No. 5

Symposium on Planetary Science
2014/02/20

Estimation of the ion acceleration from Ganymede polar region by the Galileo spacecraft observation

ガリレオ探査機の観測に基づくガニメデ極域のイオン加速の推定

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1. Introduction

- Ganymede : **The only moon that has the intrinsic magnetic field.**

The orbital radius	14.97 R_J
The orbital period (= The rotation period)	7.15 days
Radius	2631 km (= $1R_G$)

Ganymede is always located in the big Jovian magnetosphere.
→ It creates **mini-magnetosphere.**

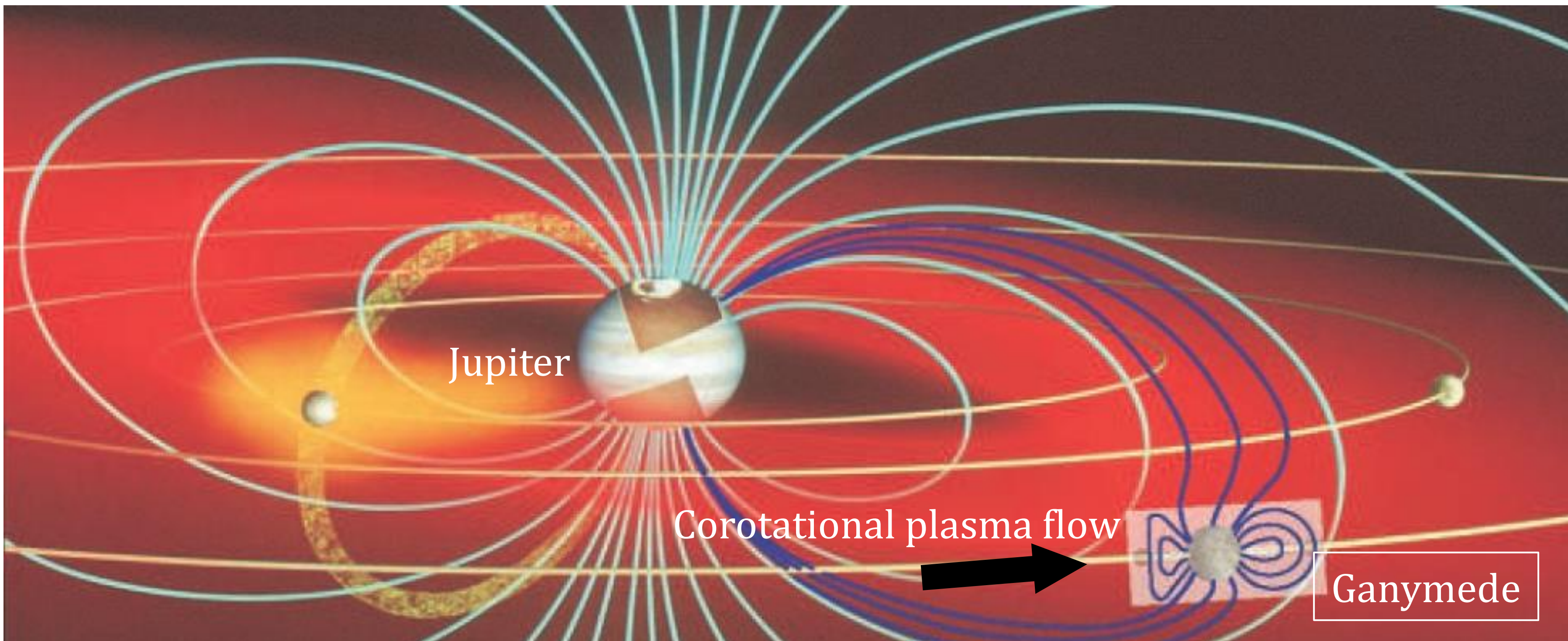
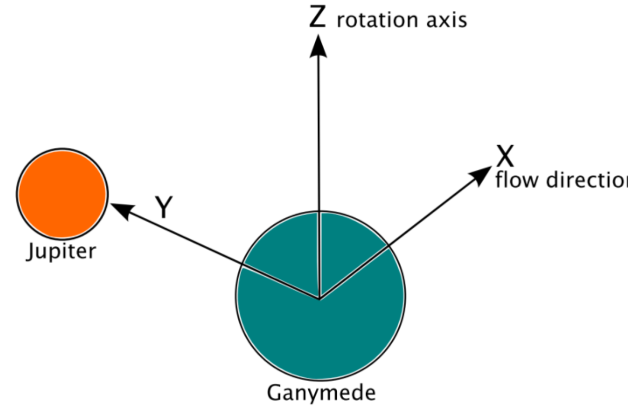


Fig.1. Schema of relationship of Jupiter – Ganymede. [Johnson, 2004]

Ganymede’s magnetosphere

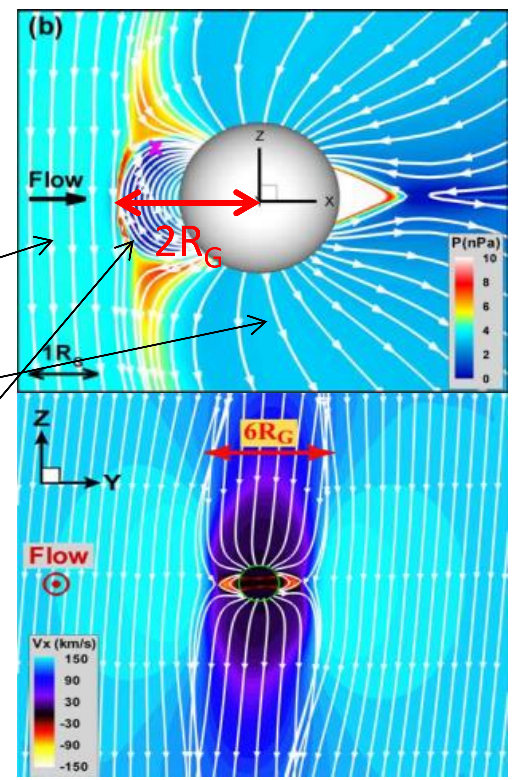


Definition of the coordinates

- **Magnetic field direction**
  Jupiter … north to south
  Ganymede … south to north

- **[Jia et al., 2009]**
  MHD simulation of Ganymede’s magnetosphere which indicates size and figure.

- **Definition of field lines**
  - Jovian field line (Jupiter - Jupiter)
  - Open field line (Jupiter - Ganymede) (high latitude)
  - Closed field line (Ganymede - Ganymede) (low latitude)



The plasma environment is expected to be different in each region.

Fig.2. MHD simulation of Ganymede’s magnetosphere. [Jia et al., 2009]

Ion outflow from Ganymede

[Frank et al., 1997]

PLS(Plasma Subsystem) measurements

Maxwellian fits

⇨ The cold plasma are H^+ flowing outward.

density : 100 cm^{-3}, speed : 50 km/s

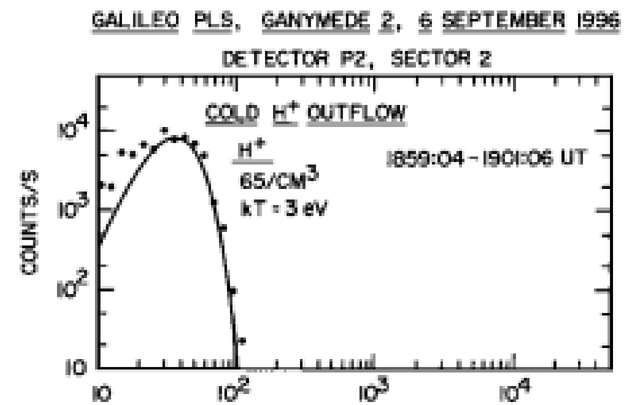
[Vasyliūnas and Eviatar, 2000]

⇨ An alternative analysis as an outflow ions are O^+.

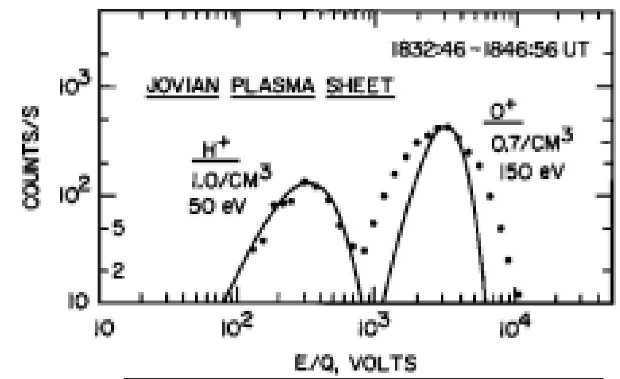
density : 200 cm^{-3}, speed : 18 km/s

The outflowing cold ions are most reasonably identified as O^+.

The process of this ion outflow is still unknown.



Ganymede encounter



Jovian plasma sheet

Fig.3. G02 PLS observation [Frank et al., 1997]

Purpose of this study

To clarify the plasma environment of Ganymede's magnetosphere

I. We discuss the altitudinal distribution of the **O^+ density** in the Ganymede's magnetosphere.

- By analyzing plasma wave spectra,
  UHR (Upper Hybrid Resonance) emissions.

II. We show evidence of **O^+ outflow** from the analysis of the density distribution.

- By assuming that the flux is conserved along the path of the ion outflow.

2. Instruments

- **Galileo spacecraft (1995~2003)**
  - PWS (Plasma Wave Subsystem)
    - Frequency range

      Electric field … 5.62 Hz ~ 5.65 MHz
      Magnetic field … 5.62 HZ ~ 160 kHz
      (cf. f_{ce} is 5kHz ~ 20 kHz near Ganymede)

    - Time resolution … 18.67 sec

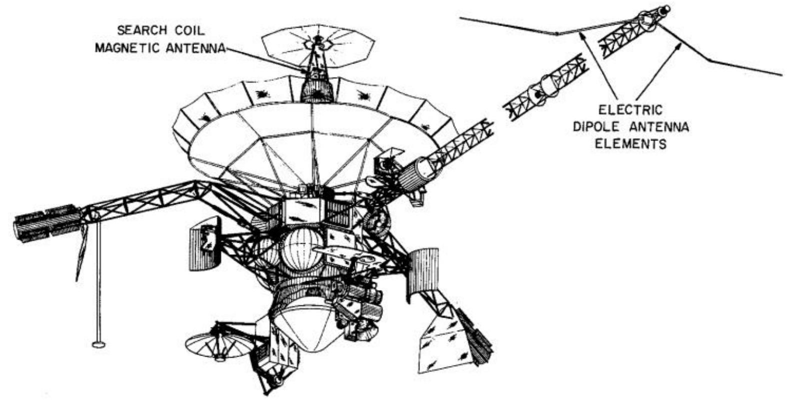


Fig.4. Galileo spacecraft [Gurnett et al., 1992]

We analyzed 4 encounters (G01, G02, G07, G29) because the spectra are clear enough to analyze.

- **Data**

Table 1. Information of Galileo's encounters with Ganymede. [Kivelson, Khurana and Volwerk, 2002]

Orbit	Date	CA(UT) (Closest Approach)	Altitude(km)	Background field (Bx,By,Bz) (nT)
G01	1996/06/27	06:29:07	838	(6, -79, -79)
G02	1996/09/06	18:59:34	264	(17, -73, -85)
G07	1997/04/05	07:09:58	3105	(-3, 84, -76)
G08	1997/05/07	15:56:09	1606	(-11, 11, -77)
G28	2000/05/20	10:10:10	900	(-7, 78, -76)
G29	2000/12/28	08:25:30	2320	(-9, -83, -79)

3. Analysis

- **UHR (Upper hybrid resonance) emission**

  f_{UHR} … identified from the spectra

  f_{ce} … computed from the magnetic field strength

- **Electron density**

f_{UHR}, f_{ce}

$$f_{UHR}{}^2 = f_{ce}{}^2 + f_{pe}{}^2$$

f_{pe}

$$n_e = \frac{4\pi^2 m_e \varepsilon_0}{e^2} f_{pe}{}^2$$

n_e

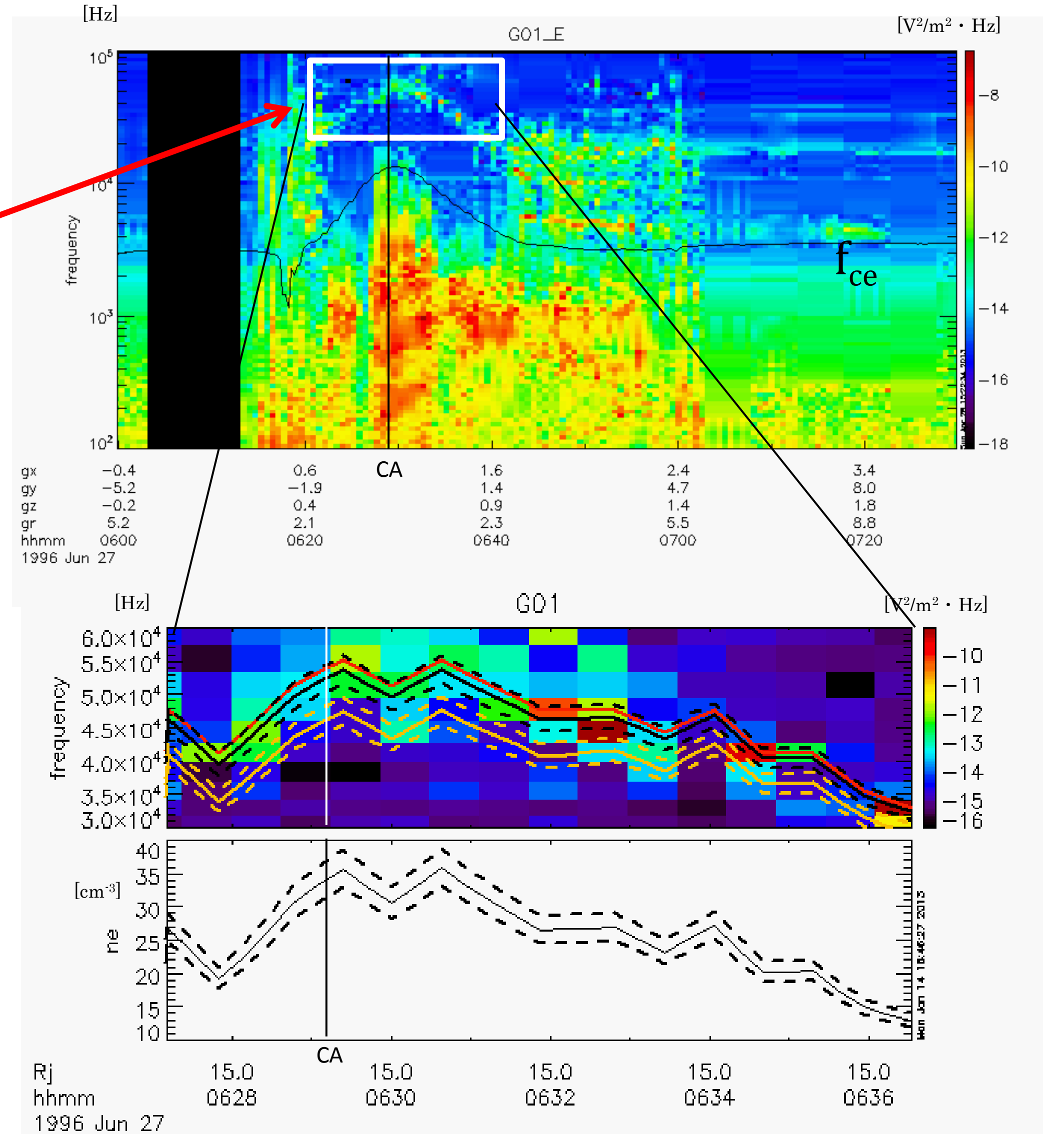


Fig. 5. (upper) Electric field's frequency–time spectrogram of G01 orbit. (lower) Zoomed spectrogram of the upper figure with plot of each frequencies. (red … f_{UHR}, black … f_{pe}, orange … $f_{z\text{-cutoff}}$)

$$\left(f_{z,\ cutoff} = -\frac{f_{ce}}{2} + \sqrt{\left(\frac{f_{ce}}{2}\right)^2 + f_{pe}{}^2} \right)$$

G01 and G02 have been analyzed by Gurnett et al [1996].

Electron density profile

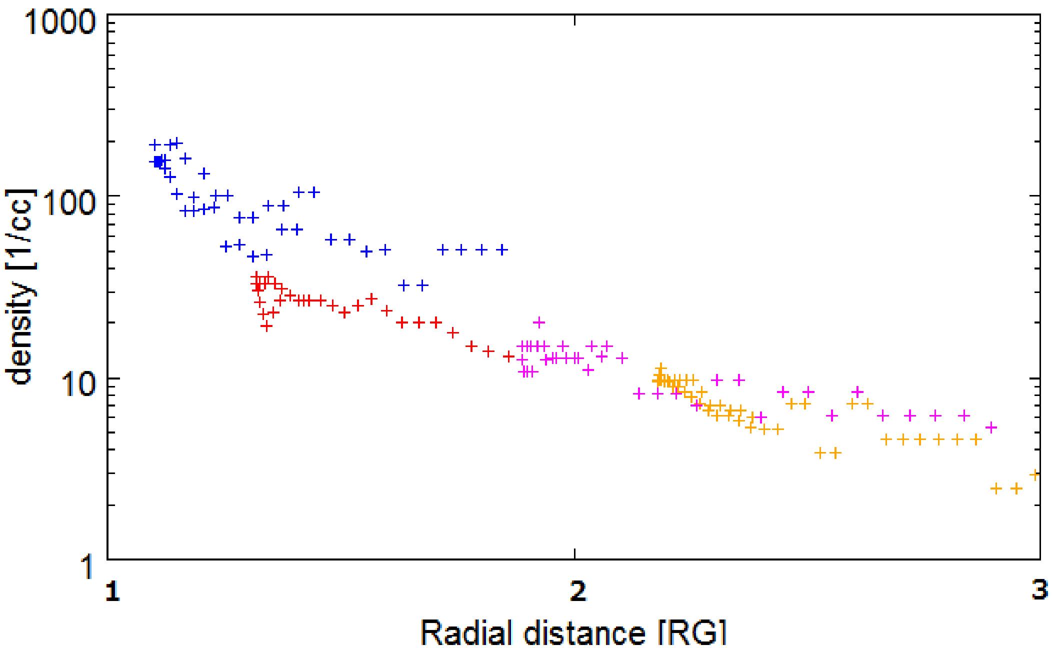
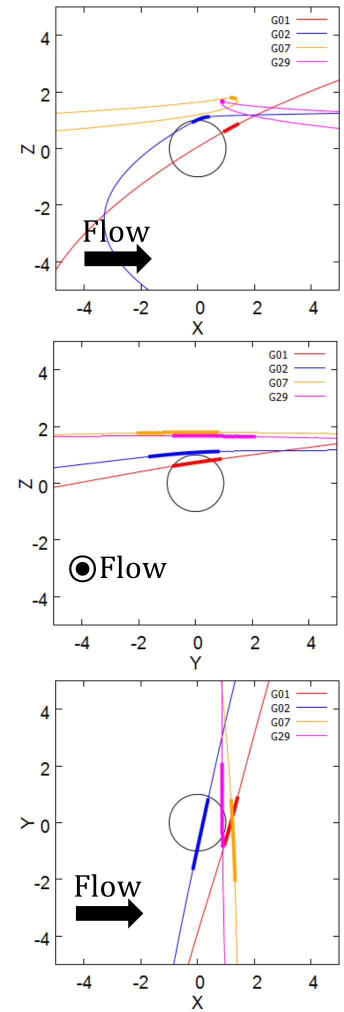
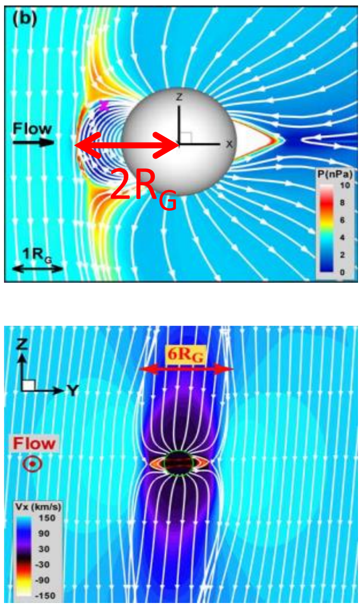


Fig. 6. The electron density as a function of the radial distance. (I R_G = 2631 km)

Orbit	G01	G02	G07	G29
Color	Red	Blue	Orange	Pink





All orbits are downstream open field line region.

Fig. 7. (left) Galileo spacecraft's orbit. (right) MHD simulation of Ganymede magnetosphere. [Jia et al., 2009]

What physical mechanism determines this density profile?

4. Discussion

Flux conservation

[e.g. Ogawa et al., 2009]

They have presented ions upflow in the Earth's topside polar ionosphere.

The total flux seemed to be conserved. (Fig.)

$$n_i(r)S(r)v(r) = \text{const.} \qquad (1)$$

n_i : ion density
S : cross section of the flux
v : outflow speed
r : distance from the planet

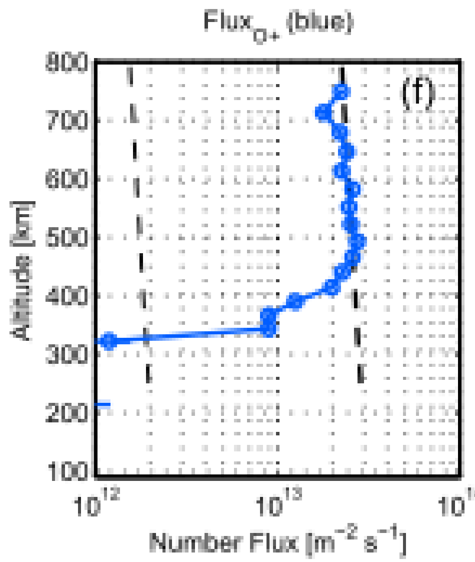


Fig. 8. Blue line is the O^+ upward number flux.
Thick dashed line is constant flux
Thin dashed line is the constant flux line from outside the cusp.

It is expected that the Ganymede's polar ion outflow flux seemed to be conserved as the case of the Earth.

We discuss the O^+ outflow from this analogy and density distribution.

(electron density $\simeq$ O^+ density)

Flux conservation

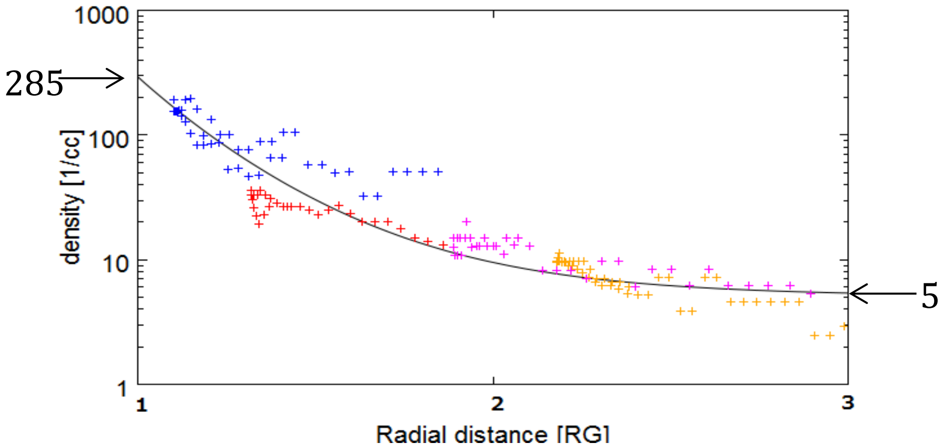


Fig.9. Ion density fitting result. Black line indicate the Eq. (2).

$$n_i(r) = A \times \frac{R_G{}^{B}}{r^{B}} + 5 \qquad \text{fitting}$$

output

$$n_i(r) = \underline{285} \times \frac{R_G{}^{\underline{5.98}}}{r^{\underline{5.98}}} + \underline{5} \qquad (2)$$

surface density

background density
(asymptote of the curve)

1. fitting of density distribution by non-linear least-squares method. (Fig. 9.)

2. setting of the cross section

   $S \propto r^2$ … radial diffusion
   $S \propto r^3$ … conservation of magnetic flux density

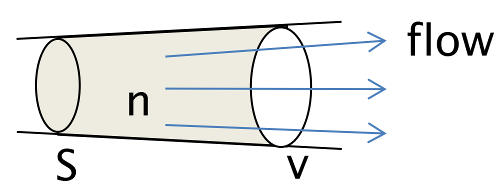
3. setting of the const. of Eq. (1)

   $$n_i(R_G)S(R_G)v(R_G) = \text{const.}$$

   $v(R_G)$: thermal velocity of O^+ ionization energy
   (8914 m/s - 13.6 eV [Schunk and Nugy])
   $S(R_G) = 1/\, v(R_G) \Leftrightarrow S(R_G) \times v(R_G) = 1$
   $n(R_G)$: substitute $r = R_G$ into Eq. (2)

4. velocity variation : $v(r) = \dfrac{\text{const.}}{n_i(r)S(r)}$

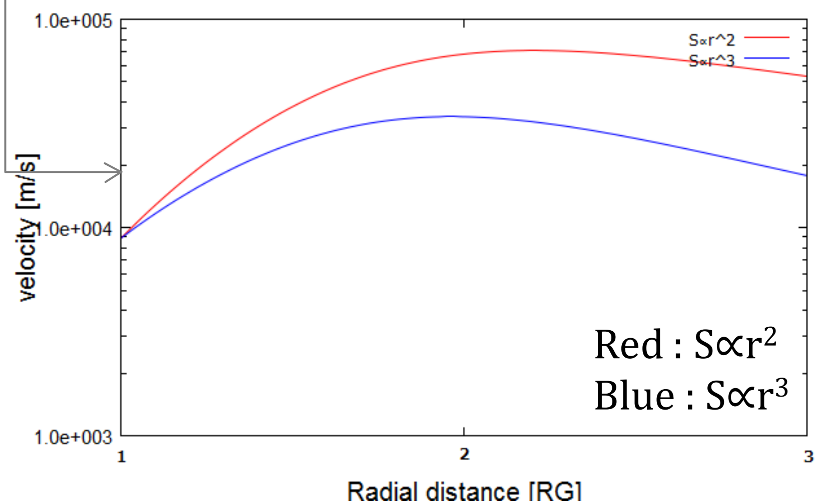
5. energy variation : $E(r) = mv(r)^2/2$



Ion acceleration

- **velocity variation [m/s]**
  Approximately consistent with the previous study.

[Vasyliūnas and Eviatar, 2000]
18 km/s



- **energy variation [eV]**
  O^+ kinetic energy gain due to this acceleration.

  Ganymede origin ion should have this energy from our conclusion.

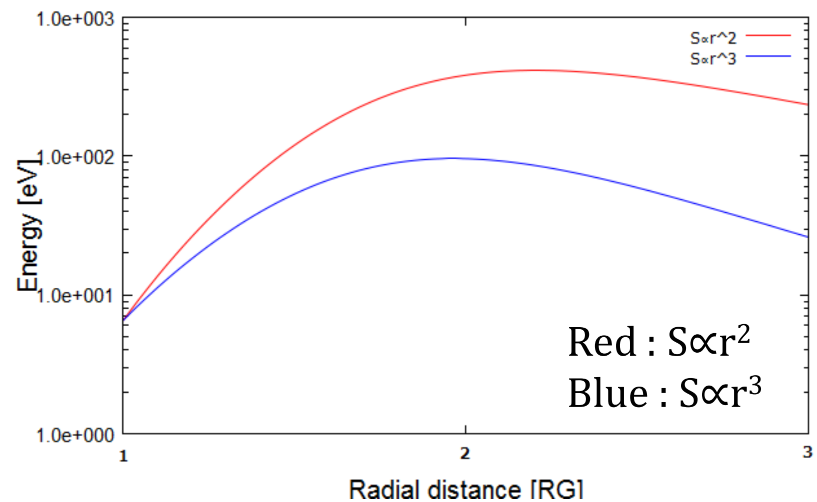


Fig. 10. (left)Estimated ion velocity variation. (right)Estimated ion energy gain. 〈The red line ($S \propto r^2$) is the maximum case〉

These results are evidence of ion outflow by another approach with Vasyliunas and Eviatar [2000].

5. Conclusion and Summary

I. We have analyzed plasma density distribution.

plasma wave spectra
→ UHR frequency
→ electron density (electron density ≃ O^+ density)

We have analyzed four Ganymede encounters including those on orbits G01 and G02 which have been analyzed in the previous study.

What physical mechanism determine this density profile?

II. We have shown the evidence of ion outflow under the assumption that <u>the flux is conserved</u> along the path of the ion outflow.

This result is consistent with the previous study which suggested the outflow O^+ velocity is 18 km/s from observations of the Galileo PLS instrument [Vasyliūnas and Eviatar, 2000]

What physical process make O^+ accelerate?

We think the most reasonable process is centrifugal acceleration.

Future work

- Test particle simulation about centrifugal acceleration.
  Because of smaller radii at such as Ganymede and Mercury, these effects are more pronounced than at Earth.
  We are developing the simulation code so as to discuss the outflow process quantitatively.

$$\frac{d\boldsymbol{v}_{||}}{dt} = \boldsymbol{v}_E \cdot \left(\frac{\partial \boldsymbol{b}}{\partial t} + v_{||}\frac{\partial \boldsymbol{b}}{\partial s} + \boldsymbol{v}_E \cdot \boldsymbol{\nabla} \boldsymbol{b} \right) - \frac{\mu}{m}\frac{\partial B}{\partial s}$$

<u>curvature of B</u> <u>curvature of E×B drift path</u>

- Other candidate mechanisms which cause this acceleration have to be considered.

  - other possibilities
    - dragged by escaping photoelectrons [Khazanov et al., 1997]
    - perpendicular heating through wave-particle interactions [Lundin et al., 1990]
      etc.

Mercury

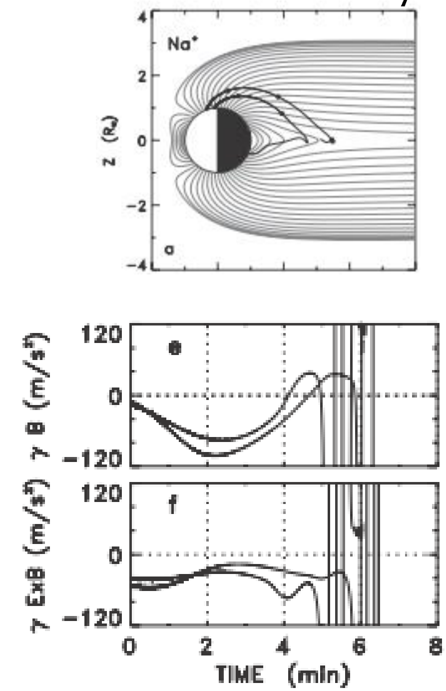


Fig. 11. Model ion (Na^+) trajectory and the acceleration variations at Mercury. [Delcourt et al., 2002]

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