FAST TRACK PAPER

The SGR 1806-20 magnetar signature on the Earth's magnetic field

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SUMMARY

SGRs denote 'soft γ-ray repeaters', a small class of slowly spinning neutron stars with strong magnetic fields. On 2004 December 27, a giant flare was detected from magnetar SGR 1806-20. The initial spike was followed by a hard-X-ray tail persisting for 380 s with a modulation period of 7.56 s. This event has received considerable attention, particularly in the astrophysics area. Its relevance to the geophysics community lies in the importance of investigating the effects of such an event on the near-Earth electromagnetic environment. However, the signature of a magnetar flare on the geomagnetic field has not previously been investigated. Here, by applying wavelet analysis to the high-resolution magnetic data provided by the CHAMP satellite, a modulated signal with a period of 7.5 s over the duration of the giant flare appears in the observed data. Moreover, this event was detected by the energetic ion counters onboard the DEMETER satellite.

Key words: geomagnetic field, magnetar, wavelet analysis.

1 INTRODUCTION

SGRs (soft γ-ray repeaters) are galactic X-ray stars that emit, during sporadic times of high activity, a large number of short-duration (around 0.1 s) bursts of hard X-rays (Duncan & Thompson 1992). A SGR is thought to be a magnetar, being a strongly magnetized neutron star powered by a very strong magnetic field ($\geq 10^{15}$ Gauss). On 2004 December 27 a powerful burst of X- and γ-rays from one of the most highly magnetized neutron stars (SGR 1806-20) of our Galaxy reached the Earth's environment (Hurley *et al.* 2005). The Solar system received a shock, which is thought to be due to a cataclysm in the magnetar that caused it to emit as much energy in two-tenths of a second as the Sun gives off in 250 000 yr. The signature of this event on the Earth's magnetic field has not previously been investigated. Here, we present the first results of the magnetar footprints on magnetic data recorded by near-Earth satellites. The magnetar SGR 1806-20 is the third such event ever recorded along with two others that were noted in 1979 and 1998 (Mazets *et al.* 1979; Hurley *et al.* 1999).

Several properties of this magnetar flare are relevant to our study. Firstly, a precursor of ~1 s was observed 142 s before the flare, with a roughly flat-topped profile (Hurley *et al.* 2005). The intensity of the main initial spike saturated all X- and γ-ray detectors. However, particle detectors on board of RHESSI and Wind spacecraft (Boggs *et al.* 2004; Mazets *et al.* 2004) were able to record reliable measurements. Several instruments designed for other purposes provided important information, as Geotail (Terasawa *et al.* 2005) and Cluster/Double star (Schwartz *et al.* 2005). The first spike was followed by a tail lasting 380 s, during which 7.56 s pulsations

were clearly observed, by the γ-ray detectors on board of RHESSI (Hurley *et al.* 2005).

Secondly, a disturbance of the Earth's ionosphere was simultaneously observed with the detection of the burst from SGR 1806-20 (Inan *et al.* 2005). This sudden ionospheric disturbance (SID) was recorded as a change in the signal strength from very low-frequency (VLF) radio transmitters, being noticed by stations around the globe (Campbell *et al.* 2005). These changes in the radio signal strength were caused by X-rays arriving from SGR 1806-20, which ionized the upper atmosphere and modified the radio propagation properties of the Earth's ionosphere (see clearing house of SID data associated with SGR 1806-20 flare at http://www.aavso.org/observing/programs/solar/sid-sgr1806.shtml). One such observation of this ionospheric signature resides within a 21.4 kHz signal that originates in Hawaii and propagates along an ionosphere waveguide to Palmer Station, Antarctica (Inan *et al.* 2005). This waveguide is some ~10 000 km in path length (Inan *et al.* 2005). As explained above, this is not a direct radio detection of SGR 1806-20 (see also http://gcn.gsfc.nasa.gov/gcn3/2932.gcn3). Moreover, due to the subburst longitude and latitude (Inan *et al.* 2005) and to the geographical distribution of LF/VLF beacons and monitoring stations, this burst was not detected by active monitoring stations in Germany, Australia, or Canada (Campbell *et al.* 2005). Here, we note that ionospheric disturbances were also reported in the case of the magnetar observed in 1998 (Inan *et al.* 1999). In the case of the 1998 magnetar the flare illuminated the nightside of the Earth and ionized the lower ionosphere to levels usually found only during daytime. The magnetar responsible for the 2004 burst was about the same distance

as the magnetar responsible for the 1998 burst, but within 5.25° of the Sun as viewed from Earth. Therefore its γ-rays arrived on the dayside of our planet. The 2004 flare changed the ionic density at an altitude of 60 km by six orders of magnitude (Inan 2006). It is thus plausible that this change in the ionospheric conductivity can cause oscillating perturbations in the current-generated magnetic field.

The thrust of this study is to find signatures associated with the explosion of the magnetar SGR 1806-20 within satellite measurements of Earth's electromagnetic field. Currently, the Earth's electromagnetic field is monitored by a number of low-Earth orbit (LEO) satellite missions. After the launch of Ørsted satellite in 1999, the knowledge of the near-Earth electromagnetic field has been dramatically improved (Hulot *et al.* 2002; Lühr *et al.* 2002; Maus *et al.* 2002; Tyler *et al.* 2003; Balasis *et al.* 2004). Since 2000, Ørsted, CHAMP and SAC-C satellites have offered a continuous flow of high-quality magnetic field measurements. Additionally, the DEMETER satellite provides 1 Hz energetic electron detector data. Finally, let us note that all these LEO magnetic missions are flying between the Earth's surface, where the temporal variations of the magnetic field are continuously monitored by geomagnetic observatories, and the magnetosphere, where an *in-situ* investigation of the 3-D and time-varying phenomena is done by the four identical spacecraft of Cluster II mission.

2 DATA PROCESSING

We have considered Ørsted (25 Hz scalar data), CHAMP (50 Hz vector data), and SAC-C (20 Hz vector data) satellite magnetic data, as well as the 1 Hz data from DEMETER satellite energetic electron detector. The giant flare occurred during a time span characterized by $k_p = 3$- and $D_{st} = -17$ nT, that is, indicating conditions of low geomagnetic activity. All available magnetic and electric field data recorded during the giant flare were analysed using wavelet methods (Alexandrescu *et al.* 1995; Balasis *et al.* 2005).

The advantage of analysing a signal with wavelets is that it enables the study of very localized features in the signal (Kumar & Foufoula-Georgiou 1997). Owing to its unique time–frequency localization, wavelet analysis is especially useful for signals that are non-stationary, have short-lived transient components, have features at different scales or have singularities, as in the case of the signal due to magnetar SGR 1806-20. The basic idea can be understood as a time–frequency plane that indicates the frequency content of a signal at every time. The decomposition pattern of the time–frequency plane is predetermined by the choice of the basis function. In the present study, we used the continuous wavelet transform with the Morlet wavelet as the basis function. The results were checked for consistency using the Paul and DOG mother functions (Torrence & Compo 1998).

3 RESULTS

In order to find convincing evidence of a causal link between the SGR 1806-20 flare and the response of the near-Earth electromagnetic field, data provided by four satellites orbiting the Earth around the time of the flare were analysed. The tracks of these satellites, with direction of flying and the position of the flare centre (Umrad Inan, personal communication 2006), are indicated in Fig. 1. During the time of the event, both the Ørsted and CHAMP satellites were flying over polar regions. The magnetic field measurements during the giant flare from the SGR 1806-20 are thus expected to be dominated by the polar current systems. This was indeed the case for the Ørsted satellite data.
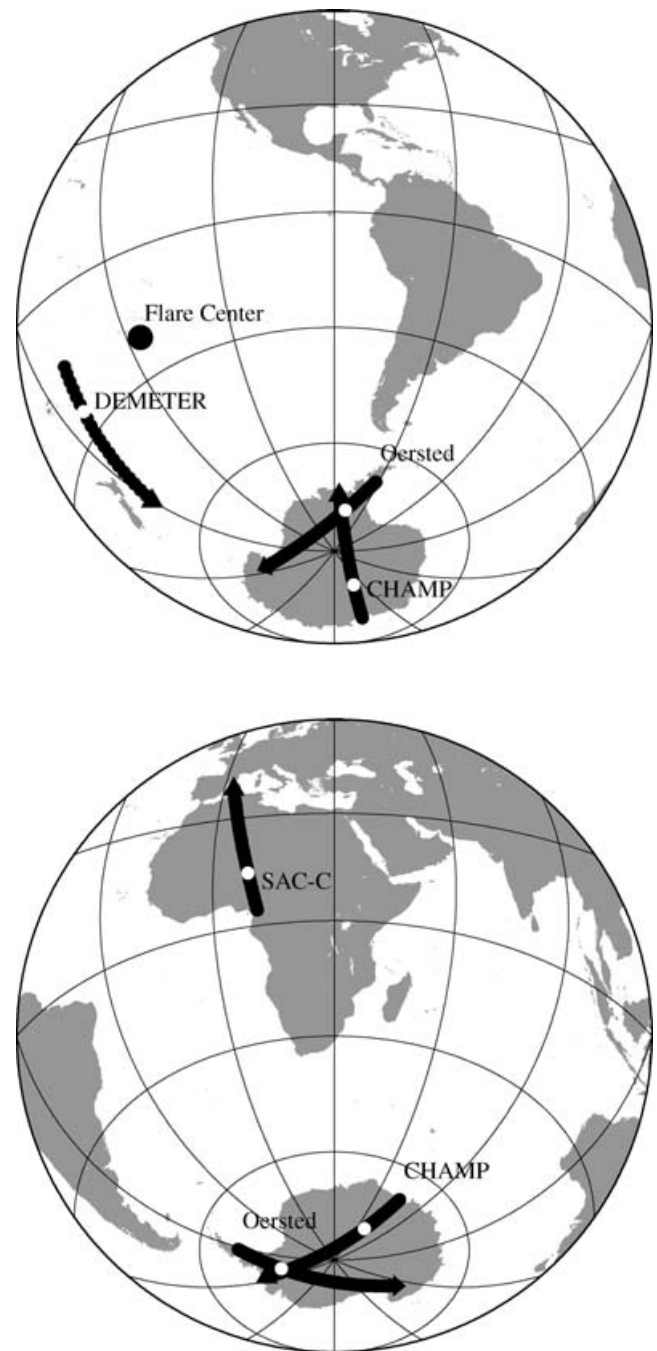
Figure 1. The position of CHAMP, Ørsted, SAC-C and DEMETER satellites on 2004 December 27 (21.46–21.62 UT). The position of each satellite at the time of the outburst (21:30:26 UT) of the flare from SGR 1806-20 is noted with a white circle. The subsolar point of the source of the flare is also shown.

Ørsted. This satellite was flying over the South Pole at an altitude of ~700 km. Unfortunately, there are no vector data available over the time interval we are interested in. The application of the wavelet transform to the scalar data has not shed any light with respect to the magnetar signature on the geomagnetic field since these high-frequency (25 Hz) data are found to be contaminated both by polar current systems and instrumental noise.

CHAMP. CHAllenging Minisatellite Payload (CHAMP) is a small near polar, low-altitude (~430 km) satellite mission. With its

highly precise magnetometer instruments CHAMP has been generated high-quality magnetic field measurements for the past 6 years. CHAMP was flying over South Pole region at this time, and about 180 s after the SGR 1806-20 outburst, began its northward orbital direction. Due to this tracking position, the magnetic field measurements are expected to reflect the variations caused by the polar magnetospheric-ionospheric current systems. However, the high sampling rate data provided by CHAMP satellite offer a fine temporal resolution which can be exploited by the wavelet analysis in order to detect any signatures caused by the magnetar. The wavelet power spectra for the three components of the magnetic field around the time of the event are shown in Fig. 2. Strong disturbances are observed on a large part of the time interval considered here. These fluctuations seem to be random, occurring at almost every frequency range in all three components. For this reason, we focus on the spectral power for higher frequencies. A high-power signal at frequency ∼1 Hz can be associated with the outburst of the magnetar, and is most prominent in the east magnetic component. Furthermore, a close up from 21.51 to 21.524 UT (≃50 s) of the wavelet power spectra is given in Fig. 3. Here a finer wavelet resolution is used to better define the period corresponding to the maximum signal power. The largest power is clearly observed at a period estimation of 7.49 s for north (X) component, 7.46 s for east (Y) component and 7.5 s for vertical downward (Z) component, all of which are

close to the 7.56 s period of modulation of the 380 s long-duration signal observed after the initial spike from SGR 1806-20. The differences (0.06–0.1 s) between the magnetar period and the period recovered from the CHAMP data could be ascribed to the different tools used to determine them. Unfortunately, due to strong influences from polar currents, it is hard to identify this modulation in CHAMP satellite vector magnetic data for the whole duration, and we can only resolve patches of this pulsation (Fig. 2). Note, however, that there has been no evidence of pulsation or other signal with this frequency in more than 5000 CHAMP tracks previously investigated (Balasis *et al.* 2005).

SAC-C. During the period of this bright flare, the SAC-C satellite was flying northwards from the equator, across Africa and Europe at an altitude of ∼700 km. This satellite, as Fig. 1 shows, was not in a privileged position to detect the SGR 1806-20 event (Campbell *et al.* 2005). However, the wavelet analysis shows an increase in the power spectra at the time of the event in X and Z components of the magnetic field (Fig. 4). We note that the Y data are too noisy to be considered.

DEMETER. This satellite was flying, from north to south over the Pacific region during the event. DEMETER (detection of electromagnetic emissions transmitted from earthquake regions) is a microsatellite with a low altitude (<800 km) and a nearly polar orbit. The scientific objectives of DEMETER are related to the
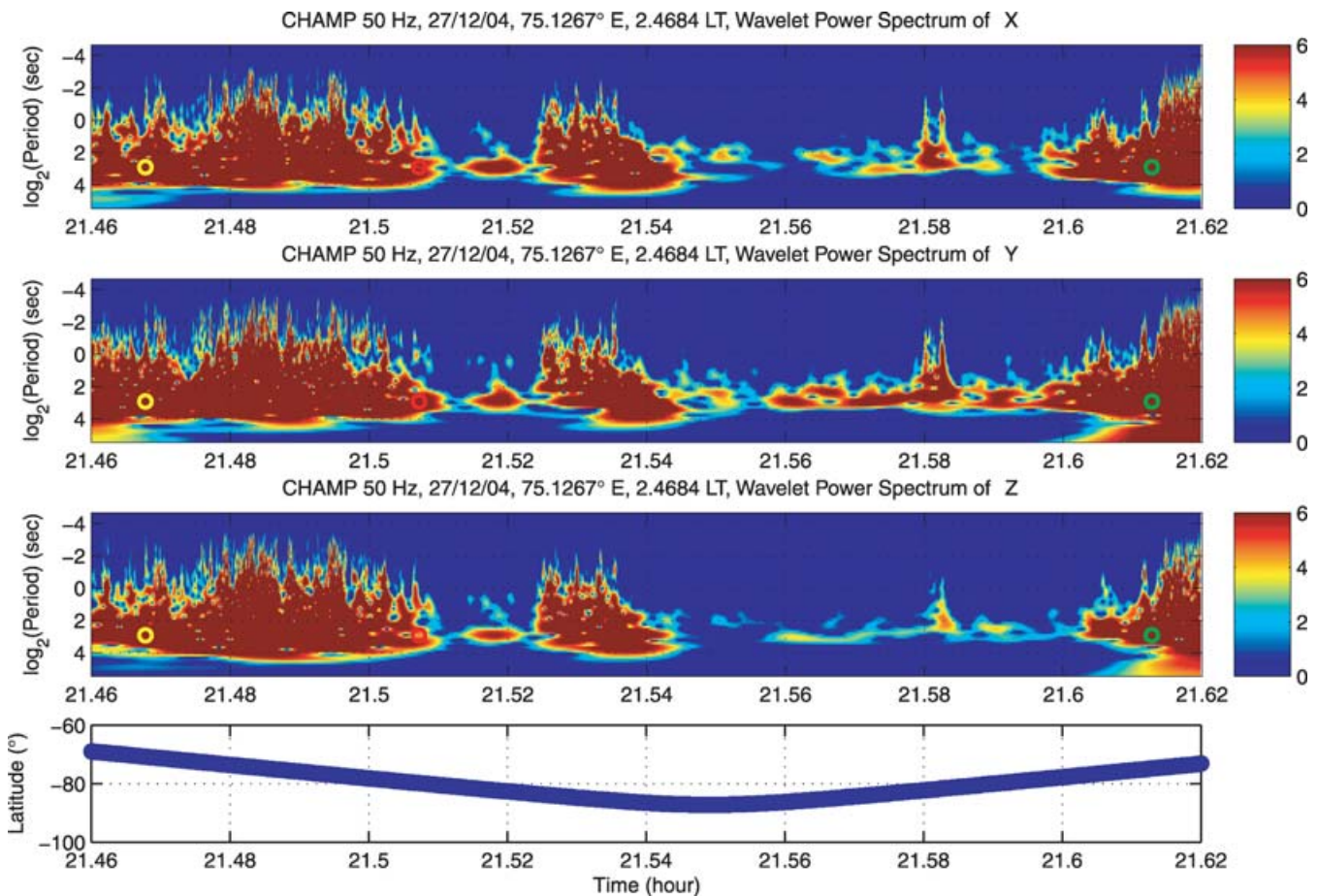

Figure 2. Wavelet analysis of the vector magnetic data provided by the CHAMP satellite on 2004 December 27. The main characteristic times of the flare from SGR 1806-20, that is, the precursor (142 s before the flare), outburst, and the end of the modulated signal (380 s after the flare), are marked with yellow, red and green circles, respectively. From top to bottom, wavelet power spectra of north (X), east (Y) and vertical downward (Z) components of the magnetic field are shown. Longitude and local time (LT) are given at the beginning of the considered time interval. Strong random fluctuations in all three components can be seen at almost all frequency ranges and for the largest part of the time interval presented here. The variation of satellite latitude with time is given in the fourth panel.
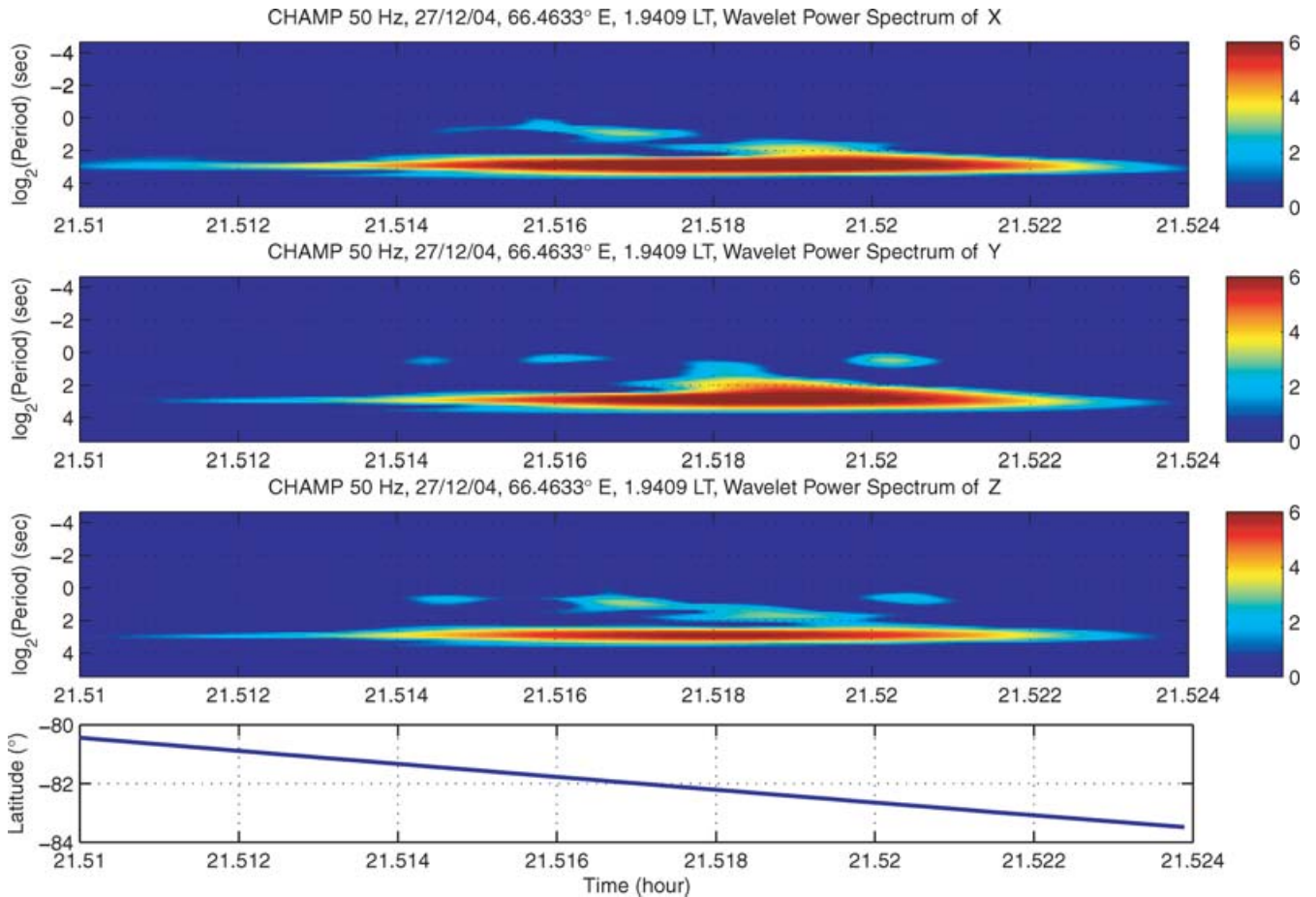
Figure 3. Zoom of Fig. 2, on the time interval 21.51–21.524 UT ($\simeq$50 s). This time span represents a relatively quiet magnetic period. The wavelet power spectra are dominated by a signal with a period centred around 7.49 s for X, 7.46 s for Y and 7.5 s for Z component, all of which are close to the 7.56 s rotation period of magnetar SGR 1806-20. The symbols and scales are as in Fig. 2.

investigation of the ionospheric perturbations due to seismic activity, as well as to the global study of the Earth's electromagnetic environment (Parrot 2002). The scientific payload is composed of several sensors, the energetic particle analyser, able to detect particles with energy higher than 30 keV, being of a particular interest for this study. DEMETER is operated in two modes: a 'Survey' mode collecting averaged data all around the Earth and a 'Burst' mode collecting high sampling data above seismic regions. DEMETER was in an ideal place to detect the outburst due to SGR 1806-20 (see the lowermost panel in Fig. 5). The particle detector data for three different energy bands (from 90.7 to 526.8 keV, 526.8 to 971.8 keV and 971.8 to 2342.4 keV) are shown for the orbit, including the time of the event (21:30:26 UT). A jump in data at the time of the outburst is clearly observed in all panels. Wavelet analysis was also performed on these data, but no additional information was derived.

4 CONCLUSIONS

The effect of the SGR1806-20 flare on the Earth's magnetic field was not large, but it was detectable. This first attempt to find a magnetar signature in the geomagnetic field clearly indicates that the high-resolution CHAMP magnetic data are optimal to capture the extremely bright flare from SGR 1806-20. Indeed, during the first half of the decay phase of the flare a 7.5 s periodicity is observed in the magnetic field over a magnetically quiet period, near the South Pole at 400 km altitude. This observation can be explained by a

mechanism through which the oscillating flux of ionizing γ-rays could alter the ionospheric conductivity and hence cause oscillating perturbations in the current-generated magnetic field.

An attempt to verify this hypothesis for the two previously recorded giant flares was not possible since no magnetic satellite missions were operating in LEO at that time (i.e. in 1979 March and 1998 August). Of course, there are many spacecraft carrying magnetometers within the Solar system, but very few near planetary ionosphere. For example, the wavelet analysis was performed on magnetometer data from the Cluster II mission that probes the Earth's magnetosphere. In order to be able to visualize, in the wavelet power spectrum graph, any significant disturbances of the magnetic field, the power spectral density of the signal was amplified by a factor of 2^6 (in comparison to the corresponding spectral density values of the CHAMP data). Although there are some indications for a weak pulsation-like signal at $\sim$8 s, the fact that this signal is almost two orders of magnitudes weaker than the one observed in CHAMP data favours the hypothesis of an ionospheric origin for the signature found in CHAMP data.

Furthermore, our analysis can be extended to 1 Hz magnetic data provided by ground-based magnetic observatories, but only a small number of them provide such high-resolution sampling nowadays. Data provided by 12 Canadian observatories, for which 1 Hz values are available over the period we are interested in, were also analysed. For five of these observatories, missing data or high-level noise, made it difficult to apply the wavelet technique. For the
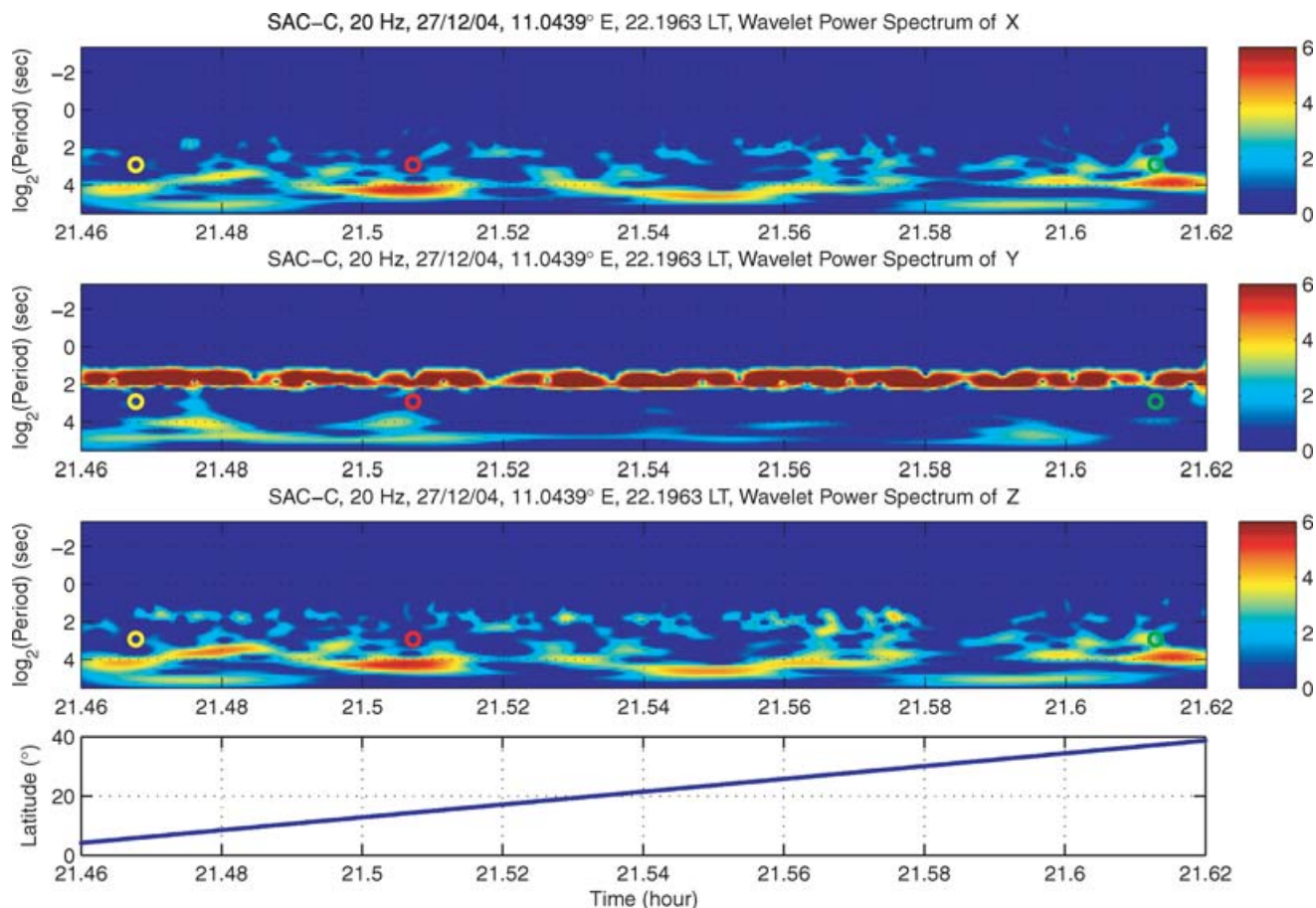
Figure 4. Wavelet analysis of the vector magnetic data provided by the SAC-C satellite on 2004 December 27. Diagrams as in Fig. 2.

others, no conclusive evidence for a signature related to SGR 1806-20 exists.

Analysing other magnetic data with such a powerful tool as wavelets techniques could be relevant for understanding the impact that giant flares have on the terrestrial and other planetary magnetic fields. However, the main difficulty in such studies is due to the availability and quality of magnetic data. For instance, wavelet analysis of Mars Global Surveyor mission magnetic measurements on 2004 December 27 was not able to detect any of the magnetar features due to the inadequate sampling rate: only 3 s data are now available (Michael Purucker, personal communication 2005).

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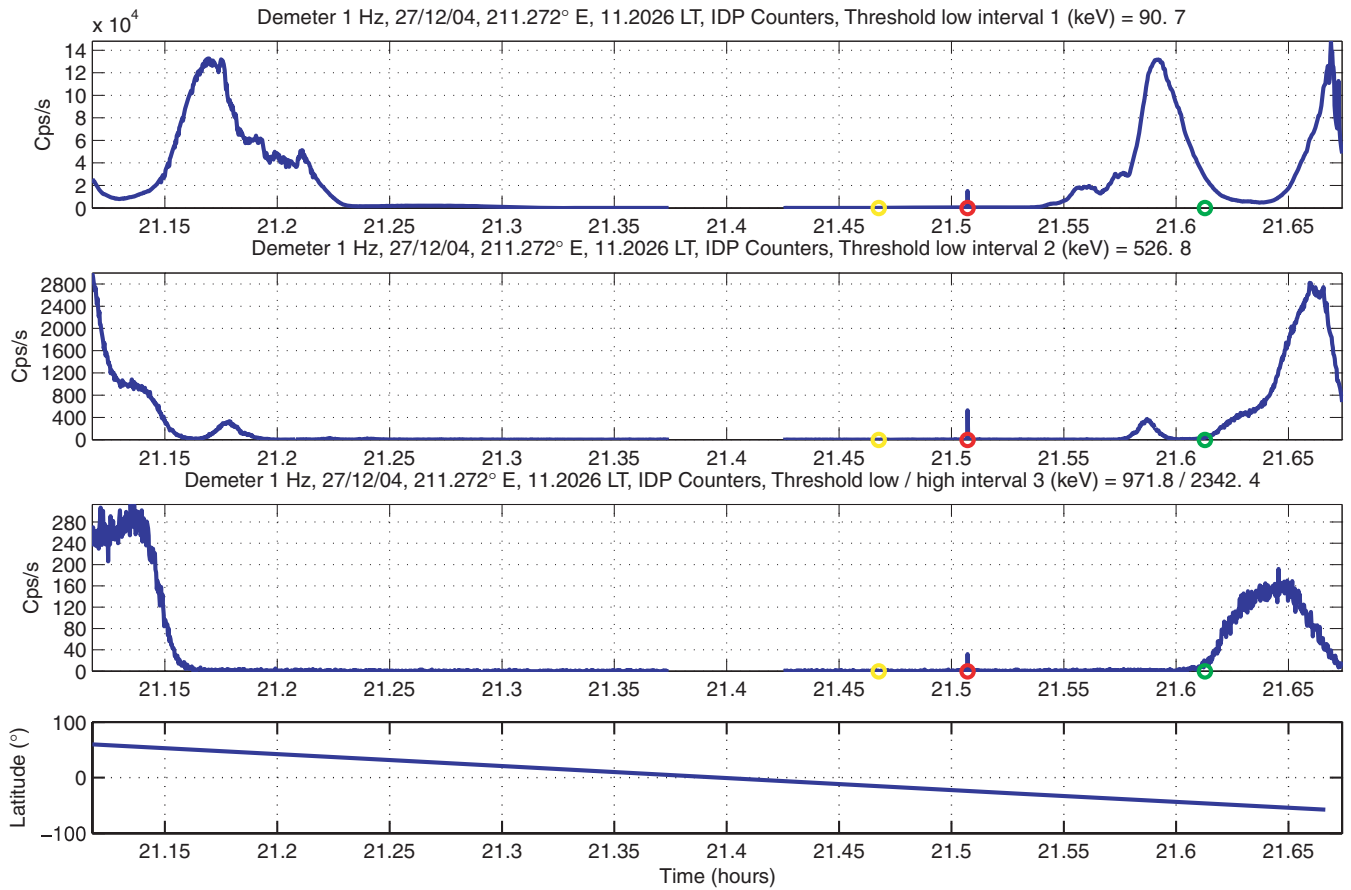
Figure 5. Energetic electron counter data from DEMETER satellite on 2004 December 27 (orbit number: 02595_0). From top to bottom, number of counts per second in three energy bands are shown. The 1 Hz data presented here were recorded in Survey mode. During the time interval 21.374 to 21.425 UT, DEMETER was operating in the Burst mode with a different sampling rate (see gap in the time-series). The beginning of the flare from SGR 1806-20 is clearly observed as a peak in all three panels. The variation of satellite latitude with time is also given (*cf.* lowermost panel).

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