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Magnetospheric line radiation event observed simultaneously on board Cluster 1, Cluster 2 and DEMETER spacecraft

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[1] We present a case study of a magnetospheric line radiation (MLR) event observed simultaneously by Cluster 1 and Cluster 2 during a perigee passage at a radial distance of about 4 R_E and, at the same time, by the low-orbiting DEMETER satellite. This unique constellation enables us to analyze spatiotemporal variability of the phenomenon. Although the Cluster spacecraft are separated by as much as 0.7 L-shells, the observed wave pattern is the same on both. The analysis of B to E ratios indicates a quasiparallel propagation, which suggests that the waves cross the geomagnetic equator over a significant range of L-shells, at least 3.9–4.6. Simultaneous observations by the DEMETER satellite separated by about 1.8 hours in MLT from the Cluster spacecraft indicate a significant azimuthal extent of the source. The obtained results show that during the MLR event the same wave pattern is observed over a significant portion of the inner magnetosphere. **Citation:** Němec, F., O. Santolík, M. Parrot, and J. S. Pickett (2012), Magnetospheric line radiation event observed simultaneously on board Cluster 1, Cluster 2 and DEMETER spacecraft, *Geophys. Res. Lett.*, *39*, L18103, doi:10.1029/2012GL053132.

1. Introduction

[2] Electromagnetic waves in the frequency range 1–8 kHz which are observed in the inner magnetosphere and represented in a traditional form of frequency-time spectrograms sometimes exhibit several clearly defined lines. These lines are typically nearly equidistant and may drift in frequency with the drift rate up to about 100 Hz per minute. Such emissions are usually called Magnetospheric Line Radiation (MLR). Although they have been observed both in the ground-based [e.g., *Helliwell et al.*, 1975; *Rodger et al.*, 1999, 2000a, 2000b; *Manninen*, 2005] and in the satellite data [e.g., *Koons et al.*, 1978; *Bell et al.*, 1982; *Rodger et al.*, 1995; *Němec et al.*, 2007; *Parrot et al.*, 2007; *Němec et al.*, 2009, 2012] for several decades, their origin is still not understood. However, they might play quite an important role in triggering whistler-mode emissions and influencing the particles in the radiation belts [*Matthews and Yearby*, 1981; *Parrot and Němec*, 2009].

[3] It has been suggested that MLR may be related to power line harmonic radiation (PLHR, an electromagnetic radiation from electric power systems on the ground), as discussed, e.g., by *Bullough* [1995]. However, the results based on ground-based measurements performed at Halley, Antarctica obtained by *Rodger et al.* [1999, 2000a] seem to contradict this hypothesis. Namely, the frequency spacings of individual lines forming the MLR events were not found preferentially near harmonics of electrical transmission frequencies (either 50 or 60 Hz), but rather the distribution of MLR line spacings was found to be roughly exponential. Moreover, the diurnal variation of MLR occurrence did not resemble the expected load pattern in the industrialized conjugate hemisphere and no evidence of a Sunday, weekend, or other 7-day cycle in the occurrence of MLR has been found.

[4] *Parrot et al.* [2007] analyzed a large-scale MLR event using simultaneous observations on board the DEMETER satellite and on the ground. They demonstrated that the event lasted for as long as two hours and spanned over a large area in the Northern hemisphere (≈7,400,000 km^2). Results of a systematic survey of MLR events observed by the low-altitude DEMETER spacecraft were reported by *Němec et al.* [2009, 2012]. The events were found to be limited within the plasmasphere and to occur more often during the day than during the night. Moreover, neither the frequency spacing of the events nor their frequency drift was found to vary significantly with the L-shell where the event was observed. The frequency drift of the events was found to be generally positive. It was shown that the individual lines forming the events are separated by a frequency step which is roughly constant for each event, but that they cannot be explained as harmonics of the base frequency equal to the frequency spacing.

[5] In this paper we present a case study of an MLR event based on simultaneous observations performed by two Cluster spacecraft located close to the equatorial region at a radial distance of about 4 R_E and by the DEMETER spacecraft at about 1.1 R_E. Simultaneous observations of the same event at several different points allow us to distinguish spatial and temporal variations of the event and to analyze MLR properties in this previously unexplored part of their propagation path. Section 2 describes the Cluster and DEMETER satellites and the relevant wave instruments on board. The results that we have obtained are presented in section 3 and they are discussed and summarized in section 4.

2. Data Set

[6] The presented study is based on the data obtained by the Cluster and the DEMETER spacecraft. The four Cluster

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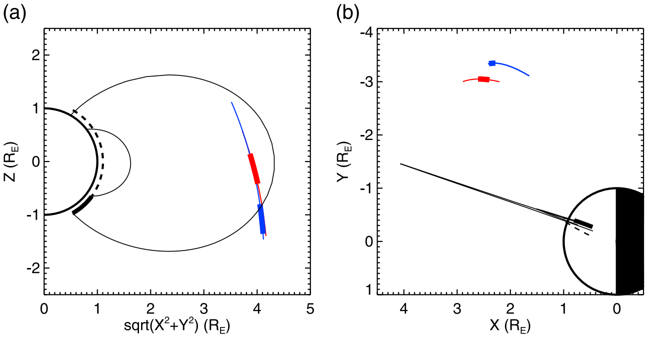

Figure 1. Orbit overview: (a) meridional view, (b) equatorial plane view. The orbit of Cluster 1 is plotted by the red line and the orbit of Cluster 2 is plotted by the blue line. Only the parts of the orbits when the WBD instruments were active are plotted. The parts of the orbits where the MLR event was observed are embedded as thicker lines. The orbit of the DEMETER spacecraft is plotted by the black dashed line. Again, the part of the orbit where the MLR event was observed is embedded. The thin black lines show the projections of the magnetic field lines calculated using IGRF and Tsyganenko 89 magnetic field models.

spacecraft are operated by the European Space Agency (ESA). They move in a close formation along an elliptical orbit with a perigee of about 24,000 km and an apogee of about 119,000 km (the spacecraft orbit slightly changed over the duration of the mission). Among all the performed measurements, we are interested in the data collected by the Wide-Band Data (WBD) Plasma Wave investigation instruments which were designed to provide high-resolution waveform measurements of both AC electric and magnetic fields [*Gurnett et al.*, 1997]. When the WBD instruments were active during the time interval of interest, one electric field component in the spin plane of the spacecraft was measured. However, during several short periods lasting for about 10 s each, one magnetic field component in the spin plane of the spacecraft was measured every 52 s instead of the electric field component. The analyzed data were band-pass filtered in the frequency range 25 Hz–9.5 kHz and measured with the sampling frequency of 27,443 Hz (36.4 μs time resolution).

[7] DEMETER was a French micro-satellite that operated between 2004 and 2010. It had a nearly Sun-synchronous (about 10:30 and 22:30 LT) circular orbit of an altitude of about 700 km [*Parrot*, 2006]. The instruments onboard measured almost continuously at geomagnetic latitudes between −65 and 65 degrees. We have used the electric field data measured by the ICE instrument [*Berthelier et al.*, 2006] in the VLF band (from 15 Hz to 17.4 kHz). Irrespective of the mode of operation of the satellite, it provides us with the power spectrum of one electric field component computed on-board with a frequency resolution of 19.53 Hz and a time resolution of 2 s or 0.5 s, depending on the mode of operation.

3. Results

[8] The WBD instruments on board the Cluster 1 and the Cluster 2 spacecraft were active during the dawn perigee passage at a radial distance of about 4 R_E on November 13, 2006. The WBD instruments on board the other two Cluster spacecraft were not active during the time interval of interest. The geomagnetic activity was notably low, Kp index was equal to 0o. The corresponding satellite paths are shown in Figure 1 by the red and the blue lines for Cluster 1 and Cluster 2, respectively. The figure is plotted in SM coordinates, so that Figure 1a shows the meridional view and Figure 1b shows the equatorial plane view. The thin black lines show the projections of the magnetic field lines calculated using combined IGRF and Tsyganenko 89 magnetic field models. The parts of the Cluster orbits corresponding to the time interval 1617:05 UT–1630:45 UT are embedded as thicker lines. Frequency-time spectrograms of power spectral density (PSD) of electric field fluctuations measured during this time interval are shown in Figures 2a and 2b for Cluster 1 and Cluster 2, respectively. The color scale used is the same in both figures and the frequency range spans between 1500 Hz and 3500 Hz. Selected orbital parameters are provided on the abscissa axis, namely: L-value, radial distance (*R*), geomagnetic latitude (*MLat*) and magnetic local time (*MLT*). The short approximately 10 s long data gaps correspond to the time intervals when the WBD instruments measured magnetic field data instead of electric field data.

[9] A set of nearly parallel lines increasing in frequency and forming the MLR event can be seen in both figures. The event lasts principally over the entire plotted time interval, i.e., approximately for 13.5 minutes. It is important to note that – albeit the different intensity of the event measured by the two spacecraft – the observed wave pattern is the same. Moreover, it should be mentioned that the event is observed also in the magnetic field data during the time intervals when these are measured by WBD (not shown). However, as the event is rather weak, only its most intense parts are seen in the magnetic field data.

[10] Multi-component STAFF-SA data are measured by Cluster in addition to the WBD data, which could in principle enable us to perform a detailed wave analysis. Unfortunately, the frequency resolution of the STAFF-SA instrument is insufficient for this type of the analysis. Nevertheless, it is possible to use the magnetic field measurements of the WBD instrument along with the electric field data measured in the neighboring time intervals to calculate the *B* to *E* ratios, and estimate the value of the refractive index. The obtained estimates of the refractive index are in the range of about 11–40. Since plasma density data are provided by the Whisper instrument [*Décréau et al.*, 2001] and the ambient magnetic field is measured by the FGM instrument [*Balogh et al.*, 2001], the theory of electromagnetic waves in the cold plasma [*Stix*, 1992] can be then used to estimate the wave normal angle. The obtained values are in the range from about 30 to 75 degrees, which correspond to the range of polar angles of the Poynting vector from about 0 to 10 degrees. Moreover, it should be noted that since the plasma density in the region of interest is too large to be properly measured by Whisper, only the lower estimate of the plasma density is obtained. Consequently, the calculated values of the wave normal angles and polar angles of the Poynting vector correspond to the upper estimates, and it is likely that the real values are significantly smaller. It is thus reasonable to assume that the wave propagation is nearly field-aligned in the first approximation.

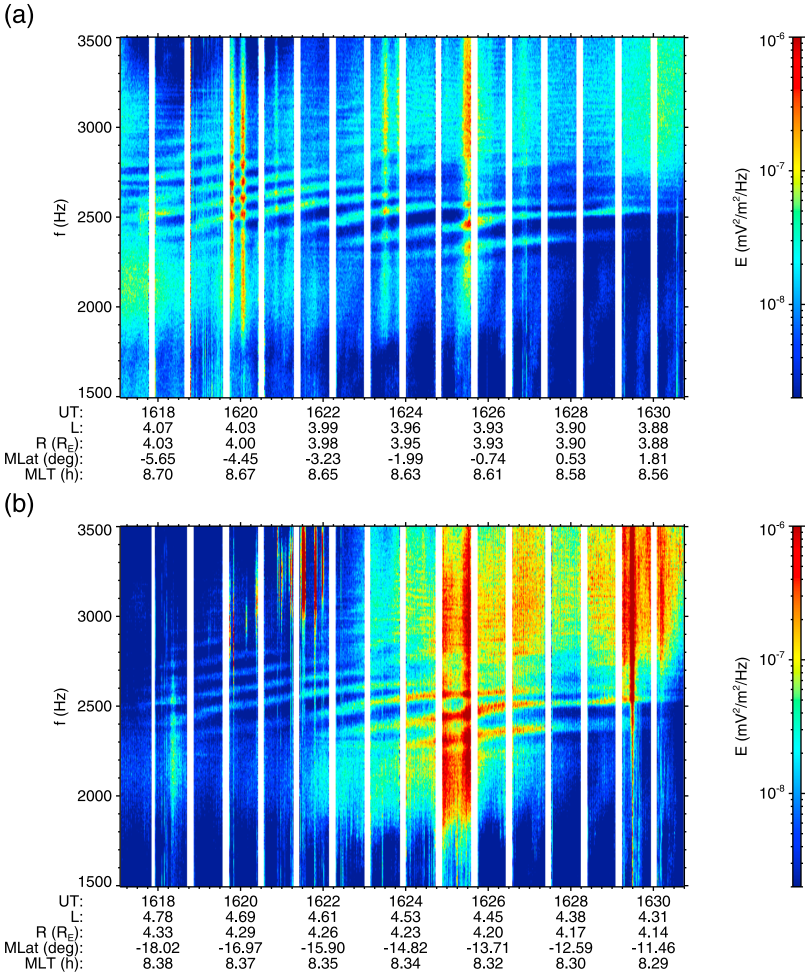

Figure 2. Frequency-time spectrograms of power spectral density of electric field fluctuations corresponding to the MLR event measured by the WBD instruments on board (a) Cluster 1, and (b) Cluster 2 spacecraft. The plotted time interval and the used color scale is the same for both panels. Additional orbital parameters are provided on the abscissa axis.

[11] This assumption, along with the data from two Cluster spacecraft located at different L-shells and observing the same wave pattern, allows us to estimate the L-extent of the MLR event. During the time duration of the event, the L-value of Cluster 1 varies between about 4.1 and 3.9, while the L-value of Cluster 2 varies between about 4.8 and 4.3. By comparing the intensity of the event observed by the two spacecraft, one can see that the intensity of the event observed by Cluster 2 is rather low at the beginning of the time interval, but it suddenly increases at about 16:22 UT when the L-value of the spacecraft drops below 4.6. Another sudden intensity change is observed shortly before 16:28 UT, when the intensity decreases significantly. However, since this variation occurs simultaneously on both spacecraft, it is likely to be due to a change in the source itself rather than due to the changes of the spacecraft position. This suggests that the intensity of the event is largest at $L \approx 3.9$–4.6. However, the lower boundary corresponds only to the upper estimate, because L-shells lower than 3.9 are not sampled by Cluster during the time duration of the event. Finally, when in the proper range of L-shells, the intensity observed by Cluster 2 is generally larger than the intensity observed by Cluster 1. This may be either due to i) MLR intensity being lower at lower L-shells, or ii) MLR intensity being lower near the geomagnetic equator. This might indicate that the waves are generated close to the geomagnetic equator at larger radial distances.

[12] In addition to the observations by Cluster, the same MLR event was observed by the low-orbiting DEMETER satellite. The satellite orbit is plotted by the black dashed line in Figure 1. The part of the orbit when the MLR event was observed is shown by a thick line. The corresponding frequency-time spectrogram of PSD of electric field fluctuations is shown in Figure 3. The plotted frequency range is the same as in Figure 2. However, there are two principal differences. First, the frequency resolution of the frequency-time spectrogram calculated on board DEMETER is equal to 19.53 Hz, which is considerably coarser than that shown for Cluster in Figure 2. Second, and more importantly, the L-value of the DEMETER spacecraft changes much faster than the L-value of the Cluster spacecraft. Consequently, although the Cluster data show that the event occurred well before 16:23 UT, the DEMETER data measured before this time are not plotted as the L-values of the satellite were too low for the event to be observed ($L < 1.6$). Nevertheless, it can be seen that the time when DEMETER ceases to see the emissions (≈16:30 UT) is about the same as the time when the Cluster spacecraft ceases to see them. Moreover,

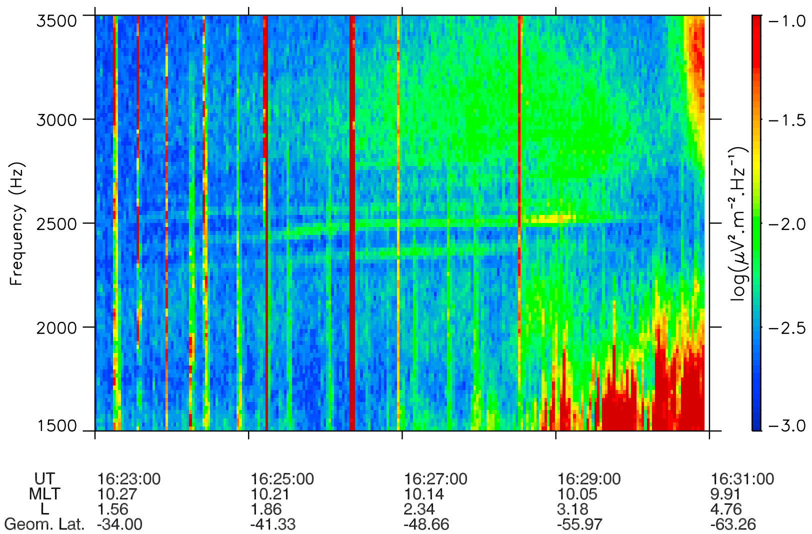

Figure 3. Frequency-time spectrogram of power spectral density of electric field fluctuations corresponding to the MLR event observed by the DEMETER spacecraft. Additional orbital parameters are provided on the abscissa axis.

the observed wave pattern well resembles the wave pattern observed by Cluster at the same time: 3 intense lines, with the top two being somewhat closer. One should also mention hiss-like emissions that occur in the second part of the time interval at higher frequencies. They seem to have some kind of internal structure which evokes a possible linkage to the MLR event, and they are observed simultaneously on board all the three spacecraft used in the study. Finally, it should be noted that the PSD of the MLR event measured by DEMETER is about one order of magnitude lower than the PSD observed by Cluster and the event extends to significantly lower L-values on DEMETER (as low as ≈1.6).

4. Discussion and Conclusions

[13] The Cluster observations of the presented MLR event are unique because they are performed at large radial distances close to the equatorial region. This is important as the equatorial region is a preferred region for wave-particle interactions [*Trakhtengerts and Rycroft*, 2008] and might be therefore a favorable region for the generation of MLR events. Moreover, we can analyze MLR properties in this previously unexplored part of their propagation path. Since B to E ratios indicate a quasiparallel propagation, the analysis of the wave pattern and the wave intensity observed simultaneously by Cluster 1 and Cluster 2 enabled us to estimate the L-extent of the region where the waves cross the geomagnetic equator to at least 3.9–4.6. Taking into account quiet geomagnetic conditions at the time of the observation as well as the plasma density data obtained by the Whisper instrument, this corresponds to locations inside the plasmasphere, in agreement with the results obtained by *Němec et al.* [2009].

[14] The fact that the low-orbiting DEMETER spacecraft separated by as much as 1.8 hours in MLT observed the same MLR event indicates that the source region must have a significant azimuthal extent. There are two additional points that should be commented on in this regard. First, the event extends to very low L-shells on DEMETER. This may indicate that it really occurs over that large interval of L-shells, just becoming rather weak at low L-values, which would be consistent with the Cluster data. Alternatively, this might be possibly explained by an oblique wave propagation at low radial distances and a related deviation to lower L-shells at altitudes of a few thousands of kilometers [*Inan and Bell*, 1977; *Němec et al.*, 2012]. The lower intensity of the MLR event observed by DEMETER may also be related to the Landau damping during the wave propagation from the source region down to DEMETER. This would be consistent with the picture of the event being generated in the equatorial region at larger radial distances, i.e., relatively close to the Cluster spacecraft.

[15] Finally, we would like to briefly discuss the detailed structure of the MLR event and a possible generation mechanism. The frequencies of the individual lines forming the event increase as a function of time, which is consistent with the finding of *Němec et al.* [2012]. Moreover, the spacecraft are located in different regions and the observed wave pattern is the same. This means that the frequency drift is indeed an inner property of the source, as suggested by *Němec et al.* [2012].

[16] It is reasonable to assume that the observed frequency spacing between the individual lines forming the event should correspond to some characteristic frequency in the source region. There are several possibilities that can be considered in this respect. First, if the MLR event was generated due to PLHR, the observed frequency spacing should be equal to the base frequency of the radiating electric power system, i.e., to 50 or 60 Hz, or its multiples. The observed frequency spacing is rather close to 100 Hz. For example, during the time interval 1619:00 UT–1619:30 UT when several lines can be distinguished and the frequency spacing can be determined quite precisely, it is found to be equal to 96.4 ± 1.5 Hz. Later on, as new lines emerge at the lower frequency boundary of the event, the frequency spacing somewhat increases and the individual lines become more irregular. However, since the event was observed at geomagnetic longitudes of North America where the base frequency of the electric power system is 60 Hz, one would expect the frequency spacing to be close to 120 Hz rather than to 100 Hz.

[17] Second, the frequency spacing might directly correspond to some characteristic frequency of the plasma

medium in the source region. However, this does not seem to be the case for two main reasons: i) No characteristic frequency in the considered range of L-shells appears to be close to 100 Hz; the proton cyclotron frequency would be that high only at very low radial distances ($L \approx 1.7$), and the electron cyclotron and plasma frequencies are too high. The lower hybrid frequency might be reasonably close. Nevertheless, it is not clear how this could contribute to the harmonic structure, and, moreover, ii) Any characteristic frequency of the plasma would necessarily change as a function of L, which is not in agreement with the same structure being observed over a significant range of L-shells.

[18] A possible explanation would be a modification effect due to a low-frequency wave propagating in the equatorial plane and thus affecting a large range of L-shells. We made an extensive search for this hypothetic modulating wave, but without success. This might be due to Cluster 1 – which is the only Cluster spacecraft located close to the equatorial plane at the time of the event – crossing the geomagnetic equator at too low L-values, i.e., out of the generation region.

[19] Although we are still not able to determine the generation mechanism of MLR events, the presented simultaneous observations by Cluster and DEMETER spacecraft allowed us to demonstrate that exactly the same wave pattern is observed over a significant portion of the inner magnetosphere. Moreover, as the B to E ratios measured by Cluster close to the equatorial region at radial distances of about 4 R_E indicate a quasi-parallel propagation, we were able to estimate the L-extent of the region where the waves cross the geomagnetic equator to at least 3.9–4.6. The azimuthal extent of the event has been shown to be at least 1.8 hours in MLT. The obtained results show that although MLR events are rather rare and a somewhat overlooked phenomenon, once present they may affect large regions of the magnetosphere. Their understanding is therefore important in order to get a correct and complete picture of the wave-particle dynamics.

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