaldehyde	122.12	115.6
	C_6H_7N	Aniline	93.13	116.5
	$C_6H_5NO_2$	Nitrobenzene	123.11	122.8
	$C_{12}H_{10}$	Biphenyl	154.20	131.3
	$C_{10}H_8O$	1-Naphthol	144.16	137.7
	C_6H_6O	Phenol	94.11	141.9
	$C_{10}H_8O$	2-Naphthol	144.16	139.1
	$C_{10}H_8$	Naphthalene	128.16	146.1
	C_7H_8O	Benzyl alcohol	108.13	153.3
	$C_{14}H_{10}$	Phenanthrene	178.22	157.8
	$C_{12}H_{18}$	Hexamethylbenzene	162.26	163.2
	$C_{14}H_{10}$	Anthracene	178.22	167.5
Linear Amides	C_3H_7NO	Dimethylformamide	70.10	120.7
	C_3H_7NO	Methylacetamide	73.10	120.8
	C_2H_5NO	Formamide	45.04	129.8
	CH_3NO	Methylformamide	59.07	130.1
	C_2H_5NO	Acetamide	59.07	153.3
	C_4H_9NO	Dimethylacetamide	87.12	154.9
	C_4H_9NO	Methylpropanamide	87.12	179.1
Carboxylic Acids	$C_5H_{10}O_2$	Valeric acid	102.13	133.6
	$C_6H_{12}O_2$	Caproic acid	116.16	148.4
	$C_7H_{14}O_2$	Enanthic acid	130.18	159.1
	$C_8H_{16}O_2$	Caprylic acid	144.23	172.4
	$C_9H_{18}O_2$	Pelargonic acid	158.23	181.1
	$C_{10}H_{20}O_2$	Capric acid	172.26	185.4
	$C_{12}H_{24}O_2$	Lauric acid	200.31	201.3
	$C_{16}H_{32}O_2$	Palmitic acid	228.36	221.4
	$C_{18}H_{36}O_2$	Stearic acid	256.42	224.3
Fullerene	C_{60}	Fullerene	720.60	465.0

Zhang and Paige, Geophysical Research Letters 36, L16203, 2009.



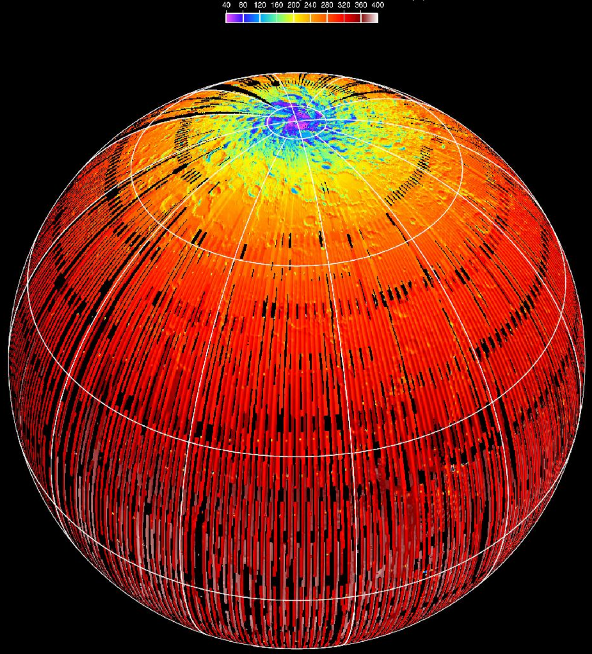
Zhang and Paige, Geophysical Research Letters 36, L16203, 2009.

LRO Diviner Lunar Radiometer Experiment

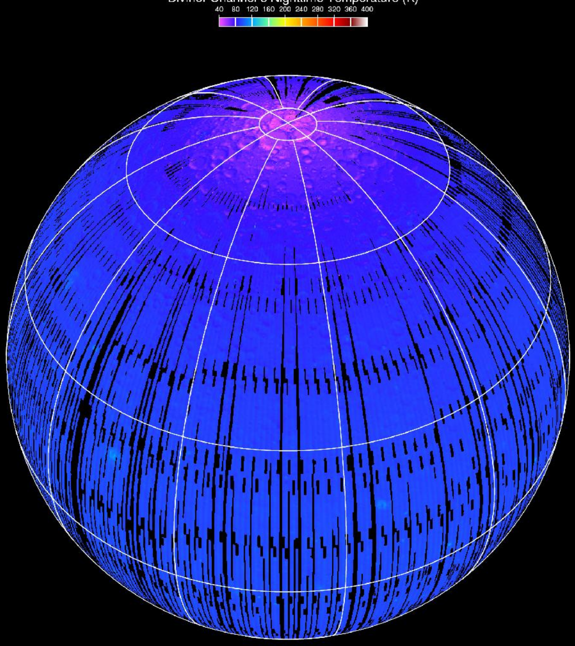


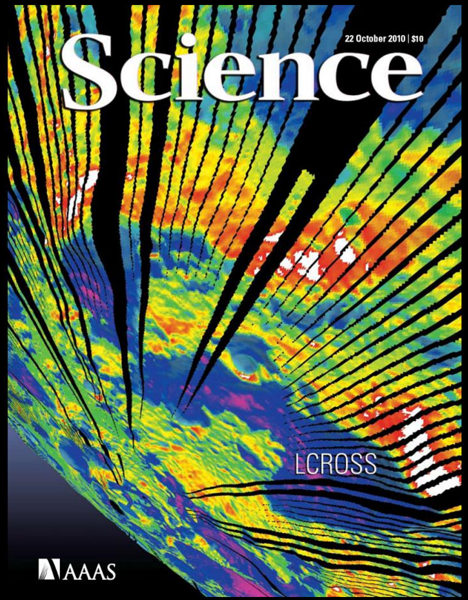
Diviner South Polar Channel 8 Thermal Image (K)

Diviner Channel 8 Daytime Temperature (K)



Diviner Channel 8 Nighttime Temperature (K)

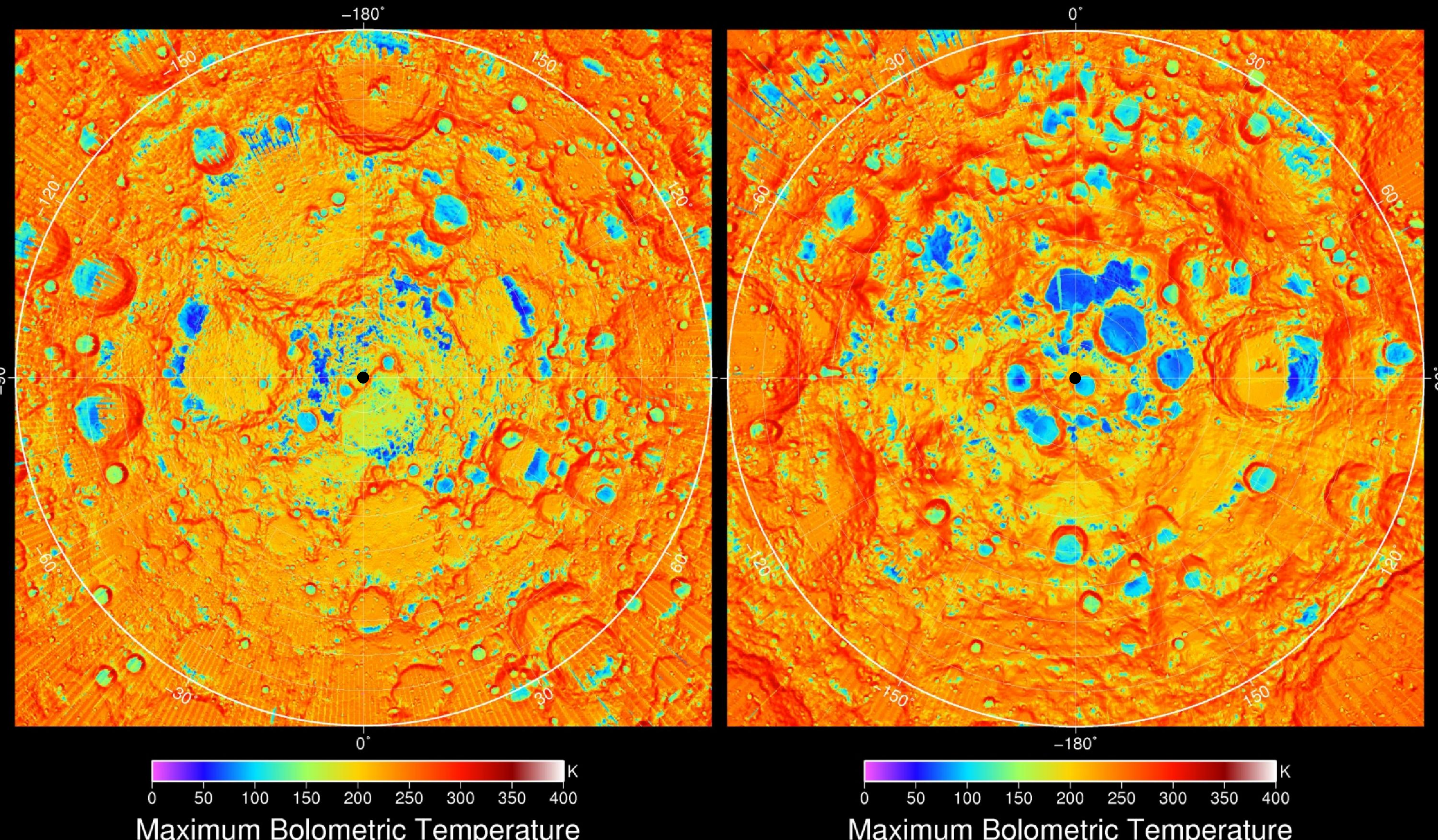




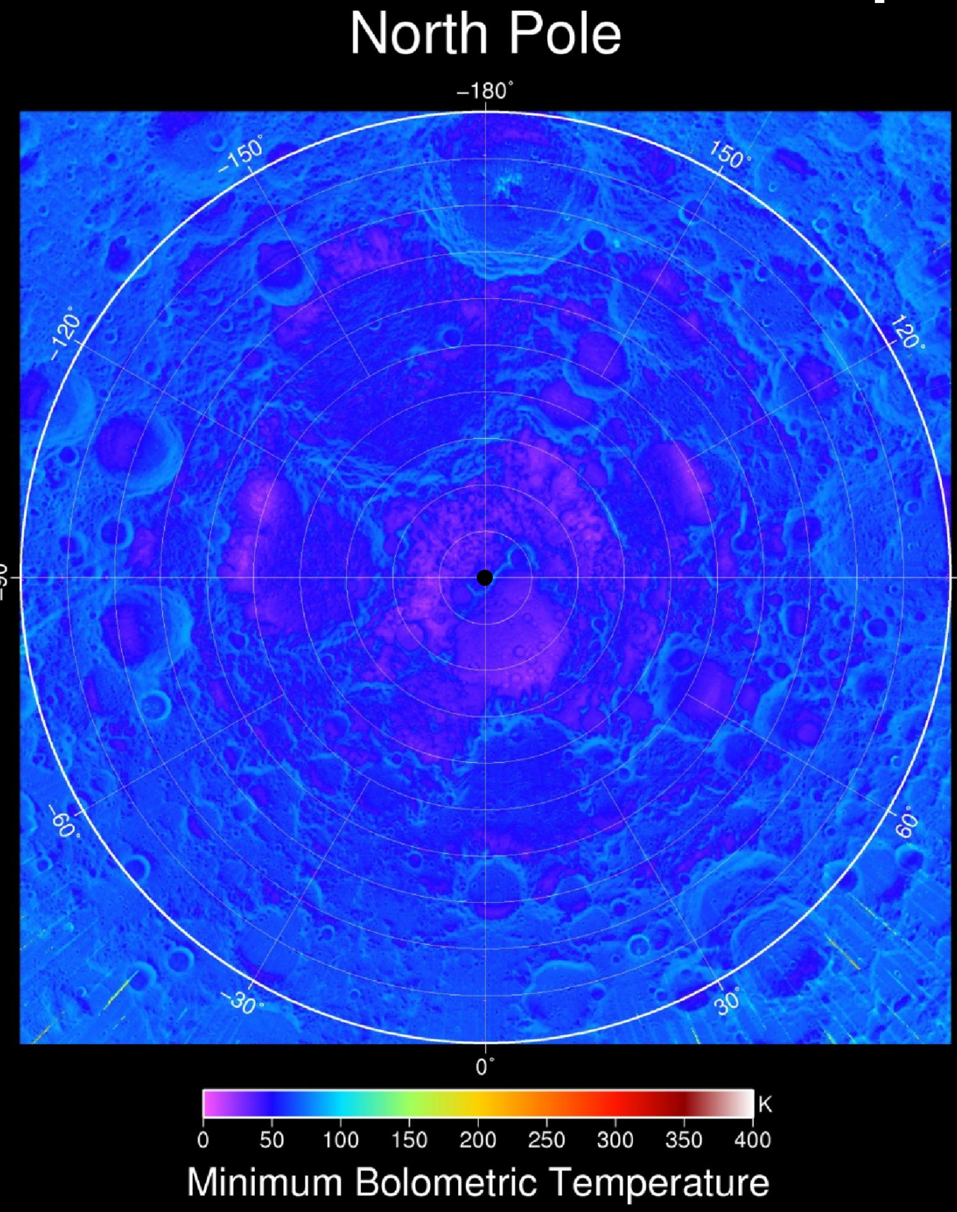
Diviner Observed Maximum Temperature

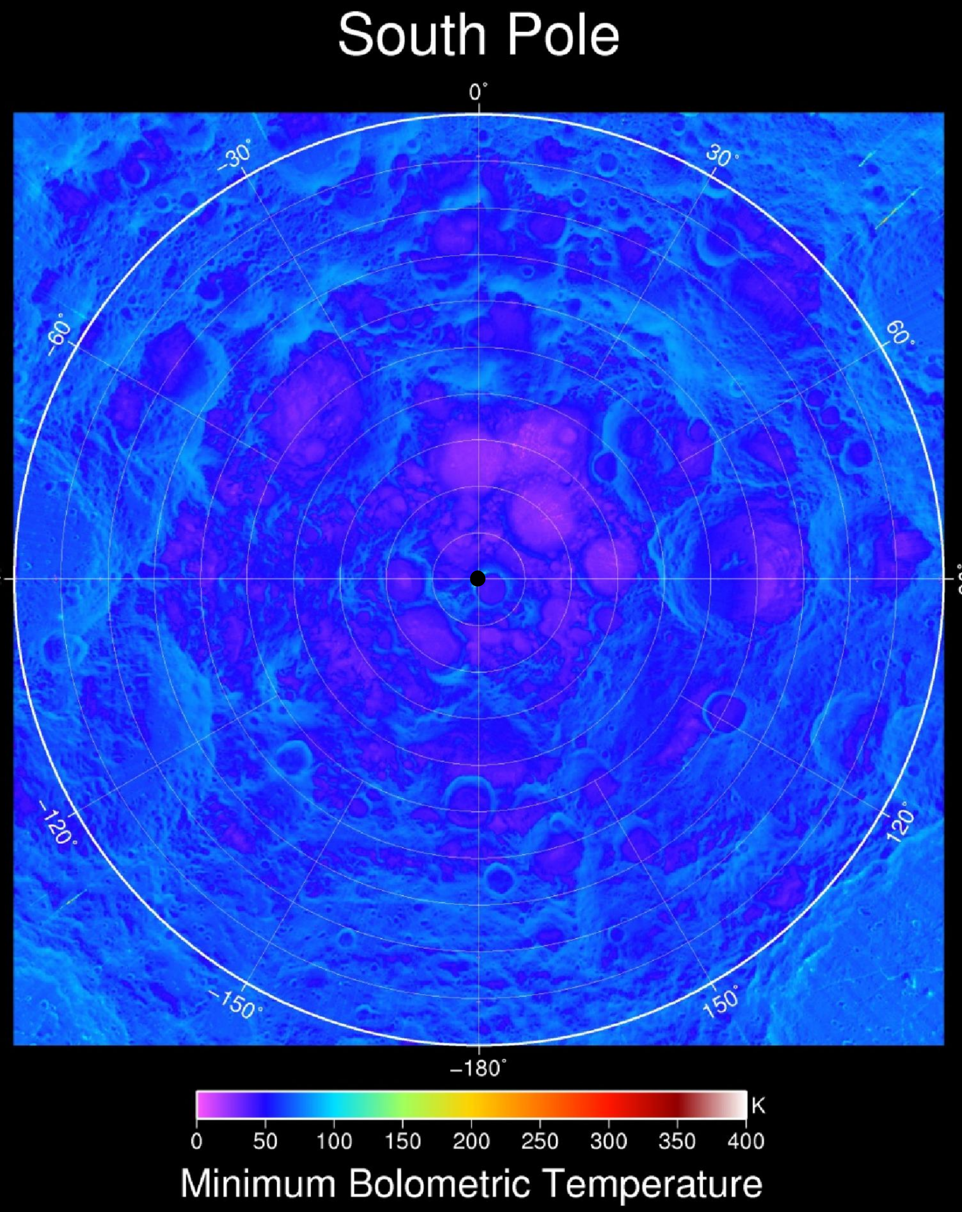
North Pole

South Pole



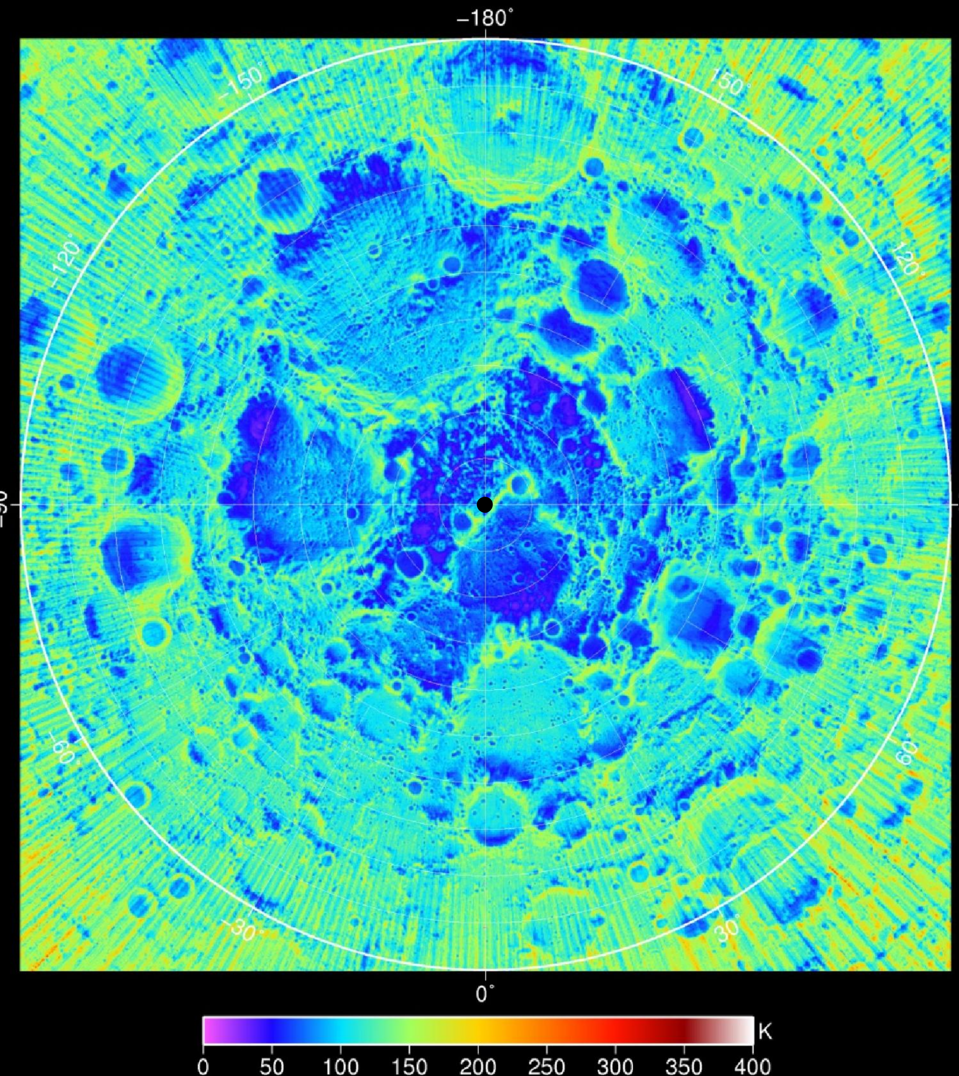
Diviner Observed Minimum Temperature



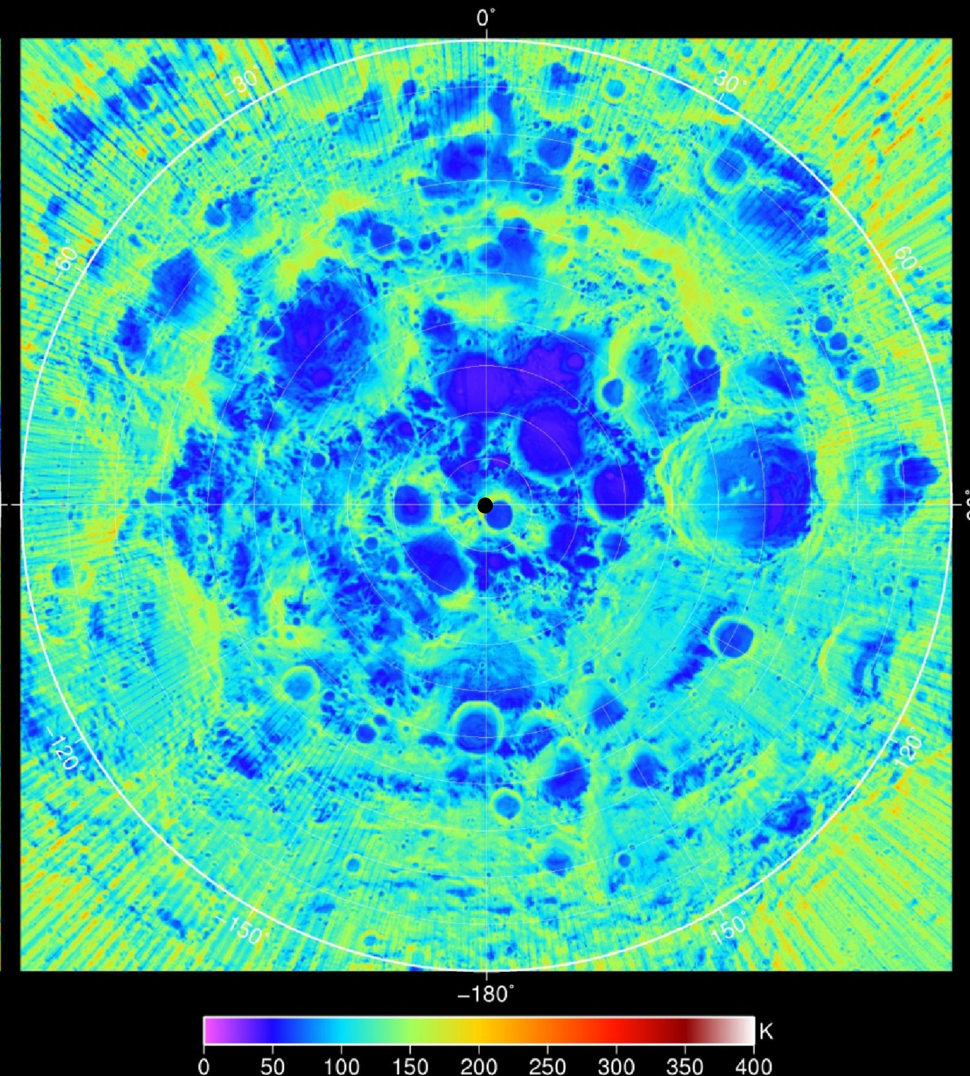


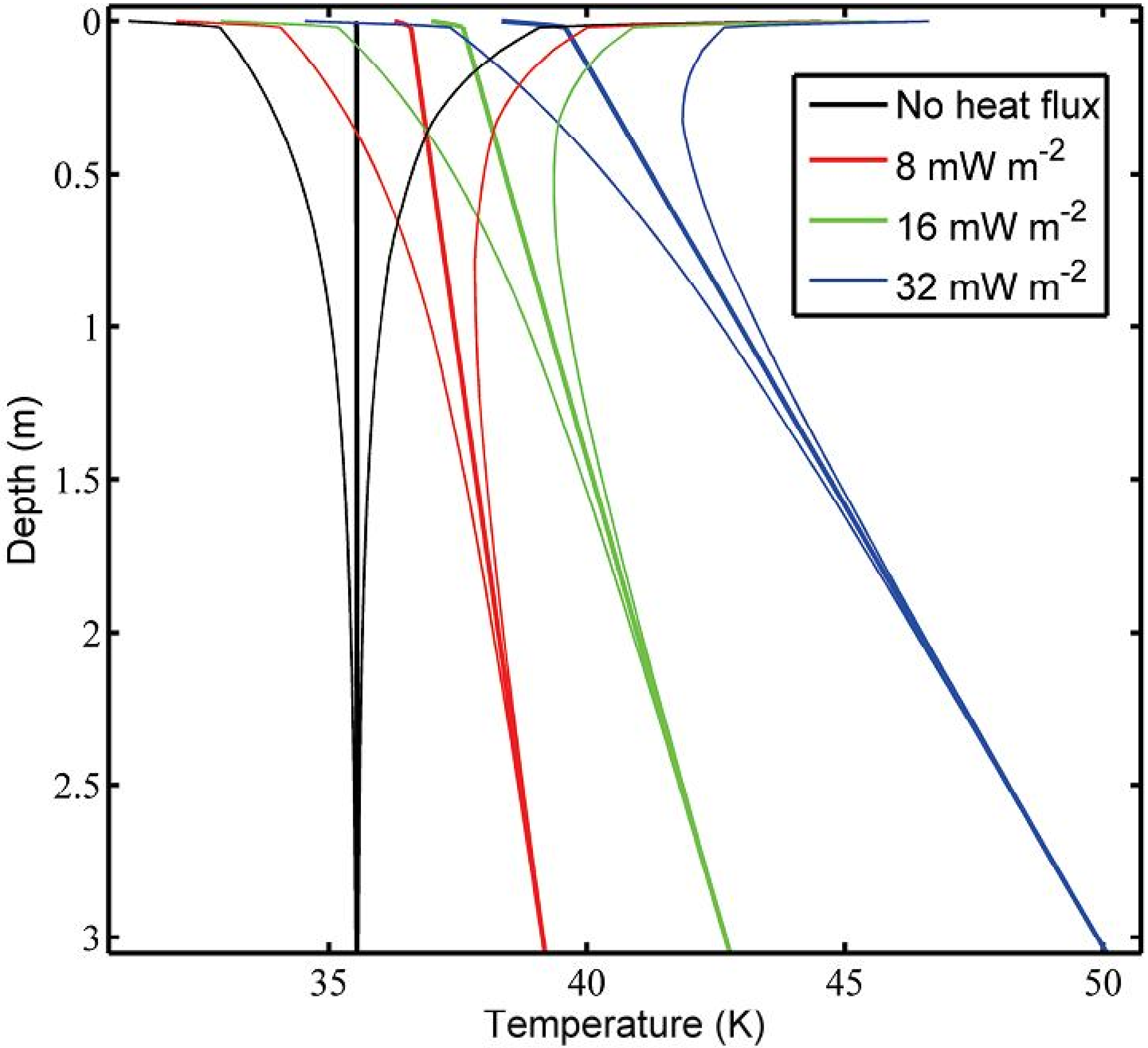
Diviner Observed Average Temperature

North Pole



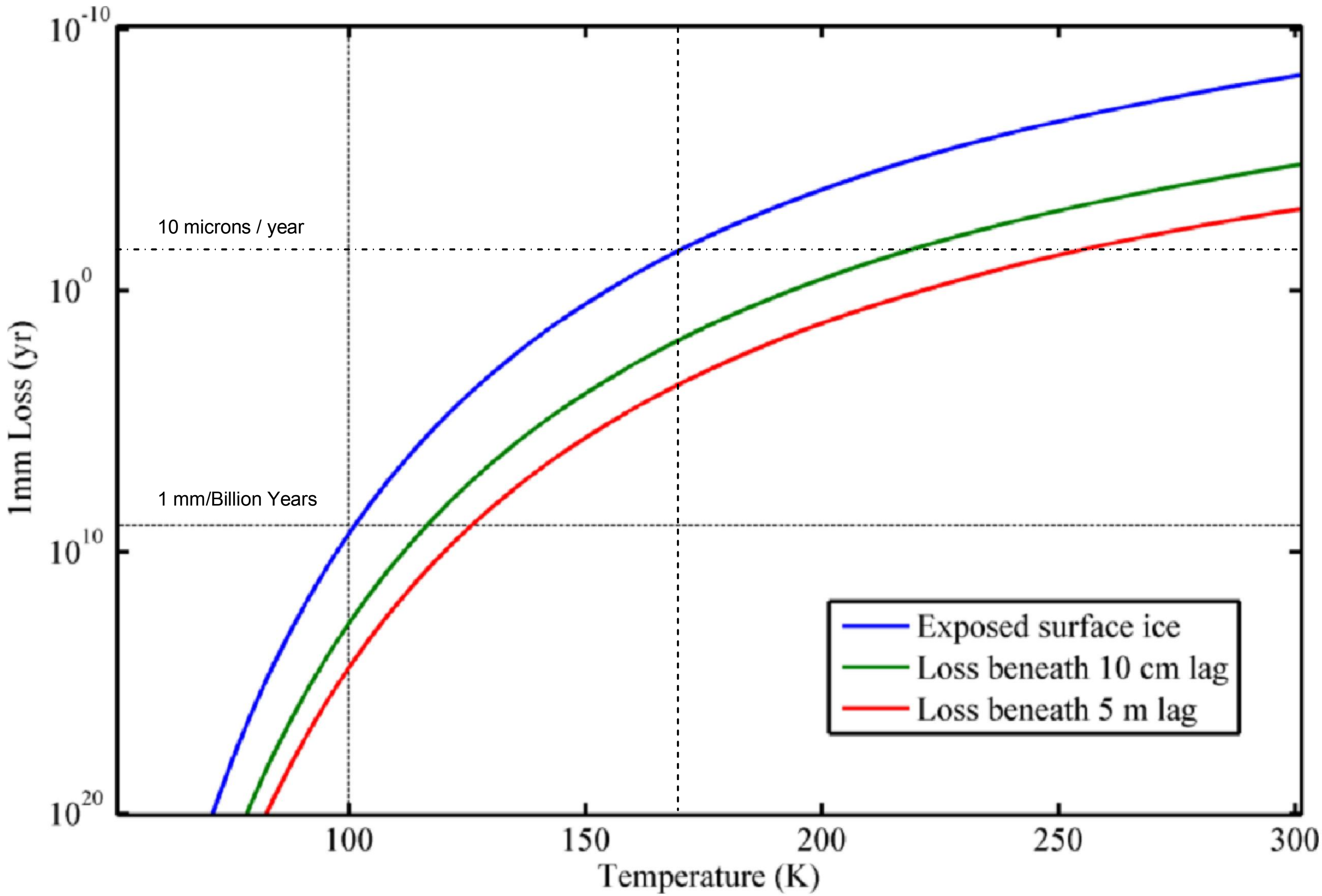
South Pole



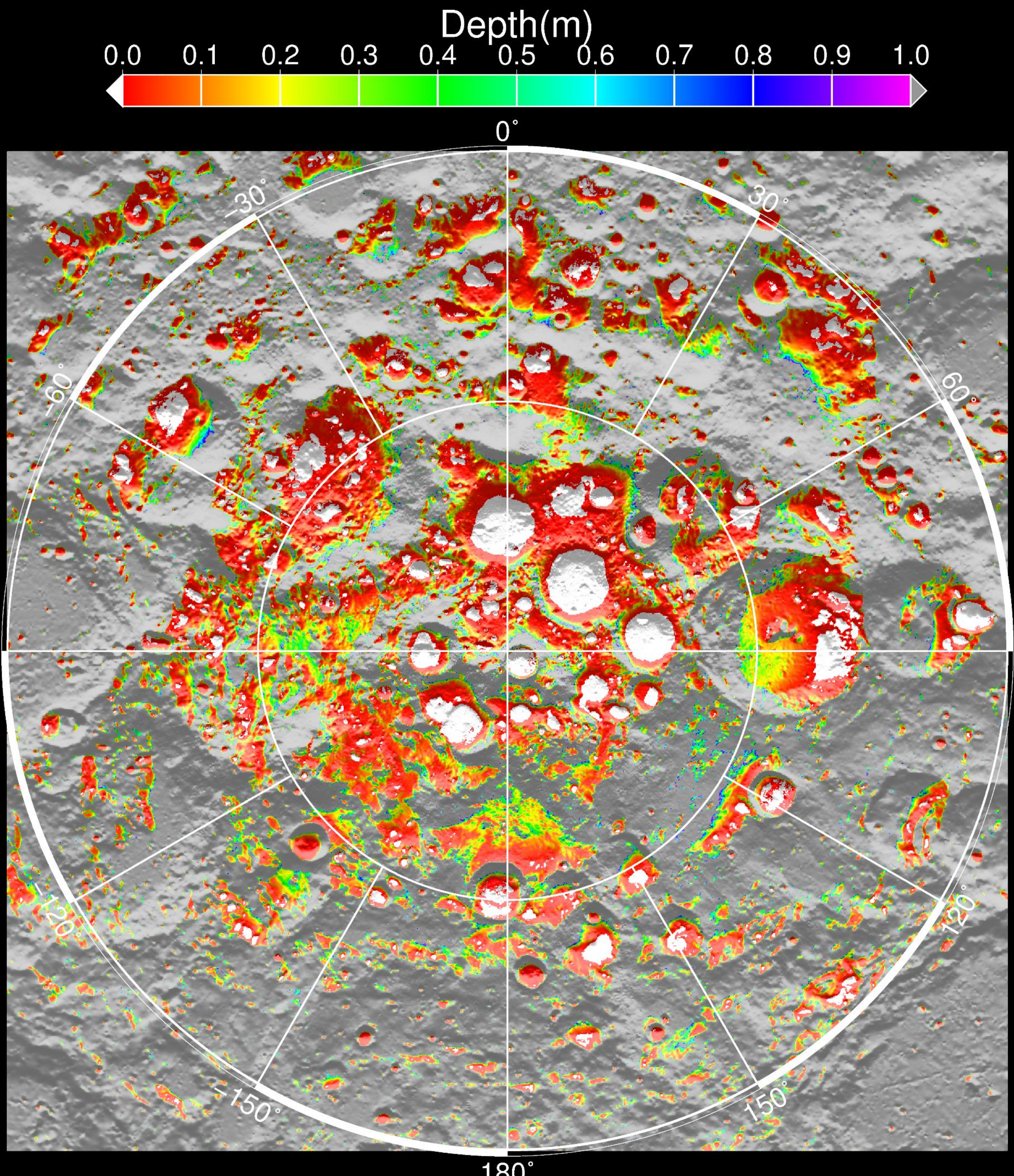


Paige et al., Science, 2010

Water Ice Thermal Stability



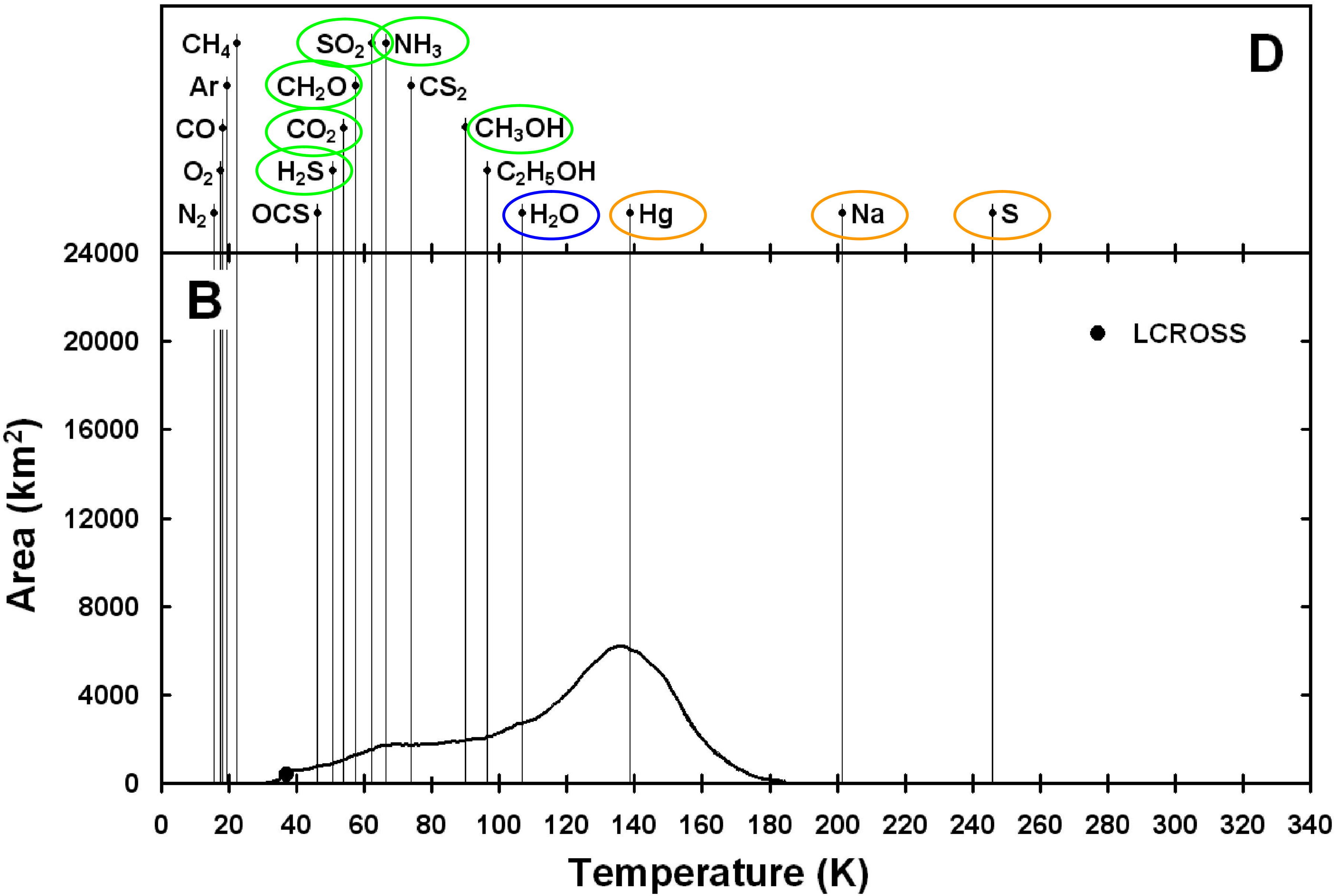
Paige et al., Science 339, 300-302, 2013

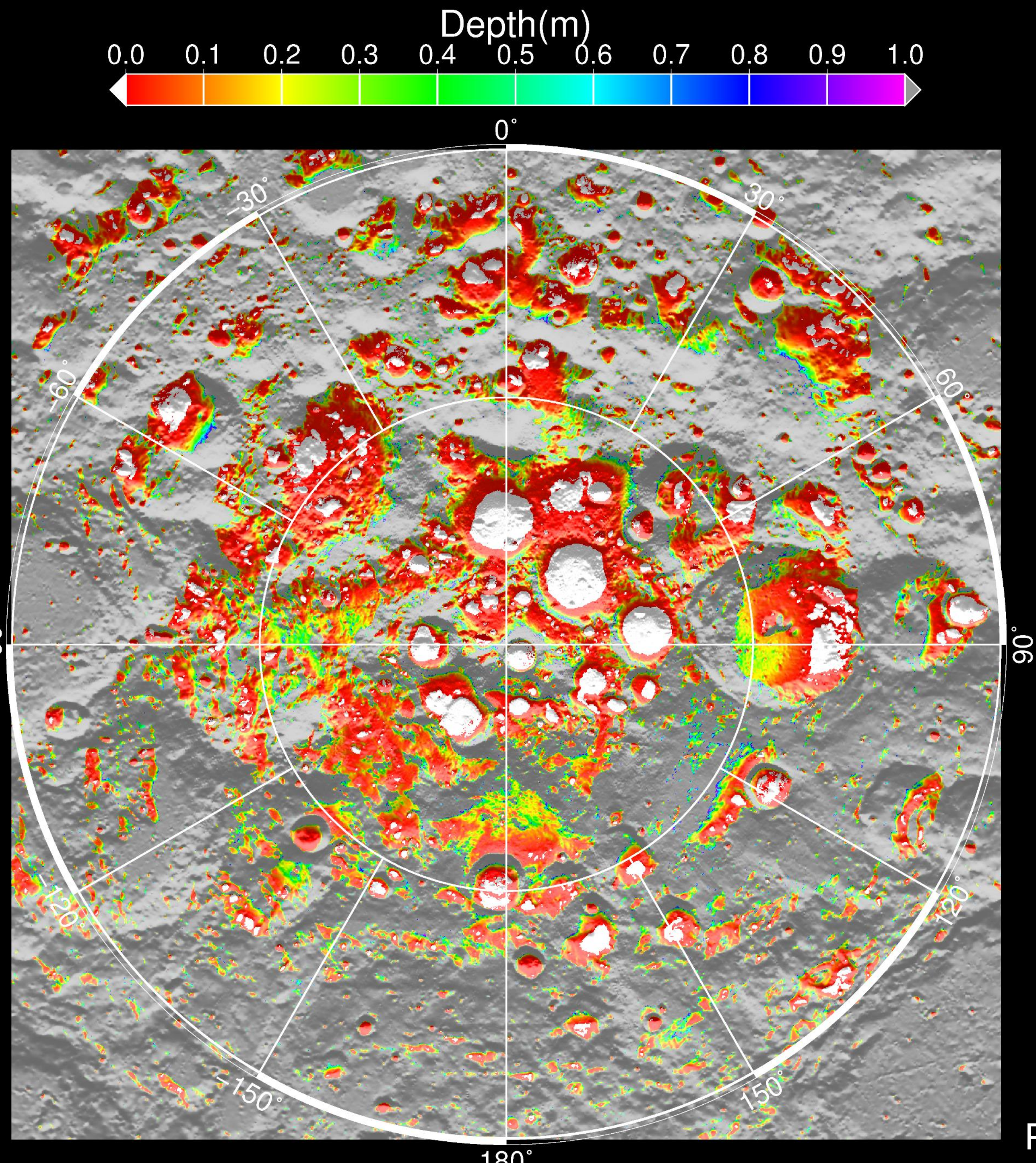


Depth to 1 mm water ice sublimation in 1 BY

Paige et al. *Science* (2010)

South Polar Annual Average Temperature Histogram





Depth to 1 mm water ice sublimation in 1 BY

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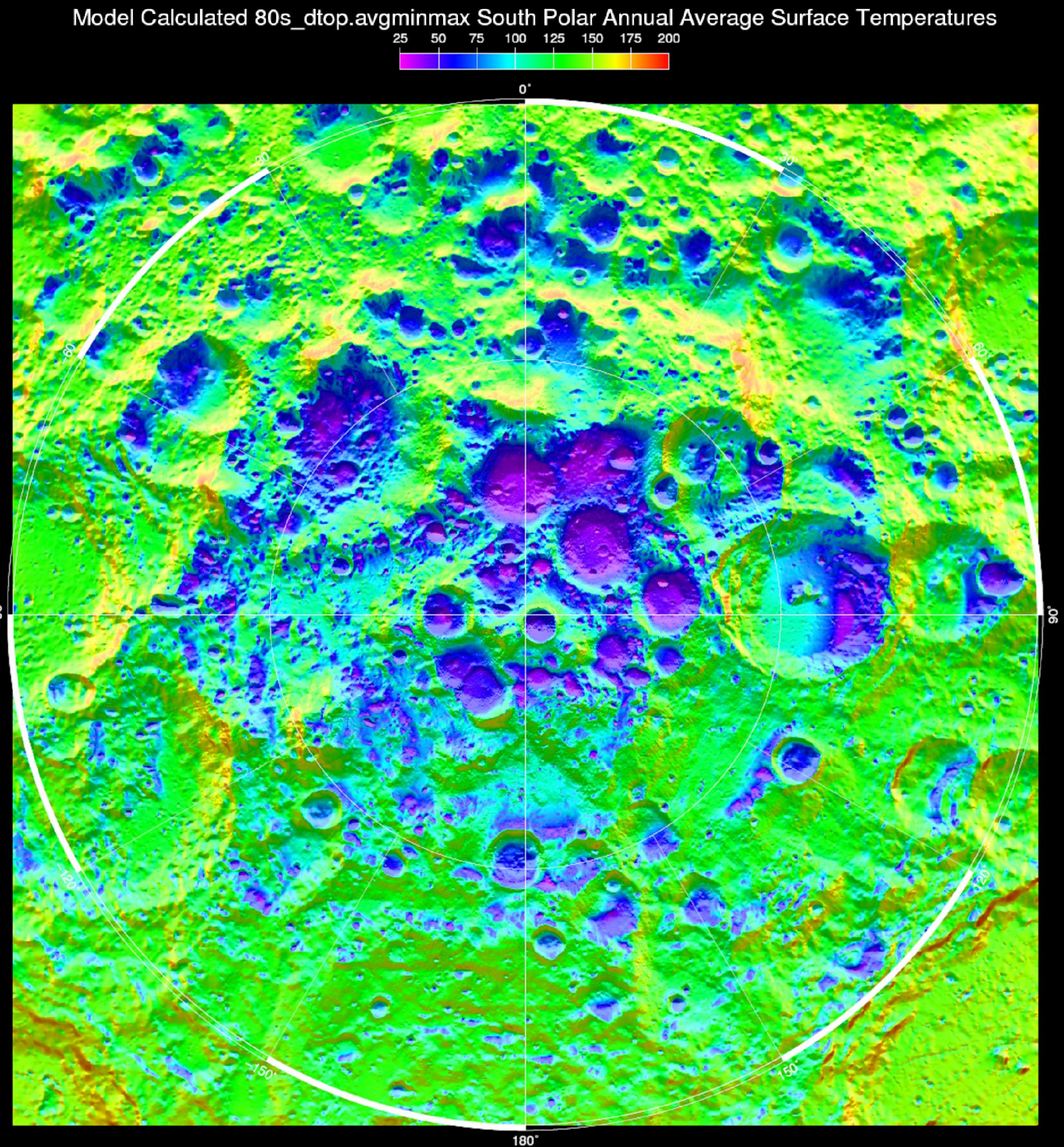
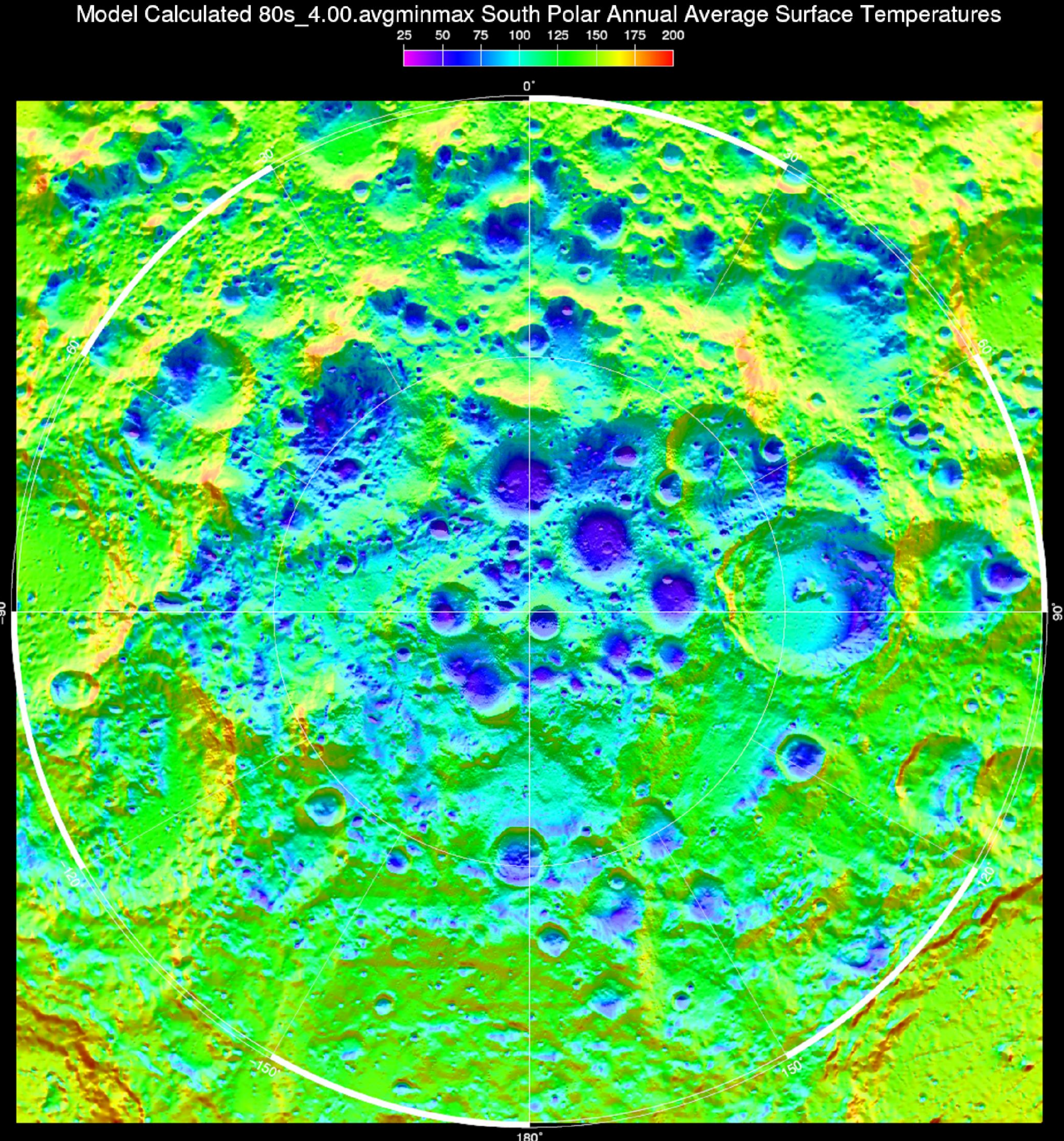
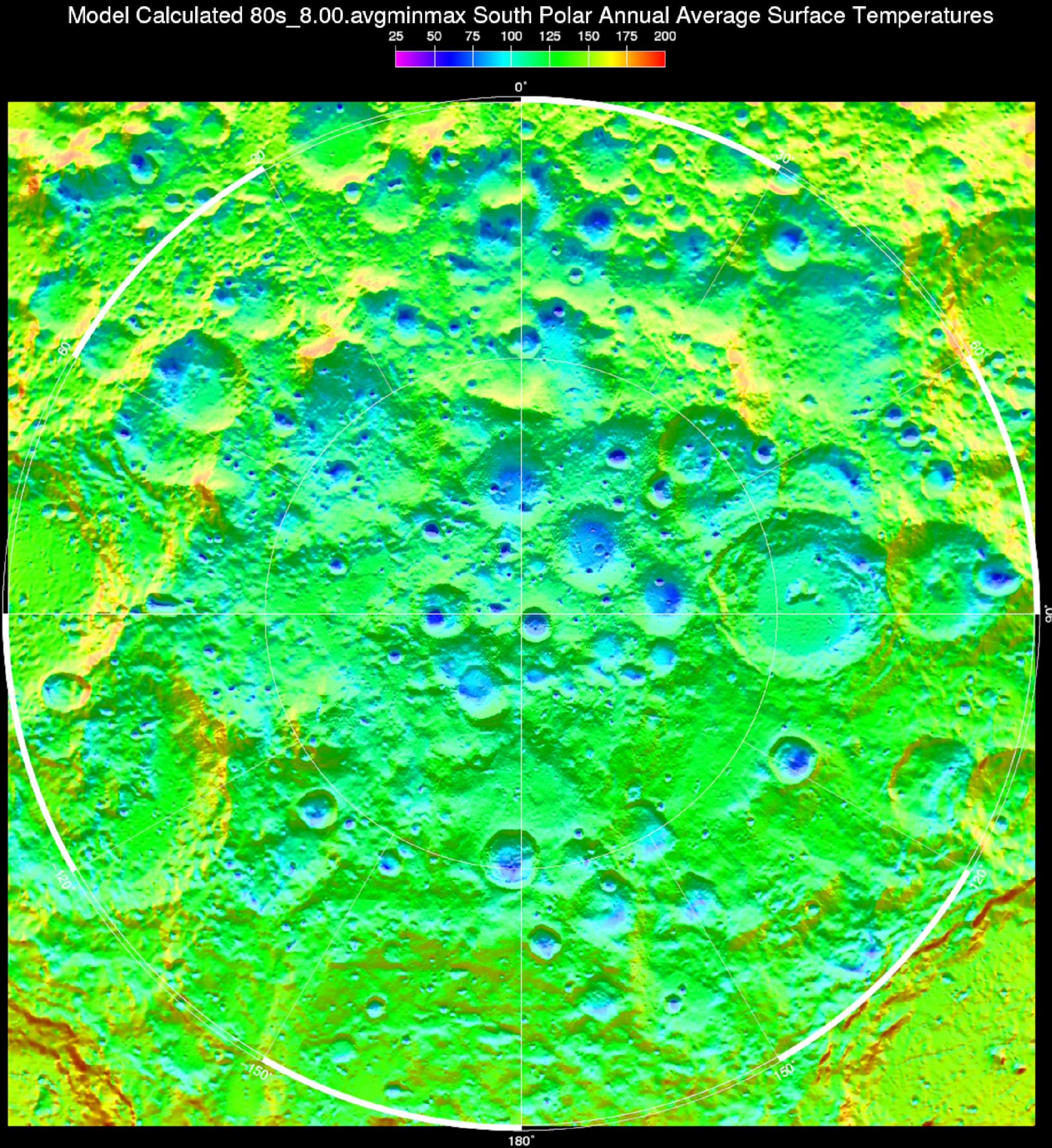


Model Calculated Annual Average Temperature Θ=1.54°

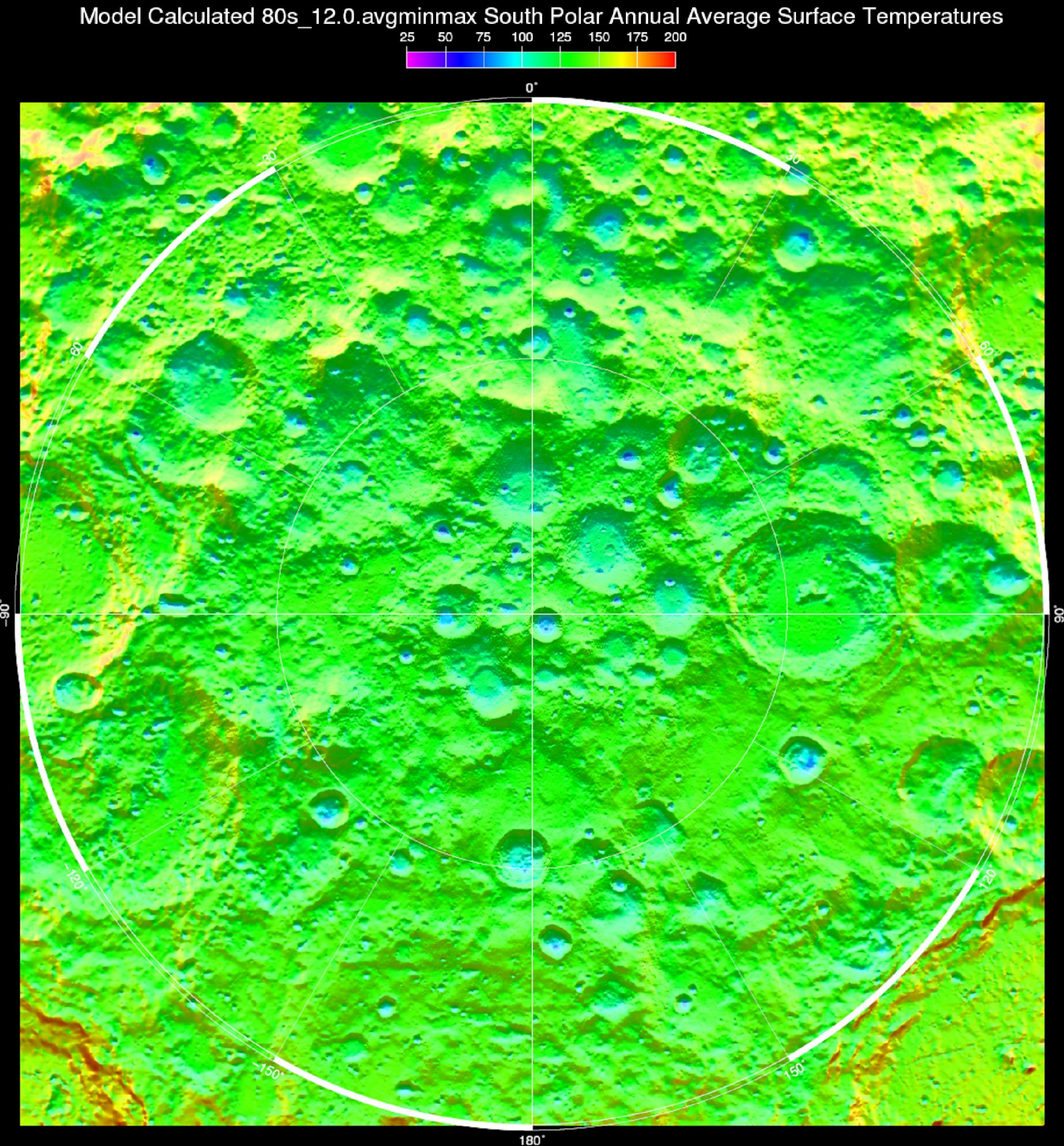


Model Calculated Annual Average Temperature

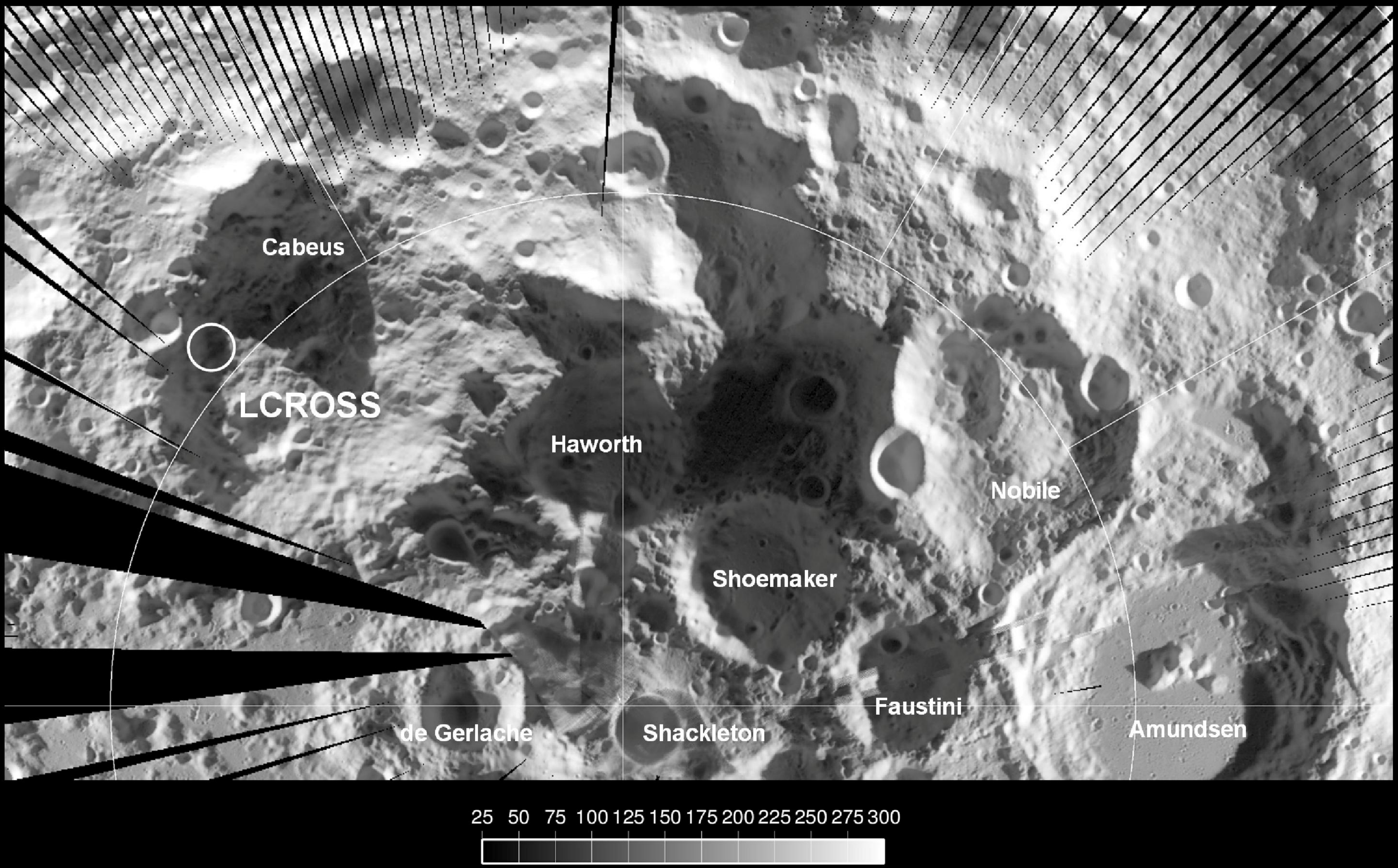
Θ=4°



Model Calculated Annual Average Temperature Θ=8°



Model Calculated Annual Average Temperature Θ=12°

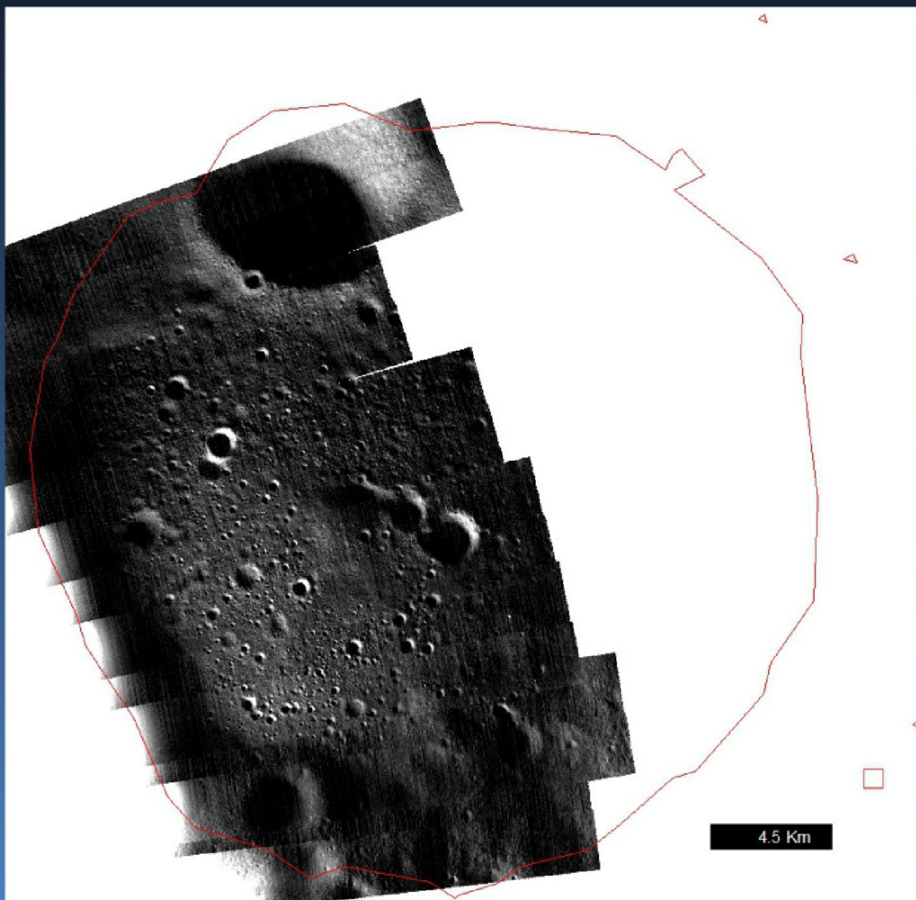


Diviner Channel 8 Brightness Temperature Map (K)

Faustini Crater 2009 vs. 2012

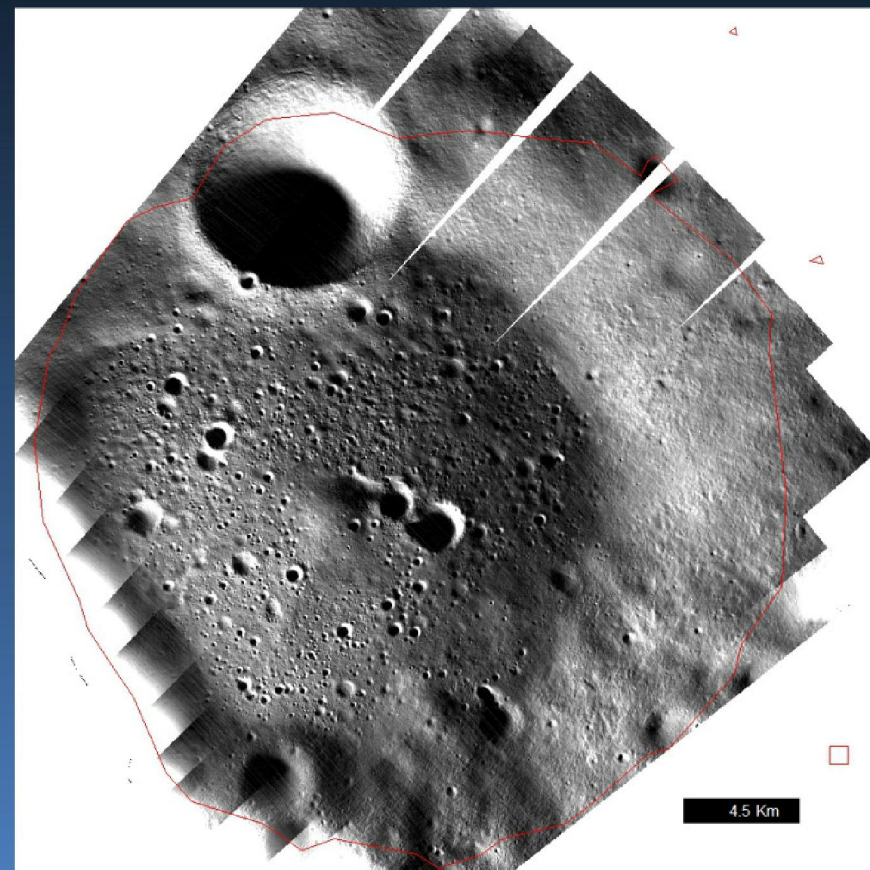
Koeber et al, NLSI LSF, 2013

2009



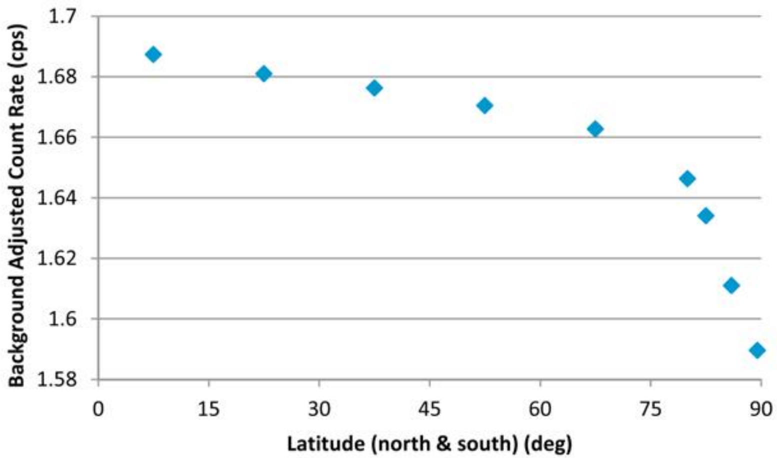
NAC Exposure time 12 ms,
resampled to 10-m mosaic

2012

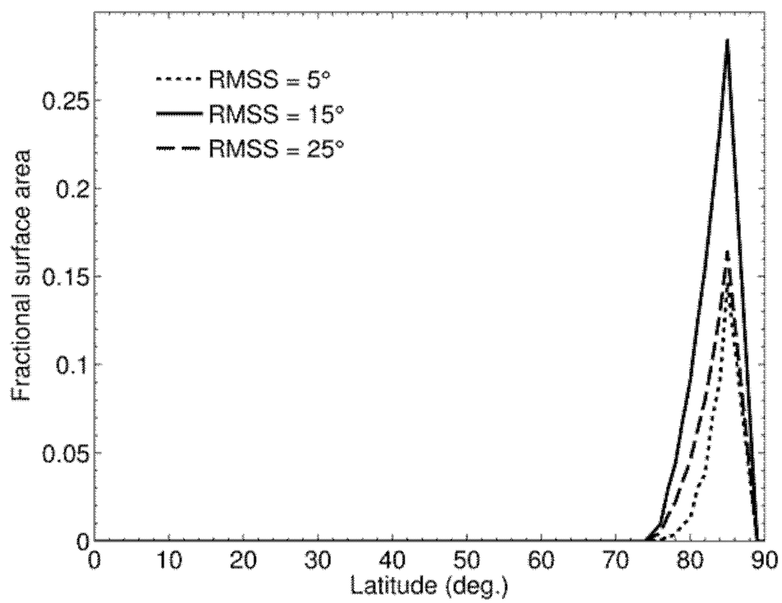


NAC Exposure time 24 ms,
resampled to 20-m mosaic

Comparison with "Background" Epithermal Neutron Suppression



LEND background neutron suppression (Boynton et al., 2012)

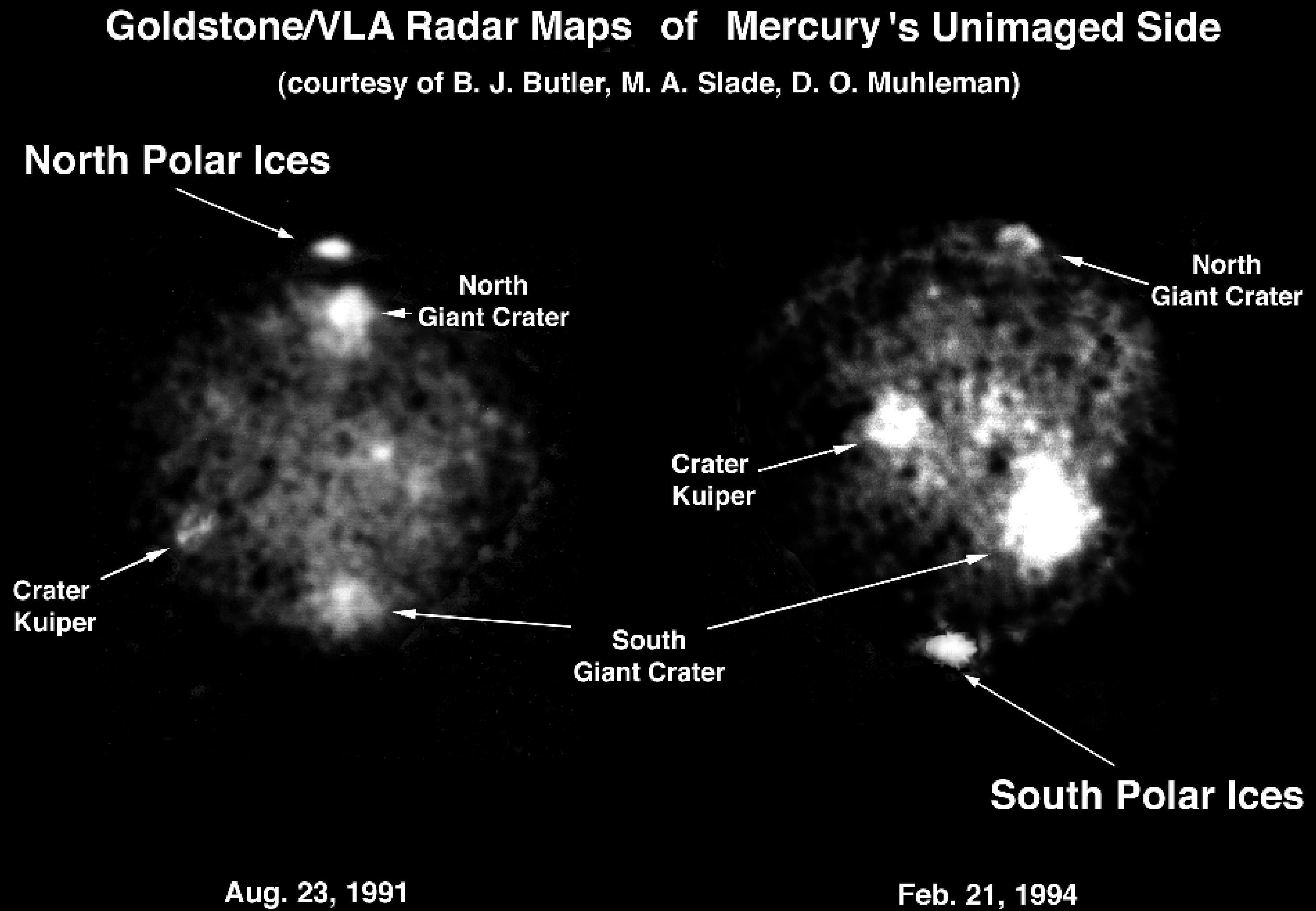


Fractional surface area with temperatures conducive to stable surface water ice

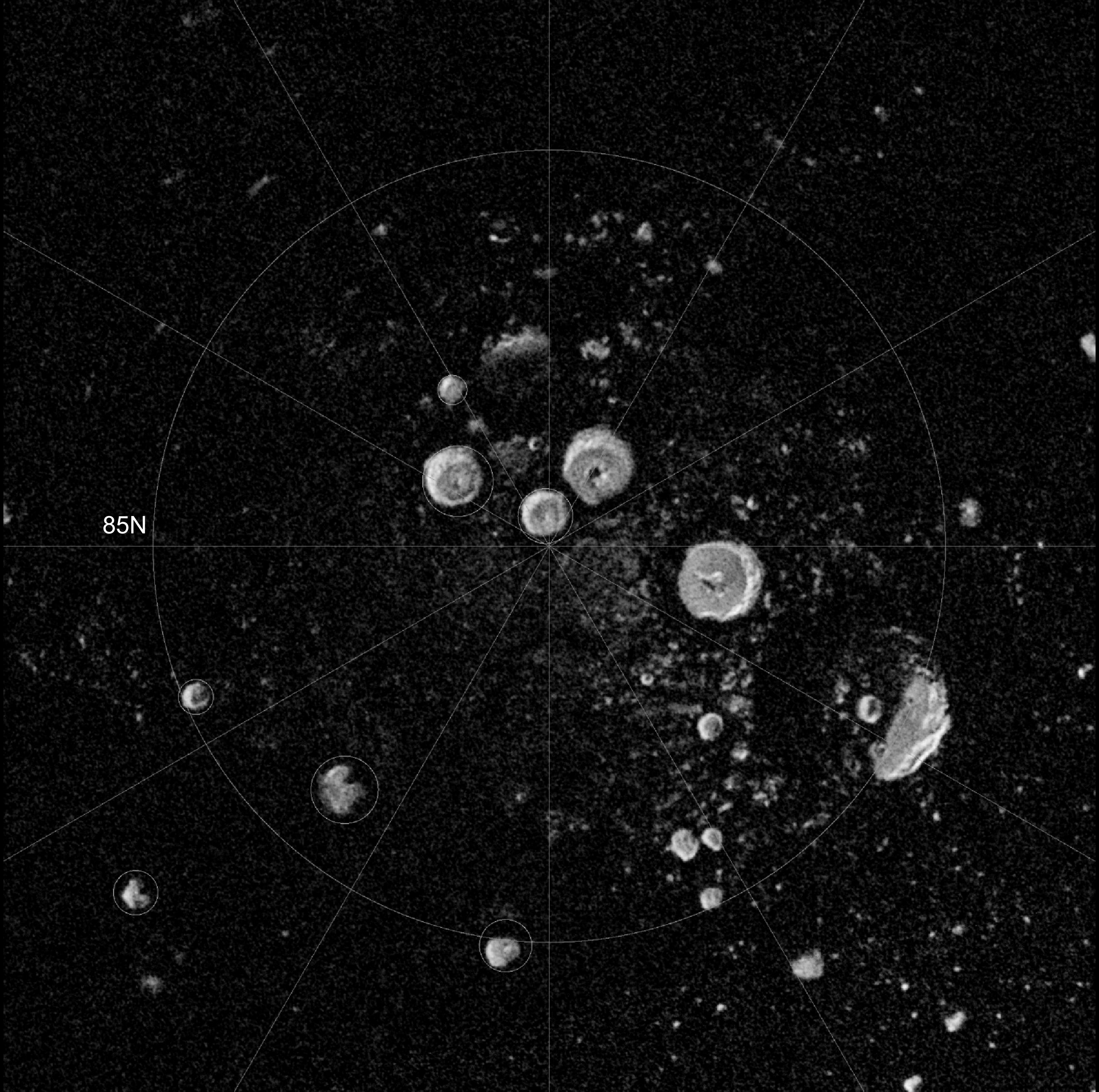
Hayne, NLSI Virtual Volatiles, 2013

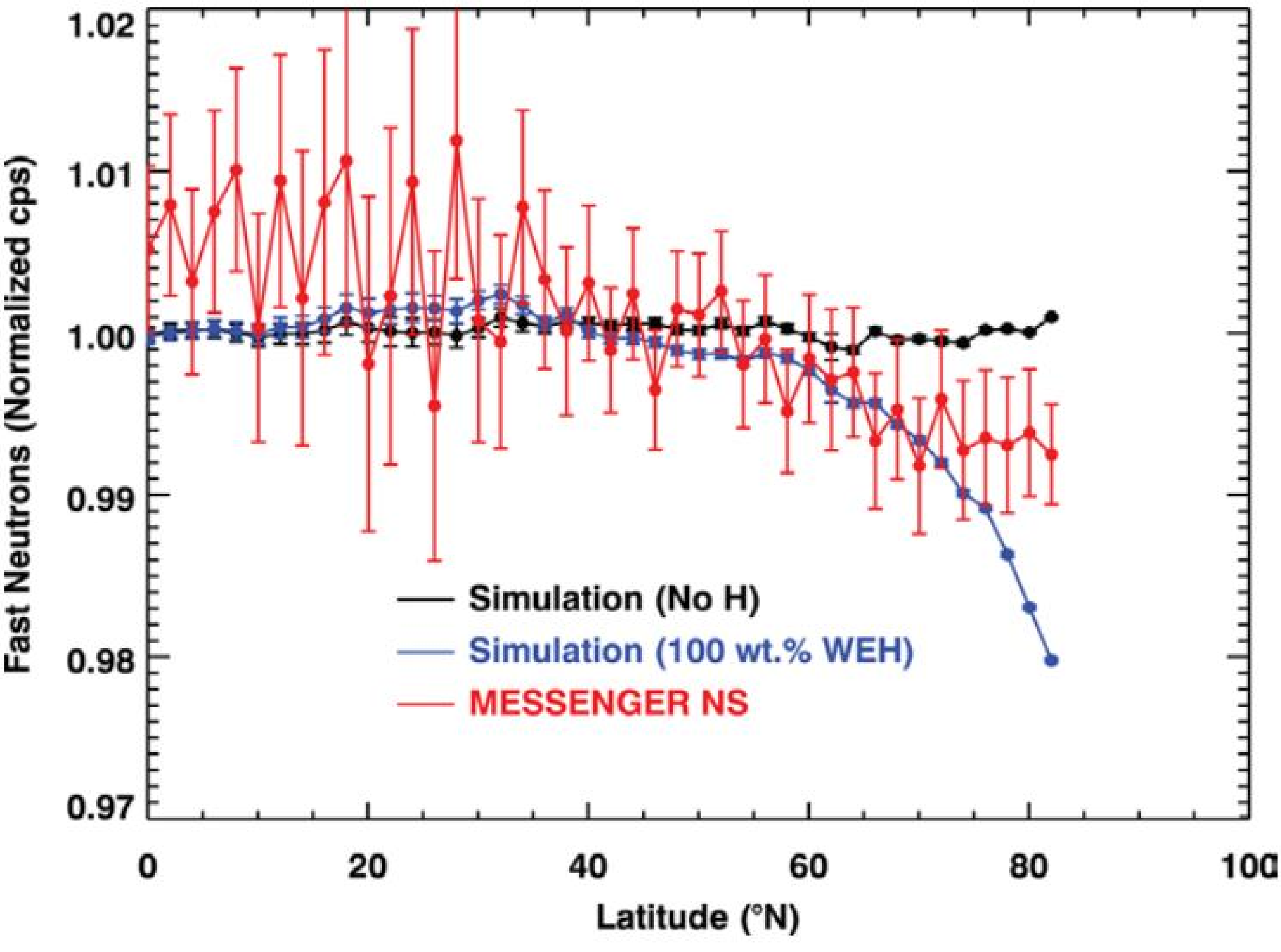
Thermal Stability of Volatiles in the North Polar Region of Mercury

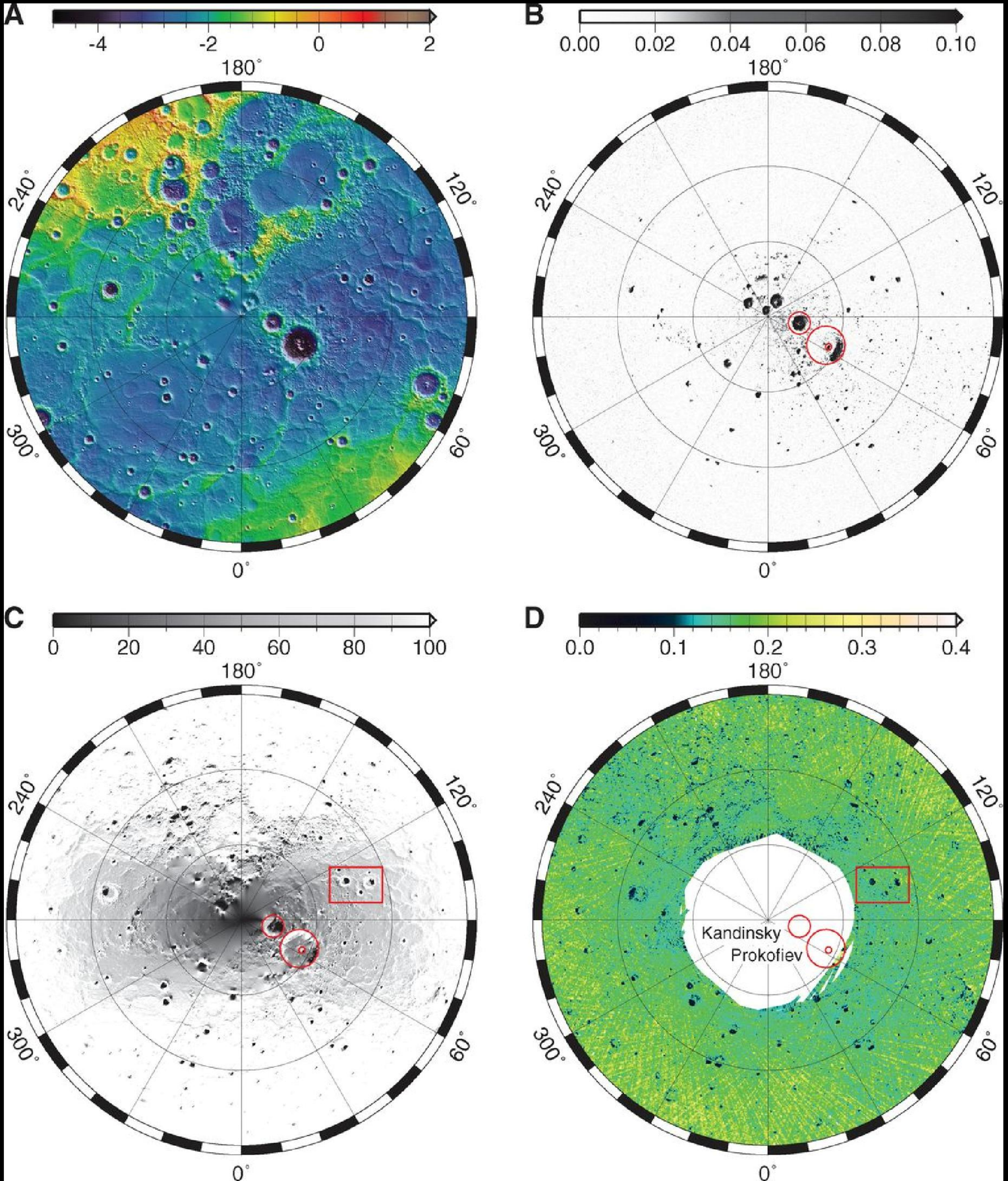
Polar Caps on Mercury?



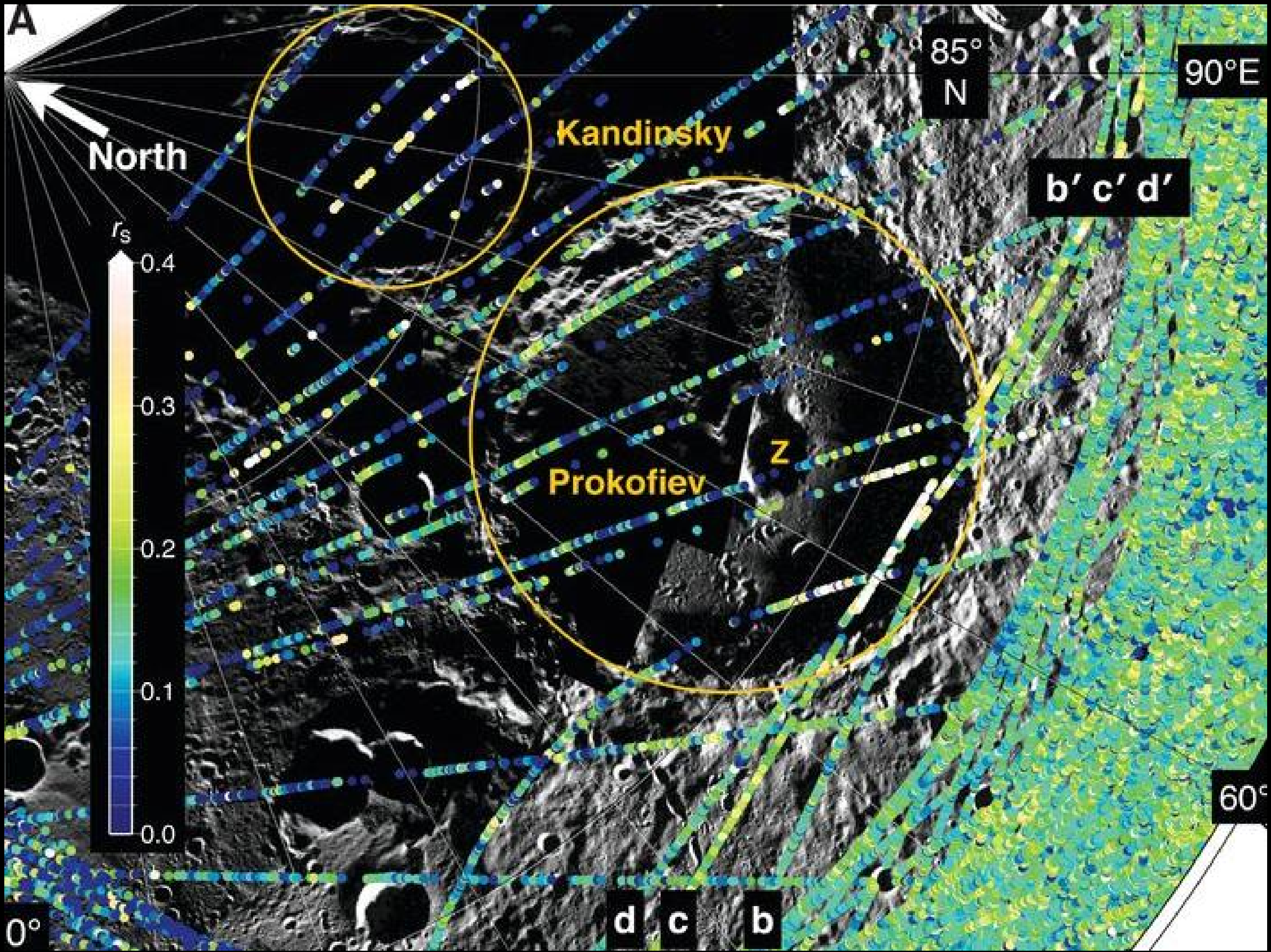
- Strong depoloarized echoes from both polar regions
- Mercury polar radar signatures suggest presence of thick, nearly pure water ice deposits below a thin (< 1 meter) covering of soil


85N

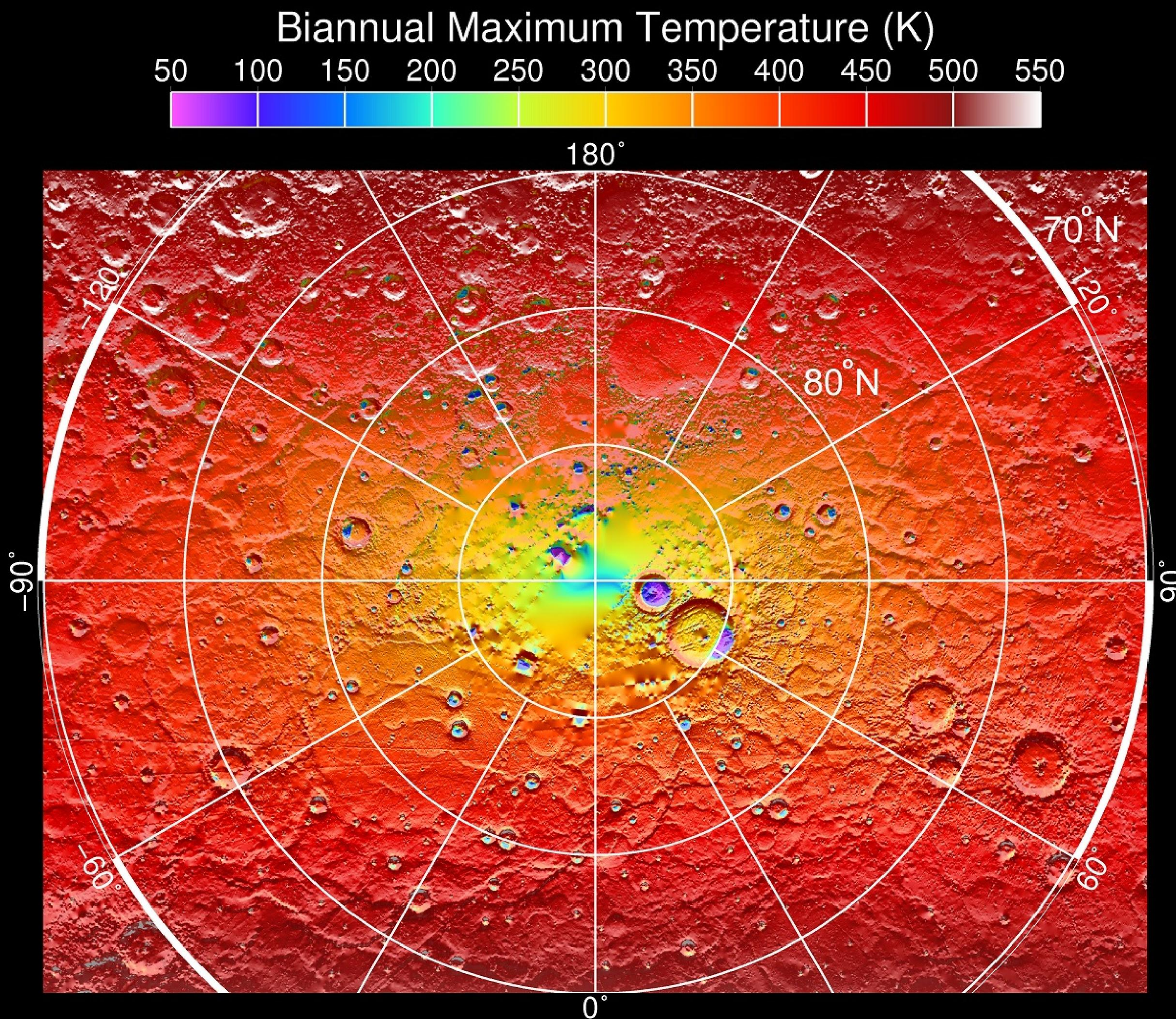

Fast Neutrons (Normalized cps)
1.02
1.01
1.00
0.99
0.98
0.97
0
20
40
60
80
100
Latitude (°N)
Simulation (No H)
Simulation (100 wt.% WEH)
MESSENGER NS



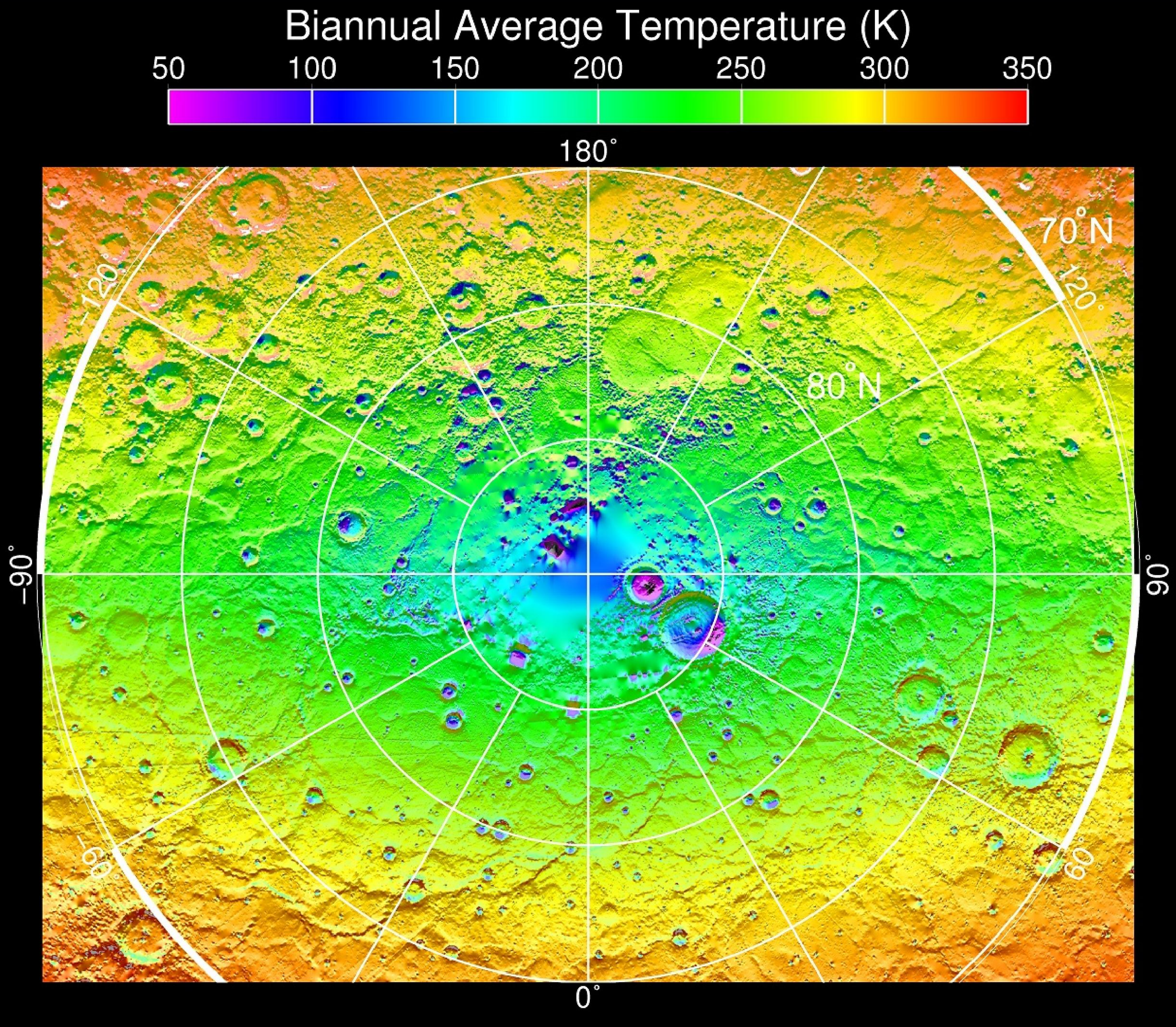
A
-4
-2
0
2
180°
240°
120°
300°
60°
0°
B
0.00
0.02
0.04
0.06
0.08
0.10
180°
240°
120°
300°
60°
0°
C
0
20
40
60
80
100
180°
240°
120°
300°
60°
0°
D
0.0
0.1
0.2
0.3
0.4
180°
240°
120°
Kandinsky
Prokofiev
300°
60°
0°

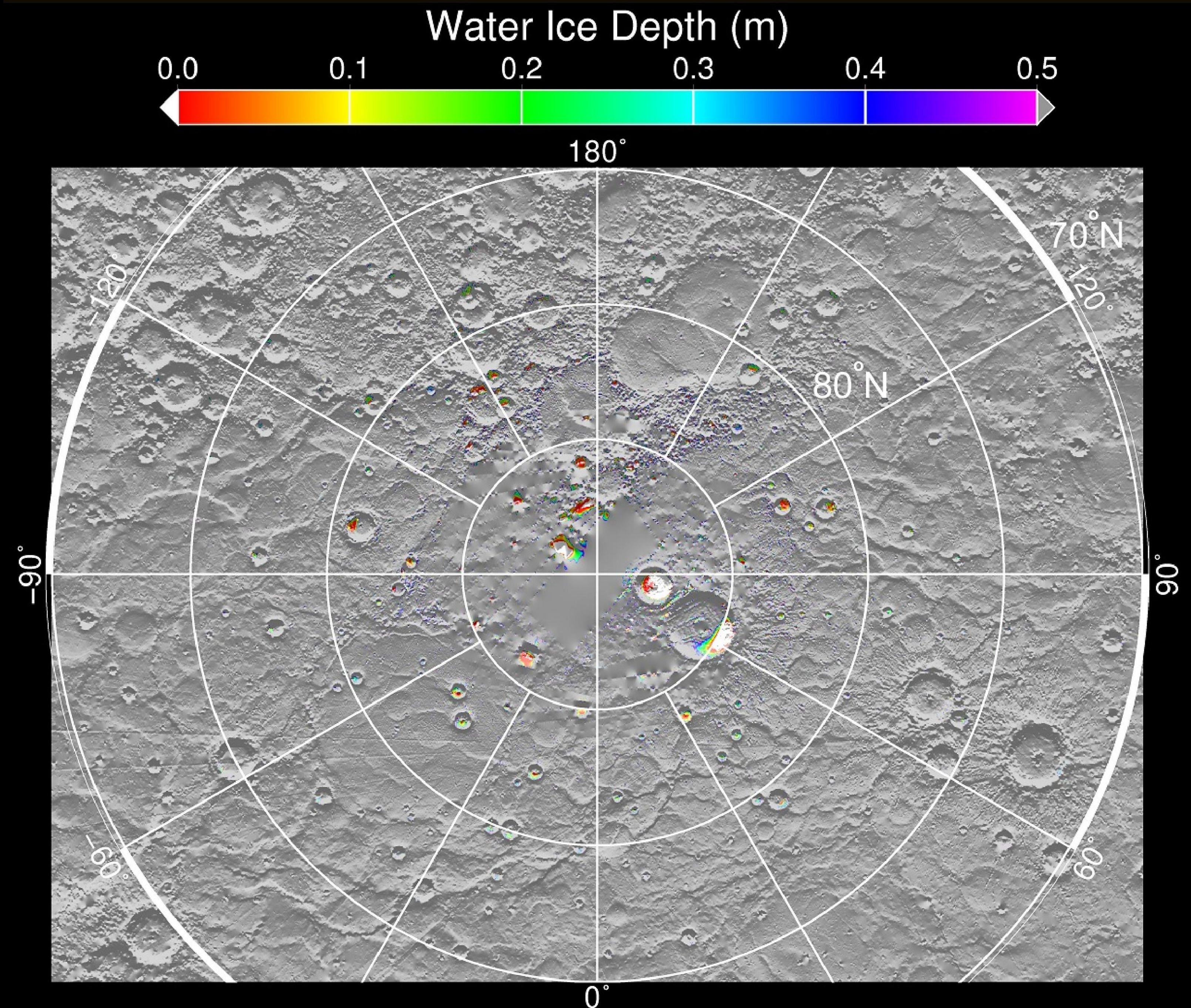


A
North
Kandinsky
Prokofiev
z
85° N
90°E
b′ c′ d′
60°
0°
d c b
r_s
0.4
0.3
0.2
0.1
0.0

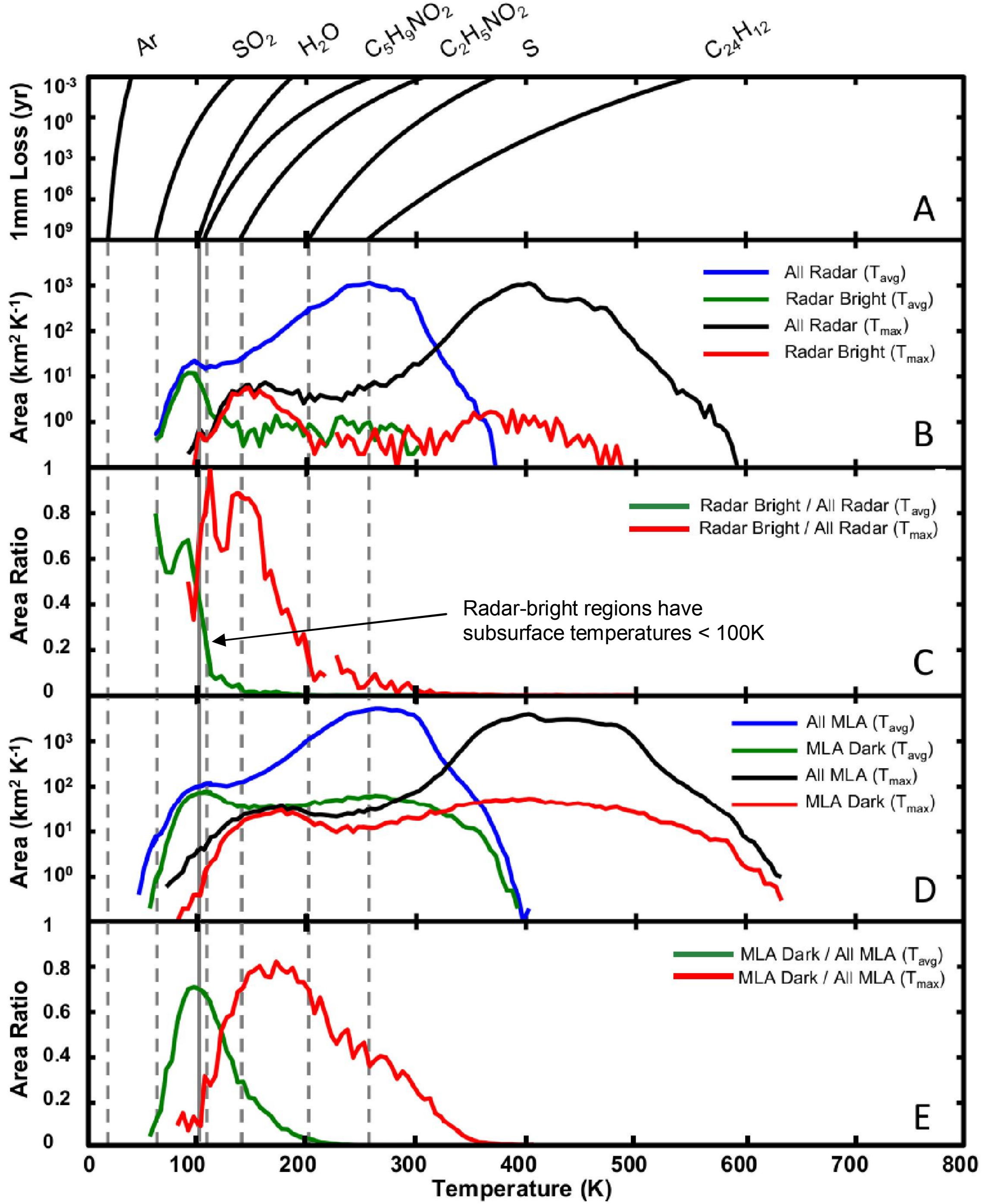


Biannual Maximum Temperature (K)
50
100
150
200
250
300
350
400
450
500
550
180˚
70˚N
80˚N
−120˚
120˚
−90˚
90˚
−60˚
60˚
0˚

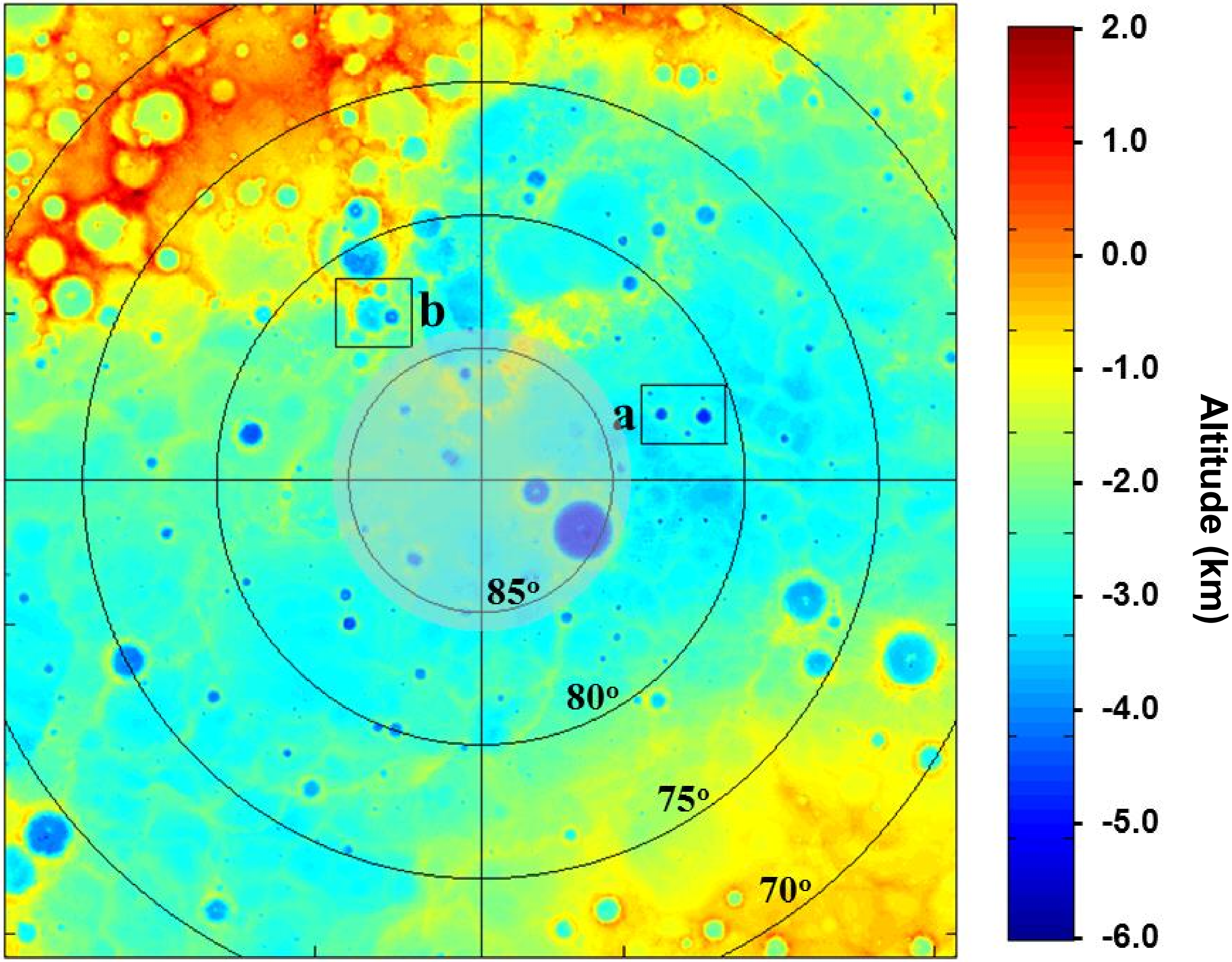

Biannual Average Temperature (K)
50
100
150
200
250
300
350
180˚
70˚N
80˚N
−120˚
120˚
−90˚
90˚
−60˚
60˚
0˚



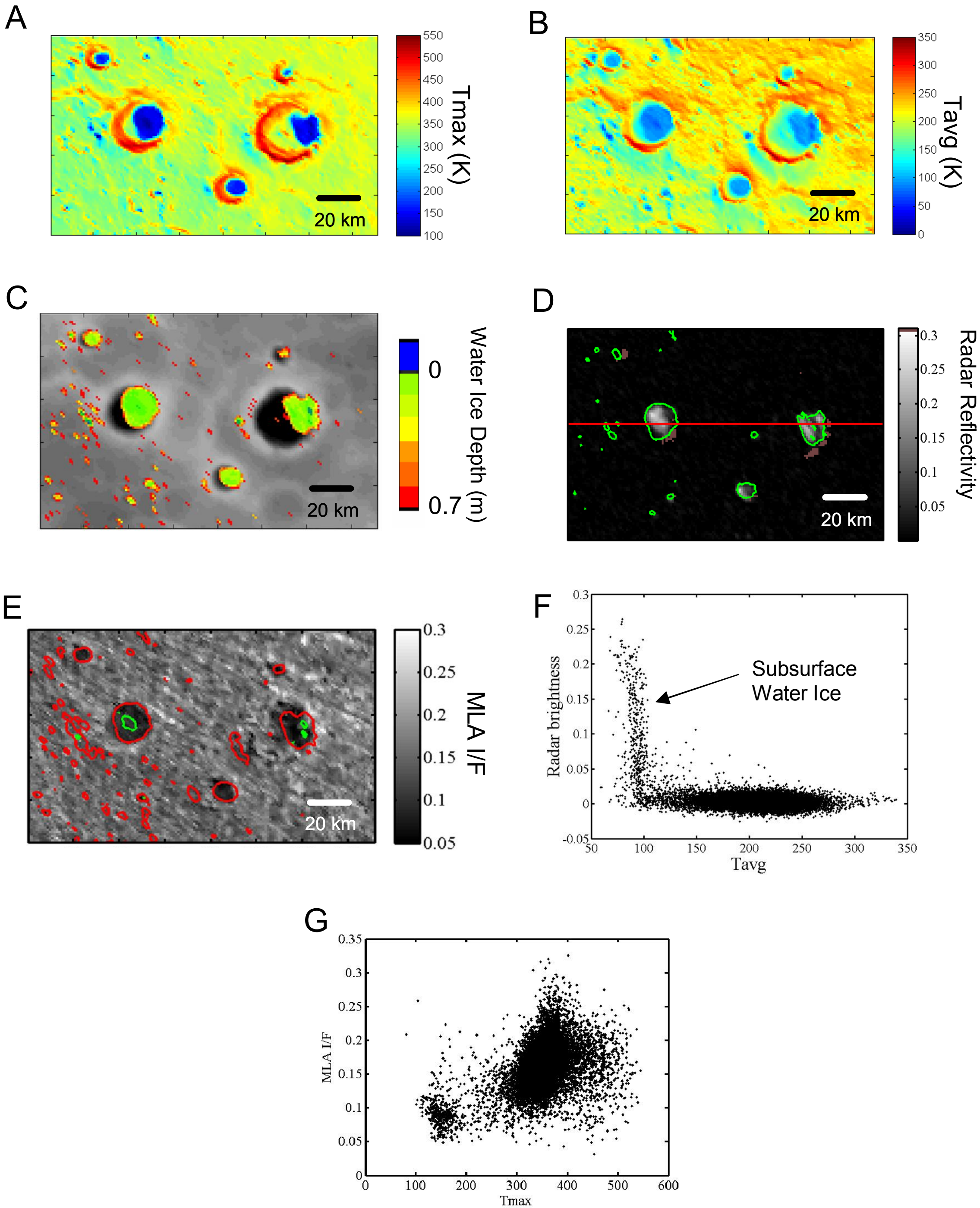
Water Ice Depth (m)
0.0
0.1
0.2
0.3
0.4
0.5
180°
70°N
120°
-120°
80°N
-90°
90°
-60°
60°
0°



Ar
SO_2
H_2O
$C_5H_9NO_2$
$C_2H_5NO_2$
S
$C_{24}H_{12}$
1mm Loss (yr)
A
All Radar (T_{avg})
Radar Bright (T_{avg})
All Radar (T_{max})
Radar Bright (T_{max})
Area ($km^2 K^{-1}$)
B
Radar Bright / All Radar (T_{avg})
Radar Bright / All Radar (T_{max})
Radar-bright regions have subsurface temperatures < 100K
Area Ratio
C
All MLA (T_{avg})
MLA Dark (T_{avg})
All MLA (T_{max})
MLA Dark (T_{max})
Area ($km^2 K^{-1}$)
D
MLA Dark / All MLA (T_{avg})
MLA Dark / All MLA (T_{max})
Area Ratio
E
Temperature (K)

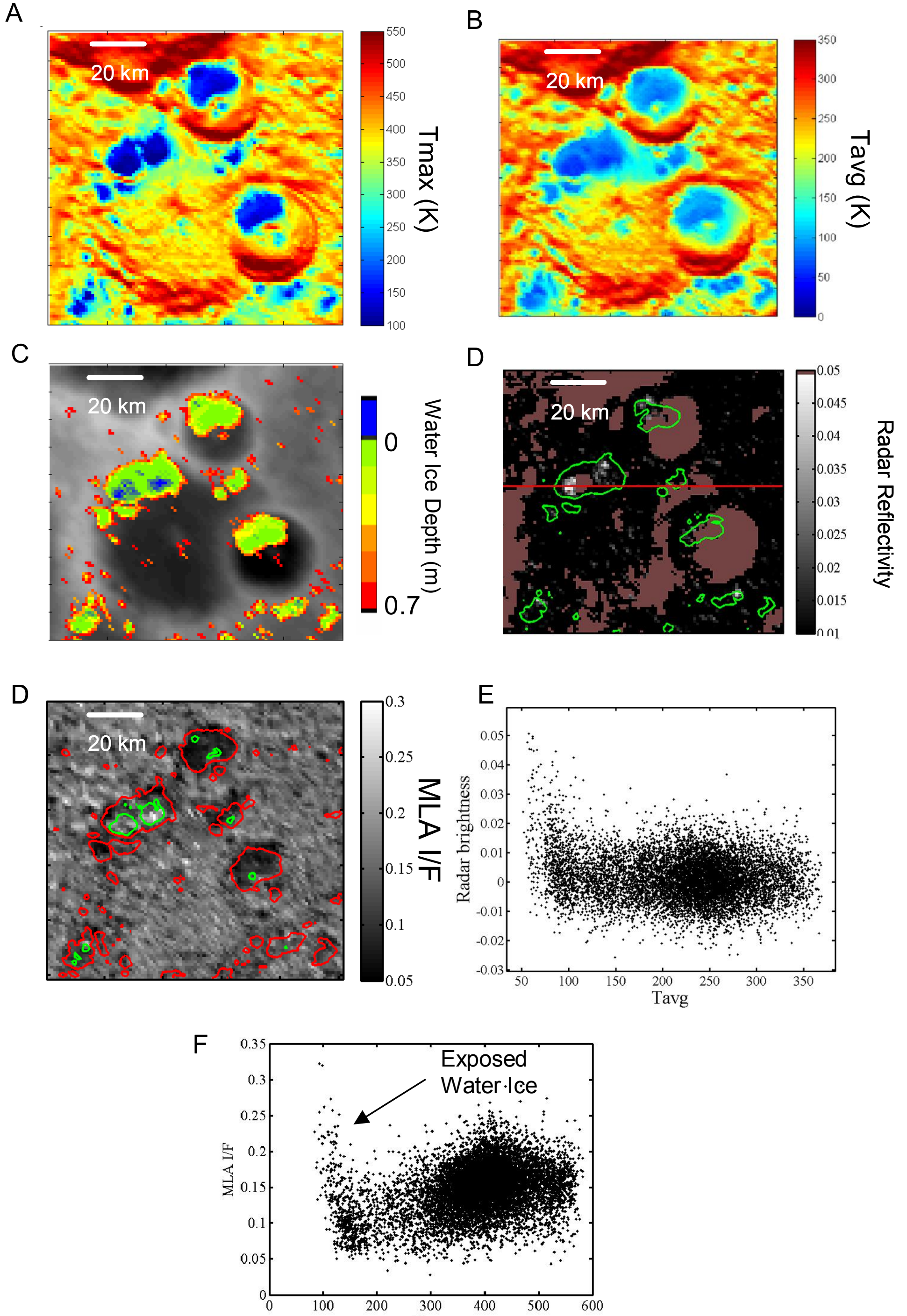


b
a
85o
80o
75o
70o
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
Altitude (km)

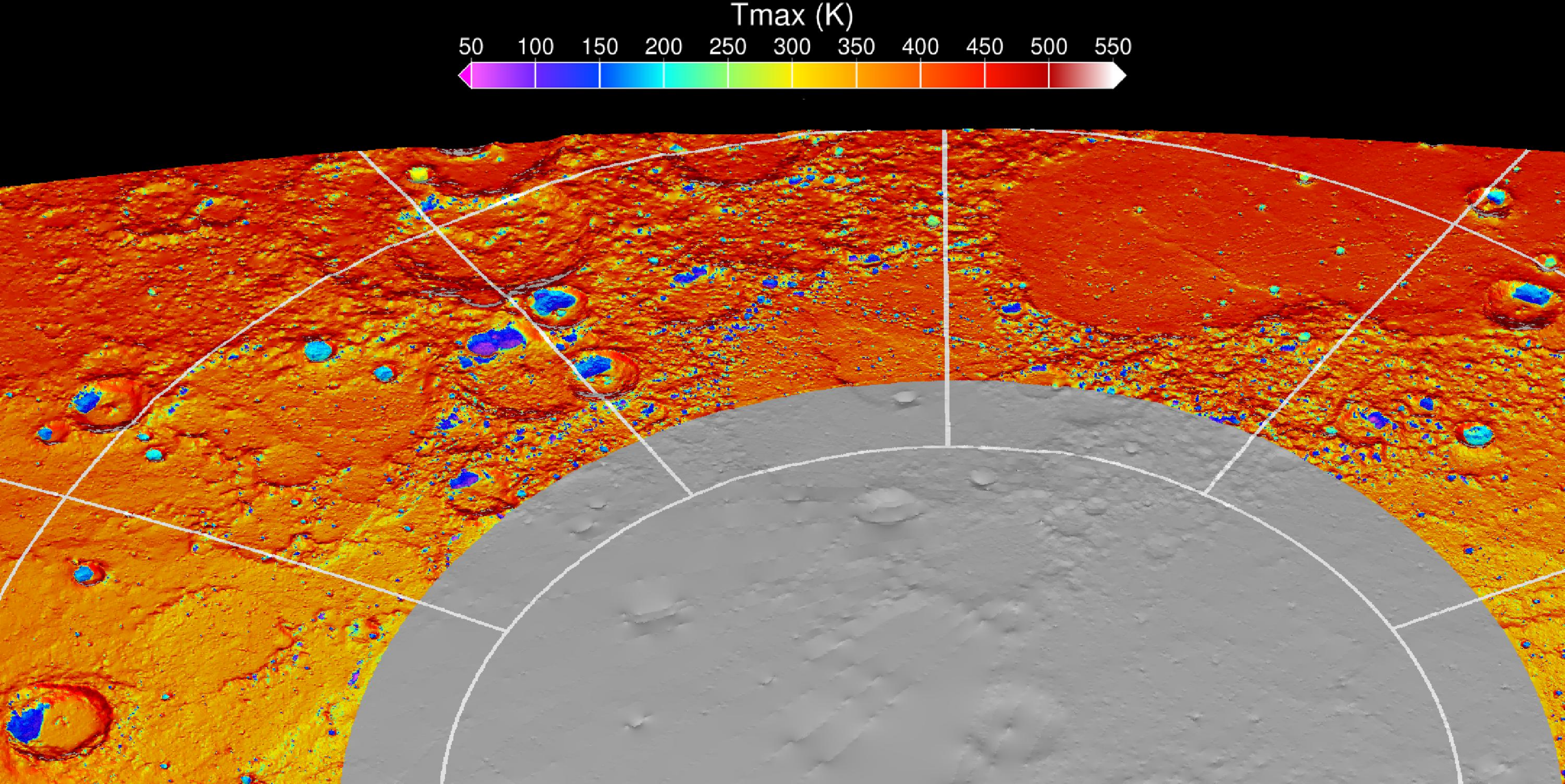


A
Tmax (K)
20 km
B
Tavg (K)
20 km
C
Water Ice Depth (m)
0
0.7
20 km
D
Radar Reflectivity
20 km
E
MLA I/F
20 km
F
Radar brightness
Tavg
Subsurface
Water Ice
G
MLA I/F
Tmax

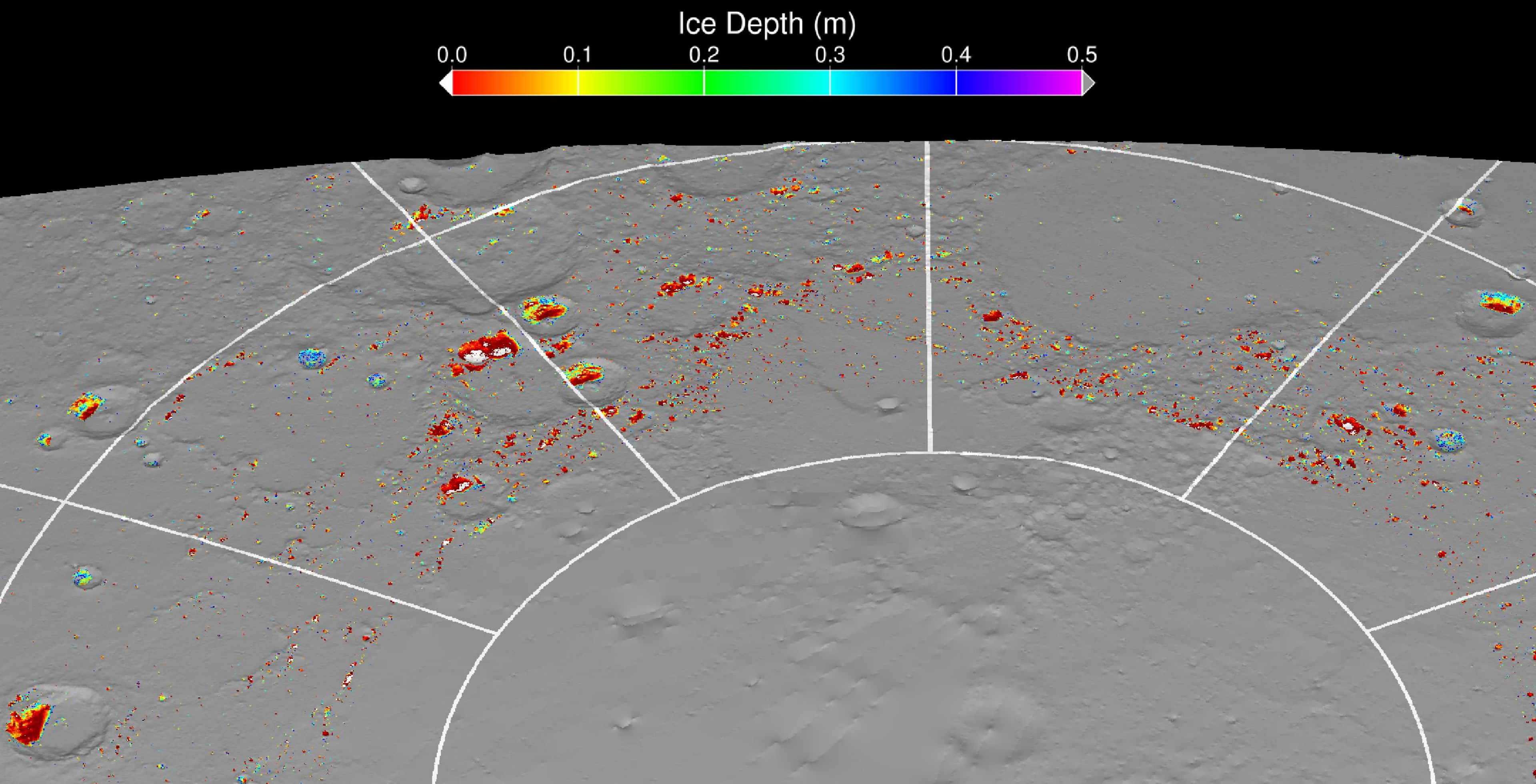
Region A

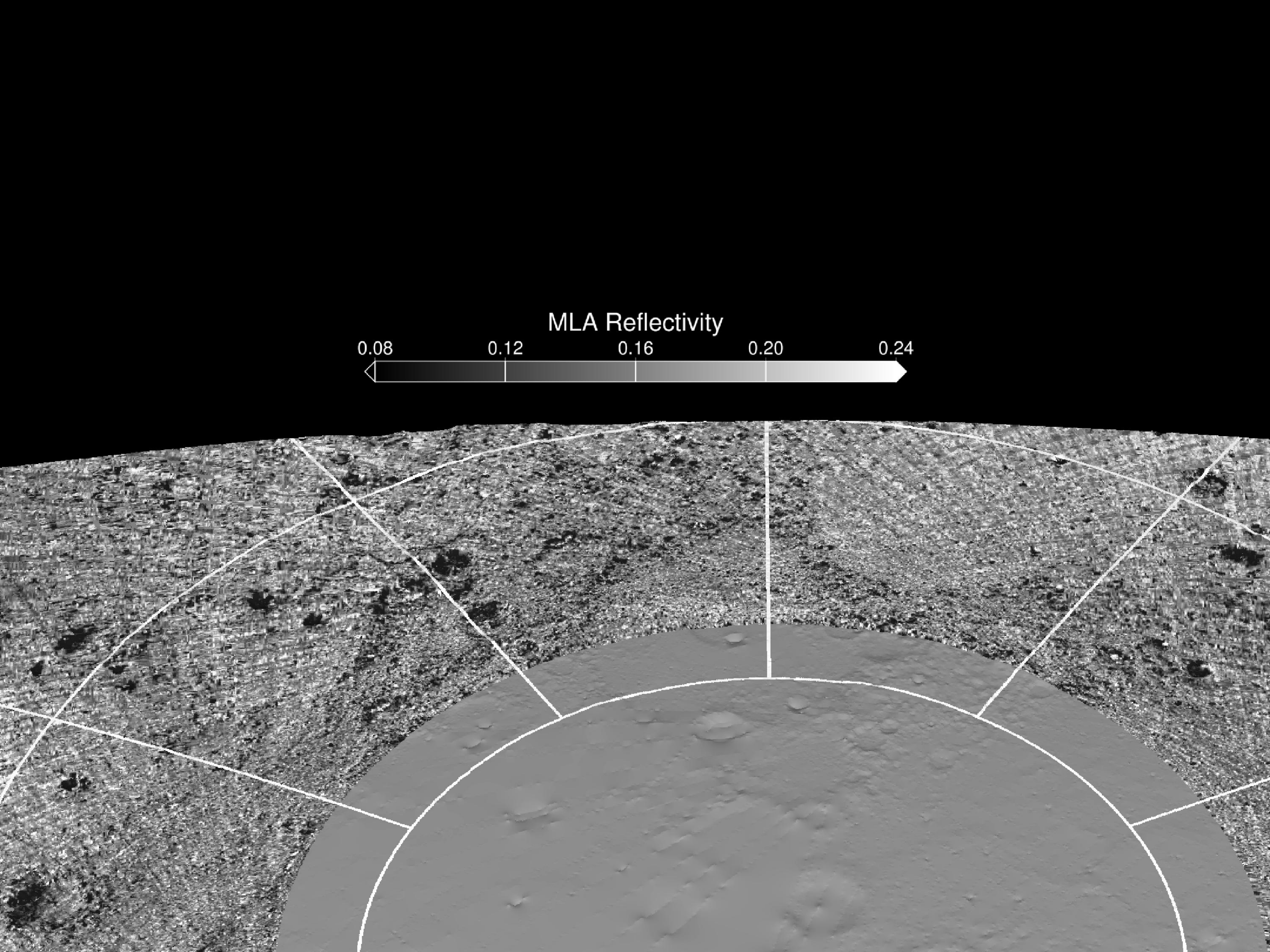

A
20 km
Tmax (K)
B
20 km
Tavg (K)
C
20 km
Water Ice Depth (m)
0
0.7
D
20 km
Radar Reflectivity
D
20 km
MLA I/F
E
Radar brightness
Tavg
F
Exposed Water Ice
MLA I/F
Tmax

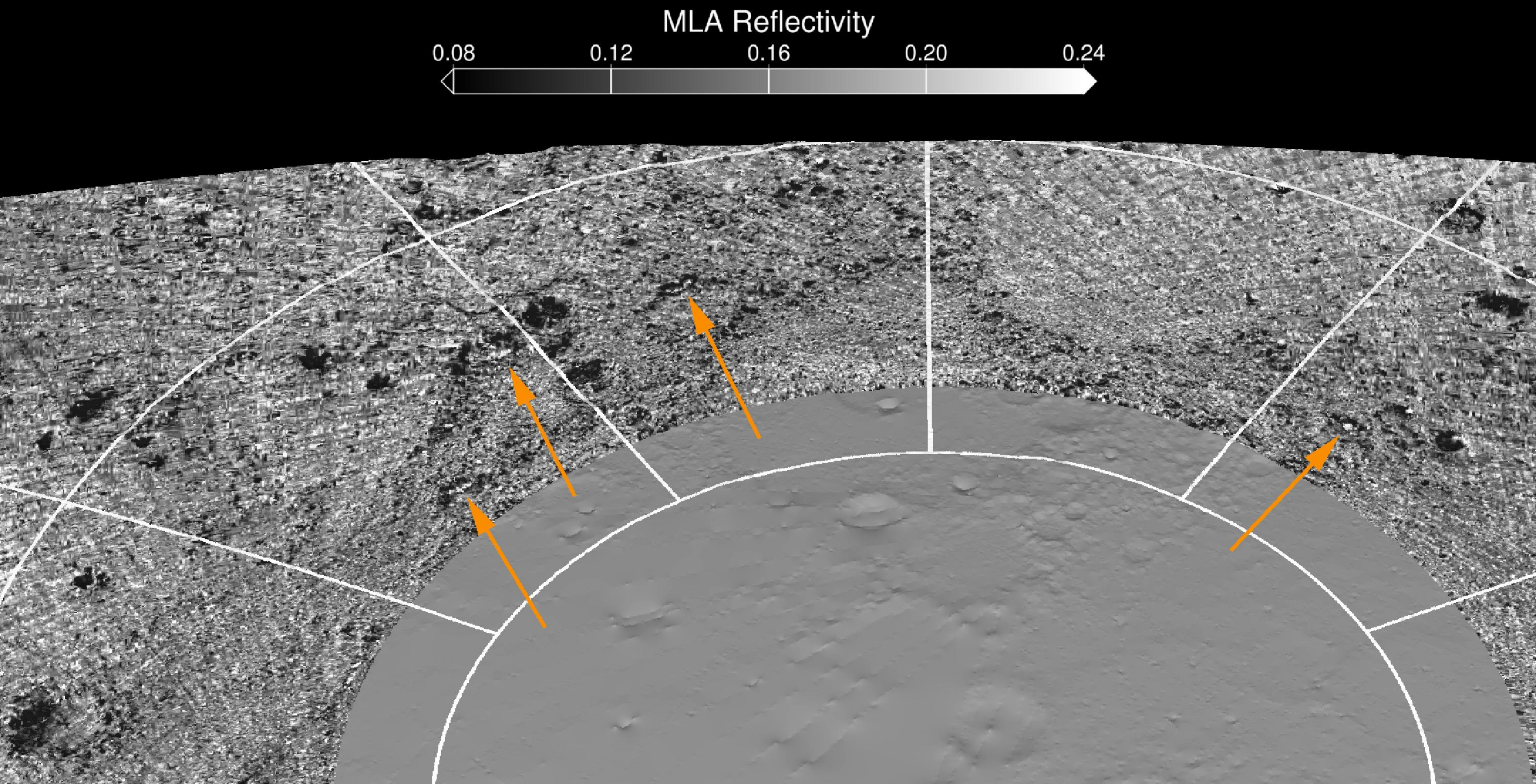
Region B

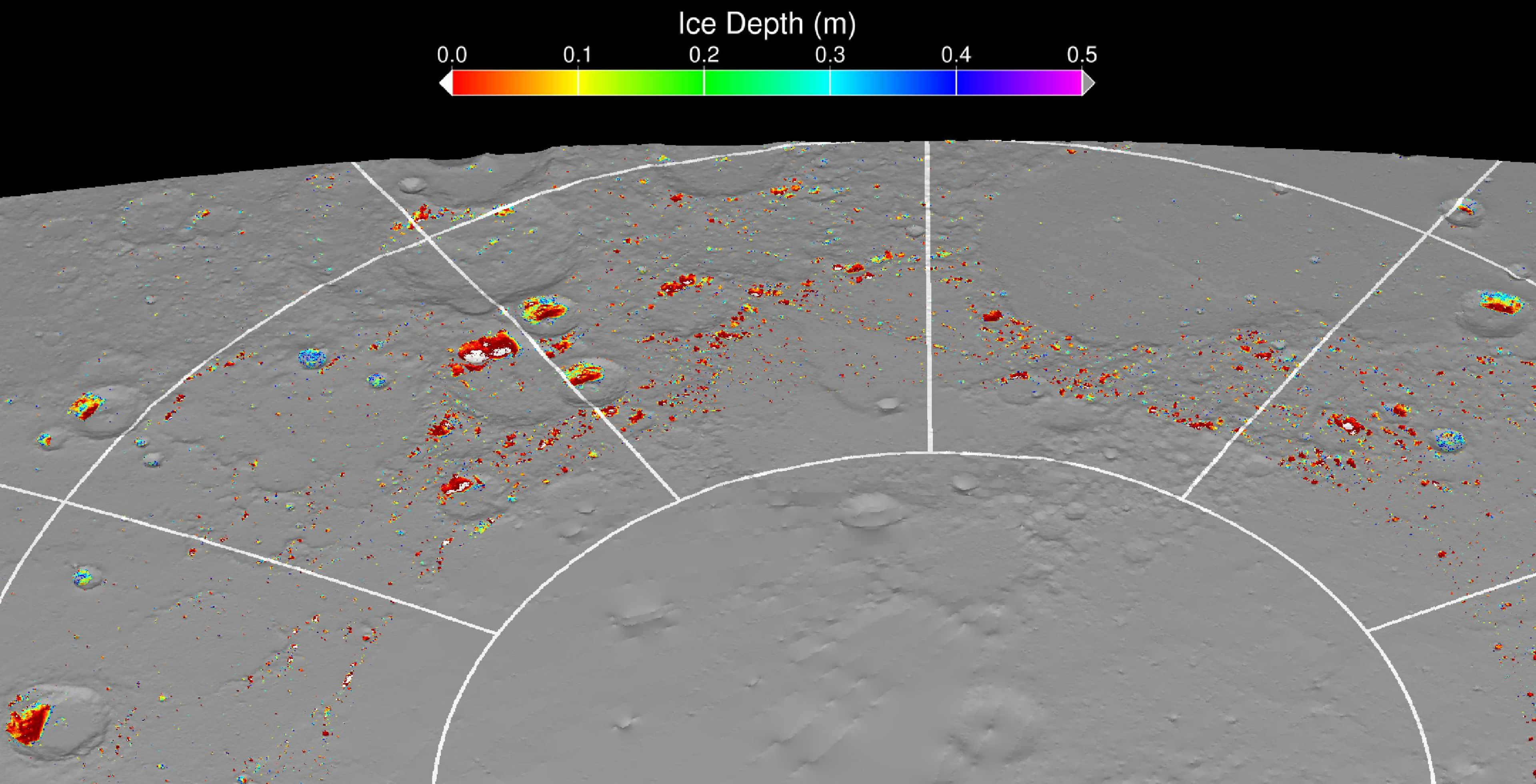


Tmax (K)
50
100
150
200
250
300
350
400
450
500
550


Ice Depth (m)
0.0
0.1
0.2
0.3
0.4
0.5


MLA Reflectivity
0.08
0.12
0.16
0.20
0.24


MLA Reflectivity
0.08
0.12
0.16
0.20
0.24


Ice Depth (m)
0.0
0.1
0.2
0.3
0.4
0.5

MESSENGER
MErcury Surface, Space ENvironment, GEochemistry, and Ranging

Prokofiev

Sunlit mosaic + shadowed terrain!

Chabot et al, 2013

Prokofiev

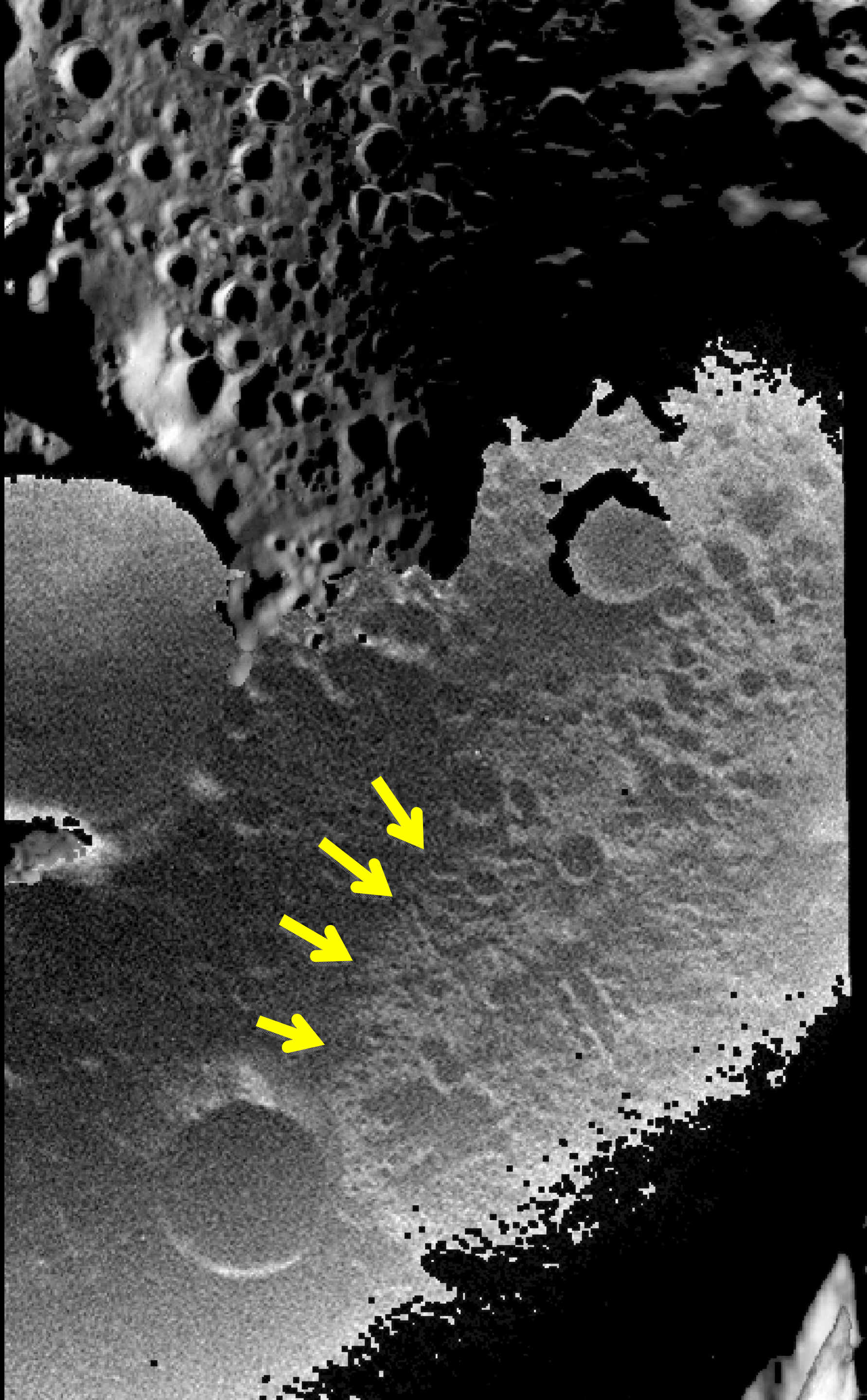
Zoom in

Sunlit mosaic
+ shadowed terrain

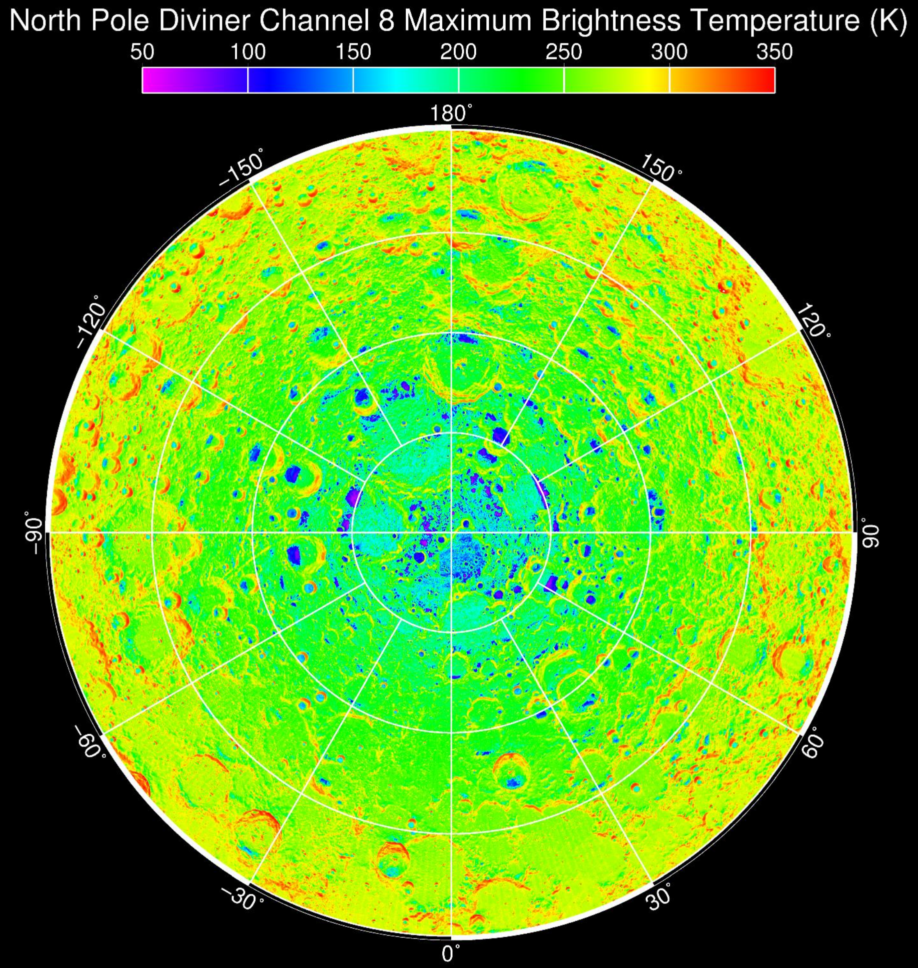
Terrain imaged is covering radar-bright, shadowed region

2nd observation – evidence for an albedo boundary that is consistent with boundary of the radar-bright material

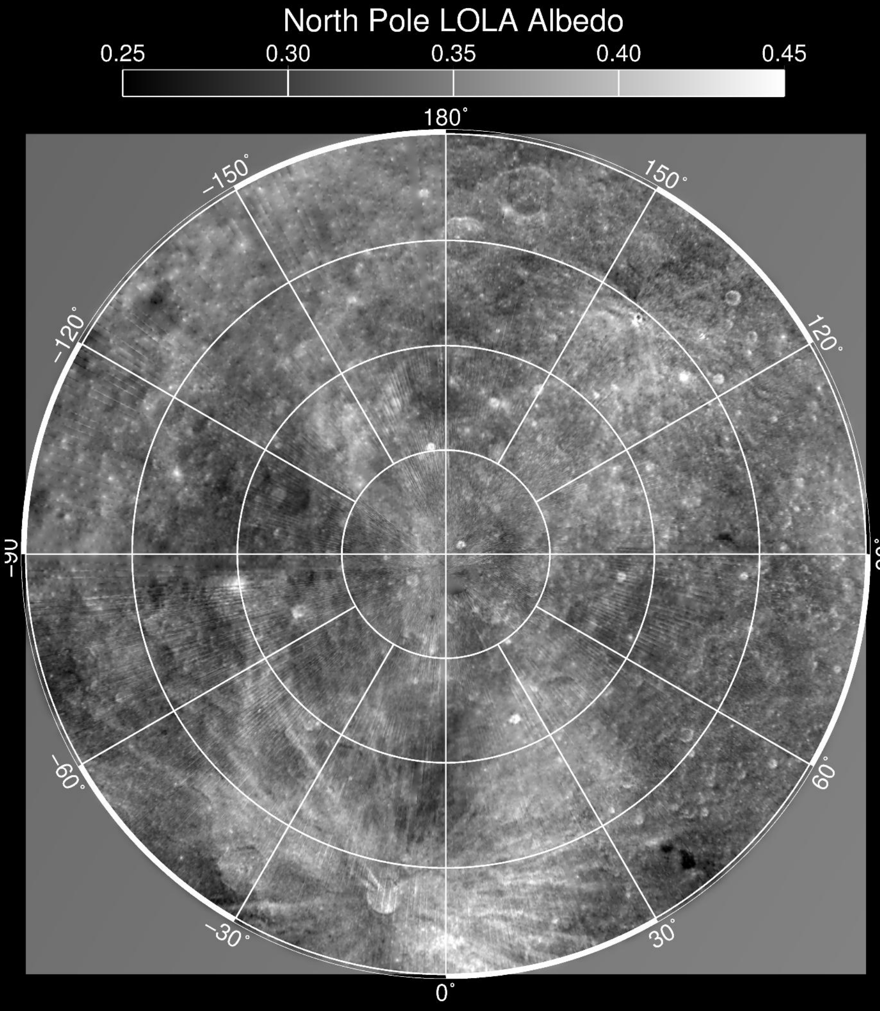
Chabot et al, 2013



North Pole

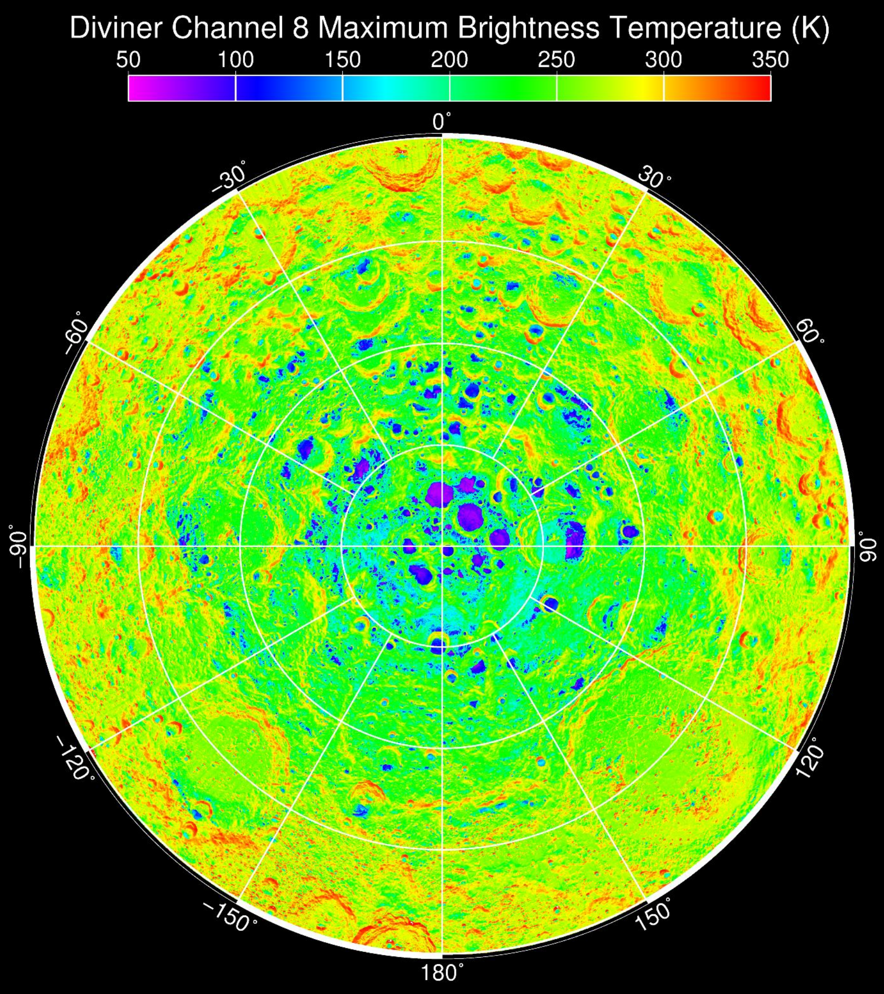


North Pole Diviner Channel 8 Maximum Brightness Temperature (K)
50
100
150
200
250
300
350
180°
−150°
150°
−120°
120°
−90°
90°
−60°
60°
−30°
30°
0°

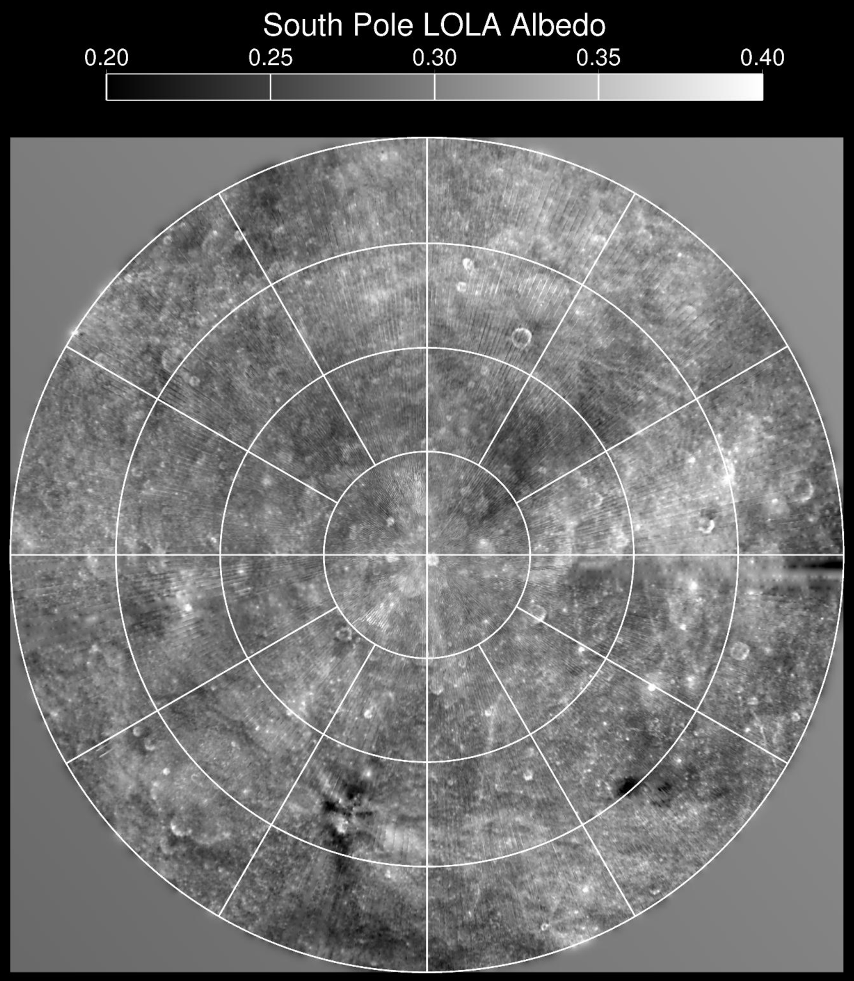


North Pole LOLA Albedo
0.25
0.30
0.35
0.40
0.45
180°
−150°
150°
−120°
120°
−90°
90°
−60°
60°
−30°
30°
0°

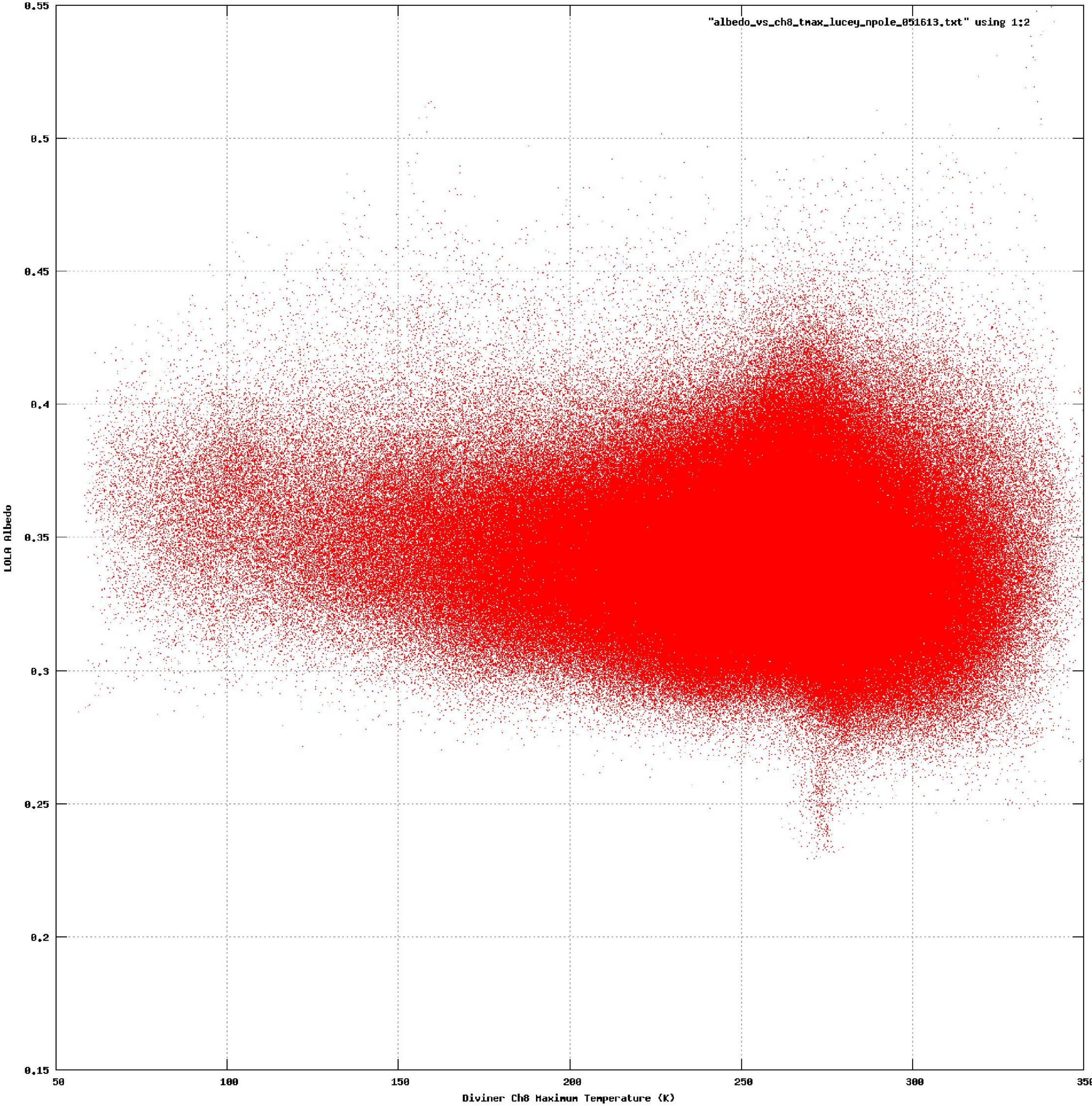
South Pole



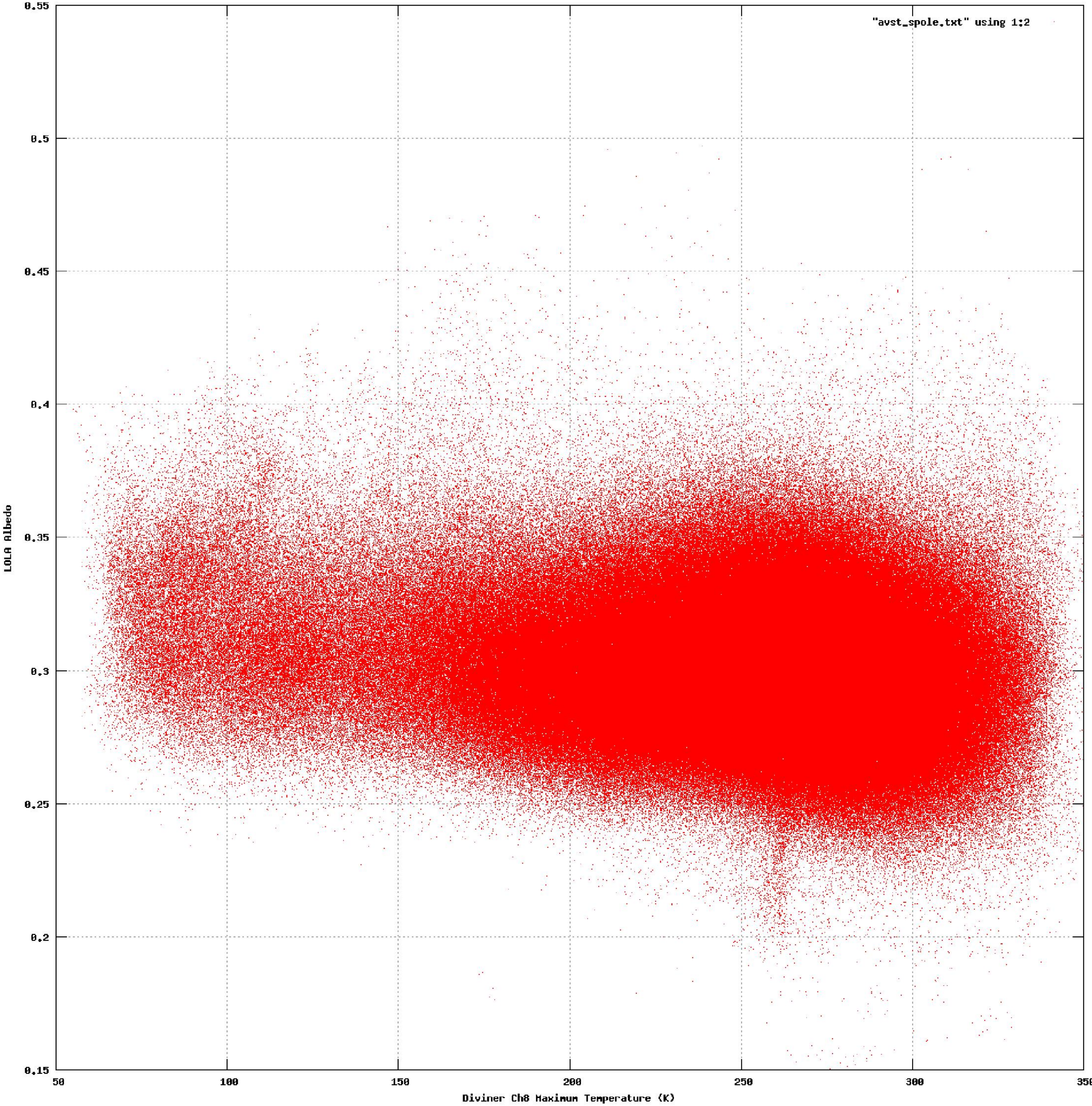
Diviner Channel 8 Maximum Brightness Temperature (K)
50
100
150
200
250
300
350
0°
30°
60°
90°
120°
150°
180°
−150°
−120°
−90°
−60°
−30°



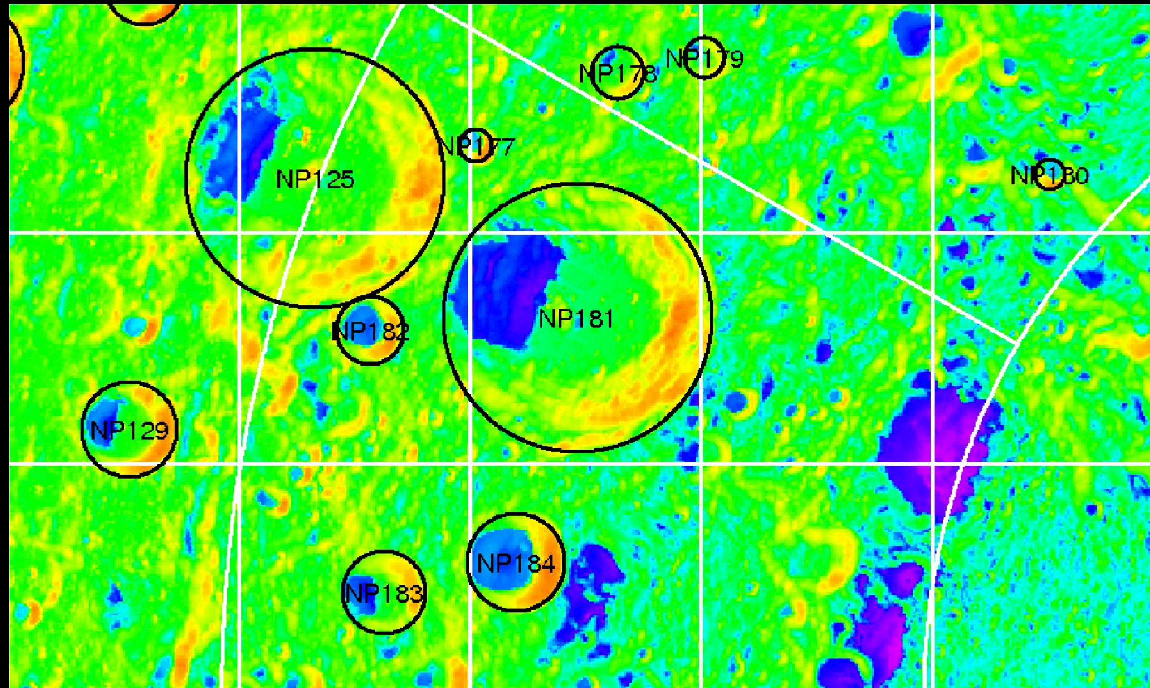
South Pole LOLA Albedo
0.20
0.25
0.30
0.35
0.40

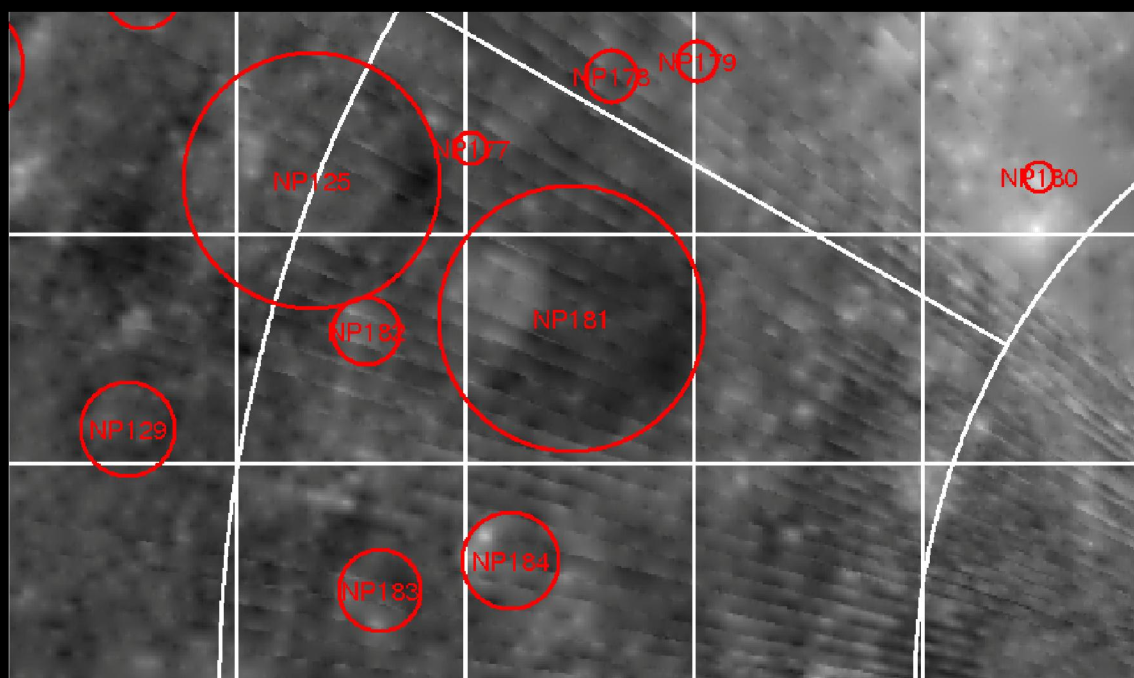


North Polar Region



South Polar Region


NP178
NP179
NP177
NP125
NP180
NP181
NP182
NP129
NP184
NP183


NP178
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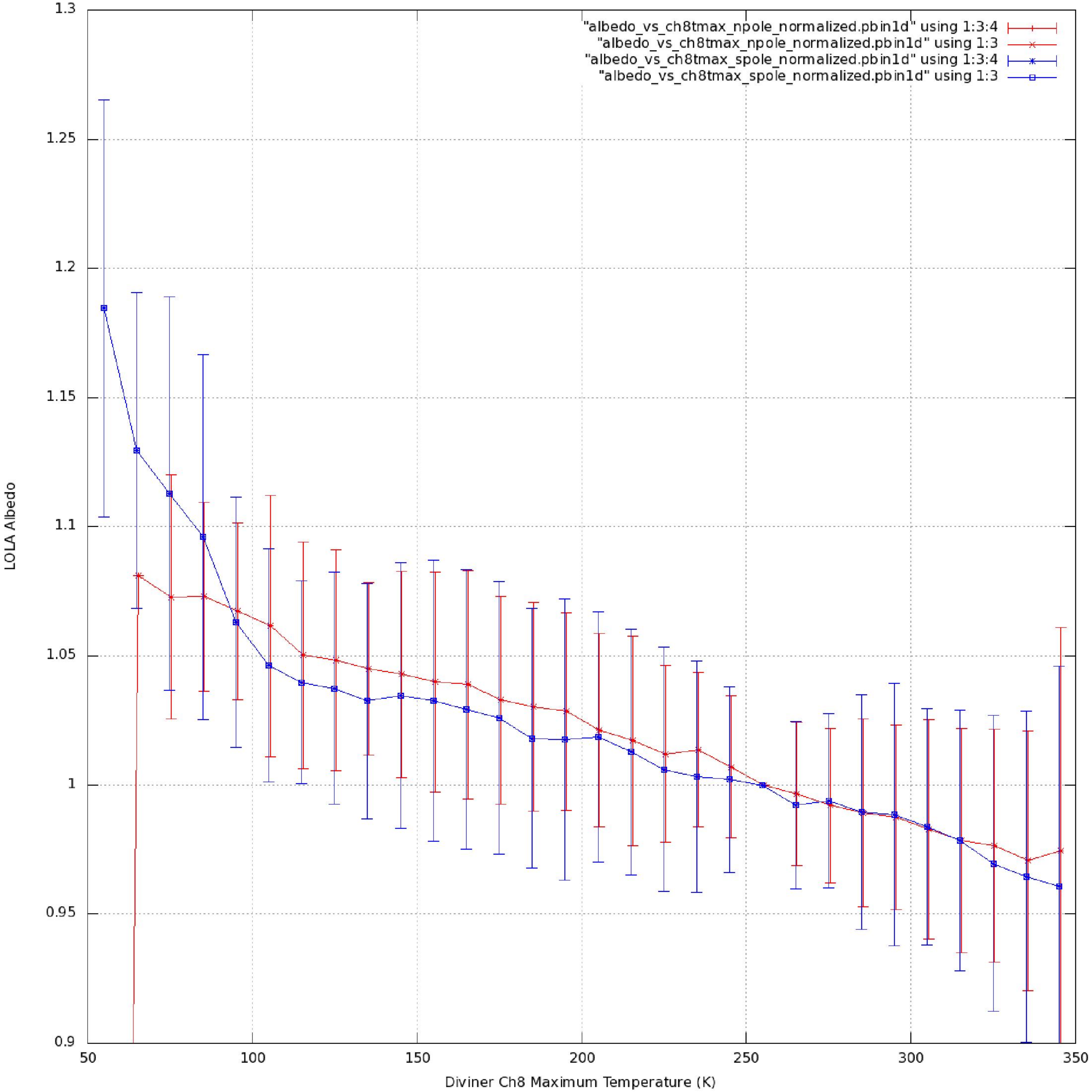
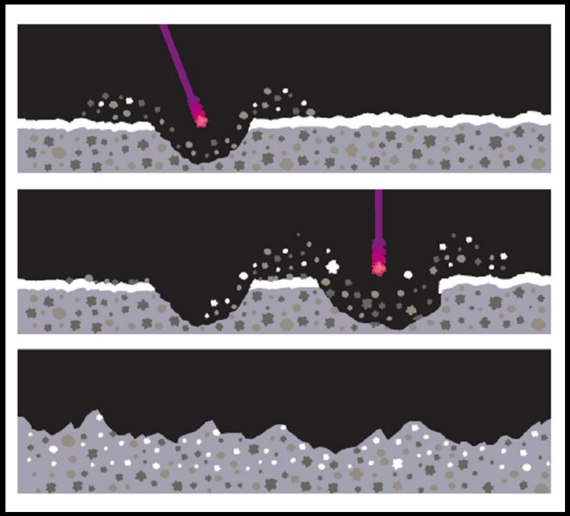


Preliminary Conclusions from Normalized Crater Reflectance Study

1. Strong, systematic increase in crater normal reflectance deviations with decreasing temperature

1. Possible high reflectance deviations within the coldest south polar craters.

Mercury vs. The Moon



- Ice deposits on the Moon and Mercury are destroyed by UV photolysis, sputtering and impact gardening

•The highly organized present-state of Mercury’s polar ice deposits suggests that the sources of water and the mobility of water in Mercury's environment are sufficiently robust to overcome the combined effects of all other processes that would tend to destroy and disrupt them

- The relative scarcity and apparently disorganized state of ice on the Moon suggests that the converse is true