Loss of Mercury's Exospheric Sodium

Shingo Kameda

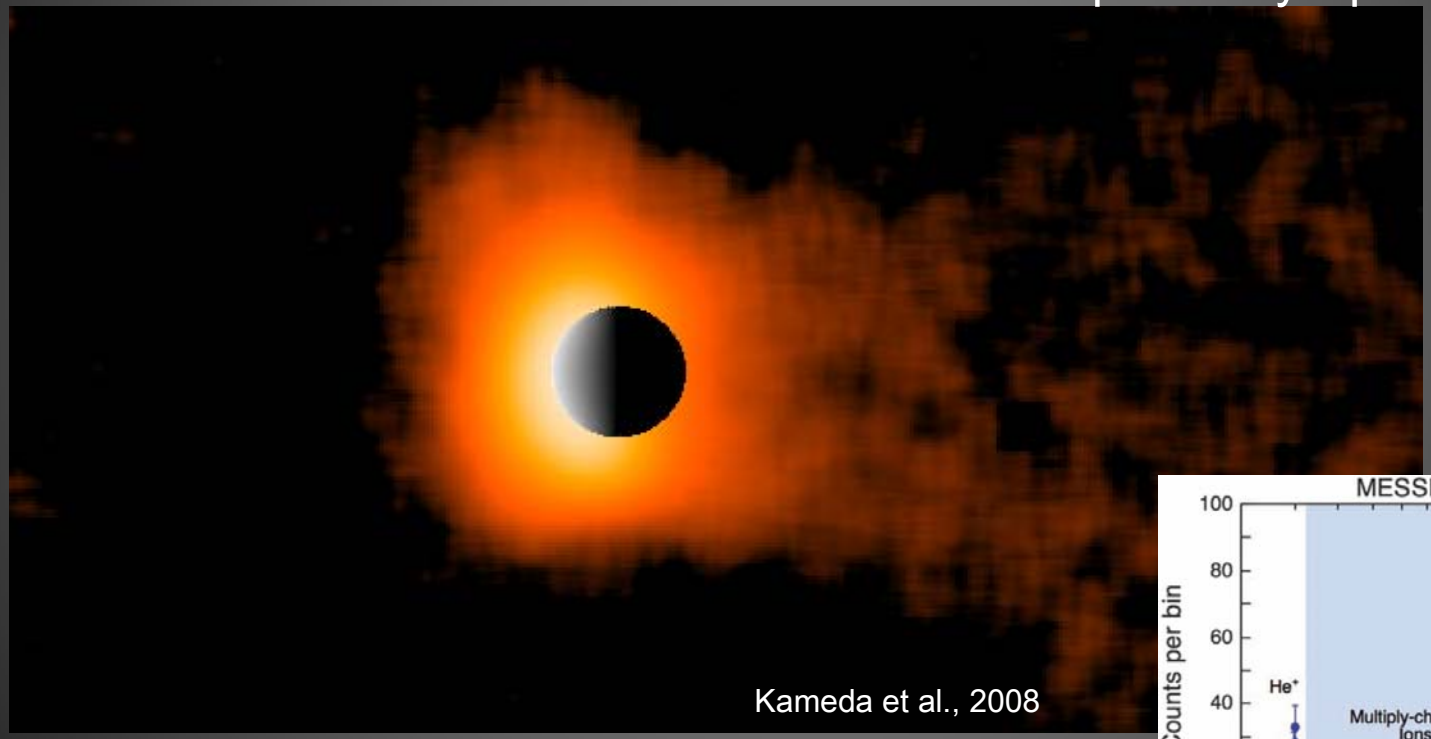
Planetary Exploration Research Center

Chiba Institute of Technology, Japan

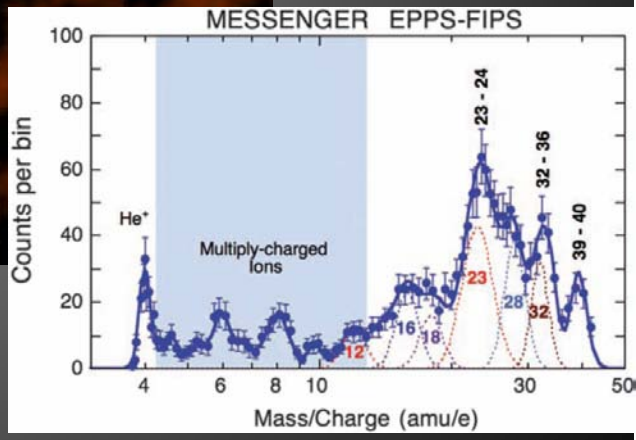
Collisionless atmosphere P~10^{-12} atm

Released from the surface ・ Impact to the surface (SP, SW, IPD)

・ Loss to the Interplanetary Space



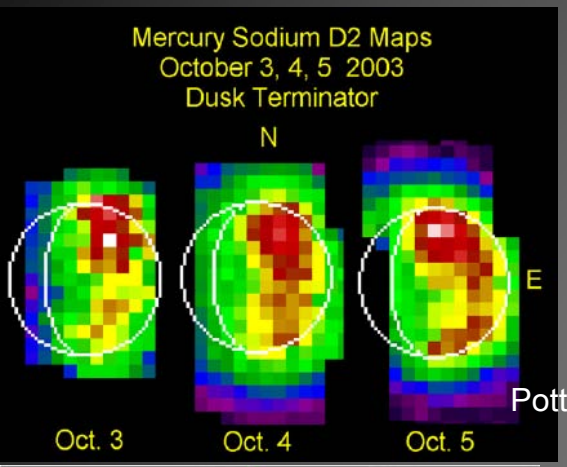
Kameda et al., 2008



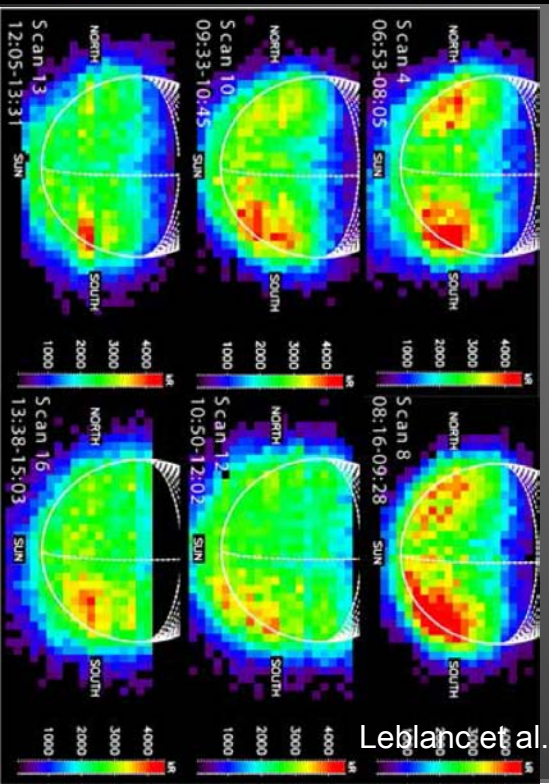
Zurbuchen et al., 2008

Remote Sensing: H,He,O,Na,K,Ca,Mg,Ca+,Al?,Fe?

In Situ : H^+,He^+,Na^+(Mg^+),O_2^+,K^+(Ca^+,Ar^+), etc.



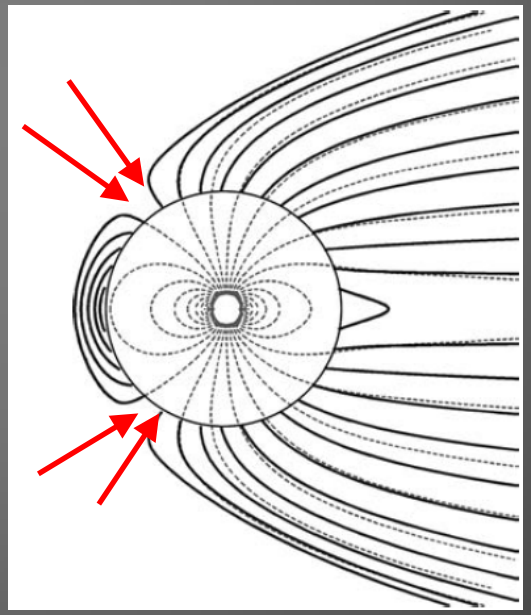
Potter et al., 2008

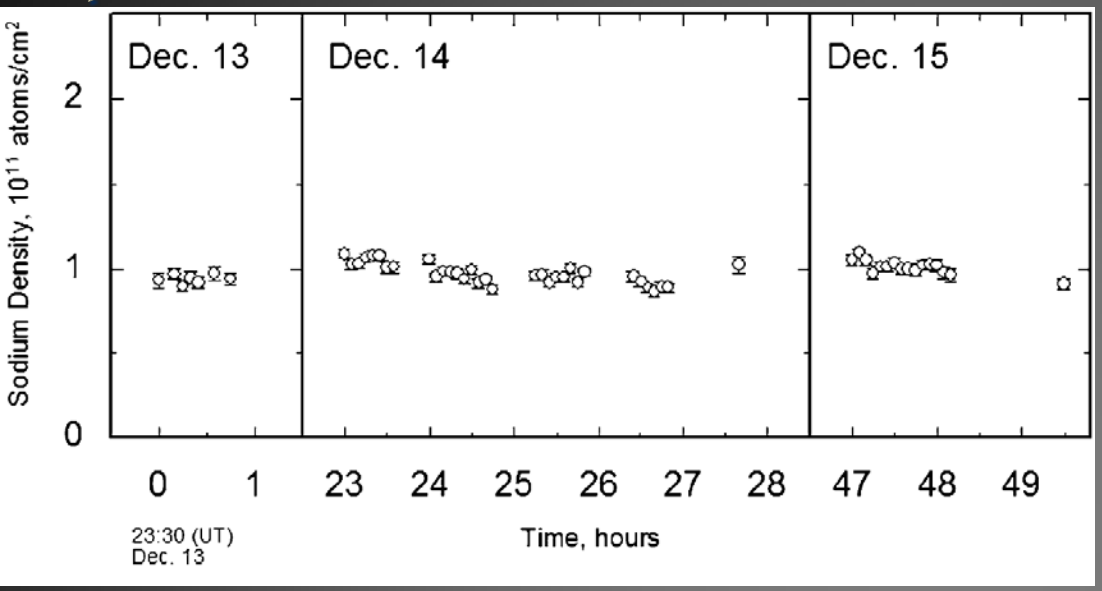


Leblanc et al., 2009

Concentration at High latitudes and Temporal variability

→ **Effect of Solar wind impact??**



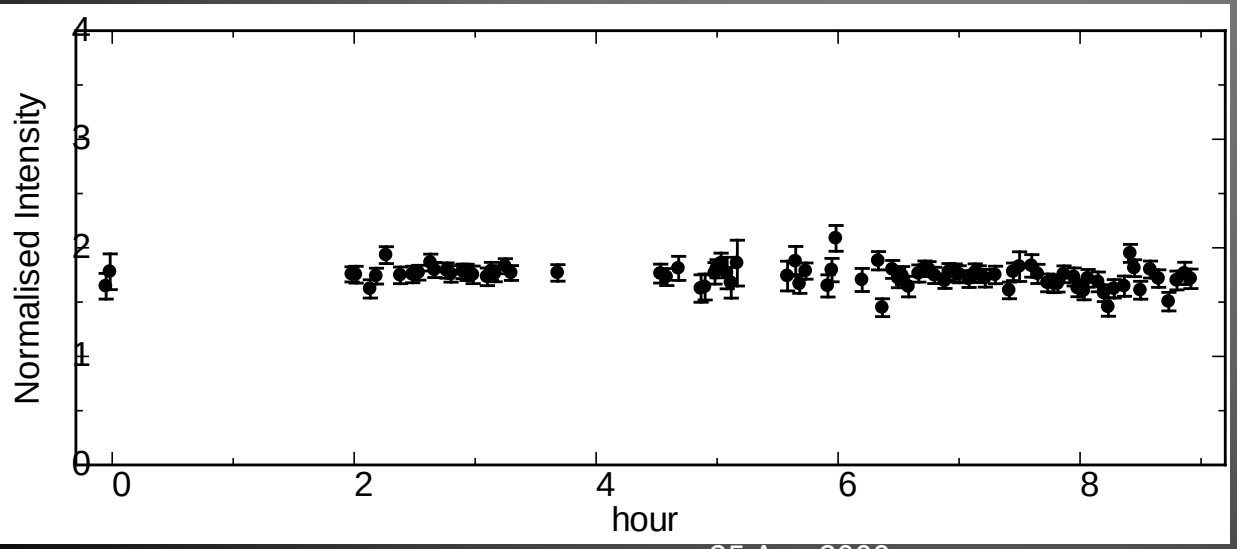


Kameda et al., 2007

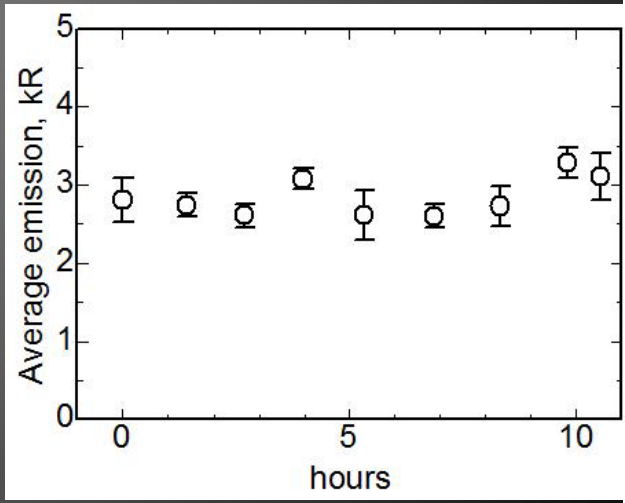
Dec 2005 & Aug 2008 (OAO in Japan)

Temporal variability of Average density <~10%

→SW variability should be higher.

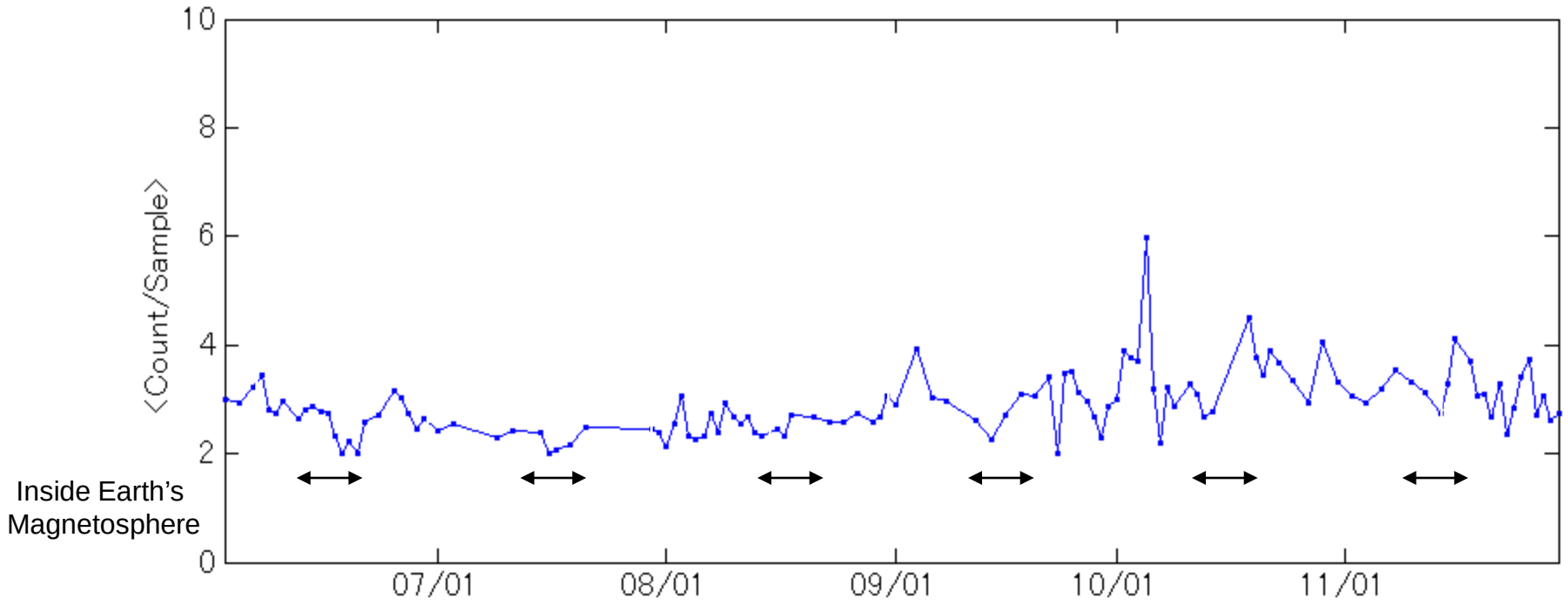


25 Aug 2008



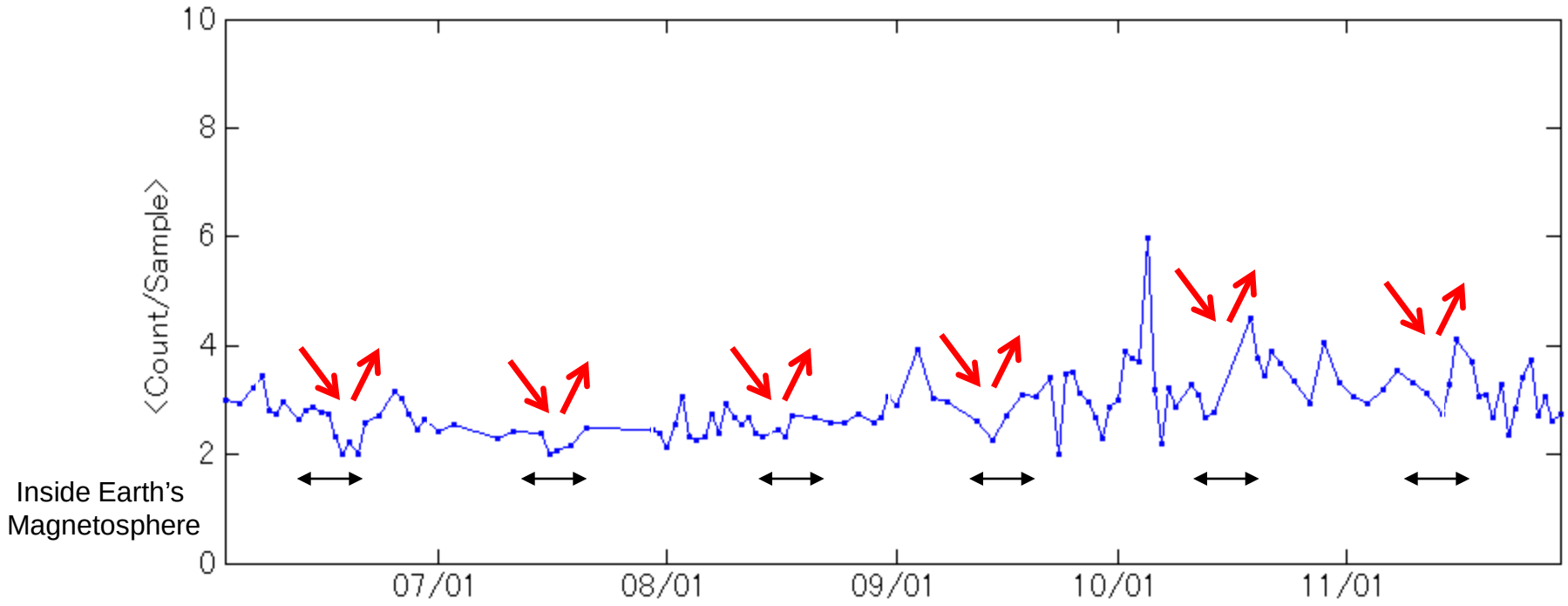
1σ~9% [Leblanc et al. 2009]

Count/Sample



Yokota et al.

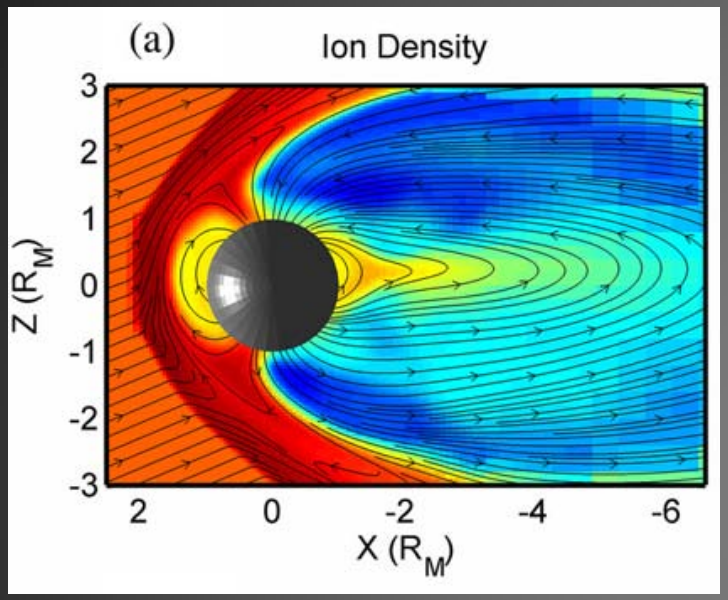
Count/Sample



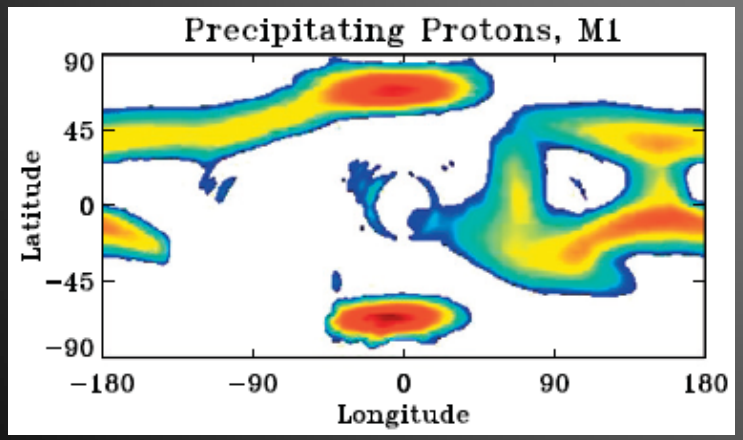
Yokota et al.

Solar Wind sputtering is not dominant source process, but "Gardening" is possibly effective.

↑SW particles sticks into the surface and diffuses material.



Benna et al., 2010

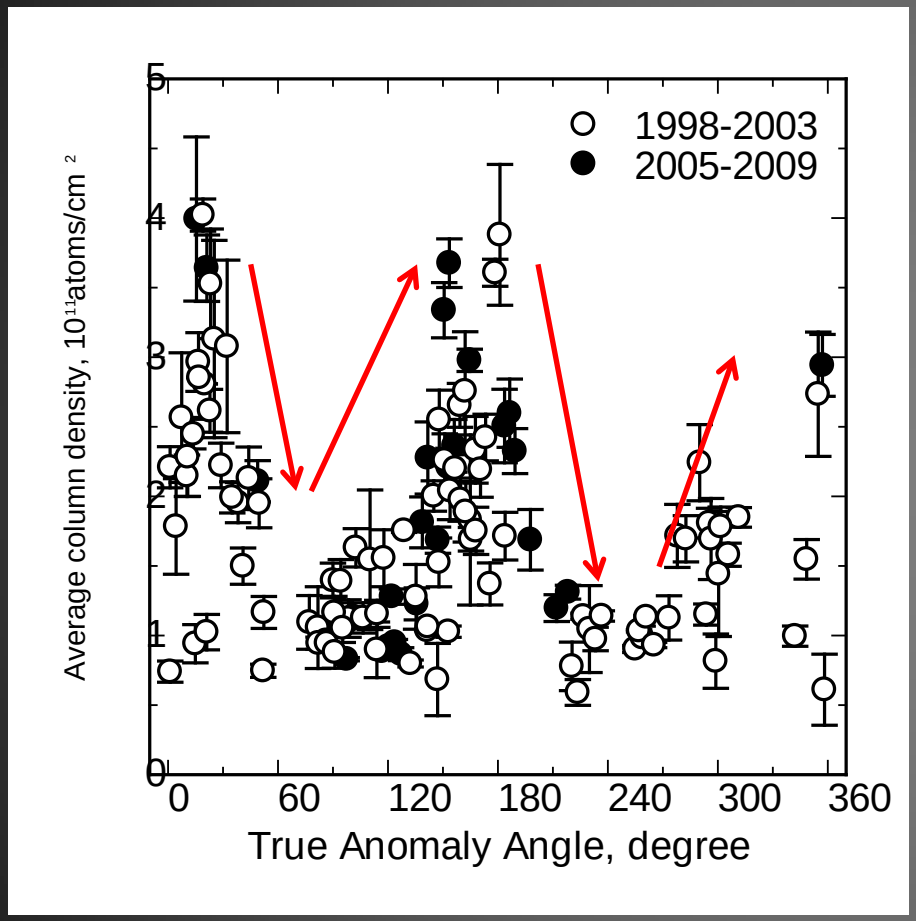


Burger et al., 2010

Simulation has already been done based on the data obtained in Messenger Flyby.

*Ion flux to the surface

*Sodium density on the dayside



$$d_{ave} = \Phi_{source}\, \tau_{lifetime}$$

$$\Phi_{PSD} \propto r^{-2}$$

$$\tau_{PI} \propto r^{2}$$

$$\rightarrow d_{ave} = const.$$

In 1 Mercury year, the average density changes by a factor of ~4.

- ●Potter et al. (2007)
- ○Kameda et al. in prep. Okayama and Haleakala

Average Na density vs

1, F10.7 solar flux

2, Solar flux (0-200nm)

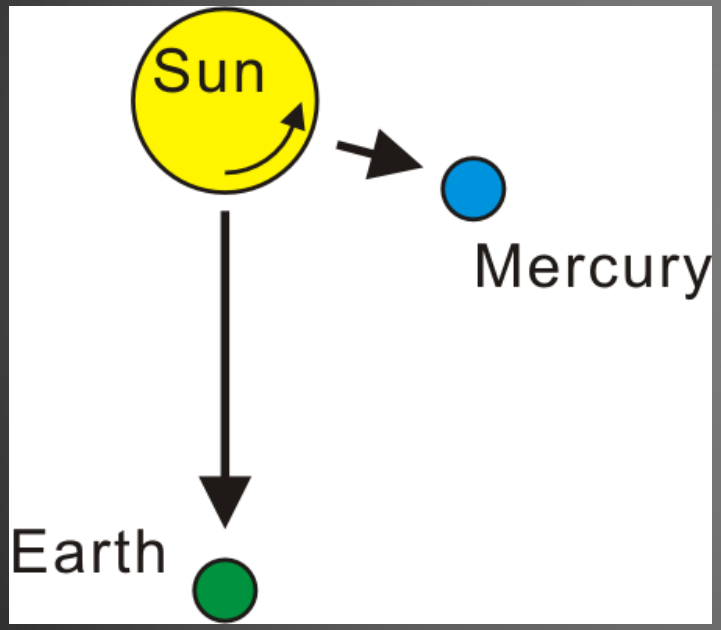
3, Solar wind proton flux

4, Distance from ecliptic plane

5, Distance from symmetry plane of Interplanetary Dust distribution

6, Tidal force

- F10.7 solar flux →UV/EUV flux

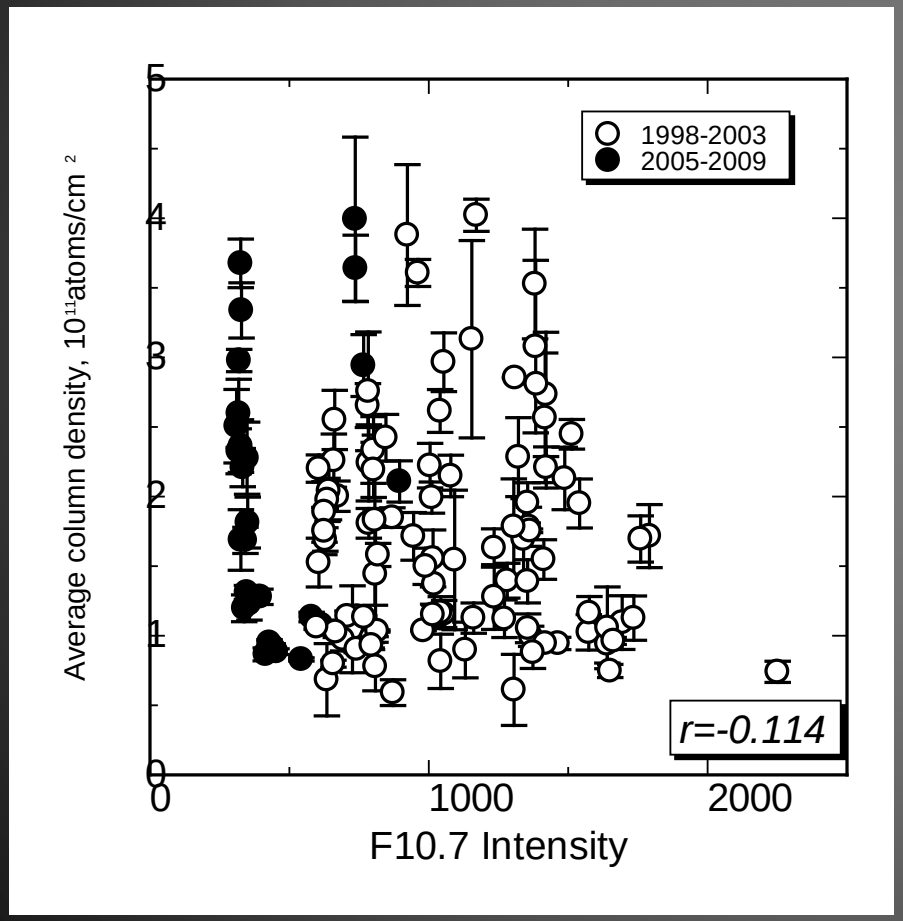


- F10.7 at Mercury is estimated considering the heliospheric distance

  and

  the rotation of the sun assuming F10.7 is dependent on longitude and independent on time.

- F10.7 solar flux →UV/EUV flux → PSD



No correlation

(the same as shown by Kameda et al. (2009) using the data obtained in 1998-2003 and 2006)

Average Na density vs

1, F10.7 solar flux → No

2, Solar flux (0–200nm)

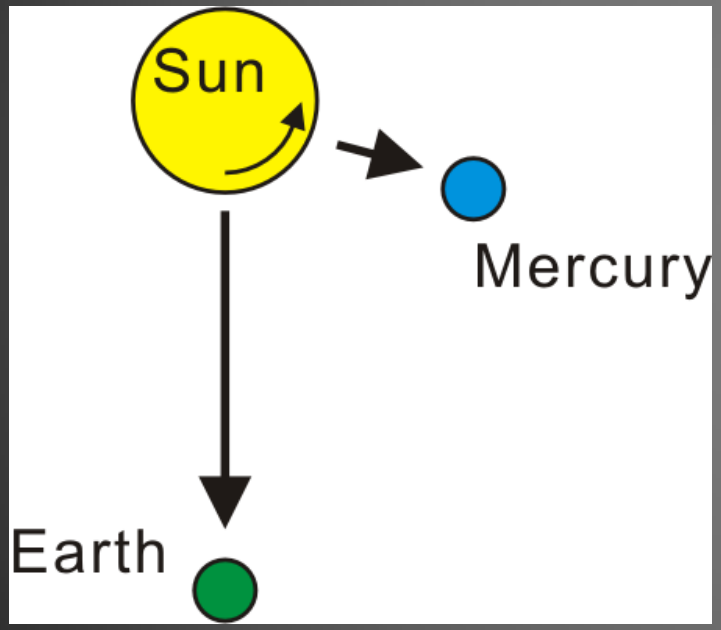
3, Solar wind proton flux

4, Distance from ecliptic plane

5, Distance from symmetry plane of Interplanetary Dust distribution

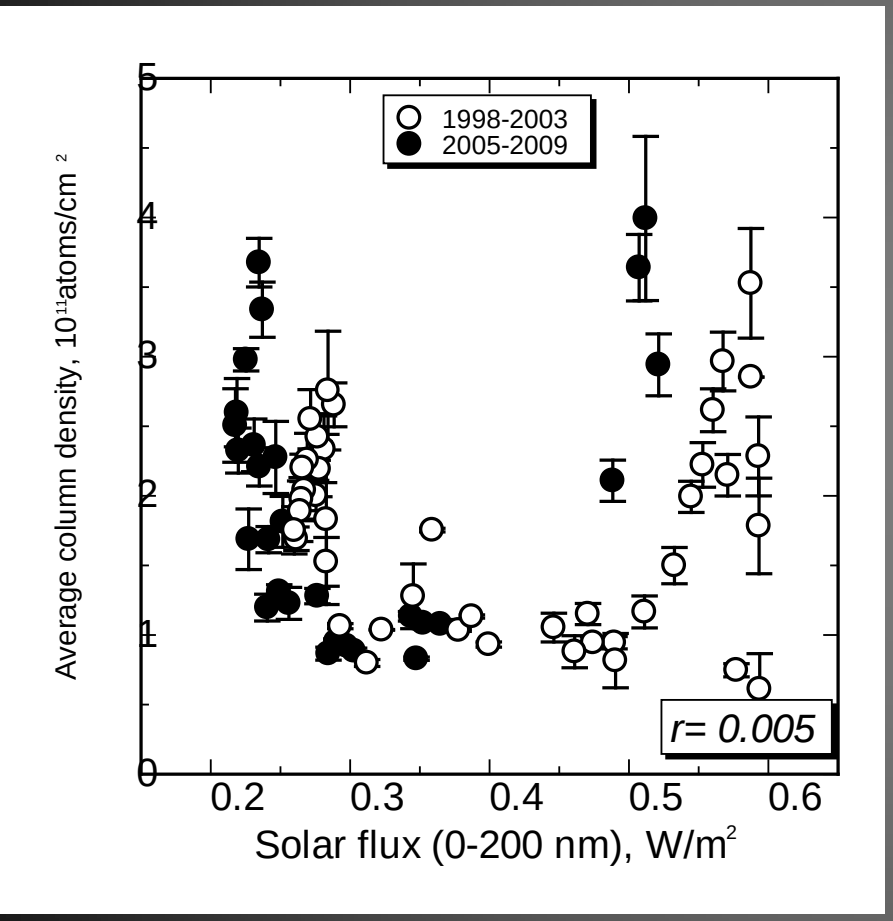
6, Tidal force

LASP



Solar EUV Experiment (SEE) on TIMED measured the solar flux at the wavelength of 0-200nm.

The flux at Mercury was estimated in the same way as F10.7.



No correlation

(SEE Observation was started in Feb 2002.)

PSD threshold wavelength is ~ 300 nm [Yakshinskiy and Madey, 2004].

Average Na density vs

1, F10.7 solar flux → No

2, Solar flux (0–200nm) → No

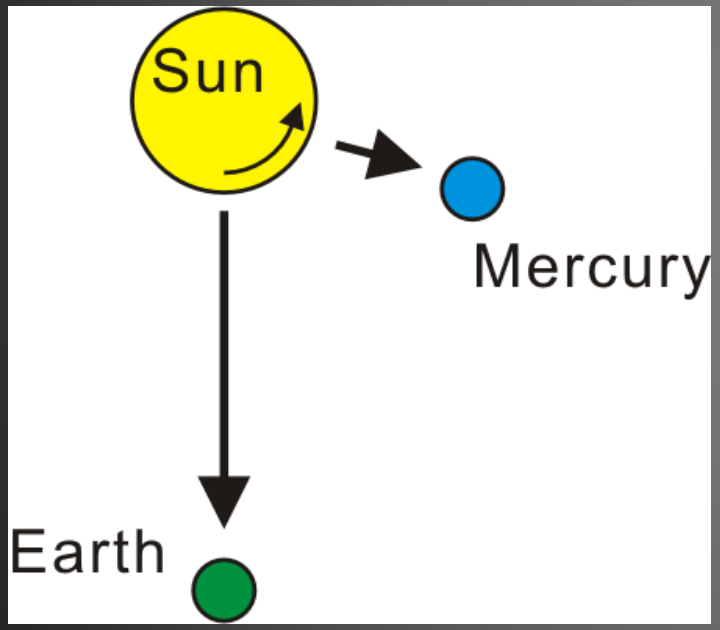
3, Solar wind proton flux

4, Distance from ecliptic plane

5, Distance from symmetry plane of Interplanetary Dust distribution

6, Tidal force

LANL



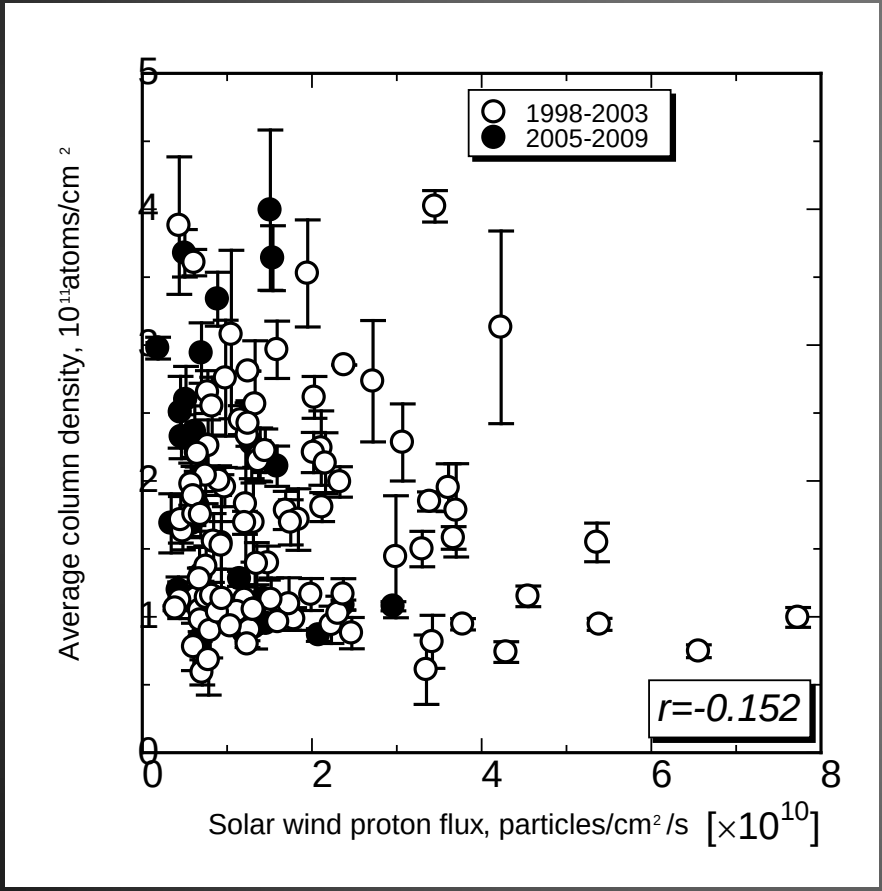
Solar Wind Electron Proton Alpha monitor (SWEPAM) on ACE measured the solar wind proton flux at L1.

SW flux is estimated to be:

dependent on longitude

$\propto r^{-2}$

velocity is constant



No correlation

Sunspot number in 1998-2003 is more than 2005-2009

Average Na density vs

1, F10.7 solar flux → No

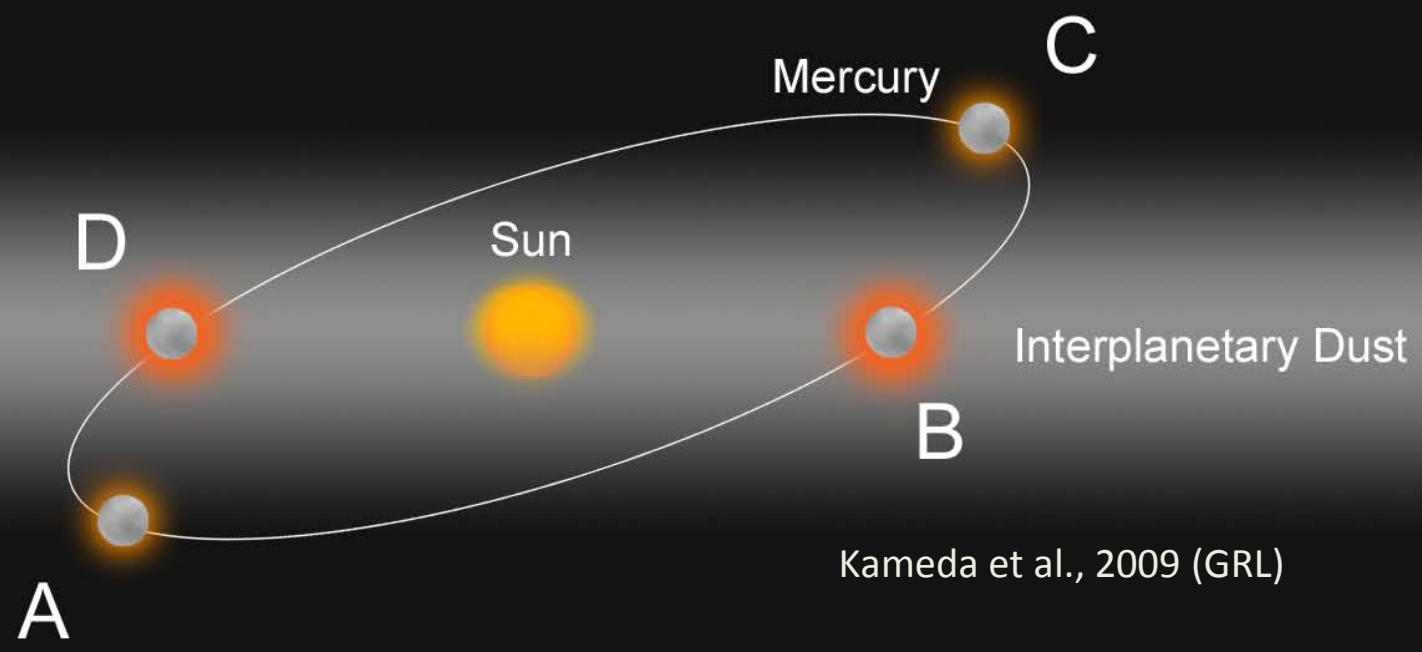
2, Solar flux (0–200nm) → No

3, Solar wind proton flux → No

4, Distance from ecliptic plane

5, Distance from symmetry plane of Interplanetary Dust distribution

6, Tidal force

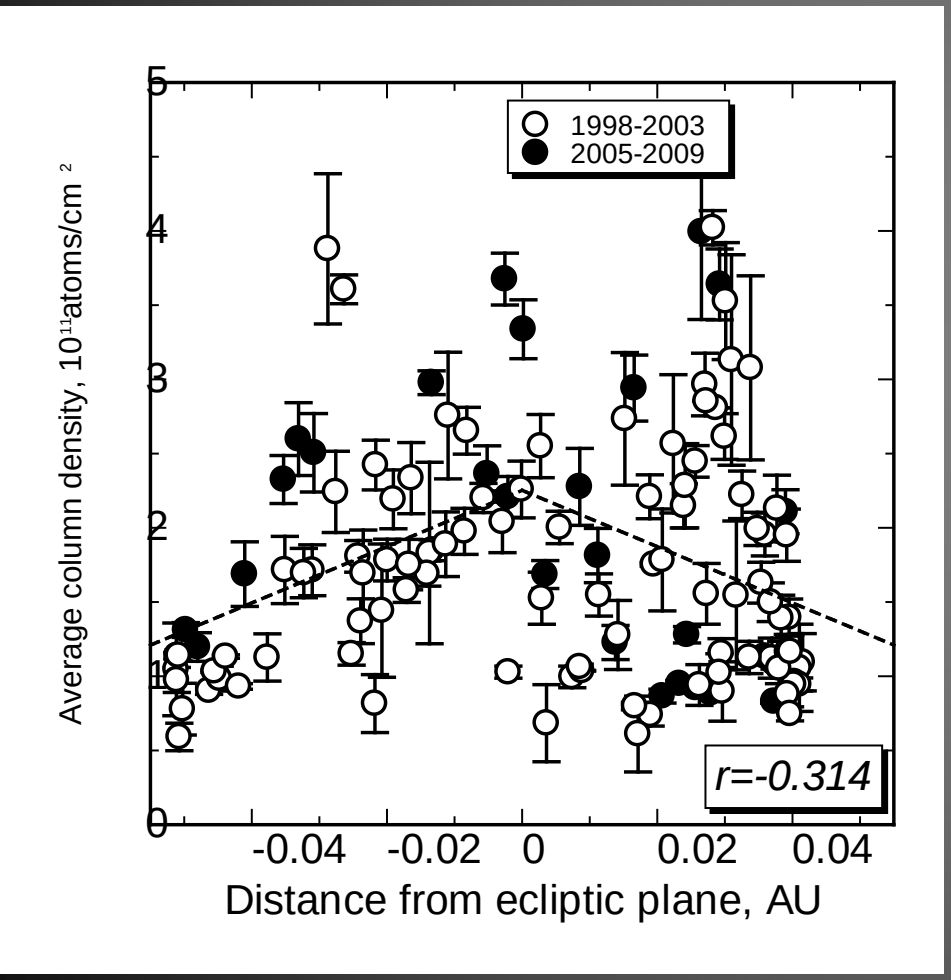


Kameda et al., 2009 (GRL)

Mercury's orbital plane is tilted (7deg) against the ecliptic plane and the interplanetary dust (IPD) is concentrated near the ecliptic plane.

→ Frequency of IPD impact is higher at B and D.

Potter et al., 2008



Weak inverse correlation

with absolute value of distance from ecliptic plane.

Average Na density vs

1, F10.7 solar flux → No

2, Solar flux (0–200nm) → No

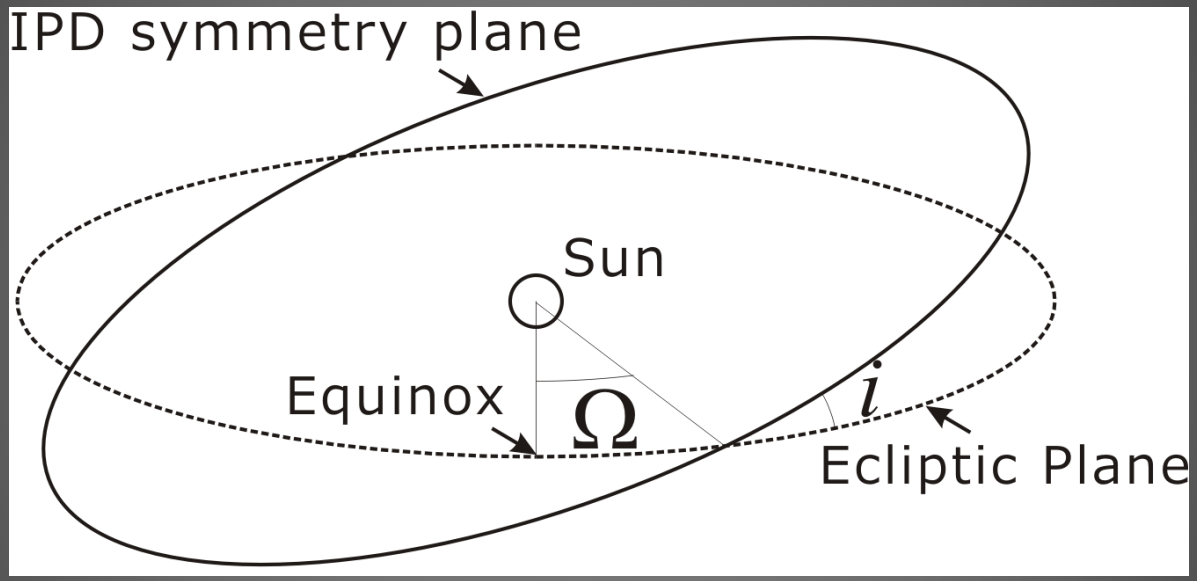
3, Solar wind proton flux → No

4, Distance from ecliptic plane → Weak

5, Distance from symmetry plane of Interplanetary Dust distribution

6, Tidal force

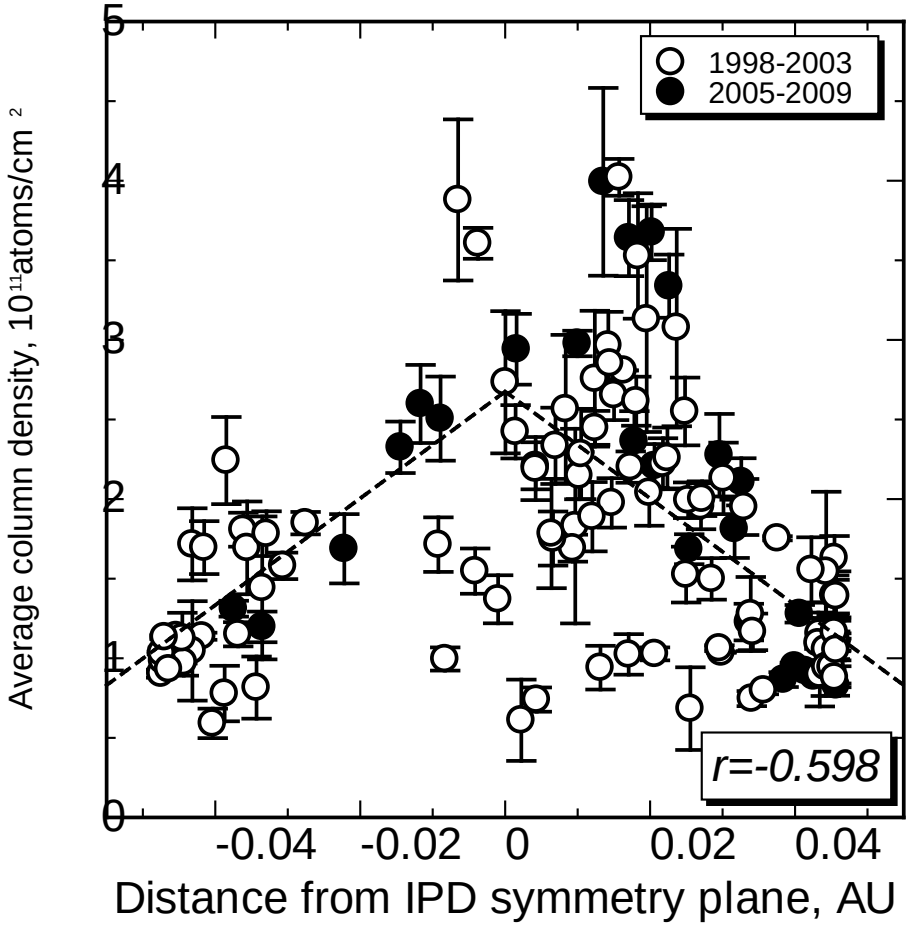
- Symmetry plane is tilted against the ecliptic.



Ω: Ascending node, i: inclination

Ω=-31 deg, i=2.9 deg [Kameda et al., 2009]

*Mercury: Ω= 48 deg, i=7 deg



Correlated with the distance from IPD symmetry plane.

→ IPD impact is effective for the release of sodium atoms from the surface.

Average Na density vs

1, F10.7 solar flux → No

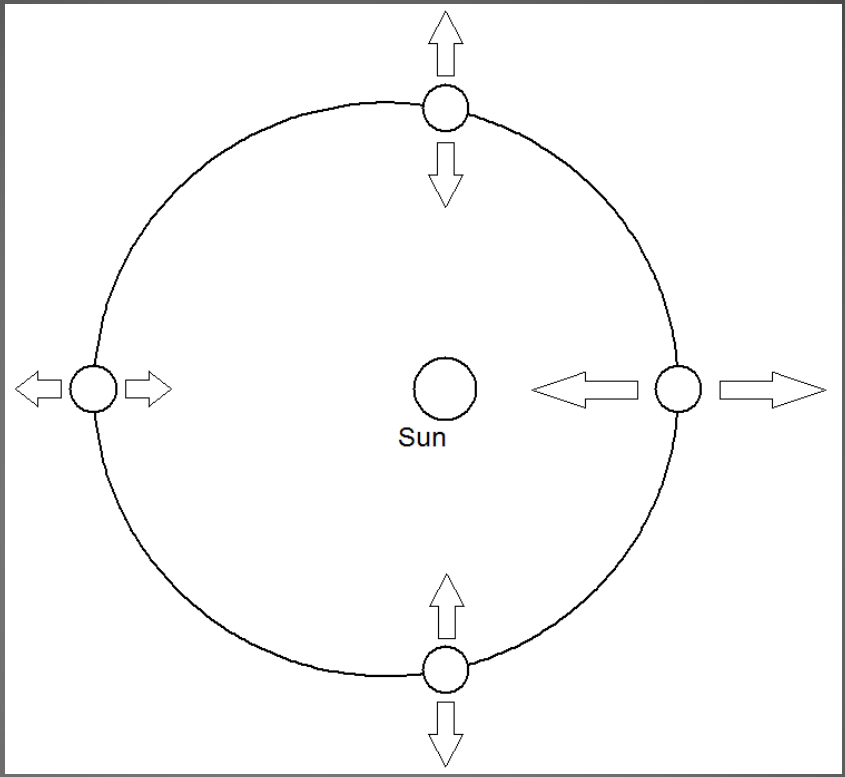
2, Solar flux (0–200nm) → No

3, Solar wind proton flux → No

4, Distance from ecliptic plane → Weak

5, Distance from symmetry plane of Interplanetary Dust distribution → Correlated

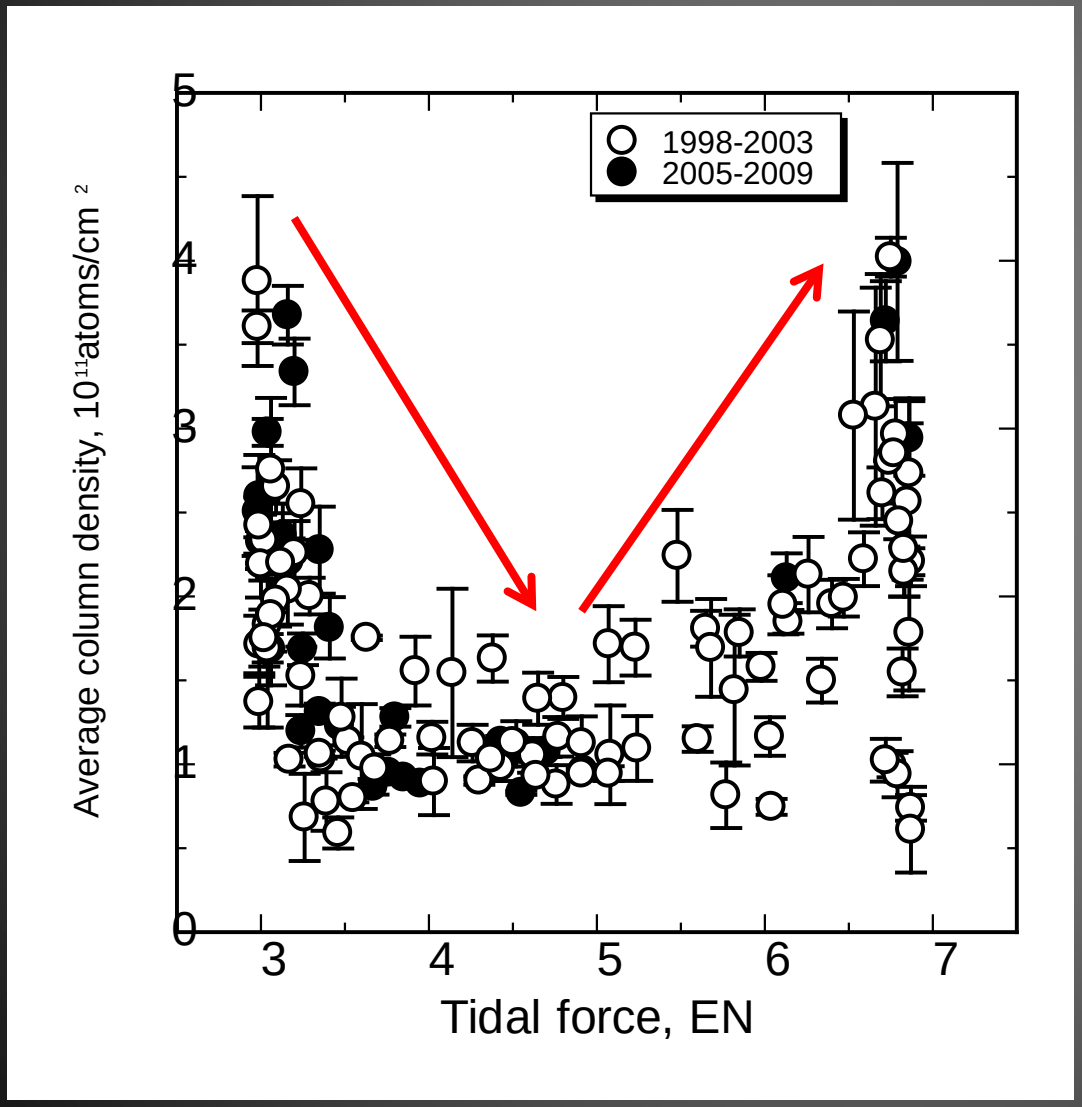
6, Tidal force



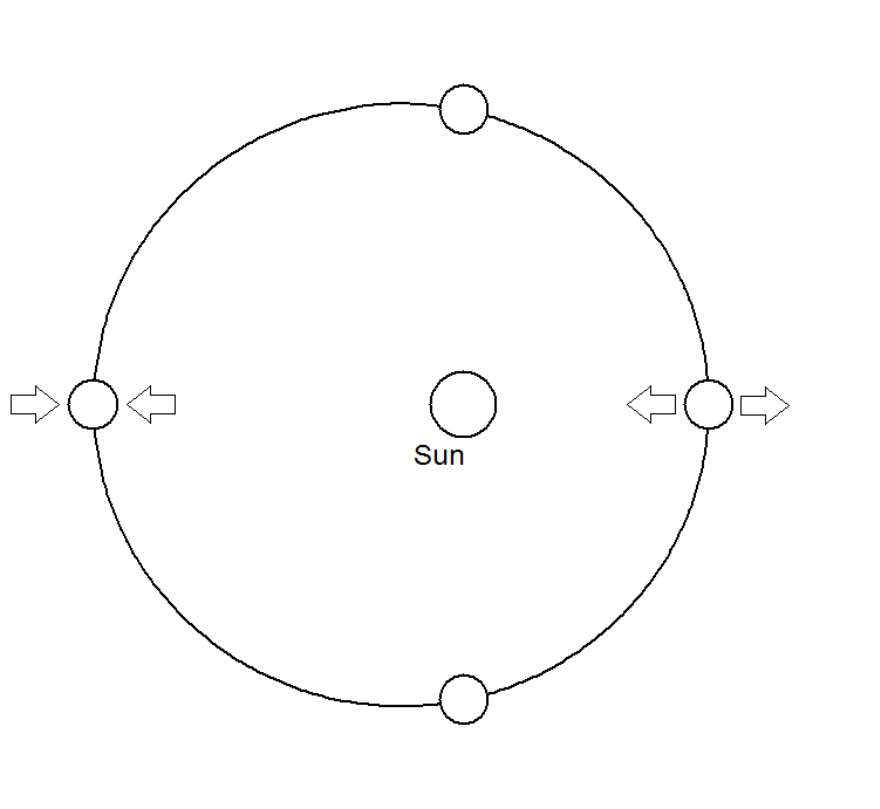
Mercury's orbital is eccentric (e ~0.2).

→ Tidal force at perihelion is twice stronger than that at aphelion.

Potter et al., 2008



Atmosphere is dense near perihelion and aphelion (but not always).

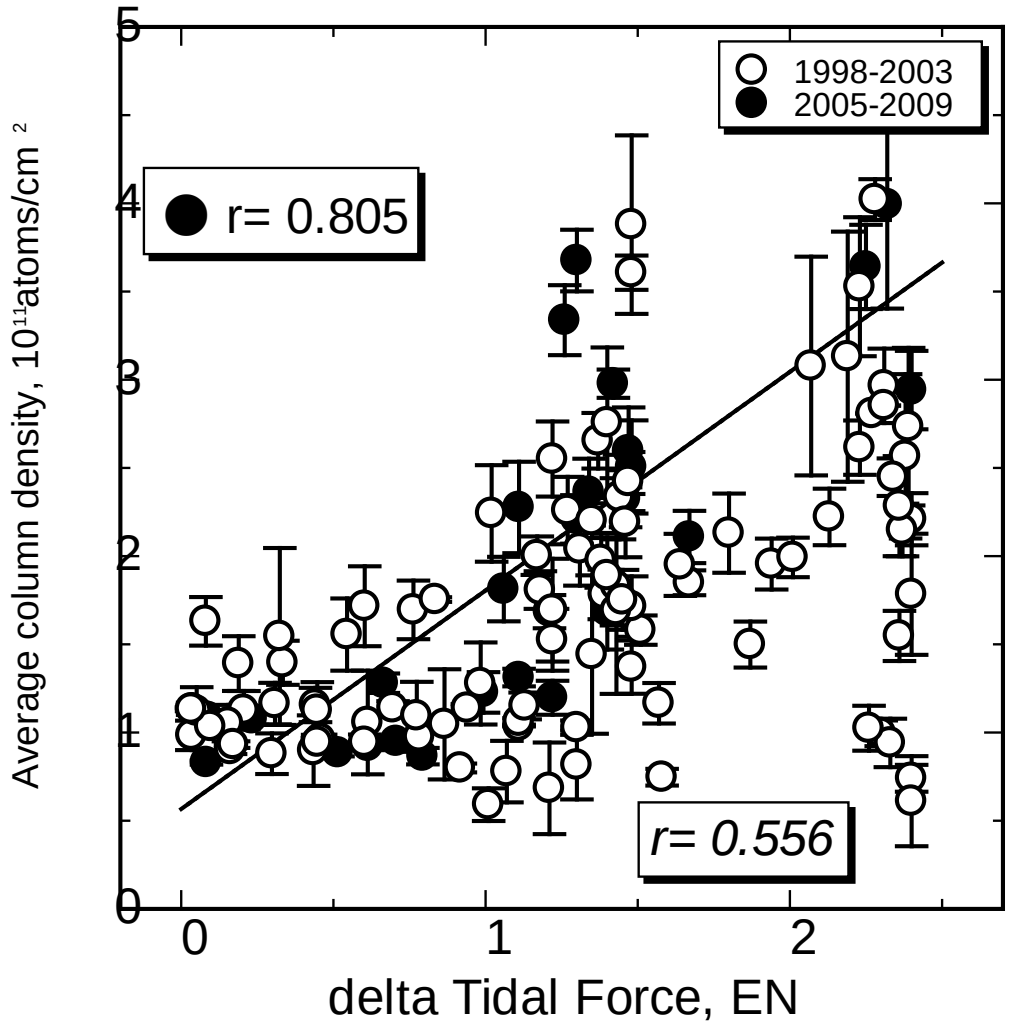


Tidal force is always outward.

→Relative tidal force is inward at aphelion and outward at perihelion.

→Distortion is greatest at perihelion and aphelion.

Foster et al., 2008



Tidal force is not a release process, however,,,

Tidal force will possibly increase the source rate, e.g., refreshing the surface layer.

Potter et al., 2008

Average Na density vs

1, F10.7 solar flux → No

2, Solar flux (0–200nm) → No

3, Solar wind proton flux → No

4, Distance from ecliptic plane → Weak

5, Distance from symmetry plane of Interplanetary Dust distribution

6, Tidal force

The perihelion and aphelion is near the ecliptic plane.

→It is difficult to know which is more effective and explain sodium concentration at high latitudes.

→Mercury Dust Monitor on BepiMMO and Mercury lander in the future.

Average Na density vs

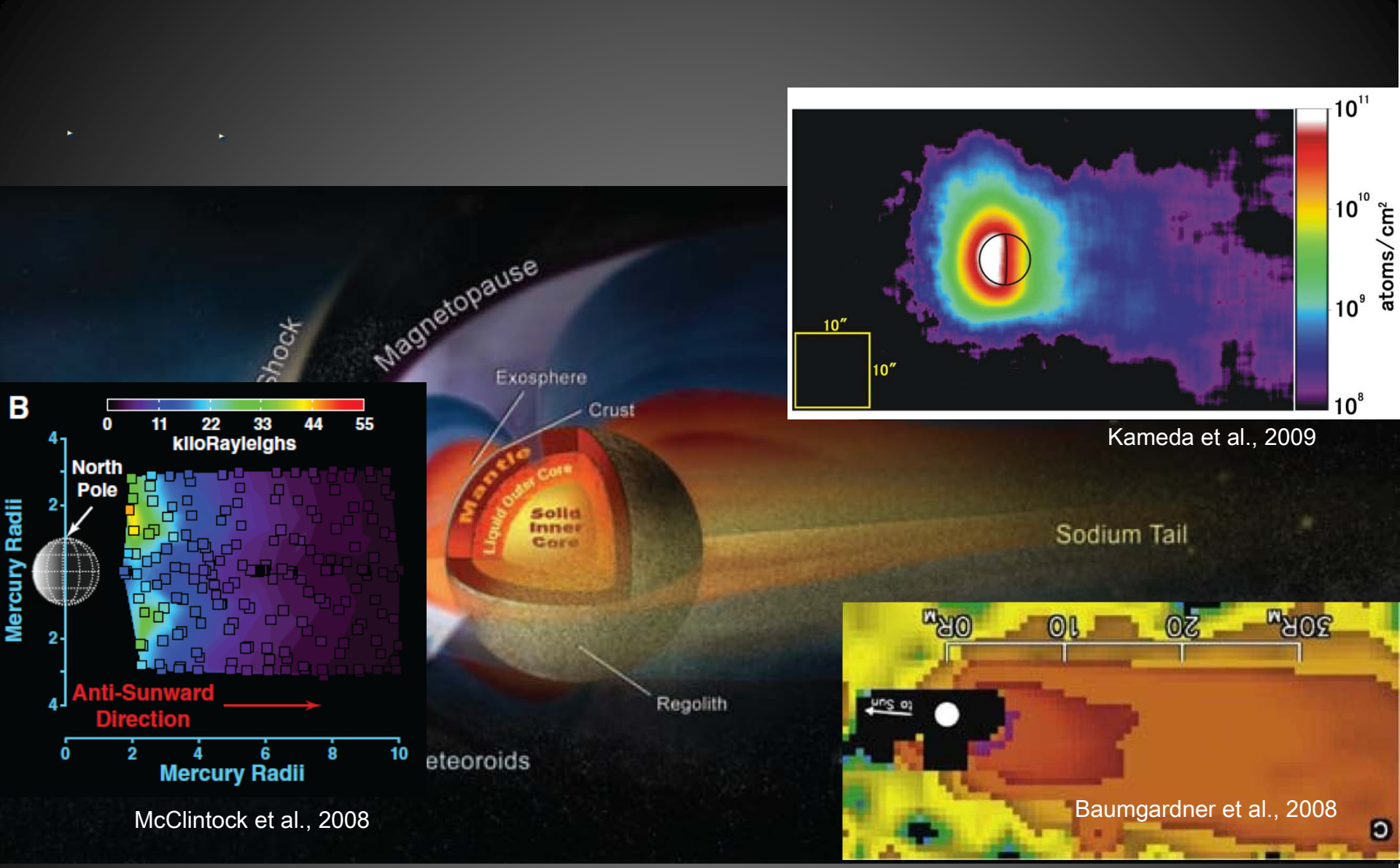
2, Solar flux (0–200nm) → No

MASCS data for UV reflected on surface

3, Solar wind proton flux → No

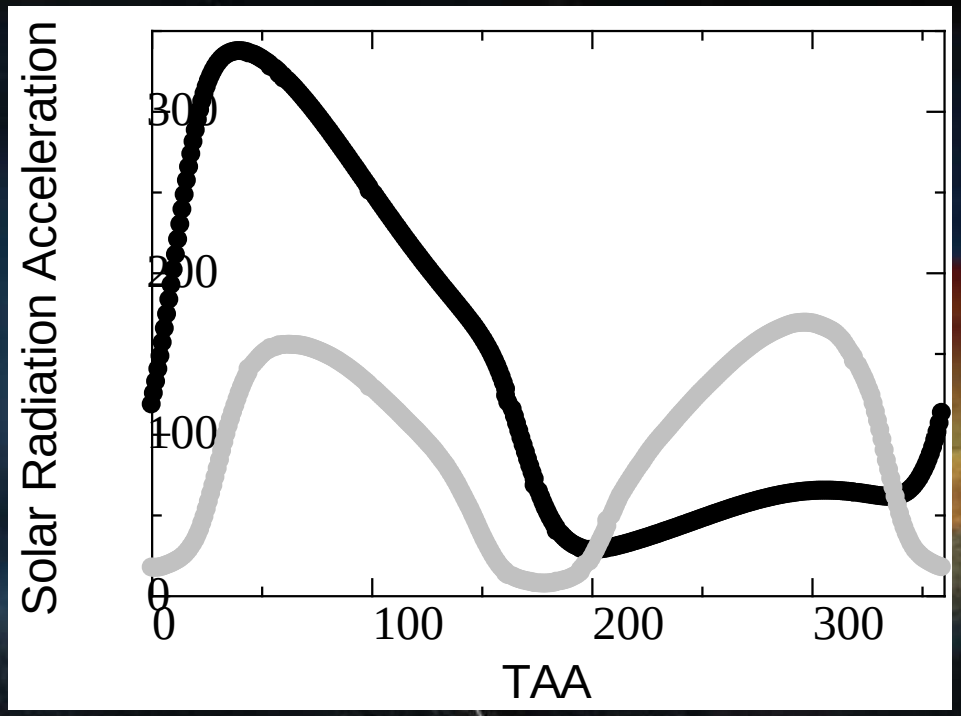
Precipitation detected using FIPS

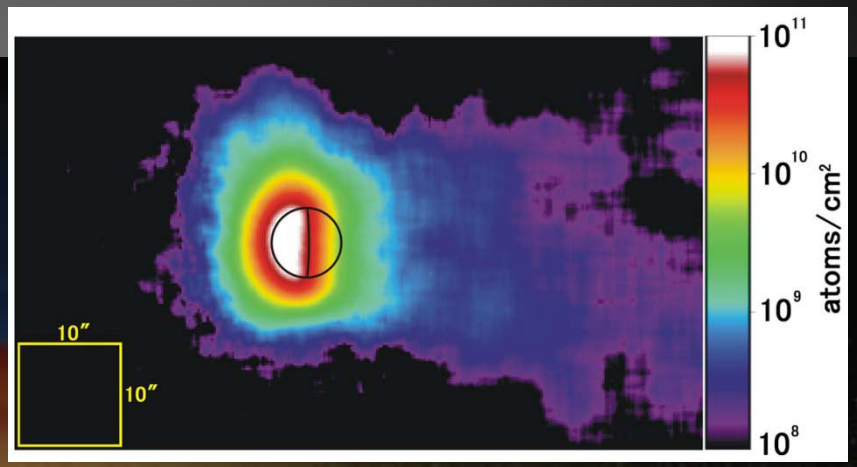
→ Long-term monitoring will provide us something new.

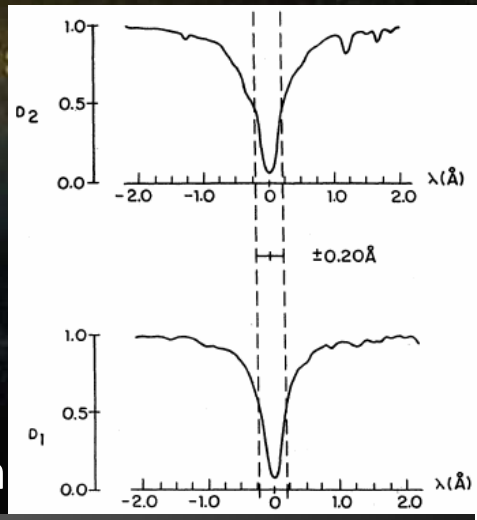


After released from the surface, sodium atoms move toward antisunward direction due to solar radiation pressure.

→ Photoionized in ~3 hours → Loss to the interplanetary space.







Solar radiation pressure depends on True Anomaly Angle.

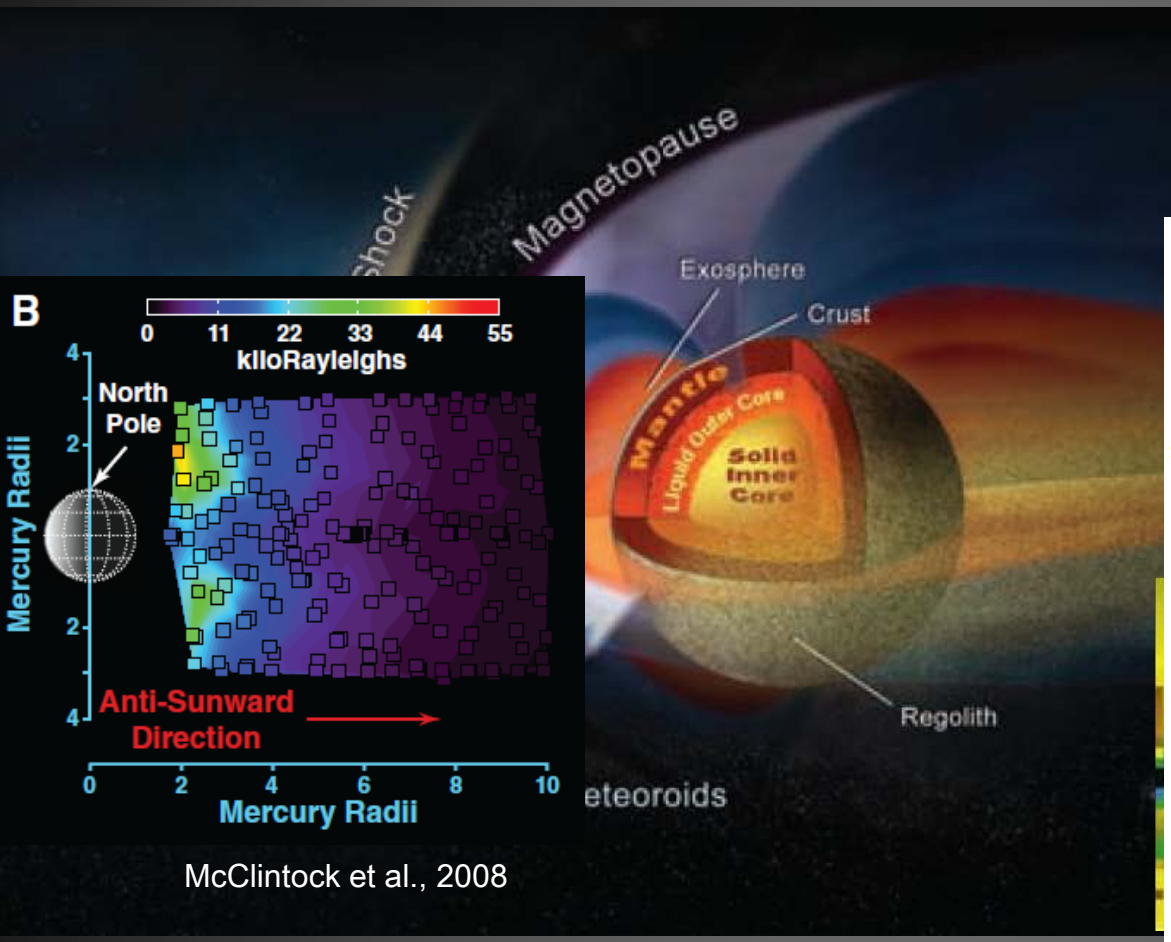
Gray line shows the result of calculation by Smyth and Marcon

Black shows the result of ours.

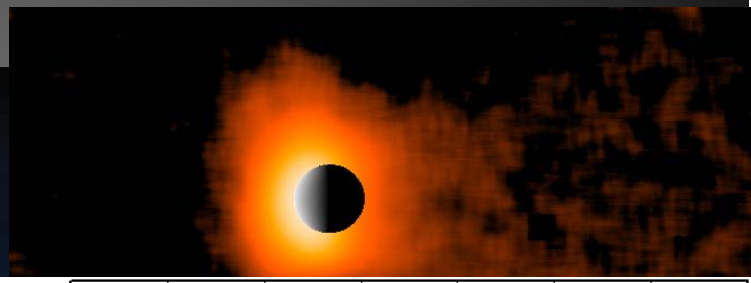
Na tail will be longest at TAA of ~40.

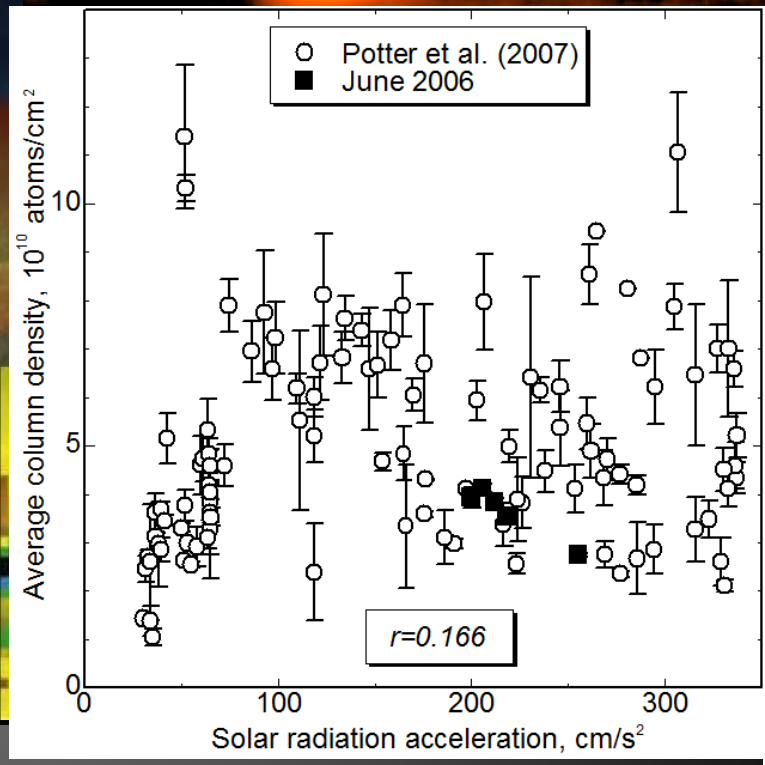
[Kameda et al., 2009 GRL]

$$A_{ave} = \frac{\int_0^\infty A_v \exp(-t/\tau)\,dt}{\int_0^\infty \exp(-t/\tau)\,dt}, \frac{dv}{dt} = A_v, v_{t=0} = 0$$



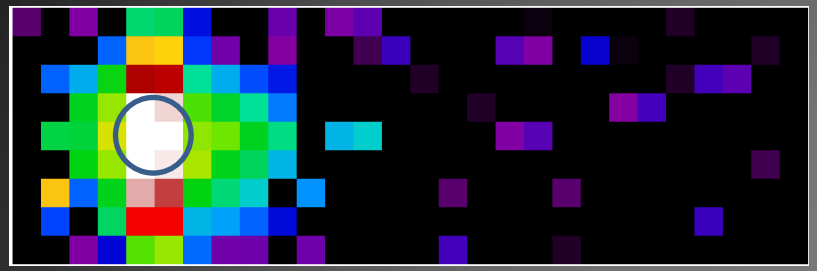
McClintock et al., 2008



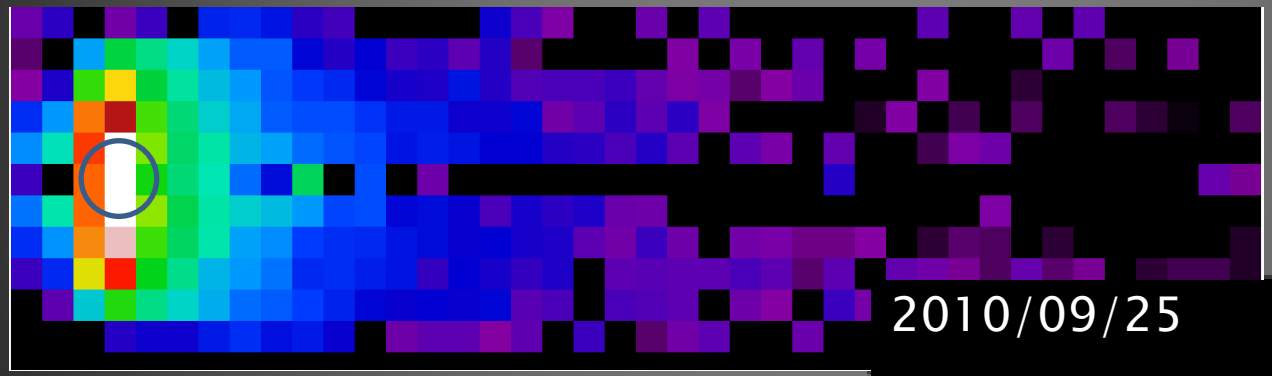


No correlation between Sodium density and solar radiation acceleration.
(Solar radiation acceleration depends on orbital position of Mercury.)

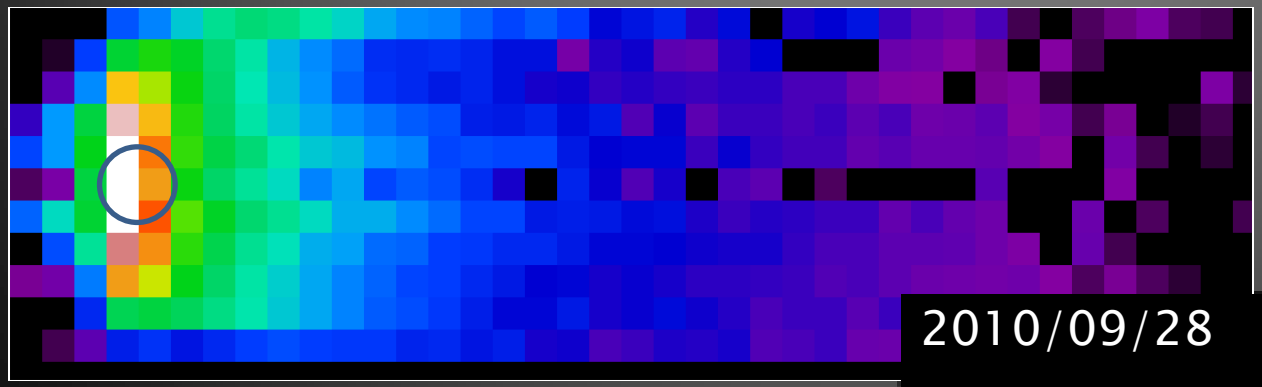
Observation at Haleakala Observatory



2010/09/19



2010/09/25



2010/09/28

Preliminary results

TAA=345, 23, 40

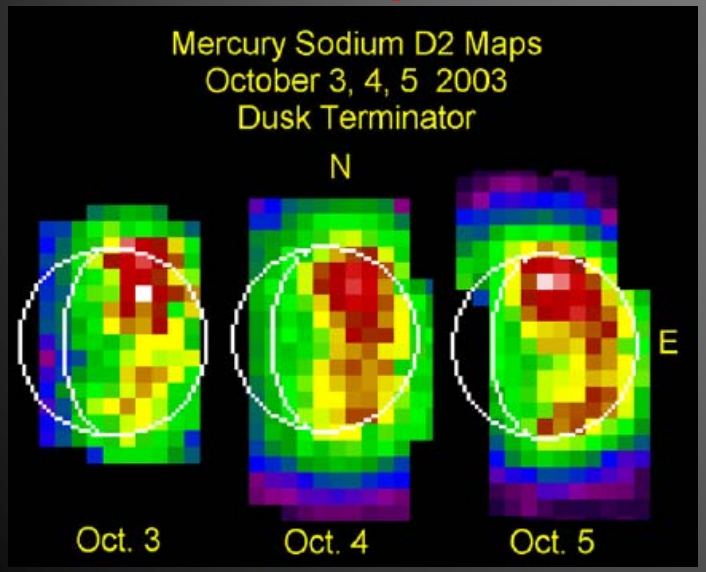
Distance of the tail varies with TAA.

Velocity resolution is~ 1km/s.

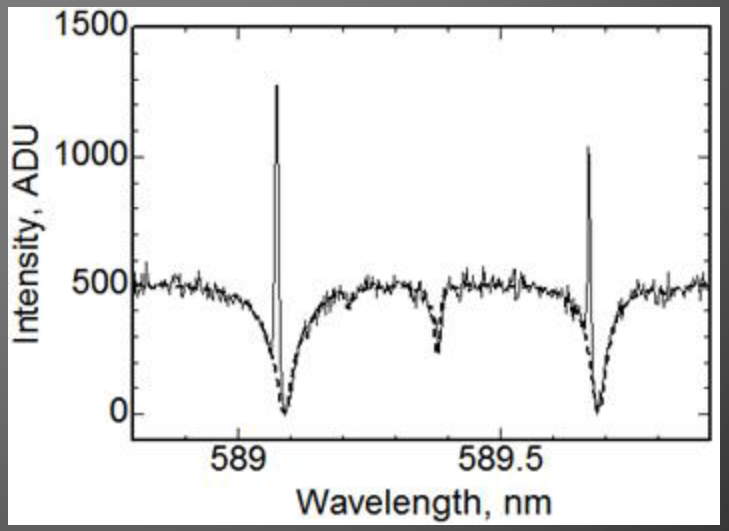
We plan to do

In 2011-2012.

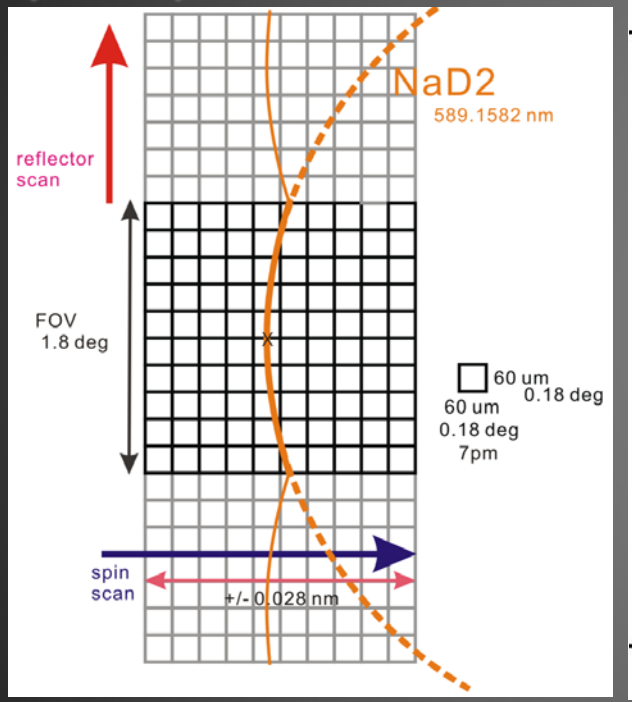
- MSASI is “Mercury Sodium Atmosphere Spectral Imager.”
- Spectral resolution of ~85,000 (7pm) enables us to observe distribution of Na exosphere on the **dayside.**

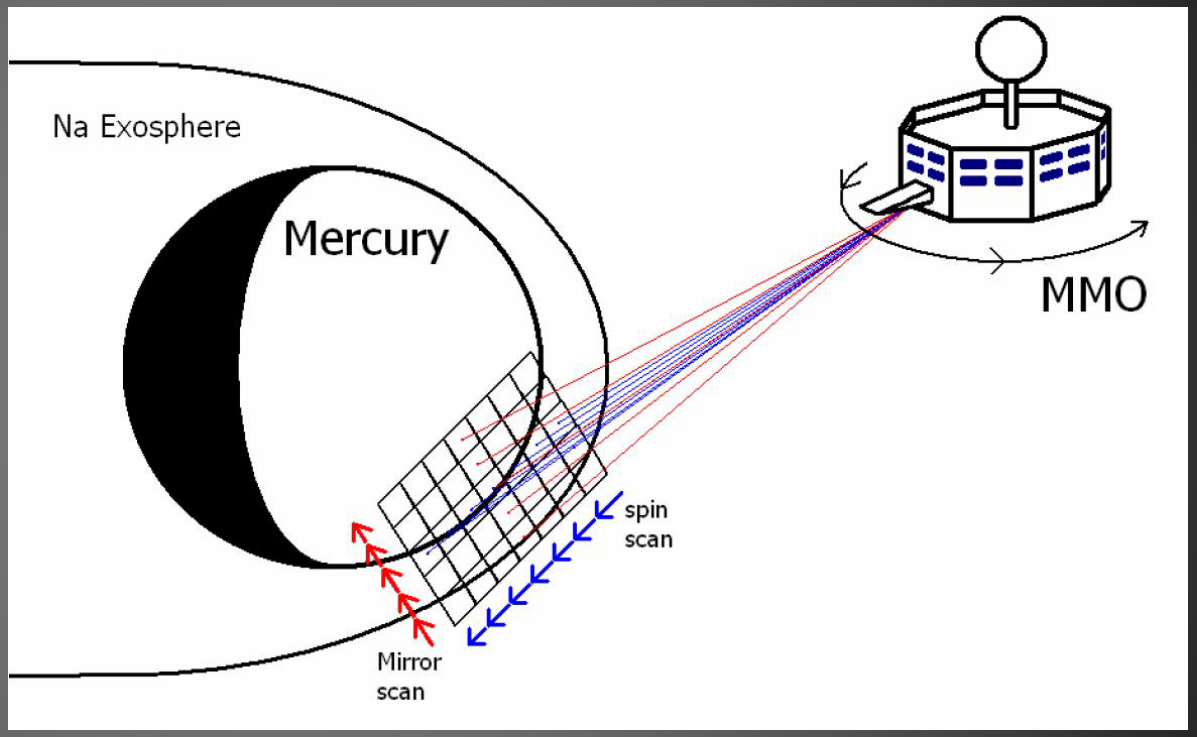


Potter et al., 2008

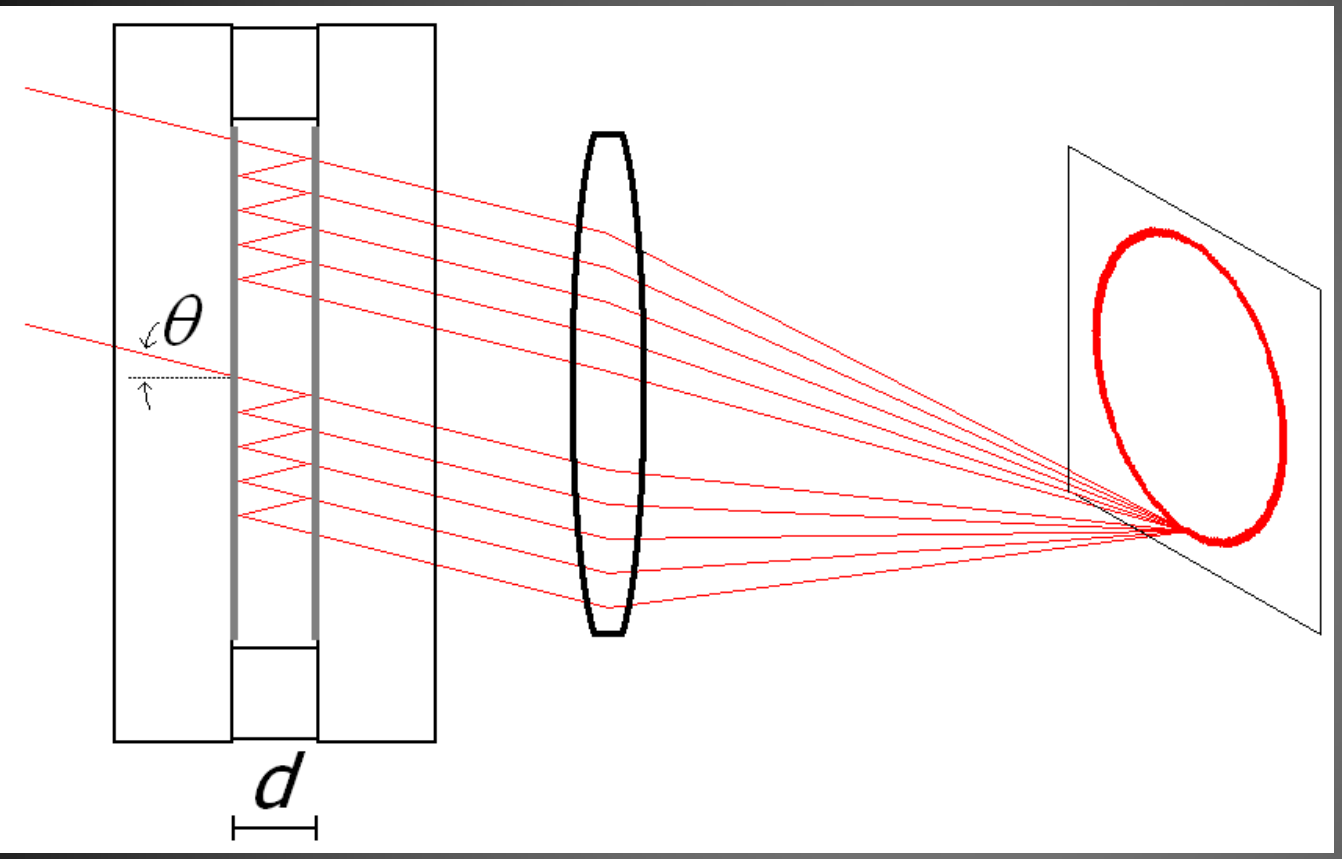


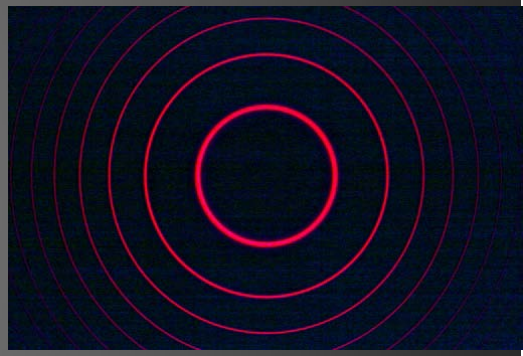
Line width of NaD is 5pm


NaD2
589.1582 nm
reflector
scan
FOV
1.8 deg
60 um
0.18 deg
60 um
0.18 deg
7pm
spin
scan
+/- 0.028 nm


Na Exosphere
Mercury
MMO
spin
scan
Mirror
scan

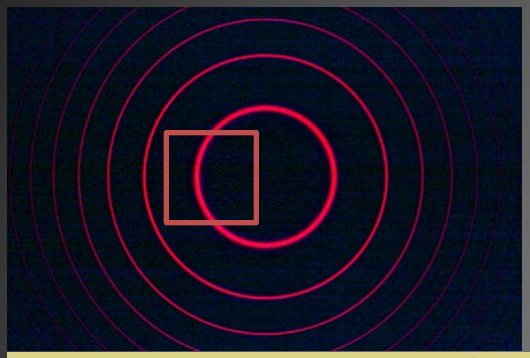
→





$m\lambda = 2nd\cos\theta$ → Transmission

Interference fringe



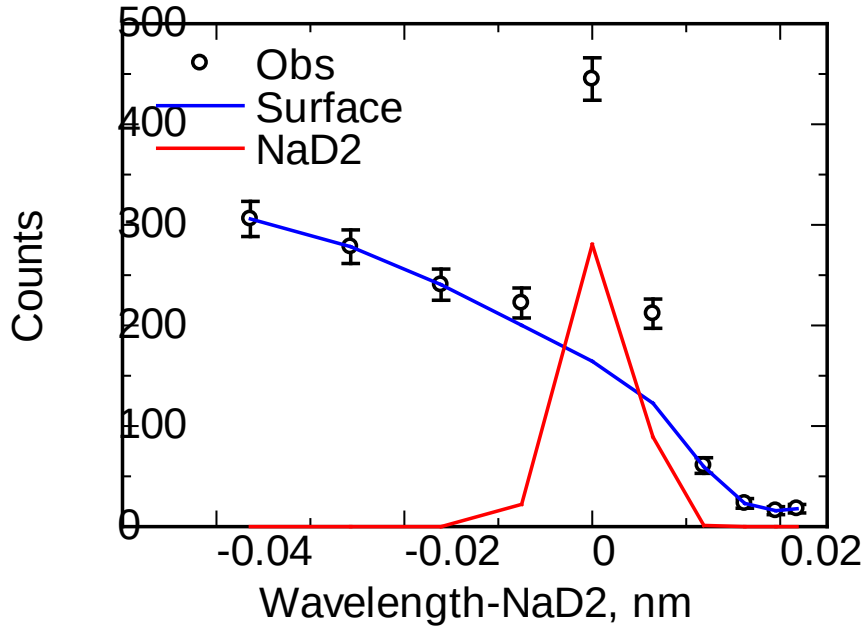
$$\lambda_\theta = \lambda_0 \left[1 - \left(\frac{Ne}{N^*}\right)^2 \sin^2\theta \right]^{\frac{1}{2}}$$

Where:
- λ_θ = Wavelength at angle of incidence
- λ_0 = Wavelength at normal incidence
- Ne = Refractive index of external medium
- N* = Effective refractive index of the filter
- θ = Angle of incidence

Transmit wavelength
∝ Cos θ (Etalon)
∝ Eq. above (Filter)

→Tilt angle
0.51 deg (Etalon)
1.39 deg (Filter)

589.11128	589.12196	589.13158	589.14015	589.14767	589.15414	589.15955	589.16391	589.16721	589.16946
589.11923	589.12721	589.13473	589.14176	589.14828	589.15423	589.15956	589.16416	589.1739	589.17064
589.11549	589.12617	589.13579	589.14436	589.15188	589.15835	589.16376	589.16812	589.17142	589.17368
589.12234	589.13046	589.13814	589.14537	589.15212	589.15835	589.164	589.16899	589.17316	589.17629
589.11865	589.12933	589.13895	589.14752	589.15504	589.16151	589.16692	589.17128	589.17458	589.17683
589.12471	589.13294	589.14076	589.14815	589.1551	589.16159	589.16757	589.17297	589.17765	589.18134
589.12076	589.13144	589.14106	589.14963	589.15715	589.16361	589.16902	589.17338	589.17669	589.17894
589.1263	589.13461	589.14253	589.15006	589.15715	589.16384	589.17009	589.17587	589.18108	589.18553
589.12181	589.13249	589.14211	589.15068	589.1582	589.16466	589.17008	589.17444	589.17774	589.17999
589.1271	589.13546	589.14343	589.15101	589.1582	589.165	589.17141	589.17742	589.18302	589.18817
589.12181	589.13249	589.14211	589.15068	589.1582	589.16466	589.17008	589.17444	589.17774	589.17999
589.1271	589.13546	589.14343	589.15101	589.1582	589.165	589.17141	589.17742	589.18302	589.18817
589.12076	589.13144	589.14106	589.14963	589.15715	589.16361	589.16902	589.17338	589.17669	589.17894
589.1263	589.13461	589.14253	589.15006	589.15715	589.16384	589.17009	589.17587	589.18108	589.18553
589.11865	589.12933	589.13895	589.14752	589.15504	589.16151	589.16692	589.17128	589.17458	589.17683
589.12471	589.13294	589.14076	589.14815	589.1551	589.16159	589.16757	589.17297	589.17765	589.18134
589.11549	589.12617	589.13579	589.14436	589.15188	589.15835	589.16376	589.16812	589.17142	589.17368
589.12234	589.13046	589.13814	589.14537	589.15212	589.15835	589.164	589.16899	589.17316	589.17629
589.11128	589.12196	589.13158	589.14015	589.14767	589.15414	589.15955	589.16391	589.16721	589.16946
589.11923	589.12721	589.13473	589.14176	589.14828	589.15423	589.15956	589.16416	589.16791	589.17064



39.13158	589.14015	589.14767	589.15414	589.15955	589.16391	589.16721	589.16946
39.13473	589.14176	589.14828	589.15423	589.15956	589.16416	589.1739	589.17064
39.13579	589.14436	589.15188	589.15835	589.16376	589.16812	589.17142	589.17368
39.13814	589.14537	589.15212	589.15835	589.164	589.16899	589.17316	589.17629
39.13895	589.14752	589.15504	589.16151	589.16692	589.17128	589.17458	589.17683
39.14076	589.14815	589.1551	589.16159	589.16757	589.17297	589.17765	589.18134
39.14106	589.14963	589.15715	589.16361	589.16902	589.17338	589.17669	589.17894
39.14253	589.15006	589.15715	589.16384	589.17009	589.17587	589.18108	589.18553
39.14211	589.15068	589.1582	589.16466	589.17008	589.17444	589.17774	589.17999
39.14343	589.15101	589.1582	589.165	589.17141	589.17742	589.18302	589.18817
39.14211	589.15068	589.1582	589.16466	589.17008	589.17444	589.17774	589.17999
14343	589.15101	589.1582	589.165	589.17141	589.17742	589.18302	589.18817
14106	589.14963	589.15715	589.16361	589.16902	589.17338	589.17669	589.17894
14253	589.15006	589.15715	589.16384	589.17009	589.17587	589.18108	589.18553
13895	589.14752	589.15504	589.16151	589.16692	589.17128	589.17458	589.17683
14076	589.14815	589.1551	589.16159	589.16757	589.17297	589.17765	589.18134
13579	589.14436	589.15188	589.15835	589.16376	589.16812	589.17142	589.17368
13814	589.14537	589.15212	589.15835	589.164	589.16899	589.17316	589.17629
13158	589.14015	589.14767	589.15414	589.15955	589.16391	589.16721	589.16946
13473	589.14176	589.14828	589.15423	589.15956	589.16416	589.16791	589.17064

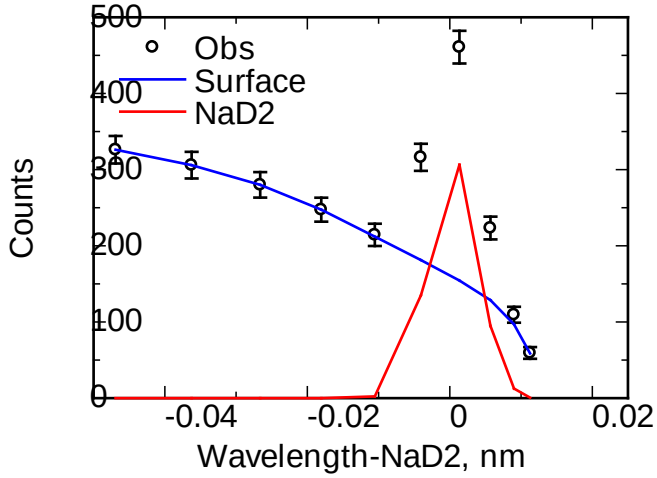
∝ Cos θ

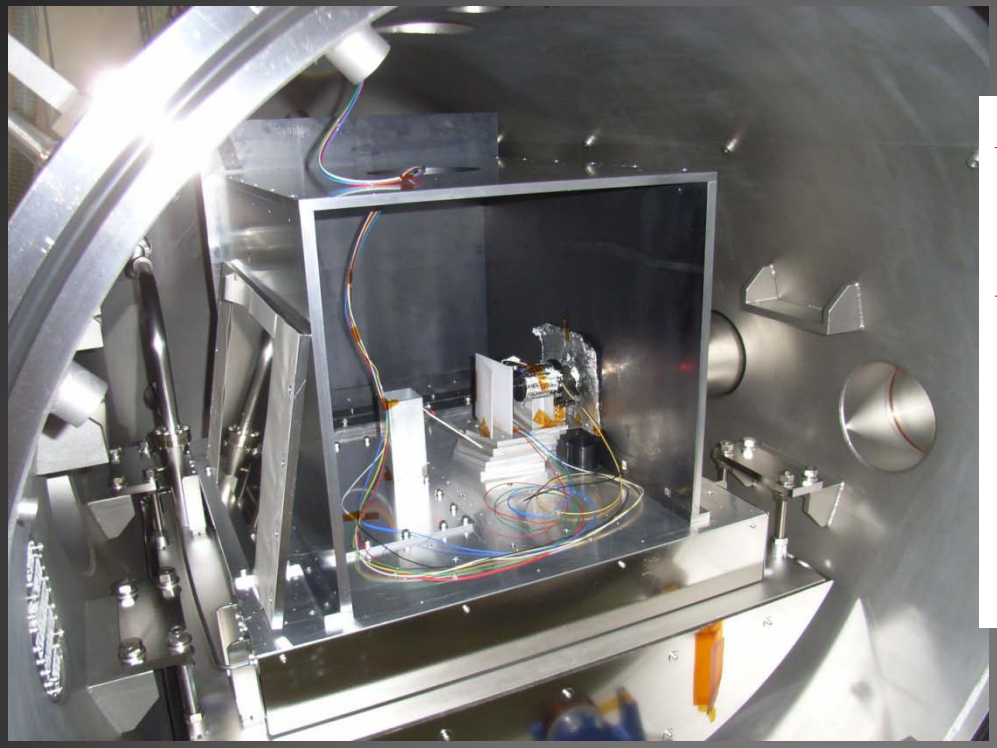
∝ Eq. a

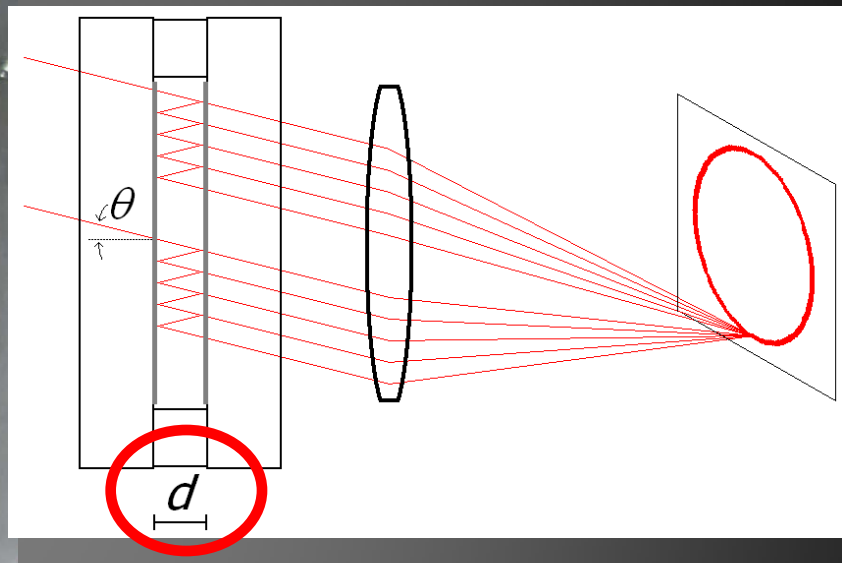
→Tilt a

0.51

1.39





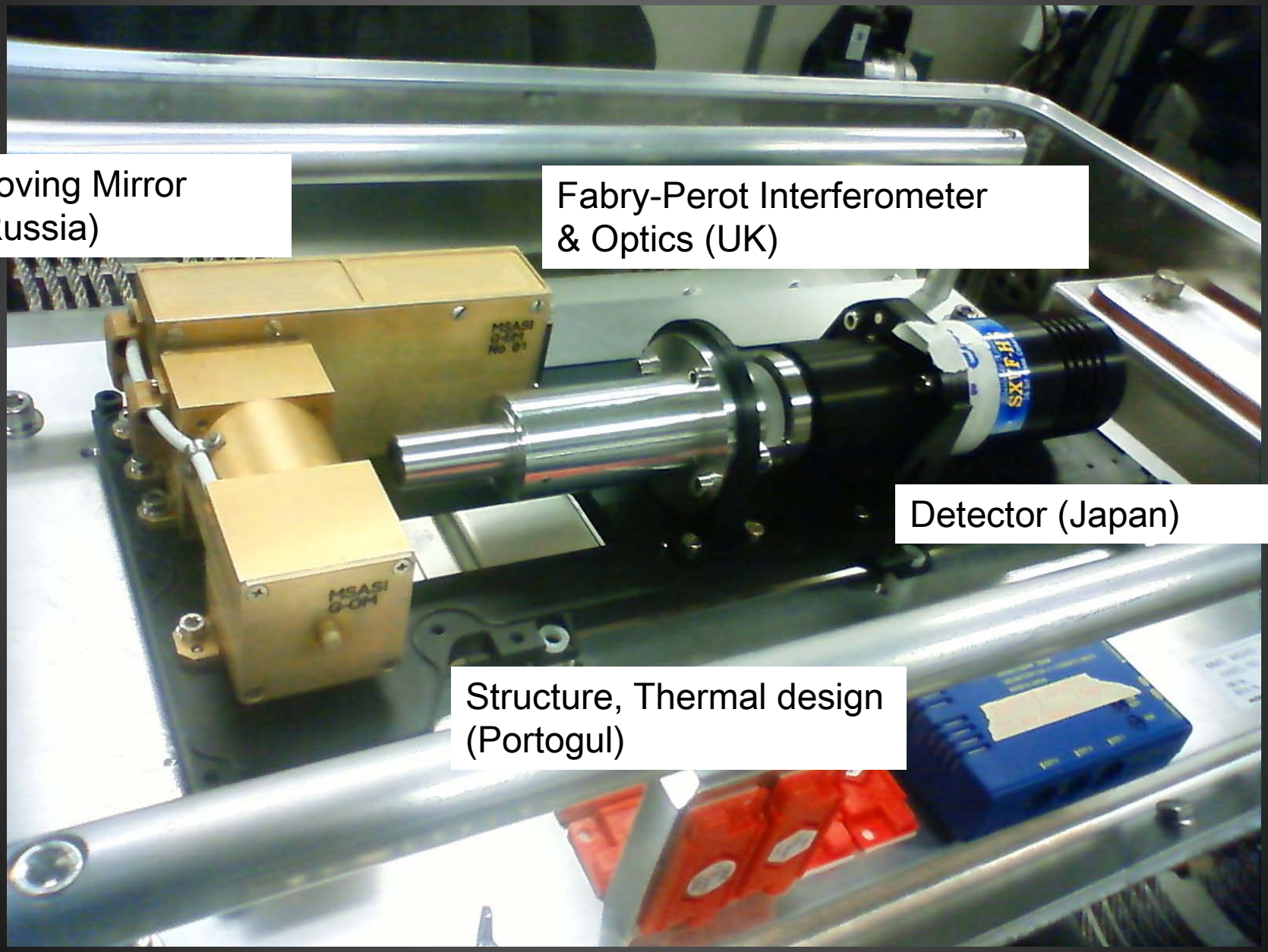


-20 degC ~ +60 degC

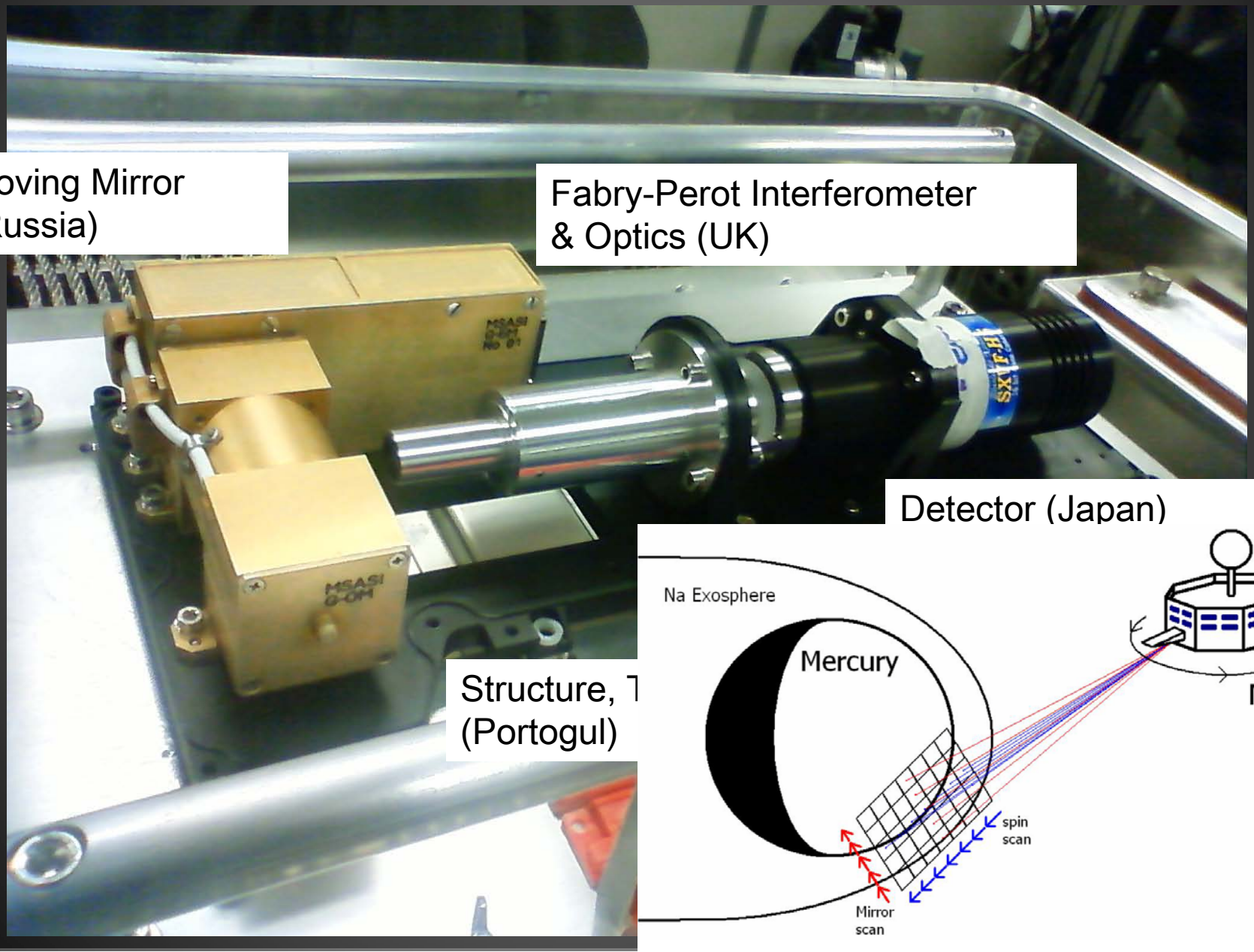
d=1.49 mm (Zerodur)

→ δd<+/- ~15 nm TEC~ 10^{-7}

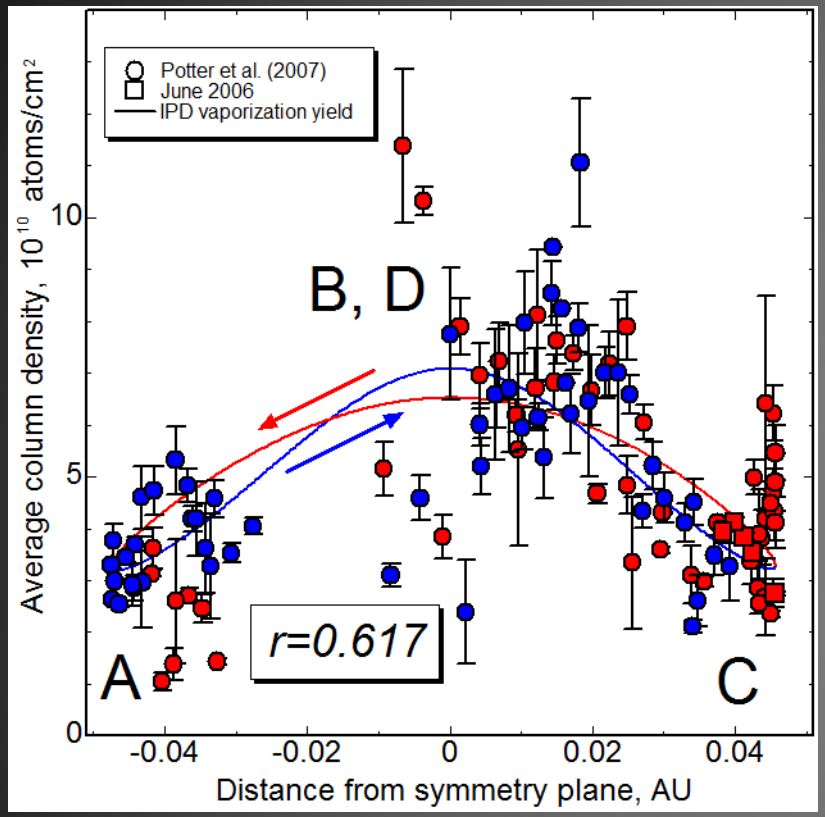
→ **δCWL < 6 pm (Center Wavelength)**


Moving Mirror
(Russia)
Fabry-Perot Interferometer
& Optics (UK)
Detector (Japan)
Structure, Thermal design
(Portogul)

Japanese Ambassador in Russia came back in Japan, yesterday!!! (temporary..)


Moving Mirror
(Russia)
Fabry-Perot Interferometer
& Optics (UK)
Detector (Japan)
Structure, T
(Portogul)
Na Exosphere
Mercury
MMO
spin
scan
Mirror
scan

BepiColombo / MMO
武蔵
Mercury Sodium Atmosphere Spectral Imager

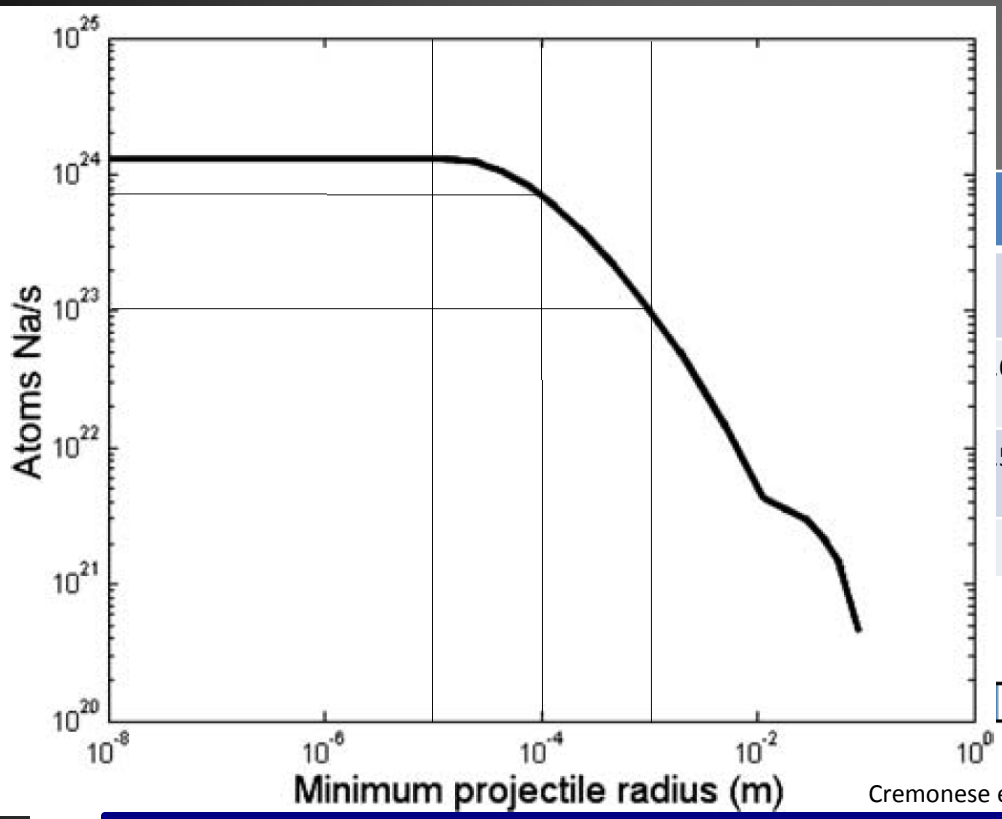


	Ω(°)	i(°)	α	β	position
Least square	-31	2.9	0.2	50	0.3-0.47AU
C.E. > 0.6	-104-+57	>1.9	-1.0-+0.9	>5	0.3-0.47AU
C. E. >0.5	-123-+62	>0.6	-1.0-+3.0	>5	0.3-0.47AU
DIRBE	77.7±0.6	2.03±0.01	1.34±0.02	10.3±0.08	1 AU
Helios	87±4	3.0±0.3			0.3-1AU
Zodiacal llight	40-55	1.3-1.54			1 AU

The correlation coefficient is more than 0.6 for $-104° < \Omega < 57°$ and $i > 1.9°$.

→ Long-term Temporal variability of sodium density is possibly caused by variability of IPD flux near Mercury.

Potter et al., 2008



Cremonese et al.

	Ω(°)	i(°)	α	β	position
	-31	2.9	0.2	50	0.3-0.47AU
6	-104-+57	>1.9	-1.0-+0.9	>5	0.3-0.47AU
5	-123-+62	>0.6	-1.0-+3.0	>5	0.3-0.47AU
	77.7±0.6	2.03±0.01	1.34±0.02	10.3±0.08	1 AU

$$D \propto R^{-\alpha} \exp\left[-\beta\left(\frac{z}{R}\right)^2\right],$$

β is estimated to be ~5 time larger than that by DIRBE.

→ IPD distribution is thin?

→ The size of dust should be taken into account.

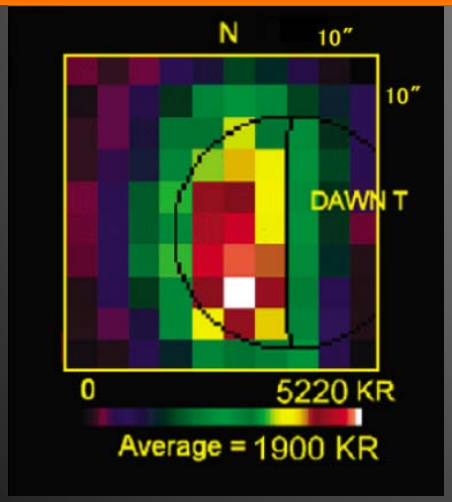
Cremonese et al estimated that total Na release rate by dust is 1.36 x 10^{24} Na/s. (Typ. radius is $10^{-5\sim-3}$ m (~90 %)).(IPD $10^{-8\sim-5}$m)

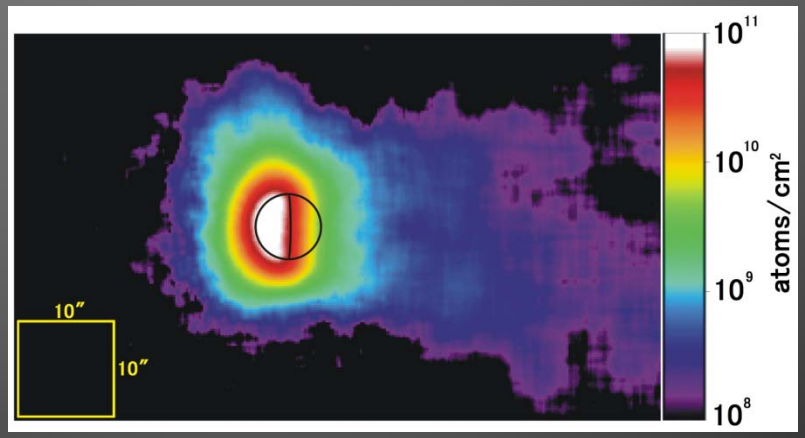
Potter et al., 2008

- Temporal variability (~88 days)of sodium density is possibly caused by variability of IPD flux near Mercury.

- The cause of Short-term variability is still unclear.

- FOV of 10 x 10”is not enough for observing total amount of sodium..? → Wide FOV observation

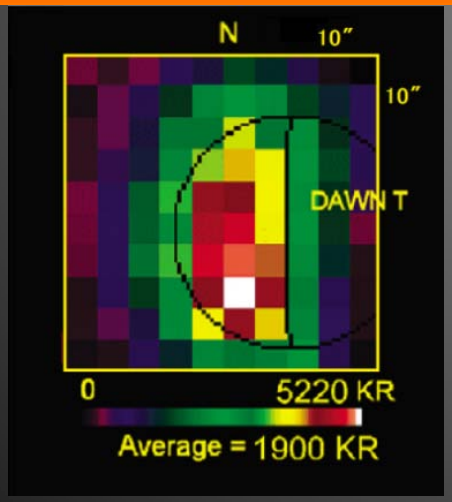


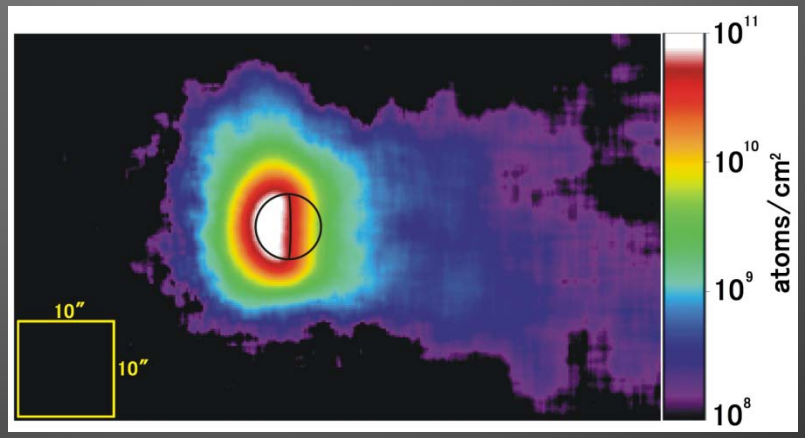


- Temporal variability (~88 days)of sodium density is possibly caused by variability of IPD flux near Mercury.

- MASCS on board Messenger can detect Ca and Mg (Fe? Al?).

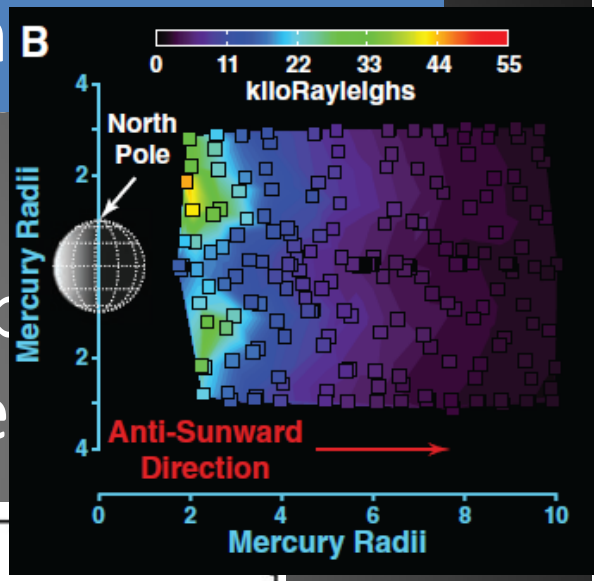
→ Does the density of Ca and Mg vary dependently on IPD distribution?



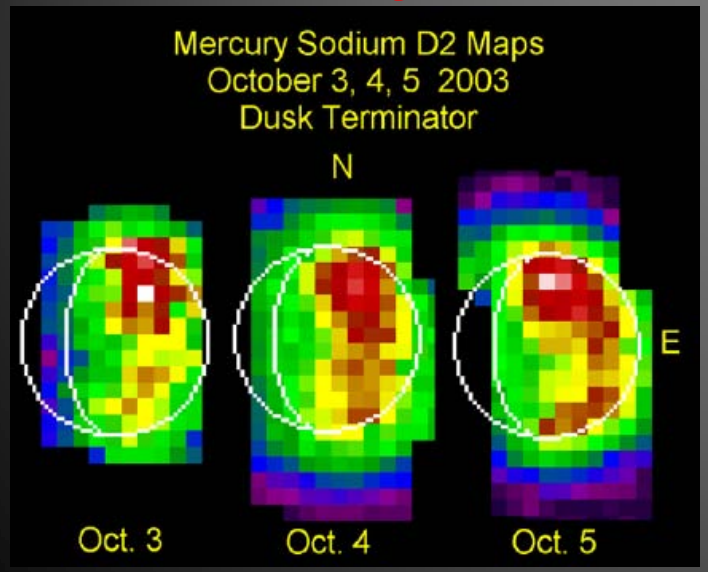


Spectral Resolution of MASCS on Messenger is Δλ~1nm

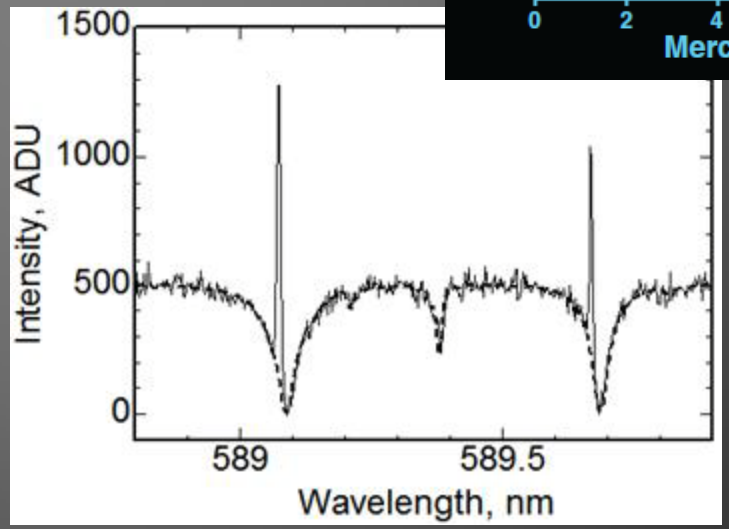
- MSASI is "Mercury S
  Spectral Imager."
- Spectral resolution of ~85,000 (7p
  us to observe distribution of Na e
  the **dayside.**



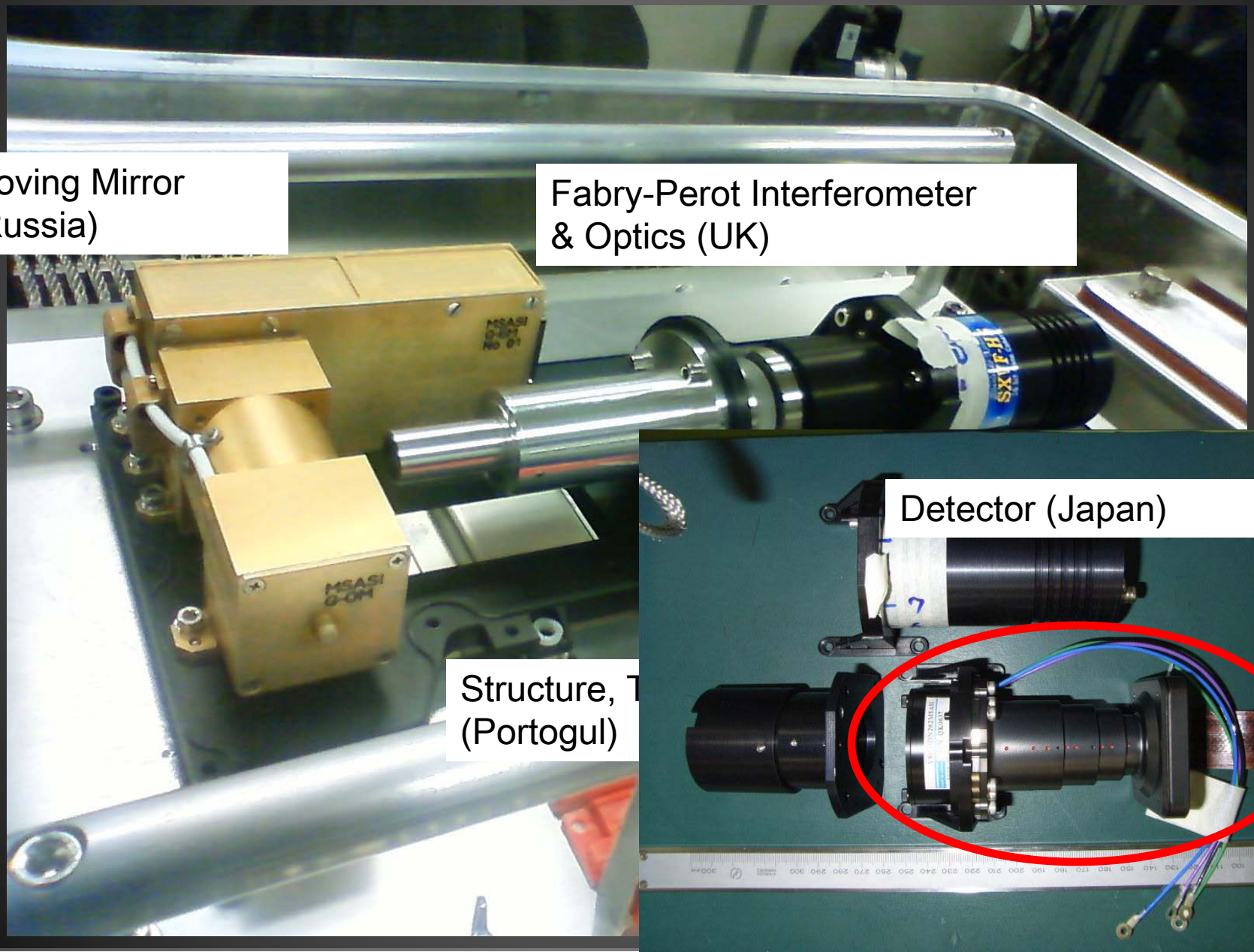
McClintock et al., 2008



Potter et al., 2008



Line width of NaD is 5pm


Moving Mirror
(Russia)
Fabry-Perot Interferometer
& Optics (UK)
Detector (Japan)
Structure, T
(Portogul)

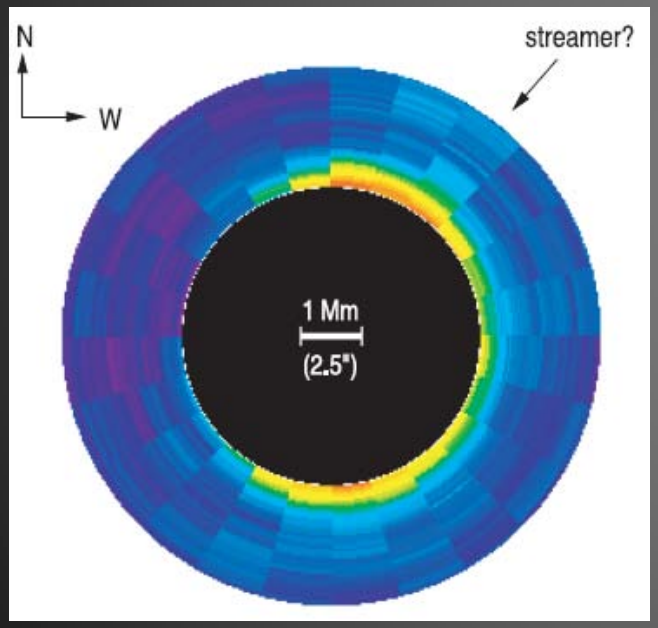
Observation at Perihelion by MSASI

Dawn-Dusk Asymmetry #1

Table 4. SODIUM DIURNAL VARIATION AT MERCURY
Mean low-latitude abundances, 10^{10} atoms cm^{-2}

Early Morning	Mid Morning	Mid Day	Mid Afternnon	Late Afternoon
17.0	19	15	6.7	5.2

Hunten and Sprague, 1997



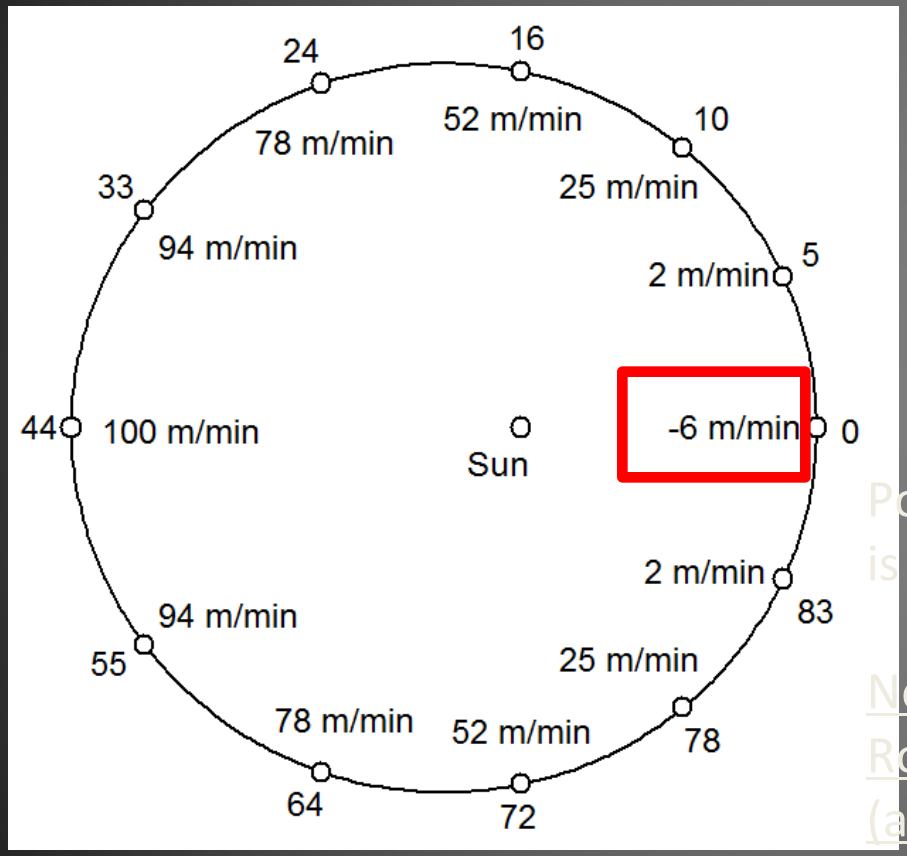
Schleicher et al., 2004

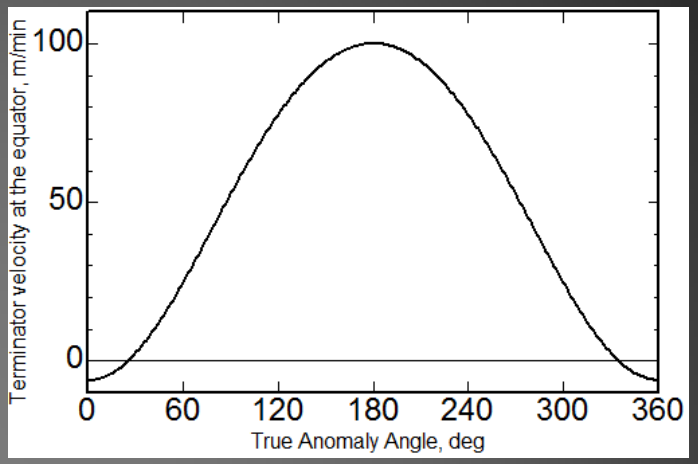
Ground-based observation
↑It is impossible to observe
Dawn and dusk side at the same time.
From statistics,
Sodium density on dawn side is
~3 times higher than that on dusk side
←Dawn-Dusk Asymmetry was observed
at transit.

Sodium adsorbs night side (Low temp)
→is released from dayside.

(or Ion sputtering rate is higher at dawn side)

Dawn-Dusk Asymmetry-2



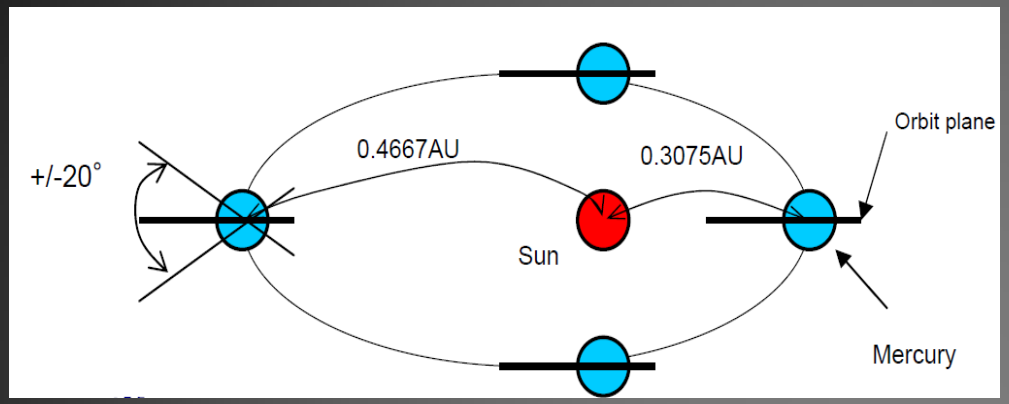


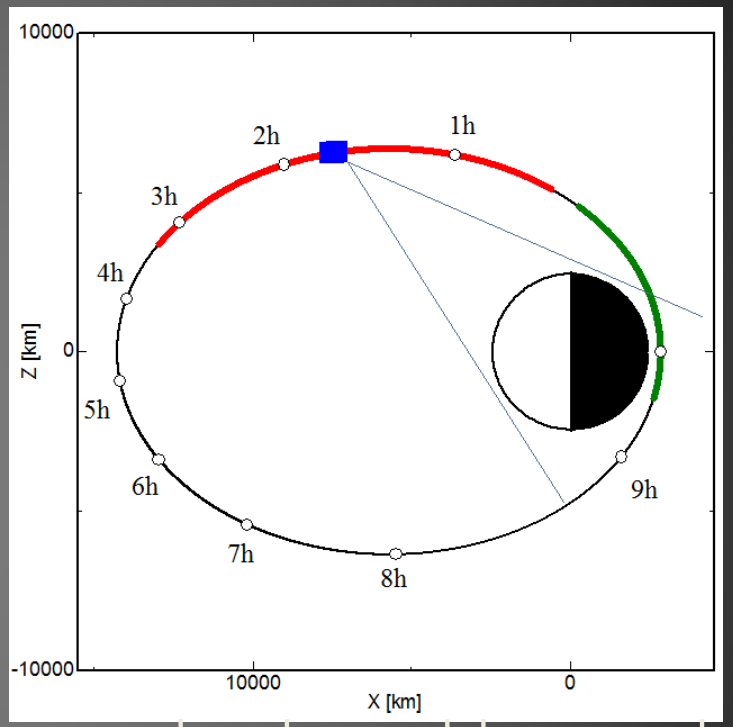
Possibly, sodium in the surface is released and depleted in the morning.

<u>Near perihelion,</u>
<u>Rotation against Sun is reversed</u>
<u>(at the TAA of 25 degrees)</u>

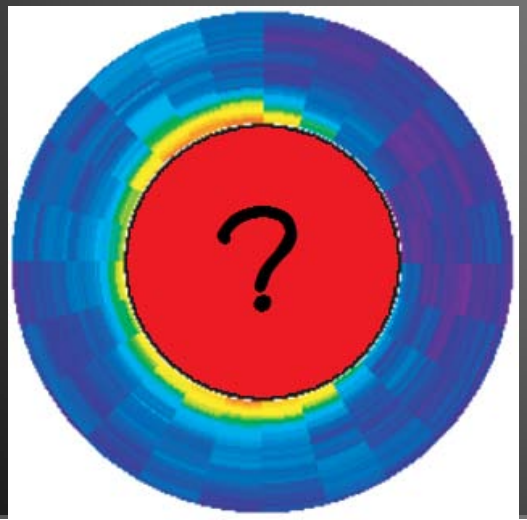
East-West asymmetry may be also reversed??

Dawn-Dusk Asymmetry #3



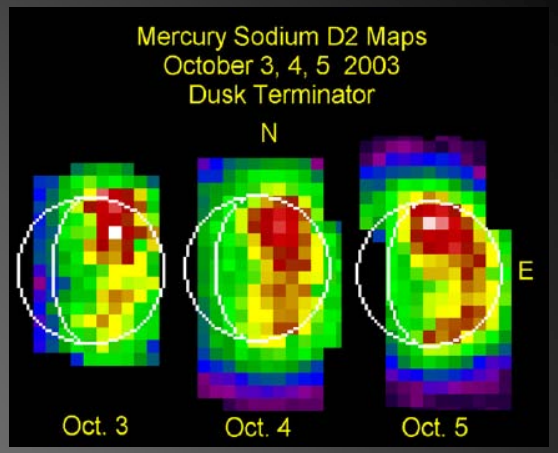


On MMO orbit, we can observe dawn and dusk side simultaneously near Perihelion



Sodium Exosphere can be observed by ground-based (or Earth orbit) telescope.
However, dayside dawn-dusk side can be observed **only by MSASI**.
20 minutes are needed for observation (inc. preparation time)
↑Minimum requirement.

Summary

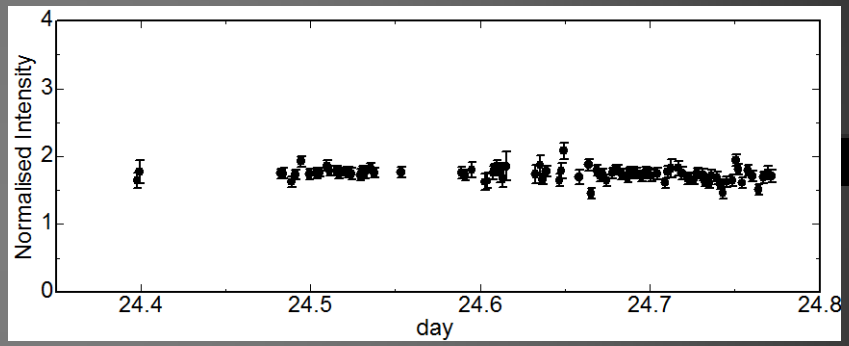


- <u>Observation of Dayside</u>

  What is source process?

- <u>Temporal variability</u>

  1 min - 1 day – 88 days

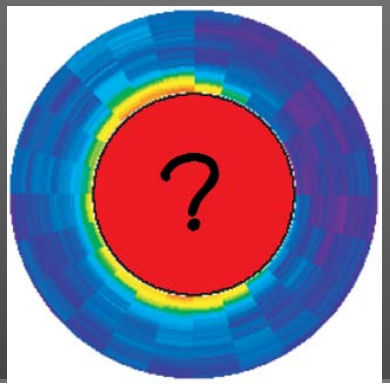


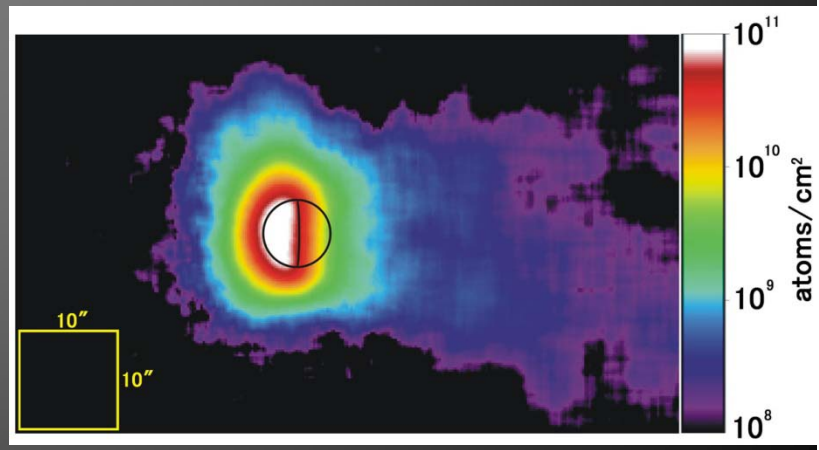
- <u>Sodium tail</u>

  → Solar radiation pressure

- <u>Dawn-Dusk assymmetry</u>

  →Priority near perihelion





- 2011-2012?

  Ground-Based: High spatial (~0.1 Rm) with AO

  Messenger: High spatial (Nightside) and observation of Magnetosphere → Short-term variability

- 2012?-2020

  Ground-Based: Low spatial (~ 1Rm) →Long-term variability

- **2020-2021**

  High spatial **(dayside)**(~0.01Rm→ geological effect), Magnetosphere, Solar wind, Dust