

# QUASI-PERIODIC MAGNETOSPHERIC ACTIVITIES OF JUPITER AND SATURN AND MAGNETO-INERTIAL OSCILLATIONS OF THEIR INNER RADIATION BELTS

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## Extended Abstract

Ulysses discovered quasi-periodic 40 minute (QP-40) bursts of relativistic electrons (energy  $E \geq 10$  MeV) and of associated low-frequency radio emissions (frequency  $\nu \leq 0.7$  MHz) from the south pole of Jupiter since early February 1992 [McKibben et al., 1993]. Such QP-40 radio bursts feature right-hand circular polarization, and their occurrence strongly correlates with recurrent arrivals of fast-speed solar winds [MacDowall et al. 1993]. Based on model analysis, empirical evidence and physical considerations, Lou [2001] advanced the scenario that these QP-40 relativistic electron bursts originate around circumpolar zones from Jupiter's inner radiation belt (IRB) occupying  $\sim 1.5 - 3 R_J$  (Jovian radii) wherein the intense synchrotron radiation reveals trapped relativistic electrons ( $E \geq 50$  MeV with Lorentz factor  $\gamma$  up to  $\sim 200$ ) and predicted then that such QP-40 polar burst activities should be global involving both Jovian poles, as indeed confirmed by Ulysses observations towards the north pole direction of Jupiter 12 years later. As Jupiter's dipole field points inward/outward at its south/north pole, outstreaming extremely relativistic electrons gyrate very rapidly around south/north circumpolar magnetic field lines (antiparallel/parallel) with very small pitch angles and emit low-frequency ( $\nu \leq 0.7$  MHz) beamed radio bursts with partially right-hand/left-hand circular polarizations. Such QP burst activities correlate with recurrent arrivals of fast-speed solar winds at Jupiter due to magnetospheric squeeze, angular momentum conservation, solar wind intermittency and magnetohydrodynamic (MHD) adjustments. Thus inside the Jovian magnetosphere, one should also detect QP-40 bursts of relativistic electrons together with QP-40 radio bursts from the north pole as from the south pole. Such QP-40 activities are linked to QP-40 magneto-inertial global IRB oscillations [Lou, 2001] that are excited by intermittent magnetized high-speed solar winds [Lou, 1996]. At a certain phase of IRB oscillations, magnetic irregularities along the circumpolar zones adjacent to the IRB would leak out relativistic electrons drifting outwards across field lines from the IRB. The energy distribution of relativistic electrons in a typical burst would generally reflect that of the IRB.

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Jupiter is known to be an important planetary source of relativistic electrons and other charged particles in the solar system. We emphasize that the Jovian polar leakage of relativistic electrons from the IRB appears in forms of drift/diffusion, escape and QP-40 or QP type bursts.

Near the end of 2000 during the joint campaign of Cassini, HST and Chandra, the high-resolution camera of Chandra captured QP-45 brightness variations of an X-ray hot spot within the north auroral oval during a 10-hour observation [Gladstone et al., 2002]. This provided supporting circumstantial evidence that the IRB neighborhood including open field polar regions oscillate in QP-40 manner as influenced by IRB oscillations and by transpolar MHD waves, leading to associated QP-40 features. Using the real-time solar wind data from the Advanced Composition Explorer and pertinent ephemeris, the analysis of Lou and Zheng [2003] shows a very likely coincidence of X-ray hot spot QP-45 variability with the arrival of a high-speed solar wind ( $\sim 700 \text{ km s}^{-1}$ ) at Jupiter. So far, this is the only case for such a correlation; there were other examples of no QP-45 X-ray variations with relatively low-speed solar winds at Jupiter [Lou et al., 2012].

Lou et al. [2012] reported 6-cm wavelength radio observations of Jupiter’s IRB synchrotron flux variations on timescales of 20–60 min using the Urumqi 25-m radio telescope in XinJiang, China. Given the empirical evidence from several spacecraft with proper ephemeris, we show likely correlations of such QP type variations with recurrent high-speed solar winds at Jupiter. It would be desirable to monitor synchrotron IRB using several radio wavelengths simultaneously. It is also important to directly probe in-situ such QP variations in relativistic electron number density and flux, magnetic field, polarized radio emissions, auroral diagnostics as well as electron energy spectrum inside the IRB. In general, a rotating magnetic dipole of Jupiter’s IRB can support magneto-inertial oscillations with longer periods of  $\sim 40 - 50$  min and shorter periods for higher harmonics with nonzero integers  $m$  and  $n$  [Lou, 1987; 2001]. Similar types of magneto-inertial oscillation modes can also appear in rotating magnetized solar and stellar atmospheric layers including those for magnetospheres of exoplanets and for a thin dense magnetized “ocean” over spinning neutron stars. The current JUNO low-frequency radio wave data seem to reflect such a fairly complex situation involving a multitude of QP type pulsations. The low-frequency receiver of JUNO is capable of detecting QP-40 radio bursts from both Jovian poles but without polarization information. QP-40 bursts of relativistic electrons with energy  $E \geq 10 \text{ MeV}$  may penetrate the shield for protecting the instruments onboard.

In reference to the model scenario and physical interpretations for Jupiter’s QP-40 phenomena [Lou 2001; Lou et al., 2012] and especially by striking similarities in several major aspects [Roussos et al., 2016; Palmaerts et al., 2016], we advance here an analogous scenario of global magneto-inertial oscillations of Kronian inner radiation belt (KIRB) for QP-60 phenomena of Saturn as widely detected by various diagnostics of Cassini in-situ observations since early July 2004 [Badman et al., 2016; Mitchell et al., 2016; Palmaerts et al., 2016 and references therein]. With a weaker field, KIRB traps relativistic electrons (up to  $E \sim 12 \text{ MeV}$  and likely higher) and energetic protons within  $\sim 5 R_S$  (Saturn radii) [Kollmann et al., 2011], and the KIRB electron number density is  $\sim 50 - 100 \text{ cm}^{-3}$  [Persoon et al., 2005]. The Saturn surface magnetic field has a range of  $\sim 0.18 - 0.84 \text{ G}$  with a mean of  $\sim 0.5 \text{ G}$  and a KIRB dipole magnetic field  $B$  at  $\sim 4 - 5 R_S$  scales to  $\sim 100$  times less. The KIRB Alfvén wave speed  $C_A = B/(4\pi\rho)^{1/2}$  is then  $\sim 2 - 3 \times 10^3 \text{ km s}^{-1}$ . For axisym-

metric ( $m = 0$ ) standing KIRB magneto-inertial oscillations of a rotating dipole [Lou, 2001], the pulsation period is  $P_S = 2\pi(2n + 1)^{-1/2}[R_B/(2\Omega_S C_A)]^{1/2}$  where integer  $n = 0, 1, 2, \dots$  is the latitudinal node number of oscillations,  $R_B \sim 4 R_S$  is the typical KIRB radius and  $\Omega_S \sim 1.63 \times 10^{-4} \text{ s}^{-1}$  is the Saturn angular spin rate with percent level variations. Naturally, such magneto-inertial oscillations involve rotation and magnetic field. With estimates of pertinent parameters and  $n = 0$ , the fundamental  $P_S$  is  $\sim 60 - 70$  minutes. The range of such QP periods may cover  $\sim 40 - 90$  min for sensible ranges of estimated parameters. For higher harmonics of  $n > 0$ ,  $P_S$  becomes shorter accordingly. Non-axisymmetric pulsations are also allowed. The almost axisymmetry of Saturn's dipole field is broken by its co-rotation facing the solar wind for MHD: on the dawn side, the dipole rotates to be squeezed, while on the dusk side, the dipole rotates to be relaxed after squeezing - giving rise to the dawn-dusk MHD asymmetry to cause more frequent QP-60 oscillations and activities on the dusk side. The reported QP-60 variations of the spherical magnetic field components  $B_\phi$  and  $B_\theta$  are generally consistent with KIRB magneto-inertial QP-60 oscillations. Intermittent high-speed solar winds, various disturbances in the magnetized solar wind, magnetospheric reconnections and Kelvin-Helmholtz instabilities can all stimulate KIRB QP-60 oscillations. It is of interests to study relations of Saturn QP-60 diagnostics and arrivals of high-speed solar winds at Saturn. KIRB QP-60 oscillations and associated activities can influence the outer magnetosphere and the open magnetic field lines across the two polar caps due to transpolar MHD waves such that various auroral and magnetic diagnostics manifest QP-60 signatures [Radioti et al., 2013; Mitchell et al., 2016]. Once such QP-60 magneto-inertial KIRB oscillations are excited, relativistic electrons trapped may leak via cross-field drifts with a QP-60 cadence during a certain phase of magnetic irregularities. For QP-60 bursts or upward injections, relativistic electrons with higher Lorentz factor  $\gamma$  (a few to several tens) gyrate rapidly in beams along magnetic field lines leading to low-frequency radio emissions with characteristic polarizations for the Saturn dipole field. Meanwhile, relativistic electrons of lower  $\gamma$  produce plasma waves and hiss in QP-60 manner. Their energy distribution would follow that within the KIRB before they drift across field lines. Cassini may intercept a fraction of an electron burst, while all electrons in a burst with various pitch angles as they drift across or travel along magnetic field lines may emit radio waves to reach Cassini. Relativistic electrons of KIRB may drift to outer closed magnetic field lines or to polar open field lines at higher latitudes. These field lines generally anchor around two circumpolar zones of Saturn where aurorae manifest. Therefore, Saturn aurorae also frequently show QP-60 features. We expect the escape of relativistic electrons from the two circumpolar and polar regions of Saturn by drifts and diffusions plus QP-60 bursts. Those QP-60 bursts/injections along outer closed magnetic field lines may be recycled into the KIRB for further acceleration and energization, while those along open field lines will escape from the system.

**Acknowledgments.** This research was supported in parts by MOST grant 2014YQ030975, by the NSFC grants 11773019, 11473018, 11073014, 10533020, and 10373009 at Tsinghua University, by the MOST grant 2012CB821800, by the TU-ISR grant 20111081008, and by the Yangtze Endowment, the SRFDP grants, as well as 985 grants from MoE.

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