Comparing the Exospheres of Mercury and the Moon

T. H. Morgan, R. M. Killen, and D. M. Hurley

- What do the Exospheres have in Common?
- How are they different?
- What can what we know about one, inform us about what we should look for on the other.
- Special topics

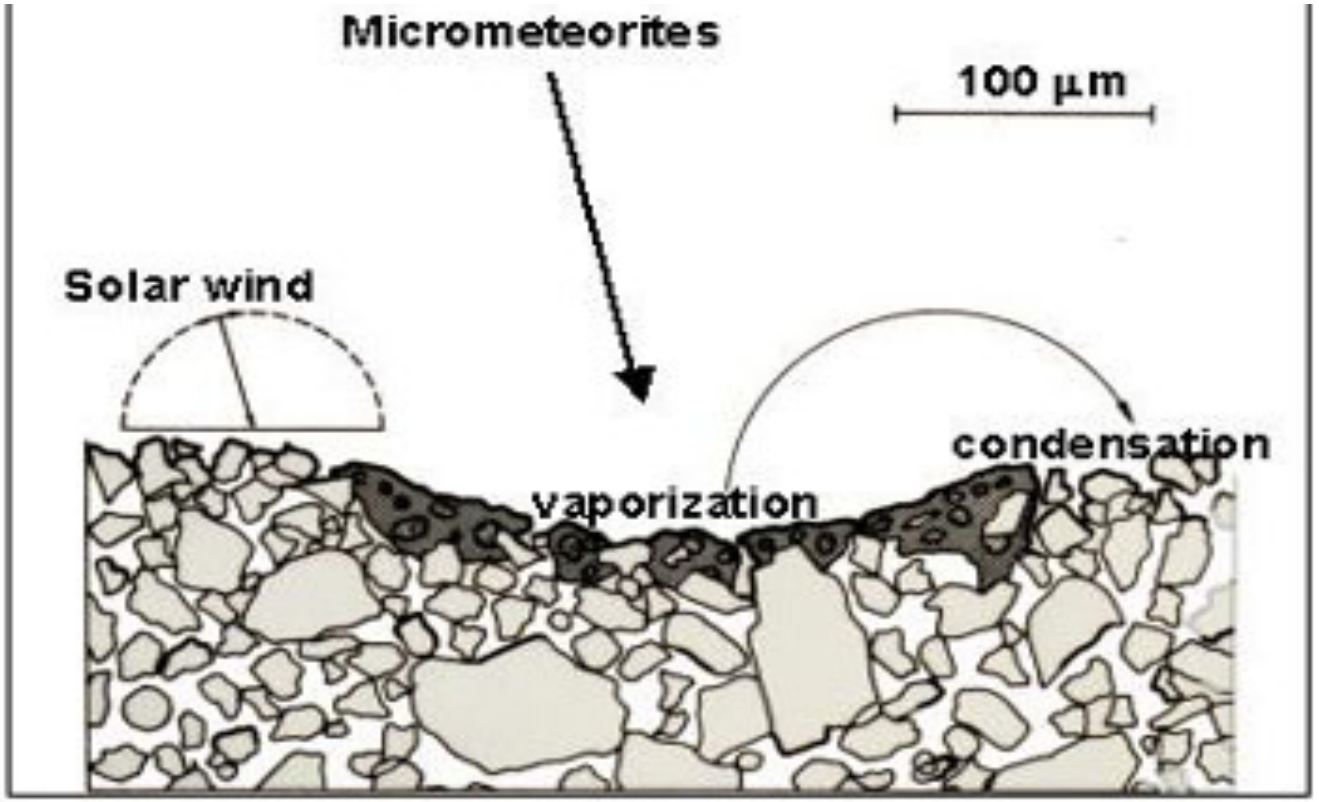
With thanks to M. Burger, R. Vervack, M. Sarantos, E. Miekowicz, C.Schmidt, P. Peplowski, L Evans

What the Exospheres of Mercury and the Moon have in Common

Exobase

They are quasi-collisionless (the peak number densities are likely a few times 10^5 atoms/cm^3).

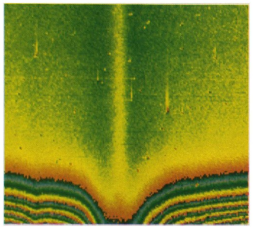
The lower boundary, the exobase, is a complex structure, the regolith. Collisions with the regolith do not, axiomatically, lead to a Maxwell Boltzmann distribution.



(Figure courtesy L. Taylor)

What the Exospheres of Mercury and the Moon have in Common?

Common species



There are three common constituents that have been detected in both Exospheres: Helium; Sodium; Potassium.

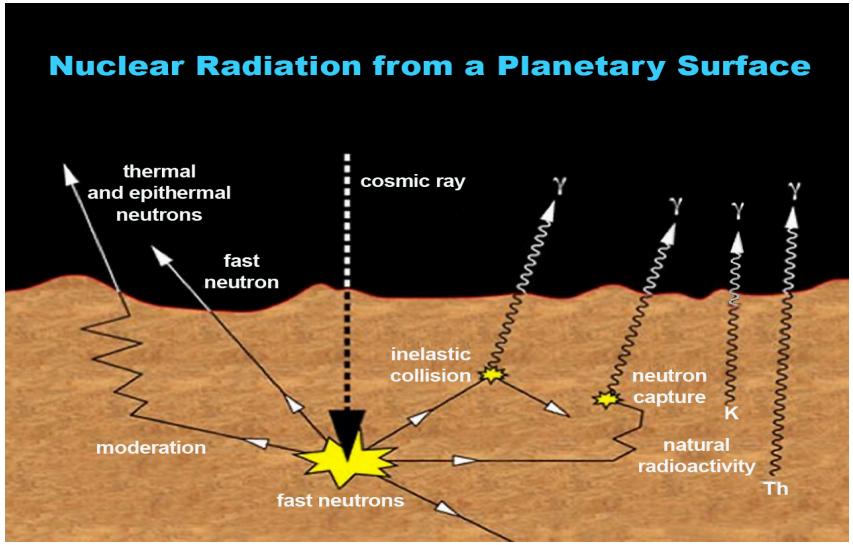
Hydrogen, Oxygen, Magnesium, Calcium, and Aluminum are known to be the exosphere of Mercury.

Argon(^{40}Ar & ^{36}Ar) and a small amount of Radon (^{222}Ra) and Polonium (^{210}Po) are present in the lunar Exosphere.

Most of these species are derived from the regolith

	Mercury	Moon Maria
$A1_20_3$	11.41	8.6
CaO	7.72	9.8
TiO_2	0.57	2.4
MgO	21.29	10.3
SiO_2	54.06	45.2
FeO	2.66	22.1
Na_20	--	0.31
K_2O	0.14	0.06

(McCubbin et al., 2012)



What the Exospheres of Mercury and the Moon have in Common
Sources

What is a source?
A source is a process that promotes an element in the surface into the atmosphere, or delivers the element to the surface by a process that allows ready release.

In the case of a sufficiently volatile and inert species, diffusion from the interior may be viewed as a source.

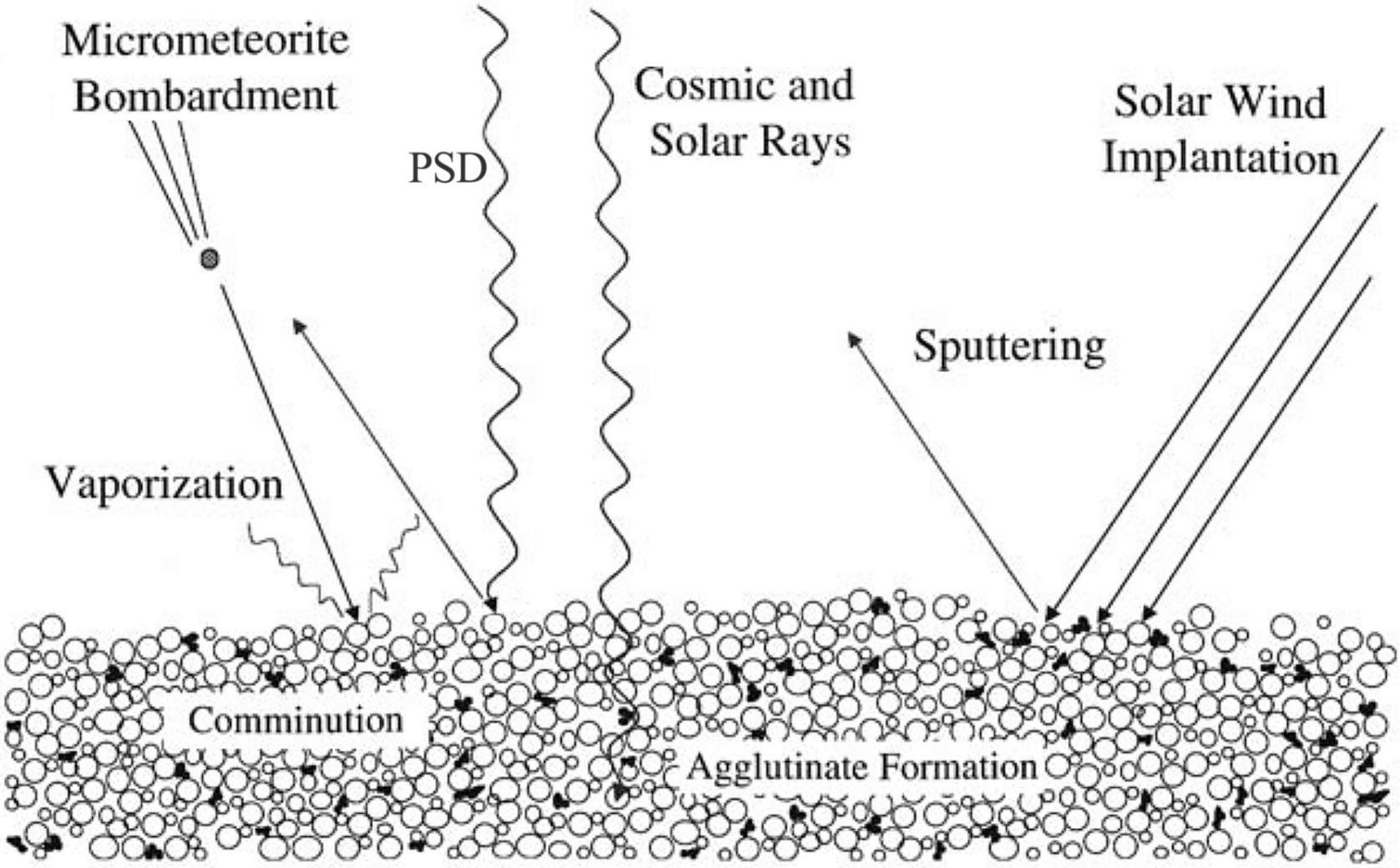
Mercury and the Moon appear to share common source processes. They are:

1. Sputtering (requires a flux of ions)
2. Impact vaporization (Requires a flux of IPDs, and may provide volatiles)
3. Photon Stimulated Desorption.
4. Diffusion

.
The differences for 1-3 are, to first order, in the external rates (which can be quite large). They also vary differently with local solar zenith angle. Diffusion is temperature dependent.

What you see in the exosphere, however, will be strongly modulated by the gas-surface interaction.

What the Exospheres of Mercury and the Moon have in Common
Sources (continued)



What the Exospheres of Mercury and the Moon have in Common Sources

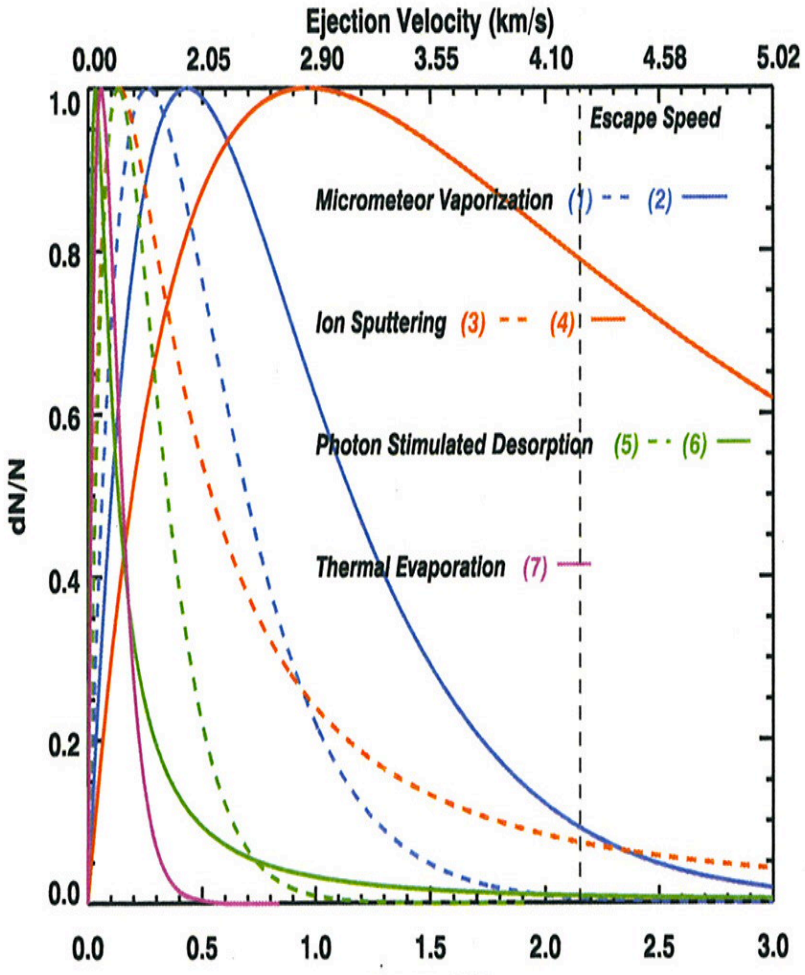
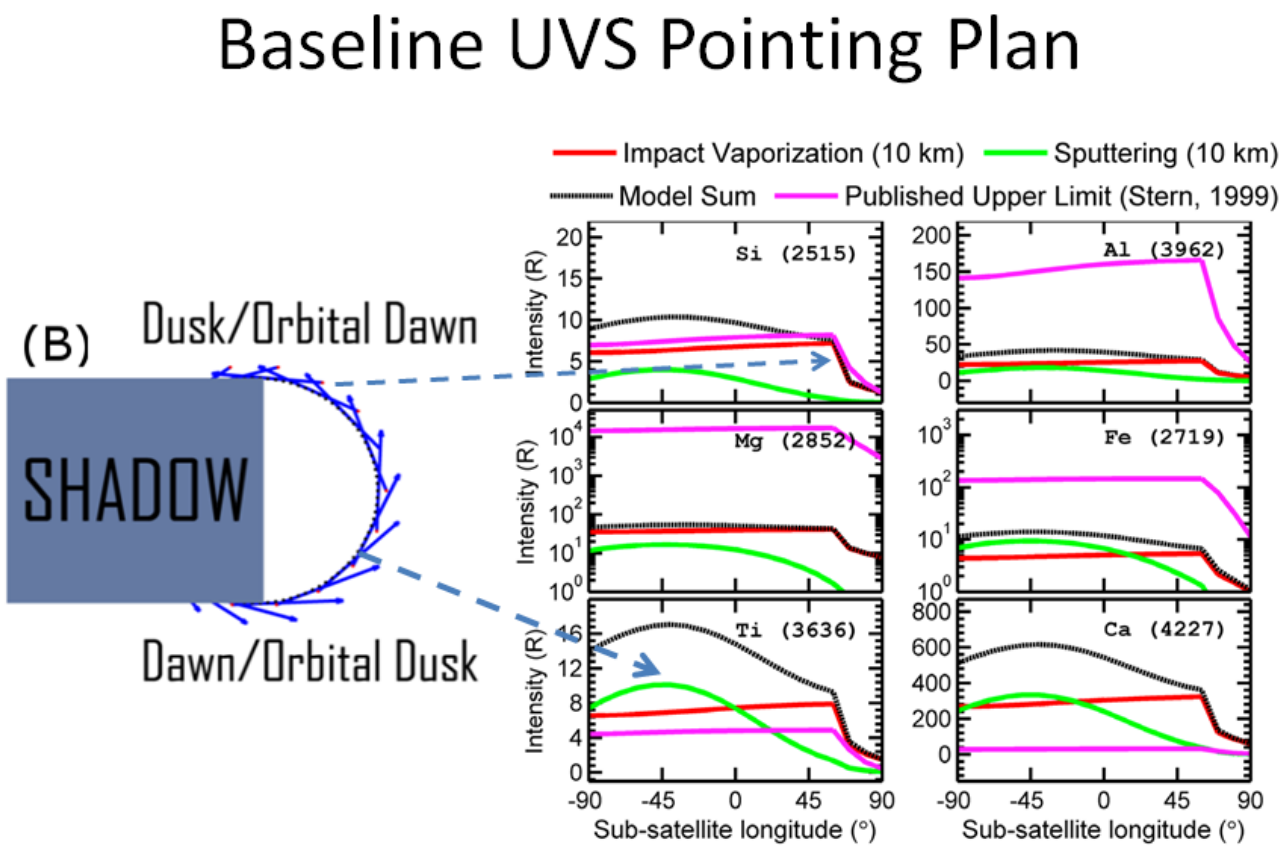


Figure from Schmidt *et al.* 2012 which illustrates the general characteristics of the source processes. (1) Leblanc and Johnson [2003]. (2) Mouawad et al. [2011]. (3) Wiens et al. [1997] (4) Wurz et al. [2010]. (5) Leblanc and Johnson [2003] (6) Johnson et al. [2002] for laboratory measurements of icy surfaces bombarded by 200 eV electrons, modified with a cutoff term at high energies [Wurz et al., 2010]. (7) Sodium thermalized to a 650 K.

What the Exospheres of Mercury and the Moon have in Common Sources--continued



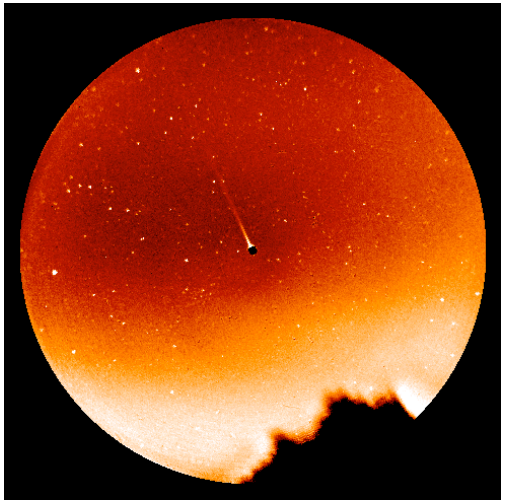
Predictions for LADEE
(SARANTOS *et al*., GRL 2012).

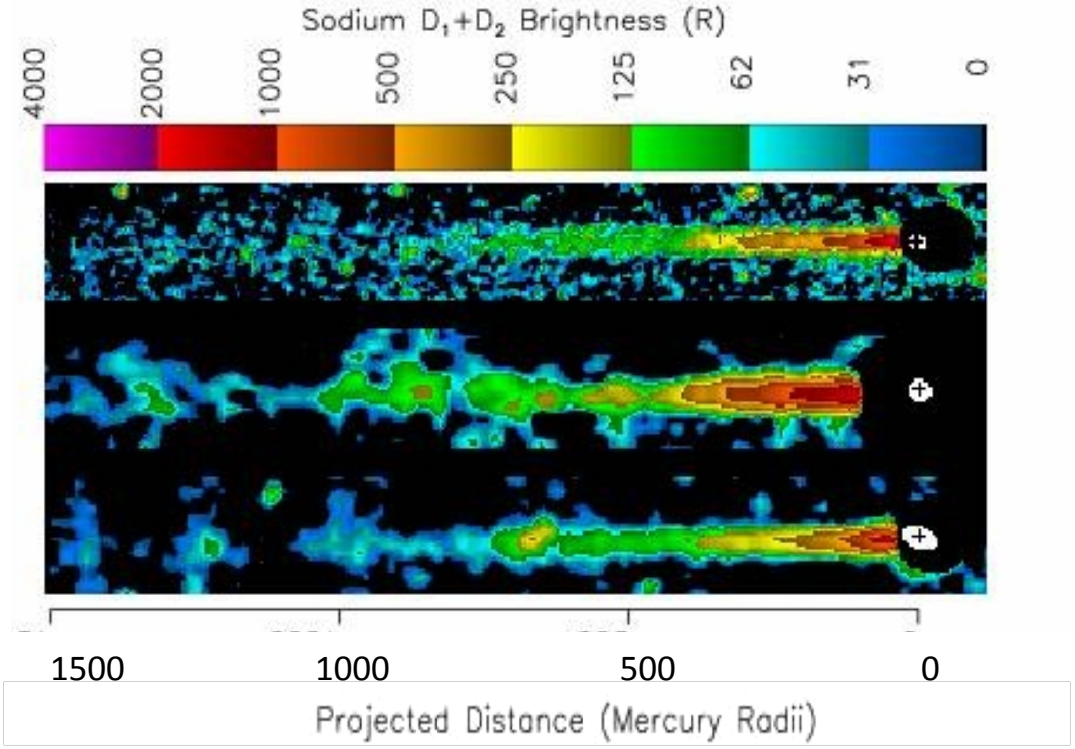
What the Exospheres of Mercury and the Moon have in Common
Loss Processes--tails

Photo-ionization leads to loss or implantation

Each source process produces a spectrum of energies, so there are direct losses.

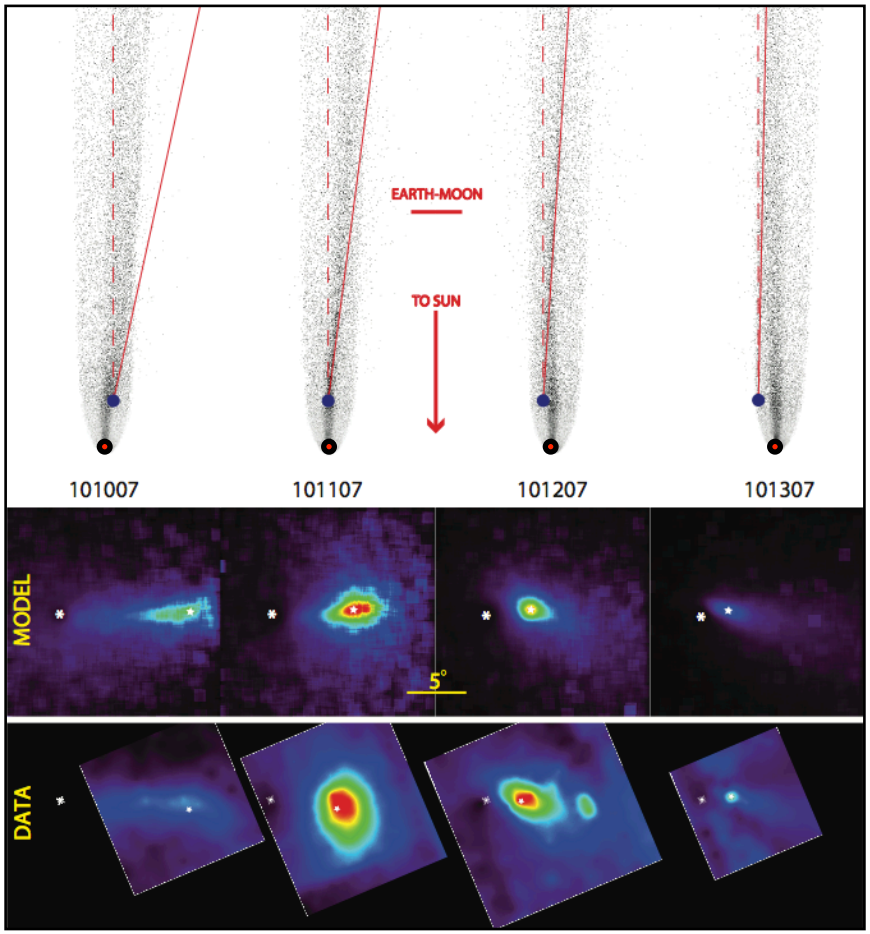
Radiation pressure driven losses are important for Sodium and Potassium



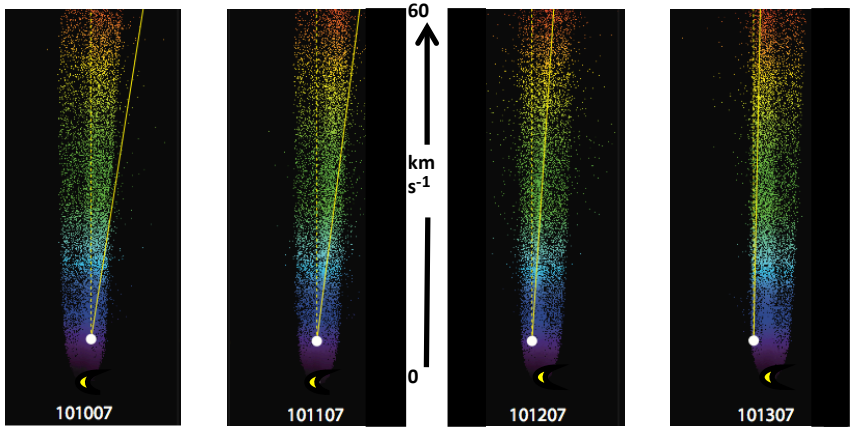


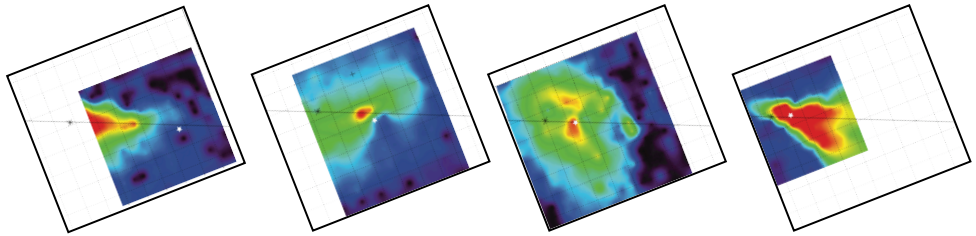
Schmidt *et al.*, 2010)

Lunar Sodium (5890 Å) Tail



- Ed Mierkiewicz *(U Wisconsin/PI),* Ron Oliversen *(NASA-GSFC),* Mike Line *(Caltech)*
- Groundbased Fabry-Perot Spectrometer data *(-1 to +2 days from New Moon)*
- Maps up to 13° x 13° with FOV 1°
- Mean Velocity 12.5 km/s with line widths *(FWHM)* up to 30 km/s
- Supports LADEE objectives – Future observations planned
- Icarus, 219, 609, June 1 (10.1016/j.ICARUS.2012.04.001)





(Top) Intensity Data vs Model *(Monte Carlo simulation)*

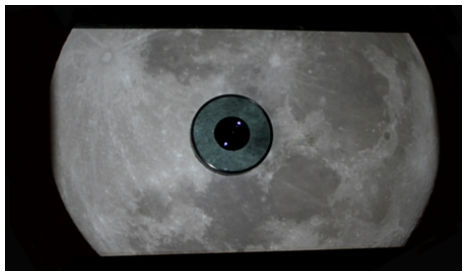
(Right) Line width: 10 – 30 km/s *(bottom);* Model Na velocities: 0 – 60 km/s *(top)*

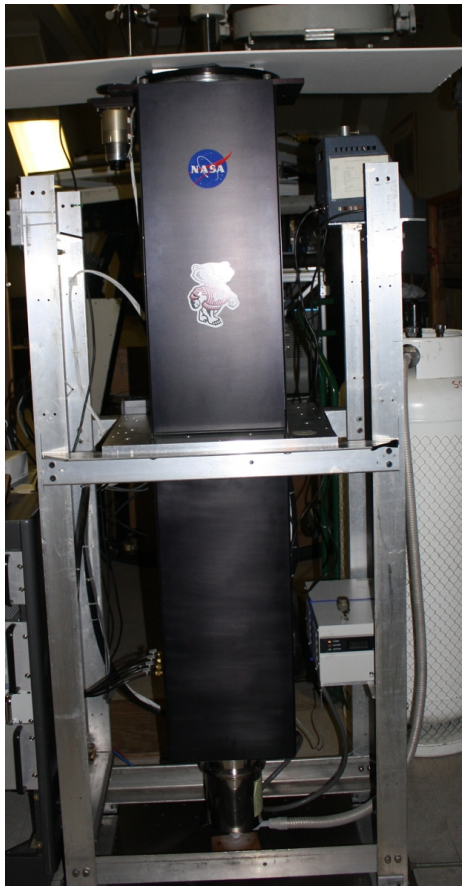
* *anti-lunar direction*

- - - anti-solar direction

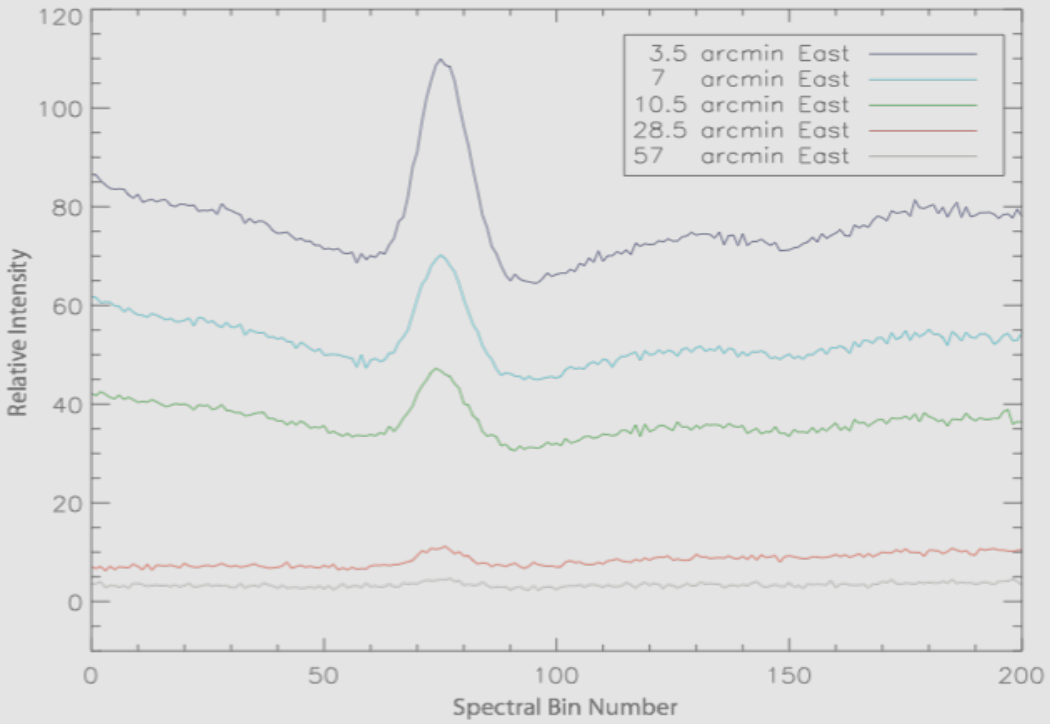
—— direction of maximum intensity

Lunar Exospheric Sodium (5890 Å) Line Profile Measurements





Line Profile Measured off Grimaldi Limb vs. Distance

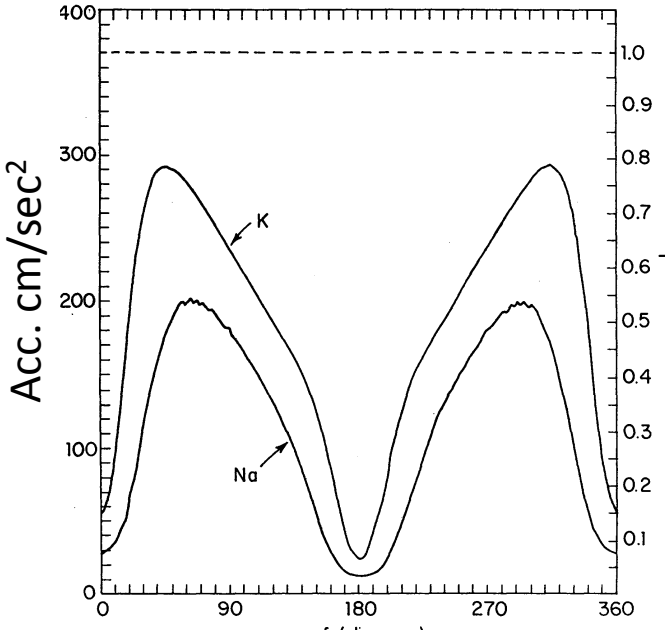


- Ron Oliversen (NASA/GSFC), Ed Mierkiewicz, Fred Roesler (U Wisconsin), Mike Line (Caltech), Olivia Lupie (NASA/GSFC)
- Dual Etalon Fabry-Perot Spectrometer
  - R = 180,000 (1.7 km/s)
  - Spectral Coverage ~ 0.8 Å
  - 3’ FOV (~360 km) typical; 1’ FOV sometimes used at limb
  - FOV centered from off limb edge to 2 Lunar Radii
- NSO McMath-Pierce solar telescope (North Port)

How the Exospheres of Mercury and the Moon can be different
Radiation Pressure

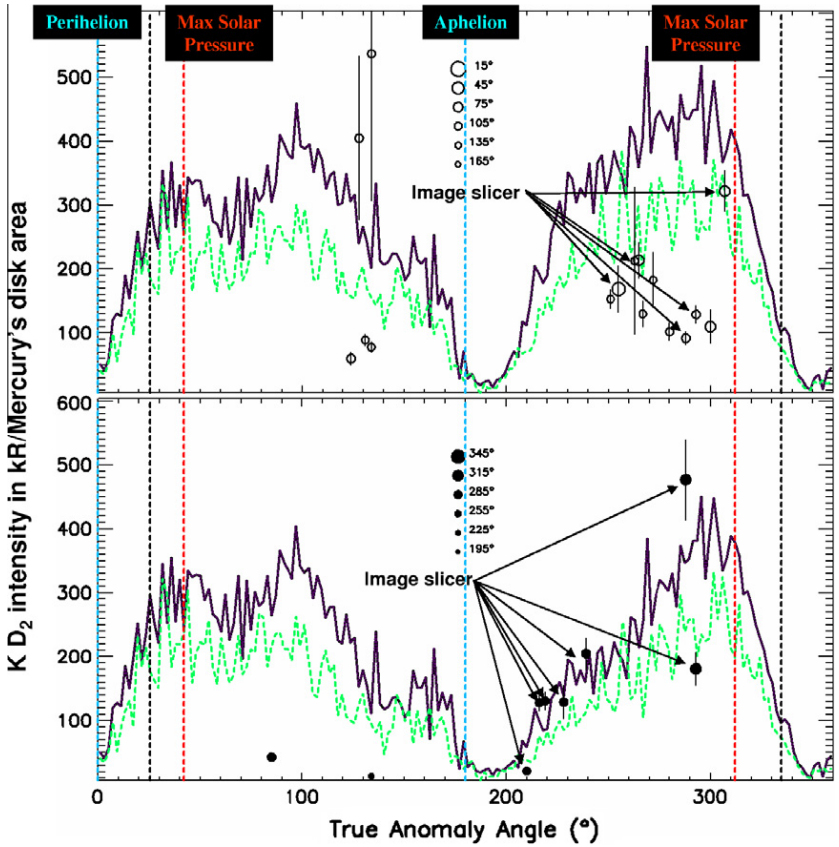
Radiation pressure which varies significantly about Mercury's orbit plays a key role in determining the global abundances of Sodium and Potassium.

acceleration due to radiation pressure below. Impact on Potassium on the right.



True Anomaly Angle

F. Leblanc, A. Doressoundiram / Icarus 211 (2011) 10–20



Effects of an ICME on the Lunar Exosphere

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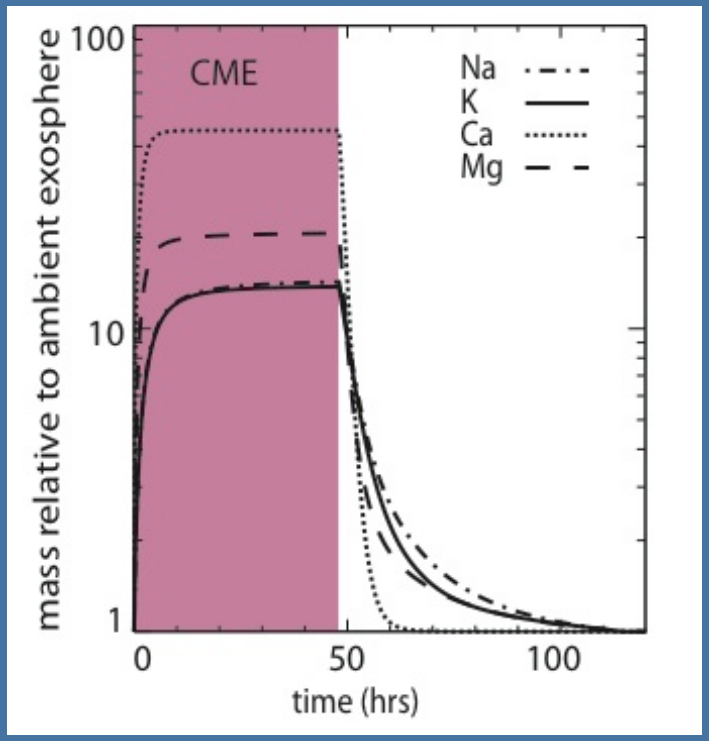
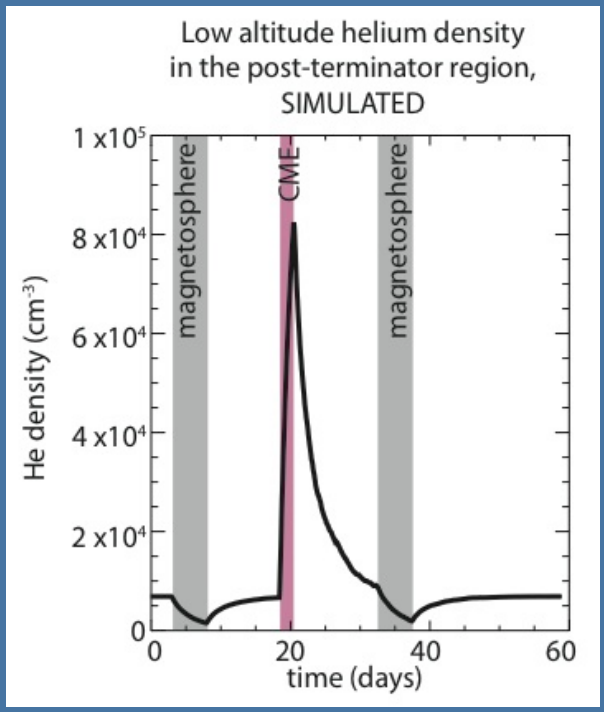
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

RESULTS OF TIME-DEPENDENT MONTE CARLO SIMULATIONS OF THE LUNAR EXOSPHERE

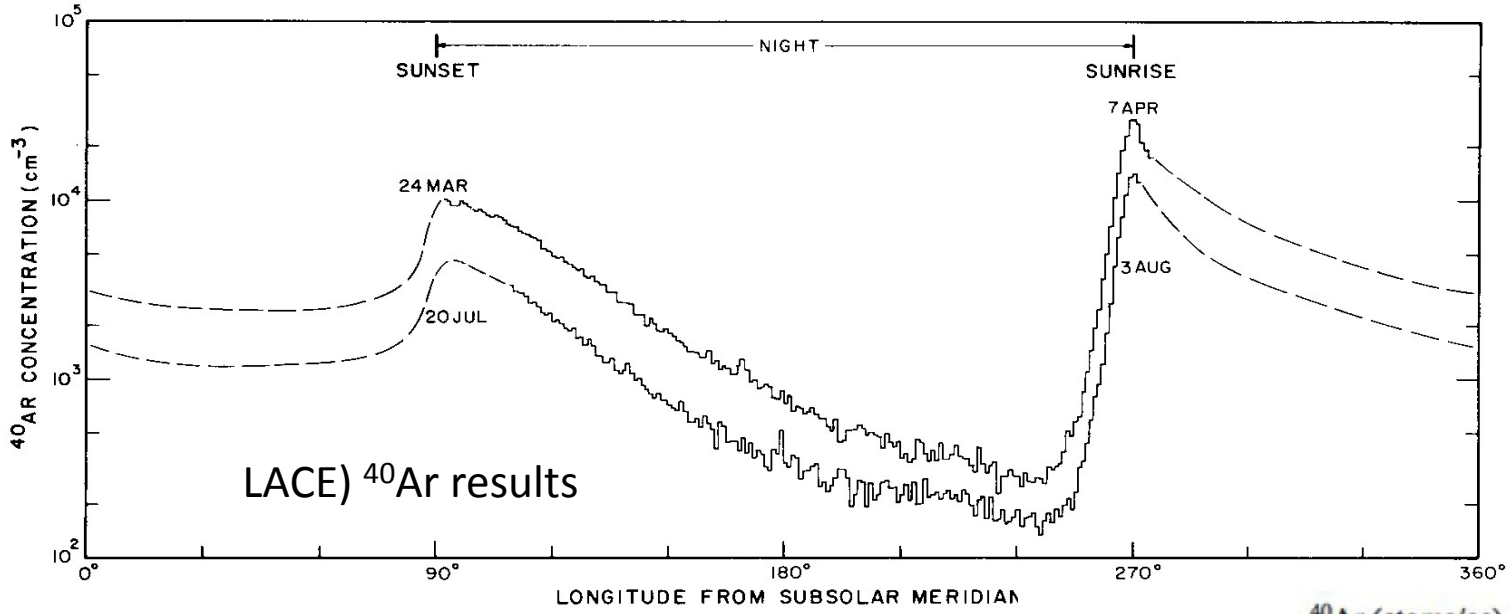


- CMEs increase mass of lunar exosphere by 10-50 because of increased sputtering yields
- Change occurs over few hours to days

- CME increases the He density on the moon because of the higher incident α flux
- Magnetotail passage reduces He atmos.
- Effects in the helium density persist for several days



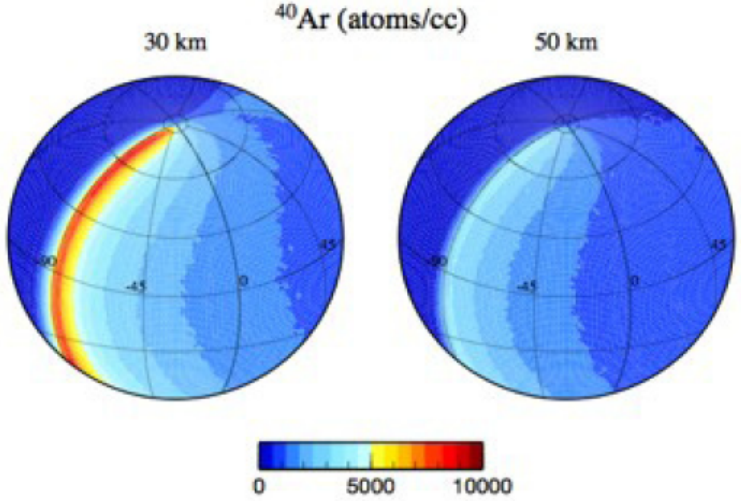
What the Exospheres of Mercury and the Moon May have in Common Ar



LACE) ^{40}Ar results

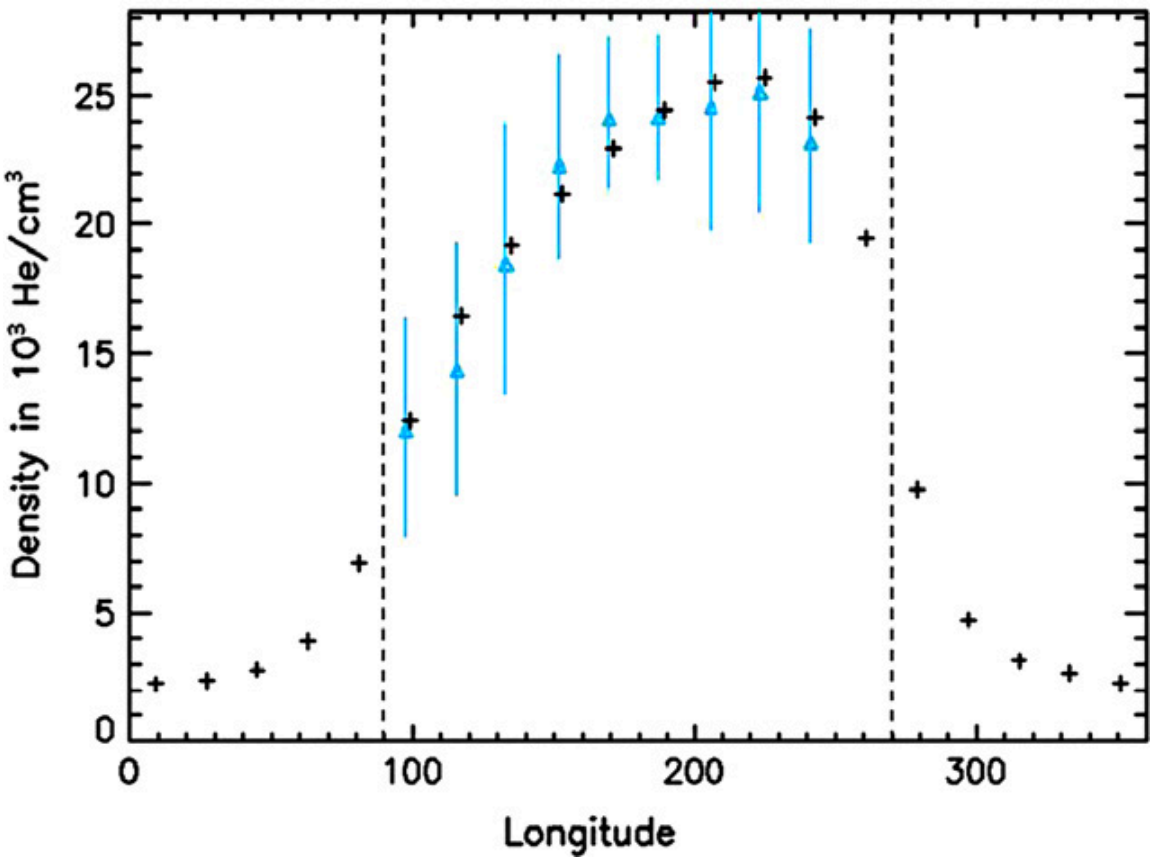
Global model distribution of ^{40} Ar at 30 km and 50 km (provided by D. Hodges). Gas densities peak at the sunrise terminator, where desorption is greatest, > 4000/cc at 50 km.

Note: Ar closure temperatures, can be as low as 300 C in rock forming silicates.



What the Exospheres of Mercury and the Moon have in Common

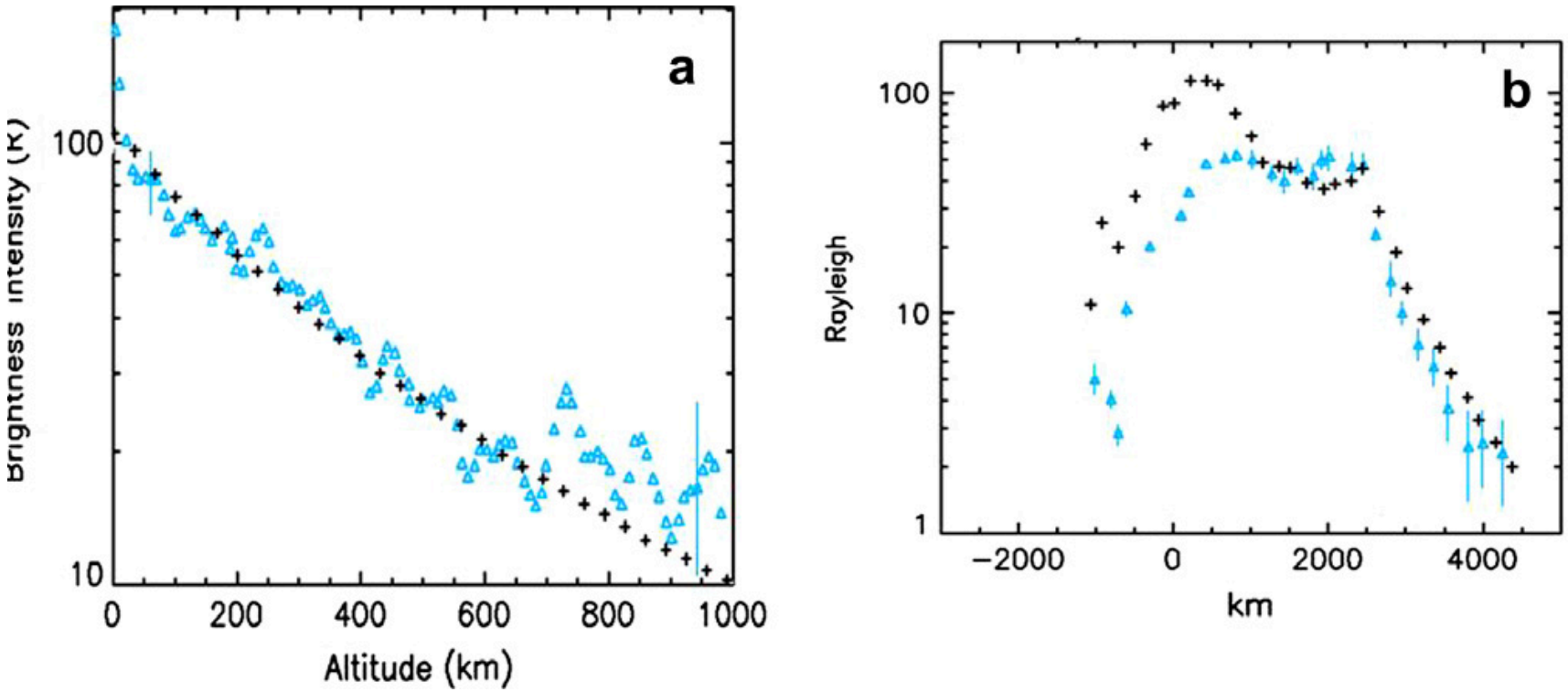
He



The blue triangles are average densities measured by Apollo 17 (Hoffman et al., 1973); the bars are the dispersion of the measured densities during 4 subsequent lunations (Hodges, 1975). The dark crosses are the Leblanc and Chaufray (2012) model densities.

What the Exospheres of Mercury and the Moon have in Common

He



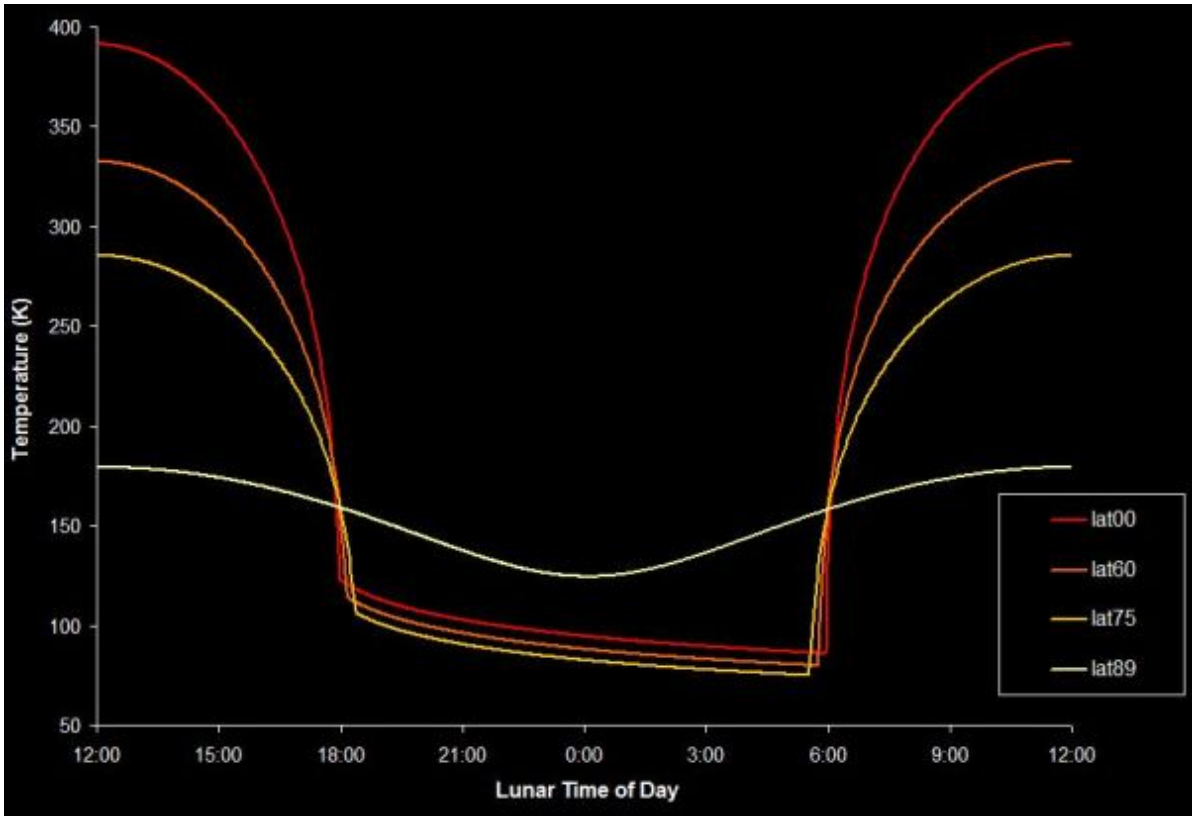
. Comparison between Mariner 10 observations and the simulation of the He exosphere. In blue observations reported by Broadfoot et al. (1976).

What the Exospheres of Mercury and the Moon may have in Common
Temperature extremes and Gas Surface-interactions

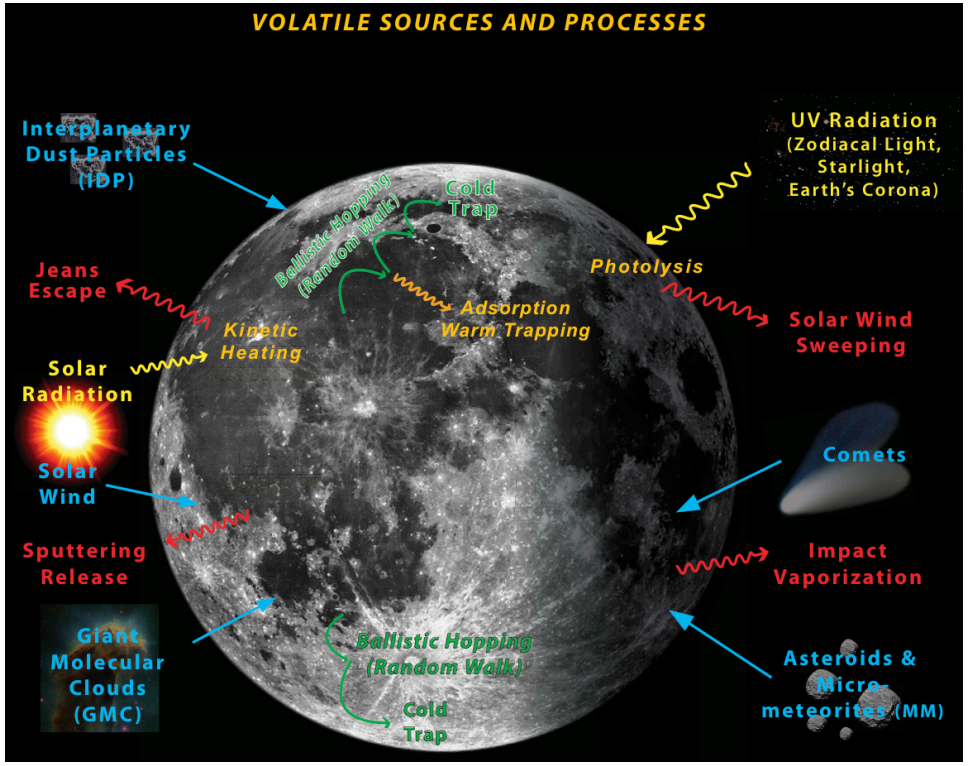
Key factors in determining the lunar atmospheric distribution

1. Temperature

- Atmospheric density increases with decreasing temperature.
- Lunar surface temperature decreases with solar zenith angle
- Atmosphere would have peak density on the nightside and minimum density at the subsolar point



Key factors in determining the lunar atmospheric distribution



2. Source distribution

- **Lunar exosphere is transient**
  - **Lifetimes of particles from hours to days**
  - **Particles make ~100 hops**
  - **Constant competition between source and loss processes**
- **Lunar exosphere originates at the surface**
  - **Outgassing, sputtering, vaporization, desorption release processes all act near the surface**

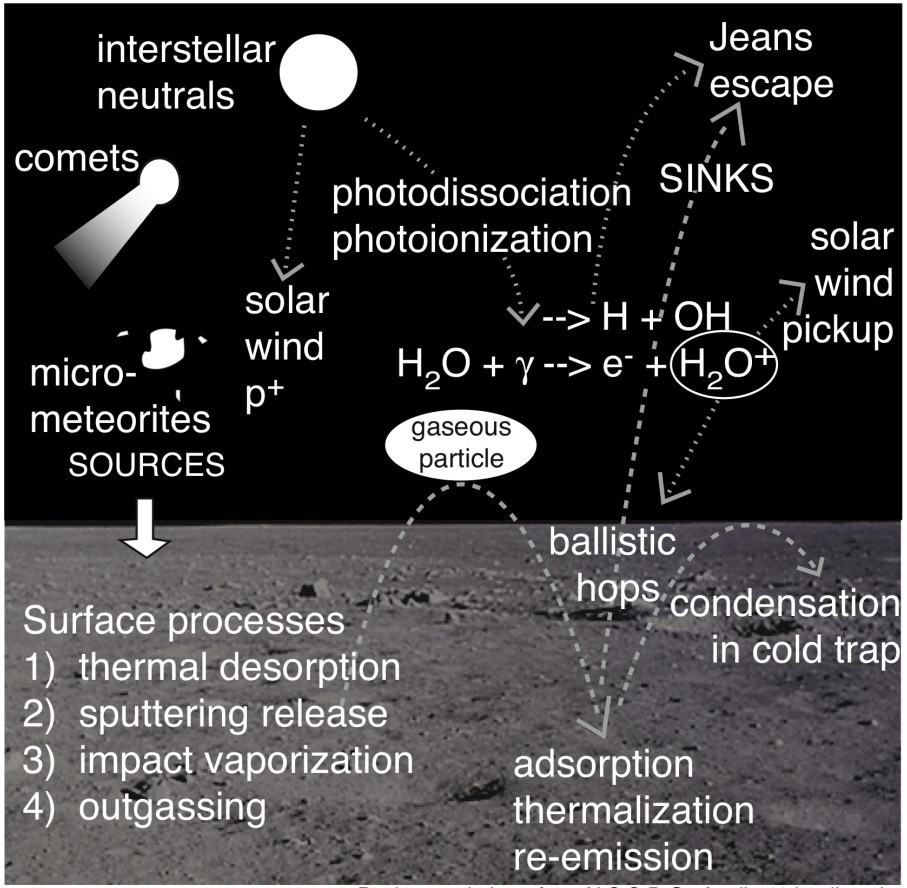
Key factors in determining the lunar atmospheric distribution

3. Surface encounters

- The surface is the exobase
  - Interactions among “airborne” particles are unlikely
  - Interactions with surface grains are most likely
- Adsorption
  - Active sites
  - Temporary cold traps
  - Permanent cold traps
- Re-release
  - Bounce elastically
  - Thermally accommodate
  - Partial accommodation
  - Inelastic bouncing

Monte Carlo Atmosphere Model

- Follows large number of particles from emission in atmosphere to eventual loss from system



Background photo from N.S.S.D.C., Apollo 11 landing site

- Species (so far)
  - H, H_2, He, OH, H_2O, Na, Ar
- Release mechanism
  - Position and velocity
- Surface interaction
  - Rerelease velocity
- Trajectory calculation
  - Gravity
  - Radiation pressure
- Loss processes

Uses of a Monte Carlo Atmosphere Model

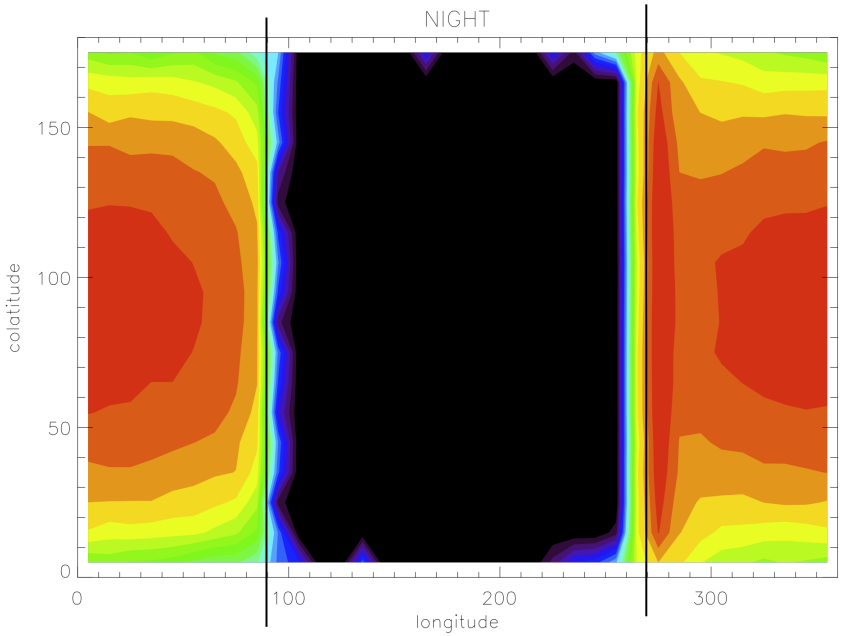
- Monte Carlo techniques have been used for to model both the lunar and Hermean applications
- This Monte Carlo model was developed with Rich Vondrak and Rosemary Killen
- The Monte Carlo exosphere model can be:
  - Used to study the effects of different physical processes on atmospheric composition and distribution
  - Paired with upcoming observations to provide insight into planetary surface, atmosphere, and plasma interactions
  - Applied to various bodies (Moon, Mercury)
- Improvements are ongoing

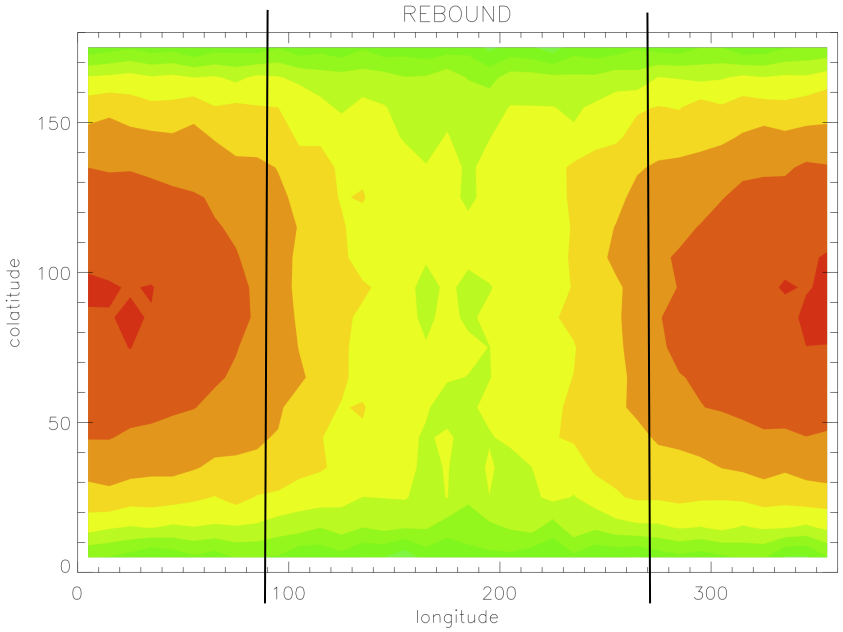
Investigation of sodium and sticking

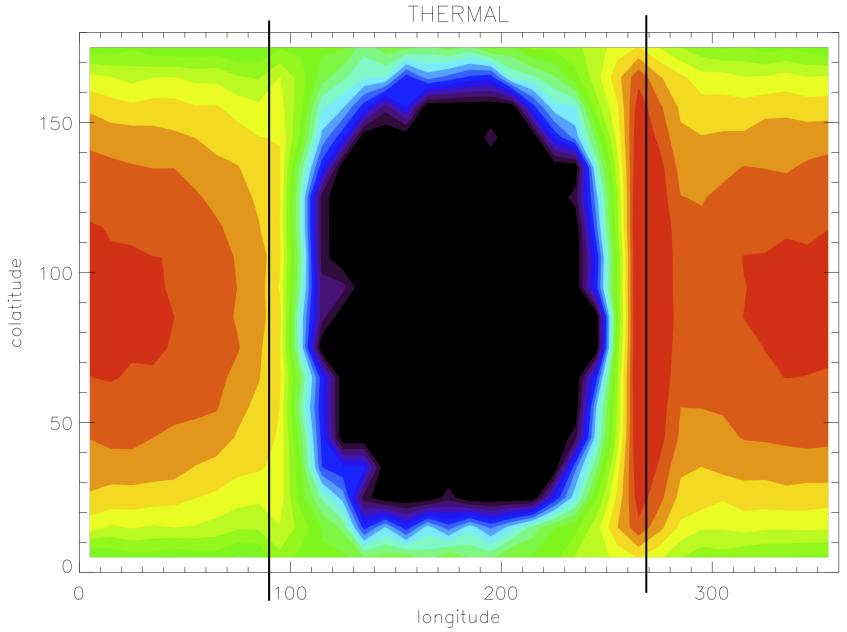
- Assume a photon-stimulated desorption source
- Include radiation pressure
- Try 3 cases of surface interactions:
  - REBOUND: particle is reemitted with the same velocity it had when it encountered the surface
  - THERMAL: particle is reemitted with a velocity selected from the distribution associated with the local surface temperature
  - NIGHT STICKING: particles hitting the night side adsorb until they reach dawn, where they are reemitted with a thermal velocity
- Plot scale is in *log*(N/latitude/longitude)

Nightside

Lower left: atoms rebound
Lower right: atoms thermalize
Upper right: atoms stick on nightside
evaporate at dawn 100%

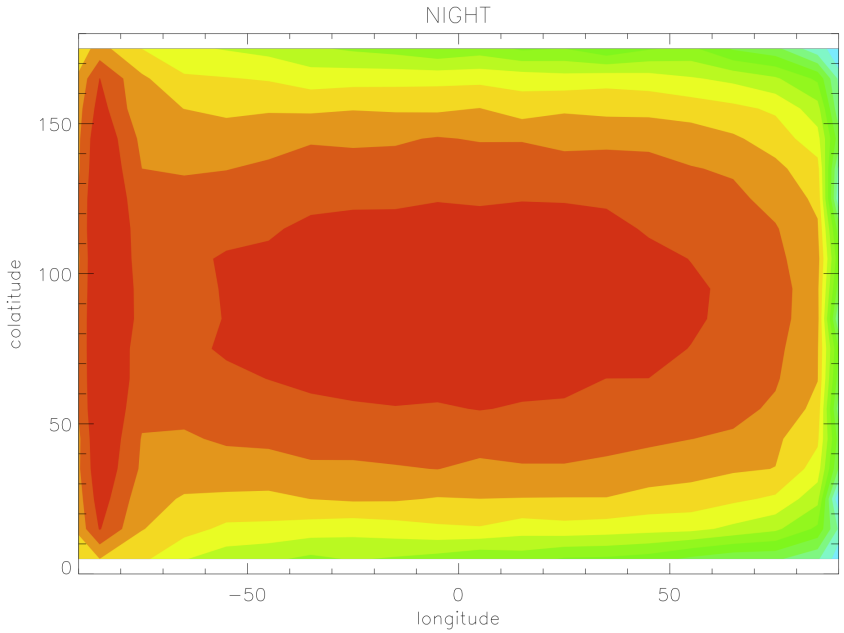


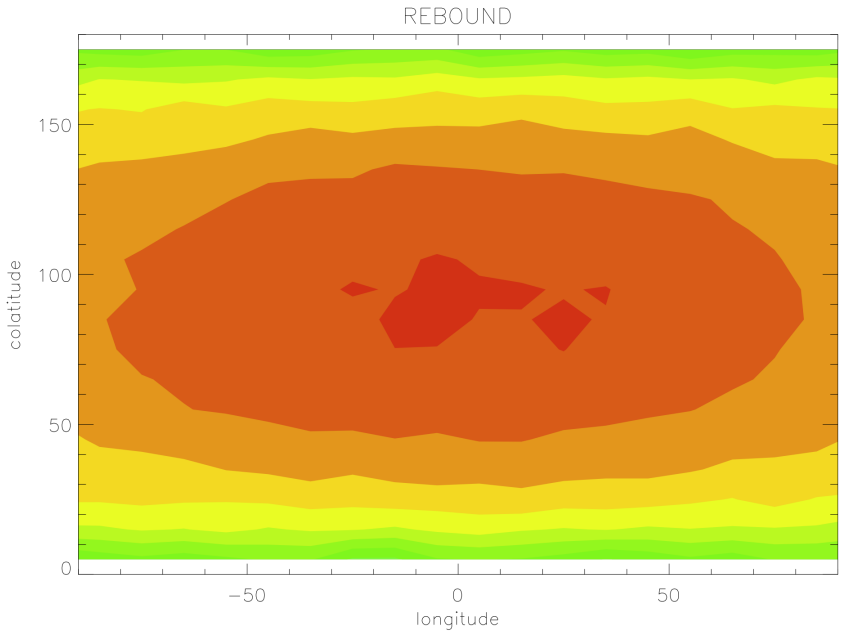


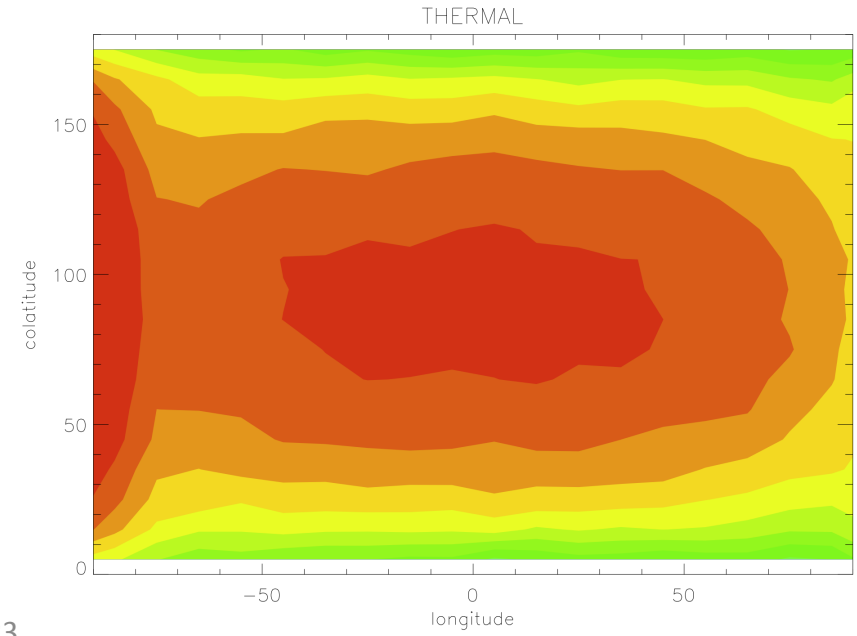


Dayside

Lower left: atoms rebound
Lower right: atoms thermalize, evaporate at dawn
Upper right: atoms stick at night, evaporate at dawn







Polar view

Dawn at 0, below

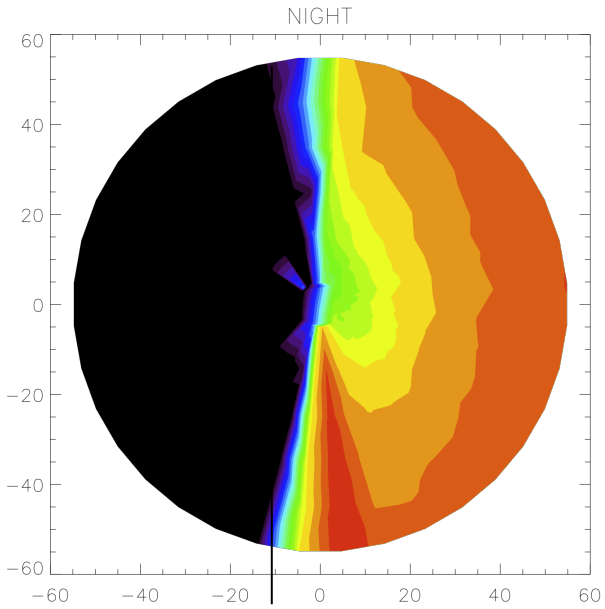
Dusk up

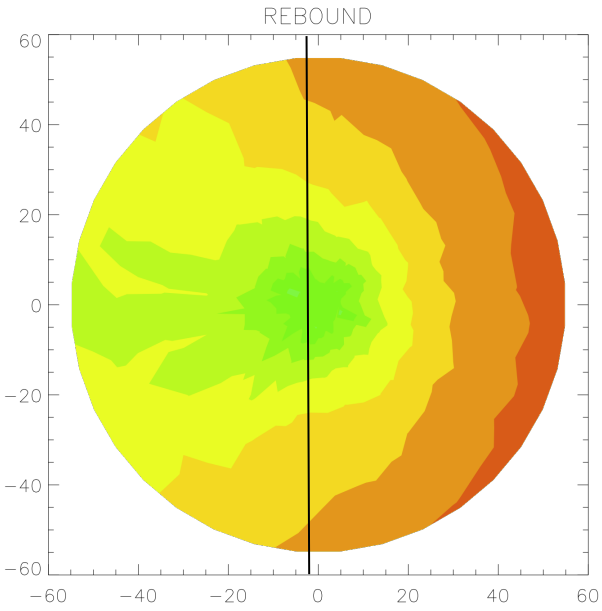
Lower left: atoms rebound

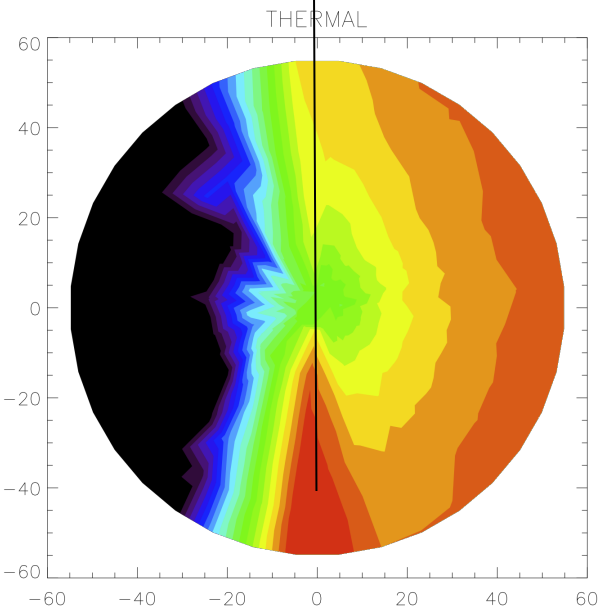
Lower right: atoms thermalize

Upper right: atoms stick at night

evaporate at dawn





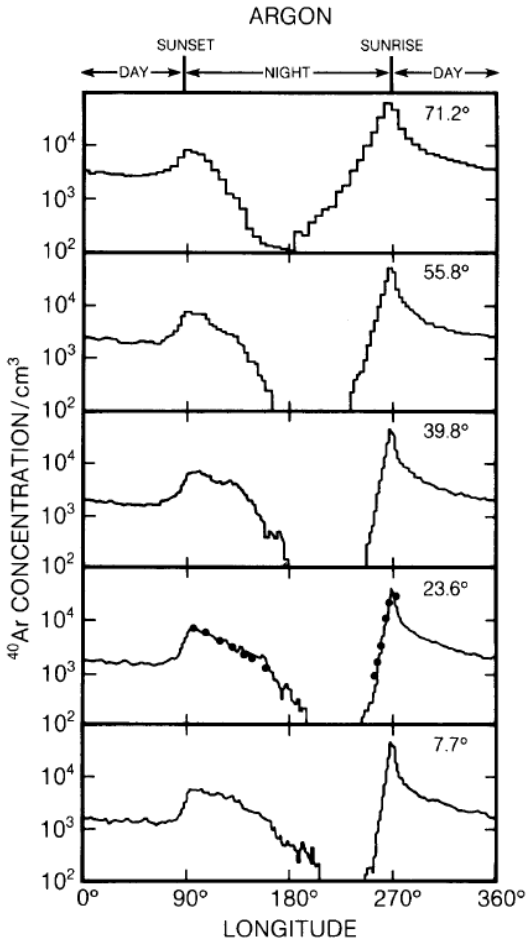


Conclusions

- Rebounding particles fill in the nightside atmosphere faster than thermalizing particles
- Thermalizing particles extend farther beyond the terminator than adsorbing particles
- Total atmospheric contents are similar for each case
- Dayside density for rebounding particles is lowest dayside density for these cases
- Competition between source rate, transportation time, and loss rate affect nightside density
- A dawn enhancement is readily apparent when the night surface acts as a sink

What happens when an atmospheric particle encounters the surface?

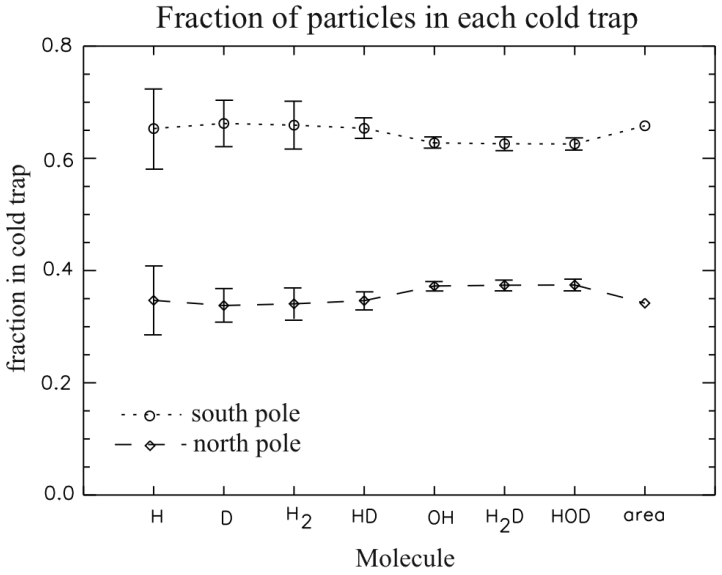
- When particles stick on the nightside, particles that are driven across the dawn terminator to the nightside are re-released at dawn in several hours.
- In contrast, the particles that are driven across the evening terminator stick to the nightside for the long lunar night and are re-released at dawn.
- Thus, the peak atmospheric density occurs at dawn.
- There is an asymmetry between dawn and dusk that depends on the efficiency of sticking and the re-release mechanism.



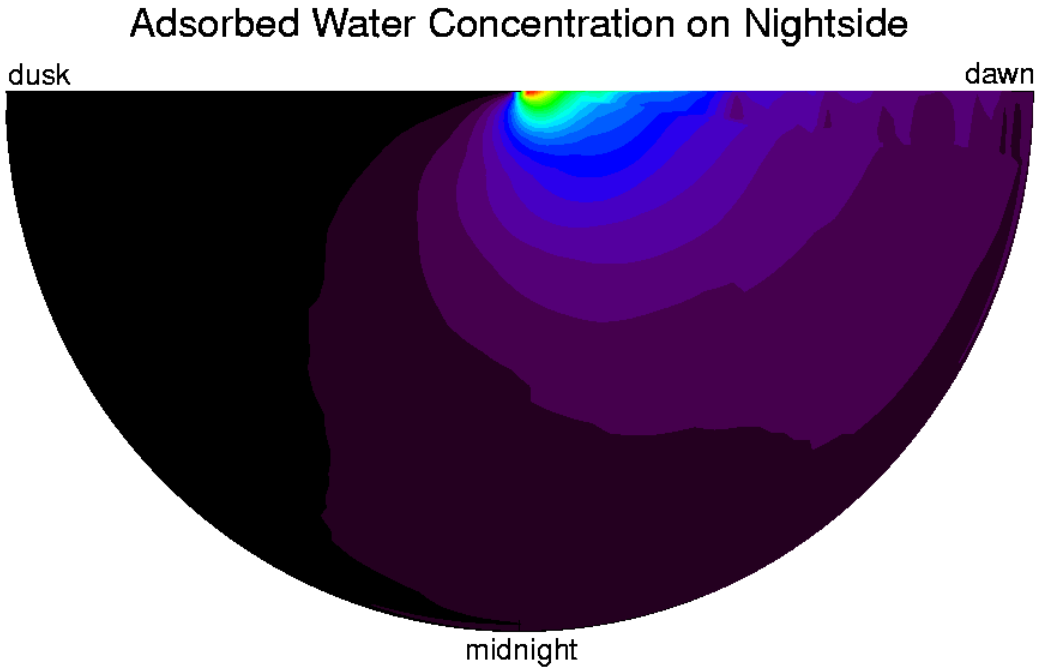
R. Hodges

How does cold trap size affect atmospheric distribution?

- A greater fraction of migrating particles condense in a larger cold trap, almost in proportion to the area.
- The Margot et al. [1999] estimate of total area in lunar shadow is smaller than the Bussey et al. [2003] estimate. Particularly, there is a great difference in the estimates for the PSR area in the northern hemisphere, where Bussey's estimate is 3x Margot's. For a small northern polar cold trap, there is more material in the atmosphere at high northern latitude than for a larger northern polar cold trap.

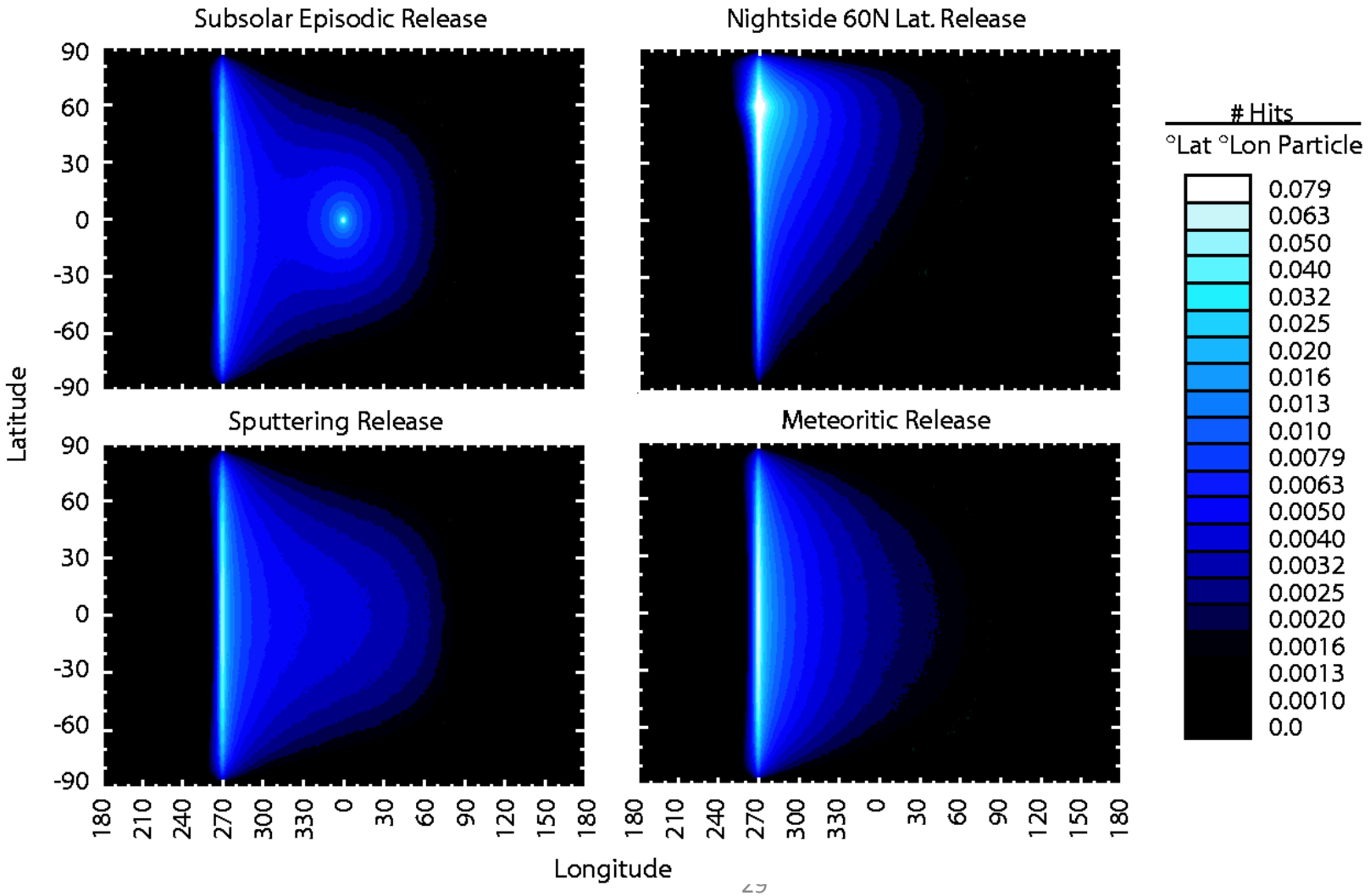


What volatiles do we expect to be adsorbed to the nightside?



- This shows the adsorbed nightside concentration of water vapor from our model.
- Spatial distribution of loss processes, which can feed additional source processes

How does release distribution relate to final distribution?



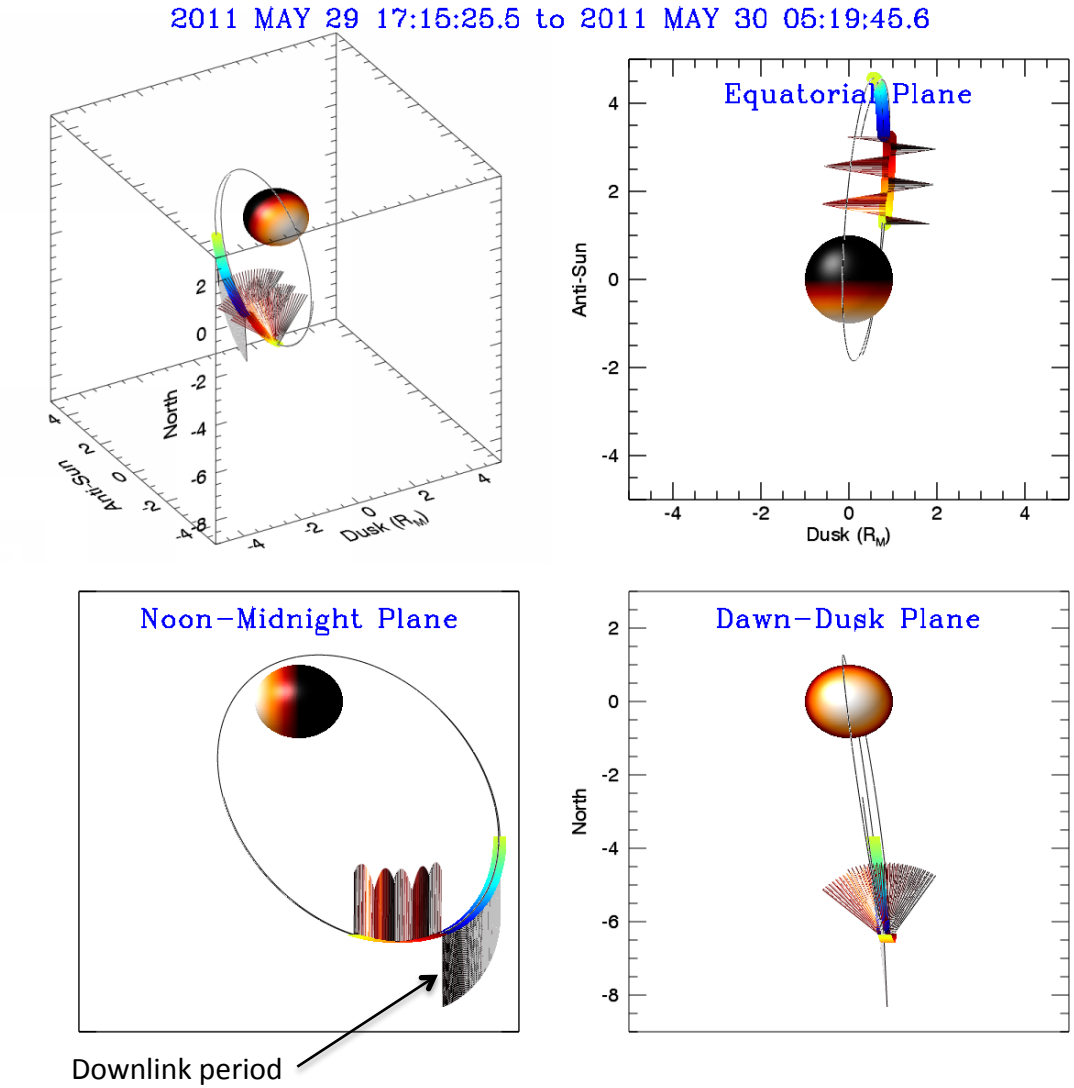
What the Exospheres of Mercury and the Moon have in Common
What can MESSENGER tell us?

Mercury Is Surrounded by a Surface-Bounded Exosphere

Interface component of Mercury's Surface-Exosphere-Space Environment System

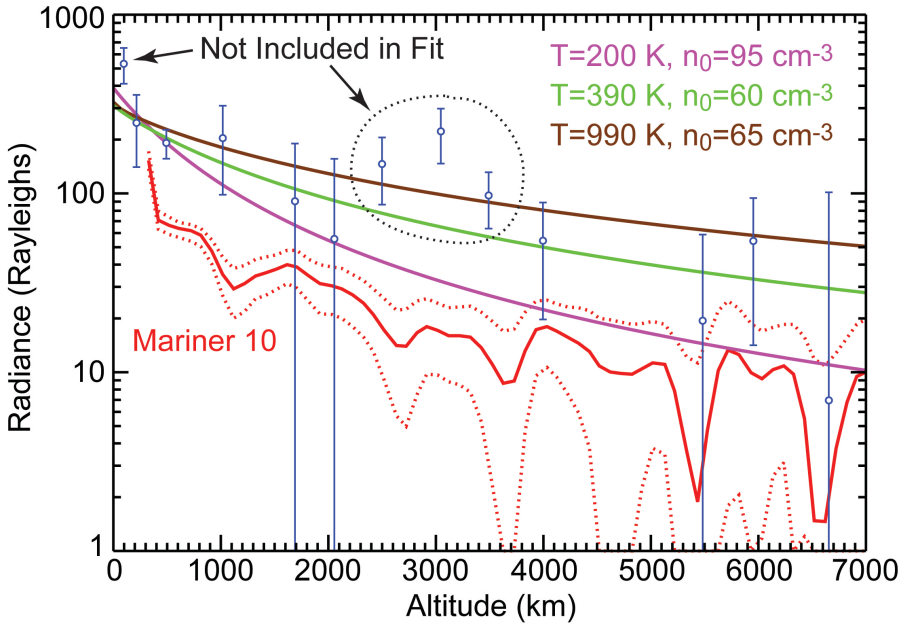
- Low-density, 'Collisionless' atmosphere
- Highly variable (both spatially and temporally)
- Driven by both seasonal and episodic processes
- Pre-MESSENGER
    - Known to contain H, He, O?, and metals (Na, K, and Ca)
    - Possess and extended neutral Na tail
- Mg detected by MESSENGER during Mercury Flyby 2
- Unexpectedly large Ca and Mg densities observed in the tail during Flyby 2
- Remote sensing measurements of Ca^+ behind the planet during Flyby 3
- May contain additional surface-derived materials (Si, Al, Fe?, S?,OH?, ??)

MESSENGER Operations Approach: Look at the Exosphere Whenever Possible



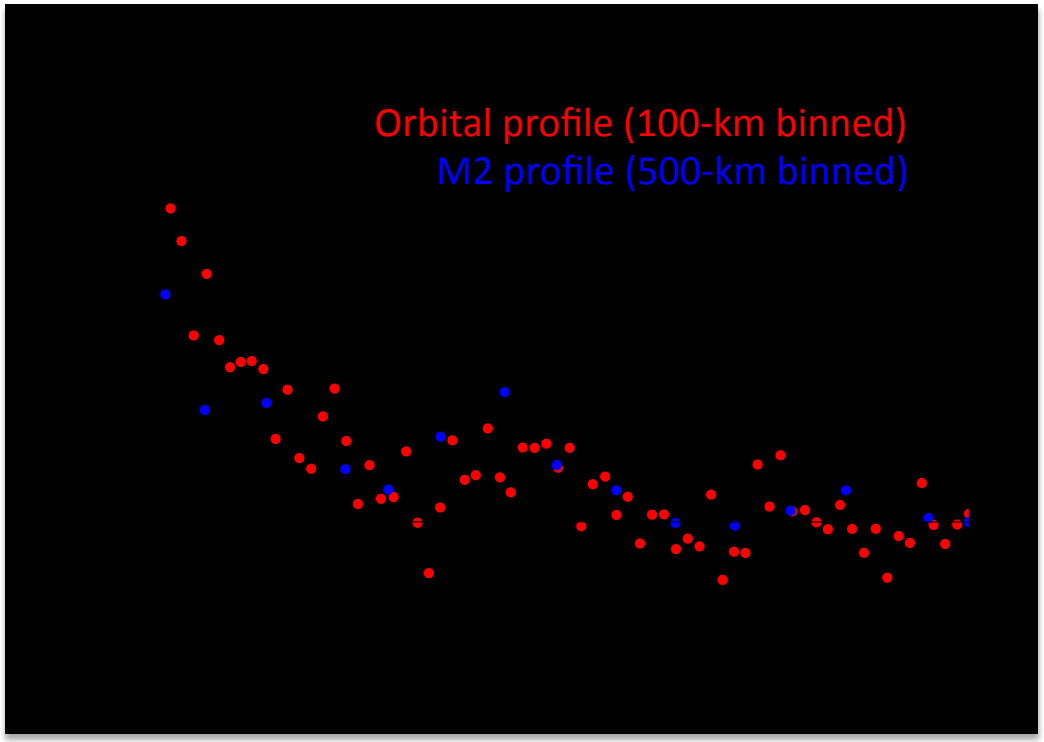
- Noon-midnight orbit
- Periapsis on the day side
- Extended observations of tail region using fan-tail scanning
- Orbit near T.A. = 285˚
- Illustrates a downlink pass
- Both dayside and nightside measurements are conducted
- Point spectrometer design results in sparse data sets that can only be intercompared using models

Hydrogen Observations



- Specialized geometry requirements limits observation opportunities
- Increased radiance values relative to Mariner 10 likely the result of viewing geometry
- T_{exo} ~ 390˚ consistent with Mariner 10 but not well constrained
- Consistent with H+ solar wind implantation followed by thermal release

Typical Hydrogen Profiles



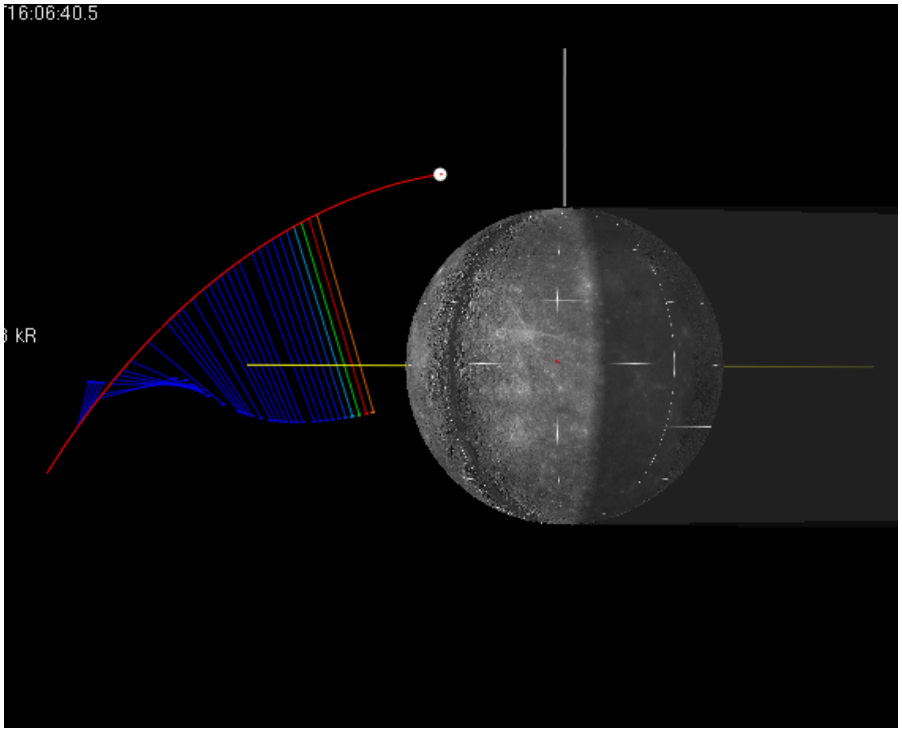
Geometry during H observations is fixed inertially to allow the observations far from the planet to be used to remove the background IPH

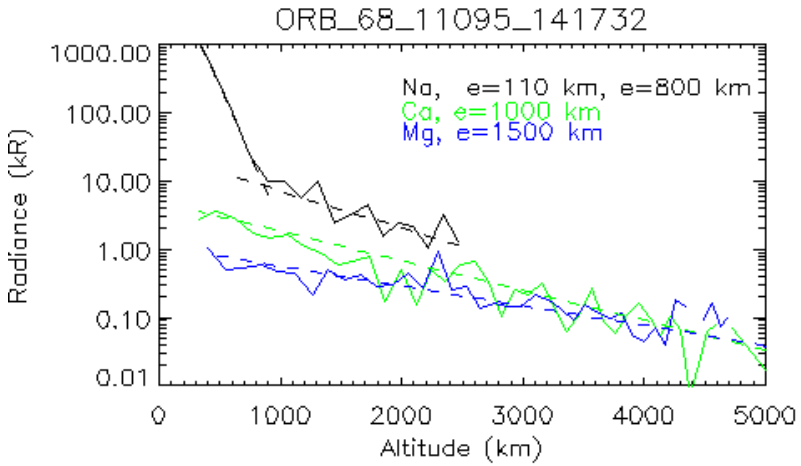
Wavy structure in the profiles possibly an indication of “bounce back” (solar protons being neutralized and reflected back on impact)

Courtesy Ronald Vervack & the MASCS Team

Sub Solar Dayside Altitude Profile Example

- Na exhibits two-component structure
  - Both e-folding heights are less than those observed for Mg and Ca
- Na observed for altitudes < 2500 km
- Mg and Ca observed for altitudes up to 4000 km
- Comparable to altitude scans above the poles conducted during the third Flyby

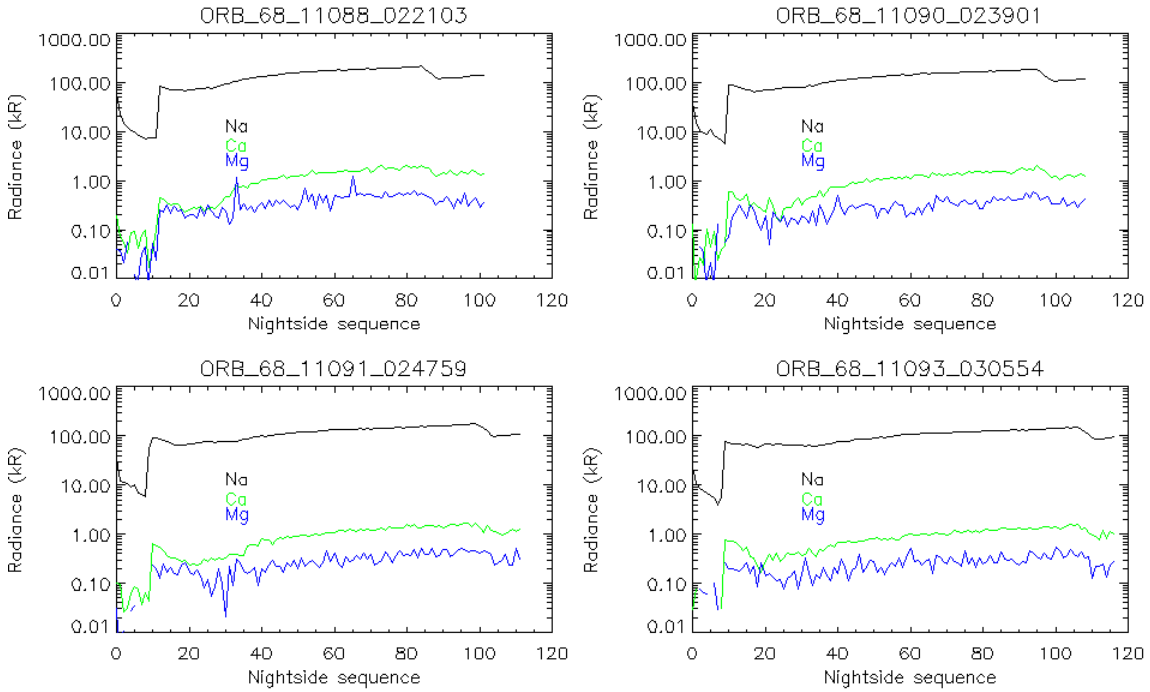


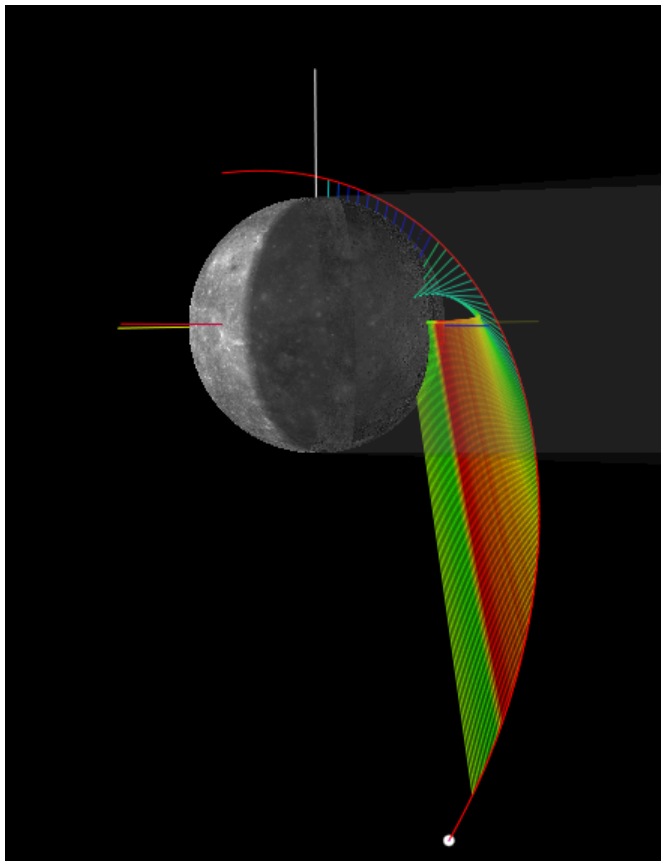


Courtesy the MASCS Team

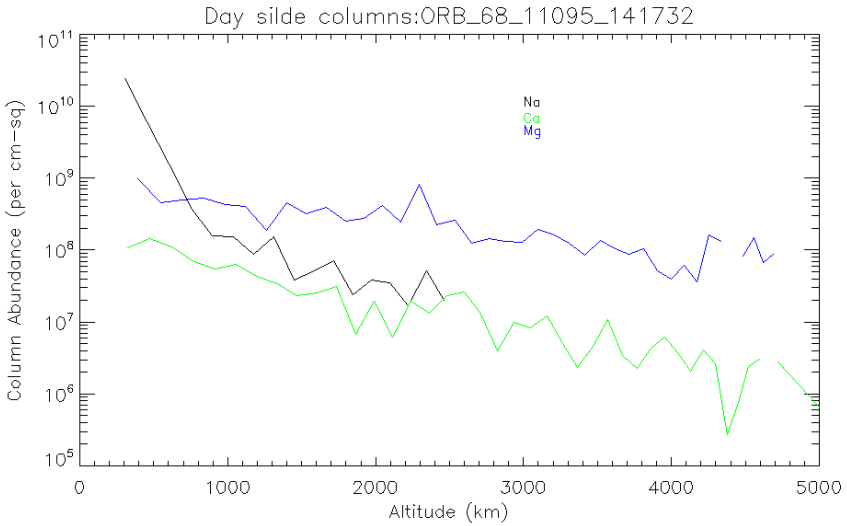
Nightside Altitude Drifts

- Spacecraft passes behind terminator looking south.
- Roll at the equator rotates the field of view to the north.





Order of Magnitude Column Densities

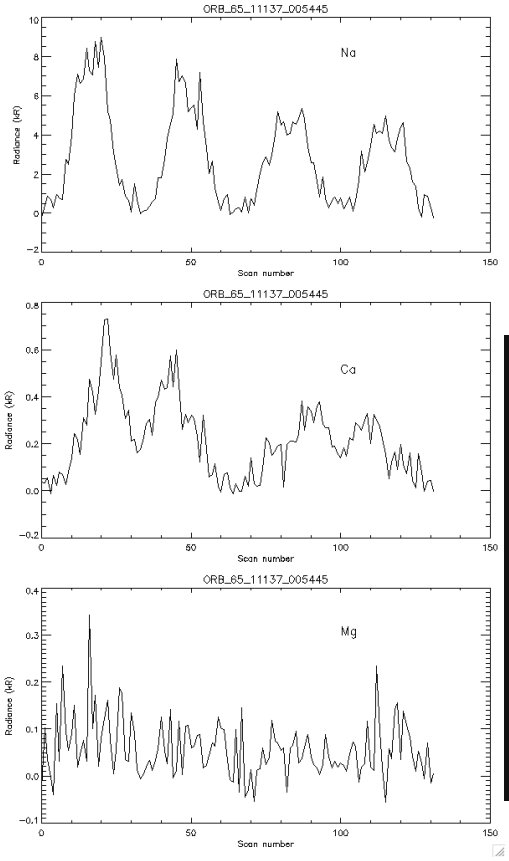


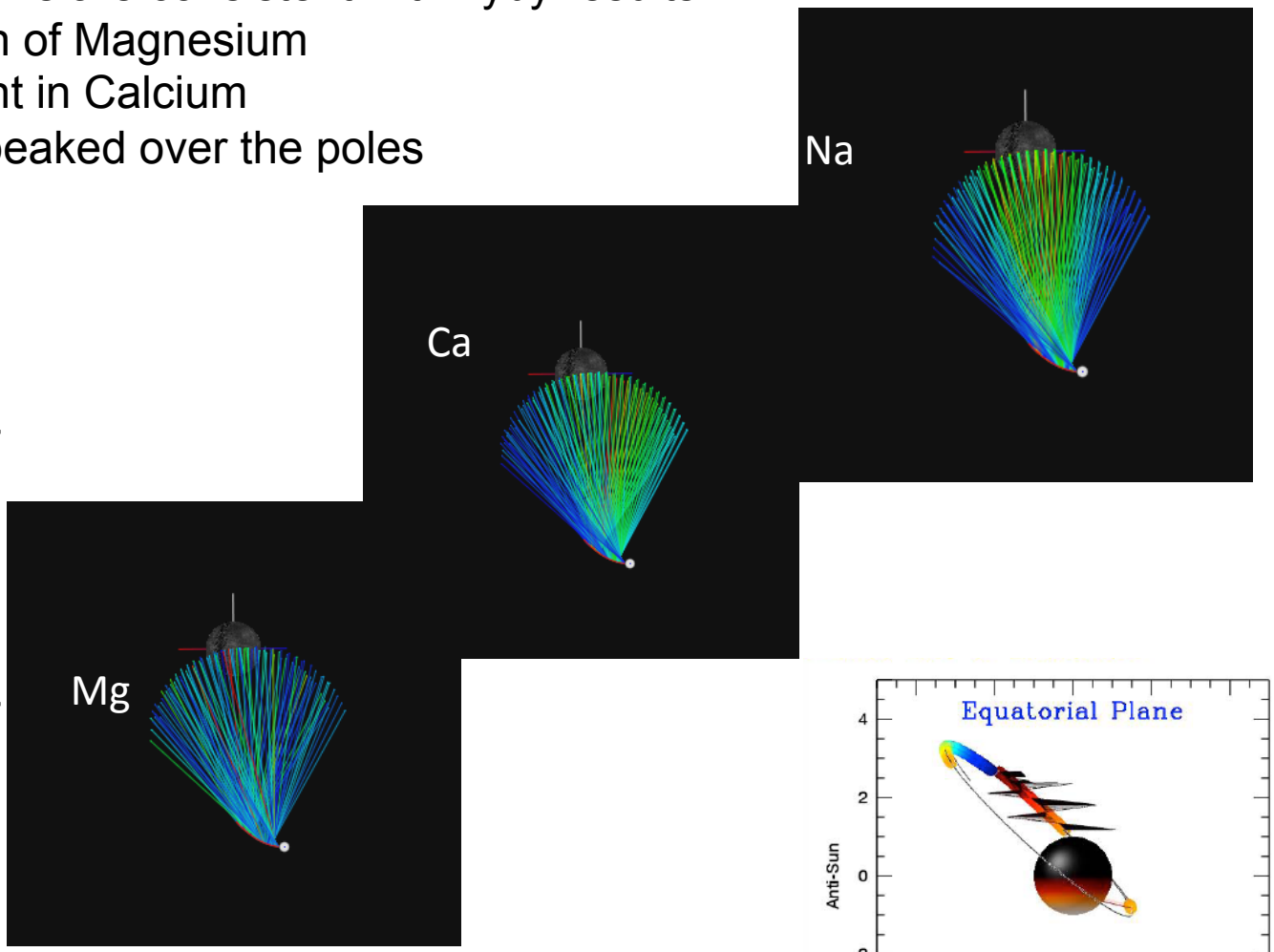
Na – black
Mg – blue
Ca - green

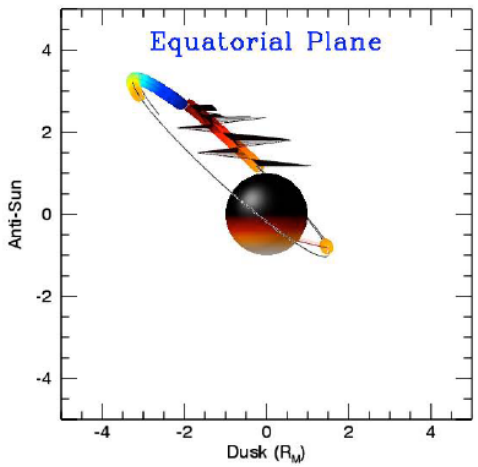
- Assumes emission factors are equal to those for atoms at rest with respect to the surface
- Not adjusted for observational geometry
- Viewing geometry is nearly north-south near noon –midnight plane

Nightside Sweep Scan Example

Nightside fantail scans are consistent with flyby results
- Uniform distribution of Magnesium
- Dawn enhancement in Calcium
- Sodium emission peaked over the poles



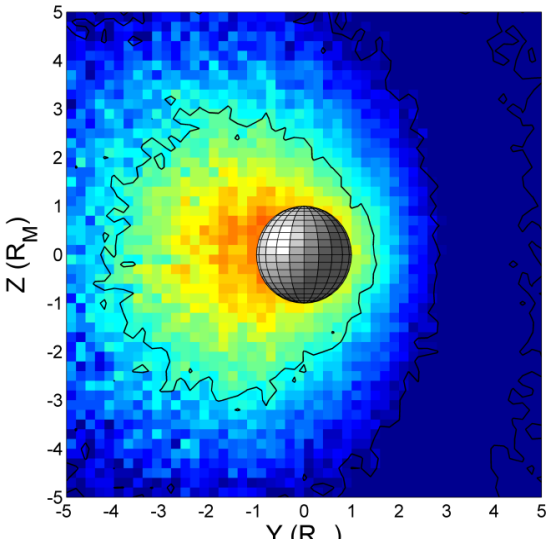




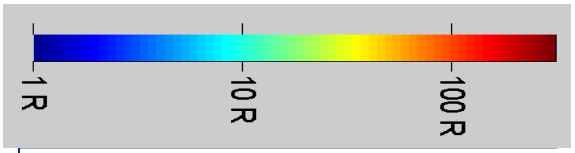
Courtesy Bill McClintock, MASCS TEAM

How geometry affects our Ca reconstructions

Forward Model (Burger et al)

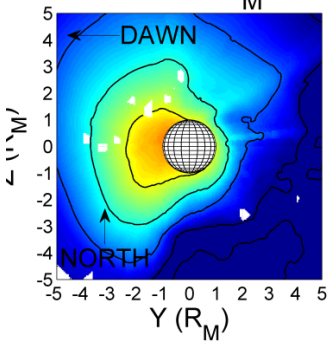


Slice X = - 2 R_M

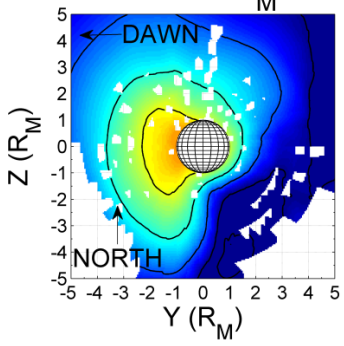


Reconstruction of Modeled Data (SNR = 100)

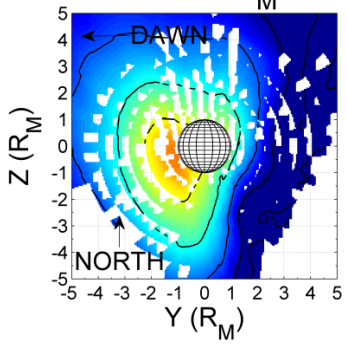
May 13, 2011: X = - 2 R_M



May 18, 2011: X = - 2 R_M

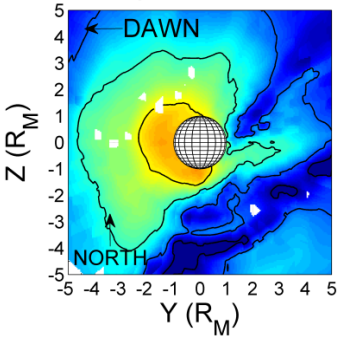


May 30, 2011: X = - 2 R_M

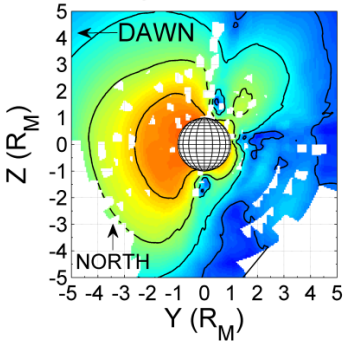


Reconstruction of Actual Data

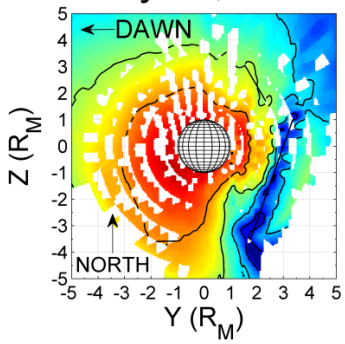
May 13, 2011



May 18, 2011



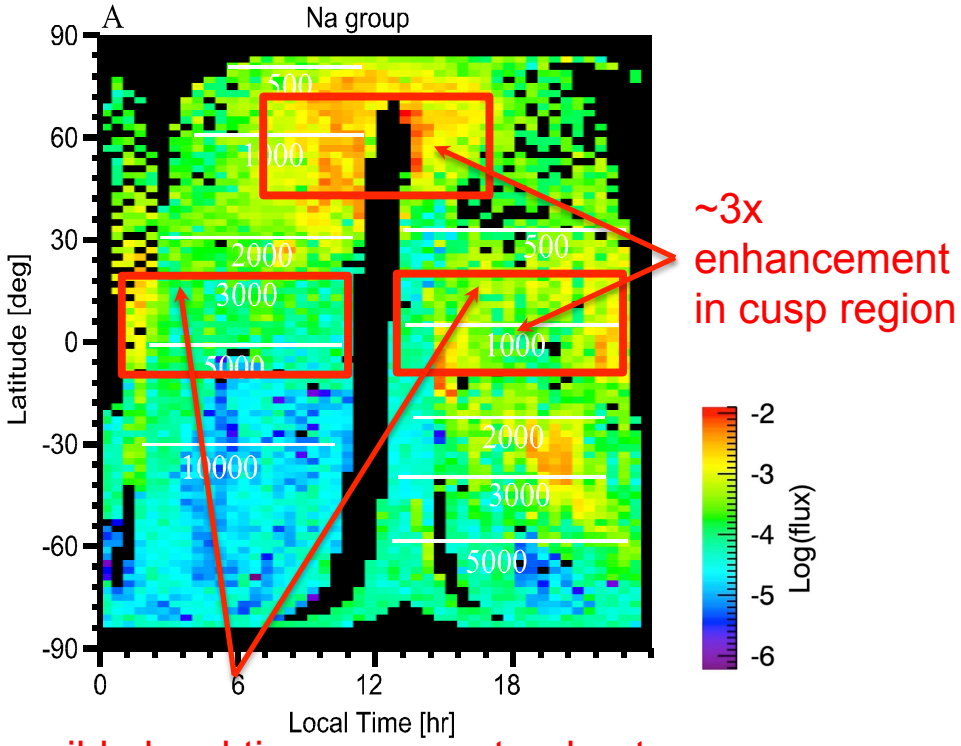
May 30, 2011



Our ability to reconstruct greatly non-uniform distributions is limited by the geometry of a particular orbit. Geometries through May 23 are favorable.

Courtesy Matt Burger and Menelaos Sarantos, MASCS Team

Ions in the Exosphere Are Measured by the Fast Imaging Plasma Spectrometer (Jim Raines)



~3x enhancement in cusp region

Possible local time asymmetry due to drifts cannot be evaluated due to different observation altitudes

- Major Species
  - He^+
  - M/Q 14-20 (O^+, H_2O^+, OH^+, etc.) – "O group"
  - M/Q 21-30 (Na^+, Mg^+, Si^+) – "Na group"
- Na+ and O^+ exhibit nearly identical morphologies
- $[Na^+] \sim 3.5\ [O^+]$
- He^+ distribution is spatially uniform suggesting the source is thermal release of neutralized implanted solar wind He^{++} followed by photoionizqtion.

Courtesy Jim Raines, MESSENGER FIPS TEAM

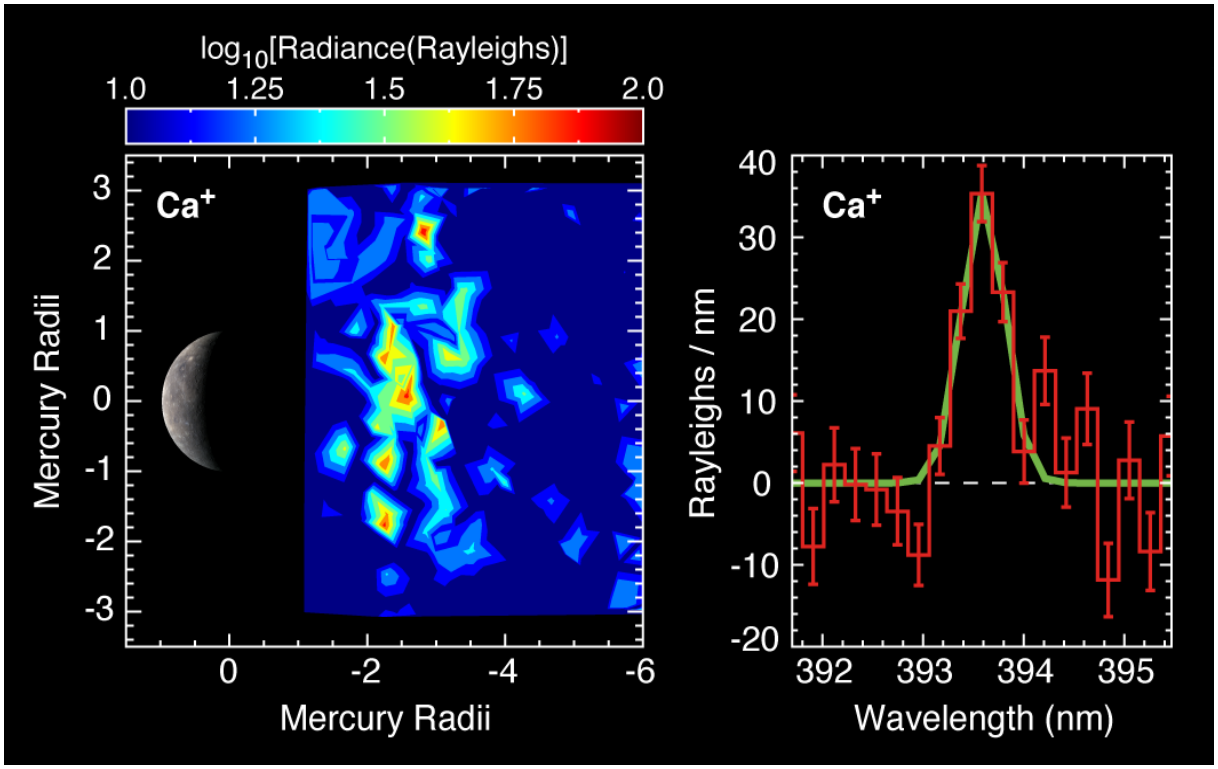
MESSENGER
Limits on Completeness

- Other than H, Na, Ca, and Mg (and Ca^+ observed during Flyby 3) MESSENGER has not yet detected other species that might populate the exosphere.
- Si, Al, Fe, and S have been measured in the surface materials in significant concentrations and O must certainly be there.
  - Si, Al, and Fe have emission factors comparable to Mg and can probably be detected at 1 -10% [Mg].
  - O may also be within the MASCS detection limit.
    - The FIPS channel of the EPPS has observed O^+ and Na^+ with $[Na^+] / [O^+] \sim 3.5$. If [Na] / [O] is comparable then $I_R \sim 10$ R, which MESSENGER can detect.
  - S will be difficult to detect unless its column density in the exosphere is very large.
- What can be observed in the exosphere also depends critically on release mechanism. Perhaps only the alkali metals (Na and K) and alkali earths (Mg and Ca) are substantially produced in forms observable by MASCS.

MESSENGER Summary

- Neutral Na, Ca, and Mg observed routinely on both dayside and nightside at daily cadence and H on the dayside infrequently.
  - Distributions of Na, Ca, and Mg are distinct indicating that these species are controlled by different source processes.
  - Sodium is the dominant species on the nightside and on the dayside below 500 km
  - Magnesium is the dominant dayside component above 1000 km altitude
  - Unexpectedly large nightside Ca and Mg densities cannot be explained by release on the dayside followed by radiation pressure transport.
  - Ca exhibits a persistent equatorial-dawn enhancement
- Ionized O and Na
  - Concentrations of Na+ and O+ are observed at high latitude centered on the subsolar meridian
- Unobserved species
  - Si, Al, and Fe are known to be present in the surface materials and are potentially detectable
  - S and O are also present in the surface but are difficult to detect by remote sensing.

Detection of Ca^+ During the Third Mercury Flyby



Ca+ was detected in the tail region during the third Mercury flyby but has not been seen in orbit thus far

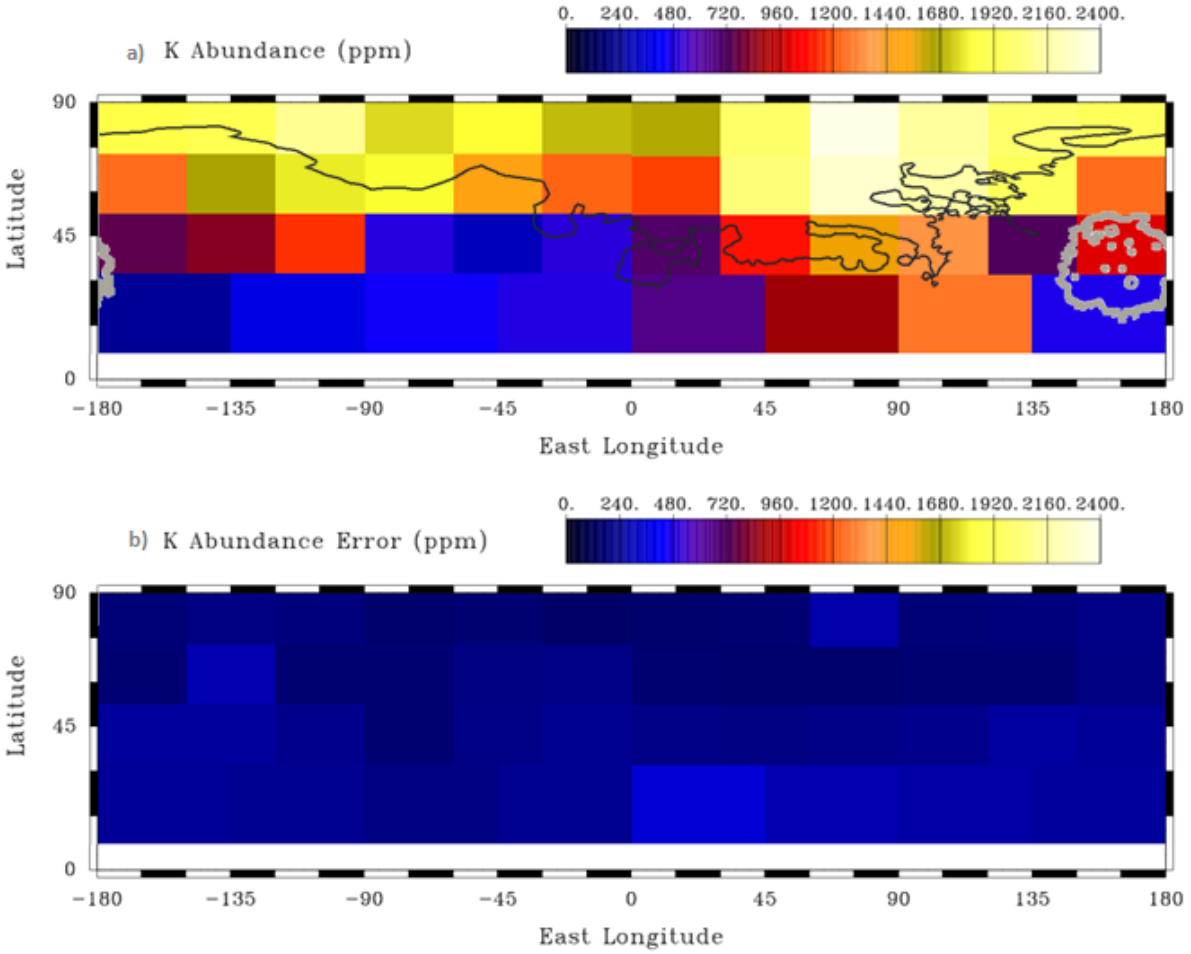
Was this a one-time detection of a plasmoid?
The spacecraft orbit limits observations of this region – are we just missing it?

Courtesy MASCS Team

Surface/Exosphere correlations for Mercury

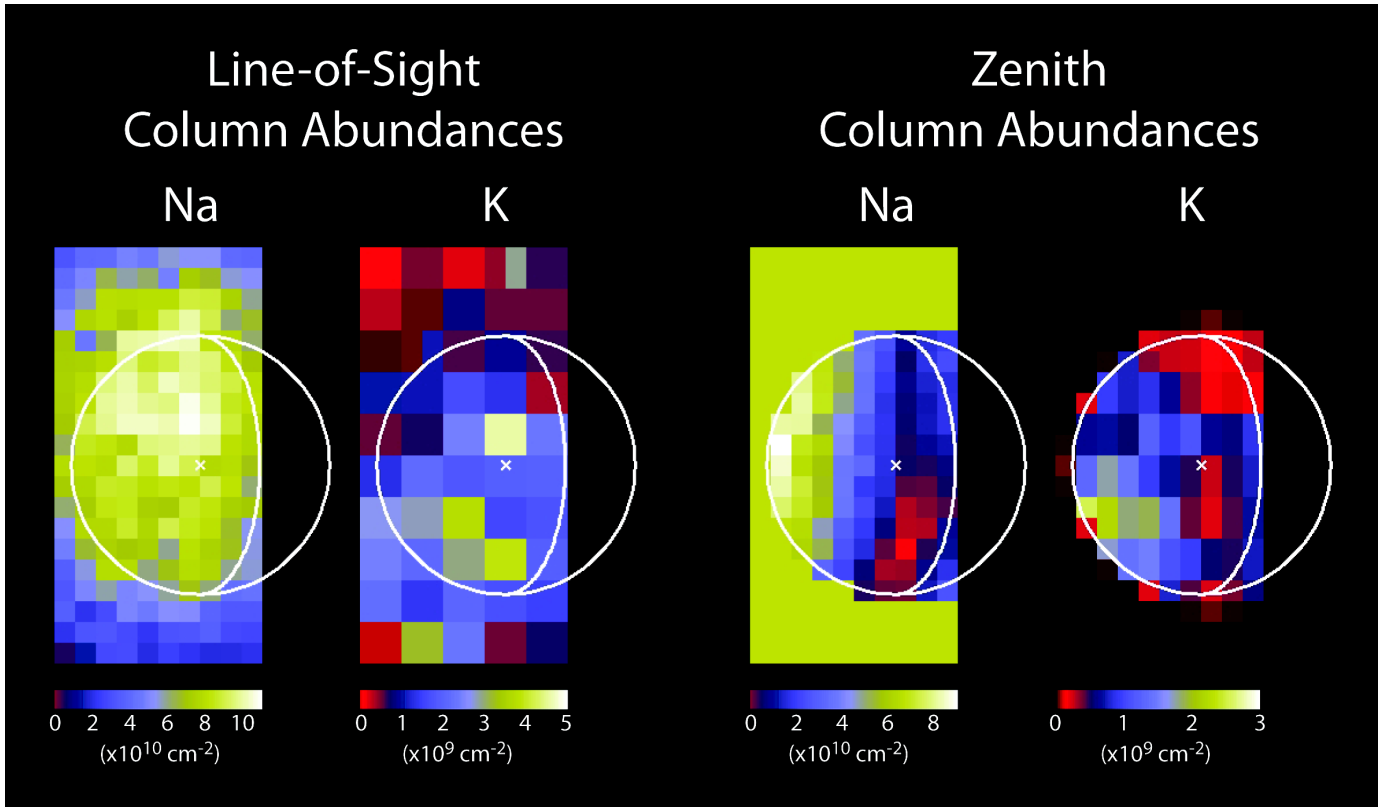
Potassium elemental abundance from MESSENGER data (Peplowski *et al*. 2012).

Map of Potassium Surface abundance of K on the surface across the northern hemi-sphere of Mercury (mean spatial resolution ~1000 km). The dark grey outlines are the boundaries of the northern volcanic plains and the light grey outline the Caloris impact basin.



Surface/Exosphere correlations for Mercury

Observations of Sodium and Potassium January 17, 2010. The Illuminated surface extends from 30 degrees of longitude to 120 degrees.



What the Exospheres of Mercury and the Moon have in Common?
Conclusion

What do the exospheres have in common?

Common processes are at work on both objects: 1. To promote atoms into the exosphere; 2. To modify the the energy distribution of the exosphere; 3. To sequester, and re-release atoms; 4. To remove atoms from the exosphere.

Both are sensitive to the external particle and field environment.

How do they differ?
The differing outcomes are the result of the differing locations of the two objects in the solar system.

The Magnetic field at Mercury modifies the interaction with the external space environment.

Each can teach us a great deal about the other.