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   low frequencies it ranges from being f0 (frequency
   independent) to f+0.4 times the power in Bs. Several
   possible explanations of the nonlinear response of AE to
   the IMF Bs driver are briefly discussed, including: 1)
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   saturation mechanisms for the low frequency regime.
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# THE NONLINEAR RESPONSE OF AE TO THE IMF $B_S$ DRIVER: A SPECTRAL BREAK AT 5 HOURS

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*Abstract.* We demonstrate the existence of a sharp break in the power spectrum of AE at ~ 5 hours. At frequencies below the break, AE has a ~ $f^{-1.0}$ dependence, and at higher frequencies it has a $f^{-2.2}$ to $f^{-2.4}$ dependence. The power spectrum of the IMF $B_S$ for the same time interval has a ~ $f^{-1.4}$ dependence with no spectral breaks or peaks. Thus, at frequencies above the break, the power in AE varies as $f^{-0.5}$ to $f^{-0.8}$ times the power in $B_S$ and at low frequencies it ranges from being $f^0$ (frequency independent) to a $f^{+0.4}$ times the power in $B_S$. Several possible explanations of the nonlinear response of AE to the IMF $B_s$ driver are briefly discussed, including: 1) variable ionospheric conductivity (increasing with $B_S$) for the high frequency regime, and 2) several AE saturation mechanisms for the low frequency regime.

## Introduction

It is well recognized that the southward component of the interplanetary magnetic field (IMF) is the major parameter which is related to the onset of magnetospheric substorms and storms (see Gonzalez et al. 1989 and references therein for a review of interplanetary parameters tested). In this work we will examine the power spectra of the Auroral Electrojet (AE) indices and the power spectra of the IMF $B_S$ to determine the efficiency of the solar wind-magnetospheric coupling for wave periods from 17 minutes to 28 hours.

## Method of Analysis

Welch's modified periodogram method (Welch, 1978; Rabiner et al., 1979) is used to calculate the spectra presented in this paper. In this method, the total data is divided into segments. The final spectral estimate is the average of the spectra calculated for the individual data segments. The number of degrees of freedom is twice the number of data segments. This method has been employed because it avoids averaging over frequency, maintaining an accurate frequency dependence. The drawback is, of course, the inability to determine wave power at very low frequencies. This is not a problem for the analyses undertaken in this study, as the full data intervals were years in length, well beyond the range of interest for this study.

## Results

Figure 1 illustrates the power spectrum of 5 minute averages of the AE index from 1978 through 1980. There are no gaps in the data. The plot spans the frequency range of 6 x $10^{-4}$ to 2 x $10^{-6}$ Hz which corresponds to 28 minutes to 5.8 day periods. There are 303 degrees of freedom; the corresponding plus and minus one standard error is indicated in the figure. It is quite small.

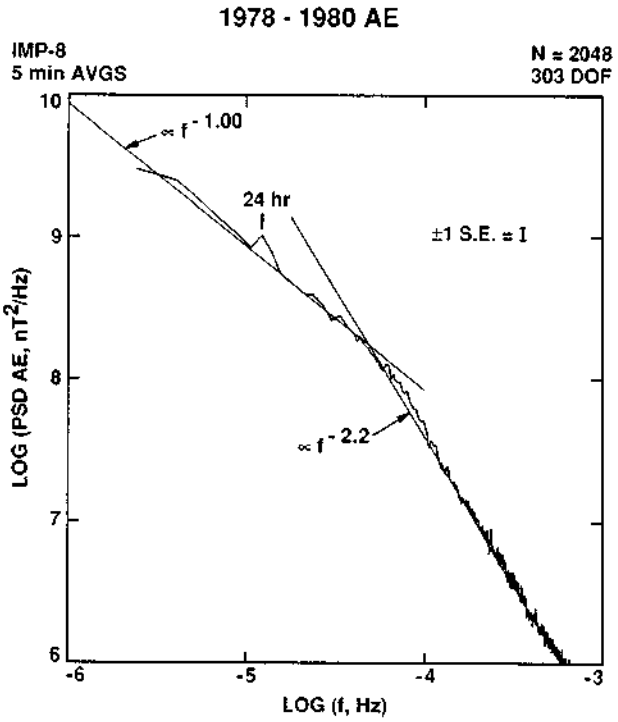

Fig. 1. Power spectrum of 5 minute averages of AE for 1978 through 1980.

The figure contains two notable features. One is a spike at ~ 1.2 x $10^{-5}$ Hz. This spike is much larger than the standard error. The frequency corresponds to a period of 24 hours. A second feature is a break in the slope of the spectrum at ~ 5.6 x $10^{-5}$ Hz or ~ 5.0 hours. This is emphasized by the addition of two straight lines drawn in by hand. (The spectral shapes quoted are, however, only approximate fits. Fits other than power law are also possible.) The spectrum is proportional to $f^{-1.00}$ prior to the break and a $f^{-2.2}$ after the break. This interval of study occurs during solar maximum.

There is a slight enhancement at 8 x $10^{-5}$ Hz (3.5 hrs). This may be associated with substorms. However we note that this "enhancement" is strongly dependent on the spectral fit used and is also relatively small in comparison to the standard error.

Figure 2 illustrates the power spectrum of the AE index for the years 1967-1970, one solar cycle earlier than the interval covered in Figure 1. This power spectrum was computed from one hour averages. Otherwise, the format is the same as

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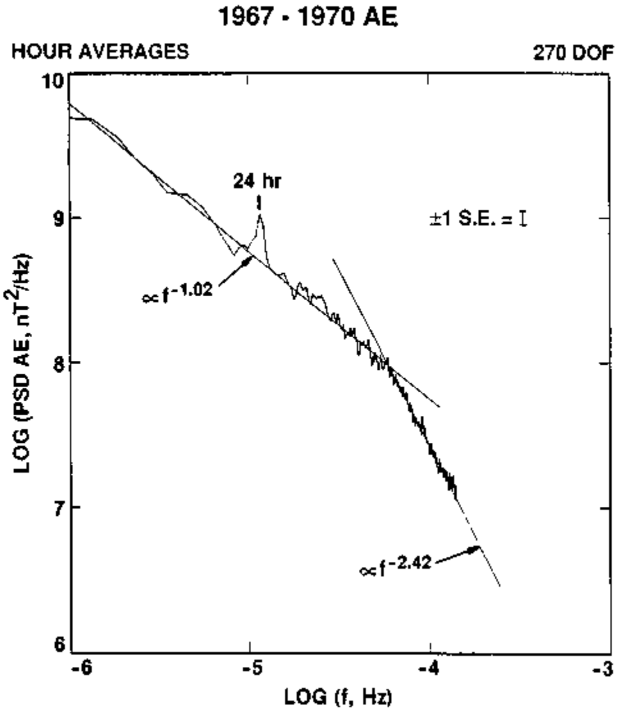

Fig. 2. Power spectrum of 1 hour averages of AE for 1967 through 1970.

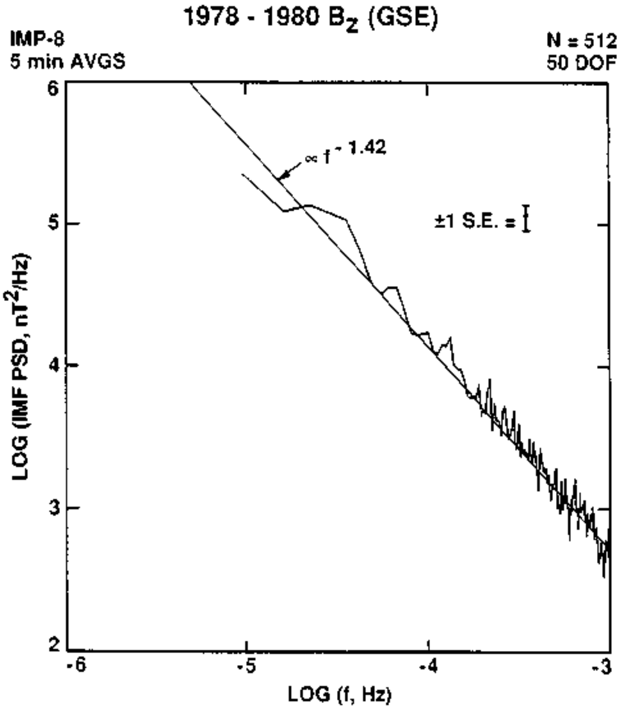

Fig. 3. Power spectrum of 5 minute averages of the GSE z component of the IMF for 1978 through 1980.

in the previous figure. Again there is a sharp peak at 1.2 x $10^{-5}$ Hz (24 hours) and a break in the spectrum at ~ 5.9 x $10^{-5}$ Hz or ~ 4.7 hours. The spectrum is proportional to $f^{-1.02}$ at low frequencies and $f^{-2.4}$ at high frequencies. The spectral break is clearly present, independent of whether one hour or 5 minute averages are used.

A power spectrum of AE was also computed from one hour averages for an interval around solar minimum, 1971-1974. The spectral break occurred at 5.0 x $10^{-5}$ Hz (5.5 hours). The spectral shapes were proportioned to $f^{-0.98}$ prior to and $f^{-2.2}$ after the spectral break. Since the results are very similar to those in Figure 2, they are not shown.

Figure 3 illustrates the power spectrum of the IMP-8 GSE-Z component of the IMF, overlapping the interval in Figure 1, 1978-1980. 5 minute averages of $B_Z$ are used. The spectrum is essentially a power law (straight line) with no apparent breaks in slopes from $10^{-5}$ to $10^{-3}$ Hz. A line representing $f^{-1.42}$ has been added for comparison. It is clear that there are no interplanetary magnetic field $B_Z$ features with periods near 4.7 - 5.5 hours.

Figure 4 illustrates the IMF $B_Z$ data of figure 3, but in solar magnetospheric (GSM) coordinates. The spectrum is again power-law in shape, with no major breaks or peaks. A line representing $f^{-1.43}$ has been added for comparison. This spectrum is very similar to that of Figure 3. It is clear that the Earth's dipole rotation does not introduce any features that would be correlated with the spectral breaks in AE observed in Figures 1 and 2. Also included in Figure 4 is the power spectrum of the IMP-8 GSM $B_S$ (zeros were used in place of $B_Z$ positive values). The spectral intensity is a factor of ~ 2 less than that of $B_Z$, as one would expect from deleting ~ half of the data. The spectral shape is slightly different, with the PSD falling off as $f^{-1.38}$. We believe that the small spectral change is due to greater power reduction at low frequencies. A simple explanation is the following: for some long wavelength (large amplitude) waves, replacing positive $B_Z$ values with zeros reduces the wave amplitude in half (reducing power by 4). Clearly the decrease in power at low-frequencies is between a factor of 2 to 4. This effect is less for higher frequency (lower amplitude) waves, as is expected.

Figure 5 illustrates the ratio of the power of AE to the power of IMF $B_S$ as a function of frequency, for the years

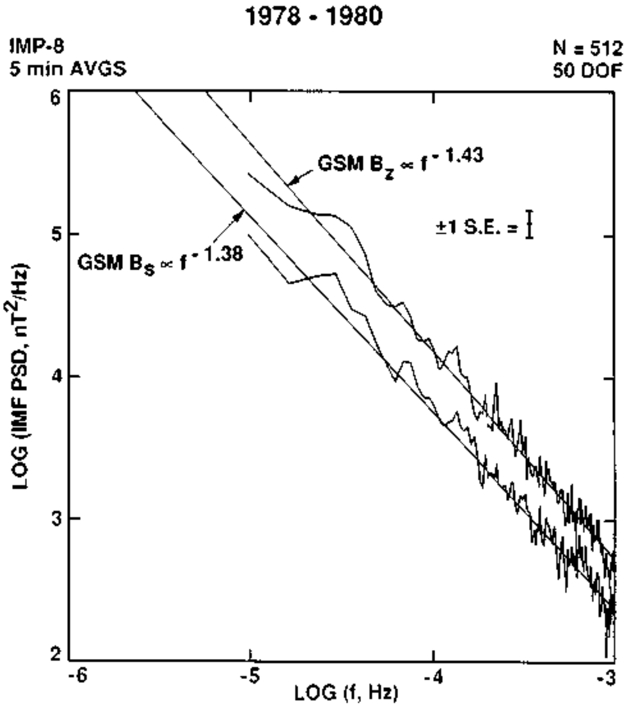

Fig. 4. Same as figure 3 but for the GSM z and GSM s (southward) components.

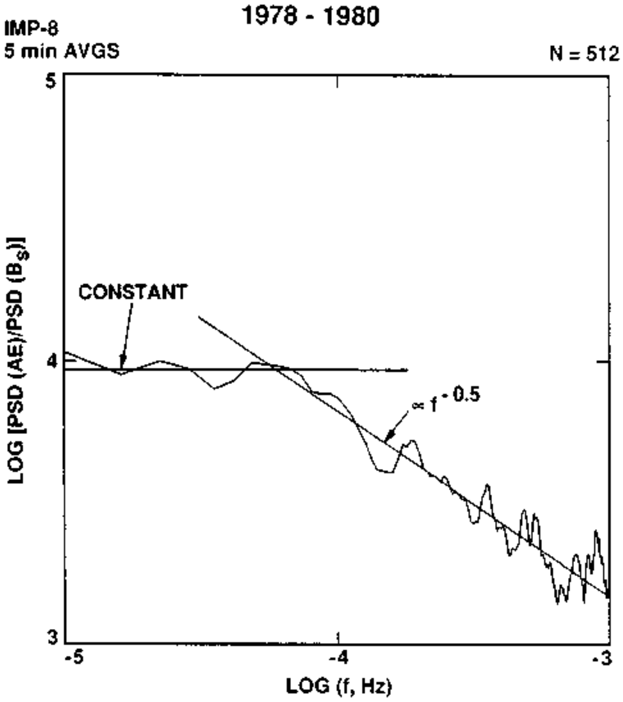

Fig. 5. The ratio of the power spectrum of AE to the power spectrum of the IMF $B_s$ for 1978-1980.

1978-1980. The break in ratio is clearly apparent at $f \approx 6 \times 10^{-5}$ Hz (4.6 hours). Below this frequency, the ratio is approximately independent of frequency. Above the break, the ratio decreases with a $f^{-0.5}$ dependence. These estimates are somewhat uncertain, however. By using the previously determined AE and $B_s$ spectral slopes, one could estimate that the ratio has a $f^{0.4}$ and a $f^{-0.8}$ dependence at frequencies below and above the break, respectively.

Since the IMF $B_s$ has a power law shape, it is not possible in this study to separate $B_s$ amplitude effects from frequency effects. In the discussion that follows, we will try to indicate which proposed mechanisms are amplitude related, in contrast to those that are frequency related.

## Summary and Conclusions

### *24 Hour Peak*

The peak in the AE spectrum at 24 hours is always present and is large in comparison to the standard error. Allen and Kroehl (1975) have similarly reported a 24 hour AL wave. They demonstrate that there is AE or AL "power" associated with the finite number of ground stations used in constructing AE. In intervals where geomagnetic activity is continuous for days to weeks (such as HILDCAA intervals, Tsurutani and Gonzalez, 1987, Tsurutani et al., 1990), AE will have artificial maxima when AE ground stations rotate under the most intense portion of the auroral electrojet. As a station rotates under the electrojet 24 hours later, a peak in AE will again occur, throwing (artificial) power into the spectrum at this period.

There are several other sources of AE power at 24 hours period. There is a daily variation in ionospheric conductivity which has a strong influence on the intensity of the electrojets. Holzer and Slavin (1981) have demonstrated a diurnal oscillation as large as 45% of the mean during winter solstice. Another mechanism is associated with the inherent 24 hour periodicity of the GSM coordinate system. If the magnetic field is steady over periods of days, such as illustrated by the interplanetary sector pattern (Smith et al., 1978), then the Earth's magnetic dipole rotation will produce a 24 hour variation in the GSM $B_s$ component. The GSM coordinate system is the relevant one for magnetic reconnection and this has been suggested for causing both daily and seasonal variations in AE (Russell and McPherron, 1973). All of the above mechanisms probably contribute to this power. Further studies are needed to resolve the relative importance of each.

### *~ 5 Hour Break*

We have demonstrated that a sharp break in the power spectrum of AE occurs at a period of about 5 hours. At frequencies below the break, the power spectrum of AE has a $\sim f^{-1.0}$ dependence, and at higher frequencies has a $f^{-2.2}$ to $f^{-2.4}$ dependence.

The ~ 5 hour period is considerably longer than most features associated with substorms. The expansive phase is typically ~ 30 minutes and the length of the substorm is approximately 2 to 3 hours (Akasofu, 1964). The latter number is very approximate, however. G. Rostoker (private communication, 1989) believes that the substorm durations are (typically) directly related to the durations of the southward IMF $B_z$ events. Our results indicate that there are no preferred period in the IMF $B_s$ and thus one should perhaps expect no particular substorm duration as well.

To rule out the possibility that the 5 hour spectral break may be an artifact caused by a lack of AE stations over certain longitudes (oceans, for example), we studied AE as a function of universal time. Although interesting features were noted, none suggested any feature that could be related to a 5 hour period. Previous work done by Kroehl (1981) has shown that there is only slight improvement of AE if the number of stations is increased from 12 to 57, thus the lower number of stations is felt to be adequate. Kroehl also found that the UT effect in AU and AL only occurred if one organized the data by IMF sector structure.

### *Power Ratio (AE/IMF $B_s$)*

We have shown that at frequencies below $\sim 6 \times 10^{-5}$ Hz, the ratio of power in AE to power in $B_s$ has a dependence of $f^{0.4}$ to $f^{0.0}$ (constant). At frequencies above $6 \times 10^{-5}$ Hz, the ratio has a dependence of $f^{-0.5}$ to $f^{-0.8}$. Below, we will discuss the high frequency regime first.

*High Frequency Region.* It is well known that the magnetosphere responds as a low pass filter, being insensitive to high frequency IMF $B_s$ fluctuations. However here, by comparing the power in AE and $B_s$, we find a specific frequency dependent response of $f^{-0.5}$ to $f^{-0.8}$ for values above $\sim 6 \times 10^{-5}$ Hz. This requires some explanation. One mechanism that should limit high frequency response is the inductance of the tail. High frequency $B_s$ fluctuations will result in magnetotail flux variations rather than driving electric fields and currents in the ionosphere. We have investigated a simple circuit analog in which the ionosphere acts as a resistor and flux stored in the tail acts as an inductor. For such a RL circuit, the predicted dependence of the power ratio of AE to $B_s$ is $f^{0.0}$ below the break frequency, and $f^{-2.0}$ above the break frequency. The predicted slope above the break frequency is steeper than the observations, and it is difficult to match the break frequency with the observed $6 \times 10^{-5}$ Hz. (See also comments about the nonlinear response of the magnetosphere in Bargatze et al., 1985 and Rostoker et al., 1988).

An amplitude related mechanism is enhanced ionospheric conductivity ($\sigma$) associated with greater particle precipitation, or $\sigma = \sigma$ (E) where E is the convection electric field. A linear increase in E could therefore result in a greater than linear increase in ionospheric current (AE).

*Low Frequency Region.* One amplitude related possibly that may explain the apparent fall-off in AE response is that the auroral oval will move equatorward of AE stations during large $B_S$ events and AE may become a somewhat insensitive measurement of the ionospheric currents. Although some of this effect may be present, it would, however, be surprising if it could cause such a sharp break in AE. A more interesting suggestion is that AE saturates at high values. This could be due to magnetosphere or ionosphere effects or could be associated with magnetosphere ionosphere current limiting effects. For a magnetospheric mechanism, if the convection electric field drives the plasma sheet earthward so strongly that the energetic electrons go on strong diffusion, filling the magnetospheric loss cone, further increase of solar wind energy input will primarily remain as trapped magnetospheric particle energy (this will eventually lead to a much larger distributed ionospheric current system, but not necessarily higher AE). Another saturation effect could occur if the precipitating electron spectrum hardens significantly with increasing $B_S$. In this case, a greater fraction of the dE/dx ionization would occur below the ionospheric current layer ( ~ 100 -160 km), perhaps causing $\sigma$ to be constant or even slightly decrease with increasing $B_S$. This is opposite to the effect discussed previously for the high frequency regime. A third possibility is the onset of current driven instabilities in either the auroral electrojet or the field-aligned currents linking the magnetosphere to the ionosphere. The increased anomalous resistance would cause a decrease in overall current.

The above mechanisms are, of course only suggestions. Further theoretical analyses and computer modelling are necessary to determine which of these processes are the relevant ones.

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