Bursty Variations of Jovian 6cm Radio Emissions and Quasi-Periodic Jupiter’s Polar Activities

Yu-Qing Lou1, 2, Huagang Song3, 4, 5, Yinyu Liu1, Meng Yang1

1 Physics Department and Tsinghua Centre for Astrophysics (THCA), Tsinghua University, Beijing, 100084, China
2 National Astronomical Observatories, Chinese Academy of Sciences (CAS), A20, Datan Road, Beijing 100012, China
3 Xinjiang Astronomical Observatory, Chinese Academy of Sciences (CAS), Urumqi, Xinjiang 830011, China
4 Graduate University of the Chinese Academy of Sciences (CAS), Beijing 100049, China
5 Key Laboratory of Radio Astronomy, Chinese Academy of Sciences (CAS), Urumqi, Xinjiang 830011, China

ABSTRACT

In reference to Jupiter south polar quasi-periodic 40-50 min (QP-40) activities and the model scenario for global QP-40 oscillations of the Jovian inner radiation belt (IRB), we validate relevant predictions and confirmations by amassing empirical evidence from Ulysses, Cassini, Chandra, Galileo, XMM-Newton, and Advanced Composition Explorer for Jupiter north polar QP-40 activities. We report ground 6cm radio observations of Jupiter by Urumqi 25m telescope for synchrotron intensity bursty variations of the Jovian IRB and show their likely correlations with the recurrent arrival of high-speed solar winds at Jupiter.

Key words: acceleration of particles — magnetohydrodynamics (MHD) — planets and satellites: individual (Jupiter) — radiation mechanisms: non-thermal — solar wind — waves

1 INTRODUCTION

The phenomenology of Jupiter south polar QP-40 activities (including QP-40 bursts of relativistic electrons and of associated low-frequency radio emissions with partially right-hand polarizations) discovered by experiments of Ulysses spacecraft in 1992-1993 (Simppson et al. 1992; MacDowall et al. 1993; McKibben et al. 1993; Zhang et al. 1995) prompted the theoretical model scenario for global QP-40 magneto-inertial oscillations of the Jovian inner radiation belt (IRB) (Lou 2001a; Lou & Zheng 2003 – LZ hereafter) recurrently triggered by the arrival of intermittent high-speed solar winds at the Jovian magnetosphere (Bame et al. 1992, 1993). Variations of solar wind ram pressure stir the IRB and the Jovian sunward magnetosphere at all radii by magnetohydrodynamic (MHD) waves and adjustments, irrespective of specific substructures therein (e.g. Waite et al. 2001; Samsonov et al. 2011; Hakekas et al. 2011). Variations of IRB may be detectable because of its synchrotron radio emissions from relativistic electrons trapped inside. Being an important planetary source of relativistic electrons in the global heliosphere, the Jovian IRB traps relativistic electrons as well as ions and is known to be an intense source of synchrotron radio emissions (Ginzburg & Syrovatskii 1965). Such global QP-40 magneto-inertial oscillations of Jupiter’s IRB may trigger QP-40 circumpolar leakage of relativistic electrons from irregular cusp zones (sandwiched between closed and open magnetic fields) with accompanying low-frequency radio bursts almost along local Jovian magnetic field lines. By this reasoning, the global QP-40 IRB oscillation scenario predicts similar Jovian north polar QP-40 activities but with partially left-hand circular polarizations for north QP-40 low-frequency radio bursts (Lou 2001a; LZ; for circular polarizations of Jovian nKOM, see Kaiser & Desch 1980) as later confirmed by spacecraft observations of Ulysses, Galileo, Cassini, Chandra, XMM-Newton and ACE during the Ulysses distant encounter with Jupiter in 2000-2004 in the north heliosphere (Mennetti et al. 2001; Bolton et al. 2002; Smith et al. 2003; Elsner et al. 2005) and for \( \sim 500 \) km \( \cdot \) hr \( ^{-1} \) at Jupiter estimated in this Letter. This plausible high-speed solar wind stimulated IRB oscillation scenario predicts occasional synchrotron IRB bursty pulsations which may be detectable by ground radio telescopes (Lou 2001a; LZ). We report here 6cm Jovian observations by the 25m Urumqi telescope for IRB bursty variations possibly stimulated by high-speed solar winds at Jupiter using the relevant ACE and ephemeris data. This would offer a valuable diagnostic prospect to coordinate ground and space campaigns in various combinations to observe Jovian IRB dynamics and QP-40 polar activities. In broader contexts of geophysics and astrophysics, this research is pertinent to the dynamics and radiation of Earth/planet magnetospheres (e.g. Wilt 1994) and of pulsar magnetospheres (e.g. Lou 2001b, 2002).
2 KEY FACTS OF JUPITER QP-40 ACTIVITIES

On the way to explore the global heliosphere at high latitudes, Ulysses first reached Jupiter in early Feb 1992. Approaching Jupiter within its magnetosphere and roughly in the ecliptic plane, Ulysses detected QP-15 min radio bursts [panel (a) in fig. 2 and table 2 of MacDowall et al. 1993]. Such QP-15 bursts at frequencies 1-50 kHz, named “Jovian Type III bursts” by their dynamic spectral nature, are pulse-like VLF/LF emissions discovered earlier by Voyager (Kurth et al. 1989). Subsequently outbound from the Jovian south pole at higher latitudes ~ 30 – 40°S, Ulysses unexpectedly intercepted well correlated QP-40 min series bursts of relativistic electrons (with energy $E \gtrsim 8.9$ MeV) as well as other energetic ions detected by the COSPIN (Simpson et al. 1992; McKibben et al. 1993) and of partially right-hand circular radio emissions (frequency $\nu \lesssim 0.7$ MHz – mostly in the range of 1 – 200 kHz) received by the URAP (Simpson et al. 1992; MacDowall et al. 1993; McKibben et al. 1993; Zhang et al. 1995) from the south polar direction. Adjacent bursts are ~ 40 – 50 min apart and each of such radio bursts has a typical emitted power of $\sim 10^8 W$ and lasts ~5 – 10 min [panel (a) in fig. 2 and table 2 of MacDowall et al. 1993; Menietti et al. 2001]. Travelling from the Jovian magnetosphere towards the Sun in the southern hemisphers, Ulysses no longer detected QP-40 relativistic electron bursts but continued to receive several thousands of such QP-40 radio bursts which bear a strong correlation with recurrent high-speed ($\gtrsim 400 – 500$ km s$^{-1}$) solar winds at Jupiter (figs 11 and 12 of MacDowall et al. 1993; Bame et al. 1992, 1993). The source or acceleration of relativistic electrons and QP-40 mechanisms challenge our theoretical and empirical understanding of Jovian QP-40 activities first detected from Jupiter’s south pole.

3 IRB QP-40 MAGNETO-INERTIAL OSCILLATIONS

With a grossly dipolar magnetic field and polar surface field strengths of $\sim 10 – 14.4 G$ (e.g. Hess et al. 2011), Jupiter possesses an IRB in the radial range of $\sim L_{IRB} = 3 – 3.0 R_J$ that traps relativistic electrons with energies up to $\sim 50$ MeV or higher as revealed by intense IRB synchrotron radio emissions in $\sim 2.2 – 90$ cm wave-lengths (e.g. de Pater 1990; Sault et al. 1997; Bolton et al. 2002). A rotating magnetic dipole of Jupiter’s IRB may support magneto-inertial oscillations with periods of $\sim 40 – 50$ min ($n = 0$) and shorter periods for higher harmonics (Lou 2001a). By formula (9) of Lou (2001a) with $n = 1, 2, 3, 4$ therein, the quasi-period ranges are $23 – 30, 18 – 22, 15 – 19, 13 – 17$ min, respectively. These oscillation modes are hybrid, involving rotation and MHD waves in dipolar IRB magnetic fields anchored at Jupiter. Such global IRB pulsations may be triggered by drastic compressions of sunward Jovian magnetosphere due to the recurrent arrival of fast solar winds; the rotating Jovian magnetosphere tends to over-correctate by angular momentum conservation due to the drastic contraction of extended sunward magnetosphere and the inevitable wind speed intermittency leads to IRB MHD adjustments and thus stimulated IRB oscillations (Lou 2001a; see estimates of IRB synchrotron emissions in Sec. 3.2 of LZ). Such global QP-40 IRB oscillations may disturb circumpolar and polar magnetospheric plasmas (e.g. Balogh et al. 1992) in a QP-40 manner in both polar caps of Jupiter. As speculated, those circumpolar zones separating the polar open field and the IRB closed field may release relativistic electrons and ions in irregular segments from the IRB in series of QP-40 bursts as modulated by QP-40 IRB oscillations during certain phases. Jupiter is known to be an important planetary source of relativistic electrons to populate the entire heliosphere (e.g. Nishida 1976; Lou 1996). As the Jovian magnetic field points towards its south pole, out-streaming extremely relativistic electrons gyrate around south field lines with very small pitch angles and emit low-frequency ($\nu \lesssim 0.7$ MHz) beamed radio bursts with partially right-hand circular polarizations (MacDowall et al. 1993; Lou 2001a; LZ). As the Jovian magnetic field points outward from north pole, out-streaming extremely relativistic electrons gyrate around north circumpolar magnetic field lines with very small pitch angles and emit low-frequency ($\nu \lesssim 0.7$ MHz) beamed radio bursts yet with partially left-hand circular polarizations (see Kaiser & Desch 1980 for nKOM). This IRB oscillation scenario may explain why Jovian QP-40 activities correlate with recurrent fast solar winds at Jupiter (MacDowall et al. 1993; Bame et al. 1993; Lou 2001a; LZ). It is crucial to collect more observational evidence to validate this model scenario in pertinent aspects.

4 PERTINENT PREDICTIONS AND CONFIRMATIONS

There are consequences for the scenario of global QP-40 IRB magneto-inertial oscillations stimulated by recurrent high-speed solar winds at Jupiter. We first anticipate similar QP-40 polar activities to also occur around the Jovian north pole (Lou 2001a; LZ). Except for in situ speed measurements near Jupiter, most of our solar wind speeds at Jupiter are inferred from ACE and ephemeris data. We simply assume that a wind speed intercepted by ACE persists. However, complications of MHD wind interactions and solar vari-ations will compromise our wind speed estimates at Jupiter. Our statements should be all qualified in this regard (see fig. 5 of Zieger & Hansen 2008 for uncertainties in wind speed inferences).

For the second “distant encounter” at a distance of ~ 0.8 – 2 AU from Jupiter in Feb 2004, Ulysses observed Jovian radio waves from high to low north latitudes (+80° to +10° Jovicentric latitude) for 6 months (e.g. Smith et al. 2003; Kimura et al. 2008). Two types of QP radio bursts were detected, i.e. quasi-periods shorter or longer than ~ 30 min, and they emerged between ~ 0.4 – 1.4R$J$ above the north pole of Jupiter (Kimura et al. 2008). The Ulysses and ACE data confirmed what we had anticipated for fast solar wind stimulated global QP-40 IRB oscillations to trigger north circumpolar QP-40 bursts of relativistic electrons escaping from the synchrotron IRB and accompanying low-frequency QP-40 radio bursts (Lou 2001a; LZ). Fig 2 of Kimura et al. (2008) shows a refreshing example of QP-40 radio bursts on 7 Feb 2004 from the Jovian north pole (see fig 2 of MacDowall et al. 1993 for comparison); the relevant ephemeris and ACE data of 22 Jan 2004 seemingly confirm an arrival of shocked high-speed $\sim 580$ km s$^{-1}$ solar wind at Jupiter on 7 Feb 2004 for $\sim 6 – 12$ hr (Fig. 2); at this shock front, the upstream wind speed was close to $\sim 690$ km s$^{-1}$. We shall detail this type of combined ephemeris and solar wind data analysis presently for Urumqi 25m telescope 6cm radio observations of Jupiter. Another important supporting evidence comes from four series of QP-40 radio bursts detected by Ulysses on 6 Oct 2003 shown in fig 10 of Elsner et al. (2005); by checking the relevant ACE data of 9 Oct 2003, this case seems to involve a fast solar wind of $\sim 600$ km s$^{-1}$ at Jupiter on 6 Oct 2003 (Fig. 2); the wind was maintained at $\sim 550 – 650$ km s$^{-1}$ for ~1 day. Radio observations (10-20 kHz) of Ulysses during 24 – 26 Feb 2003 together with simultaneous Chandra X-ray observations show no evidence for strong QP-40 oscillations (fig. 10 of Elsner et al. 2005). The pertinent ephemeris and ACE data analysis indicate a likely arrival
wind speed of $\lesssim 500 \text{ km s}^{-1}$ at Jupiter; the wind was maintained at $\sim 430 - 500 \text{ km s}^{-1}$ for $\sim 5$ days (Fig. 2). These cases appear to agree with our anticipation (Lou 2001a; LZ) that north QP-40 radio bursts also correlate with recurrent fast solar winds at Jupiter similar to south polar QP-40 activities. Within the Jovian magnetosphere and by the analogy to what occurred around the south pole, it is most likely (though impossible to verify) that QP-40 bursts of extremely relativistic electrons from Jovian north circumpolar region also accompanied these low-frequency QP-40 radio bursts detected by Ulysses from the north pole (Lou 2001a; LZ). The Jovian magnetic field points outwards from the north pole. QP-40 low-frequency radio bursts beam out from stream-outstreaming extremely relativistic electrons gyrating around magnetic field lines with tiny pitch angles from north circumpolar zones were predicted to give rise to partially left-hand circular polarizations (Lou 2001a; LZ) and this prediction appears now confirmed by Ulysses/URAP observations (Kimura private communications 2010).

5 QP-40 POLAR PULSATIONS OF X-RAY HOT SPOTS

On 18 Dec 2000 (10−20 UT) in support of the Cassini fly-by of Jupiter, the Chandra HRC targeted Jupiter for $\sim 10$ hr and revealed remarkable QP-45 pulsations of X-ray brightness in the hot spot inside the north Jovian auroral oval (fig 3 of Gladstone et al. 2002). For such strikingly similar quasi-periods of $\sim 40−45$ min, this X-ray diagnostics might be supportive to and consistent with global Jovian IRB QP-40 polar activities (Lou 2001a) and associated polar QP-40 magnetospheric oscillations (LZ), and we speculate that QP-40 bursts of relativistic electrons and accompanying left-hand circular low-frequency radio emissions might have emerged from north circumpolar zones during such polar QP-40 X-ray hot spot pulsations. In our scenario, QP-40 IRB oscillations are probably stimulated by the drastic Jovian magnetospheric compression due to high-speed intermittent solar wind; QP-40 IRB magnetic field disturbances may affect adjacent polar open magnetic fields across the oval zones around the poles (Southwood & Hughes 1983). Fast MHD waves or magnetosonic modes may effectively transmit QP-40 MHD disturbances over magnetic polar caps. Thus, global QP-40 IRB oscillations also make polar open magnetic field to pulsate via transmissions of MHD waves across the polar caps by compression and rarefaction of polar field lines and plasmas (Samsonov et al. 2011; Halekas et al. 2011). To buttress this hypothesis, we examined the relevant ephemeris and ACE data of 9 Dec 2000 (Fig. 2) and verified that a persistent $\sim 700 \text{ km s}^{-1}$ solar wind likely arrived Jupiter on 18 Dec 2000 (LZ). On 24-26 Feb 2003, there was another campaign of Chandra, Ulysses radio, HST UV targeting Jupiter (Elsner et al. 2005). Neither 40 hr Chandra X-ray (both north and south) nor 72 hr Ulysses radio (north) data in fig 10 of Elsner et al. (2005) show evidence of QP-40 oscillations. The pertinent ephemeris and ACE data of 10-12 Feb 2003 indicate that during $\sim 3$ days, Jupiter may have encountered relatively slow winds of $\sim 450 - 500 \text{ km s}^{-1}$, XMM-Newton observed Jupiter from 23:00 25 Nov to 12:00 29 Nov 2003 for 245 ks and found no $\sim 45$ min X-ray pulsations (Branduardi-Raymont et al. 2007). The solar wind speed was likely $\sim 400 - 500 \text{ km s}^{-1}$ at Jupiter for 25-29 Nov 2003 by the ephemeris and ACE data. These three contrasting cases of 18 Dec 2000 (Gladstone et al. 2002; LZ), 24-26 Feb 2003 (Elsner et al. 2005) and 25-29 Nov 2003 (Branduardi-Raymont et al. 2007) offer preliminary supporting evidence that QP-40 X-ray pulsations in both north and south poles might possibly correlate with the recurrent arrival of sufficiently fast solar winds at Jupiter. Meanwhile, the combined analysis of Ulysses and ACE data (Fig. 2) on the three cases of 6 Oct 2003, 7 Feb 2004 and 24-26 Feb 2003 may suggest that north partially left-hand circular QP-40 radio bursts likely correlate with the recurrent fast solar winds at Jupiter. By speculative inferences, such partially left-hand circular QP-40 radio bursts from Jupiter north pole should have been produced by QP-40 bursts of extremely relativistic electrons streaming out of north circumpolar regions.

6 URUMQI 6CM RADIO OBSERVATIONS OF JUPITER

The predicted QP-40 synchrotron IRB variations excited and sustained by recurrent fast solar winds at Jupiter may be captured by ground radio telescopes (Lou 2001a; LZ). If firmly established, this would provide observational verification and a strong empirical link for the global IRB QP-40 oscillation scenario and pertinent phenomena of Jovian QP-40 polar activities. Due to the on-and-off nature of Jovian QP-40 polar activities and practical constraints of telescope time allocation, it is only by chance to observe Jupiter’s IRB bursty variations given available times of the 6cm receiver of Urumqi 25m radio telescope. This telescope with a 3m secondary mirror was built in 1991-1993, commenced to operate in Oct 1994, and has been active in international VLBI collaborations and for the Chinese VLBI in the two successful ChangE Moon missions. The antenna was refurbished and calibrated in May 2005 for a higher surface accuracy of $\lesssim 0.4 \text{ mm} (\text{rms})$. The telescope works at 1.3, 2.8, 3.6/13, 6, 18/21, 49, and 92cm with receivers mounted at either primary or secondary focus. The antenna sits at longitude $87.0^\circ 10.67'$ East and latitude $43.28.27'$ North with the track level at 2080.5m above sea level. With the primary focal length of 7m and a pointing accuracy $\lesssim 15''$ (rms) and for the efficient and convenient data reduction, we used the 6cm receiver in both the vertical and horizontal scanning modes with a resolution (HPBW) of $10.066'$. The 6cm receiver remains cooled for a central frequency at $4620\text{MHz}$ or $6.49\text{cm}$ wavelength with a bandwidth of $100-490$ MHz and an antenna efficiency $\sim 52.2\%$.

Radio flux densities were determined with “cross-scans” in both azimuth and elevation, four at each point. This enables us to check the pointing offsets in both coordinates. A Gaussian fit is performed for every subscale. The peak amplitude of such Gaussian fit measures the flux density of each pointing. After applying a correction for small pointing offsets, peak amplitudes of both AZ and EL in one cross-scan are averaged. We next correct the measurements for atmospheric effects and the antenna gain (the elevation-dependent effect), using secondary flux calibrators which are known to show no variations on short timescales, and correct the remaining, systematic time-dependent effects in the measured flux densities. Error bars include subsan errors and those of pointing corrections. Finally, we check our observations against an absolute flux density scale using the primary calibrator quasar 3C286.

The distance range between the Earth and Jupiter is $\sim 4-6 \text{ AU}$ yearly. Jupiter radius $R_J = 7.14 \times 10^7 \text{ cm}$ spans angular sizes of 0.4' to 0.27'. The radial range of Jovian IRB spans $\sim 1.5 - 3.5 R_J$ at 6.1cm (fig. 5 of de Pater 1990). Thus, the beam of 25m telescope completely covers Jupiter and IRB together for 6cm emissions. As Jupiter rotates in $\sim 10$ hr period, the mean intensity variation can be detected as in Figs. 1, 3, 4 and 5 (also fig. 1 of de Pater 1990). Depending on seasonal, weather and local conditions, we can track Jupiter for $\sim 5 - 9$ hrs daily.

On 1 Jan 2009, we observed Jupiter using the 6cm receiver of Urumqi 25m telescope. Shown in Fig. 1, bursty flux inten-
sity variations with ~20-40 min timescales (a mean timescale of ~22 min) We also show the stable radio flux density of planetary nebula NGC 7027 as the control calibrator. Using the pertinent ACE data (see Fig. 2), we show below that this epoch may coincide with a rapid rise of solar wind speed at Jupiter from ~290 km s\textsuperscript{-1} up to ~550 km s\textsuperscript{-1} and a sustained solar wind speed > 500 km s\textsuperscript{-1} thereafter for ~1 day. By the ephemeris, the distance from the Sun to Jupiter is 5.1129AU in Jan 2009. For a solar wind speed of ~550 km s\textsuperscript{-1}, this wind stream left the Sun 16.09 days earlier on 16 Dec 2008 when the longitude of Jupiter is 302.32\textdegree relative to the Equinox. On 2008-12-16, the Earth is at 0.984 AU from the Sun with a longitude 84.77\textdegree relative to the Equinox and an orbital speed of 1.08 km s\textsuperscript{-1} per day. For such an isolated fast wind stream to persist to several solar rotations as evidenced by the ACE data of several months, this wind stream would reach the Earth 15.0 days later for a solar rotation period of ~27 days (e.g. Lou 1987), i.e. early on 2008-12-31. From the ACE data, the solar wind speed is ~550 km s\textsuperscript{-1} on 2008-12-31 noon (Fig. 2). The explicit analysis here serves as an example; all cases of our solar wind speed estimates at Jupiter are performed in the same spirit (more documentation of the ACE SWEPAM level 2 data can be found at the website http://www.srl.caltech.edu/ACE/ASC/level2/swepam_j2desc.html).

For the 6cm Jupiter observation at Urumqi on 19 Jan 2008 in Fig. 3, we examined the relevant ACE data of 20 and 21 Jan 2008. On 19 Jan 2008, Jupiter encountered a fast wind of ~580 km s\textsuperscript{-1} and had a longitude of 273.20\textdegree relative to the Equinox; this same wind stream was intercepted by ACE between late 20 and before 21 Jan 2008 (Fig. 2). As this wind was launched from the Sun in early 3 Jan 2008, the Earth longitude was ~102.05\textdegree relative to the Equinox. The mean intensity of Jupiter was ~4.05 Jy and there were 4 bursts relative to the mean Jovian spin variation and the stable control calibrator quasar 3C286. The 6cm data on 20 Jan 2008 (Fig. 4) also indicated bursty features while the flux control calibrator quasar 3C286 remained stable. The ACE data of 21 Jan 2008 indicate that Jupiter on 20 Jan 2008 in Fig. 2 also encountered a ~550 km s\textsuperscript{-1} solar wind which was later intercepted by ACE early 2008. This wind speed pattern persisted recurrently and can be identified in Dec 2007 and Feb 2008.

We also observed Jupiter at Urumqi on 5 and 15 Dec 2008 for ~6 and ~6.5 hrs, with quasar 3C286 as control calibrator (see Fig 5). Our 6cm data show slow variations of Jovian 10 hr rotation but no QP bursts, and the pertinent ACE data indicate arrival wind speeds < 460 km s\textsuperscript{-1} at Jupiter for these two cases.

7 SUMMARY AND CONCLUSIONS

We advanced the model scenario for global QP-40 IRB magneto-inertial oscillations excited by the dramatic compression of sunward solar wind which was later intercepted by ACE toward the Sun 16.09 days earlier on 16 Dec 2008 when the longitude of Jupiter is 302.32\textdegree relative to the Equinox. Between 5 and 8 hrs, eight radio flux density peaks emerge, giving a mean timescale of ~22 min.

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Figure 1. Observations of Jupiter on 1 Jan 2009 by the Urumqi 25m radio telescope with the 6cm receiver and of the stable control calibrator planetary nebula NGC 7027. The abscissa is UT in hrs. Between 5 and 8 hrs, eight radio flux density peaks emerge, giving a mean timescale of ~22 min.
Jupiter Bursty Radio Emissions Observed at Urumqi

Figure 2. Pertinent ACE solar wind speed data for cases of 18 Dec 2000, 24-26 Feb 2003, 24-26 Feb 2003, 6 Oct 2003, 25-29 Nov 2003, 7 Feb 2004, 19-20 Jan 2008, and 1 Jan 2009 from top to bottom.

Figure 3. Observations of Jupiter on 19 Jan 2008 by the Urumqi 6cm receiver for 4 major peaks and of the stable quasar 3C286 as the flux calibrator with errors. The 4 major consecutive peaks are separated by 45, 50 and 73 min. The ∼10 hr mean Jovian rotational variation can be discerned. The ephemeris and ACE data for 20 Jan 2008 (Fig. 2) indicated a likely sustained high-speed solar wind of ∼600 km s⁻¹ for ∼1 day.

Figure 4. Observations of Jupiter on 20 Jan 2008 by Urumqi 6cm receiver with several major peaks and of the stable quasar 3C286 as the flux calibrator with errors. The radio peak time separations are 48, 30, 47, 44, 26, and 32 min (left to right). By the ephemeris and ACE data of 21 Jan 2008 (Fig. 2), there was a likely sustained solar wind of ∼550 km s⁻¹ for ∼1 day.

Figure 5. Urumqi 6cm observations of Jupiter on 15 Dec 2008 and of the stable 3C286 as the flux calibrator. By the ephemeris and ACE data, there was a likely sustained solar wind of <440 km s⁻¹. The case of 5 Dec 2008 is similar to this case with a likely wind speed <460 km s⁻¹.

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