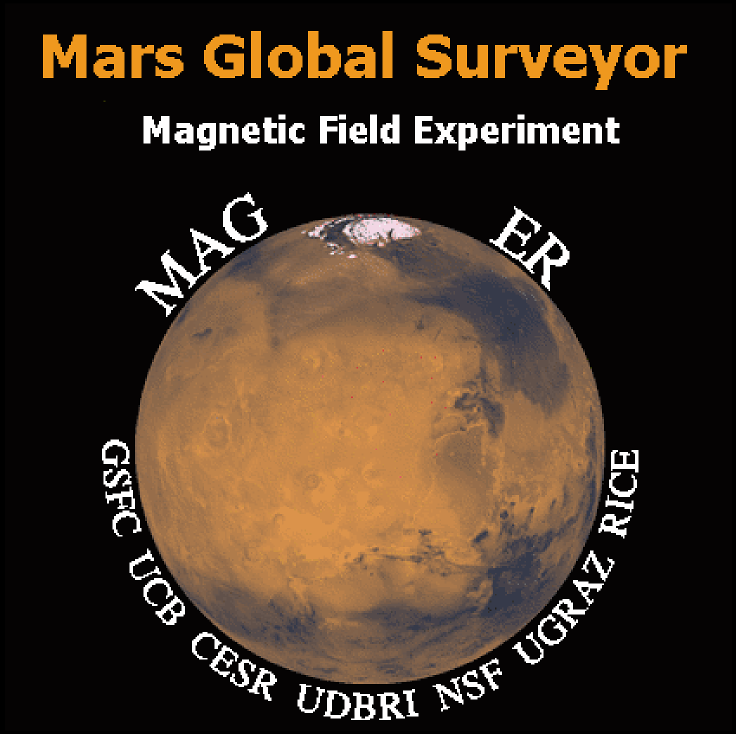
University of California, Berkeley
Space Sciences Laboratory

Giant impacts and the death of the Martian Dynamo

Robert Lillis
Herb Frey
Michael Manga
James Roberts
Weijia Kuang



The ancient Martian dynamo

- Why study it?
  - To constrain models of the formation, evolution and dynamics of the planet as a whole (initial hot core etc.).
  - Dynamo-generated global magnetic field shielded the early atmosphere from solar wind stripping, affecting early climate, e.g. temperature, atmospheric pressure, habitability etc.

Outline

1. Giant impacts on early Mars.
2. Magnetic signatures of giant impact basins.
3. The death of the Martian dynamo: when and how.
4. Comparisons with subcritical dynamo simulations
5. Did giant impact kills the Martian dynamo?

Impact origin for Mars' hemispheric dichotomy

ct,

he

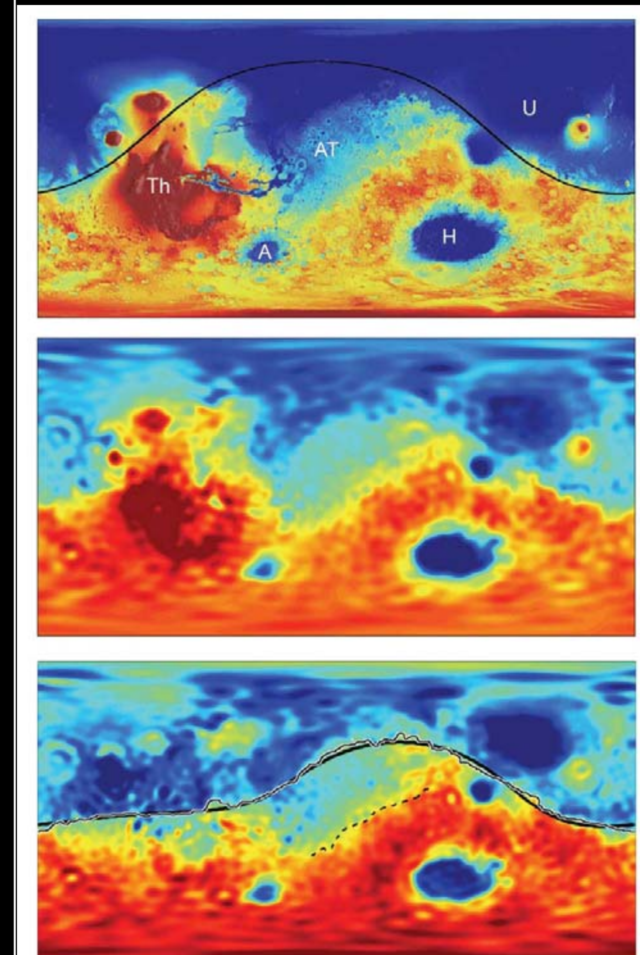
re.

of

8].

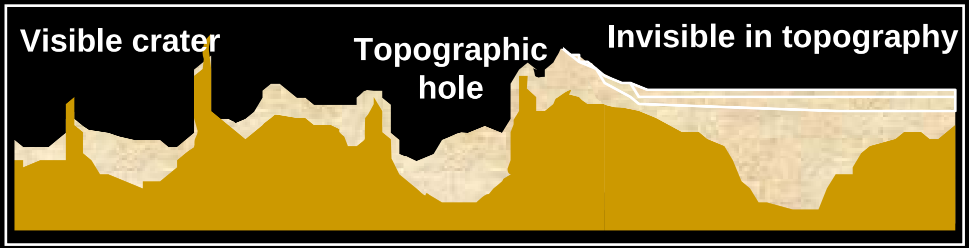
igin

rts

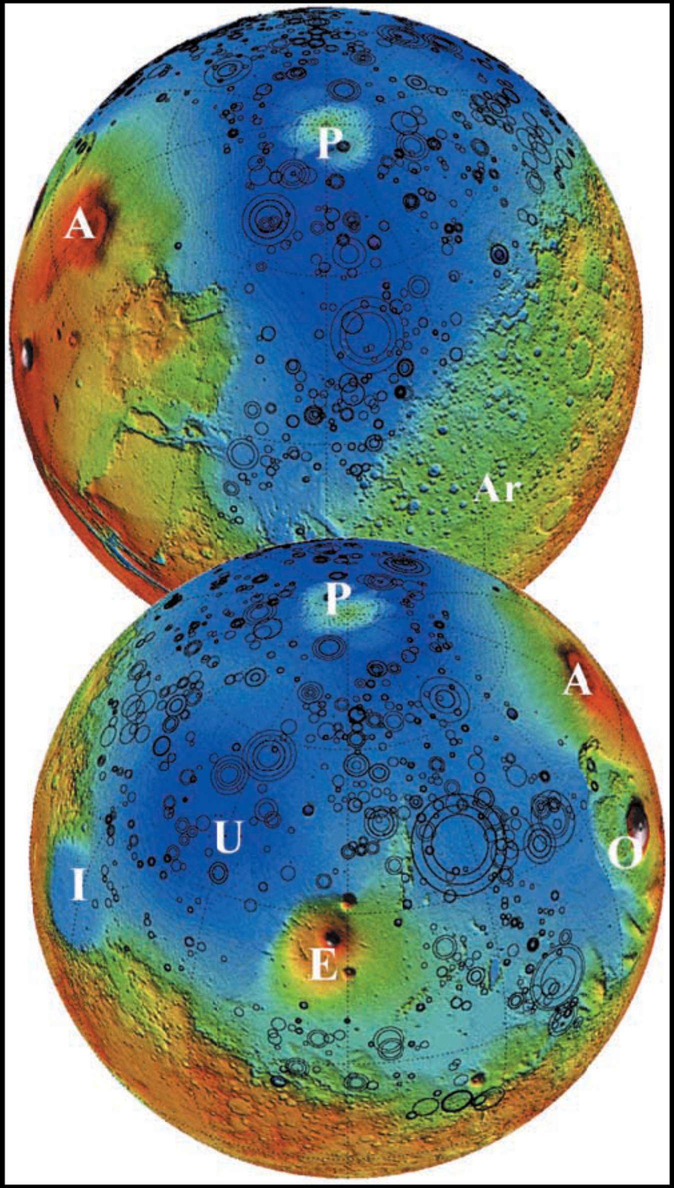


Quasi-Circular Depressions (QCDs) on Mars

- Topography reveals a large population of buried impact basins.
- Indicate that most of Mars is older than we thought [Frey, 2002, 2006].
- But QCDs only yield <u>minimum</u> crater retention ages



<u>Some basins will be so deeply buried that topography alone will not reveal their presence</u>



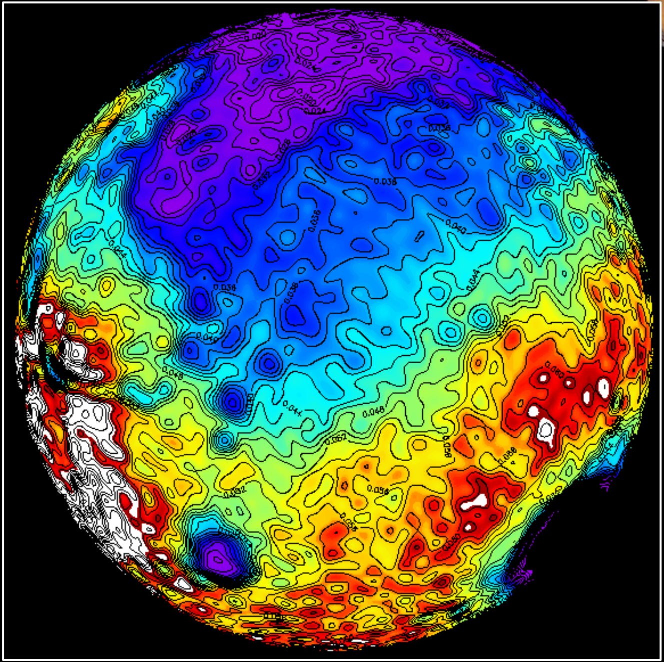
CRUSTAL THICKNESS DATA (Neumann et al.)

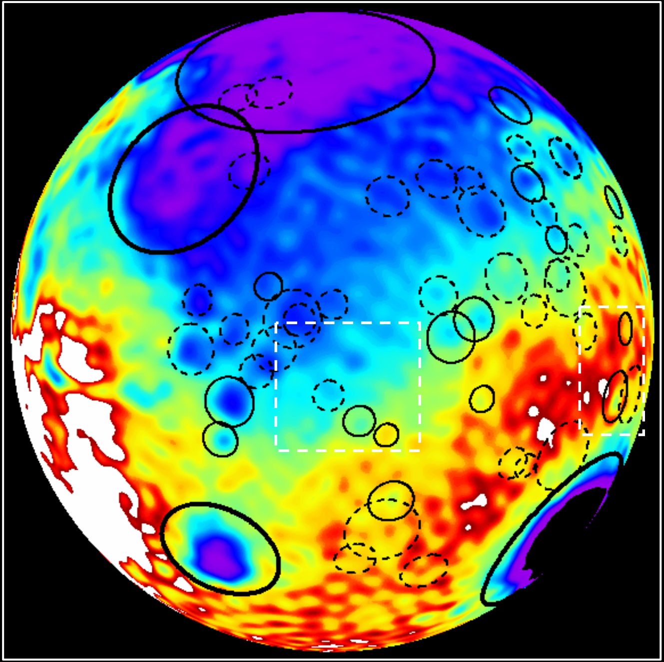
Circular Thin Areas (CTAs) may be additional buried impact basins

Many correspond to visible or buried Quasi-Circular Depressions (QCDs) [but many do not]

Ratio of non-QCD CTAs to QCDs is greatest in areas of greatest burial (lowlands, Tharsis)

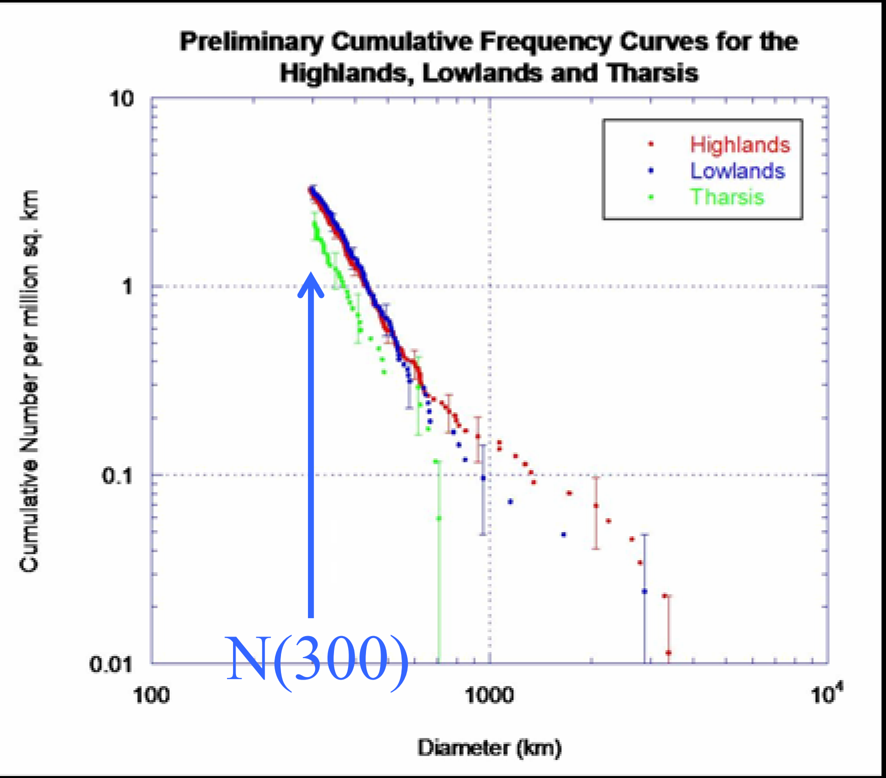
Cumulative frequency curves for the combined QCDs + CTAs are very similar in character to QCDs alone.
→ CTAs are likely impact basins.





Cumulative Frequency Curves of Combined QCDs and CTAs

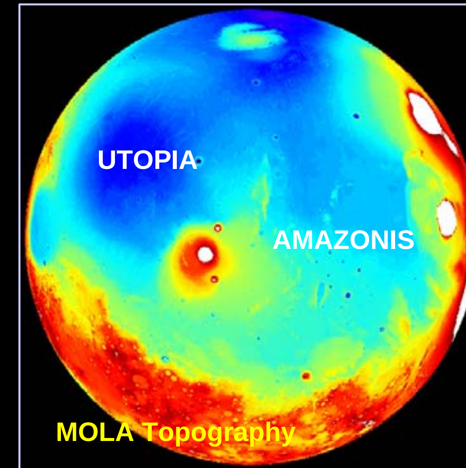
Highlands and Lowlands have *identical curves* (within their errors), are completely indistinguishable over the diameter range 300-800 km, and ***have the same N(300) age ~ 3.3.***



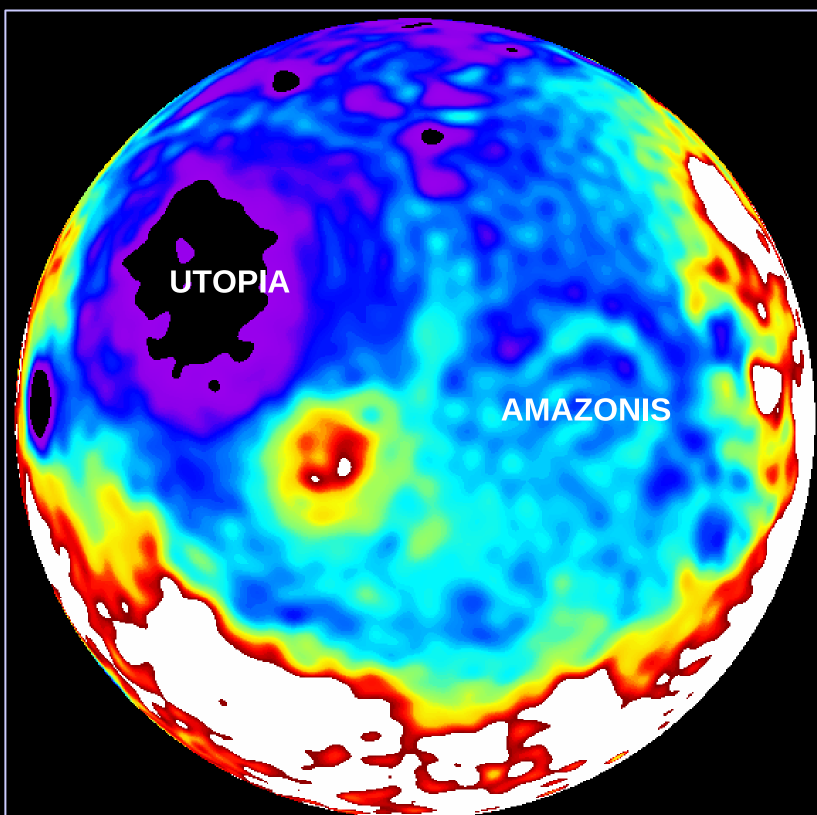
Two hemispheres formed at almost the same time, very early in Martian history.

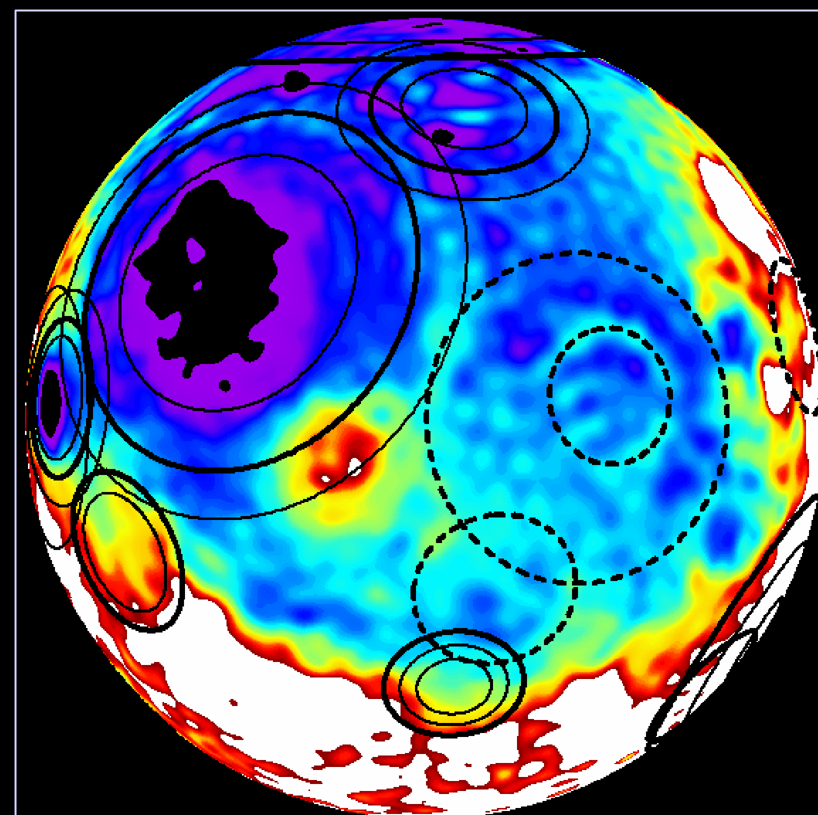
Edgar and Frey, 2007

Crustal thickness data suggests several new large impact basins



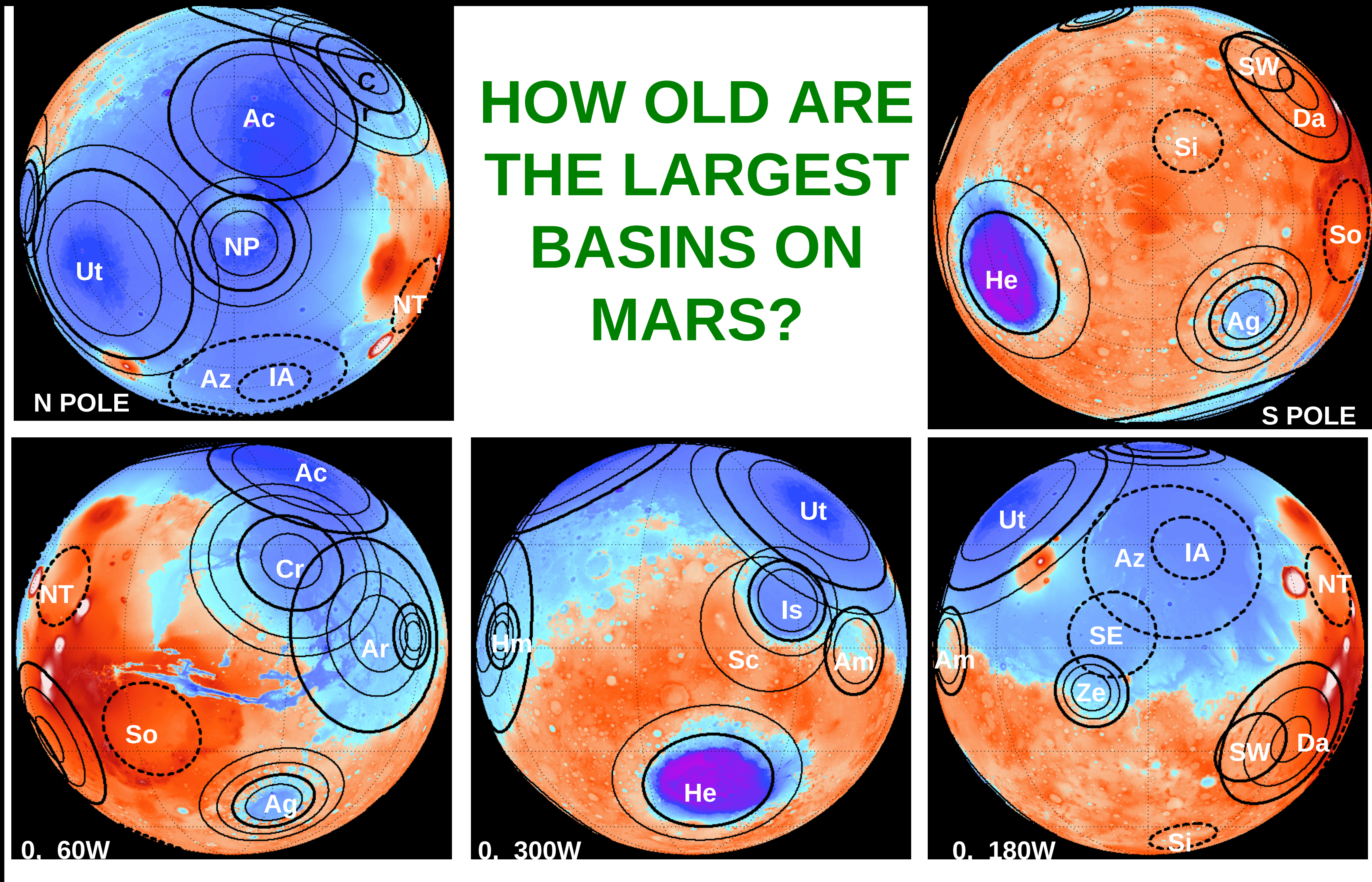
The largest is a 2870 km wide basin in Amazonis





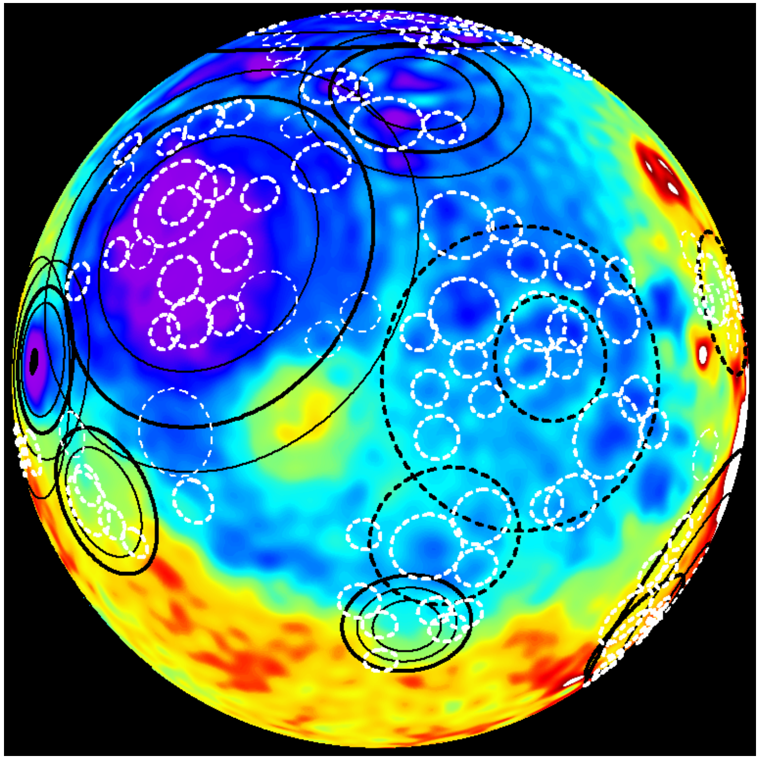
New basins identified from crustal thickness data:

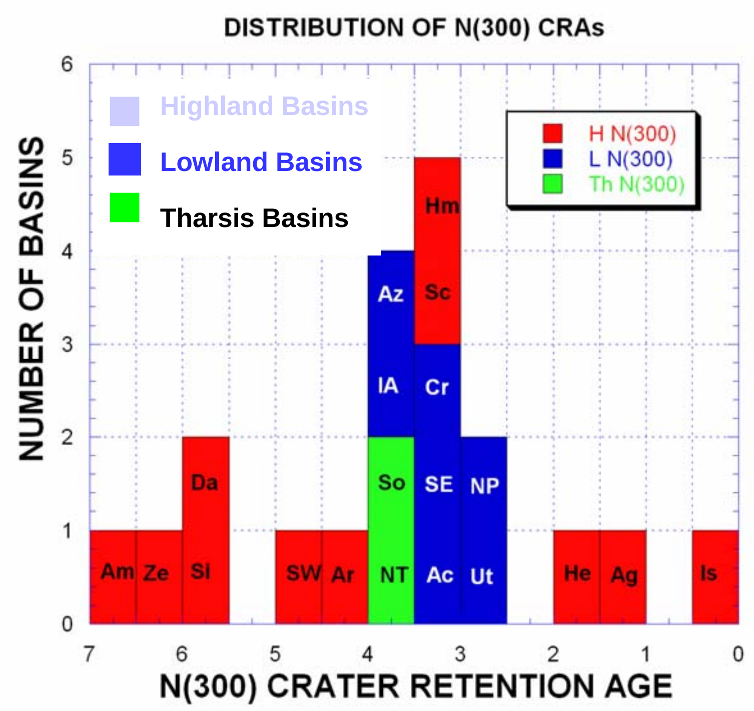
Amazonis (Az), inside Amazonis (IA), North Tharsis (NT), Solis (So), Sirenum (Si) and SE Elysium (SE)



N(300) AGES FOR LARGE BASINS

From counting smaller basins on rim and interior
(both QCDs and non-QCD CTAs > 300 km)





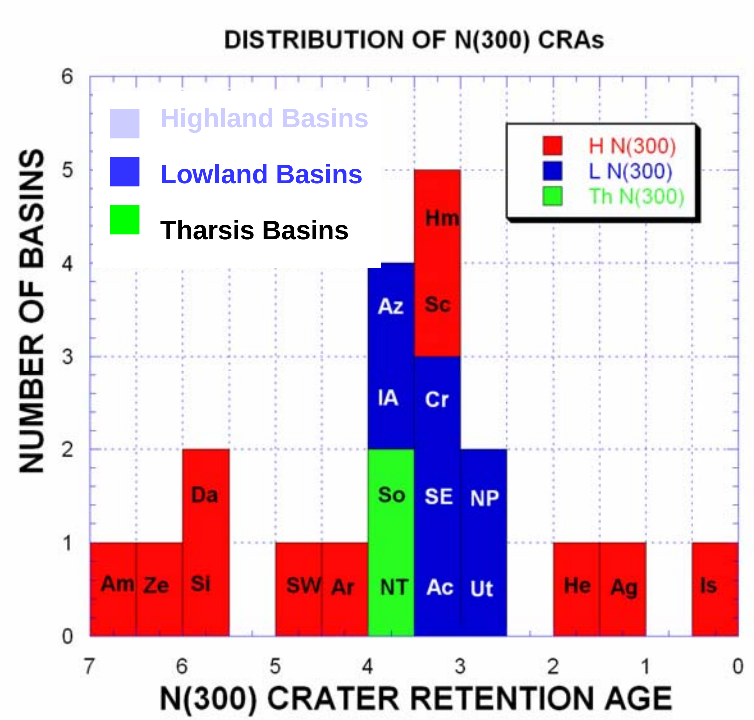
N(300) AGES FOR LARGE BASINS

Distribution of N(300) ages shows a peak

All the lowland and Tharsis basins have N(300) CRA in the range (2.5-4.0)

11 out of 20 basins – and 3 of the 4 largest - have an N(300) age in this range

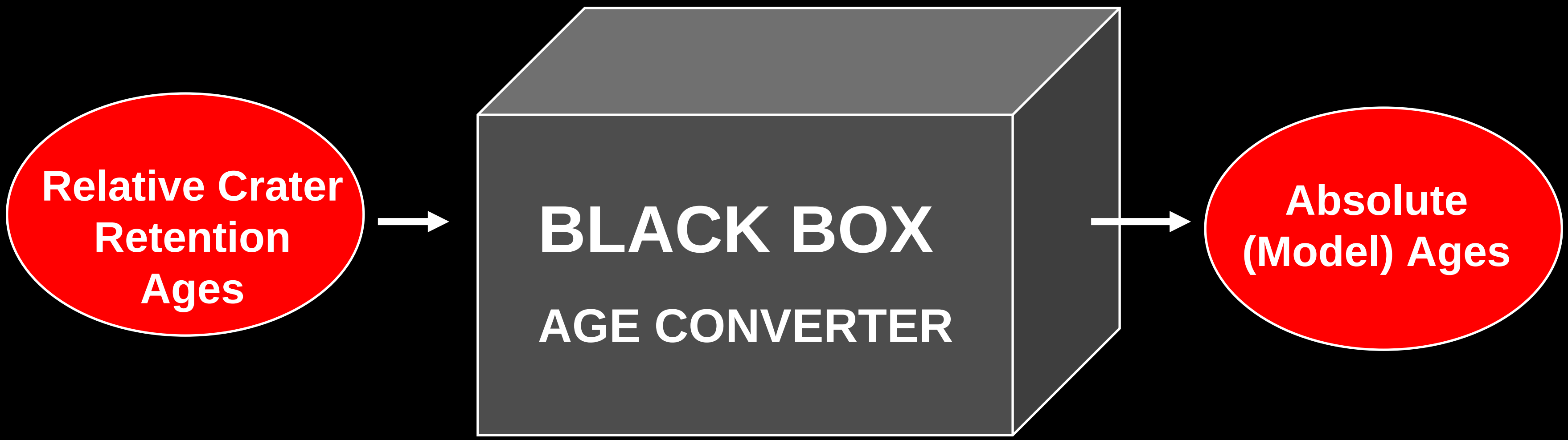
Could this represent a spike in large basin formation?



WHAT ABOUT ABSOLUTE AGES?

WHAT ABOUT ABSOLUTE AGES?

Need a “relative-to-absolute” age converter



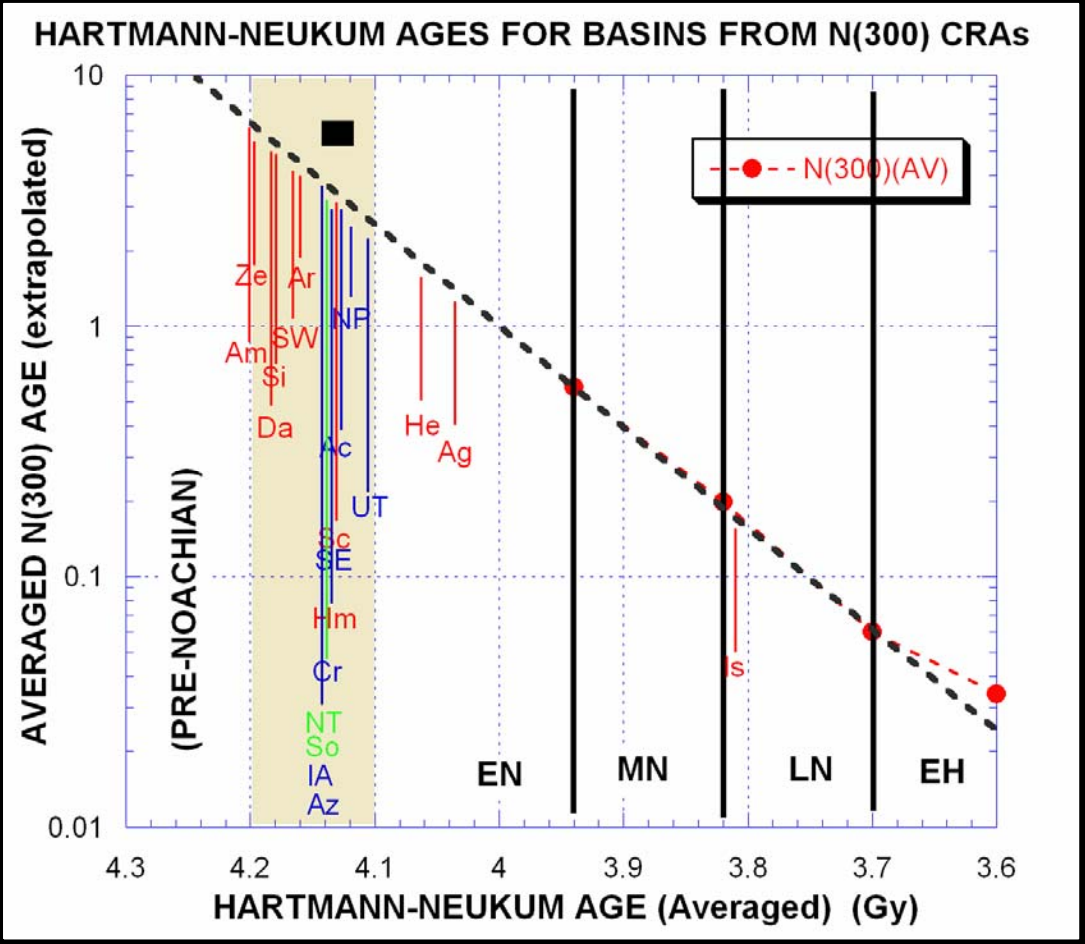
A “relative-to-absolute” age converter

BLACK BOX

AGE CONVERTER

Using the Hartmann-Neukum Model Chronology

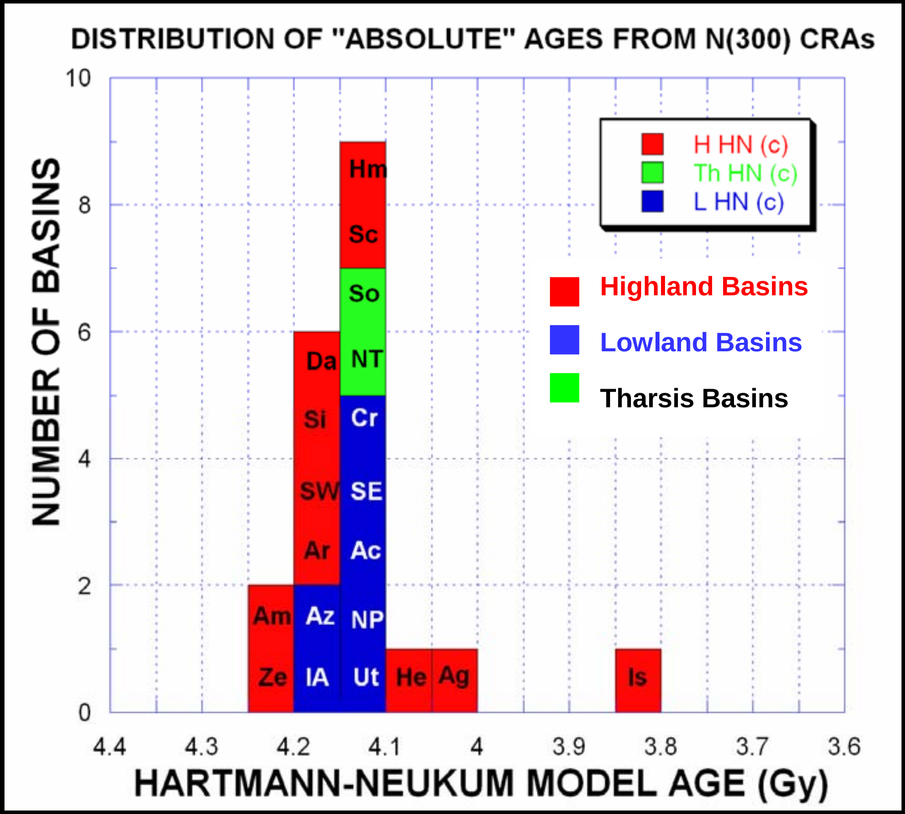
Tanaka’s [1986] counts for major stratigraphic boundaries were first averaged, then extrapolated to N(300) with a -2 power law, and plotted against averaged Hartman-Neukum “absolute ages” for the same boundaries. The nearly linear relation was fitted and extrapolated to “pre-Noachian” time.



SUMMARY: "ABSOLUTE" AGES OF LARGE BASINS ON MARS

Most large basins have model absolute ages in a relatively brief interval (100MY)

15/20 (75%) may have formed 4.10 to 4.20 BYA



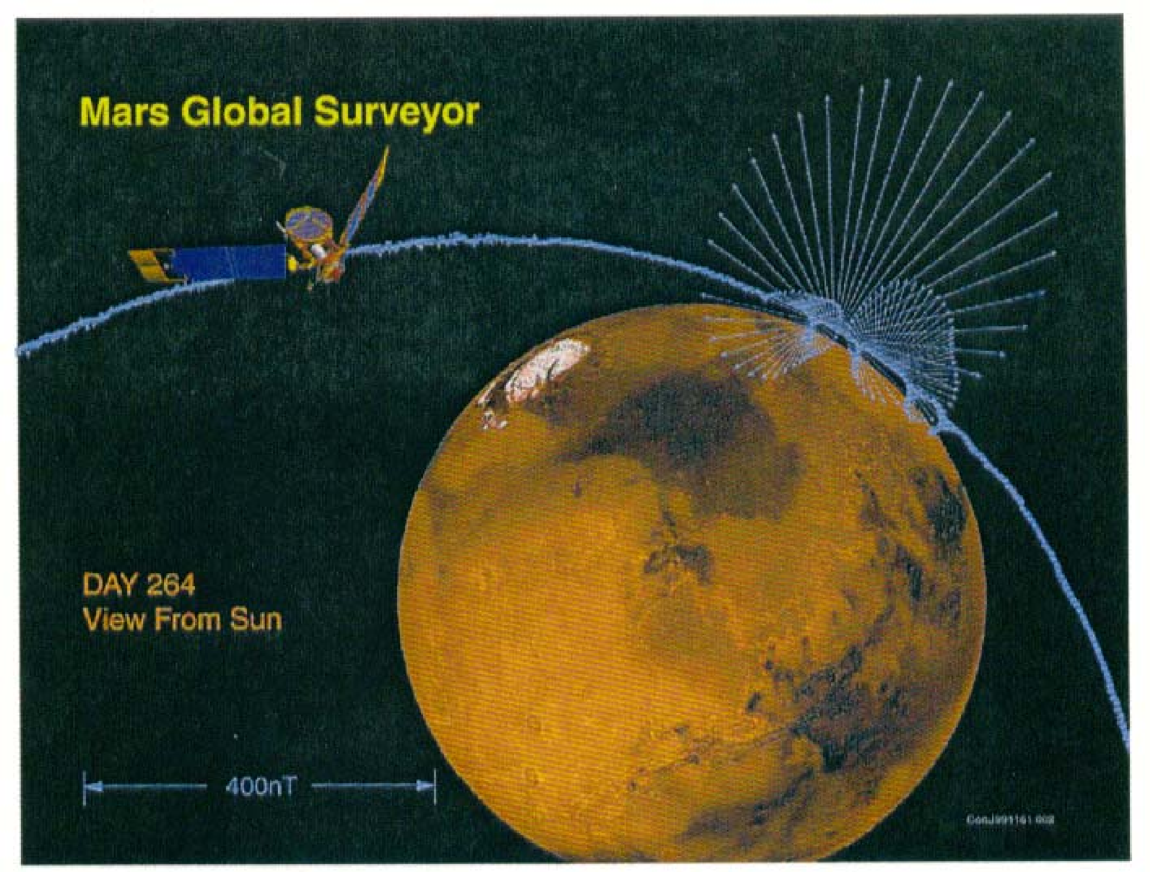
Only Hellas, Argyre and Isidis are younger than 4.10 BY
Only 2 basins are older than 4.2 BY

Magnetism of Martian impact basins

Magnetic Properties of Mars

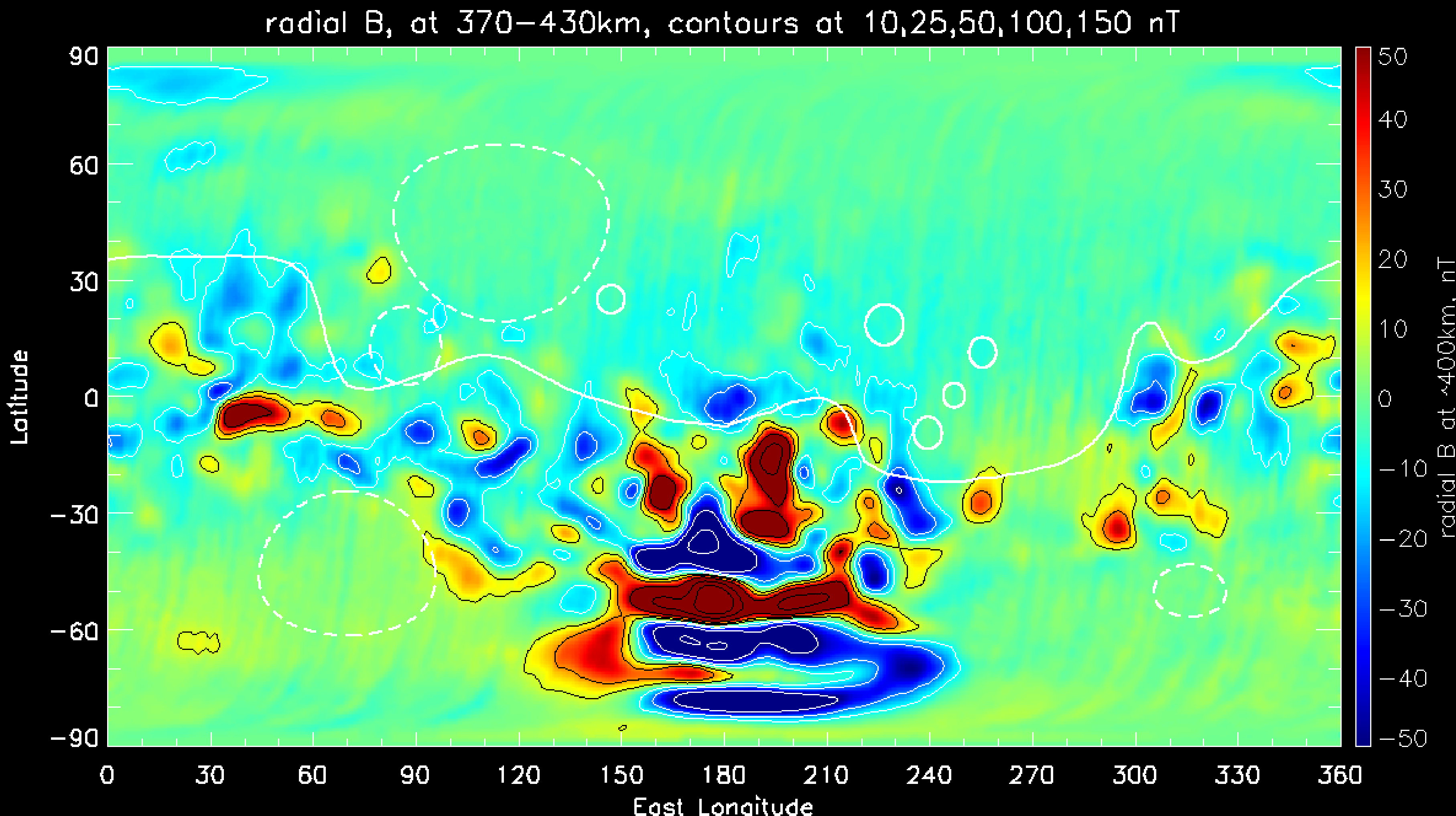
- Lack of internal dynamo-driven magnetic field.

- Localized intense crustal remanent magnetism, ~10 times stronger than Earth at orbital altitudes.



Magnetic field vectors plotted emanating from Spacecraft position, from *Connerney et al.*

Magnetic Properties of Mars

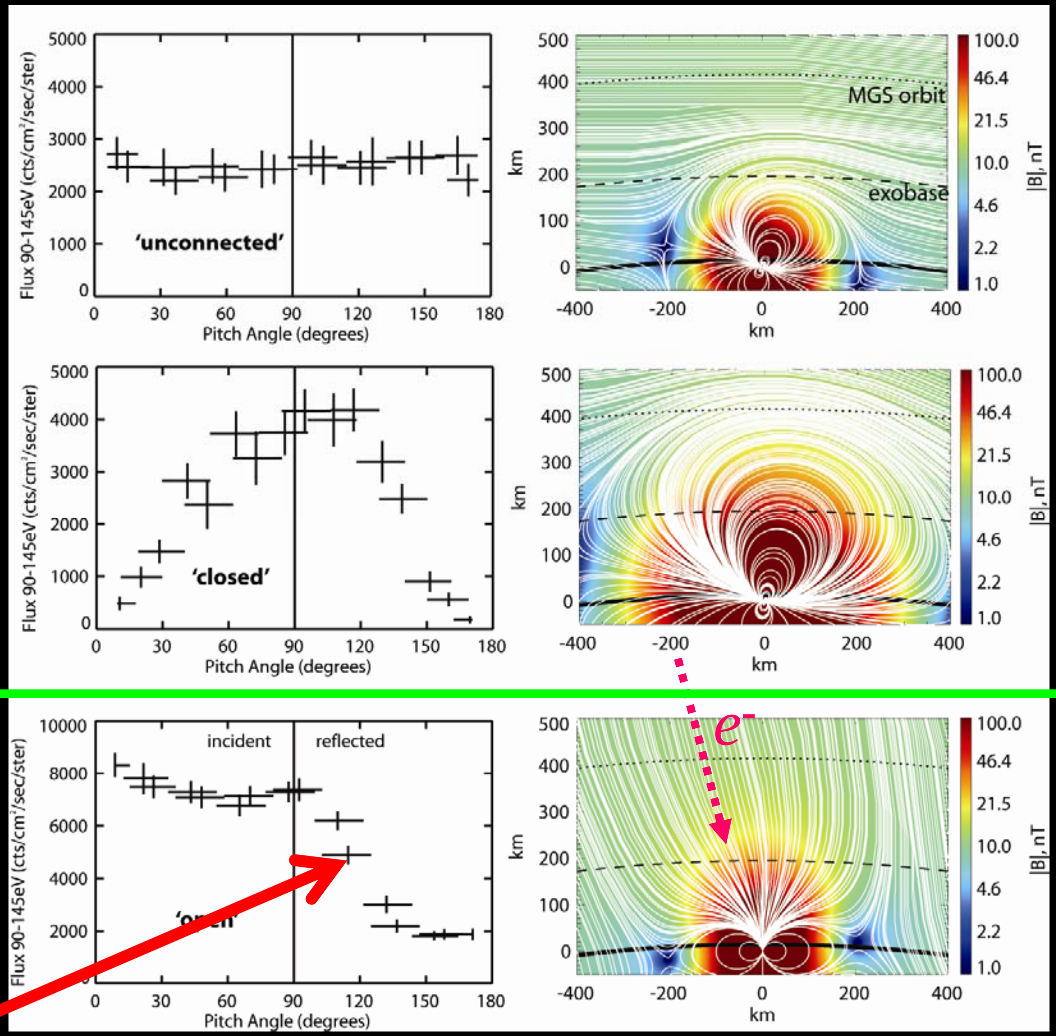


Magnetic topologies encountered near Mars

- 'unconnected' field lines have no access to the atmosphere → no information

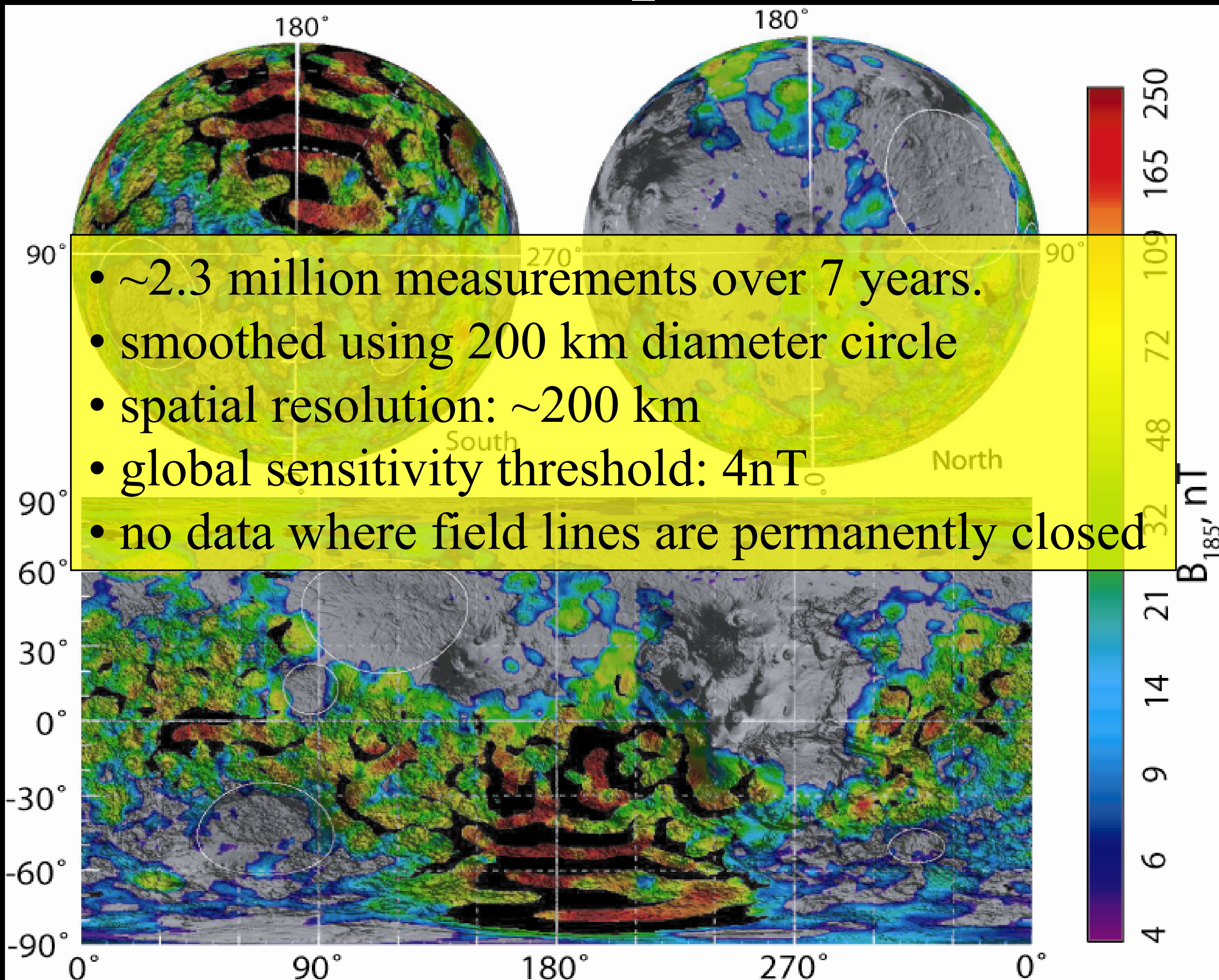
- electrons reflect multiple times on 'closed' field lines where crustal fields are strong. Absorption far from 90°.

- incident solar wind electrons can reflect or strike the atmosphere when crustal field lines are 'open'.



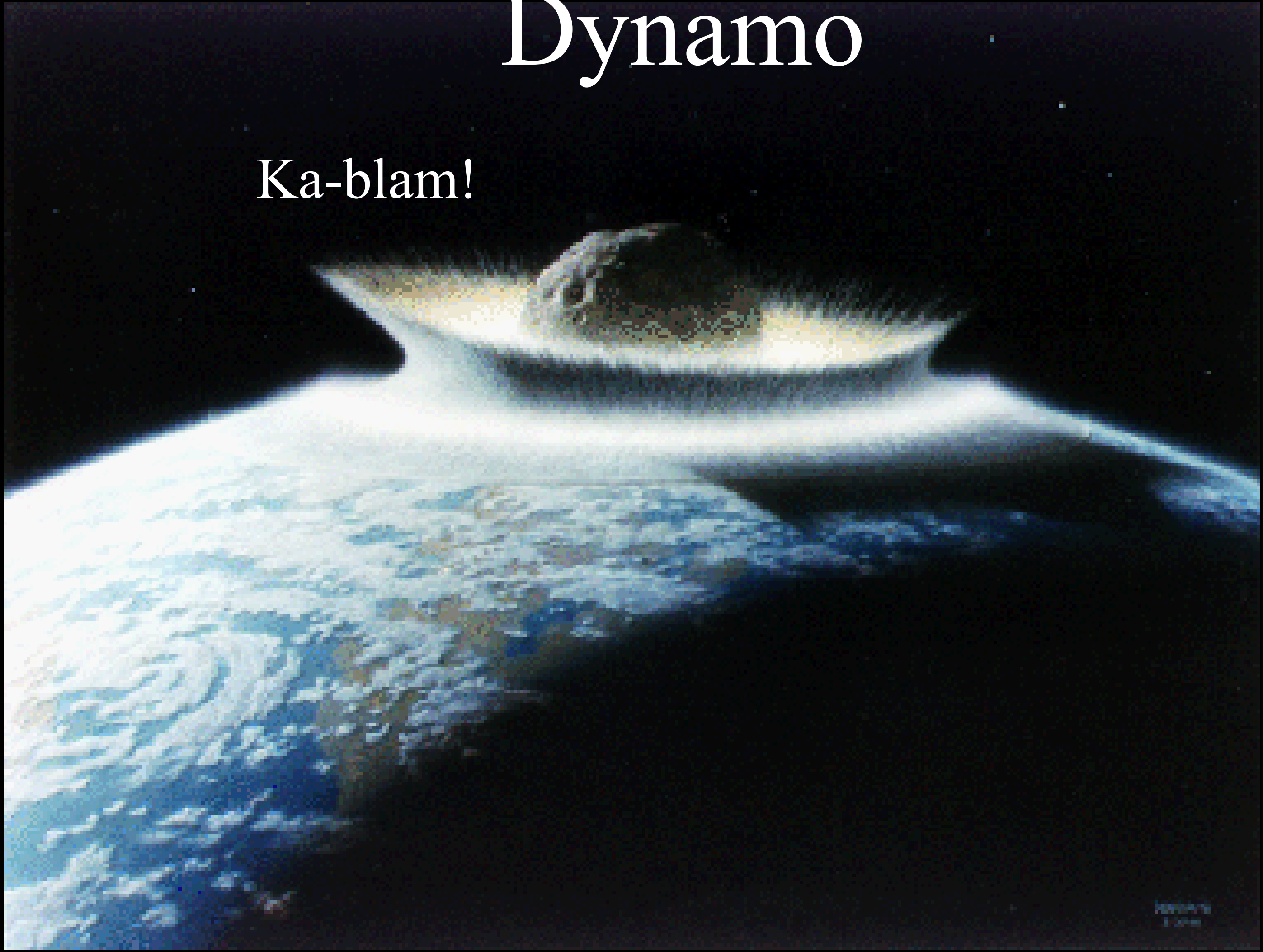
Shape of attenuation tells us about crustal field and atmosphere!

Global ER map at 185km



- ~2.3 million measurements over 7 years.
- smoothed using 200 km diameter circle
- spatial resolution: ~200 km
- global sensitivity threshold: 4nT
- no data where field lines are permanently closed

Impact Cratering & the ancient Dynamo



Ka-blam!

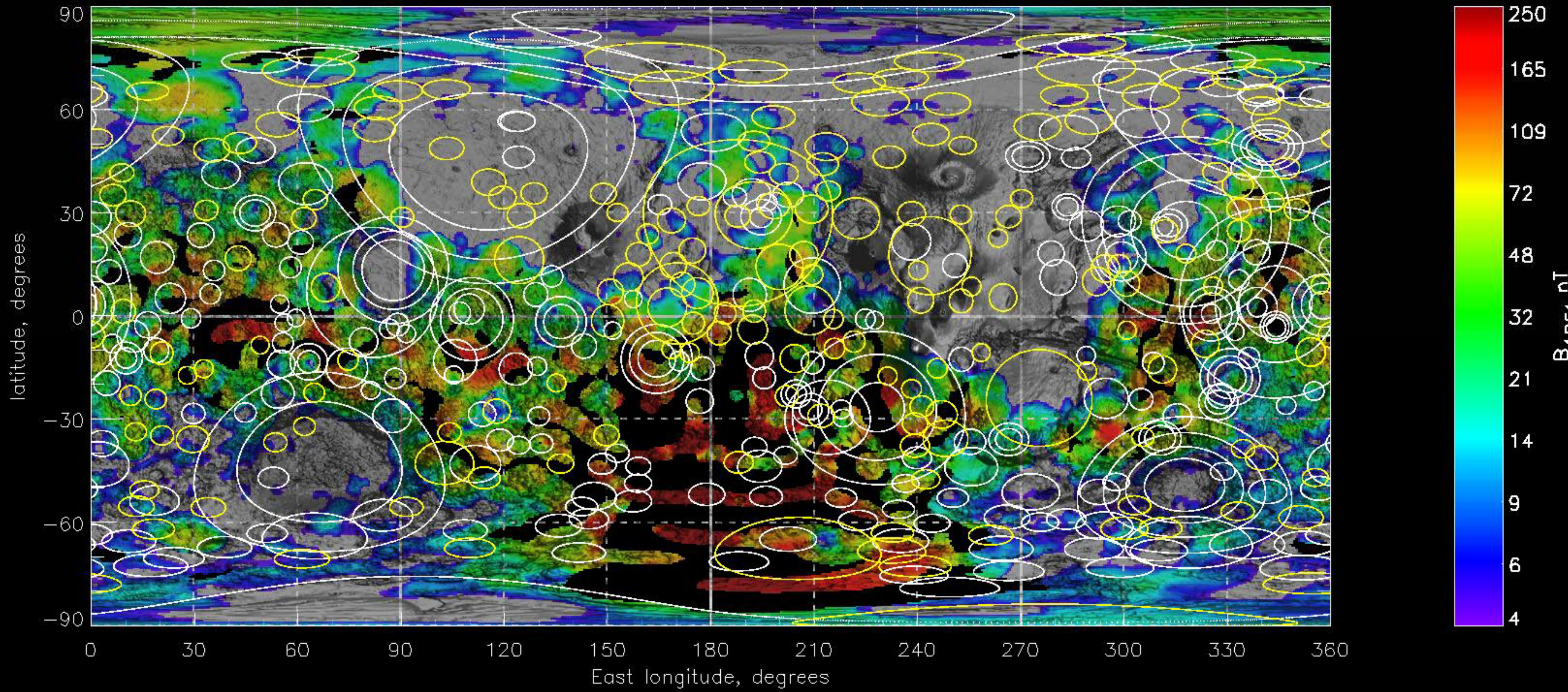
Impact basins as 'Magnetic Markers'

- Heating, shock demagnetizes area ~ size of basin.
- Crust can reacquire magnetization through SRM or TRM if a strong ambient magnetic field is present.

TRM acquired is $\propto$ ambient magnetic field.

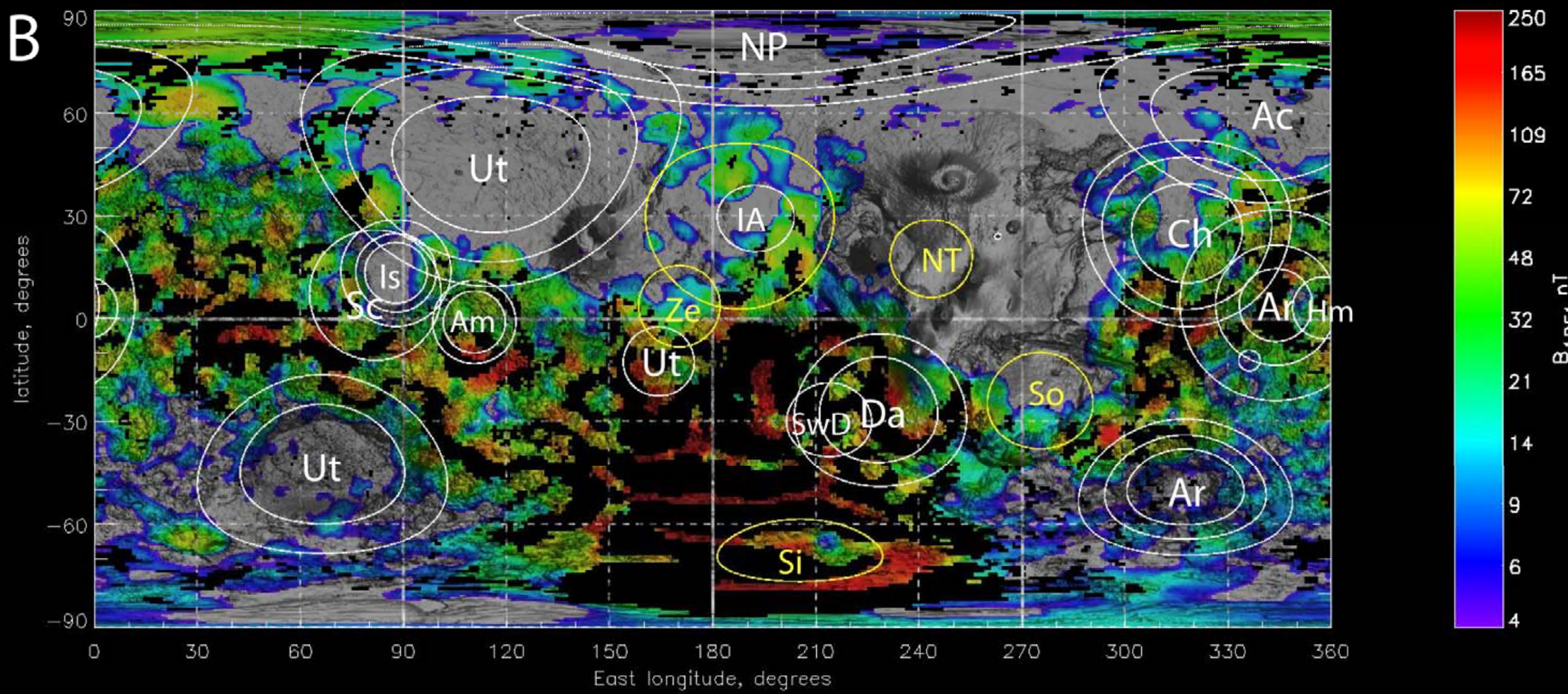
$\Rightarrow$ Basins leave a record of the magnetic conditions at the time of impact.

Impact demagnetization signatures

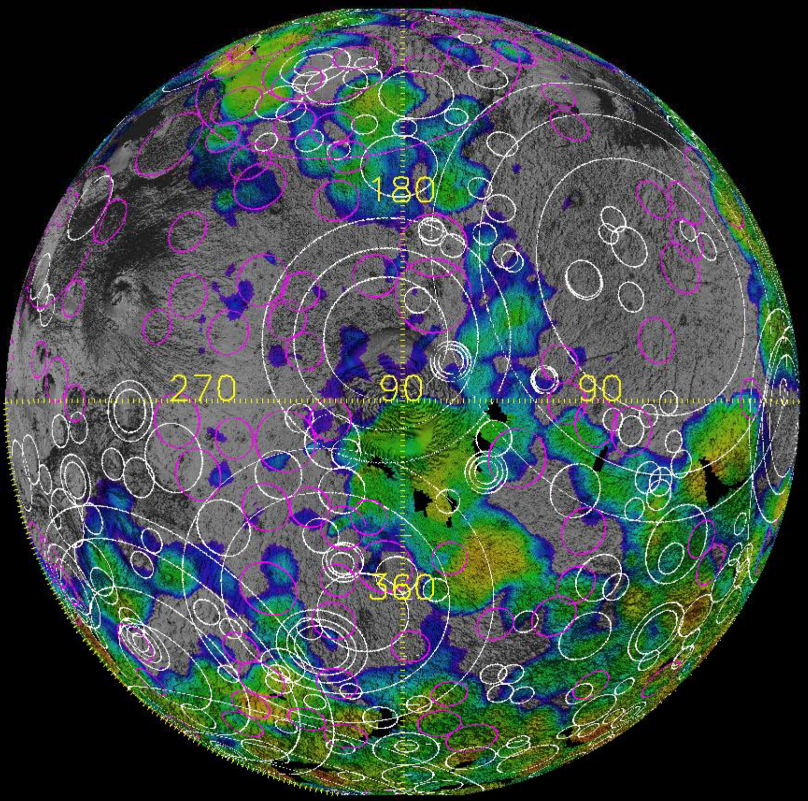


Let's examine the 20 largest basins, all >1000 km in diameter.

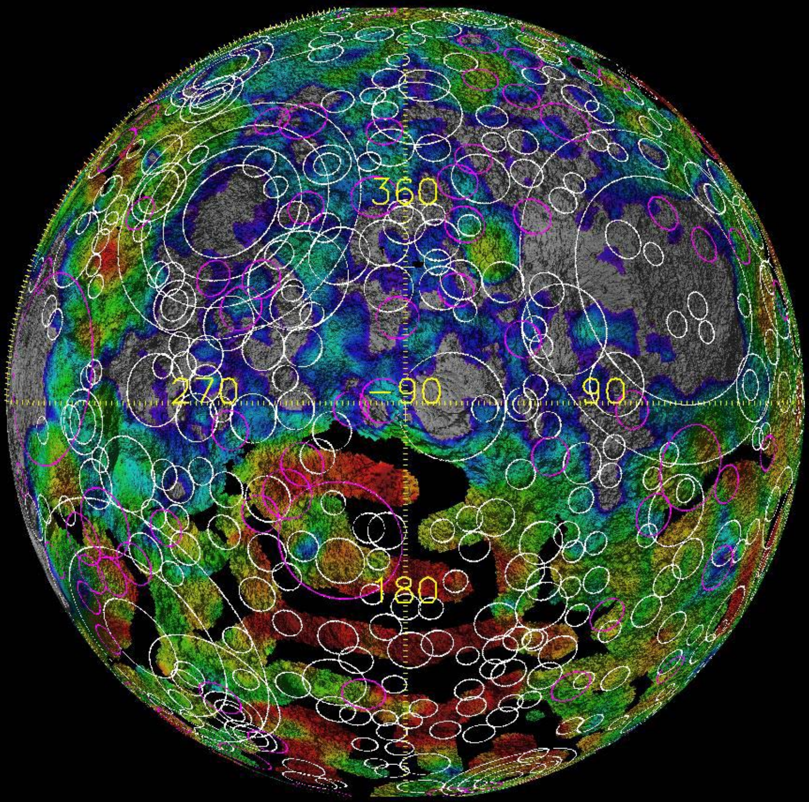
Impact demagnetization signatures



Impact demagnetization signatures



North pole



South pole

The ancient Martian dynamo

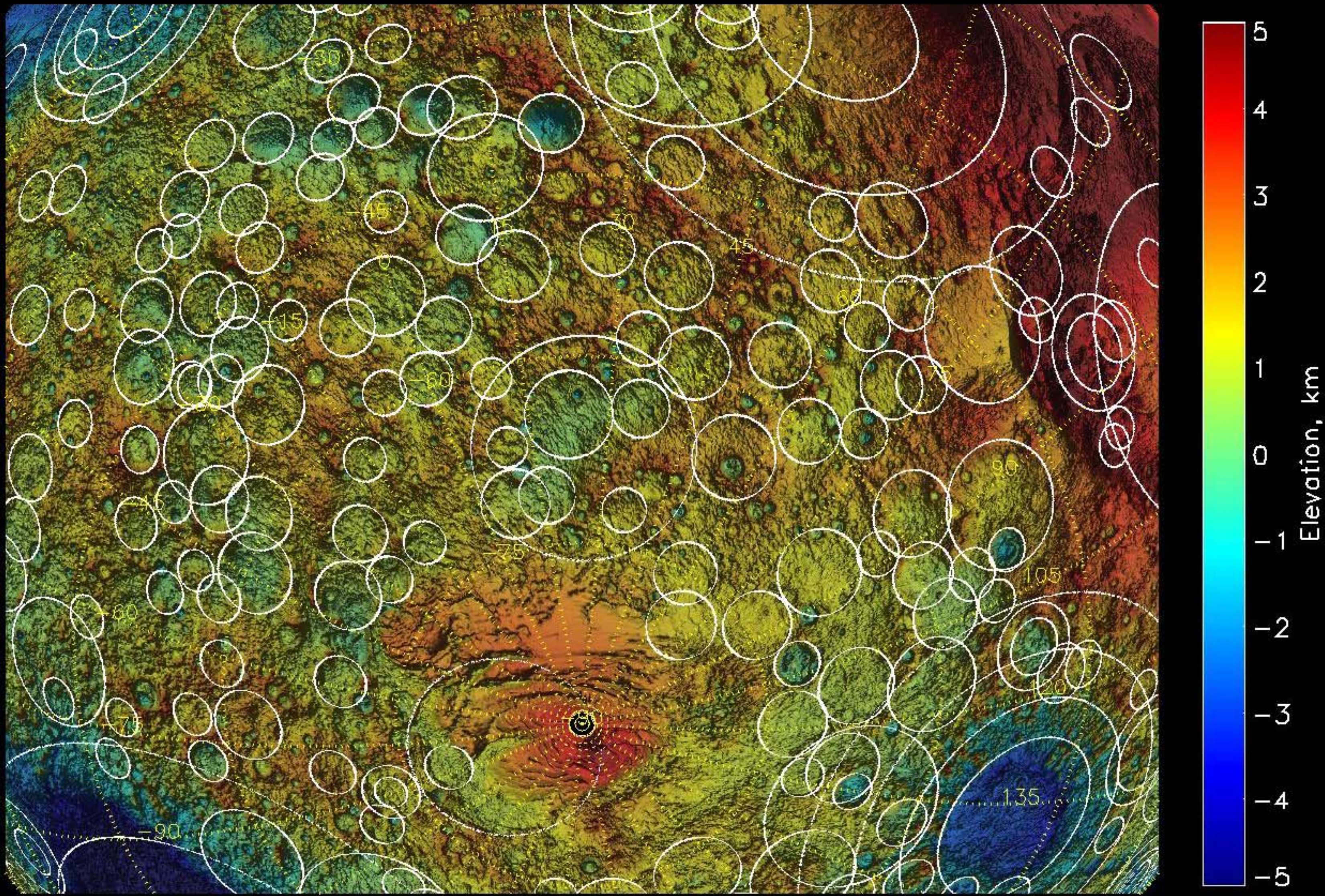
- How will we study it?
  - Examine magnetic signatures of giant impact basins to estimate magnetic conditions at impact.
  - Correlate with crater retention ages calculated for these basins. Attempt to construct a dynamo ‘timeline’ for early Mars.

Major caveats:
$|B|$ at 185 km ↔ paleofield at impact?

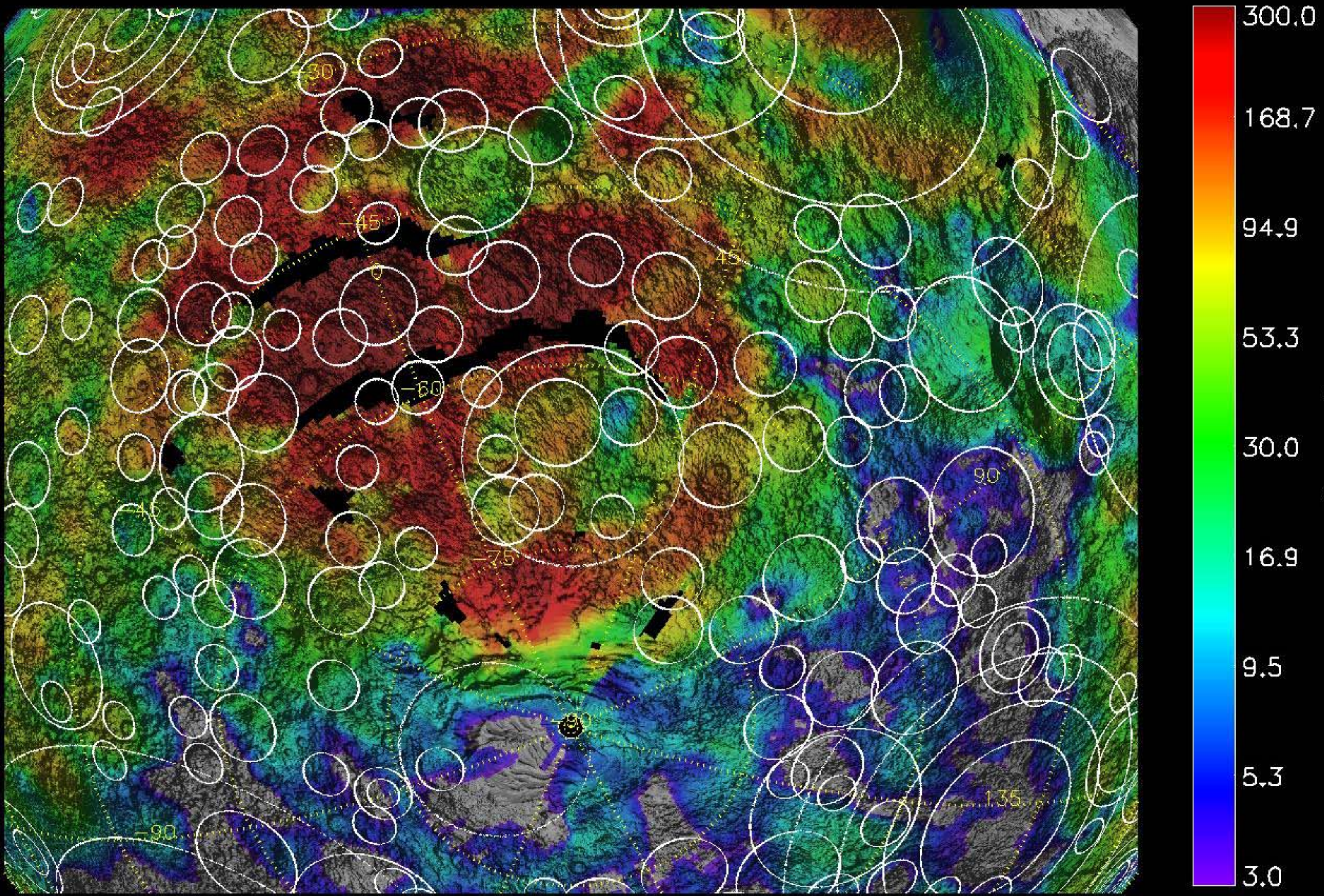
- All basins > 1000 km >> observation altitude. Lateral magnetic coherence scale < 600 km. Hence, low/high crustal field ↔ weak/strong magnetization.
- Assume no large differences in crustal magnetic susceptibility. Hence, $|M| \sim |B_{paleofield}|$ approx.
- Assume no basin-scale subsequent magnetic alteration by non-impact, non-volcanic (i.e. 'invisible') processes.
- Take account of thickness of crust/magnetizable layer.

With these qualifiers, we can roughly relate |B| at 185 km to the magnetizing paleofield (low, medium, high)

Sirenum basin signature



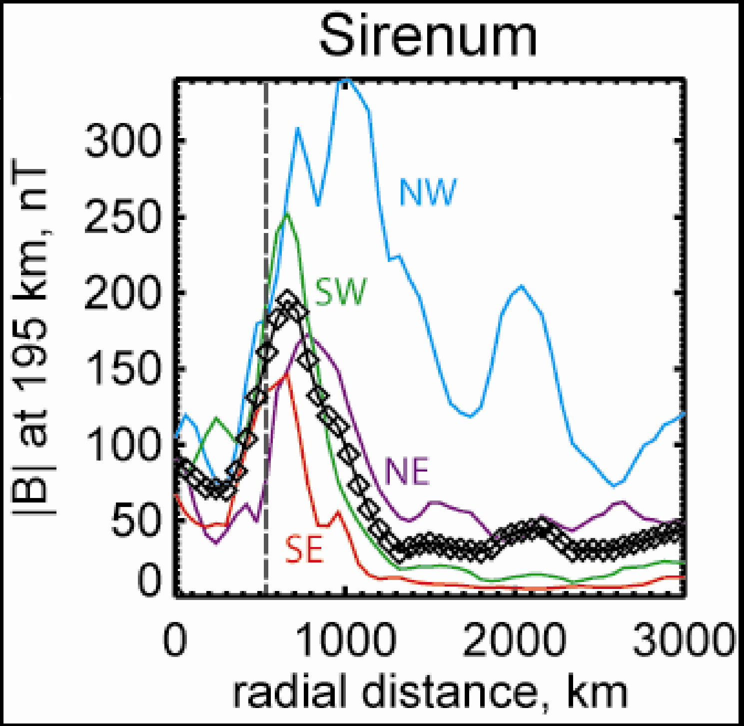
Sirenum basin signature



Sirenum basin signature

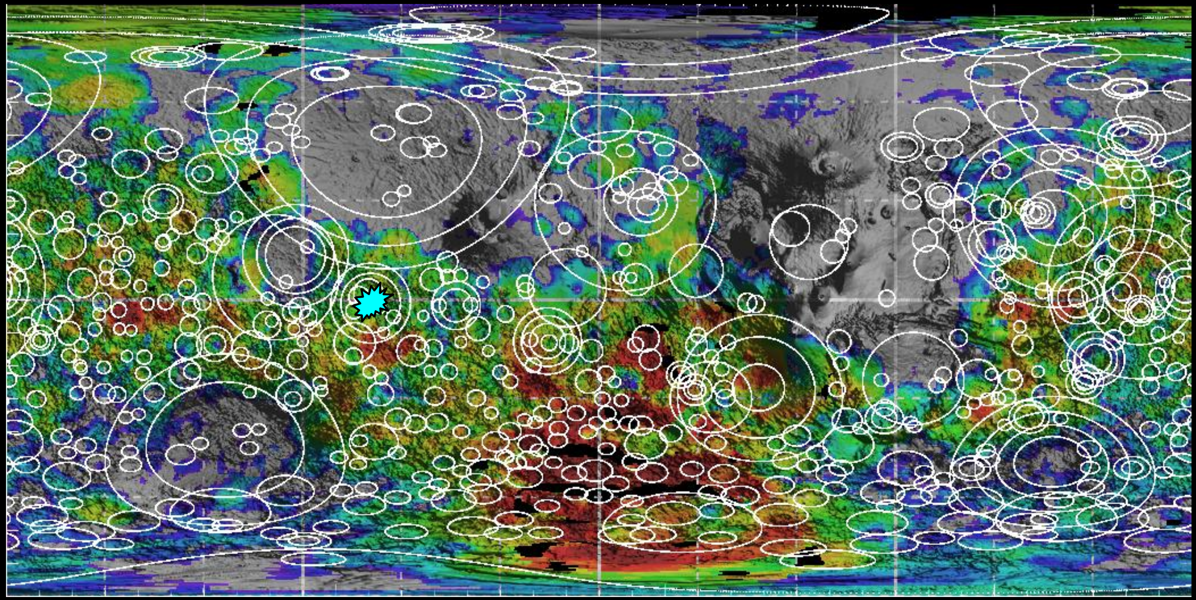
- First very large basin identified in strong crustal field regions.
- Extremely old surface, N(300) ~5.6.

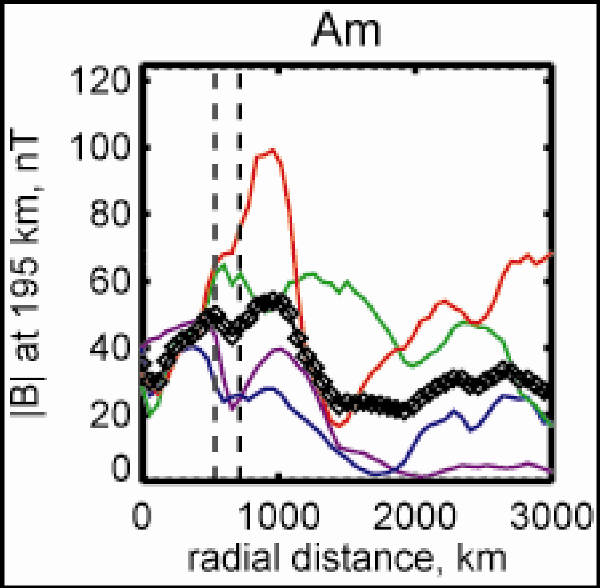
- Signature of partial demagnetization
- Impact must have occurred after emplacement of very strongly magnetized crust.
- Net magnetization was reduced by shock and thermal effects *in an active dynamo field.*

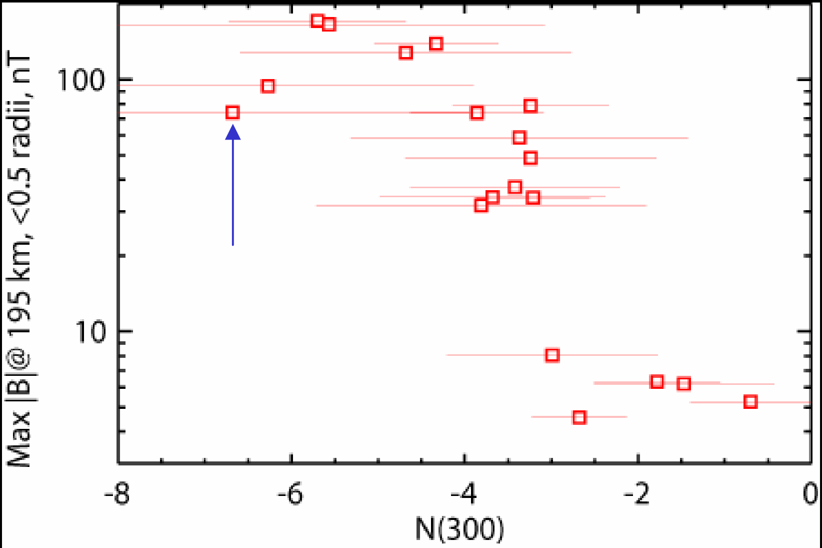


Strong magnetization is older than any datable surface on Mars, perhaps formed when crust cooled → dynamo may predate crust.

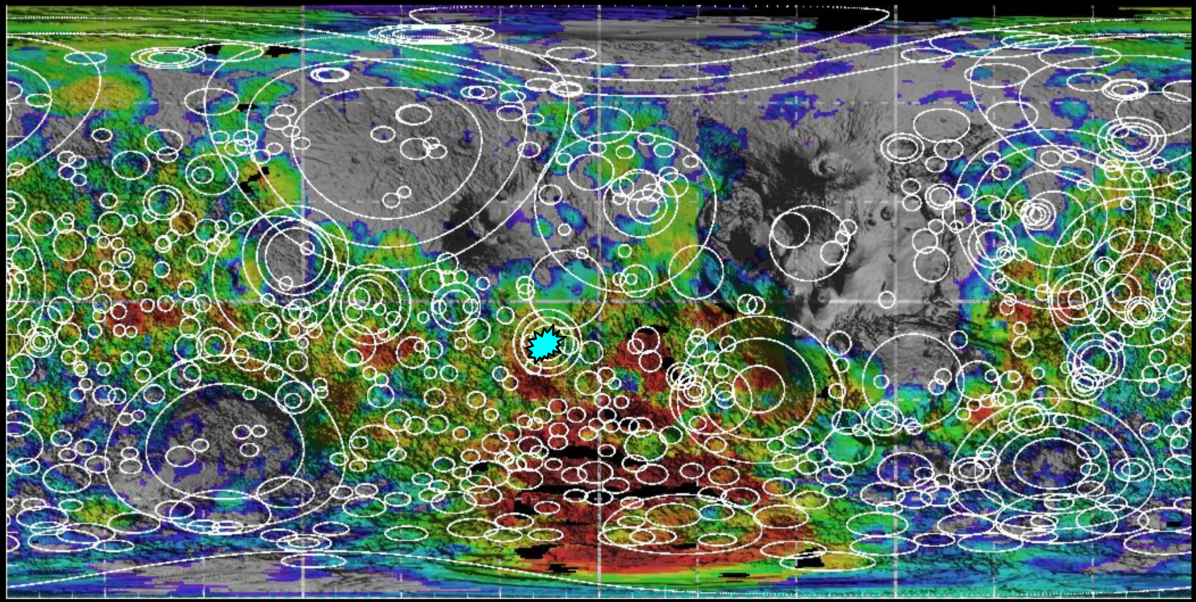
Impacts in order of crater retention age

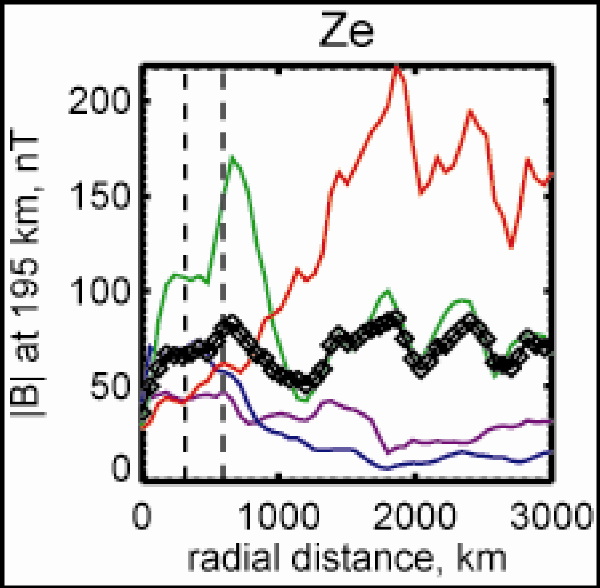


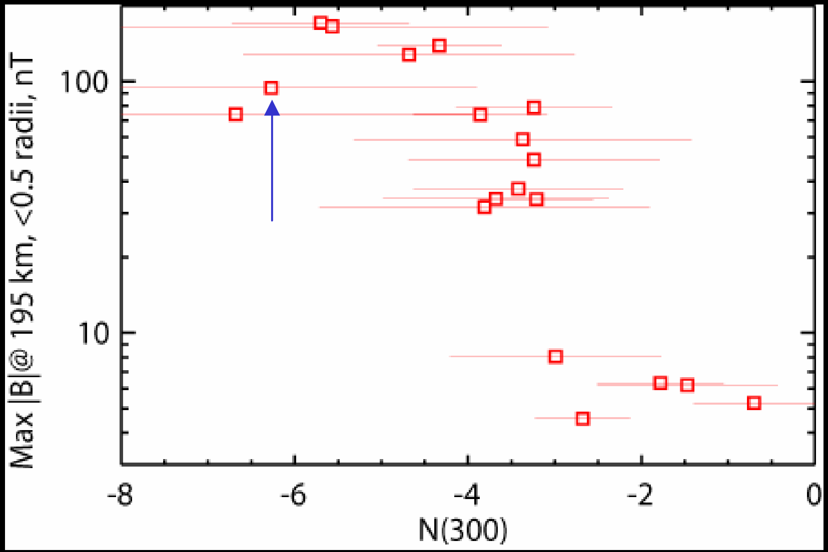




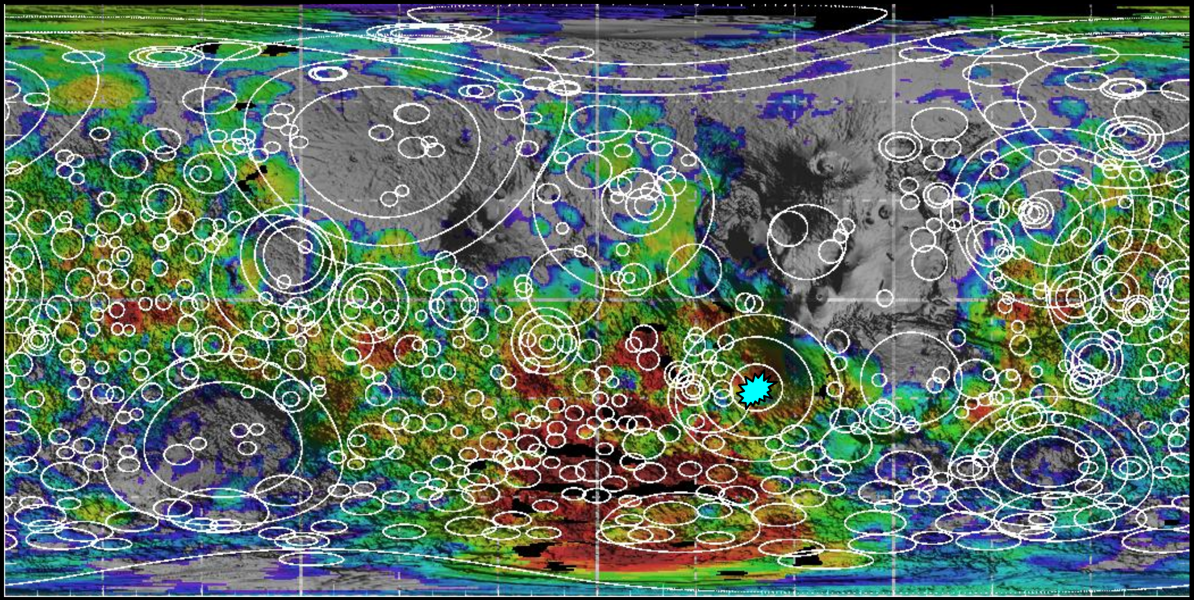
Impacts in order of crater retention age

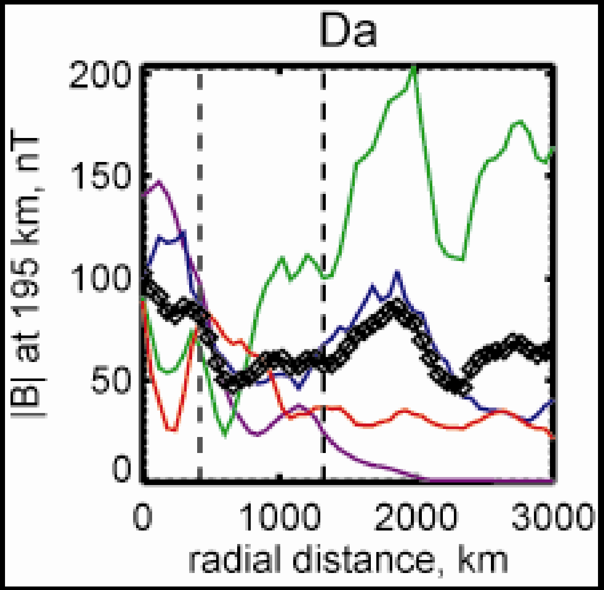


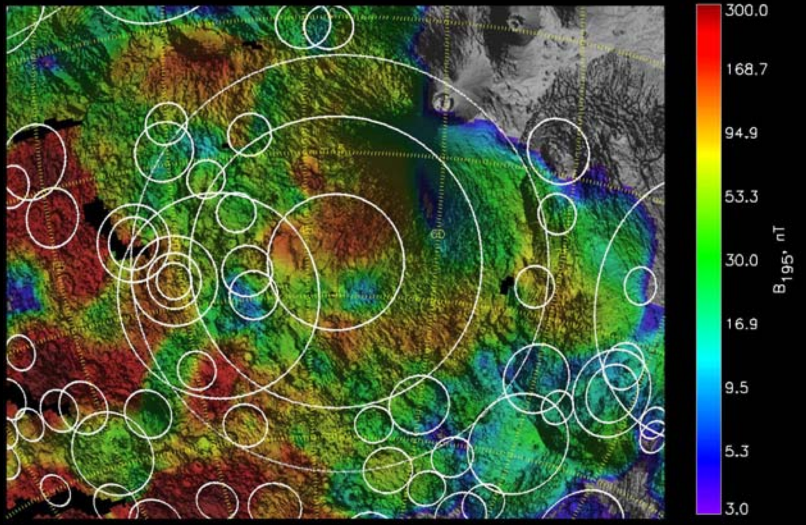


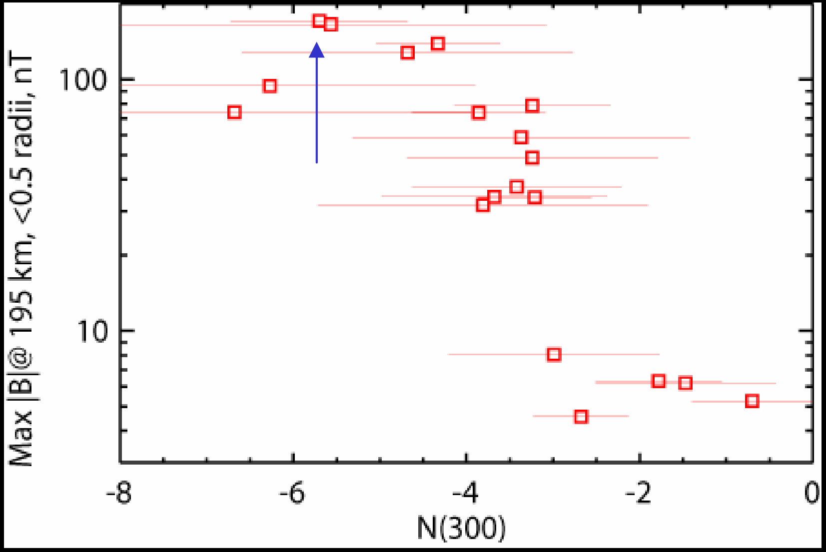


Impacts in order of crater retention age

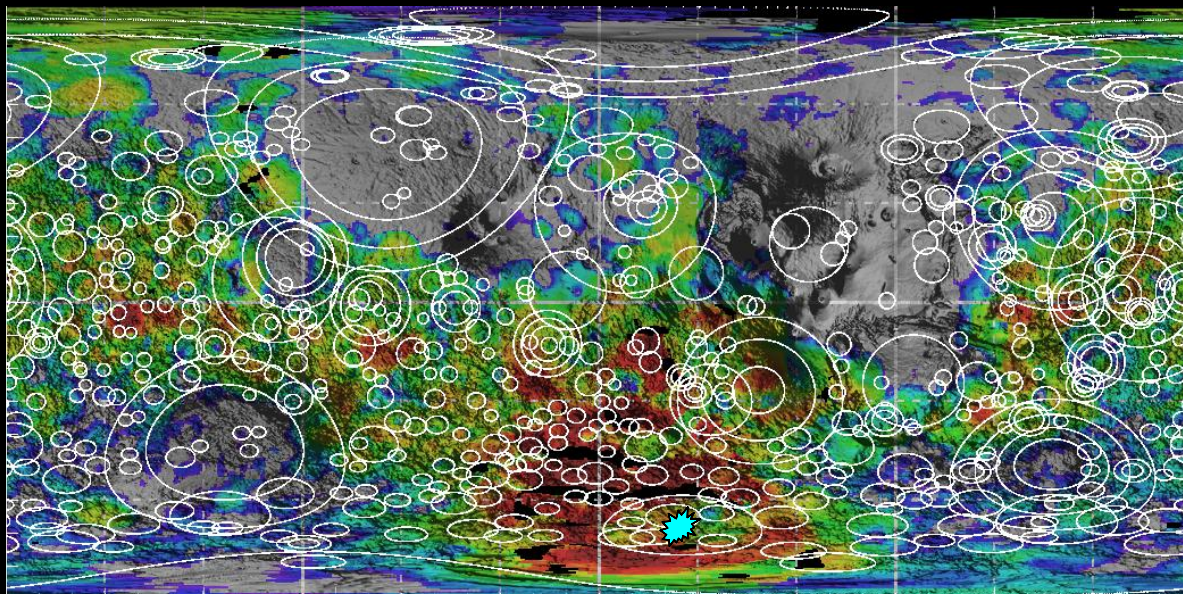


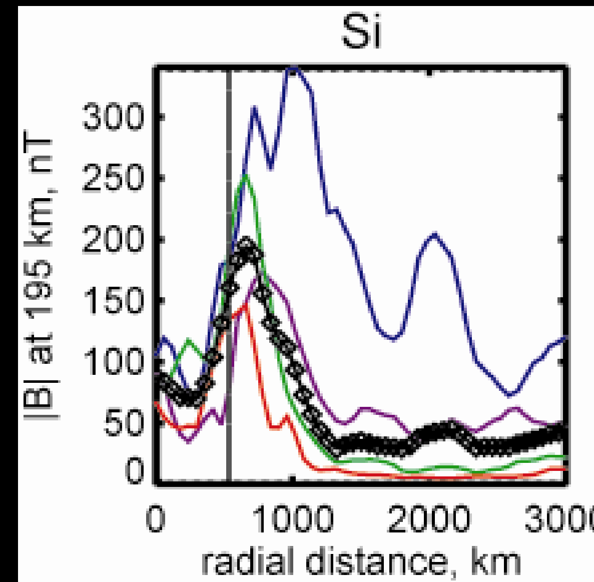


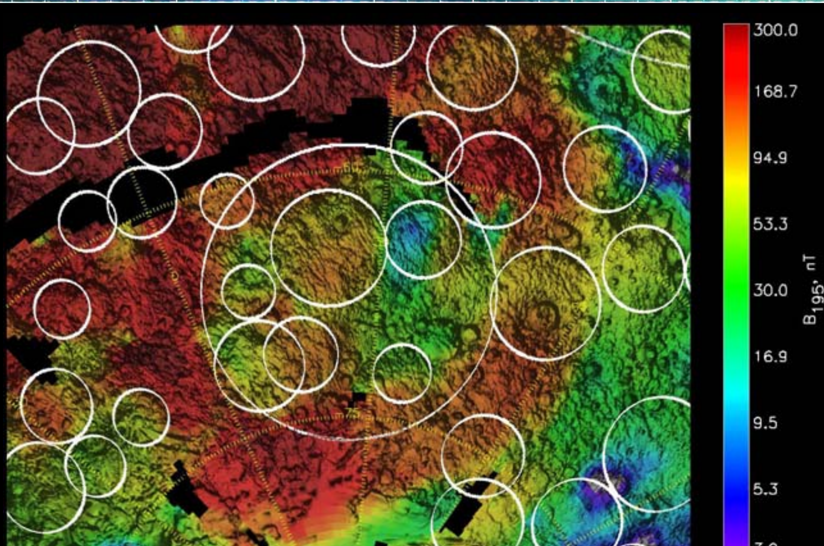


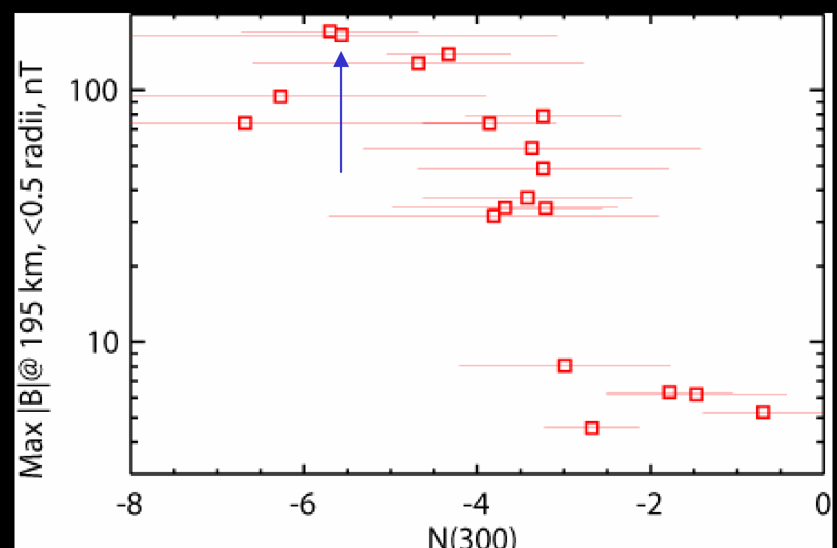


Impacts in order of crater retention age

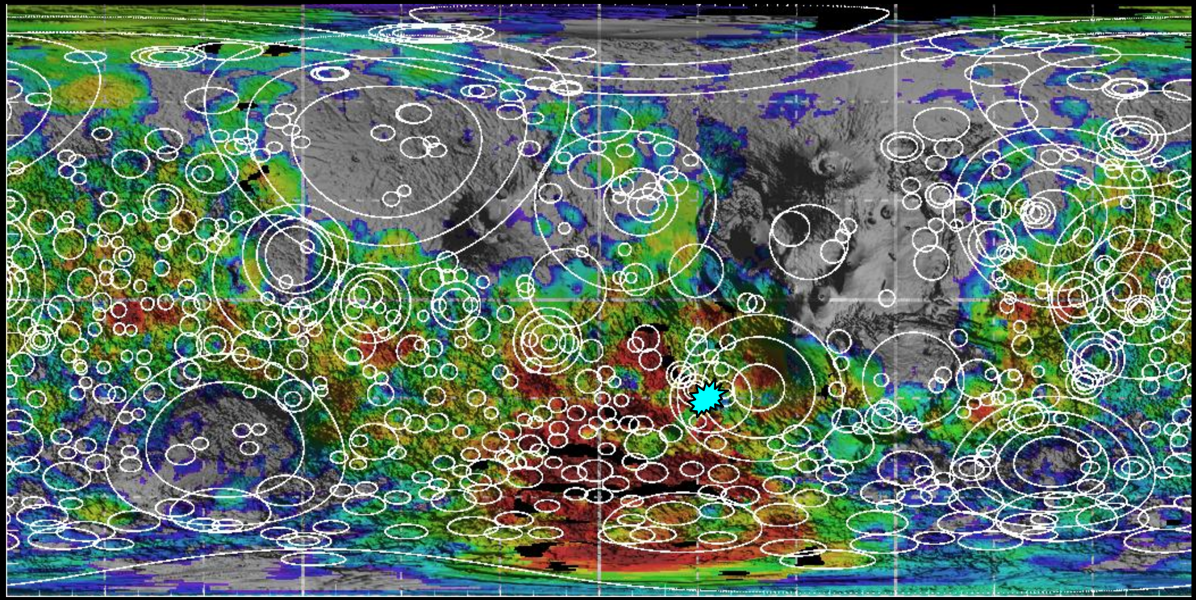


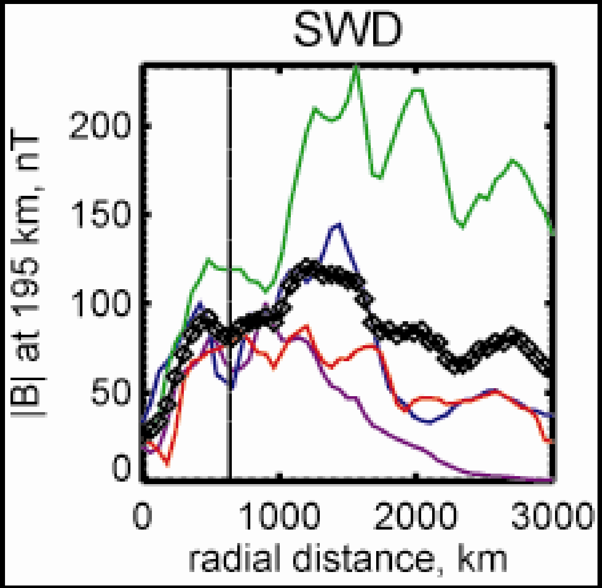


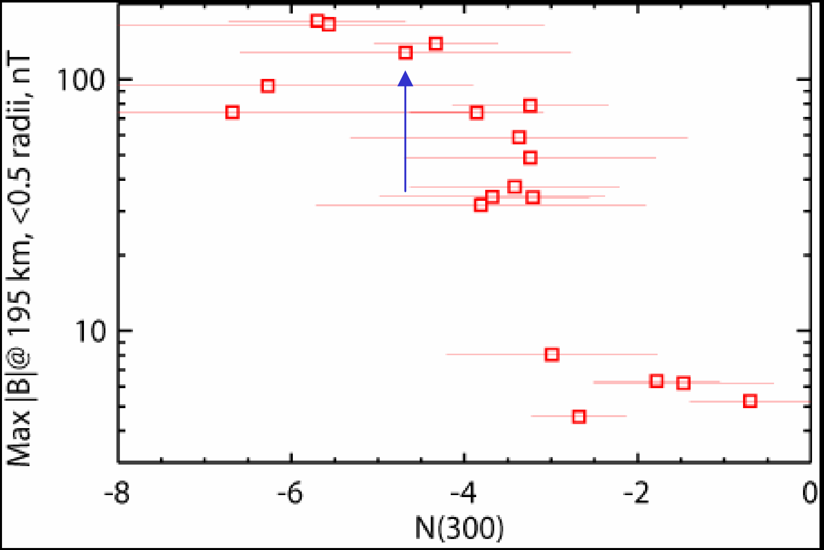




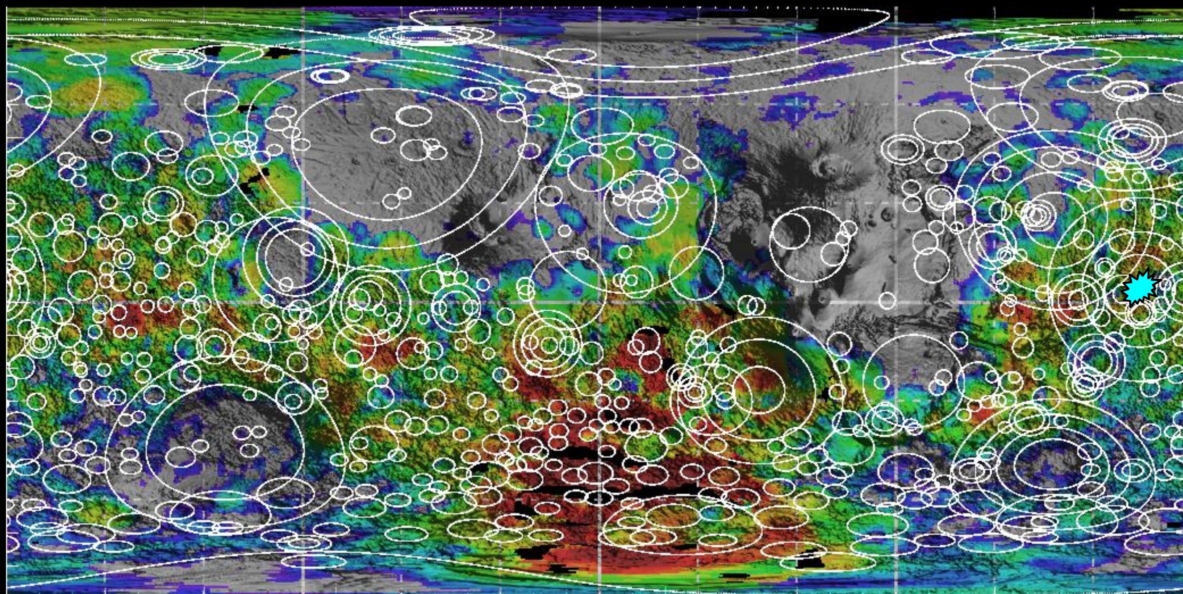
Impacts in order of crater retention age

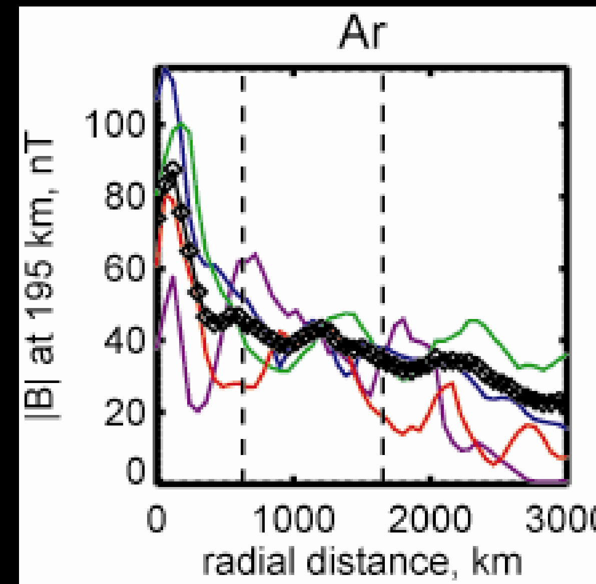


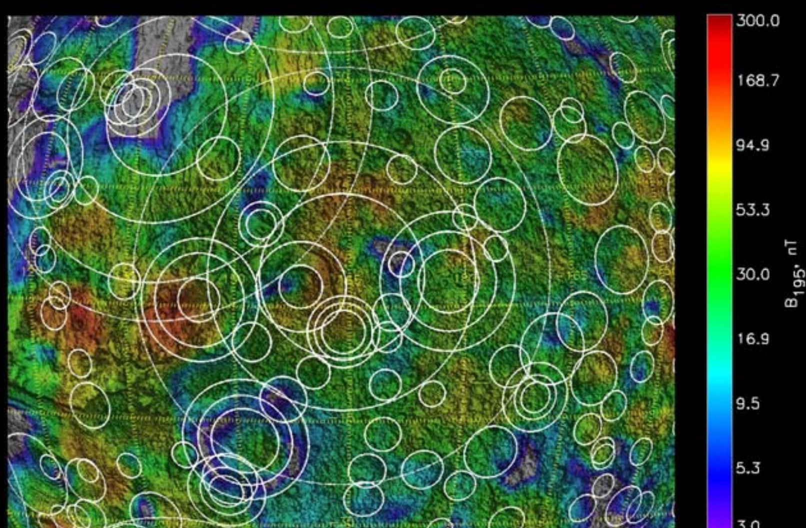


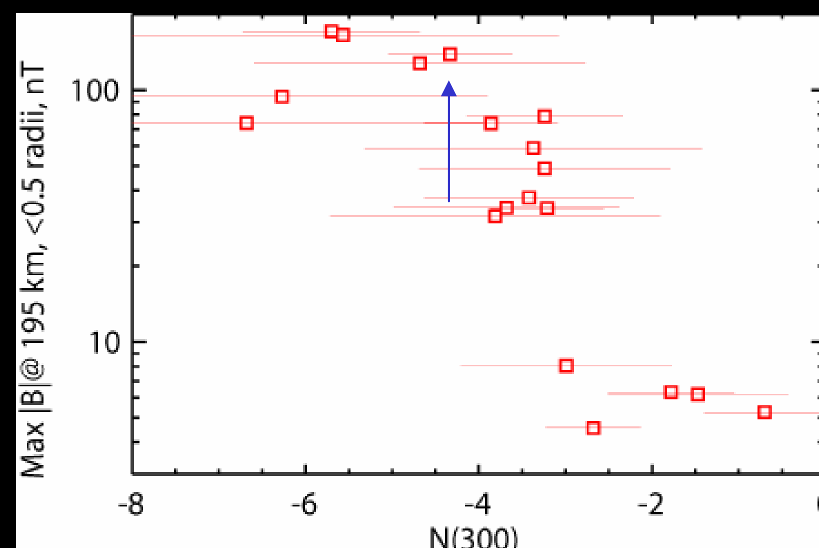


Impacts in order of crater retention age

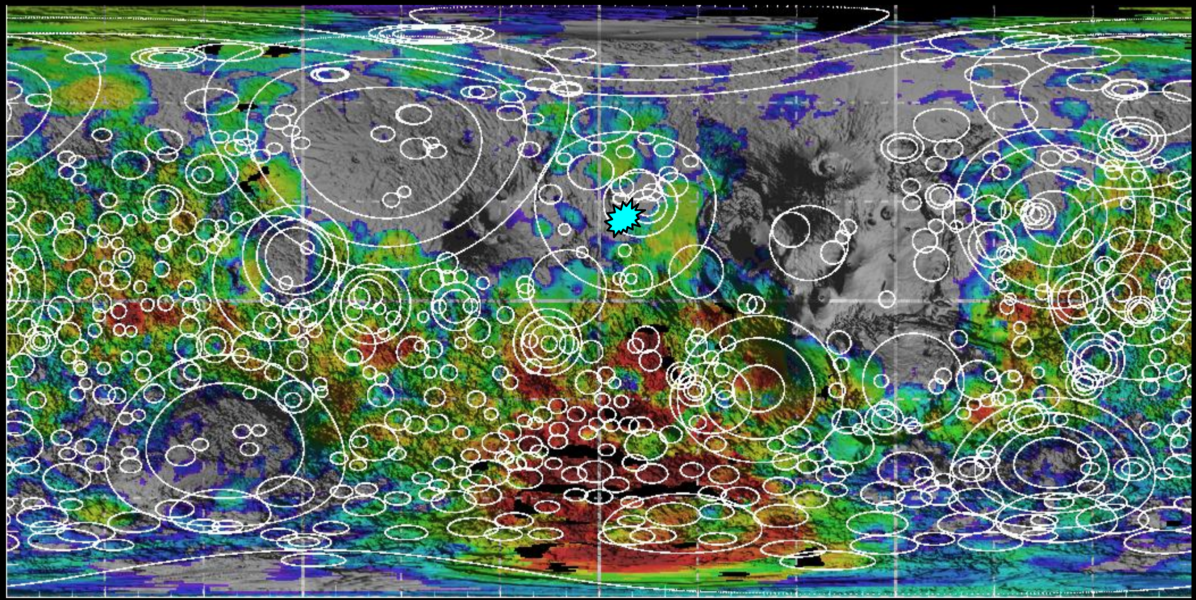


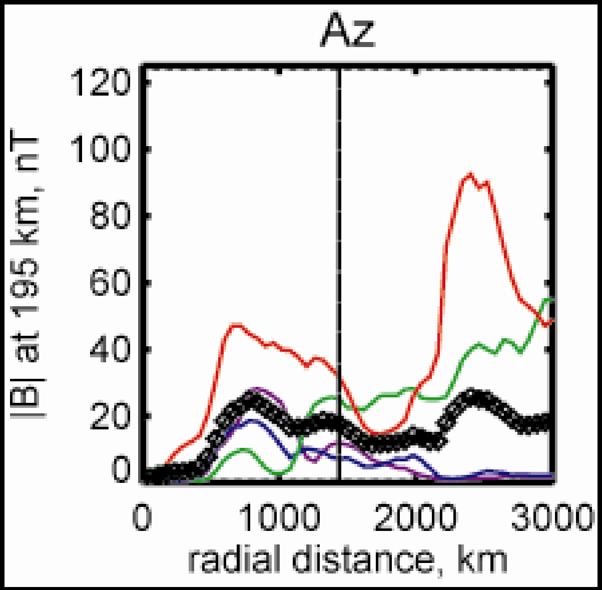


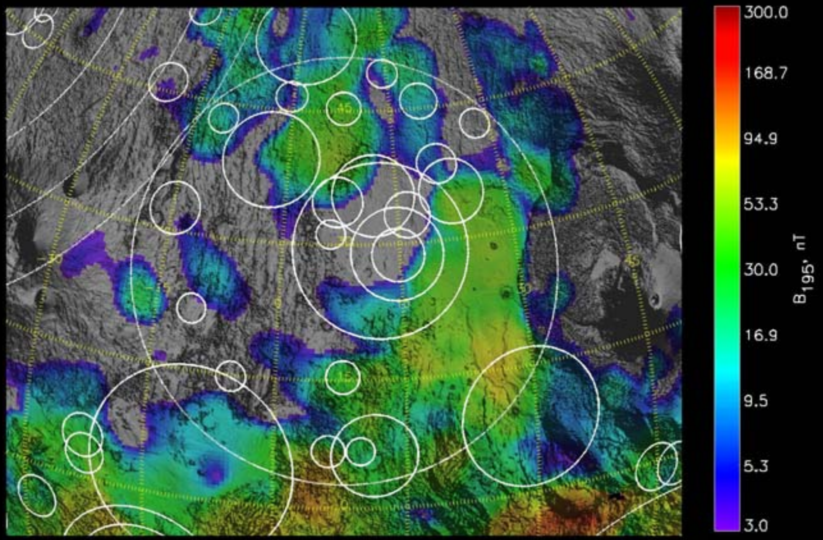


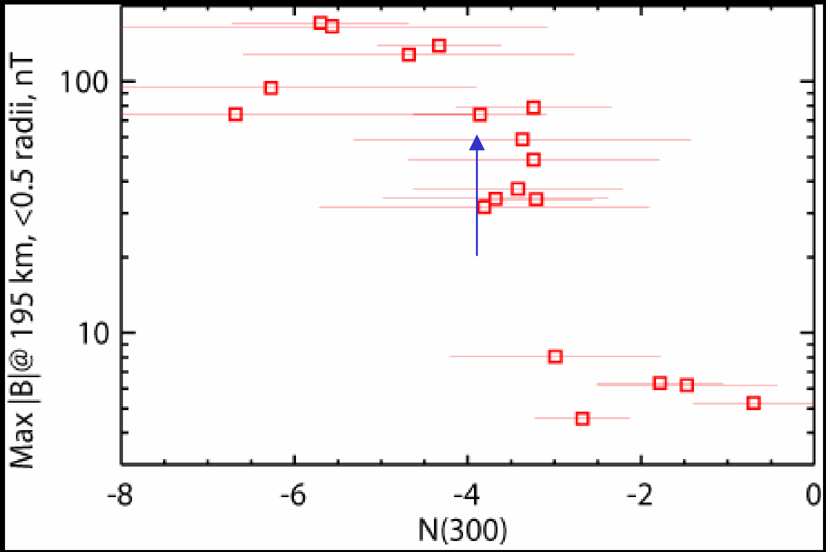


Impacts in order of crater retention age

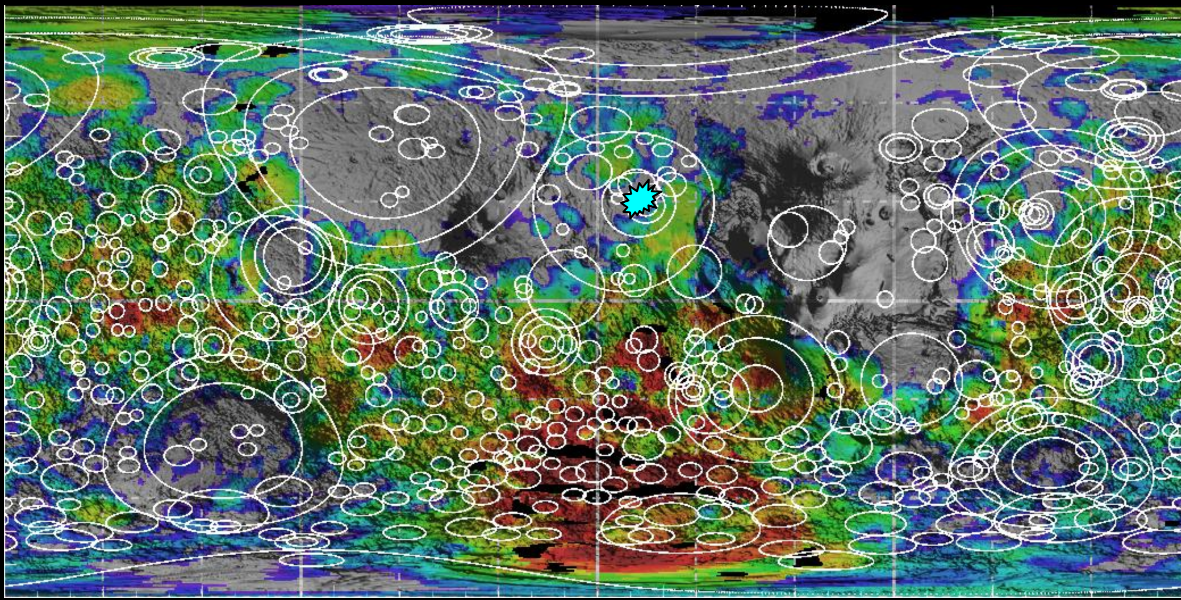


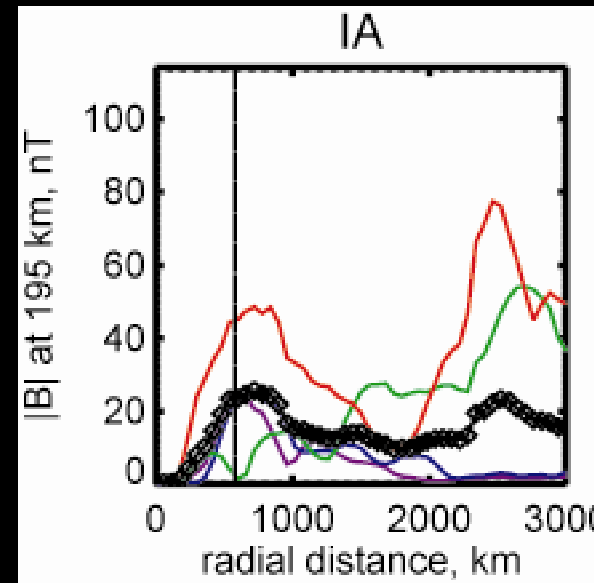


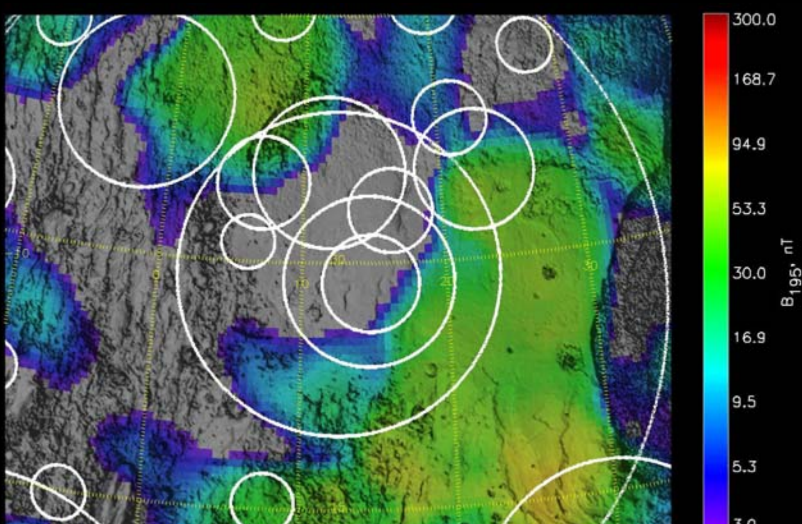


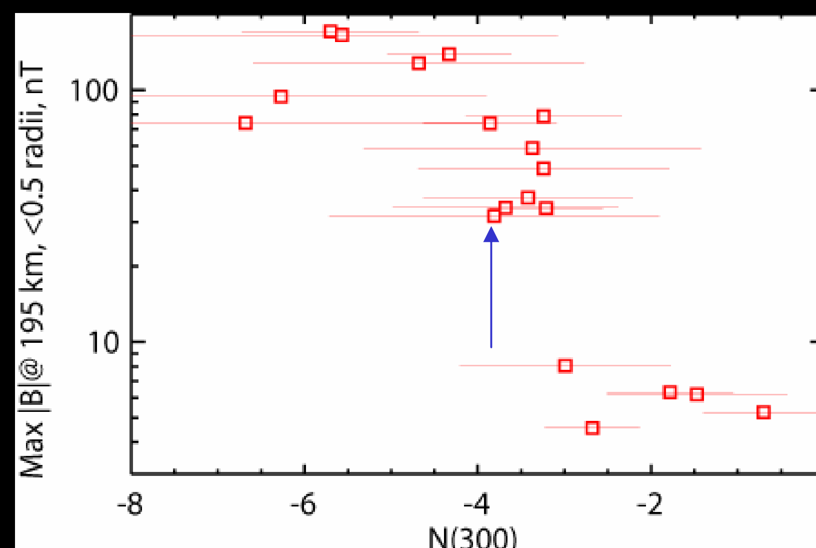


Impacts in order of crater retention age

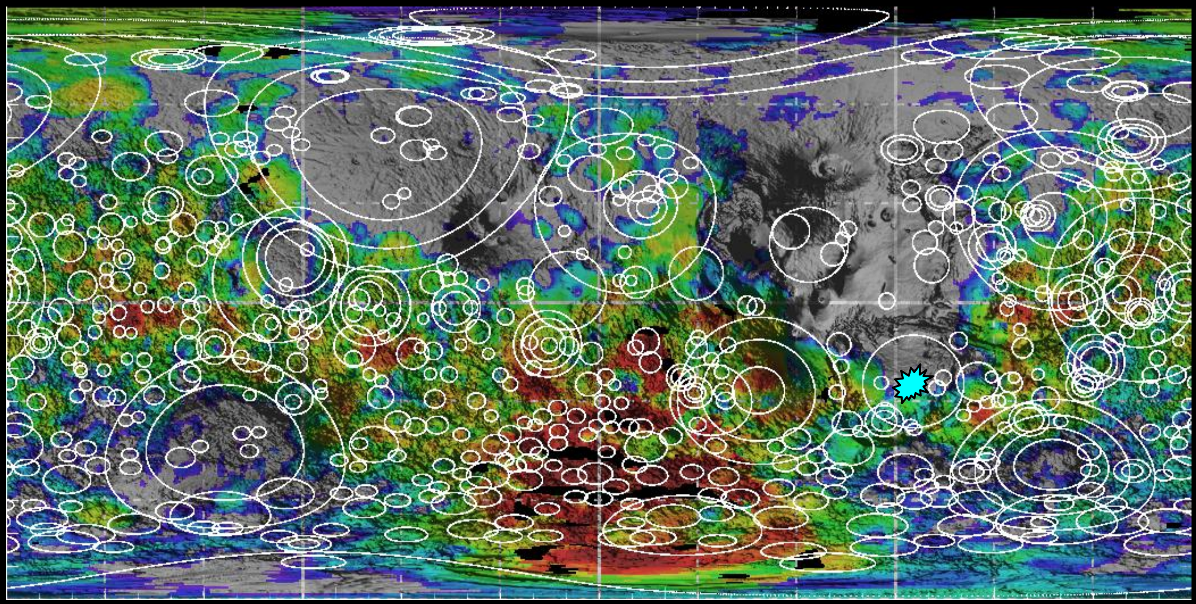


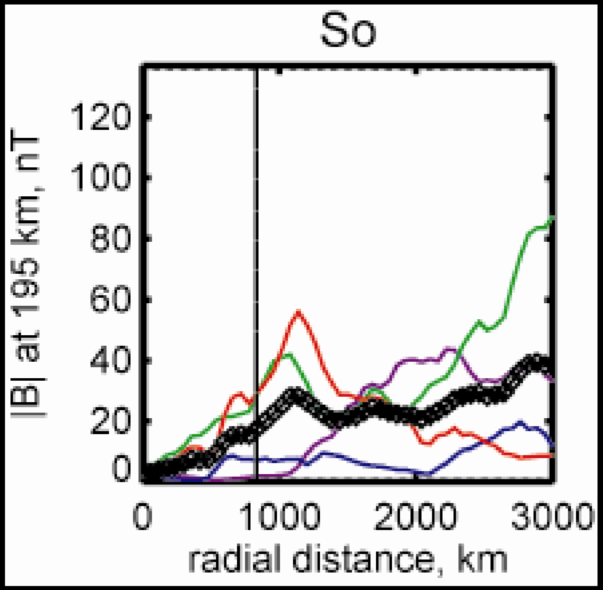


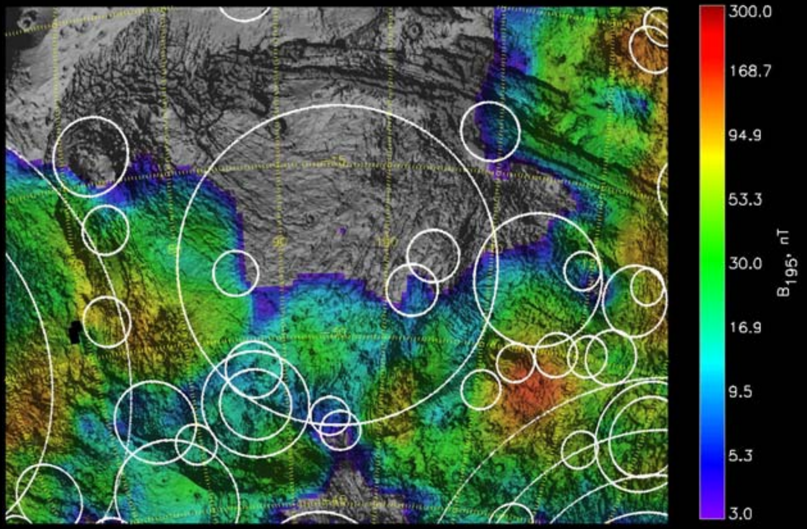


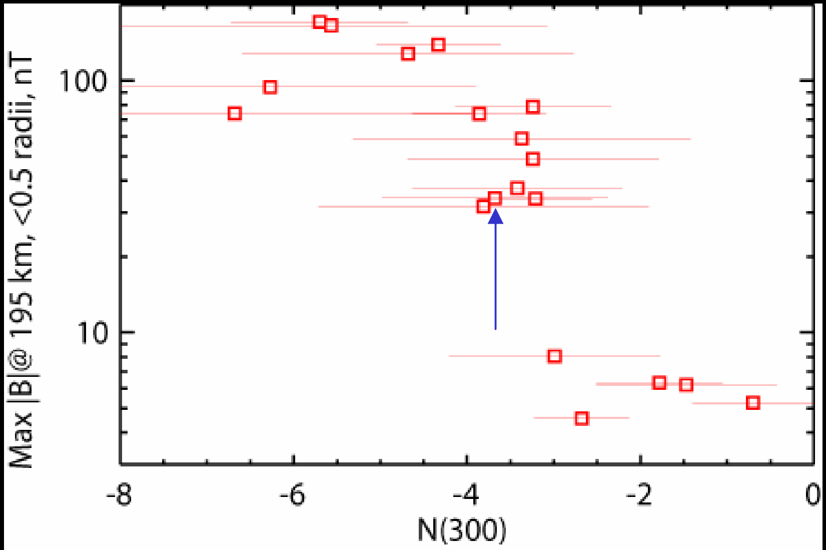


Impacts in order of crater retention age

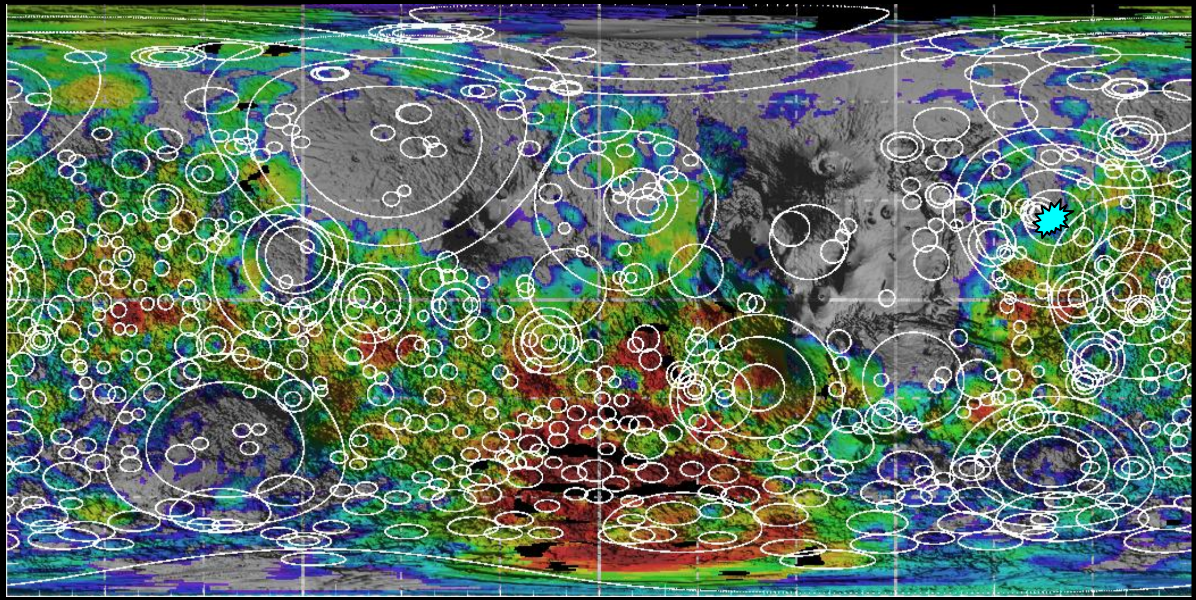


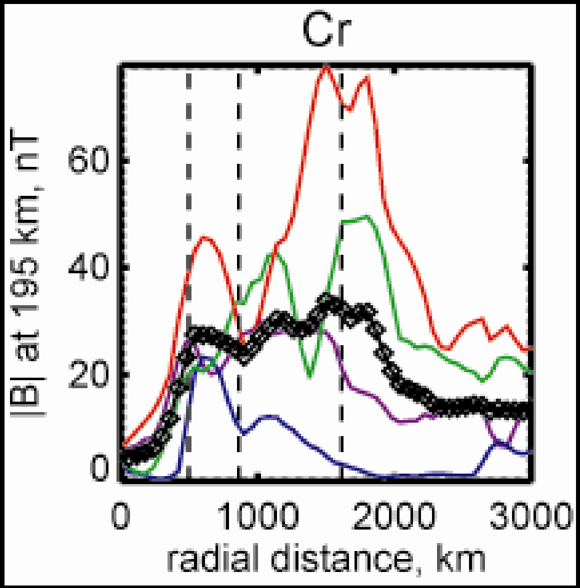


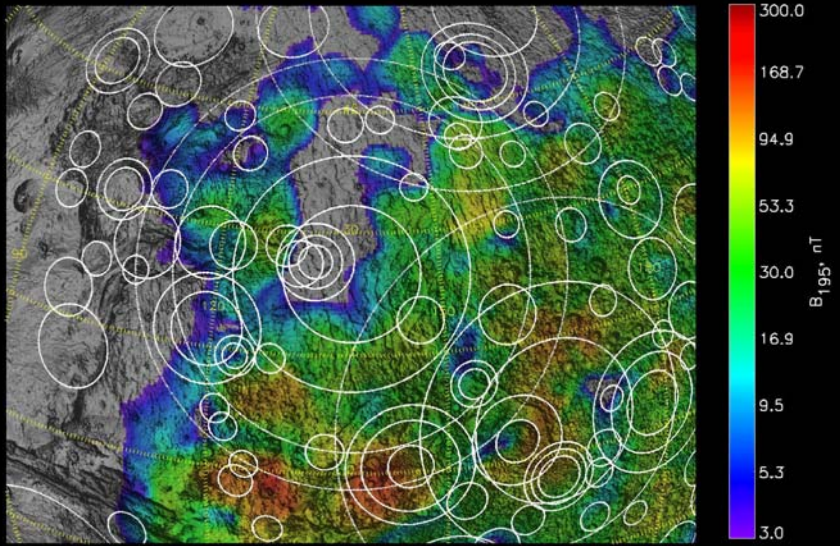


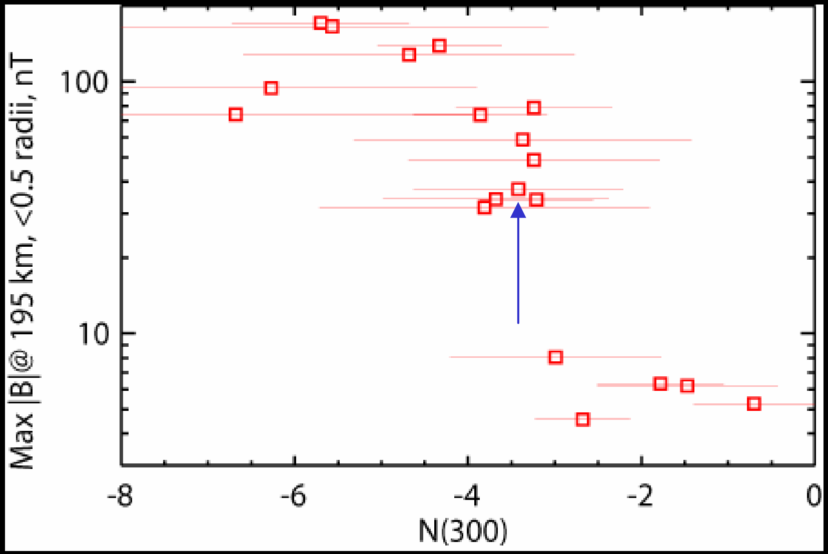


Impacts in order of crater retention age

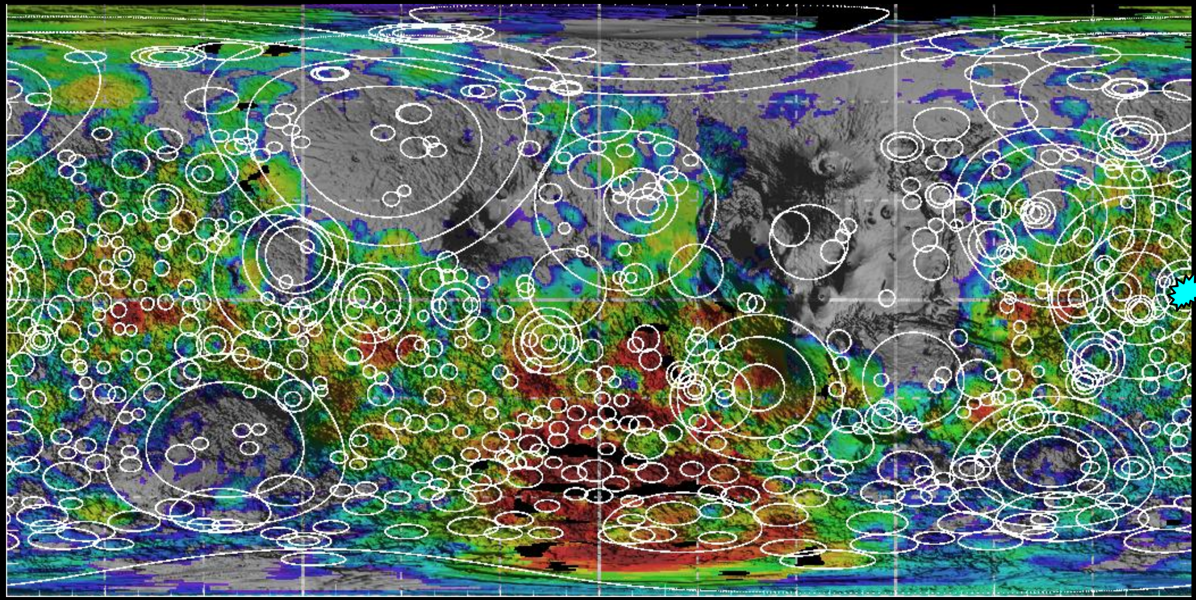


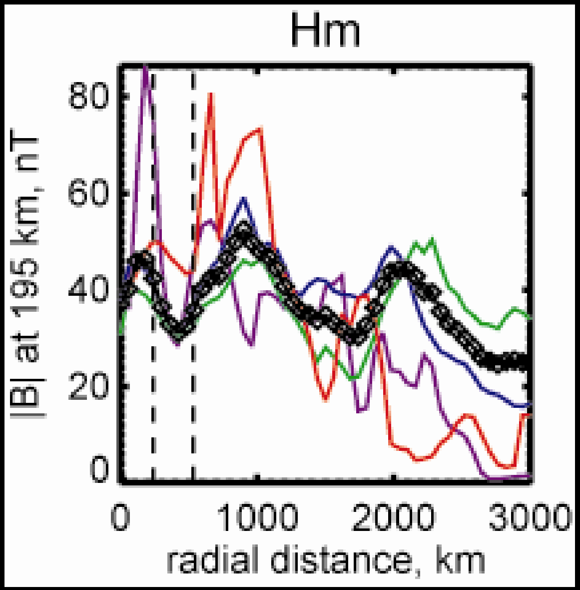


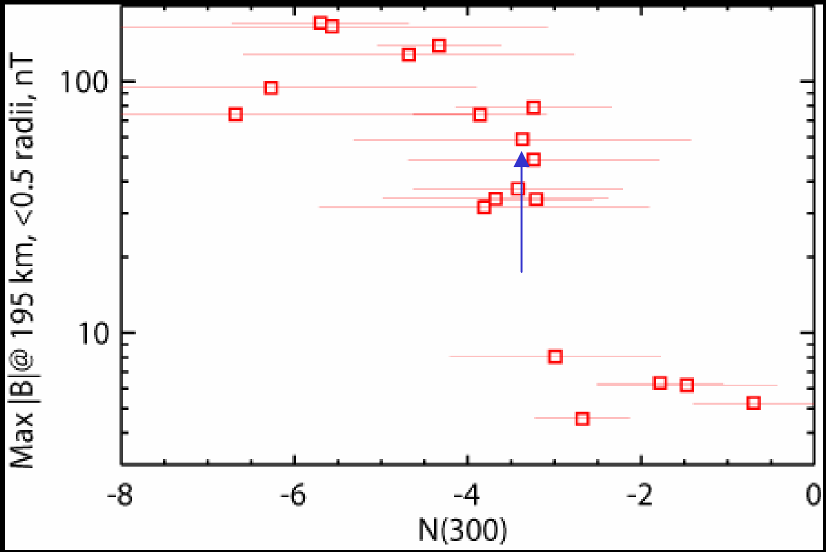




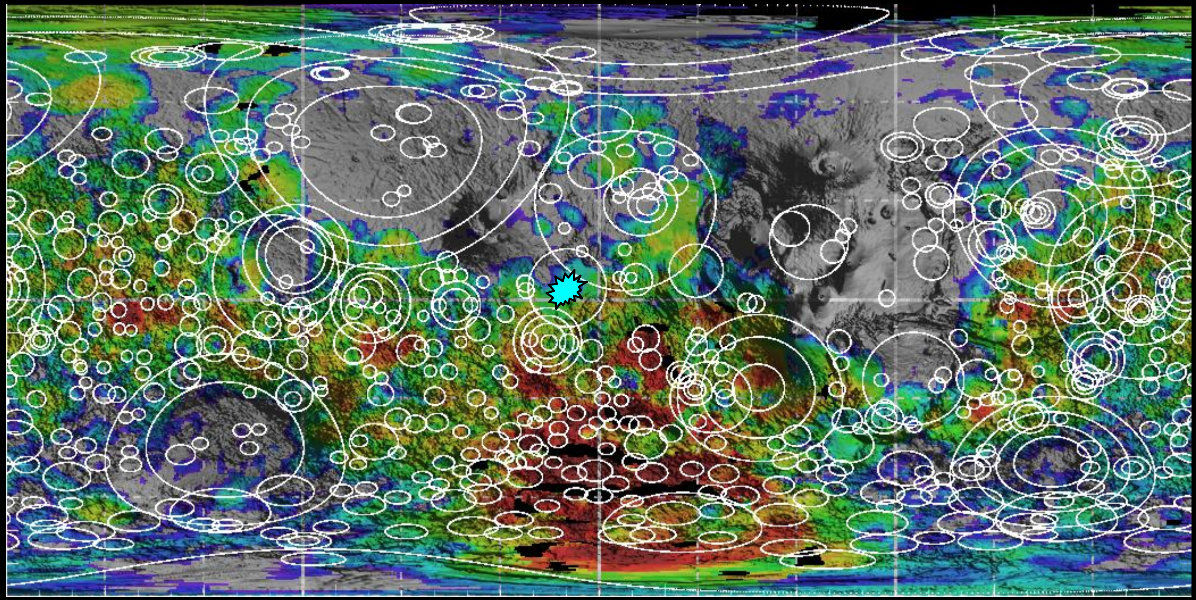
Impacts in order of crater retention age

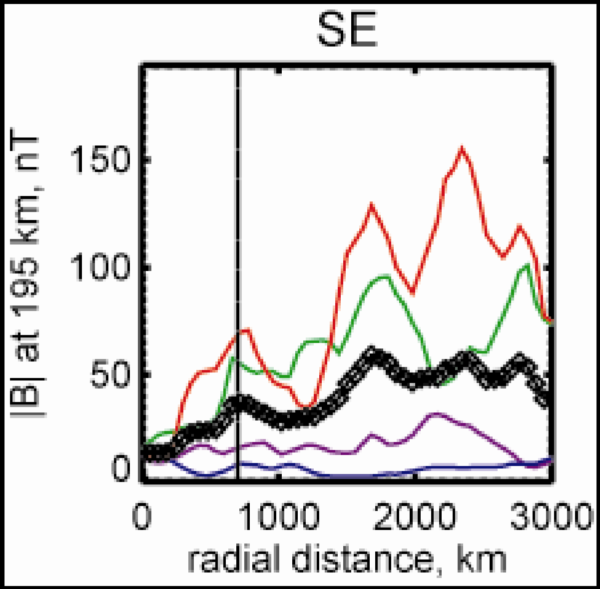


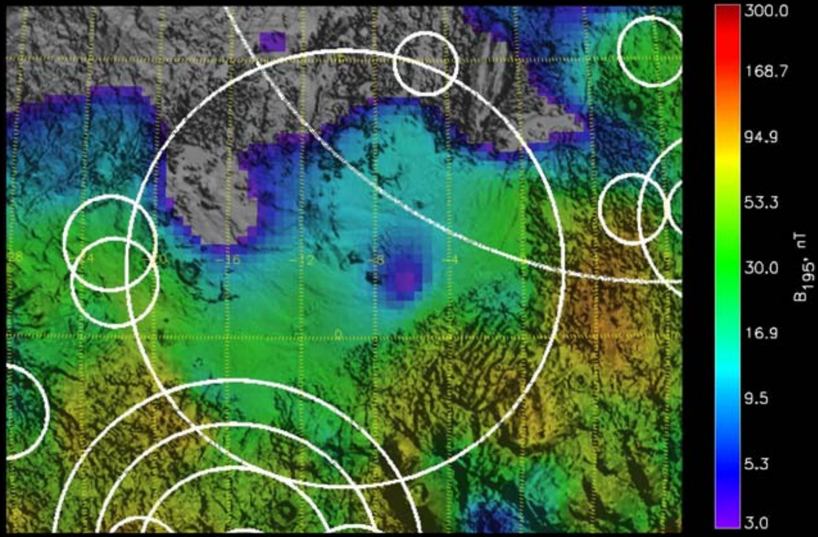


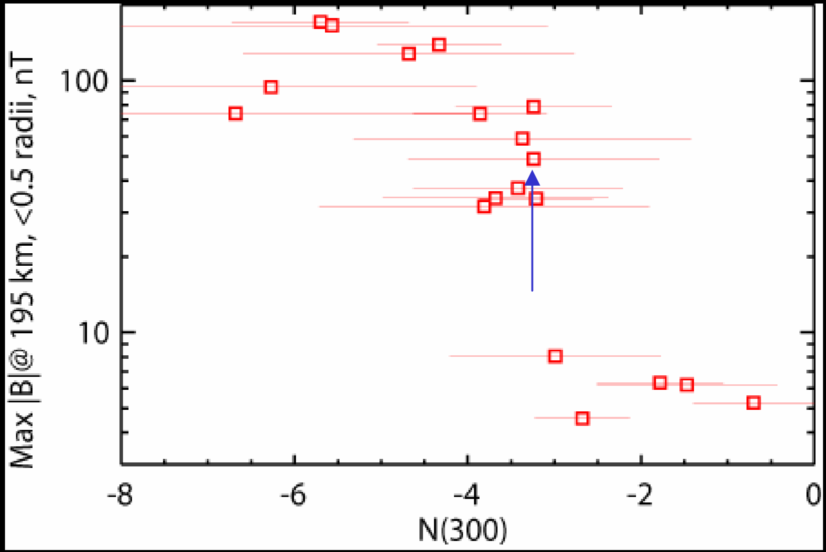


Impacts in order of crater retention age

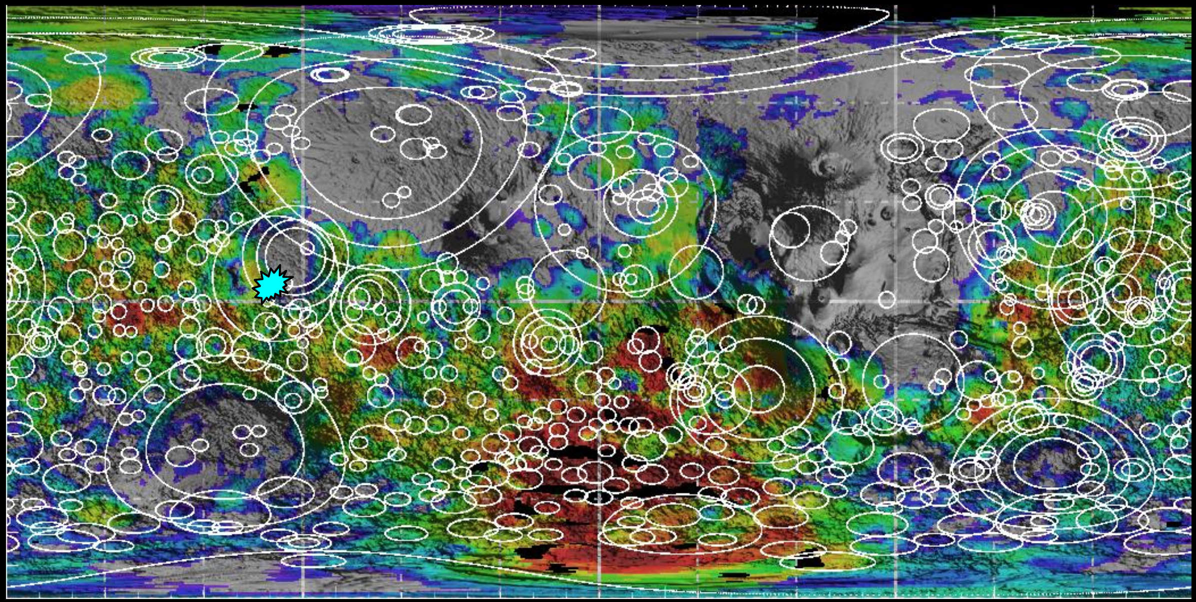


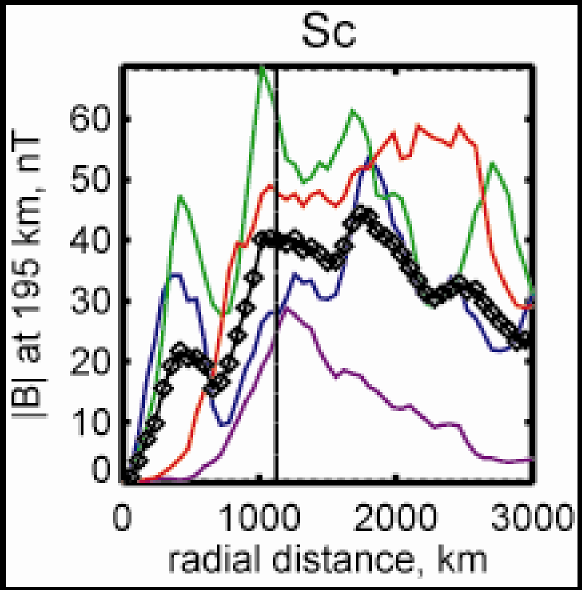


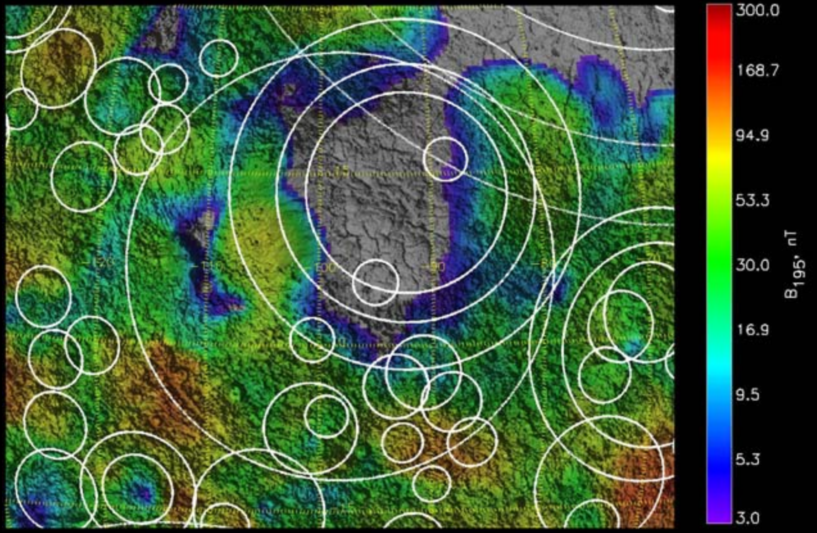


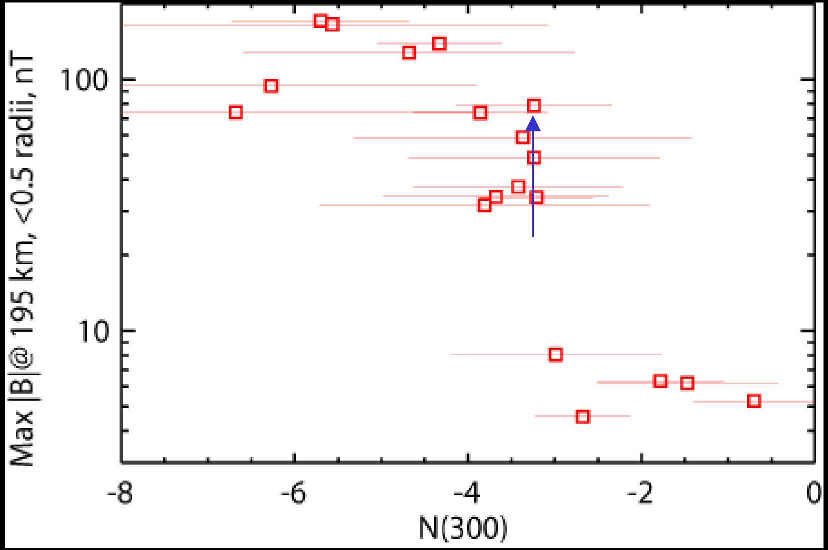


Impacts in order of crater retention age

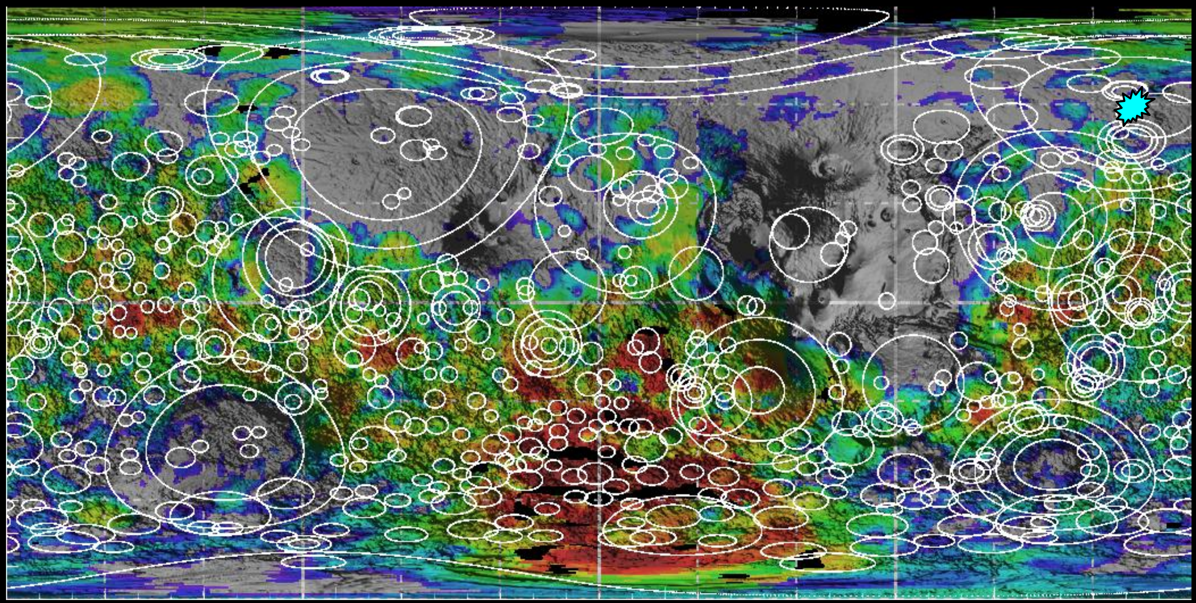


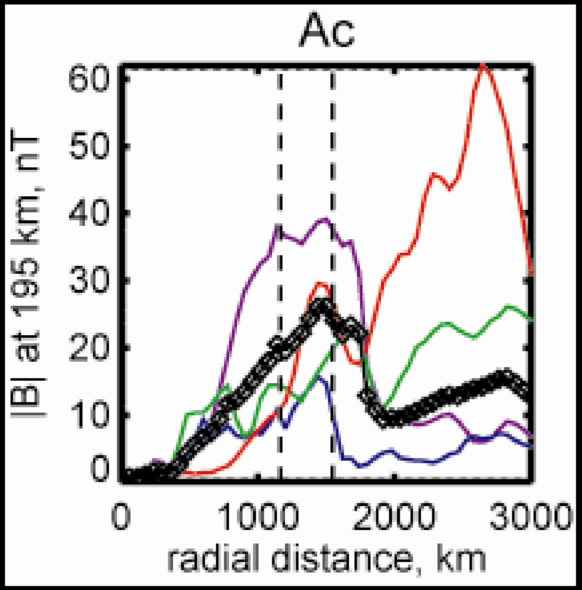


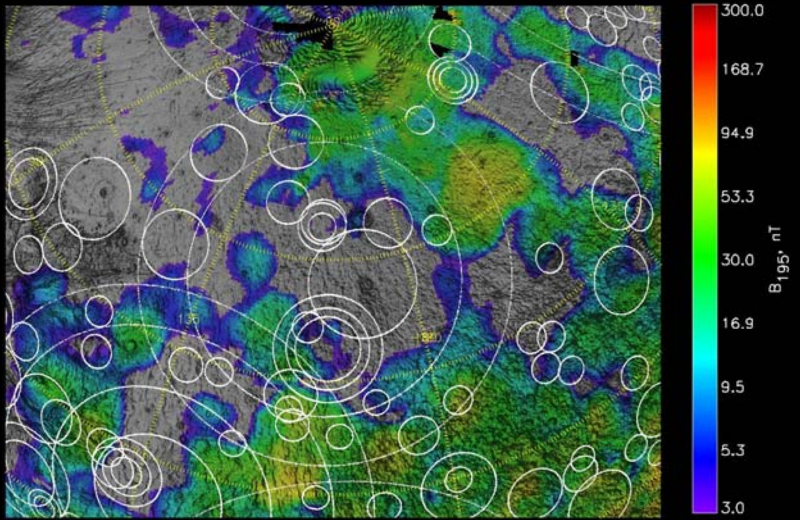


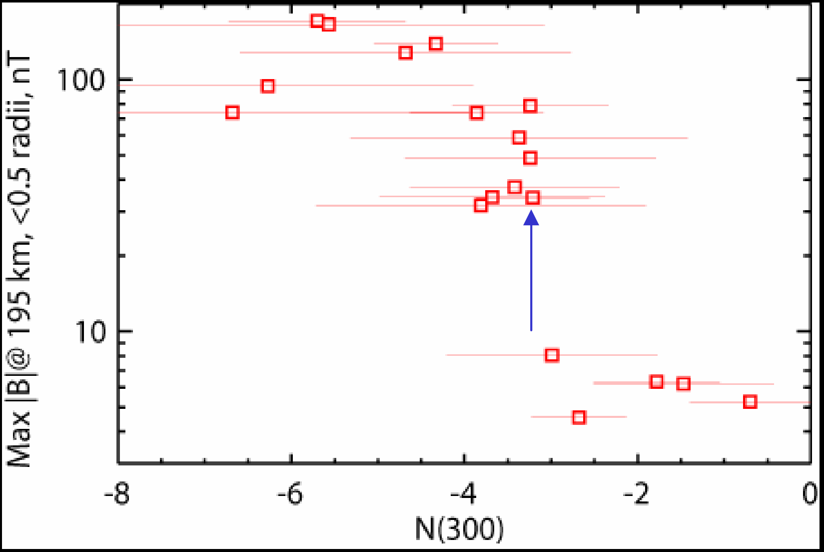


Impacts in order of crater retention age

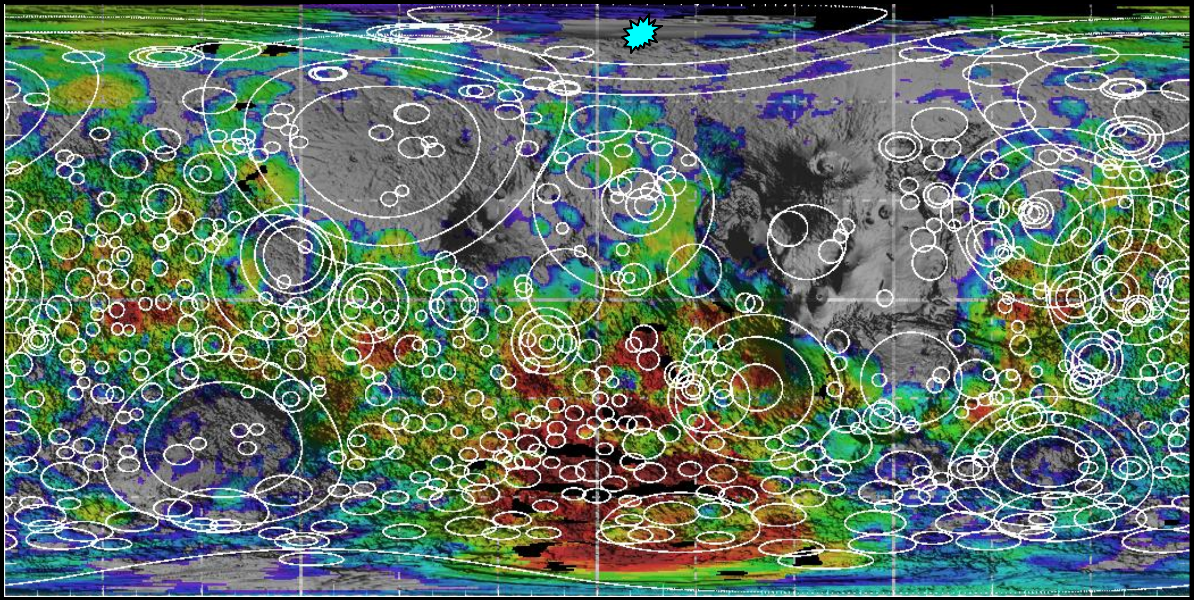


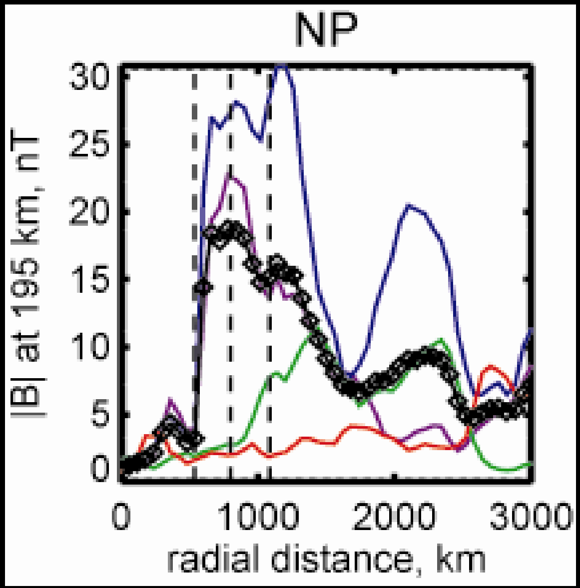


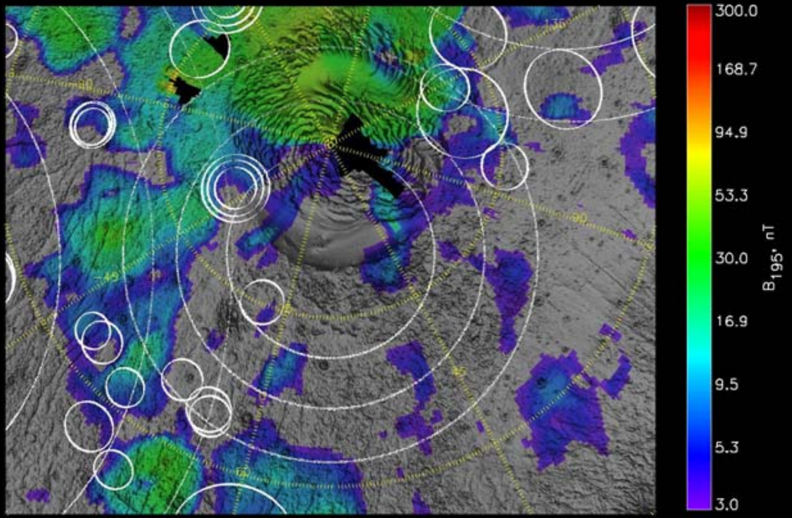


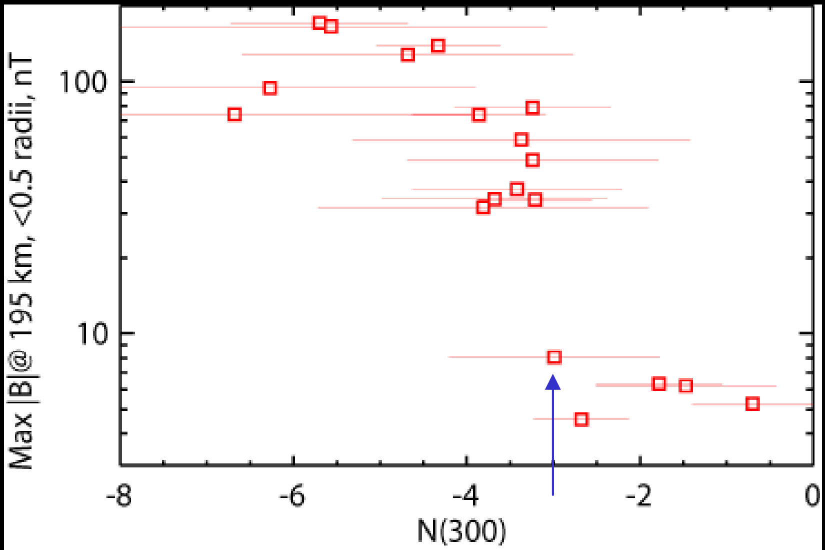


Impacts in order of crater retention age

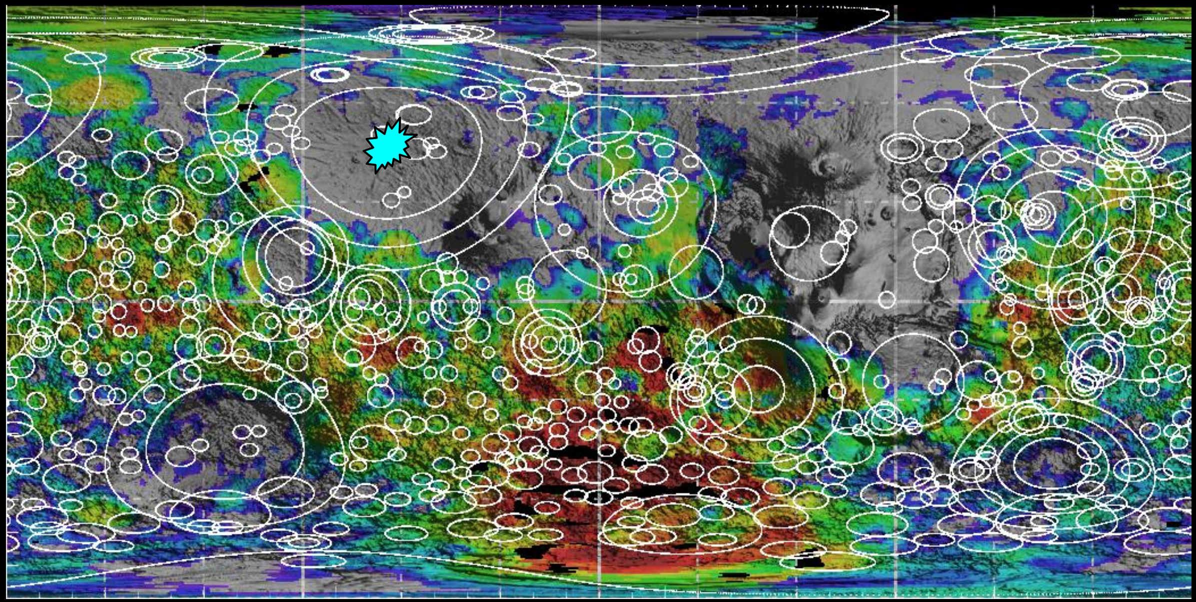


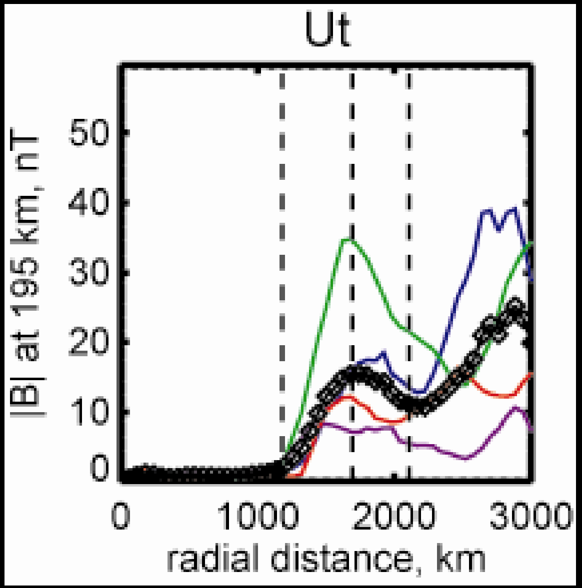


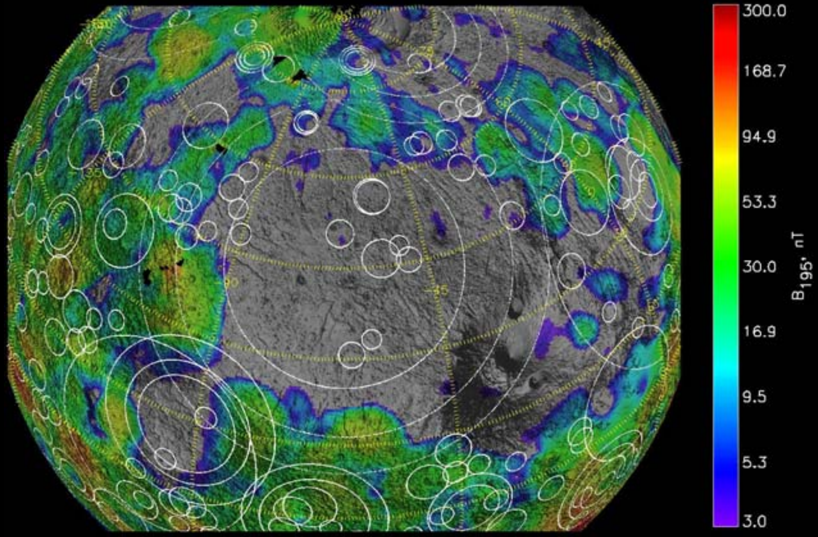


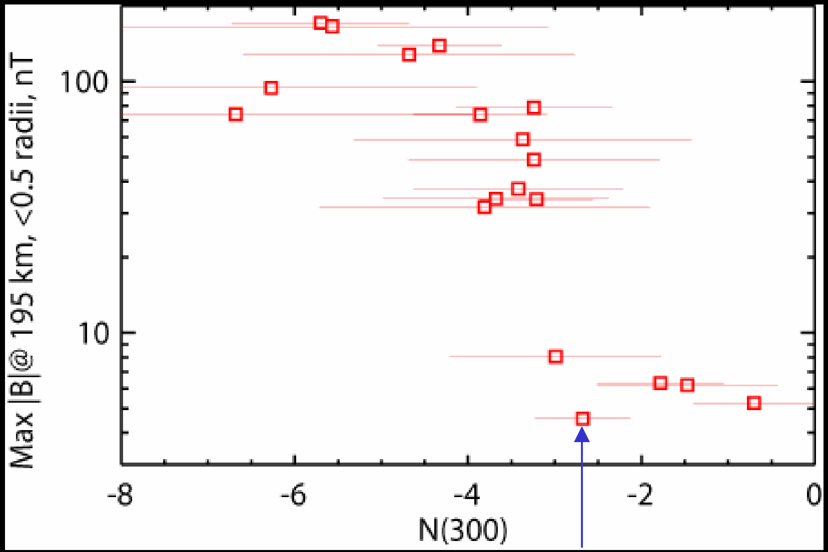


Impacts in order of crater retention age

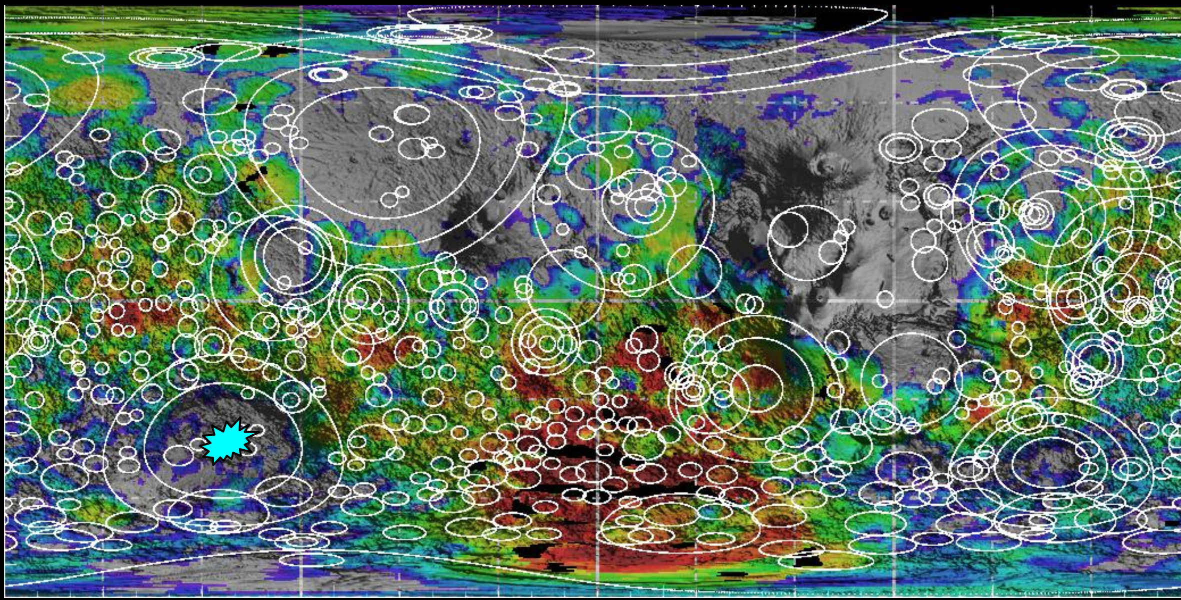


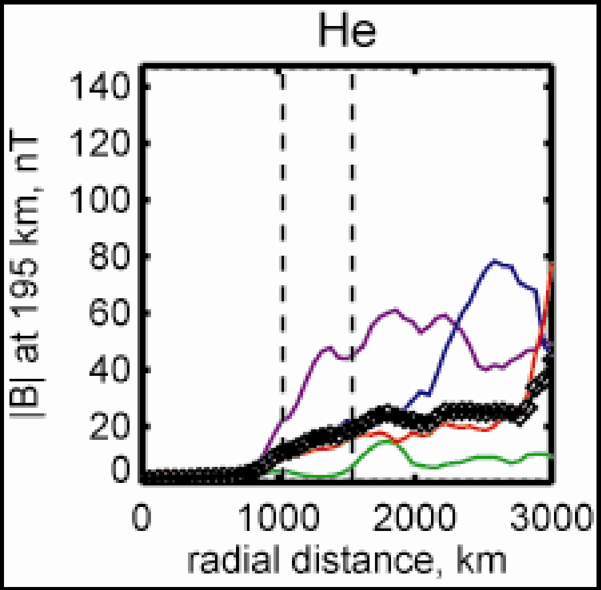


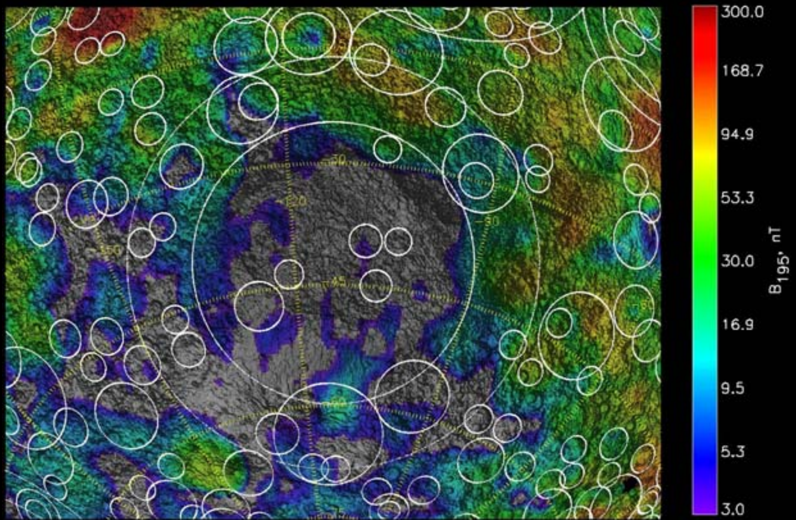


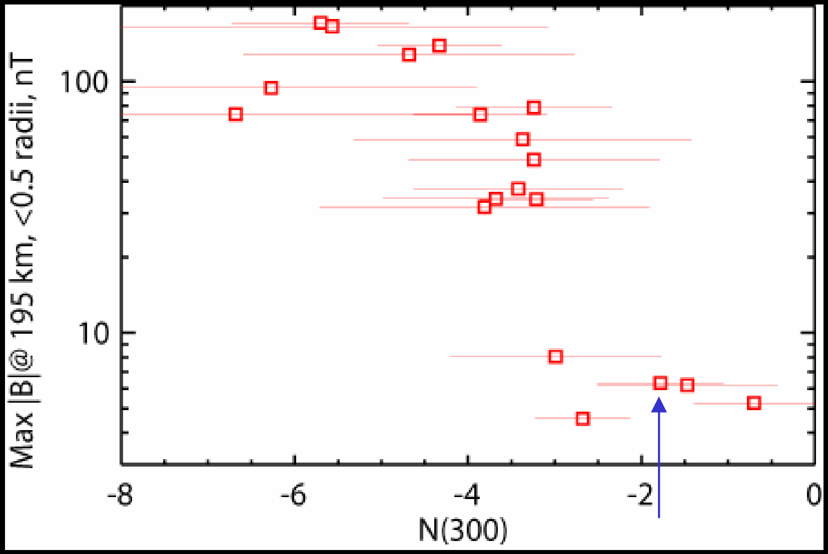


Impacts in order of crater retention age

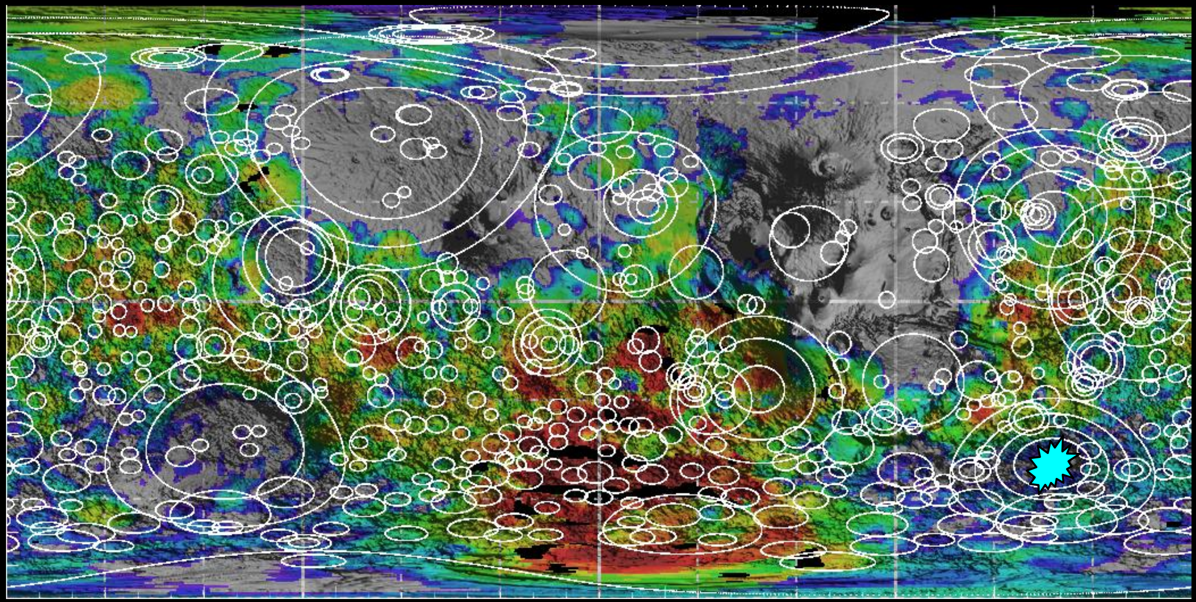


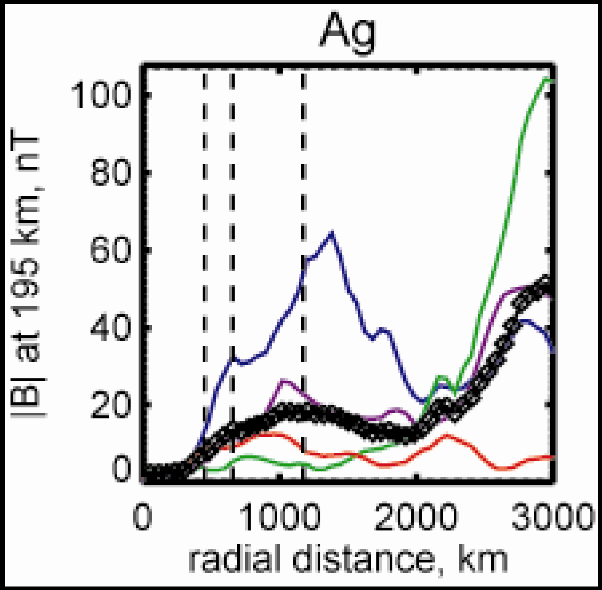


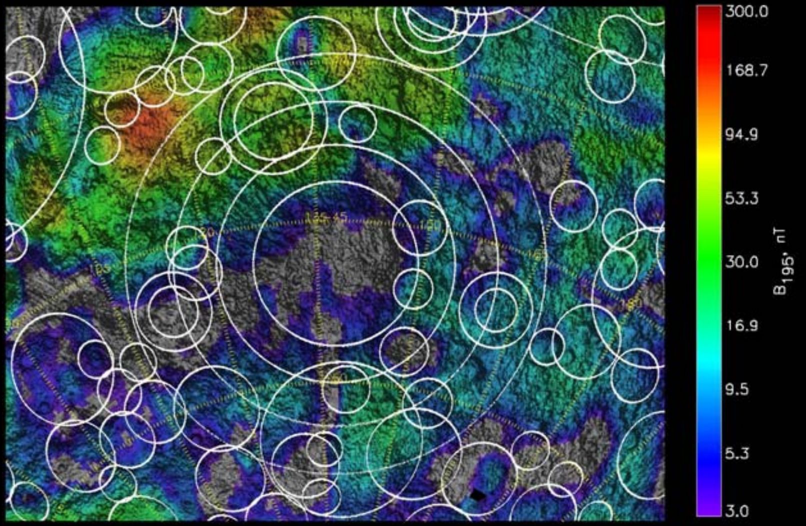


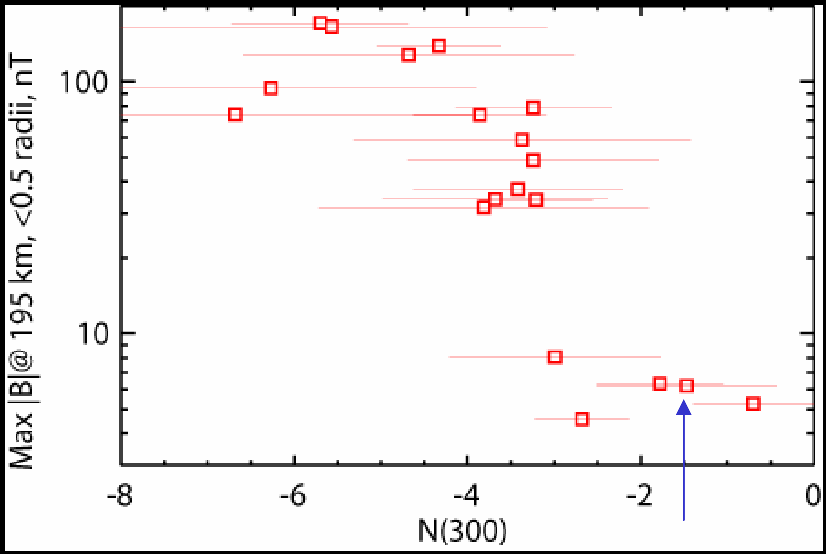


Impacts in order of crater retention age

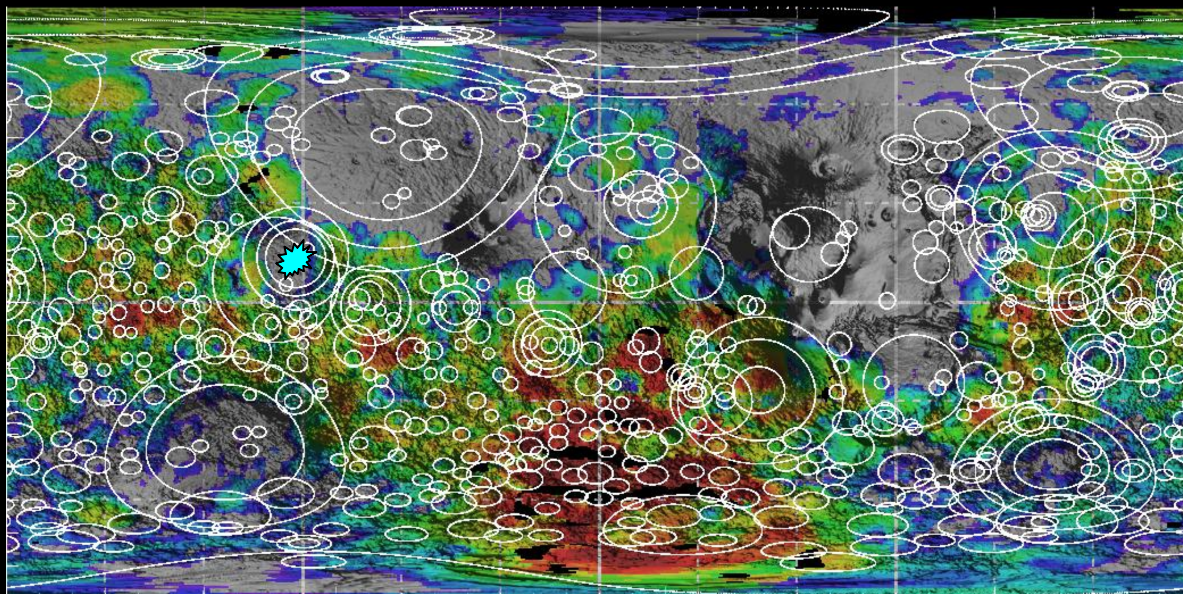


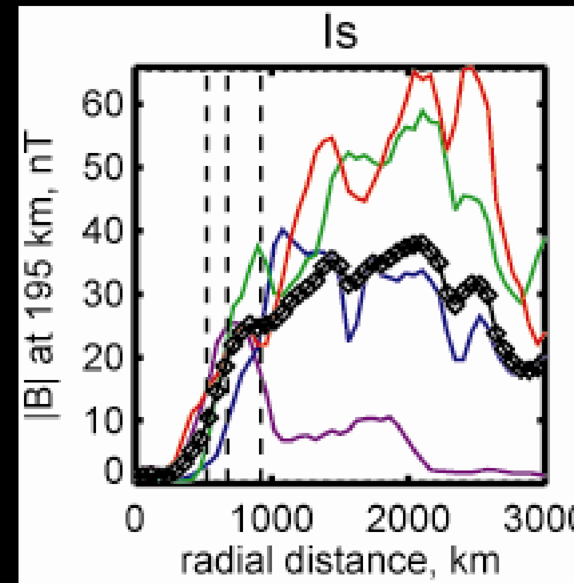


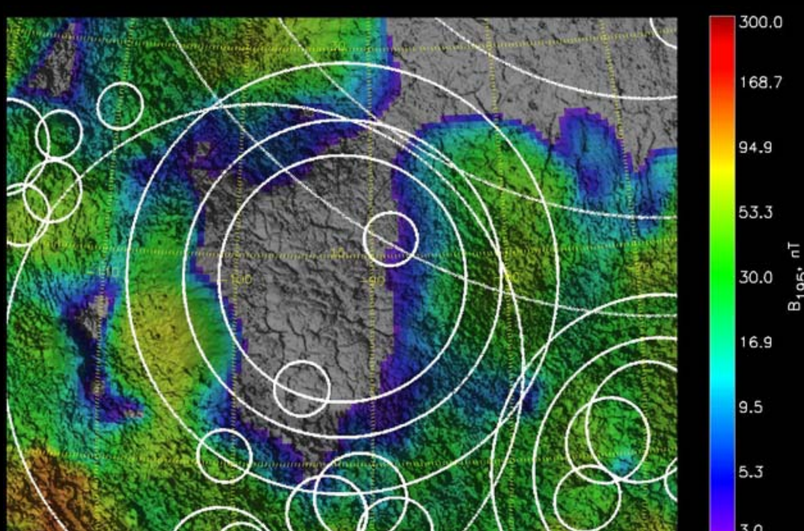


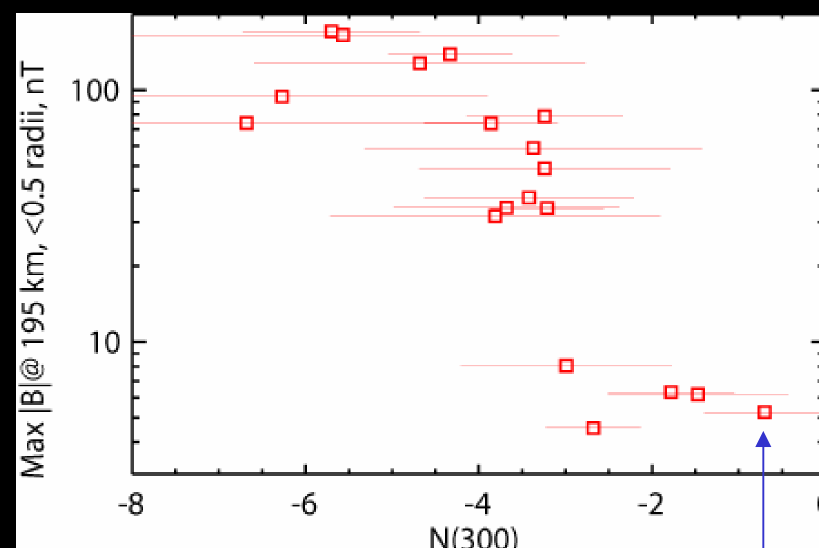


Impacts in order of crater retention age



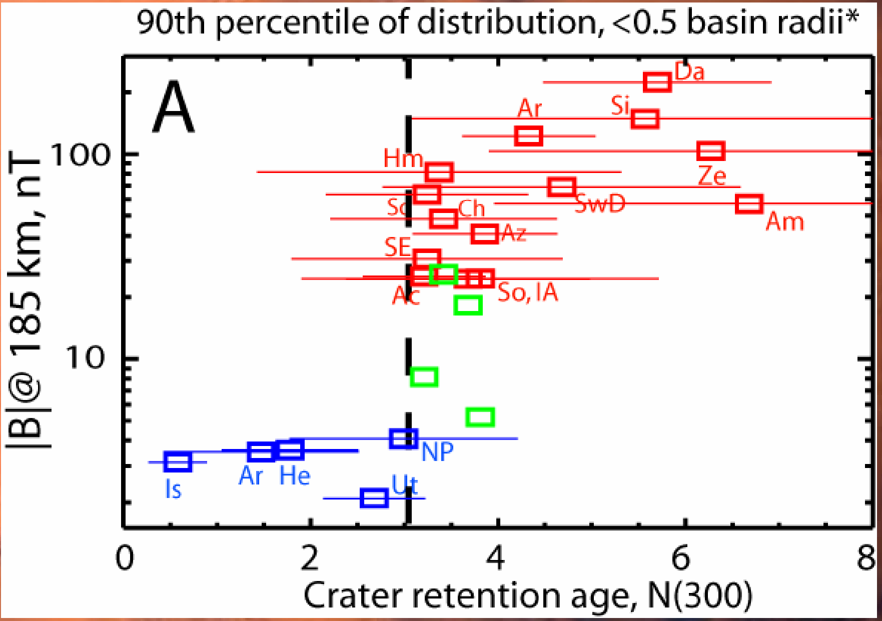






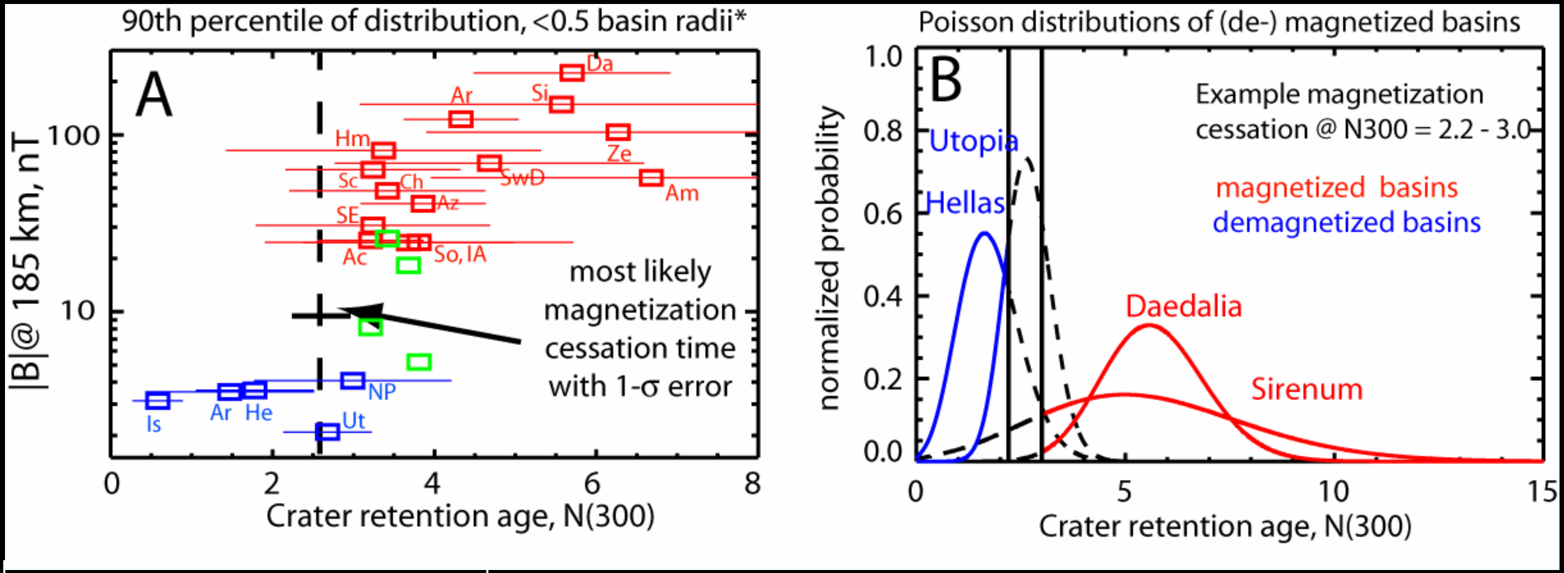
Implications for the Mars Dynamo

- Young basins are at least an order of magnitude less magnetized than older basins.
  - → separate Dynamo and post-Dynamo epochs on early Mars
- 8 magnetized and 2 demagnetized basins occur in the narrow range N(300) ~2.7 - 3.8, within their errors.
  - → *Dynamo cessation was rapid if it only happened once.*



Statistical analysis: death of the Dynamo

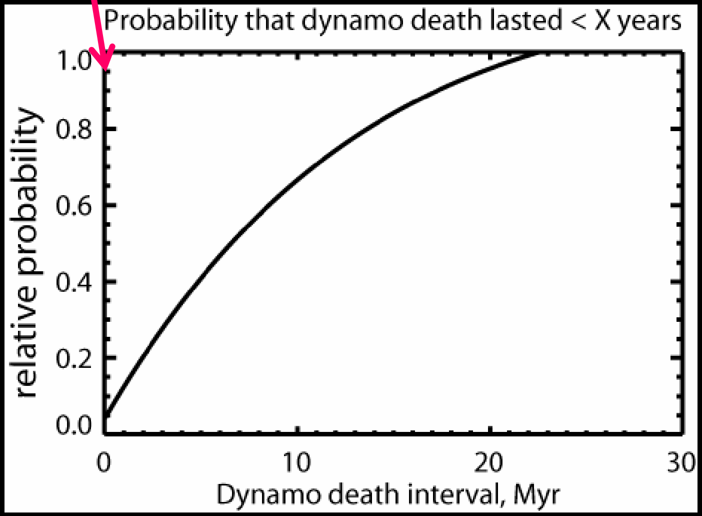
- Calculated Poisson distributions for the age of each basin.
- For a given Dynamo shut off time and interval, we summed the probabilities of magnetized basins forming before, and demagnetized basins forming after, the interval.
- This gives an overall relative probability for that time, interval over which the Dynamo died.

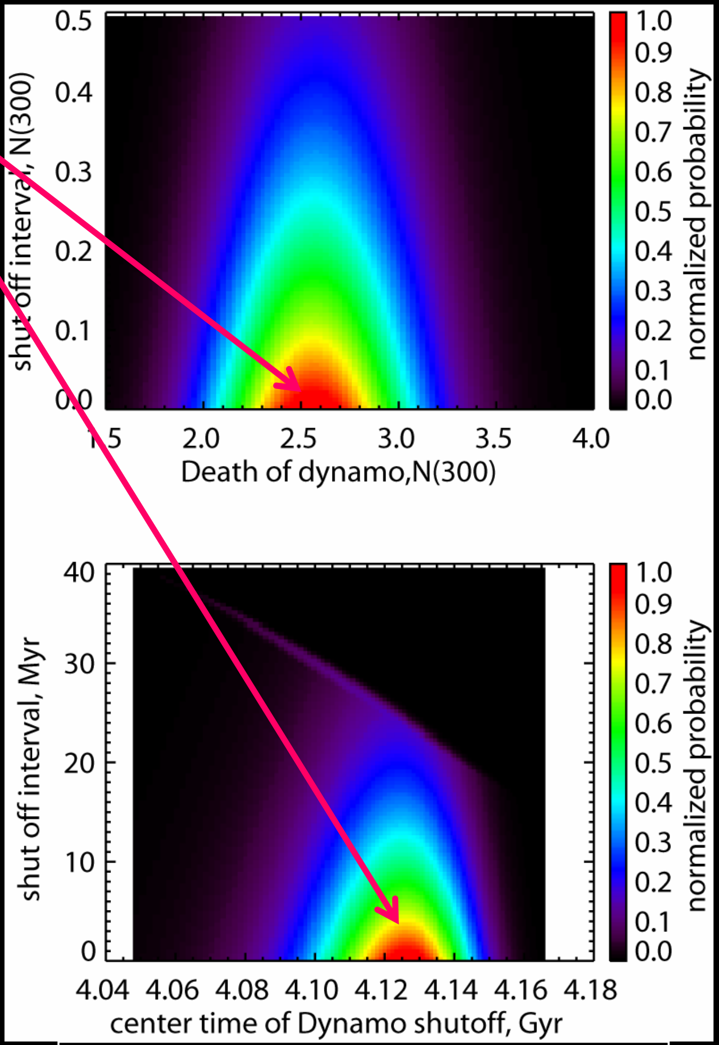


From Lillis et al., 2008, *GRL*.

Dynamo death was likely rapid

- Most likely shutoff time was N(300) = 2.6 or 4.125 Gyr in *absolute model age* [Hartmann and Neukum, 2001. Statistical error is small (10 Myr) but systematic error may be 300 Myr.
- More confidence in dynamo death interval:
  - 96% chance it took less than 20 Myr.
  - 67% chance it took less than 10 Myr.
  - 41% chance it took less than 5 Myr…. Etc. etc.





From Lillis et al., 2008, *GRL*.

Mars subcritical dynamo simulations

A quick overview of recent, related work by Weija Kuang and others.

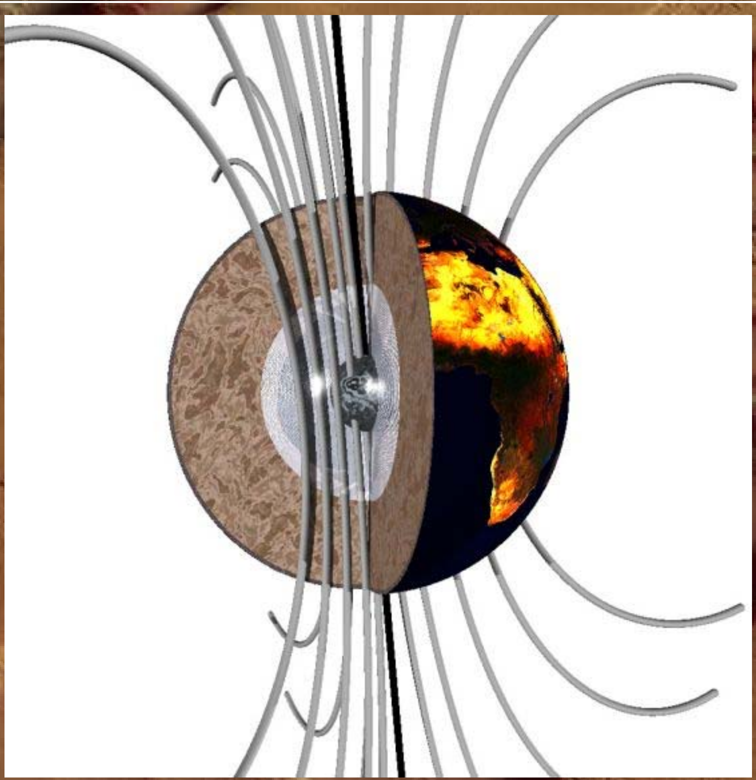


Illustration courtesy of Max Planck Institute

Subcritical dynamos

- Def: when the energy required to maintain a dynamo is significantly higher than that required to excite it.
- In a strong-field dynamo, the Lorentz force from the existing magnetic field helps drive convection and can be comparable to the Coriolis force.
- But to excite a dynamo in the first place, convection must be driven without the help of the Lorentz force

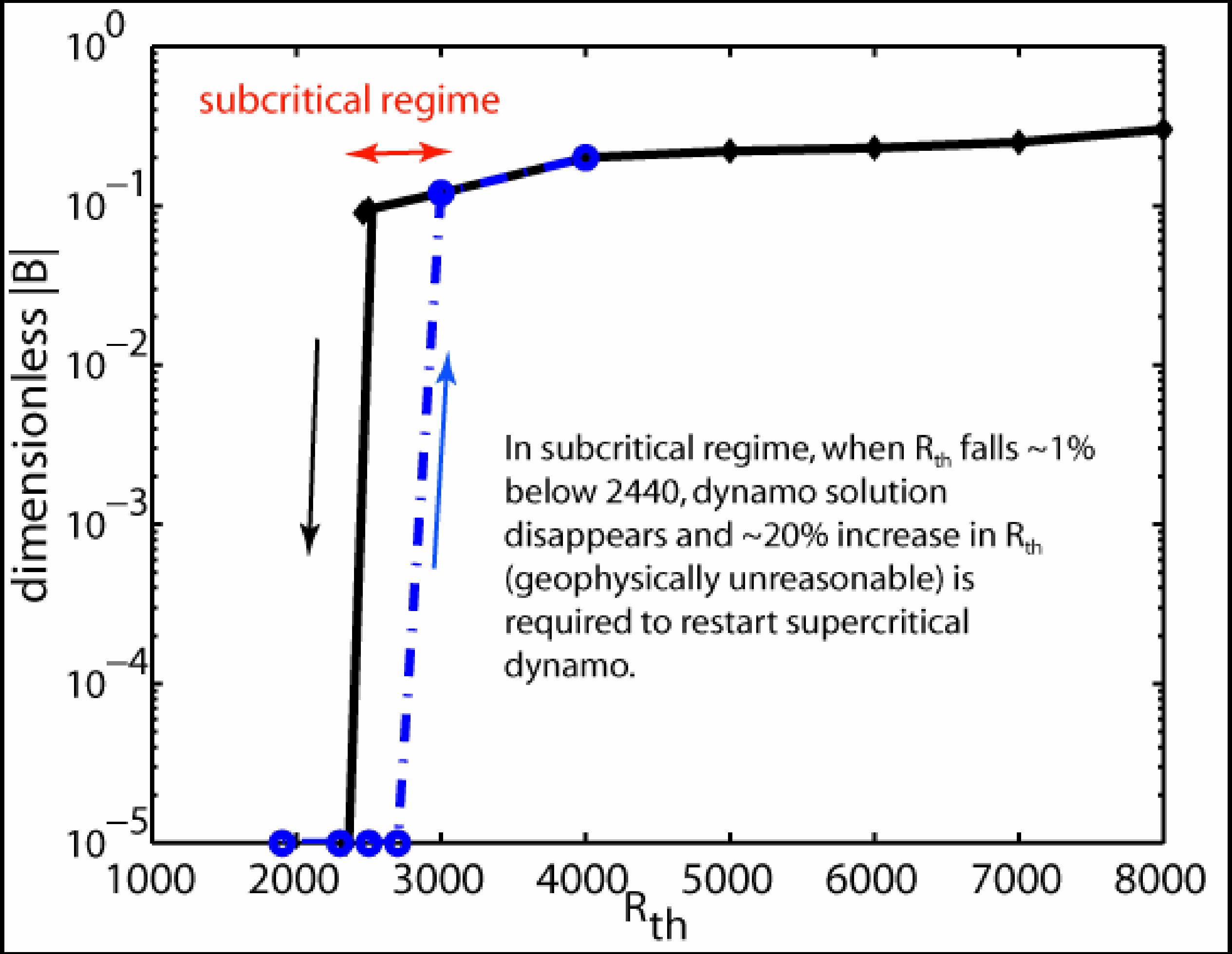
  → need larger buoyancy forces for initiation than maintenance.
- Demonstrated analytically by Childress and Soward [1972] and confirmed numerically by St. Pierre [1993].

Could the Martian Dynamo have been in a subcritical regime during its final stages?

Mars Dynamo modeling framework

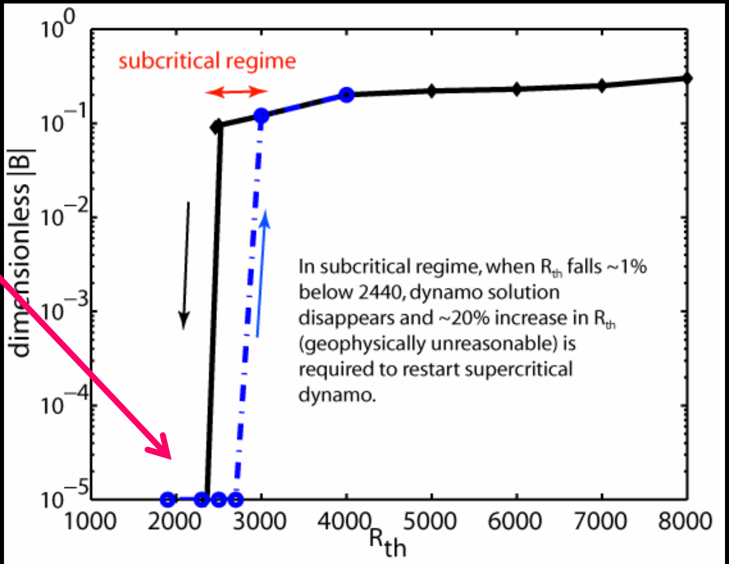
- Adapted from terrestrial codes developed by Kuang & Bloxham [1999], Kuang & Chao[2003], Kuang and Jiang [2007].
- Assume $Ro = E = 1.25 \times 10^{-6}$ (too big for Mars by 100 and 10^8).
- $R_{Mars} = 3400$ km, $R_{cmb} = 1600$ km, $R_{icb} = 500$ km.
- The Rayleigh number R_{th} describes the buoyancy force, *i*.e. the energy for the dynamo. It is the adjusted parameter.
- The initial state for each new simulation starts with the final state from the previous Rayleigh number.
- Idea is to find the critical Rayleigh numbers for turn-on and turn-off of the Martian Dynamo.

Mars Dynamo simulation results



Comparison to data?

- Subcritical dynamo's field strength can fall by ~2 orders of magnitude following a ~1% decrease in the core Rayleigh number.
- Or roughly ~1% of its lifetime: ~5 Myr, *consistent with basin magnetic signatures.*
- Therefore, a small perturbation in the superadiabatic core-mantle heat flux (i.e. the dynamo's power source) at the right moment can shut it down permanently.



Dynamo died during a "heavy bombardment". A Coincidence?

Two Hypotheses

- Impacts dump a lot of heat into the interior
- Mantle temperature rises
- Temperature gradient at CMB drops
- Core HF is reduced
- Dynamo shuts down

- Impacts dump a lot of heat into certain regions of the interior
- Lateral temperature variations create additional buoyancy
- Convective vigor increases
- Core HF is enhanced

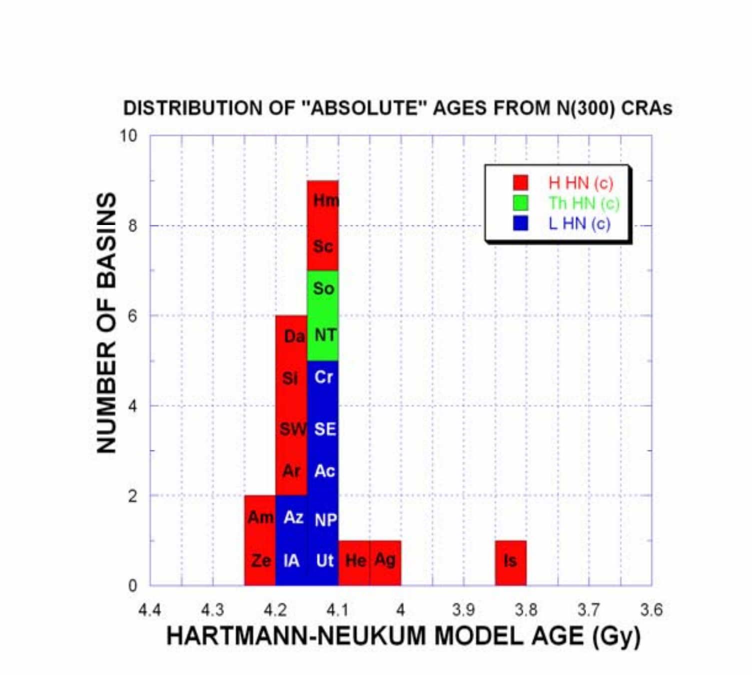
Two competing effects:

Mantle heating vs. Convective vigor

Which one is more important?

Impact Ages

- Timing of the impacts may be important
- If they all happen at once, all the heat is dumped in at once, may overheat the mantle
- More gradual time spacing of impacts gives the heat a chance to dissipate
- Sequence of impacts based on absolute model ages for 20 giant impact basins [Frey et al., 2008]

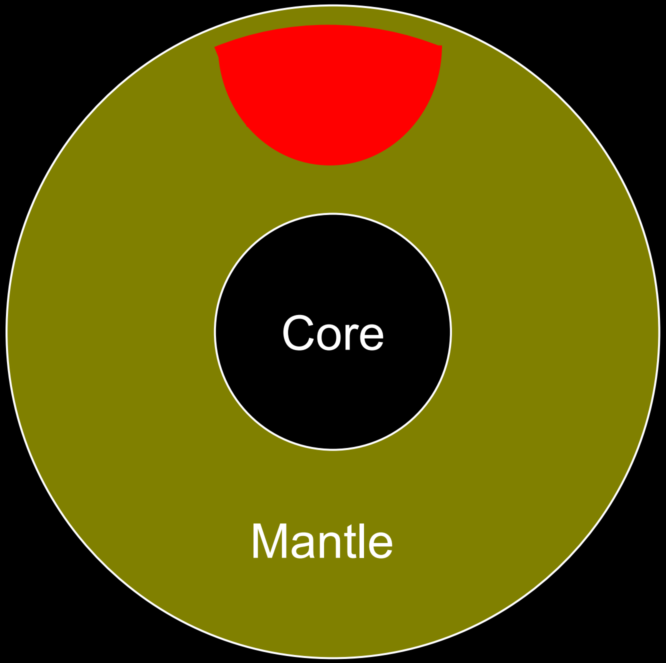


Mantle Convection Modeling

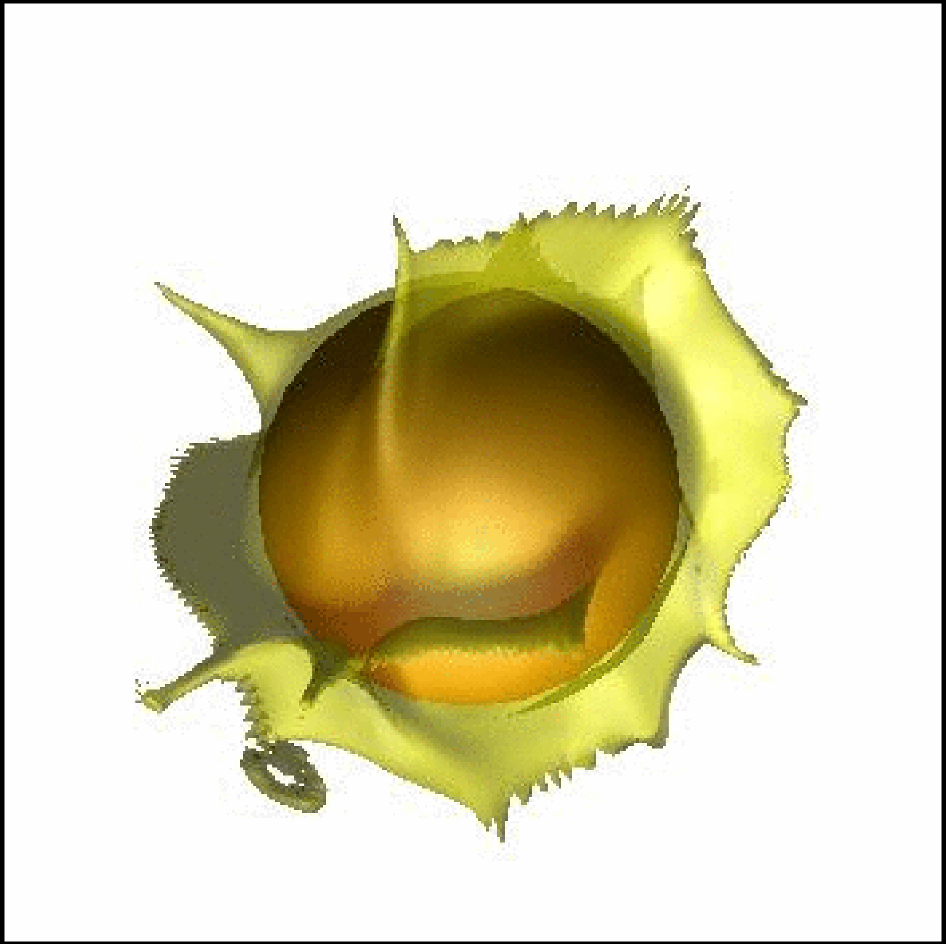
- CitcomS
  - 3D spherical FE mantle convection code [Zhong et al., *JGR*, 2000]
- Temperature- and pressure-dependent viscosity
- Internally heated by radioactive decay [Wanke and Drebius, 1994] and potentially by impacts
- 1.3 million elements in numerical grid
- Isothermal and Free-slip Boundary Conditions
- Random initial perturbation to temperature field
- Special thanks to Shawfeng Dong, Gary Glatzmaier, and Shijie Zhong for access to computing resources

Impact Heating

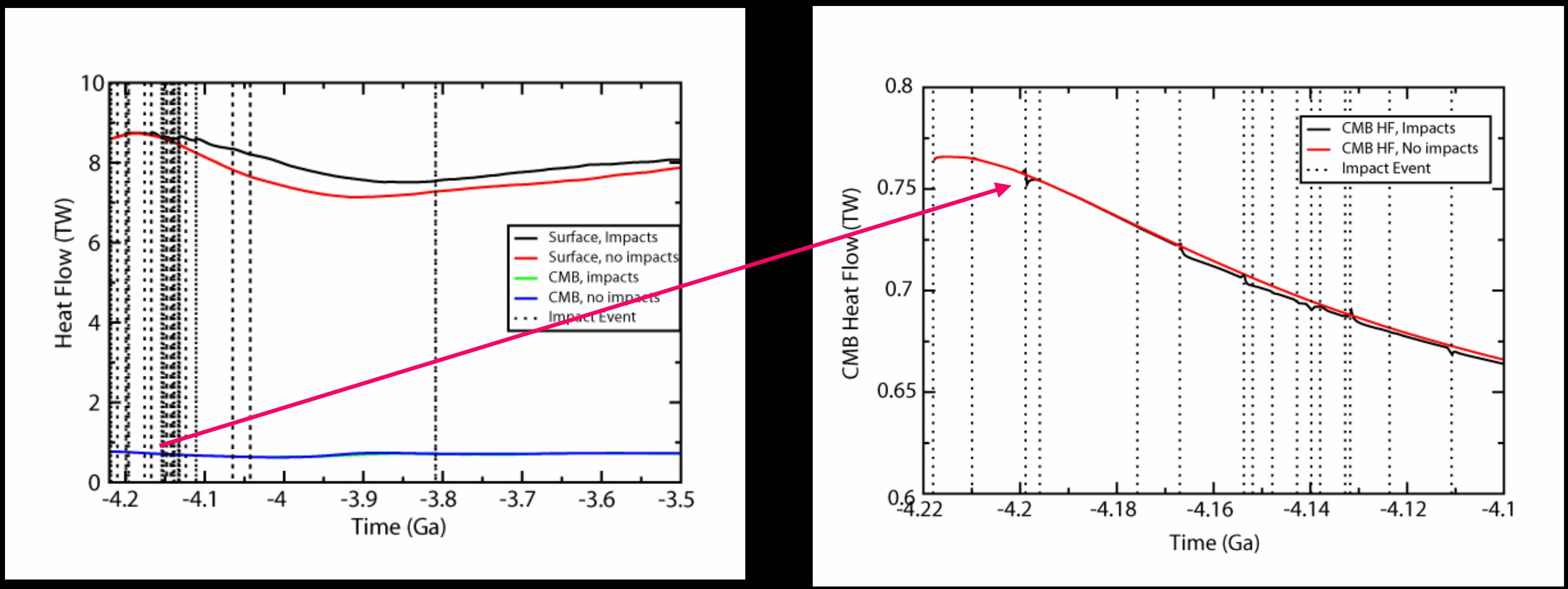
- Each impact has a heating region associated with it
- Hemispherical, size scales with size of basin [Reese et al., *JGR*, 2002].
- Temperature in heating region increased by 300 K
- Also run a control case with no impact heating



Heat dissipation from impacts



Surface/CMB heat flux



- Impact melt induces a buoyant plume.
- Plume rises, increases surface heat flow.
- However, only ~1% effect on *total* CMB heat flow.

Related work at CIDER

- Better impact heating model, to include melt.
- Keep track of and analyze spatial variations of heat flow, velocity
- Try different initial and boundary conditions

30-second summary, in case you fell asleep

1) Several newly-discovered giant, old impact basins on Mars.
2) 'Spike' in impacts ~4 Ga. Mars equivalent of lunar LHB?
3) Giant impacts remove crustal magnetization. Crust is only re-magnetized if a dynamo magnetic field is present.
4) Magnetic signatures of old basins suggest Martian Dynamo lasted ~400 Myr, then died quickly, <10 Myr, toward the end of this 'spike' in giant impacts.
5) Rapid death is consistent with recent subcritical dynamos simulations. ~1% drop in CMB heat flux kills dynamo.
6) Mantle convection simulations show giant impact can deliver ~1% variations in CMB heat flux: enough to hasten Dynamo death by a modest amount: maybe ~20 Myr. Likely coincidence.