TERRESTRIAL LF BURSTS: SOURCE AND SOLAR WIND CONNECTION

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Abstract

Terrestrial low frequency (LF) bursts represent a new and interesting class of radio emissions, apparently associated with the auroral kilometric emissions and having close analogs with a remarkably similar class of Jovian low-frequency bursts. In this paper, I 1) review the recently recognized strong correlation of LFs with the solar wind (bulk speed) input as measured just upstream of Earth by the WIND spacecraft, and 2) show via superposed epoch analysis that when the data are examined on shorter time scales, LFs also manifest a clear dependence on IMF direction, similar to that associated with magnetospheric substorms, and entirely consistent with the bulk speed correlation. The 40-minute magnetospheric response time indicated by the epoch analysis is in agreement with studies showing that weak-to-moderate levels of magnetospheric activity are triggered in a time delay fashion by energy storage and release in the magnetotail. Finally, I show that the measured group velocity dispersion of LFs is consistent with a magnetotail source approximately 100-200 R_E downstream of Earth. In view of the correlation results shown here, some comments regarding earlier studies of AKR and Jovian QP (Jovian Type III) bursts with regard to solar wind triggering are appropriate.

1 Introduction

The terrestrial LF bursts were first detected by ISEE-3 [Steinberg et al., 1989] and described more recently by Kaiser et al. [1996] using the WIND/Waves observations. As seen outside Earth's magnetosphere, they strongly resemble miniature solar Type III bursts, much like the Jovian QP bursts [Kurth et al., 1989; MacDowall et al., 1993; Desch, 1994]. Unlike the (15-min and 40-min periodic) Jovian QPs, however, LFs are not periodic on any known time scale except for their pronounced tendency to recur in groups separated by approximately half a solar rotation ($\sim$ 13 days) [Desch et al., 1996; hereinafter paper 1]. This periodicity is driven by the solar wind, specifically by variations in the solar wind speed (V_{sw}) such that there is a many-fold increase in the occurrence rate of LFs when V_{sw} is enhanced above $\sim$ 500 km/sec.

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Paper 1 used 1-hr averaged solar wind data. In this paper we show that when the solar wind data are carefully examined on short time scales ($\sim$ 1min), a clear association with the IMF direction is seen and that this observation is not inconsistent with the V_{sw} correlation described in paper 1. This result has obvious implications for the AKR and for Jovian QP bursts, both of which have manifested correlations with the solar wind speed in past studies using somewhat coarse time resolution. Finally, the measured frequency drift of the burst onsets when viewed in the solar wind helps localize the LF source.

2 Instrumentation

Data from three WIND experiments are used in this paper: (1) the thermal noise receiver (TNR) portion of Waves [Bougeret et al., 1995] provided electric field measurements in the 4-256 kHz band, (2) the Faraday cup subsystem of SWE [Ogilvie et al., 1995] provided in-situ solar plasma speed and density, and (3) MFI [Lepping et al., 1995] provided the IMF magnitude and direction information.

3 Observations

Figure 1 from the TNR receiver portion of WAVES (adapted from Figure 1 of Kaiser et al., [1996]) is a 45-minute dynamic spectrum showing 4 LF bursts. The two horizontal bands are the solar wind f_p line (bottom) and the $2f_p$ line (top). The characteristic negative frequency drift of LFs becomes apparent only below $2f_p$. It is this feature of LFs by which they are identified in the WAVES data and by which 265 bursts were so catalogued during the 7-month analysis interval of paper 1.

Early on in the analysis it was realized that long periods of time sometimes passed without any detection of LFs despite excellent observing conditions in the solar wind at radio wavelengths. Subsequently, many tens of bursts might be detected over a several-day span. The data in Figure 2 illustrate why this was the case.

Here the solar wind speed for $V_{sw} \geq 500$ km/sec (vertical up) is plotted and compared with the number of LFs in a given 6-hr span (vertical down). The data are for the first 210 days of 1995. Solar wind data were derived from $1-hr$ averages. The correlation between high solar wind speed and the generation of LFs is overwhelming, and statistically is equal to 52%, greater than for any other solar wind parameter examined [paper 1]. There are two points to be made about this. First, it was somewhat encouraging to find that the LFs, manifestly associated in some way with AKR [Kaiser et al., 1996], were driven by the same

Figure 1: (plate, next page) TNR radio spectrogram from WAVES showing 4 successive LF events over a 45-minute interval. The LF events are characterized by a rather amorphous negative drifting structure at frequencies between the local f_p and $2f_p$ (adapted from Kaiser et al. [1996]).

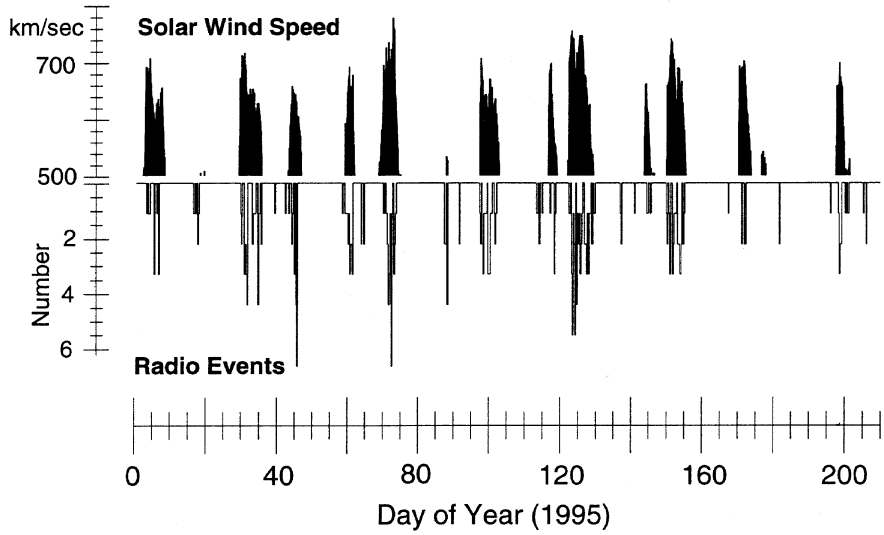

Figure 2: Plot of the solar wind speed for V_{sw} > 500km/sec (plotted vertically up) compared with the number of radio events in a 6-hr interval (plotted vertically down). On this coarse time scale there is a strong dependence of LF occurrence on high speed streams.

solar wind parameter as AKR [Gallagher and D'Angelo, 1981]. But second, correlations with V_{sw} are in and of themselves extremely problematic. No other characteristic of energy dissipation in Earth's magnetosphere (substorms etc.) correlates with V_{sw} alone. As we discussed in paper 1, such correlations have been taken as an indicator of viscous coupling between the solar wind and the magnetopause [e.g., Axford, 1964; Vasyliunas et al., 1982]; however, such mechanisms for coupling energy into the magnetosphere are not currently high on anyone's list of favored physical processes. There is far more evidence for MHD processes, such as those involving field line merging when B_z in the IMF turns southward. In view of this, I began to look at higher time resolution solar wind data to explore the possibility that the operation of some other parameter was being masked by time averaging effects. This point was raised by Baker [1986] in an earlier study of solar wind correlations with substorms. As I will discuss, this result has implications for earlier solar wind correlation studies of AKR and Jovian QPs.

4 Correlation with B_z

The principal rival to viscous forces as an effective solar wind-magnetosphere coupling mechanism is electromagnetic (MHD) coupling, predominantly in the form of magnetic field line merging as indicated by correlations with southward (-B_z) turnings of the IMF at the nose of the magnetosphere. To examine the possibility of IMF influences on LFs requires high time resolution solar wind data because the directional changes in B_{IMF} can be rather swift.

I analyzed 92-sec IMF data and performed a superposed epoch analysis using LF data from two of the most active periods of time in 1995: days 30-36 and 104-130. Together,

these intervals accounted for 87 LF events. The procedure was to stack 6-hour spans of the high-resolution B_z data centered on the time (zero epoch) of each LF event. If there is no effect of the IMF on the occurrence of LF events, then the superposed epoch stacking will show no significant change in the magnitude of B_z before the zero epoch (a change in B_z *after* the zero epoch defies causality).

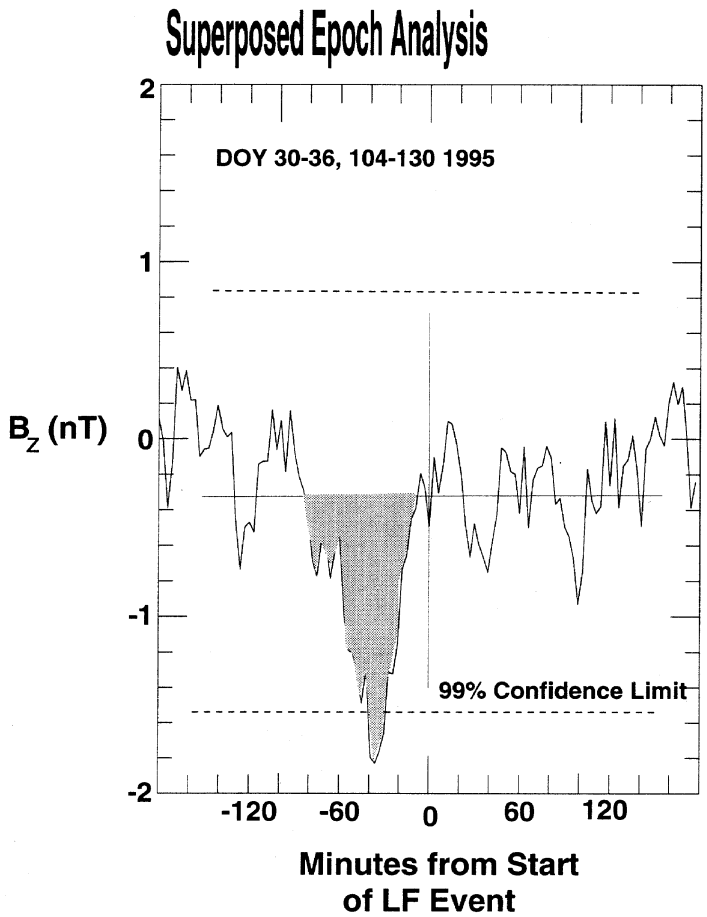

Figure 3: Superposed epoch analysis of high resolution (92-sec) IMF data (B_z) using the time of the start of each LF burst as the zero epoch. Data from days 30-36 and 104-130 were included. Results show pronounced negative bay in B_z approximately 40 minutes prior to the onset of LF events.

The result of this analysis is shown in Figure 3. B_z is plotted as a function of time, from 3 hours before to 3 hours after the zero epoch defined by each LF event. Dotted lines indicate the upper and lower 99% confidence limits defining significant departures from simply random fluctuations in the IMF direction. There is only one significant variation in B_z and that comes about 40 minutes before the zero epoch. The observed change in B_z is in the negative sense, as expected for an electromagnetic type coupling process involving field line merging as a trigger.

As a check, I also looked at stacking the data in such a way that a χ^2 analysis could be performed. The result is shown in Figure 4 where 92-sec samples with B_z < -2.5nT

were stacked just as in the above analysis. The result is the same, namely that a highly significant statistic is derived ($\chi^2 = 211$, $p > 99.99\%$) for a delay time of 40 minutes from the midpoint of a major southward turning of B_{IMF} to the start of an LF event.

Thus it appears, based on at least an analysis of a subset (albeit a large subset) of the data, that the direction of B_z is important in triggering LFs, just as it is (and in the same sense) for triggering substorms and other measures of energy dissipation within the magnetosphere. How then do we reconcile the result of paper 1 which showed a strong correlation with bulk speed?

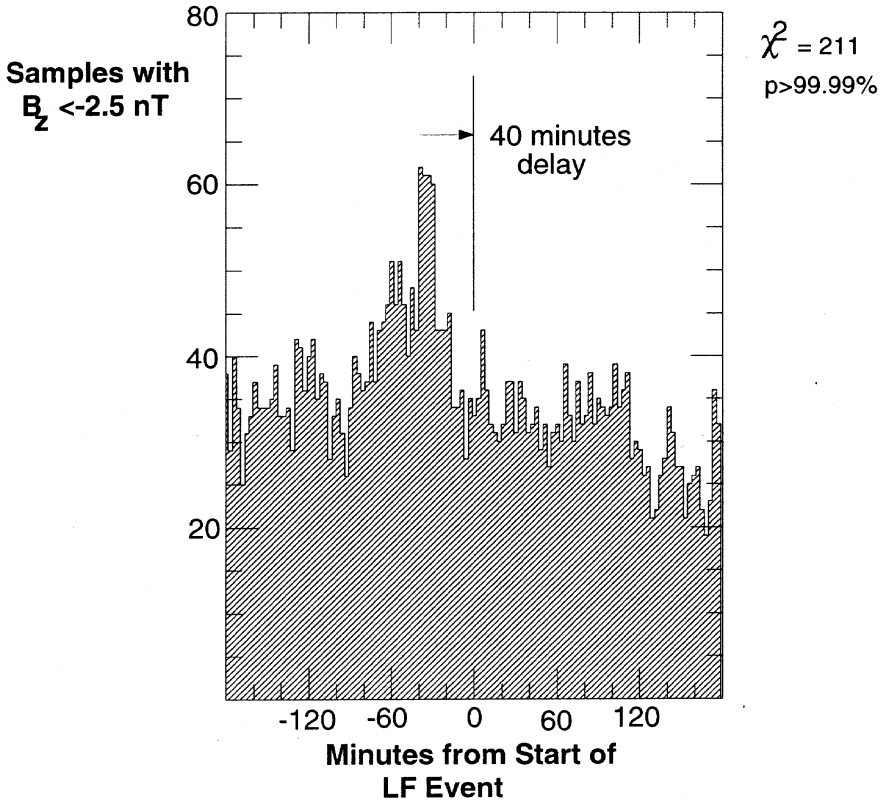

Figure 4: χ^2 analysis of the same data as in Figure 3 but using only B_z < -2.5nT for stacking. Results again show that there is a significant enhancement in the occurrence of large negative B_z 40 minutes before the start of LF emission.

Figure 5 shows how these two apparently divergent results came about. When the number of negative B_z "events" is compared with simultaneous measurements of V_{sw}, we see that the former occur overwhelmingly during periods of high speed streams, as during the interval from about day 122 - 130 in Figure 5. Here, V_{sw} has been averaged over 6-hr intervals and $-B_z$ has been summed over the same interval. Outside of the high speed stream, the IMF is far steadier, with fewer rotations out of the ecliptic plane and a lower rms in general (the latter not shown here). Therefore the results of paper 1 showing a high correlation with V_{sw} were statistically sound, but possibly physically an artifact due to masking of the correlation with B_z owing to excessive smoothing of the solar wind

data. Of course the true picture must await a detailed analysis with a fair comparison using all the solar wind parameters.

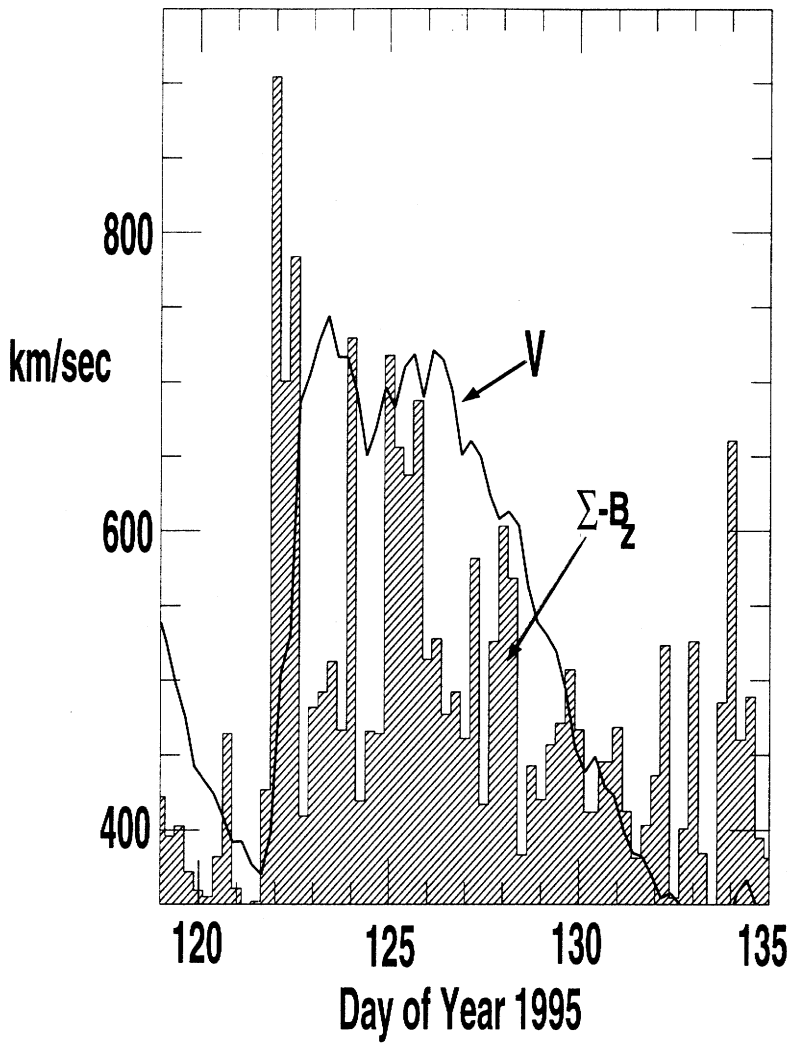

Figure 5: Plot of the solar wind speed and the sum of (negative) B_z for the period from day 119 to 135 of 1995. V is averaged over 6 hours and $-B_z$ is summed over 6 hours (scale is arbitrary). The plot shows how the occurrence of negative B_z in the solar wind is tied to high-speed stream intervals.

5 The Source Location of LFs

The defining feature of LF bursts observed by a spacecraft in the solar wind is their negative frequency drift below the $2f_p$ line. In a previous study it was shown that the similar negative drift manifested by Jovian QP bursts could easily be interpreted as due to group velocity dispersion, $v_g = c(1 - \nu_p^2/\nu^2)^{1/2}$ in the Jovian magnetosheath [Desch, 1994]. Here, v_g is the wave group velocity in the dispersive medium, and ν_p and ν are the electron plasma and wave frequencies, respectively. Given typical Jovian sheath densities

and propagation paths through the sheath, the observed QP drift rate could be matched extremely well.

LF burst dispersions (see Figure 1) are about 4-5 times as great as that measured for QPs (Figure 5 of Desch, 1994). In modelling the QPs, a sheath density of 0.85cm^{-3} and path length of 35 R_J were used. Therefore to first order, given a terrestrial magnetosheath density of 20cm^{-3} , the dispersion path length required to model LFs is about 300-400R_E. I believe what this number points to is a source that is far down Earth's tail, but certainly not at the distance given by this overly simple calculation. What has been neglected here is the effect of multipath propagation owing to the fact that the wave is propagating in a dense, non-uniform medium in which scattering off of density irregularities is an important consideration [e.g., Steinberg et al., 1989]. That the LFs are strongly scattered can be inferred from the fact that the antenna spin modulation usually disappears below $2f_p$, indicative of an extended source image. Additionally, source structure, which is very evident above $2f_p$, virtually disappears below $2f_p$. Without careful ray tracing it would be difficult to estimate the increased path length due to such scattering effects; however, a factor of at least 2-3 increased path length close to f_p does not seem unreasonable given the measurements of AKR scattering above $2f_p$ seen by Steinberg et al. [1989]. Given this estimate, the inferred source location is probably 100-200 R_E down the tail.

6 Summary and Discussion

High resolution analysis of solar wind data has shown that southward turnings of the IMF are effective in triggering LF bursts. Since southward turnings (and rms fluctuations in B_{IMF}) are also closely associated with high speed streams, the earlier result of paper 1 that showed an LF-high speed stream correlation is consistent with the present study, but possibly not entirely physically meaningful.

The results of this paper and of paper 1 further emphasize the point (see also Baker [1986]) that the time scale used in solar wind correlation analyses can, in and of itself, determine outcome. A number of earlier studies using rather long-term averages might reasonably be questioned for this reason. The results of Gallagher and D'Angelo [1981] for AKR and of MacDowall et al. [1993] for Jovian QPs showing the strongest correlation to be with V_{sw} were both based on very long term averages (hours to days in the case of the former). Both of these studies could benefit from higher time resolution analyses; although, the Ulysses data do not readily permit good studies of B_{IMF} correlations because of the difficulty of propagating solar wind parameters over great distances [e.g., Rucker et al., 1986].

Finally, we have seen that the temporal relationship between changes in B_{IMF} and LF response indicates a 40-minute delay based on the superposed-epoch analysis performed here (Figure 3). Previous studies have also demonstrated significant delays between the solar wind driving function and magnetosphere response. Goertz et al. [1991] found 20-40 minute delays between solar wind changes and AE index. Using linear prediction filtering, Bargatze et al. [1985] found magnetospheric response times of 20 minutes for strong levels of activity and 60 minutes for weak-to-moderate levels of magnetospheric activity. The

latter was taken as an indication of magnetospheric response driven by energy storage and release in the magnetotail. Given the 40-minute response time found in the present study and the deep-tail source location inferred from the LF drift rates, a similar conclusion might be drawn here: that the LF bursts are a manifestation of energy released in the tail following stimulation by repeated or prolonged southward turning of B_{IMF}.

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