Detection of ionospheric perturbation due to a soft gamma ray repeater SGR J1550-5418 by very low frequency radio waves

Sushanta K. Mondal · Sandip K. Chakrabarti · Sudipta Sasmal

Abstract We wish to report our observations of ionospheric disturbances made by incident Gamma Rays from the Soft Gamma Repeater SGR J1550-5418 which took place on 22nd of January, 2009. The observations were made by a loop antenna and a Gyrator-II type receiver which was tuned to the 500KW VTX station transmitting Very Low Frequency (VLF) signal at 18.2 kHz. We looked for signatures of sudden ionospheric disturbances (SID) which commenced within seconds of the observations reported by various satellites. We used Long Wave Propagation Capability code to compute the changes in the ionospheric parameters due to the repeated passage of the high energy radiation. We detected seventy six events in our VLF detector which appear to be associated with the SGR J1550-5418. We found that 28 of them are within three seconds of the satellite observations and 38 (fifty percent) of them are within seven seconds of the satellite observations. We also compute the evolution of the electron number density of the ionosphere due to this events and found that the ionosphere was becoming increasingly charged due to repeated bombardment of the high energy radiations. The lower ionospheric height went down significantly. We found convincing evidence that the source SGR J1550-5418 repeatedly caused ionospheric disturbances on the 22nd of January, 2009. The electron number density went up significantly at all the heights. The height of the lower ionosphere went down by about 15 km due to these repeated events.

Keywords Observational 1 · Magnetars 2 · Gamma-ray burst 3

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1 Introduction

The ionosphere of the earth can be thought of as a gigantic detector which responds to the ionizing agents be they terrestrial or extra-terrestrial. Sudden Ionospheric Disturbances (SIDs) by auroral precipitations (Cummer et al. 1997), lighting discharges (Inan and Carpenter 1987), Solar flares (Mitra 1975) are known to have been detected by observations of Very Low Frequency (VLF) signals. A case of very bright soft gamma ray repeater (SGR) SGR 1806-20 that erupted in 2004 (Inan et al. 2007) and another not so bright one SGR 1900 + 14 which erupted in 1998 (Tanaka et al. 2008) have been reported in the literature. Similarly, Fishman and Inan (1988) reported VLF signal perturbations due to Gamma Ray Bursts (GRBs). These events lasted for a few seconds to tens of minutes depending on the energy of the impinging radiation on the ionosphere. These events are very exciting as they are located very far away and yet affect the ionosphere as they are intrinsically energetic. There are several dedicated space missions such as RHESSI to monitor solar X-ray and gamma-ray activities and Swift, Suzaku, FERMI to observe X-ray and gamma-ray activities of extra-terrestrial compact sources such as black holes, neutron stars, soft gamma-ray repeaters (SGRs) and gamma-ray bursts (GRBs). While the ionosphere is open to all types of perturbations of terrestrial and extra-terrestrial origin and thus the signals from multiple types of events are easy to be confused and perhaps difficult to identify, the observations of the satellites can help us identify the events.

Brown (1973) modeled the X-ray and γ-ray transport in a model atmosphere. With a burst energy flux of 3×10^{-4} erg/cm^2 over a range of 11–800 keV, it was found that approximately 85 eV cm^{-3} was deposited at an altitude of 28 km, at zenith angle 0°, which could produce 2–3 electrons cm^{-3}. At that altitude, the only competing ionizing process is cosmic rays. Observations at low geomagnetic latitudes are preferable, where the ionization induced by galactic cosmic rays would be of lower intensity than that produced by the X-ray or Gamma-ray events. Since Indian Centre for Space Physics (ICSP) is located at ∼22 °N, the observing condition for SIDs is favorable.

In one of the most exotic cosmic events in the recent history, a soft gamma-ray repeater AXP 1E1547.0-5408/SGR J1550-5418 (Camilo et al. 2008; Halpern et al. 2008) erupted hundreds of times on January 22nd, 2009 (Gronwall et al. 2009; Connaughton and Briggs 2009; Savchenko et al. 2009; Terada et al. 2009; Bellm et al. 2009). It recurred again on the 25th and 29th of January, 22nd of February and 22nd of March, 2009 (Golenetskii et al. 2009a, 2009b, 2009c; Del Monte et al. 2009). Repeated bursts of radiation from this object bombarded the ionosphere and caused the so-called sudden ionospheric disturbances (SIDs). In the present paper, we shall describe the results of the observations of the VLF receiver of ICSP which observed and reported the first observation of this object through VLF perturbation (Chakrabarti et al. 2009a, 2009b, 2010a, 2010b; Mondal and Chakrabarti 2010). After each significant energy deposition, the signal showed fast rise and exponential decay or FRED type behavior. The coincidence of so many VLF events gives an indications that the energy release is much lower (∼1 keV or less) than what is reported in the X-ray observational results through satellites.

In Sect. 2, we present a summary of the satellite observations of SGR J1550-5418. In Sect. 3, we present our observational setup and the location of the source vis-a-vis ICSP receiver. In Sect. 4, we present the observed results and analysis of the results. Finally, in Sect. 5, we make concluding remarks.

2 Summary of the satellite observations of SGR J1550-5418

On 22nd of January, 2009, the Anomalous X-ray Pulsar AXP 1E1547.0-5408/SGR J1550-5418 triggered the detectors in several satellites. Swift Burst Alert Telescope (BAT) first detected short bursts of radiation having characteristics of Soft Gamma Repeaters (Gronwall et al. 2009). The peak count rate varied from ∼30,000/sec to 170,000/sec in 15–350 keV range. Fermi Gamma-Ray Burst Monitor (GBM) also saw at least 31 triggers at least up to 100 keV (Connaughton and Briggs 2009; von Kienlin and Connaughton 2009). Savchenko et al. (2009) reported that the SPI Anti-Coincidence System (ACS) aboard INTEGRAL observed 167 bursts above 50 keV in a period of ∼10 hours having count rates of 10^4–10^6/sec. Terada et al. (2009) reported results of the Wide-band All-sky Monitor (WAM) which covers an energy range of 50 keV to 5 MeV. They detected about 250 bursts in a period of 24 hours. Bellm et al. (2009) reported series of bursts through RHESSI at least up to 400 keV. Golenetskii et al. (2009a, 2009b, 2009c) reported several triggers in Konus-Wind observation. The spectra of most bursts were well fitted by a power-law cut-off having exponential tail peaking near 25–35 keV. The characteristics were seen to be similar to the SGR 1627-41 (Mazets et al. 1999). Subsequently, Konus-Wind also observed numerous short bursts in soft X-rays. Kaneko et al. (2009) made a thorough study of the spectral and timing properties of the events and found a pulsation at a period of 2.07 s, typical of a spinning magnetar. Golenetskii et al. (2009a, 2009b, 2009c) reported recurring of the events on 25th of January, 2009. It is to be noted that a quiet Sun has a radiation flux in soft X-rays at a C-level (10^{-6} Watt/m^2) of about 2000 cm^{-2} sec^{-1} at 3–6 keV range. In comparison, Swift BAT telescope, with an effective collecting area of about 1500 cm^2 obtained a photon flux of ∼20–100 cm^{-2} sec^{-1} in 15–300 keV. Thus the photon flux from SGR is strong enough to cause perturbation in the ionosphere.

3 ICSP VLF observation

ICSP has been monitoring VLF signals from the Indian Navy Station VTX (18.2 kHz) located at 8.387 °N, 77.753 °E since 2002 primarily for studies relating to seismic events and solar flares and their effects on ionospheres (Chakrabarti et al. 2005; Sasmal and Chakrabarti 2009; Chakrabarti et al. 2010a, 2010b; Ray et al. 2011). The receiver is a Gyrator-II type and the antenna is a loop type. The data was automatically logged in a computer and sampling rate was four sample per second. The data quality was good at the location of the antenna. On 22nd of January, 2009, when the Anomalous X-ray Pulsar AXP 1E1547.0-5408/SGR J1550-5418 triggered the detectors in several satellites, ICSP receivers made the first detection in VLF. It was possible because the object was in the visible sky of ICSP and the VTX-ICSP propagation path was in the night side of the terminator. At the location of receiver (22.583 °N, 88.417 °E), the night time signal is expected to be stronger as compared to that in the daytime (Chakrabarti et al. 2011). The usual signal was perturbed several tens of times and showed fast rise and exponential decay (FRED) type signals. Brief mentions of these observations have been made in Chakrabarti et al.

Fig. 1 The hemisphere of the Earth in which we showed the locations of the VTX transmitting station, ICSP receiving station, the day-night terminator and the location of the sub-event point when the first detection of the flare took place. At subsequent flaring, both the terminator and the sub-flare point moves left as the Earth rotates

(2009a, 2009b, 2010a, 2010b) and Mondal and Chakrabarti (2010). Below we present detailed results of our observations.

4 Observed VLF signals and their analysis

In Fig. 1, we show the illuminated half of the Earth's surface when the flare began. As the VTX-ICSP path was at the night side of the terminator, the signal strength was higher and the signal was more sensitive to ionospheric perturbations. During this early phase of flaring ICSP has a better data and these were the first VLF data reported in GCNs (Chakrabarti et al. 2009a, 2009b, 2010a, 2010b). As the flare progresses, the sub-flare point moves left and eventually was over southern American sky when the SAVNET workers observed the flare with a different type of instruments (Tanaka et al. 2010). In Fig. 2(a–b) we show a few samples of the effects of the repeated bursts in our data after background subtraction. Figure 2a begins at 01:14:10 UT and Fig. 2b begins at 02:29:10 UT. Though the data was a bit noisy as our antenna was smaller, the fast rise and exponential decay shape of each signal can be identified beyond 3σ level. We superposed on these figures the times of the triggers by the Satellites (t_S) whenever they are available (not all satellites gave precise time but a time slot in which several triggers were recorded) and the time of the estimated VLF trigger (t_V). There is an obvious uncertainty in identifying t_V due to random electronic noise built into the circuit which gives an uncertainty of $\sim$1 s. Further more, there are ionization and simultaneous recombination effects associated

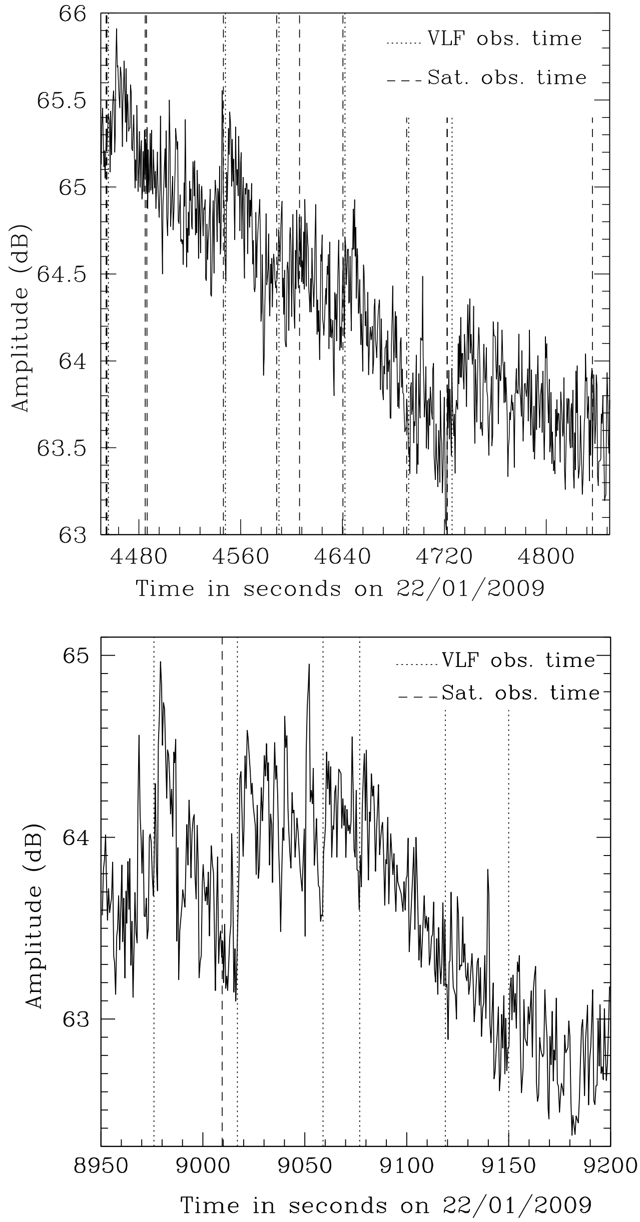

Fig. 2 Two examples of the VLF events associated with SGR J1550-5418 as observed by our antenna. Superposed are the assumed VLF trigger time and the satellite trigger time (if available)

with the impulsive radiation. The latter causes a further delay of $\Delta t_{\max} = \frac{1}{2\alpha N_{\max}}$ between the time of the satellite trigger and the time when VLF signal has the peak (e.g. Zigman et al. 2007). In most of our observation, we do see that the VLF trigger lags the Satellite trigger. In Fig. 3, we provide a statistical analysis by plotting the ratio of events with $dt = t_V - t_s > 0$ (N_+) and $dt < 0$ (N_-) as a function of the dt. We find that the number of events with $\sim$1 s lag is five times larger for $dt > 0$ than for $dt < 0$. In fact, the width at the half maximum is only 3 s. For fifty percent of the events $dt > 0$ was found to be less than 7 s. This shows that our estimations of the VLF triggering of events were generally ac-

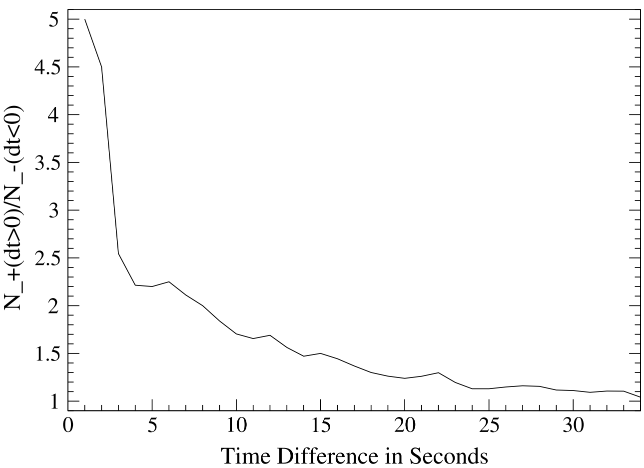

Fig. 3 A statistical analysis of the observed signals. The ratio of events with $dt = t_V - t_s > 0$ and $dt < 0$ is shown as a function of dt. We observe that the width at full maximum is 3 s while fifty percent of the events occur at $dt \sim 7$ s. Thus the VLF data mostly lags the satellite data due to recombination process in the ionosphere

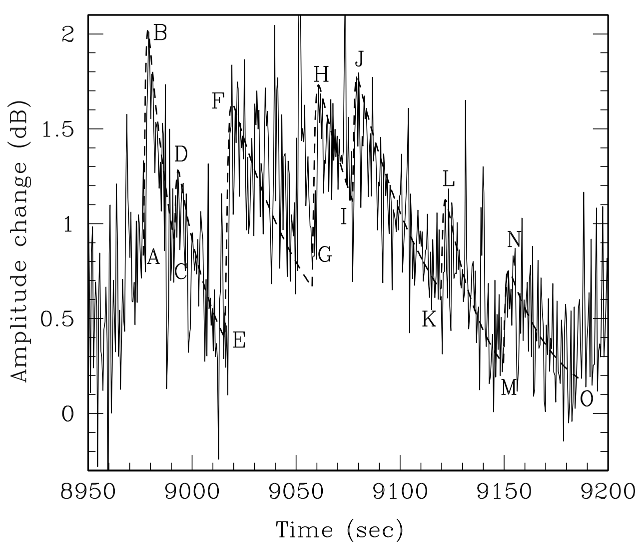

Fig. 4 An example of fitting several observed signals with Fast Rise and Exponential Decay (FRED) type curves (*dashed*) which are due to the quick response of the ionosphere to the flares and subsequent slow decay due to the recombination of the ions. Ionospheric electron densities are computed at points marked by the English alphabets

curate and that our association of these with the high energy events is correct. We believe that the events with apparent $dt < 0$ had difficulty in pinpointing the precise triggering time of the VLF signal.

In order to study the effects of Soft Gamma Ray Repeater on the ionosphere, we first fit the time variation of the flux $F(t)$ of each of the events with a fast rise and exponential decay (FRED) signal shape given by the flux variation (Kocevski et al. 2003):

$$F(t) = F_m \left(\frac{t}{t_m}\right)^r \left[\frac{d}{d+r} + \frac{r}{d+r}\left(\frac{t}{t_m}\right)^{(r+1)}\right]^{-(r+d)/(r+1)},$$

where, F_m is the maximum flux at t_m, r and d are the rising and decaying indices, respectively. We plot the signal and the fit in Fig. 4. The decay constant of about 7 s gives the typical recombination time of the ions in the lower ionosphere. The edges of the fits are indicated by English alphabets. The fast rise and exponential decay (FRED) type events are characteristics of sudden irradiations of UV and soft X-rays. These indicate that the source was considerably strong in softer radiations.

We use the Long Wave Prediction Capability (LWPC) code (Ferguson 1998) to fit the signal strength with the model to obtain the information of the so-called h and β parameters of the ionosphere. We obtain two important parameters from these, namely, how the height of the ionosphere changes with the signal amplitude and how the electron number density changes at the onset of each event. In Fig. 5(a–b) we present the variation of the height of the lower ionosphere. The alphabets correspond those in Fig. 4. We note that the height of the ionosphere does not fully recover when a certain flare decays and on an average goes down steadily due to repeated bombardment of the events. Similarly, the electron number density at a height of 80 km continues to go up as the next flare begins before the complete recombination of the excess ions and electrons.

In order to study the effect of the flares on the ionosphere as a whole, we computed the electron density enhancement at each height due to the flares. With the arrow in Fig. 6 we indicated how the height variation of electron density changes with time. Here too it is clear that even before the ionosphere returns back to a 'pre-flare' state, a new flare raises its number density. This happens at all the heights simultaneously.

5 Concluding remarks

Soft Gamma-Ray repeaters are enigmatic objects as they are believed to be originated from neutron stars having extremely strong magnetic fields. The immense energy release at a great distance is capable of 'burning' the ionosphere of the Earth. The ionosphere, though a noisy detector having poor or no directionality, is as big as the size of the earth and is always active without any maintenance cost. Thus it is of great important to detect celestial events using this gigantic detector, as the response of the detector would give away information about the nature of the detector itself. So far, only a handful of such extremely rare events have been detected. Most certainly our first VLF observation of the series of flaring events is an important addition.

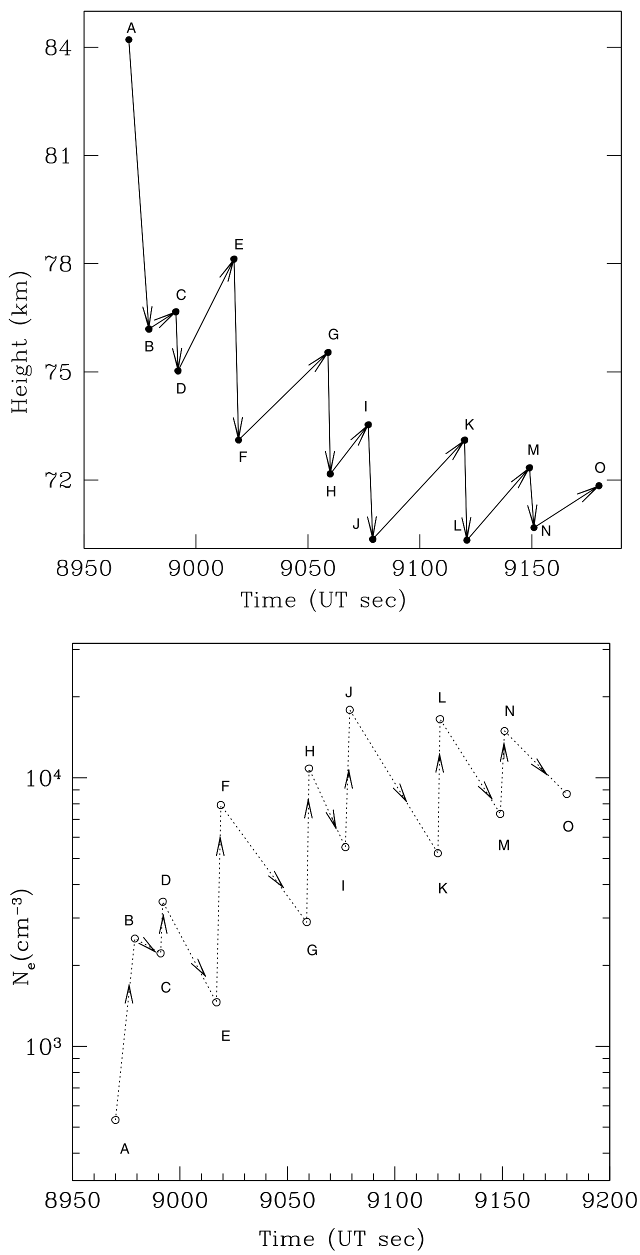

Fig. 5 Variation of the (**a**) height of the lower ionosphere and (**b**) the electron number density at a height of 80 km at each point of the events marked by the English alphabets in Fig. 4. We note that the height of the ionosphere does not fully recover when a certain flare decays and on an average, the electron number density continues to go up due to repeated bombardments

We have observed seventy six events especially before the sunrise, since after the sunrise the signal is attenuated along the VTX-ICSP propagation path. This is the first time that so many events have been detected through VLF observations of a single system. The estimated VLF triggering time generally lags behind the satellite observation time which is what is expected. We fitted each event flux variation with a FRED type signal and found that the signal decays with a time scale of about seven seconds. Most interestingly we found that the height of the lower ionosphere hardly gets time to relax to a pre-flare height due to the repeated bombardments of the X-rays and gamma rays from this object. A similar behavior is observed for the electron number density as well. Since the lower ionosphere is known to respond to soft X-rays, observation of so many events clearly indicate the presence of a large amount of soft X-rays in the spectrum.

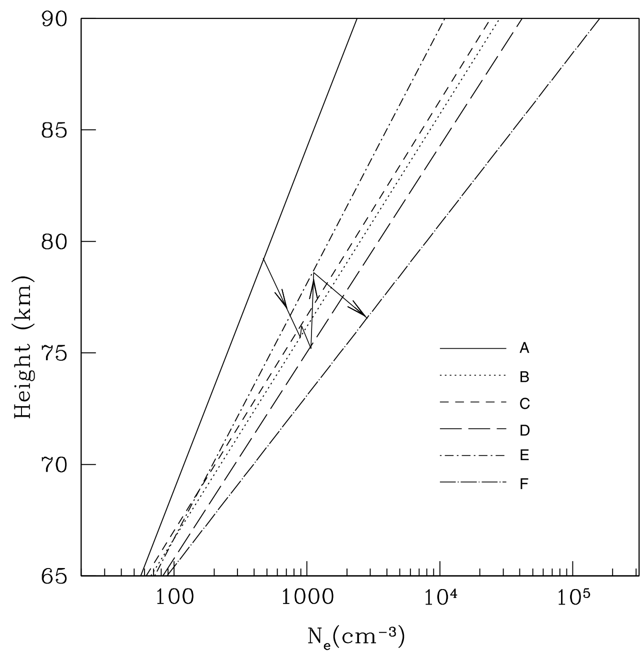

Fig. 6 Variation of the electron number density as a function of height during the events shown in Fig. 4. We note that at all heights the electron number density behaves similarly and on an average it goes up with time

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References

Bellm, E., Smith, D.M., Hurley, K.: GCN 8857 (2009)
Brown, R.T.: Nature **246** (1973)
Camilo, F., Reynolds, J., Johnston, S., et al.: Astrophys. J. **679**, 681 (2008)
Chakrabarti, S.K., et al.: Indian J. Radio Space Phys. **34**, 314–317 (2005)
Chakrabarti, S.K., Mondal, S.K., et al.: GCN 8881 (2009a)
Chakrabarti, S.K., Mondal, S.K., Sasmal, S.: GCN 9315 (2009b)
Chakrabarti, S.K., Sasmal, S., Chakrabarti, S.: Nat. Hazards Earth Syst. Sci. **10**, 1751 (2010a)
Chakrabarti, S.K., Mondal, S.K., Sasmal, S., et al.: Indian J. Phys. **84**(11), 1461–1466 (2010b)
Chakrabarti, S.K., Mondal, S.K., Pal, S., et al.: Ind. J. Phys. (2011). doi:10.1007/s12648-012-0070-x

Connaughton, V., Briggs, M.: GCN 8835 (2009)
Cummer, S.A., Bell, T.F., Inan, U.S., Chenette, D.L.: J. Geophys. Res. **102**, 7477–7484 (1997)
Del Monte, E., Evangelista, Y., Feroci, M.: GCN 9014 (2009)
Ferguson, J.A.: Computer programs for assessment of long-wavelength radio communications, ver. 2.0, Technical document 3030, Space and Naval Warfare Systems Center, San Diego (1998)
Fishman, G.J., Inan, U.S.: Nature 331 (1988)
Golenetskii, S., et al.: GCN 8851 (2009a)
Golenetskii, S., Aptekar, R., et al.: GCN 8863 (2009b)
Golenetskii, S., Aptekar, R., Mazets, E., et al.: GCN 8913 (2009c)
Gronwall, C., Markwardt, C.B., Stamatikos, M.: GCN 8833 (2009)
Halpern, J.P., Gotthelf, E.V., Reynolds, J., et al.: Astrophys. J. **676**, 1178 (2008)
Inan, U.S., Carpenter, D.L.: J. Geophys. Res. **92**, 3293–3303 (1987)
Inan, U.S., Lehtinen, N.G., Moores, R.C., et al.: Geophys. Res. Lett. **34**, L08103 (2007)
Kaneko, Y., Gogus, E., Kouveliotou, C., et al.: APJ **710**, 1335 (2009)
Kocevski, D., Ryde, F., Liang, E.: Astrophys. J. **596**, 389 (2003)
Mazets, E.P., Aptekar, R.L., Butterworth, P.S., et al.: Astrophys. J. **519**, L151 (1999)
Mitra, A.P.: J. Atmos. Sol.-Terr. Phys. **37**, 805–913 (1975)
Mondal, S.K., Chakrabarti, S.K.: AIP Conf. Proc. **1286**, 311–330 (2010)
Ray, S., Chakrabarti, S.K., Mondal, S.K.: Nat. Hazards Earth Syst. Sci. **11**, 2699–2704 (2011)
Sasmal, S., Chakrabarti, S.K.: Nat. Hazards Earth Syst. Sci. **9**, 1403–1408 (2009)
Savchenko, V., Beckmann, V., Neronov, A., et al.: GCN 8837 (2009)
Tanaka, Y.T., Terasawa, T., Yoshida, M.: J. Geophys. Res. **113**, A07307 (2008)
Tanaka, Y.T., Raulin, J.P., Bertoni, F.B., et al.: Astrophys. J. Lett. **721**, L24 (2010)
Terada, Y., Tashiro, M., Urata, Y., et al.: GCN 8845 (2009)
von Kienlin, A., Connaughton, V.: GCN 8838 (2009)
Zigman, V., Grubor, D., Sulic, D.: J. Atmos. Sol.-Terr. Phys. **69**, 775–792 (2007)