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Chorus source locations from VLF Poynting flux measurements with the Polar spacecraft

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Abstract. Previous studies have used indirect evidence to argue that whistler-mode chorus emissions are generated near the magnetic equator. In this paper a spatial survey of wave normals and Poynting vectors computed from three-component electric and magnetic field measurements is used to show that chorus is generated very close to the magnetic equator. One surprising result is that there are almost no chorus emissions propagating toward the magnetic equator, such as might be expected from high-latitude magnetospheric reflections. The absence of a reflected component indicates that the chorus is reabsorbed, probably by Landau damping, before returning to the magnetic equatorial plane.

Introduction

Whistler-mode chorus is one of the most common very-low-frequency (VLF) emissions in the Earth's magnetosphere [Storey, 1953; Allcock, 1957, Helliwell, 1965]. For many years it has been widely believed that chorus is generated near the magnetic equatorial plane [Helliwell, 1969]. However, there are no direct measurements of the source location. In this study, three-component electric and magnetic field measurements from the Plasma Wave Instrument (PWI) on the Polar spacecraft are used to show that chorus is generated within a few degrees of the magnetic equator.

Chorus occurs at frequencies from a few hundred Hz to a few kHz and is characterized by fine structure that consists of rising or falling tones, and sometimes short impulsive bursts [Burtis and Helliwell, 1969; Dunkel and Helliwell, 1969; Burton and Holzer, 1974; Cornilleau-Wehrlin et al., 1978; Hayakawa et al., 1990; Lauben et al., 1998, and references therein]. Near the magnetic equator chorus often occurs in two bands separated by a gap at one-half the electron cyclotron frequency ($f_c = 28B$ Hz, where B is the magnetic field strength in nT). The emission frequency is closely correlated with the equatorial cyclotron frequency of the magnetic field line passing through the observing point, and is nearly independent of the local electron cyclotron frequency [Dunkel and Helliwell, 1969; Burtis and Helliwell, 1969]. The correlation with the equatorial cyclotron frequency provides indirect evidence that chorus is generated near the magnetic equator. Tsurutani and Smith [1977] have also shown that chorus is most intense near the magnetic equator, which further supports the view that chorus is generated near the magnetic equator.

Several previous investigators have studied the wave normal distribution of chorus. Using three axis magnetic field measurements, Burton and Holzer [1974] showed that the wave normal angle, θ_k, measured relative to the magnetic field, is symmetrically distributed around $\theta_k = 0°$ for magnetic latitudes, λ_m (defined in Burton and Holzer [1974]), near the equator ($0° < \lambda_m < 2.5°$), but is shifted toward larger values at higher latitudes. This latitudinal dependence is consistent with generation near the magnetic equator. However, since only magnetic measurements were used the wave normal direction had a 180° ambiguity. For a discussion of the reasons for the 180° ambiguity, see Means [1972]. Therefore, Burton and Holzer could not conclusively prove that the waves were propagating away from the magnetic equator. More recently, Nagano et al. [1996] used five-component wave field measurements (three magnetic and two electric fields) from the Geotail spacecraft to calculate the wave normal direction of chorus. Electric field measurements were used to eliminate the ambiguity in the wave normal direction. For a case studied near the magnetopause, the wave normal directions were shown to be consistent with generation near the magnetic equator, although some emissions were observed to be propagating toward the equator [Nagano et al., 1996].

At frequencies above one-half of the electron cyclotron frequency chorus is found to have wave normal angles closely related to the resonance cone angle. For the definition of the resonance cone angle, see Stix [1962]. Hayakawa et al. [1984] and Muto et al. [1987] have shown that in this frequency range the wave normal angle is very close to the resonance cone angle near the magnetic equator, but is 15° to 20° less than the resonance cone angle at higher latitudes. Again, the wave normal determination had a 180° ambiguity because only magnetic measurements were used. Muto and Hayakawa [1987] have interpreted this wave normal dependence as indicating that chorus above one-half of the electron cyclotron frequency is generated near the magnetic equator.

In this study three-component measurements of electric and magnetic wave fields from the Plasma Wave Instrument (PWI) on the Polar spacecraft are used to compute the wave normal and Poynting vector of chorus. Since simultaneous, three-axis electric and magnetic field measurements are used, the 180° ambiguity in the wave normal directions is eliminated. For a description of the Polar Plasma Wave Instrument see Gurnett et al. [1995], and for a description of the Polar spacecraft see Harten and Clark [1995].

Analysis and Results

The orbit of the Polar spacecraft has an apogee of 9 R_E, a perigee of 1.8 R_E, and an inclination of approximately 90°. The Polar Plasma Wave Instrument (PWI) includes a Sweep Frequency Receiver (SFR) that provides high-frequency resolution measurements of electric and magnetic field intensities from 26 Hz to 808 kHz, and a High Frequency Waveform Receiver (HFWR) that provides simultaneous waveforms of three orthogonal components of the electric and magnetic wave fields from 20 Hz to 25 kHz. In the high-telemetry rate mode, the HFWR produces a set of simultaneous, 0.45-s waveform snapshots from each antenna once every 9.2 s. The wave normal, $\hat{k}$, is determined using the Means [1972] method, which involves computing a spectral matrix that consists of the auto- and cross-power spectrums from the three magnetic field components. As mentioned earlier, this method has an inherent 180° ambiguity in the wave normal direction. Since the wave normal must have a component in the direction of the energy flow, this ambiguity can be resolved by computing the Poynting

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vector, $\vec{S}$, and requiring that $\vec{S} \cdot \hat{k} \geq 0$ (see Stix [1962]). The Poynting vector is calculated directly using $\vec{S} = (1/2)\ \mathrm{Re}\ \{\vec{E}(f) \times \vec{H}^*(f)\}$, where * indicates the complex conjugate, Re stands for the real part, and $\vec{E}(f)$ and $\vec{H}(f)$ are the Fourier transforms of the electric and magnetic field waveforms. For a derivation of this equation , see Reitz and Milford [1967].

To carry out the above analysis, the computations are first performed in a despun spacecraft-centered coordinate system. The results are then transformed to a coordinate system in which the z-axis is parallel to the local geomagnetic field, and the x-axis is directed outward from the Earth in the meridian plane. The local magnetic field direction is obtained from the Polar Magnetic Field Experiment (MFE) [Russell et al., 1995]. Once computed, the polar and azimuth angles of the wave normal and the Poynting vector are displayed on a conventional frequency-time spectrogram. To avoid plotting background noise, the directional measurements are displayed only when a sufficiently high coherence is present between the three magnetic components (see Means [1972] for the definition of coherence), and only when the waveforms can be interpreted as a single plane wave. A coherence threshold of 0.85 has been found to provide adequate discrimination between background noise and coherent chorus signals. The planarity of the wave is determined by the ratio of the largest eigenvalue of the spectral matrix to the sum of the eigenvalues, $R_\lambda = \lambda_1/(\lambda_1 + \lambda_2 + \lambda_3)$, where $\lambda_1 > \lambda_2 > \lambda_3$ [Storey et al., 1991]. The eigenvalue ratio is one for a single plane wave and one-third for an isotropic distribution of uncorrelated waves. An eigenvalue ratio threshold of 0.9 has been used to assure that the wave can be interpreted as a single plane wave. Most chorus waveforms satisfy this condition.

A series of frequency-time spectrograms illustrating a chorus event observed on November 25, 1996, is shown in Figure 1. The spectrograms cover a 27.6-s interval in three 0.45-s snapshots starting at 0023:34.340 UT ($L \approx 4.5$, $\lambda_m \approx 10°$, and MLT = 9.1 hr). The frequency range of each spectrogram is 0 to 10 kHz. The magnetic coordinates are provided by the Goddard Space Flight Center and are derived by fitting an eccentric dipole to the International Geomagnetic Reference Field 1995 (IGRF-95). The top panel shows the magnetic field spectral density from the search coil magnetic antenna. Intensity is indicated by the color bar to the right. Each 0.45-s snapshot is separated by a 8.75-s gap that is compressed and plotted as a vertical black stripe. Rising tones, characteristic of chorus, are clearly evident. The second panel shows the angle, θ_k, between the wave normal and the local magnetic field. The third panel shows the angle, θ_s, between the Poynting vector and the local magnetic field. The fourth panel shows the sign of the z-component of the Poynting vector, $S_z = \vec{S} \cdot \hat{B}_0$, where $\hat{B}_0$ is a unit vector parallel to the magnetic field. When S_z is positive the Poynting vector has a component in the $+\vec{B}_0$ direction (i.e., northward at the equator). These emissions are plotted as red. When S_z is negative the Poynting vector has a component in the $-\vec{B}_0$ direction (i.e., southward at the equator). These emissions are plotted as green. As can be seen, all the chorus emissions in this example are propagating northward (i.e., $\vec{S} \cdot \hat{B}_0 \geq 0$). Since the spacecraft is in the northern hemisphere ($\lambda_m \approx 10°$) the chorus is propagating away from the magnetic equator.

Chorus events lasting from a few minutes to more than an hour are frequently observed in the Polar HFWR data. A SFR spectrogram of a relatively long-lasting chorus event is illustrated in the top panel of Figure 2, which shows the electric field spectral density measured from 1915 to 2115 UT on December 14, 1996. The white line is the electron cyclotron frequency. A band of chorus can be seen rising slowly in frequency from about 1918 to 2025 UT in the northern hemisphere ($\lambda_m \approx 31°$ to $\lambda_m \approx 3.4°$), and a similar band of shorter duration can be seen decreasing slowly in frequency from about 2045 to 2100 UT in the southern hemisphere ($\lambda_m \approx -13°$ to $\lambda_m \approx -23.8°$). The bottom panel of Figure 2 shows the sign of the S_z component of the Poynting vector. These measurements are obtained by averaging S_z over each 0.45-s snapshot, thereby giving a time resolution of 9.2 s. The frequency resolution is 140 Hz. The chorus in the northern hemisphere is seen to be propagating northward ($\vec{S} \cdot \hat{B}_0 \geq 0$), away from the magnetic equator. There is no indication of equatorward propagation. The chorus in the southern hemisphere is seen to be propagating southward ($\vec{S} \cdot \hat{B}_0 \leq 0$), again away from the magnetic equator. Only one brief period occurs where an emission is observed to be propagating toward the equator. This exception occurs at approximately 2026 UT ($\lambda_m \approx 3°$), where a brief narrowband emission is observed shortly after the spacecraft has entered the plasmasphere. The entry into the plasmapause is indicated by the steep rise in the upper hybrid resonance frequency, hence plasma density, at approximately 2020 UT. This emission is not believed to be chorus, since it has a nearly steady frequency and does not have the usual discrete structure of chorus.

In order to see if the results shown in Figure 2 can be generalized, we have examined all of the available high-telemetry rate HFWR data to determine the direction of propagation of chorus. Data from a total of 394 orbits over a time interval from March 28, 1996, to September 16, 1997, were examined. Chorus was observed both above and below one-half the local electron cyclotron frequency, and during all magnetic local times except the midnight local time quadrant. The predominant spectral shapes

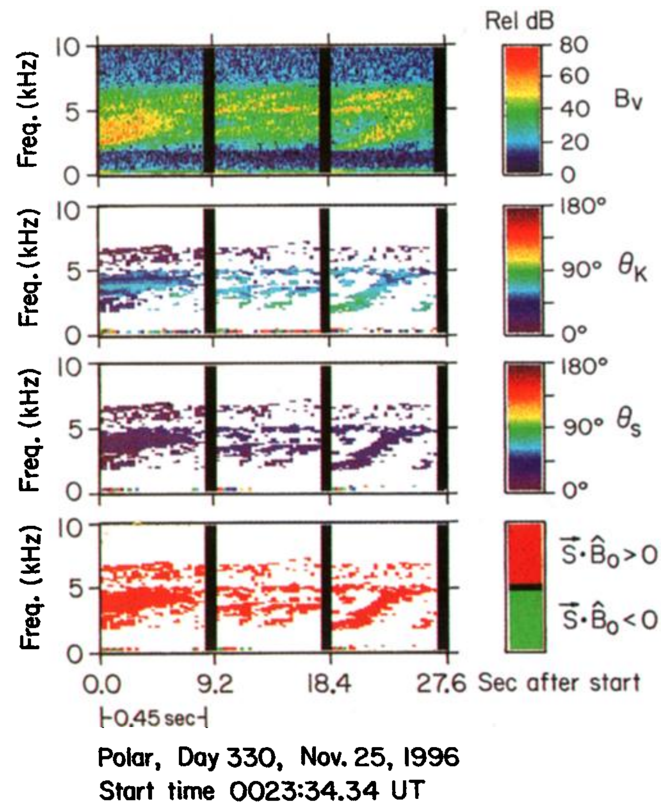

Figure 1. Frequency-time spectrograms of chorus observed by the Polar Plasma Wave Instrument. The top panel shows the magnetic field spectral density from the B_v-axis of the search coil magnetometer. The next two panels show the wave normal angle, θ_k, and the Poynting vector angle, θ_s, relative to the magnetic field. The bottom panel shows the sign of $S_z = \vec{S} \cdot \hat{B}_0$. The enhancement near zero frequency shortly after the beginning of each snapshot is an instrumental effect.

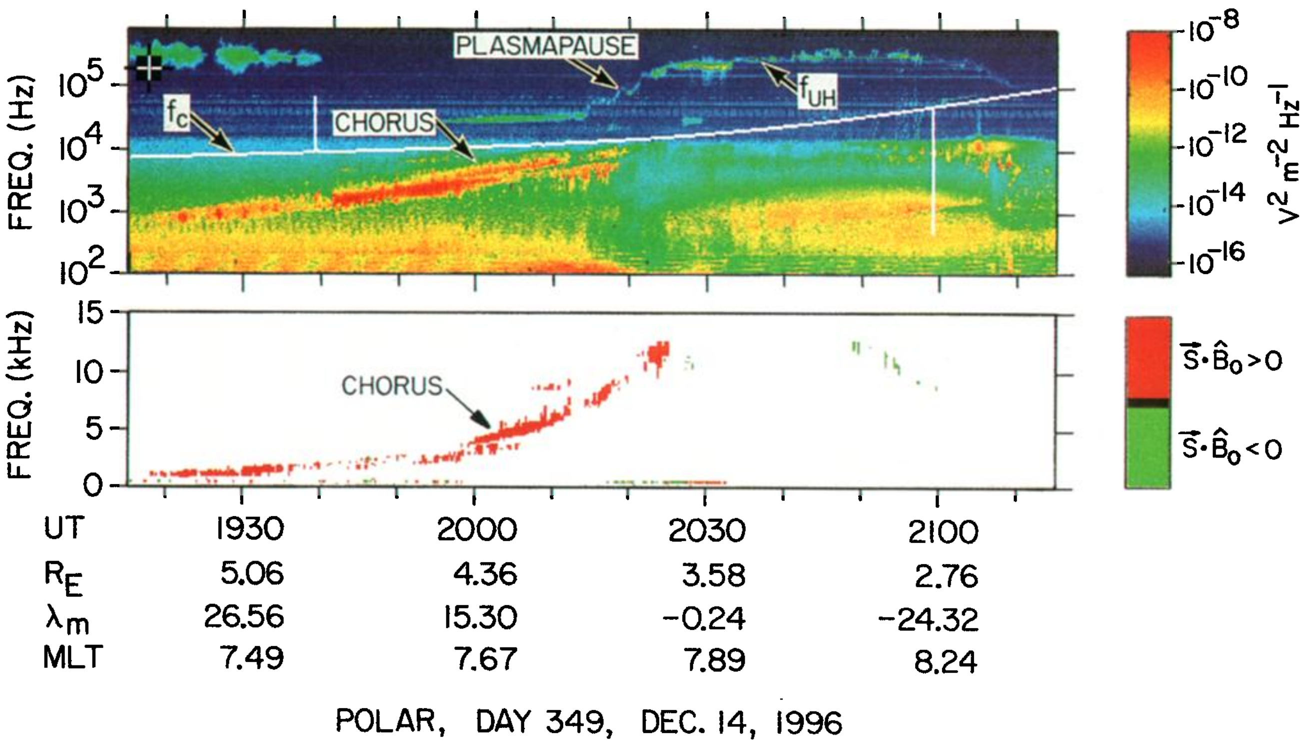

Figure 2. Spectrograms of chorus observed both north and south of the geomagnetic equator on December 14, 1996. The top panel is from the Sweep Frequency Receiver (SFR). Note the logarithmic frequency scale. The bottom panel is from the High Frequency Waveform Receiver (HFWR), and shows the sign of $S_z = \vec{S} \cdot \hat{B}_0$. Note the linear frequency scale.

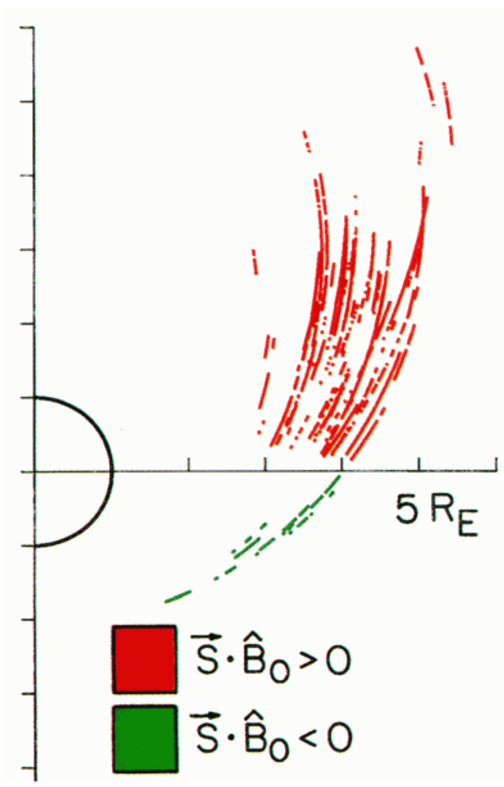

Figure 3. A magnetic meridian plane plot showing the direction of propagation of chorus with respect to the magnetic field. Events with $\vec{S} \cdot \hat{B}_0 \geq 0$ (red) are propagating northward, and events with $\vec{S} \cdot \hat{B}_0 \leq 0$ (green) are propagating southward. As can be seen, chorus always propagates away from the magnetic equator.

were rising tones and impulsive chorus. The observations were grouped into one-minute time bins and then separated into two categories, northward-propagating ($\vec{S} \cdot \hat{B}_0 > 0$) and southward-propagating ($\vec{S} \cdot \hat{B}_0 < 0$). The orbital paths for these two categories were then plotted in a magnetic meridian plot (radial distance versus magnetic latitude). The results are shown in Figure 3. As can be seen, in the northern hemisphere all of the chorus emissions are observed to be propagating northward ($\vec{S} \cdot \hat{B}_0 \geq 0$), and in the southern hemisphere all of the chorus emissions are observed to be propagating southward ($\vec{S} \cdot \hat{B}_0 \leq 0$). Thus, without exception, chorus is observed to be propagating away from the magnetic equator.

Discussion and Summary

We have shown that chorus observed in the northern magnetic hemisphere propagates northward away from the magnetic equator, and chorus observed in the southern magnetic hemisphere propagates southward away from the magnetic equator. These results provide conclusive evidence that chorus is generated very close to the geomagnetic equator. The transition from northward to southward propagation at the magnetic equator is very abrupt. There is no overlap of the regions of northward and southward propagation. The observations also show that there is essentially no evidence of high-latitude magnetospheric reflections, such as often occurs for lightning-generated whistlers inside the plasmapause [Smith and Angerami, 1968].

The very rapid transition from southward to northward propagation, within just a few degrees of the magnetic equator, implies that the chorus source region is extremely small, probably not more than a few thousand kilometers in north-south extent. The absence of an equatorward-propagating component implies that the wave does not grow to significant amplitudes until after it has crossed the magnetic equator. Since the wave reaches saturation amplitudes within about 3° of the magnetic equator, the growth rates must be very high. Assuming a convective instability, for typical whistler-mode group velocities near the equatorial plane, which are about 2×10^4 km/s, growth rates of at least 10^3 s^{-1} are required. For a discussion of chorus generation mechanisms, see Sazhin and Hayakawa [1992]. The almost complete absence of a reflected component indicates that the chorus emissions must eventually encounter strong damping as they propagate to high latitudes. In the absence of damping, reflection would occur as soon as the lower hybrid resonance frequency exceeds the wave frequency. The possibility of strong Landau damping at high latitudes has been previously suggested by Burton and Holzer [1974] and Goldstein and Tsurutani [1984]. They showed that chorus observed at high magnetic latitudes has larger wave normal angles than near the equator. However, the very large wave normal angles expected for magnetospherically reflected waves were not observed. Therefore, they concluded that the wave energy must be dissipated, probably by Landau damping, before the wave returns to the magnetic equator. Since there is no evidence of reflection, our observations rule out steady-state generation mechanisms that require multiple passes through the magnetic equatorial plane, such as the mechanism of Kennel and Petschek [1966].

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