STP seminar

"Generation and propagation of Jovian quasi-periodic low frequency radio bursts"

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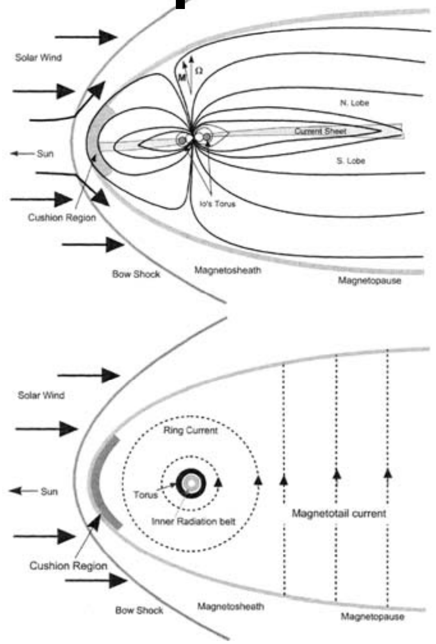
Jovian magnetosphere

① 強力な磁場
② 高速自転
③ 衛星イオ起源重いプラズマ

- 自転エネルギーが支配する「自転駆動磁気圏」

⇔地球:「太陽風駆動磁気圏」

- 太陽系惑星中で、最も強力な粒子加速過程が存在。



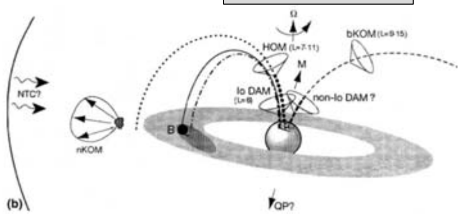
Fig．A schematic of Jovian magnetosphere (Khurana et al., 2004)

Jovian radio emissions

- 放射線帯(シンクロトロン放射)
- Io,プラズマトーラス活動 (DAM, nKOM)
- MI結合電流、オーロラ粒子加速 (DAM,HOM, bKOM, **QP burst**)
- **極冠域の周期的MeV粒子加速 (QP burst)**
- 自転エネルギー放出 (JAC, **QP burst**, bKOM?)

⇔

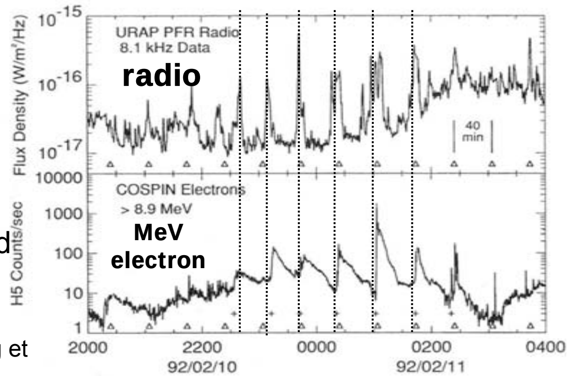
- 発生位置 (高度・L-value)
- 時空間パラメータ依存 (CML,MLAT, etc…)
- モード・励起機構
- 放射・伝搬特性
- 周波数帯域・スペクトル
- 周期性・時間変動
- 太陽風応答



Fig．A schematic of Jovian radio emissions (Zarka, 2004)

Quasi-Periodic bursts

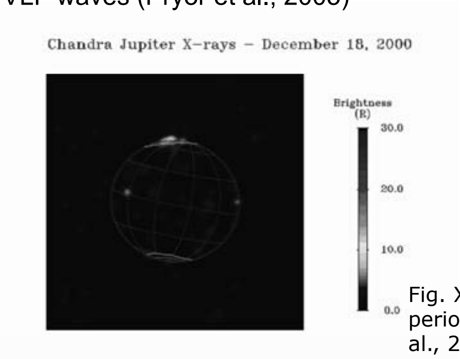
- Quasi-Periodic burst：VLF radio bursts with quasi-periodicity (a few-tens min.)
- Relativistic particle bursts：electron/proton outbursts accompanied by QP bursts with 40-min period (McKibben et al., 1993; Zhang et al., 1995)



Fig．QP radio bursts with 40 min periodicity accompanied with relativistic electron outbursts (MacDowall et al., 1993).

Periodic aurorae

- X-ray "hot spot" in the polar cap region pulsating with 45 min period (Gladstone et al., 2002)
- Particle penetrations to the stratosphere in the hot spot ? (Flasar et al., 2004)
- Polar UV aurora positively correlated with VLF waves (Pryor et al., 2005)



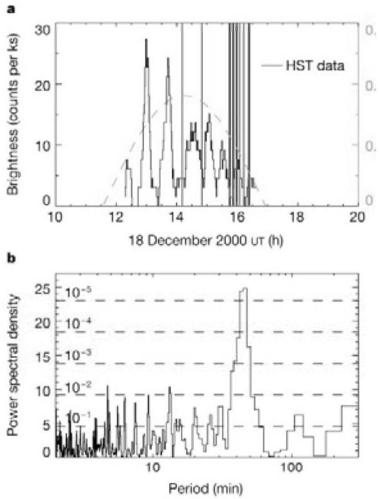


Fig. X-ray "hot spot" with ~45 min periodicity observed by CXO (Gladstone et al., 2002).

What process drives the quasi-periodic radio and auroral emissions ?

Problems

- Relativistic & periodic particle accelerations
  - Driver, cause of quasi-periodicity, corresponding magnetospheric dynamics…
- Description of QP bursts
  - Source location, propagation process, generation…

Purpose of this thesis

- Elucidation of QPBs' generation and propagation

→Restrictions on particle accelerations

→Elucidation of strong & periodic particle accel.

→Probe magnetospheres and particle accel. by planetary radio emissions…

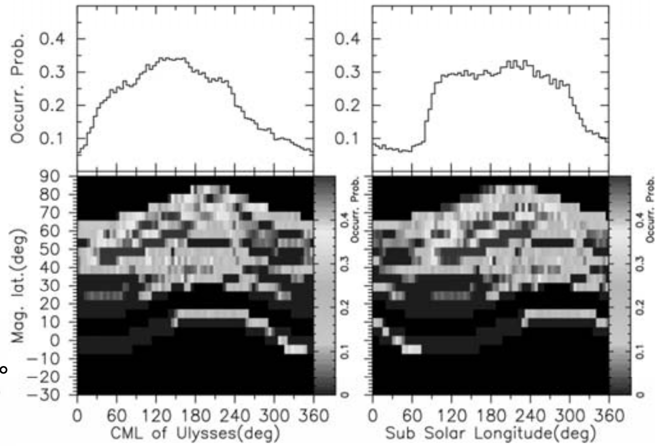
Approach

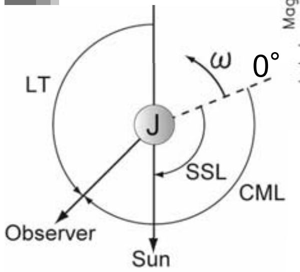
Observation	• Occurrence dependence • Periodicity • Polarization and source directions
Interpretation	• Interpretation of observations based on ray tracing • →Source location, directivity, wave modes, etc. • →Restrictions on generation mechanisms
Generation mechanisms	• Theoretical validation of wave generation mechanisms • Validation of particle acceleration scenario based on in-situ observations

3. OCCURRENCE CHARACTERISTICS

QPB at high lat-Ulysses

Fig . Statistical distribution of QP bursts observed at high latitudes (Kimura et al., 2008b)





$$CML = SSL - (LT - 12) \times 15^{\circ}$$

QPBs observed at high lat.:
dependent on longitudes
they are observed at MLAT>30°

QPBs at low lat.-Galileo

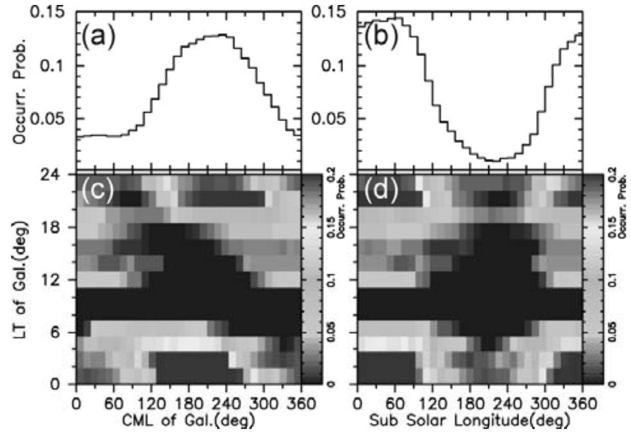
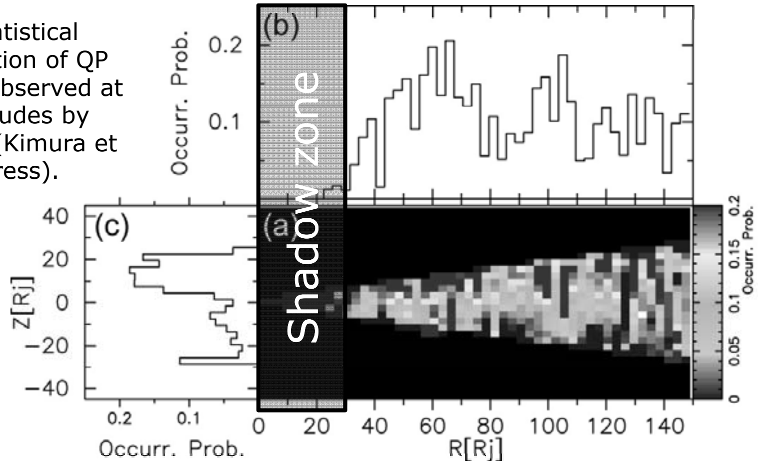


Fig . Statistical distribution of QP bursts observed at low latitudes (Kimura et al., in press)

QPBs observed at low latitudes:
dependent on longitudes.
similar rotational phase dependence in almost all local times.

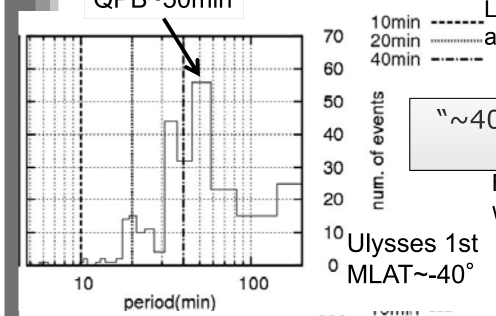
Meridional distribution-Galileo

Fig . Statistical distribution of QP bursts observed at low latitudes by Galileo (Kimura et al., in press).



QPBs at low lat.:
shadow zone in a region of |MLAT|<10° , R<30Rj

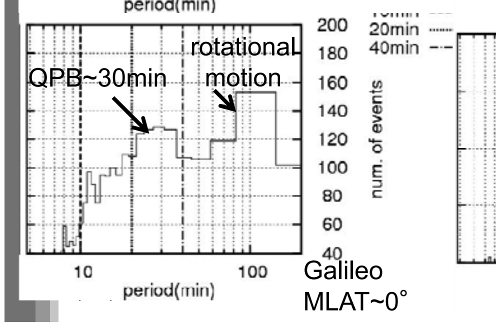
Periodicity of QP bursts

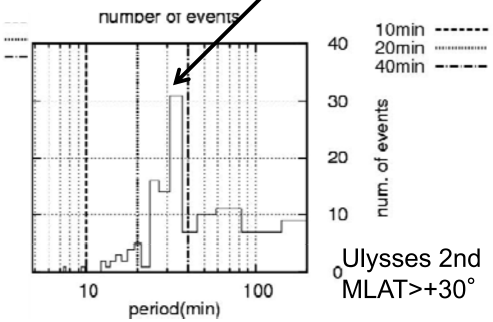


Lomb periodgram:spectral data with false alarm probabilities less than 0.5

"~40min" periods are dominant at all geometries

Fig .Distributions of periodicities with high occurrence probabilities.





4. POLARIZATION PROPERTIES

Stokes parameters-Ulysses

- Ulysses
  - R:~0.8AU
  - LAT: 41deg
  - LT: 17.1hr
  - CML: 193-301deg

- V~+0.8
- Q~U~0.0

=>LH circular

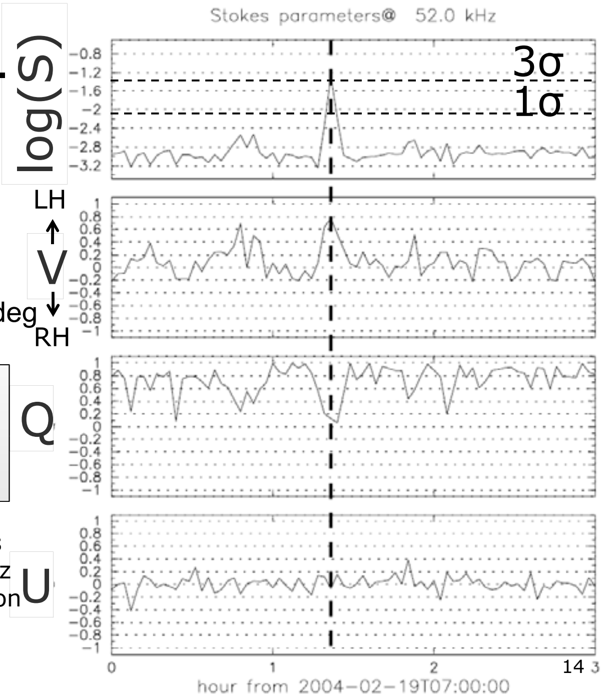


Fig . A plot of Stokes parameters at 52 kHz from 7:00 to 10:00 on Feb 19, 2004.

Statistics-Cassini

- criteria：pulse groups with intensities 20db larger than backgrounds at <30kHz
- assumption：source is located at the center of Jup.
- num. of events:44

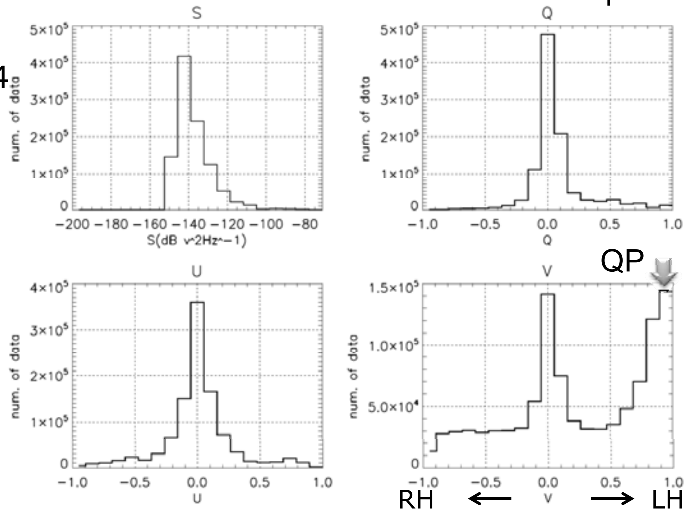


Fig . Histograms of QP bursts' Stokes parameters during the present analysis period.

Direction finding-Cassini

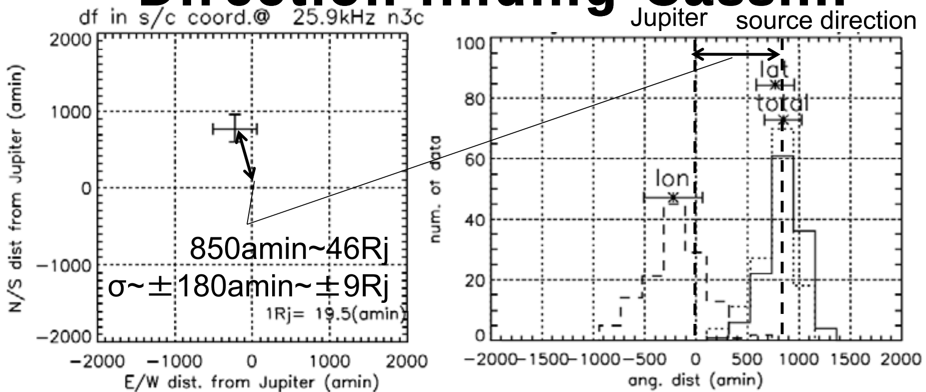


Fig . The direction and angular distribution of QP bursts measured by Cassini on Dec 22, 2000.

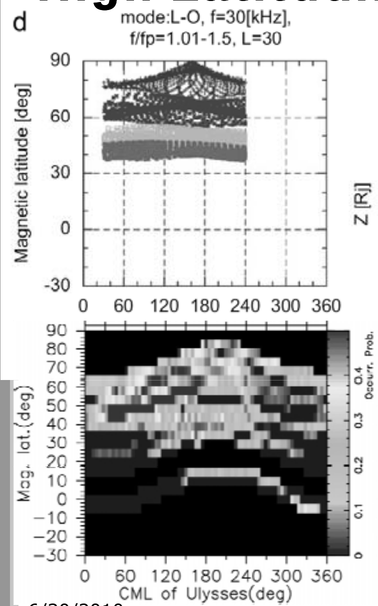
- apparent altitudes~850amin~46Rj(±9Rj)
- source of L-O mode: f_p=20kHz surface~2Rj
- source of R-X mode: f_{RX}~f_c=20kHz surface~10Rj

① refraction/scattering by sheath
② real source region at sheath

※error estimation:
σ<±220amin~±11Rj
offset<290amin~15Rj
for point source

5. INTERPRETATION OF OBSERVATIONAL RESULTS BASED ON PROPAGATION ANALYSIS

High Latitudinal Results-Ulysses



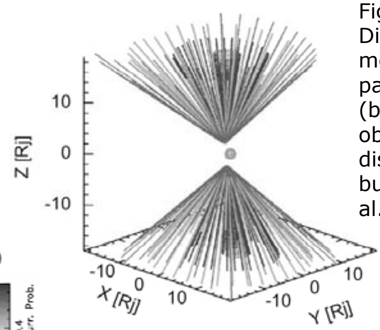


Fig . (top) Distribution of modeled ray paths and (bottom) the observed distribution of QP bursts (Kimura et al., 2008b).

- mode：LO mode
- $f \sim f_p$ surface~2Rj
- filled cone like radiation
- excited at particular rotational phase

→observed structures in lon&lat

QPBs observed at low lat.

- mode：RX(LO) mode
- $f \sim f_{RX} \sim f_c$ surface~10Rj
- filled cone like radiation

→"shadow zone"

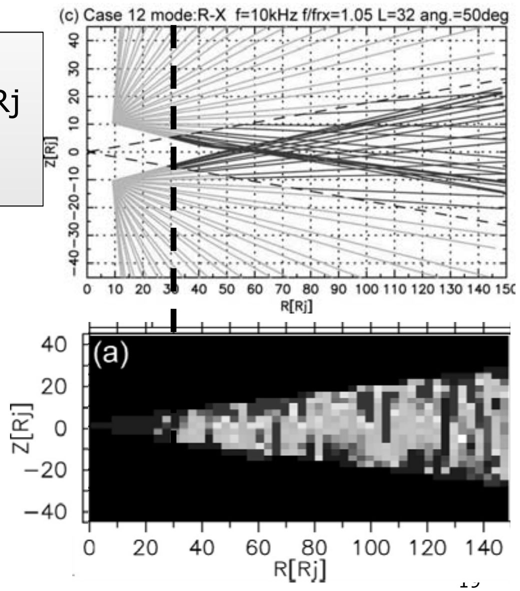


Fig . (top) Distribution of modeled ray paths and (bottom) the observed meridional distribution of QP bursts (Kimura et al., in press).

Brief Summary-Interpretation of Observations

	altitude	L-value	region	mode	direct.
High lat.	f~fp~2Rj	30<	pol. low alt.	LO	filled
Low lat. (in MS)	f~fc~10Rj	20<	pol. high alt.	RX (LO)	filled

- See Kimura et al. (2008b); Kimura et al. (2010) for more details.

6.1. MICROSCOPIC GENERATION MECHANISM OF QUASI-PERIODIC BURSTS

Characteristics of electron bursts

- McKibben et al. (1993) & Zhang et al.(1995): observations by Ulysses/COSPIN
  - Particle flux：~315/cm²/sec (>16MeV, R~54Rj)

	R~10Rj, >16MeV	R~2Rj, >16MeV
Particle flux	~9.5*10⁴/cm²/sec	~9.5*10⁶/cm²/sec
Number density	~3.2*10⁻⁶/cc	~3.2*10⁻⁴/cc
BG density	~1.1*10⁻⁵/cc (model)	~120/cc (model)
n_{beam}/n_{BG}	~3.2*10⁻¹	~2.6*10⁻⁶

- duration: ~120sec
- outbursts from Jovian polar region
- Energy flux:~2.9*10¹²W (QPB~10⁸W)

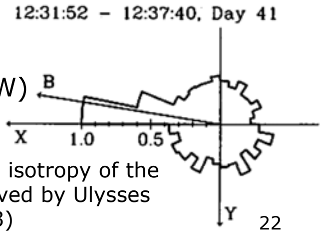


Fig. A plot showing isotropy of the proton burst observed by Ulysses (Zhang et al., 1993)

Linear Growth Rate

- Linear wave growth rate by cyclotron resonance
  (e.g., Baldwin et al., 1969; Lee et al., 1979; Nishimura et al., 2007)

$$\omega_i = \omega_r \sum_s \frac{2\pi^2\omega_{ps}^2}{G\omega^2 n_s}\int d\mathbf{u}\sum_{n=0}^{\infty}\frac{u_\perp n\Omega_e}{\gamma k_\perp}\left(\alpha_1 J_n^2+\alpha_2 J_n J_{n+1}+\alpha_3 J_{n+1}^2\right)\cdot \left(n\Omega_e\frac{\partial}{\partial u_\perp}+k_\parallel u_\perp\frac{\partial}{\partial u_\parallel}\right) f_s(u_\perp,u_\parallel)\cdot\delta\left(\gamma\omega-k_\parallel u_\parallel-n\Omega_e\right)$$

- ω_i : linear growth rate
- ω_r : real part of frequency
- ω_{ps} : plasma frequency of s-th component
- n_s : number density of s-th component
- u=γv (specific momentum)
- Ω_e : cyclotron frequency
- k : wave number
- n: order of resonance
- J_n : n-th order Bessel function
- $G=G(u,k,\omega,n,\Omega_e,\omega_p)$
- $\alpha_i=\alpha_i(u,k,\omega,n,\Omega_e,\omega_p)$

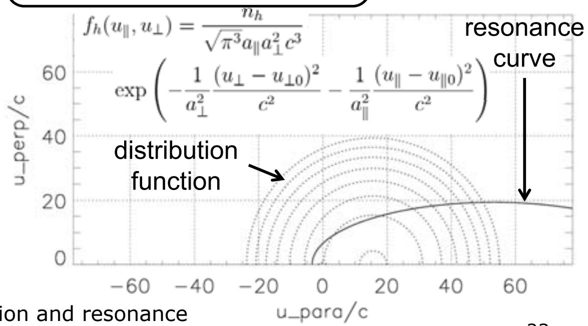
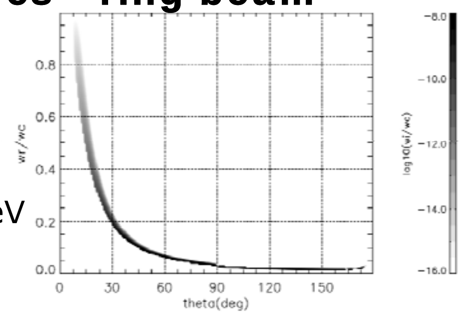


Fig. Distribution function and resonance curve in the momentum space.

O mode waves - ring beam

- Condition
  - mode: O
  - ω_p/ω_c=0.001
  - ω_c=30kHz
  - u_{x0}~15MeV, u_{y0}~4MeV
  - $A_{||}=A_\perp$~300keV
  - n=1



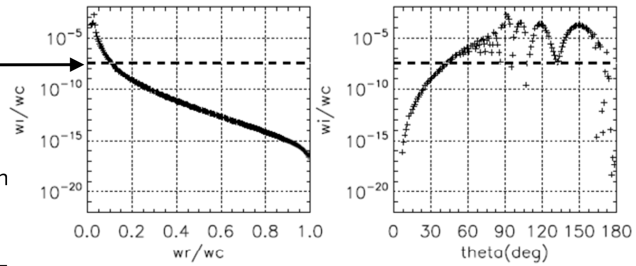
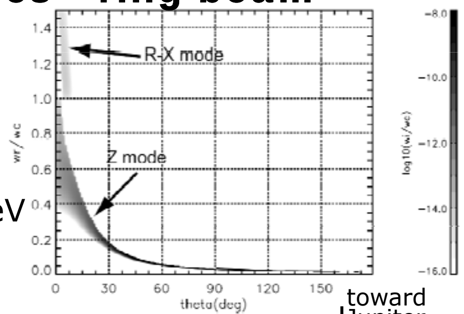


Fig. Growth rate of O mode waves as a function of propagation angle and resonance frequency for the case of polar high source altitudes.

Ring beam：LO mode waves with broad beaming and significantly high growth rates

X mode waves - ring beam

- Condition
  - mode: X
  - $\omega_p/\omega_c=0.001$
  - $\omega_c=30kHz$
  - u_{x0}~15MeV, u_{y0}~4MeV
  - $A_{||}=A_{\perp}$~300keV
  - n=1



outburst duration ~120sec

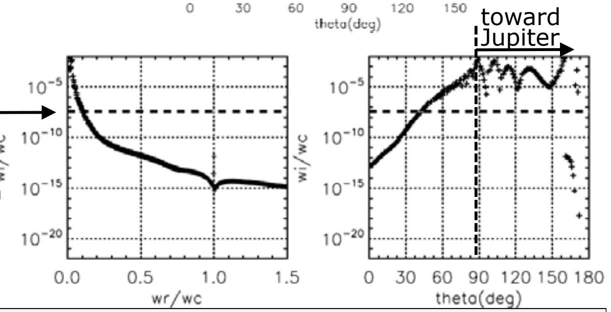


Fig. Growth rate of X mode waves as a function of propagation angle and resonance frequency for the case of polar high source altitudes.

Ring beams cannot generate RX (free-space) mode wave consistent with observations. Z mode waves are locally generated.

Discussion and Summary

- Direct generation：possible
  - Free-space waves are generated at possible source region of QPBs.
    - Dist. func.: unstable structure is required (e.g., ring beam).
    - Directivity：broad beaming, being consistent with obs.& rtc(Kimura et al., 2008b, 2010)
    - Wave mode：LO mode=>possible,
      RX mode=>impossible
  - Z mode waves are locally generated.
    - A good candidate for energy sources of the mode conversion process (e.g., Oya, 1974).

6.2. MACROSCOPIC GENERATION PROCESS OF QUASI-PERIODIC PHENOMENA

Flux Transfer Event Scenario

- twin-vortex at cusp by FTE (pulsed dayside econnection) ??
- ↓ ionospheric Pedersen currents ??
- ↓ upward/downward FAC ??
- ↓ field aligned potential drop ??
- ↓ relativistic particle bursts — McKibben et al. (1993) (obs.) Zhang et al. (1995) (obs.)
- ↓ QP bursts, Periodic X-ray aurorae, etc... — Gladstone et al. (2002) (obs.); Pryor et al. (2005) (obs.); MacDowall et al. (1993) (obs.); Morioka et al. (2006) (obs.); Kimura et al. (2008b) (obs.)

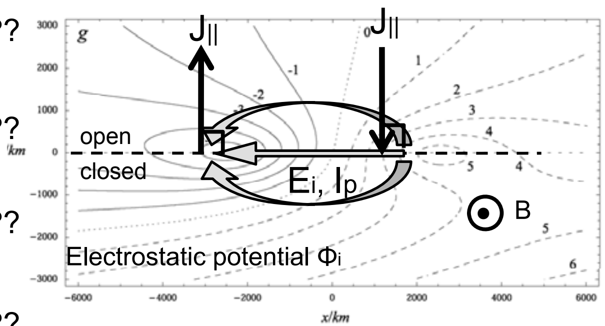


Fig. Electrostatic potential of “twin-vortex” (Bunce et al., 2004).

FTE scenario(Bunce et al., 2004):strong parallel accel. at cusp

Validation: Cross Correlation

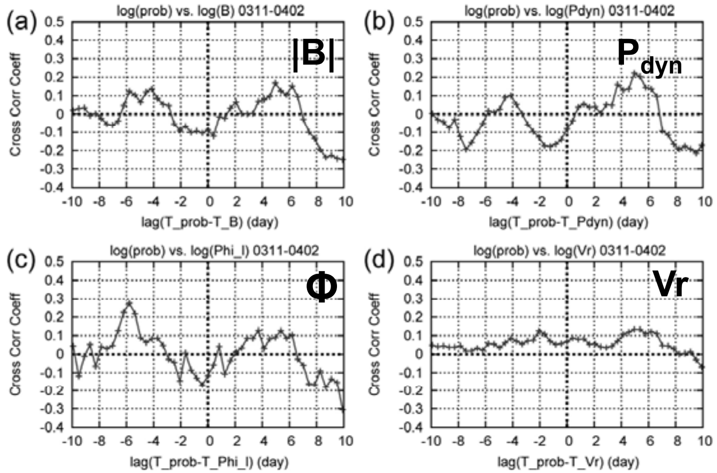


Fig. Cross correlation coefficients as functions of lag time between QP bursts' occurrence and solar wind parameters.

- QPB occurrence v.s.

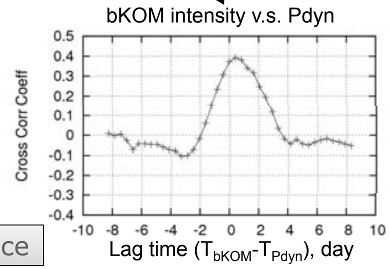
P_{dyn} : dynamic pressure, |B| : magnitude of IMF
Φ : reconnection voltage, Vr : radial velocity of SW

- no significant correlation

Comparison with other radio components

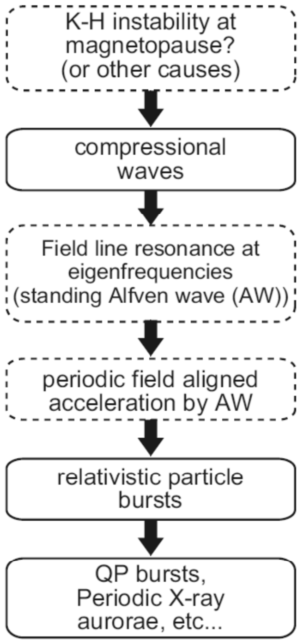
	nKOM	HOM	bKOM	QPB
Related to	inner MS	middle MS	open-closed boundary	outer MS (cusp?)
IMF |B|	○	○	○	×
Pdyn	×	○	○	×
reconnection voltage	×	△	○	×
Time lag	10h>	10h>	10h-1day	N/A

○ : positively-correlated (one peak of r>=0.3 within ±5 days lag)
× : uncorrelated



FTE scenario : no supportive evidence

Field Line Resonance Scenario



FLR scenario : analogy to Earth. Phenomena with characteristic periods.

?? (K-H instability at magnetopause?)

e.g, Russell et al. (2000) (obs.)

?? Khurana and Kivelson. (1989) (obs.) Wilson and Dougherty (2000) (obs.)

?? 大河原. (1999) (obs.)

McKibben et al. (1993) (obs.)
Zhang et al. (1995) (obs.)

Gladstone et al. (2002) (obs.); Pryor et al. (2005) (obs.); MacDowall et al. (1993) (obs.); Morioka et al. (2006) (obs.); Kimura et al. (2008b) (obs.)

- 1997/04/01-1997/04/03 Galileo@LT:5.3-7.2[hr], 38.2-21.2[Rj]

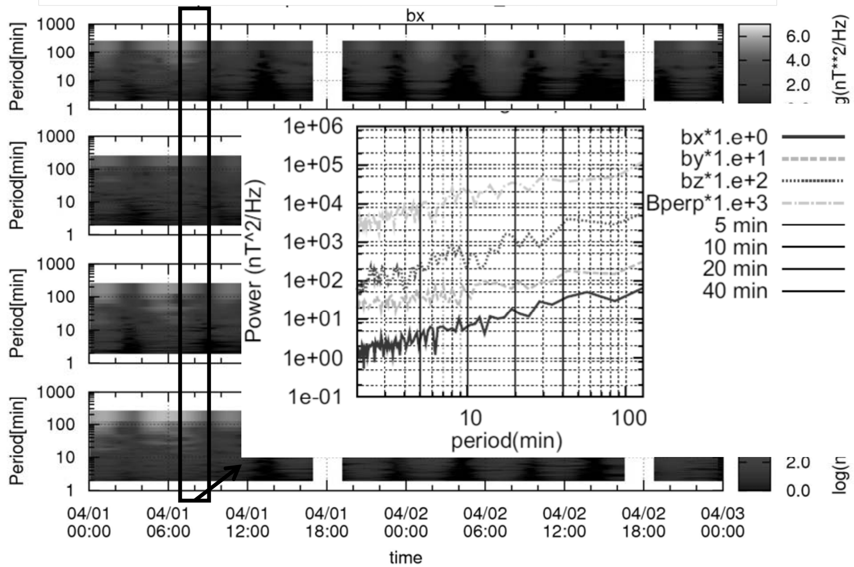
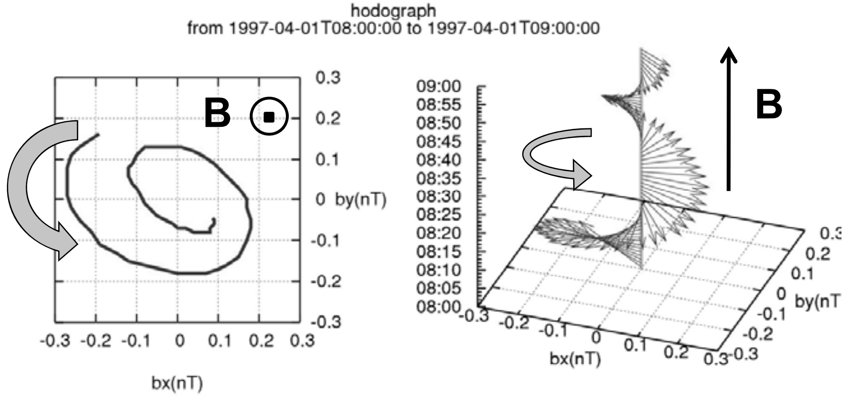


Fig . A dynamic spectrum of the perturbation field.

perturbation fields in the mid. MS with a few-tens min. periods

Hodograph of perturbation field

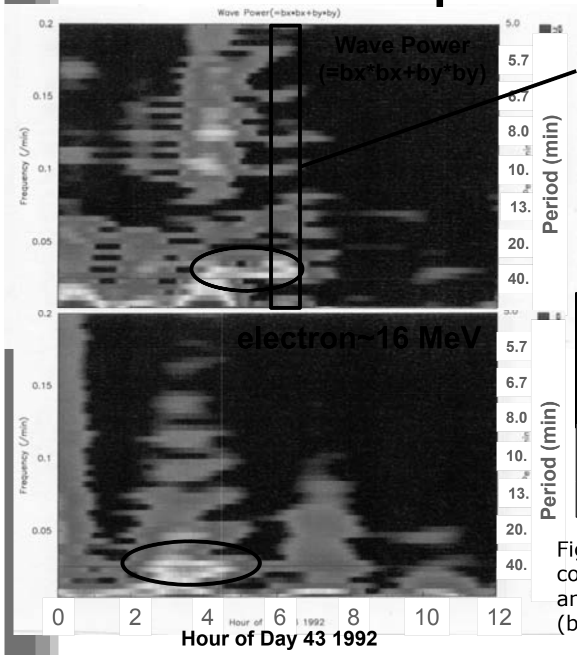
- Perturbation fields above/below current sheet
  →Alfvenic circular variations with small amplitudes
- propagation angle～tens deg

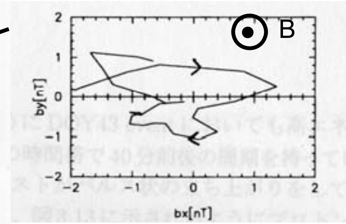


- Radial distance~30Rj
- ~6Rj from Mag. Eq.
- prop. ang.：~25°（or 25° +180°）
- amplitude/BG～1%

Fig . Hodograph of the perturbation field in a plane perpendicular to background field

Polar Alfvenic perturbation





- Ohgawara (1999)：QP electron bursts accompanied with Alfvenic fields.

FLR scenario：possible by AW propagating between polar and equatorial region ?

Fig. Power spectrum of transverse component of magnetic field (top) and energetic electron count rates (bottom) (大河原, 1999).

Picture of QP phenomena

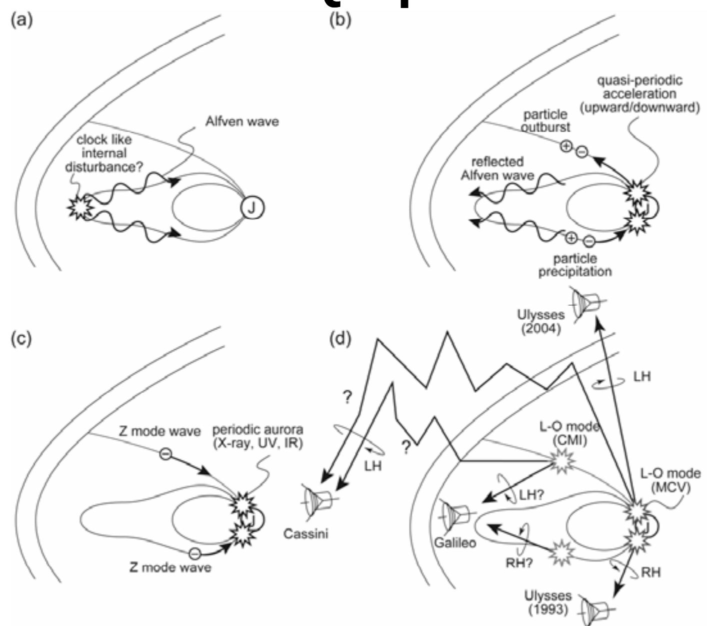


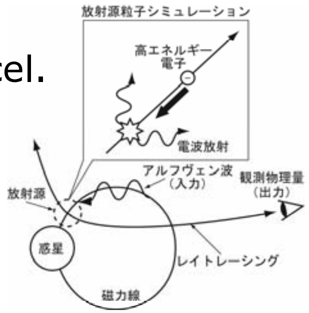
Fig A picture of Jovian quasi-periodic phenomena proposed by this thesis.

Summary & Conclusions

- Observational characteristics of QPBs
  - Occurrence ：rotational phase, "shadow zone", "40min" period
  - Polarization：LH@high lat, LH@low lat outside MS
- Interpretation of obs. by ray tracing. Two kinds of source region
  - polar low altitudes：LO mode, propagating to high lat.
  - polar high altitudes：RX mode, propagating to low lat.
- Generation mechanisms：
  - direct generation：LO mode generated directly at low and high altitudes
  - unstable structures (e.g., ring beam) are required
  - indirect generation：Z mode at high and low alt.→propagate to low alt.→converted to LO mode
- periodic particle accel.：internal process is more plausible than external process.

Plans at ISAS

- particle simulation
  - demonstration of DAW accel. accompanied with QPBs
  - including electron kinetics (for w-p interaction)
  - PIC code
  - details: TBD



- Particle sim.+Ray tracing

  =>numerical model for generation and propagation of PRE