On the importance of searching for oscillations of the Jovian inner radiation belt with a quasi-period of 40 minutes

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ABSTRACT

Experiments aboard the \textit{Ulysses} spacecraft discovered quasi-periodic bursts of relativistic electrons and of radio emissions with \(\sim 40\)-min period (QP-40) from the south polar direction of Jupiter in 1992 February. Such polar QP-40 burst activities were found to correlate well with arrivals of high-speed solar winds at Jupiter. We advance the physical scenario that the inner radiation belt (IRB) within a distance of \(\sim 2–3\) \(R_\text{J}\) (where \(R_\text{J}\) is the radius of Jupiter), where relativistic electrons are known to be trapped using the diagnostics of synchrotron emissions, can execute global QP-40 magnetoinertial oscillations excited by arrivals of high-speed solar winds at the Jovian magnetosphere. Modulated by such QP-40 IRB oscillations, relativistic electrons trapped in the IRB may escape from the magnetic circumpolar regions during a certain phase of each 40-min period to form circumpolar QP-40 relativistic electron bursts. Highly beamed synchrotron emissions from such QP-40 burst electrons with small pitch angles relative to Jovian magnetic fields at \(\sim 30–40\) \(R_\text{J}\) give rise to QP-40 radio bursts with typical frequencies \(\lesssim 0.2\) MHz. We predict that the synchrotron brightness of the IRB should vary on QP-40 time-scales upon arrivals of high-speed solar winds with estimated magnitudes \(\gtrsim 0.1\) Jy, detectable by existing ground-based radio telescopes. The recent discovery of \(\sim 45\)-min pulsations of Jupiter’s north polar X-ray hot spot by the \textit{Chandra} spacecraft provides strong supporting circumstantial evidence that the IRB neighborhood did oscillate with QP-40 time-scales. Using the real-time solar wind data from the spacecraft Advanced Composition Explorer (ACE), we show here that such QP-40 pulsations of Jupiter’s north polar X-ray hot spot did in fact coincide with the arrival of high-speed solar wind at Jupiter. We note also that properly sampled data of simultaneous far-ultraviolet images of auroral ovals obtained by the \textit{Hubble Space Telescope} imaging spectrograph (\textit{HST}-STIS) would have contained QP-40 oscillatory signatures. Based on our theoretical analysis, we offer several predictions that can be tested by further spacecraft and ground-based telescope observations.

Key words: MHD – polarization – radiation mechanisms: non-thermal – waves – solar wind – planets and satellites: individual: Jupiter.

1 INTRODUCTION

Quasi-periodic bursts of relativistic electrons (Simpson et al. 1992; McKibben, Simpson & Zhang 1993; Desch 1994) and of accompanied radio emissions (MacDowall et al. 1993) were discovered by the \textit{Ulysses} spacecraft a decade ago. The burst relativistic electron energy ranges from a few to \(\gtrsim 10\) MeV and the frequency of radio bursts is usually \(\lesssim 200\) kHz, with occasional rises to \(\sim 700\) kHz. These burst activities, characterized by a quasi-period of 40 min (QP-40), were inferred to occur in the south polar direction of Jupiter and were found to correlate closely with arrivals of high-speed solar winds at Jupiter (see figs 11 and 12 of MacDowall et al. 1993; Bame et al. 1992). Polarizations of these radio bursts are predominantly right-handed. There were other evidence, though less certain, for Jovian QP-40 phenomena such as magnetic field fluctuations and proton fluxes from observations of various spacecraft (e.g. Schardt, McDonald & Trainor 1981; Balogh et al. 1992).

Prompted by these observations and based on a theoretical magnetohydrodynamic (MHD) analysis, we proposed (Lou 2001) that

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the underlying physical mechanism may involve global QP-40 magneto inertial oscillations of Jupiter’s inner radiation belt (IRB) within a distance of $\sim 2–3 R_J$ (where $R_J \equiv 7.14 \times 10^9$ cm is Jupiter’s radius). In the scenario of QP-40 IRB oscillations, several seemingly disparate key phenomena can be plausibly linked together. In the past, variabilities from weeks to years of the Jovian system have been searched for in response to solar wind variations (e.g. Bolton et al. 1989; Miyoshi et al. 1999). The central question posed in this Letter is whether the synchrotron brightness of the IRB varies on QP-40 time-scales and shorter ones resulting from solar wind speed variations at Jupiter.

The recent Chandra observations (Gladstone et al. 2002) detected QP-40 pulsations of north polar X-ray hot spots on Jupiter. From space, Cassini synchrotron radio observations at 2.2 cm (Bolton et al. 2002) revealed relativistic electrons with energies $\gtrsim 50$ MeV inside the IRB. These observations provide valuable circumstantial evidence for QP-40 IRB oscillations. In this Letter, we derive physical consequences from empirical facts, provide relevant estimates, propose further observational tests, and establish that $\sim 45$-min pulsations of Jupiter’s north polar X-ray hot spot did coincide with an arrival of high-speed solar wind at Jupiter using the real-time data from the spacecraft Advanced Composition Explorer (ACE). It would be significant to search actively for QP-40 IRB synchrotron brightness variations upon arrivals of high-speed solar winds at Jupiter using existing ground-based radio telescope facilities. Once established, this would enable us to study the dynamics of the IRB from a new perspective, both observationally and theoretically.

2 THE PHYSICAL SCENARIO

By tracing QP-40 radio burst directions (MacDowall et al. 1993) in the plane of sky, comparing arrival times of various energetic particle species (Zhang et al. 1995) and analyzing electron anisotropies (Zhang, Simpson & McKibben 1993), it is fairly certain that these charged particles burst from Jupiter’s south magnetic polar region. Jupiter has long been known to be an important source of relativistic electrons populating the heliosphere (Simpson et al. 1975; Nishida 1976). Although specific aspects remain to be understood, the Jovian magnetospheric system interacting with the solar wind appears to be capable of producing relativistic electrons to supply and sustain the IRB and to compensate magnetic polar leaks.

What is then the origin or source of such polar QP-40 bursts of relativistic electrons and ions? By all accounts, it is plausible (Lou 2001) that QP-40 burst electrons and ions leak out from the narrow circumpolar zone separating the magnetic polar region with open magnetic fields from the adjacent Jovian IRB with closed magnetic fields (e.g. Schultz & Lanzerotti 1974). The IRB can trap relativistic electrons with energies up to $\sim 50$ MeV or higher, as inferred from IRB synchrotron emissions with wavelengths of $\sim 2.2–9.0$ cm (Roberts, Berge & Bignell 1984; de Pater 1990; Sault et al. 1997; Bolton et al. 2002). Moreover, by combined effects of Jupiter’s fast rotation with a $\sim 10$-h period and a strong dipole magnetic field with a polar surface strength $|B|$ of $\sim 10–14$ G (e.g. Rogers 1995), the IRB is capable of magneto inertial oscillations with periods of $\sim 40–50$ min and shorter (Lou 2001).

Such magneto inertial oscillations of a rotating IRB involve both Lorentz and Coriolis forces. For low-frequency and large-scale oscillations, the mode frequency is a hybrid of Alfvén and rotation frequencies; for high-frequency and small-scale oscillations, the mode frequencies are essentially those of globally trapped fast MHD wave modes. For the hybrid mode of the lowest frequency, the IRB plasma swings to and fro about the Jovian rotation axis.

With this scenario in mind, the gross overall correlations among QP-40 bursts of radio emissions (MacDowall et al. 1993), of relativistic electrons (Simpson et al. 1992; McKibben et al. 1993), of protons and, occasionally, of alpha particles (Zhang et al. 1995) seems to indicate that (i) QP-40 polar relativistic electron bursts are most likely to be responsible for QP-40 polar radio bursts, and (ii) a global resonant oscillatory mechanism may underlie the quasi periodicity of $\sim 40$ min for polar bursts of relativistic electrons and ions (Schardt et al. 1981; Zhang et al. 1995).

To relate QP-40 IRB oscillations and QP-40 circumpolar bursts of electrons, we invoke large-scale asymmetries as well as small-scale irregularities in magnetic field structures of the IRB (Lou 2001). During a certain phase of each IRB pulsation period, relativistic electrons may drift across thin vulnerable layers randomly spreading along circumpolar magnetic footpoints with a perpendicular gradient drift speed $\mathbf{v}_d = -m_e\gamma v^2_e c B \times \nabla |B|/(2eB^2)$ into a narrow circumpolar strip (e.g. Northrop 1963) and thus give rise to an electron burst, where $m_e$ is the electron mass, $\gamma$ is the Lorentz factor, $v^2_e$ is the electron velocity perpendicular to $B$, $c$ is the speed of light and $e$ is the electron charge. Hence, QP-40 IRB oscillations lead to QP-40 bursts of relativistic electrons and ions from magnetic circumpolar zones. Then QP-40 radio bursts are produced by highly beamed synchrotron radio emissions from such escaped relativistic electrons with very small pitch angles $\alpha$ ($\sim 6–4 \times 10^{-3}$ radians at $\sim 30–40 R_J$) relative to magnetic field lines such that radio burst frequencies detected by Ulysses are typically $\lesssim 200$ kHz (MacDowall 2001). It requires relativistic electrons of higher $\gamma$ to produce occasional rising frequencies of up to $\sim 700$ kHz at Ulysses. The fact that onsets of QP-40 radio bursts (McKibben et al. 1993; Desch 1994) sometimes precede relevant relativistic electron bursts by $\sim 4–8$ min is likely to be a result of radio emissions from those relativistic electrons that travel along neighboring magnetic field lines but that are not intercepted by Ulysses (Lou 2001). Admittedly, we do not yet know full details of circumpolar electron leak processes without information of magnetic field inhomogeneities and irregularities or defects. There might be a possibility that diocotron instability is somehow involved.

3 THEORETICAL CONSIDERATIONS

In reference to spacecraft observations, we now provide theoretical analyses and offer testable predictions.

3.1 Excitations of global IRB oscillations

Empirically, onsets of enhanced QP-40 burst activities correlate well with arrivals of high-speed solar winds at Jupiter (MacDowall et al. 1993). Whereas the solar wind mass flux remains roughly constant for either fast or slow winds, variations in the solar wind speed $U (~ 800–400$ km $s^{-1}$) cause the radial size of the sunward Jovian magnetosphere to change drastically ($\sim 50–100 R_J$). This offers a valuable clue for the excitation of QP-40 IRB oscillations and thus for the observed correlation of QP-40 polar burst activities with high-speed solar winds. Drastic changes of solar wind speed at the Jovian magnetosphere or persistent Jovian magnetospheric compressions sustained during a high-speed solar wind phase with irregular intermittent relaxations caused by wind speed variations can both drive QP-40 magneto inertial IRB pulsations resonantly and hence induce neighboring magnetic field oscillations (Balogh et al. 1992) through the conservation of the magnetic field angular momentum (Nishida & Watanabe 1981). Furthermore, such MHD pulsations of the IRB should lead to QP-40 brightness variations.
3.2 Estimates for IRB brightness variations

The solar wind mass flux is estimated by $\rho u D_J$, where $\rho$ is the solar wind mass density and $D_J$ is Jupiter’s distance to the Sun. Changing from slow to fast solar winds at Jupiter, the wind ram pressure $\rho u^2$ increases by a factor of $\sim 2$. After a transient time of adjustment and for a negligible IRB thermal pressure, this increase of wind ram pressure is balanced grossly by an increase of magnetic pressure $B^2/(8\pi)$ of the IRB temporarily. Therefore, the relative field strength variation $\delta B/B$ in the IRB may be as much as $\sim 40$ per cent stirred by drastic solar wind speed variations; by the magnetic flux conservation, the radial extent of the IRB may vary by $\sim 20$ per cent, accordingly.

In the IRB, for a power-law distribution of electron number density $N(\gamma) \propto \gamma^{-5} d\gamma$ in the dimensionless energy interval $(\gamma, \gamma + d\gamma)$, the spectral intensity $I_\nu$ of synchrotron radiation is $I_\nu \propto B^{\delta+1}/\nu^{\delta-1/2}$ (Ginzburg & Syrovatskii 1965; Rybicki & Lightman 1979). At a given frequency $\nu$, one has $\delta I_\nu/I_\nu \equiv (S + 1)\delta B/2B$. For the Jovian IRB, the spectral index $S > 1$ and $I_\nu$ takes on values of $\sim 0.44 \pm 0.15, \sim 0.42 \pm 0.08, \sim 0.15 \pm 0.7$ Jy at $\nu = 13.8, 5, 2.3$ and 0.333 GHz, respectively (Bolton et al. 2002). Approximately, in two separate frequency ranges $0.333 < \nu $ has $\delta I_\nu/I_\nu \approx \sim 1.9$ and $\sim 1.4$, respectively. Conservatively, $\delta I_\nu$ is thus estimated to be $\approx 0.1$ Jy. As a crucial test, such QP-40 IRB brightness variations in wavelengths $6-90$ cm should be carefully searched for using existing ground-based radio telescopes.

3.3 Polarization properties of QP-40 radio bursts

There are several physical reasons and observational tests to support and to further check our physical scenario. The radiation electric field $E_{\text{rad}}$ from an accelerating electric charge $q$ is simply given by (e.g. Rybicki & Lightman 1979)

$$E_{\text{rad}}(r, t) = q \frac{n}{c \times R} \times \left[ (n - \beta) \times \beta \right],$$  \hspace{1cm} (1)

where brackets denote variables at retarded times, $\beta \equiv u/c$ is the particle velocity normalized by $c$, $\beta$ is the time derivative of $\beta$, $n$ is the unit vector along the line of sight distance $R$ at retarded times, and $\kappa \equiv 1 - n \cdot \beta$. Meanwhile, the radiation magnetic field $B_{\text{rad}}(r, t) \equiv [n \times E_{\text{rad}}(r, t)]$. The south polar magnetic field $B$ points towards Jupiter. For a relativistic electron stream outgoing from the south pole with a small pitch angle $\alpha$ (nearly antiparallel to $B$), the instantaneous $E_{\text{rad}}$ is nearly along $\beta$. Given the right-hand gyration of an electron with respect to $B$, the radio polarization at $Ulysses$ should be right-handed; this qualitative conclusion has also been confirmed by more detailed numerical computations. This right-handed radio polarization should prevail for a bunch of electrons so long as their spatial distribution is not completely random. This theoretical result is consistent with the $Ulysses$ Radio and Plasma Wave Experiment (URAP) observations (MacDowall et al. 1993).

In 2004, $Ulysses$ will have a second rendezvous with Jupiter in the northern heliosphere with a closest approach of $\sim 1000 R_J$. For global IRB oscillations and qualitatively similar polar $B$ configurations as well as levels of irregularities, QP-40 bursts of relativistic electrons and of accompanied radio emissions from the north pole are anticipated, especially during arrivals of high-speed solar winds at Jupiter. Although $Ulysses$ particle instruments cannot intercept QP-40 bursts of relativistic electrons (one still expects to observe a gradual increase of relativistic electron flux towards Jupiter), URAP will have a good opportunity to observe north polar QP-40 radio bursts outside the Jovian magnetosphere. As $B$ points outward from the Jovian north pole, we predict that polarizations of north circumpolar QP-40 radio bursts should be predominantly left-handed.

3.4 Frequencies of QP-40 radio bursts

Let us now estimate typical frequency components of a radio burst. As relativistic electrons leak out quasi-periodically during a certain phase in each period of IRB QP-40 oscillations, radio burst emissions are produced by the synchrotron process from relativistic electrons in nearly antiparallel motions outward along Jovian south polar magnetic field lines. Such IRB relativistic electrons initially drift across the narrow circumpolar zone about the magnetic axis and they gyrate transverse to the local surface $B$, radiating intensely in a perpendicular plane as a result of the relativistic beam effect (i.e. strongest synchrotron emissions within an angle $\gamma \approx 1/\alpha$ about $\nu$ direction). The total power emitted by a gyrating relativistic electron is $P(\gamma) = (2(\gamma^2-1)^{\delta/2} \sin^2 \alpha)/(3m_e c^3)$. As electrons stream outward from circumpolar magnetic footpoints with gyroradii $r_e \sim \gamma m_e c^2/|eB| = 1.7 \times 10^3 \gamma B^{-1} c < R_J$, the magnetic mirror force converts transverse gyration rapidly into parallel motions by conserving both particle energy $E = \gamma m_e c^2$ and magnetic moment $E_c/|B|$. Hence, $E_c$ is the particle kinetic energy of transverse gyration (Northrop 1963). The synchrotron emission cone ahead of a relativistic electron gyration around $B$ shrinks in conal angle towards the forwards direction of $\nu$ with decreasing characteristic radiation frequencies (Ginzburg & Syrovatskii 1965; Walt 1994).

For a dipole magnetic field $|B| \propto r^{-3}$ and a polar surface $|B|$ strength of $\sim 10 G$, the pitch angle $\alpha$ of relativistic electrons, independent of $\gamma$, becomes $\sim 6 \times 10^{-3}$ at $\sim 30 R_J$ or $\sim 10^{-3}$ radians at $\sim 40 R_J$. The characteristic synchrotron emission frequency $\nu_c$ from a gyrating electron is given by $\nu_c = (0.29 \times 3\gamma^2 c^2 B \sin \alpha)/(4\pi m_e c)$ (Rybicki & Lightman 1979). For parameters of interest, we have $\nu_c \sim 3\gamma^2$ and $\sim 0.87\gamma^2$ at $\sim 30 R_J$ and $\sim 40 R_J$, respectively. For typical spectral profiles of QP-40 radio bursts, the dominant peak falls between $\sim 10–80$ kHz (MacDowall et al. 1993).\footnote{A reduced intensity at about 40–50 kHz may not be a common feature of the QP-40 bursts. The transition from the URAP Radio Astronomy Receiver (RAR) low- to high-band receivers occurs around $\sim 50$ kHz.} For a power-law number distribution of IRB electrons in $\gamma$, this would imply relativistic electrons with a $\gamma$ range of as high as $\sim 160–300$. The recent $Cassini$ synchrotron radio observation in space at $2.2$ cm (13.8 GHz) revealed high-energy tails with $\gamma \gtrsim 200$ at $\nu \gtrsim 2 R_J$ (Bolton et al. 2002). It is important to realize that $\alpha$ can be a very small number here. If $\sin \alpha$ is taken to be $\sim 1$, as commonly assumed, then $\nu_c$ would be very much higher than several hundred kHz.

3.5 QP-40 pulsations of north polar X-ray hot spots

With both magnetic poles being qualitatively similar, we focus on pulsations of northern auroral X-ray hot spot of Jupiter with a $\sim 45$-min period discovered lately (Gladstone et al. 2002) using the high-resolution camera (HRC) of the $Chandra$ X-ray Observatory on 2000 December 18. Although physical processes leading to such polar X-ray hot spots inside the main far-ultraviolet (UV) polar auroral oval are currently unexplained, their QP-40 pulsations offer none the less extremely valuable diagnostics for probing the inner magnetospheric environment.

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In the scenario of QP-40 IRB oscillations (Lou 2001), the northern auroral X-ray hot spots should pulsate with a quasi-period of \( \sim 40 \) min as QP-40 magneto-inertial oscillations of the IRB will affect, through fast MHD wave transmissions, the immediate environments that include circumpolar zones of open magnetic fields and leave QP-40 oscillatory signatures there (Balogh et al. 1992). Almost certainly, \( \sim 45\)-min pulsations of southern auroral X-ray hot regions were not seen this time (Gladstone et al. 2002), primarily owing to an unfavorable viewing geometry from the Chandra HRC. We anticipate that, similar to QP-40 polar burst activities and IRB oscillations (MacDowall et al. 1993), pulsation magnitudes of such X-ray hot spots poleward of the far-UV auroral oval should also be enhanced upon arrivals of high-speed solar wind at Jupiter. One primary goal of the Chandra and Hubble Space Telescope (HST) campaigns supporting the Cassini fly-by is to search for connections between jovian auroral transients and the interaction of the solar wind with Jupiter’s magnetosphere; in fact, this is already in hand but not yet fully appreciated.

It is promising to pursue a direct detection of Jupiter’s QP-40 IRB brightness variations in the wavelength range of \( \lambda \sim 6\text{–}90 \) cm with magnitudes \( \gtrsim 0.1 \) Jy by the ground-based radio telescope facilities such as those at Effelsberg, Very Large Array, Westerbork Synthesis Radio Telescope, Owen’s Valley Radio Observatory, and Australia Telescope Compact Array. The optimal condition for a detection can be derived in advance by combining the information of locations of the Earth and Jupiter relative to the Sun and the knowledge of low-latitude solar X-ray coronal holes where fast solar winds emanate. As the Sun rotates with an equatorial period of \( \sim 25\text{–}26 \) d, fast solar wind streams recur in the interplanetary space (Lou 1994, 1996). Meanwhile, it is crucial to establish the correlation of QP-40 pulsations of solar X-ray hot spots with arrivals of high-speed solar winds using the Chandra HRC. As jovian auroral oval marks the boundary zones separating the closed \( B \) of IRB and the open polar \( B \), it is inevitable that far-UV auroral oval should pulsate with a QP-40 period upon arrivals of high-speed solar winds; this prediction can be tested by HST imaging spectrograph (HST-STIS) observations.

3.6 Coincidence with a high-speed solar wind

For the Chandra HRC 10-hour observation for X-ray QP-40 pulsations of Jupiter’s north polar hot spot on 2000 December 18 from 10–20 UT (Gladstone et al. 2002), we show that this observation run happened to coincide with an arrival of high-speed wind at Jupiter. We obtained pertinent information from the solar system dynamics website of the Jet Propulsion Laboratory (JPL) in the ‘mean orbital elements’ section for both the Earth and Jupiter, and from the archival data on the Advanced Composition Explorer (ACE) Real Time Solar Wind website. At 12:00 UT on 2000 January 1, the Earth longitude \( \varphi_E = 100.464^\circ \) and the Jupiter longitude \( \varphi_J = 34.404^\circ \), respectively. The mean angular rate of the Earth is 129 597 740.63 arcsec (100 yr)\(^{-1} = 3548.1928 \) arcsec d\(^{-1} = 0.985 6091 \) d\(^{-1}\) and the mean angular rate of the Jupiter is 10 925 078.35 arcsec (100 yr)\(^{-1} = 299.112 34 \) arcsec d\(^{-1} = 0.083 086 76\)^\(\circ\).

\(^{2}\)Grodent et al. (2001) indicated that the sampling of the HST-STIS at the time did not permit them to highlight a 40-min oscillation in the corresponding UV light curve.

\(^{3}\)http://ssd.jpl.nasa.gov/

\(^{4}\)http://www.sec.noaa.gov/ace/ACErtsw_home.html; http://www2.crl.go.jp/dk/c231/ace/

D 4 SUMMARY AND CONCLUSIONS

Based on empirical clues, intuitive considerations and theoretical analysis, it is physically plausible and appealing that polar QP-40 bursts of relativistic electrons of and radio emissions involve global QP-40 IRB oscillations of Jupiter. With this scenario in mind, we summarize below a few key results and testable predictions.

(i) QP-40 burst electrons, protons and alpha particles with relativistic energies are most likely to have originated from the jovian IRB (Lou 2001), where relativistic electrons with \( \gamma \) as high as \( \sim 100\text{–}200 \) are known to exist (Bolton et al. 2002). They escape from the jovian magnetic circumpolar regions and are modulated by global QP-40 IRB oscillations. Diocotron instability might be involved in leaking processes. Some of these escaping relativistic electrons may attain large \( \gamma \), as indicated.

(ii) As estimated here, the predicted QP-40 brightness variations of the IRB should be observable by existing ground-based radio telescopes. In addition, it is extremely important to verify the expected correlation of such QP-40 brightness variations with arrivals of high-speed solar winds at Jupiter. Under favourable situations, higher harmonics of QP oscillations of fast MHD modes with shorter periods (Lou 2001) might also be detectable.

(iii) The QP-40 IRB oscillations are most likely to be excited and sustained by the combined effects of solar wind speed variations, of short-term intermittent wind speed variations during either fast or slow wind phase, and of angular momentum conservation of jovian magnetospheric plasma.

(iv) Assuming a comparable level of inhomogeneities for both north and south pole magnetic fields, we predict QP-40 bursts of relativistic electrons of the IRB from Jupiter’s north polar region. Moreover, such QP-40 north polar activities are expected to
correlate well with arrivals of high-speed solar winds at Jupiter. In coordination with spacecraft observations of solar wind properties, another spacecraft needs to be launched to enter jovian magnetosphere and to probe the north polar region in order to test this prediction.

(v) At 30–40 R\textsubscript{J} away from Jupiter, synchrotron emissions with small pitch angles \(\alpha\) are stronger than curvature emissions in QP-40 radio bursts associated with relativistic electrons streaming along south polar magnetic field lines of Jupiter. The observed predominance of right-handed polarization of radio burst emissions is consistent with the gyration sense of outstreaming electrons in the south polar magnetic field pointing towards Jupiter. North polar QP-40 radio bursts associated with north polar QP-40 bursts of relativistic electrons are expected and should be detectable by \textit{Ulysses}, now approaching Jupiter in the northern hemisphere. Because Jupiter’s north polar magnetic field points outward, we therefore predict the polarization of north polar QP-40 radio bursts to be predominantly left-handed. These predictions can be tested by \textit{Ulysses} observations in the near future (2003–2004).

(vi) Based on one case of coincidence of QP-40 pulsations of north polar X-ray hot spots with an arrival of high-speed solar wind at Jupiter reported here for the first time and our global QP-40 IRB oscillation scenario, we would like to emphasize the importance of establishing this correlation empirically through more coordinated spacecraft observations. Once confirmed, the physical link among the arrival of high-speed solar winds at Jupiter, the observed QP-40 polar activities and the global QP-40 oscillations of the IRB would be more certain.

(vii) Latitudinally, the Jovian auroral ovals lie between the IRB and the polar X-ray hot spots. Naturally, through magnetospheric wave transmissions of IRB oscillations to neighboring polar magnetic fields, we expect QP-40 pulsations of Jovian aurora ovals in correlation with arrivals of high-speed solar winds at Jupiter. For example, this prediction can be tested by well-prepared \textit{HST-STIS} observations of far-UV auroral ovals with appropriate sampling rate.

By this Letter, we hope to stimulate more observational and theoretical studies on QP-40 polar activities of Jupiter and to identify and understand the physical cause of QP-40 phenomena.

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