Spectra of polar heliospheric fields and implications for field structure

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[1] The predictions of the "Fisk" model for a peak at the equatorial solar rotation frequency in the spectrum of the latitudinal component of the heliospheric magnetic field were found to give values significantly larger than those observed. The observed values were statistically the same as observed in the ecliptic and were consistent with random fluctuations about the (null) Parker field component. These conclusions are based on spectra of field and plasma quantities using Ulysses data from the first southern and northern polar passes. There was also no evidence for solar photospheric differential rotation in the latitudinal component. A related search for signatures of the differential rotation (not directly part of the Fisk magnetic field model) yielded the strongest evidence for a photospheric influence on the radial component of the solar wind velocity and related "compressive" quantities.

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1. Introduction

[2] The basic structure of the time-averaged heliospheric magnetic field is well predicted by the *Parker* [1963] model. It has been long known that the expected Archimedian spiral in the ecliptic and progressively more radial field in the polar regions is observed, especially at solar minimum when the heliospheric current sheet is relatively well-defined and stable [e.g., *Smith*, 2001]. Alfvénic fluctuations [e.g., *Goldstein et al.*, 1995] and structures [*Roberts et al.*, 2005, and references therein] are also common. Recently, *Fisk* [1996] considered the possible effects of the differential rotation of the solar photosphere and the superradial expansion of the magnetic flux tubes near the Sun. This model leads to significant modifications of the Parker field and in particular to a nonzero latitudinal component of the field in RTN coordinates (i.e., a component in the direction perpendicular to the radial and to the tangential in a spherical coordinate system). We might also expect to see signatures of the solar photospheric differential rotation directly in the measured heliospheric fields, and evidence that this latter is true was found by both *Zurbuchen et al.* [1997] and *Roberts and Goldstein* [1998] using different methods.

[3] Here we reexamine the low-frequency spectra of the polar fields, focussing on the above issues. Various different methods are shown to yield significant problems for the predictions of the Fisk theory, although it is possible that the parameters of the model have been incorrectly estimated or that the distance of the observation region from the Sun may lead to a dilution of expected signatures. This study may be considered to be complementary to that of *Forsyth et al.* [2002], who found similar conclusions through a careful examination of the time series domain.

2. Data Sets and Analysis Procedure

[4] Ulysses data provide an excellent set for understanding the above questions. Figure 1 shows the wind speed, radial magnetic field, and spacecraft heliocentric latitude as a function of time using hour-averaged data from COHOWeb, which is the basis of most of our analysis. The study of *Roberts and Goldstein* [1998] focused mainly on the interval from day 247 of 1992 to day 90 of 1993 when Ulysses was in one magnetic sector but was periodically sampling the polar wind. Here we focus on the two intervals either side of the "fast latitude scan" in which the speed is nearly constant and the spacecraft is immersed in simple streams from polar coronal holes. Our intervals are at about 3–4 AU from the Sun. We also use 30 years of hourly averaged solar wind data upstream of the Earth from the OMNI data set prepared by J. King for comparison.

[5] Our analysis consists primarily of finding spectra by Fourier analysis. We will use zero-padding to improve the accuracy of spectral peak determination when searching for evidence of photospheric rotation. (Zero-padding is the addition of zeros to the end of the time series such that, for example, doubling the length of the time series produces half the frequency spacing in the Fourier series; this will not

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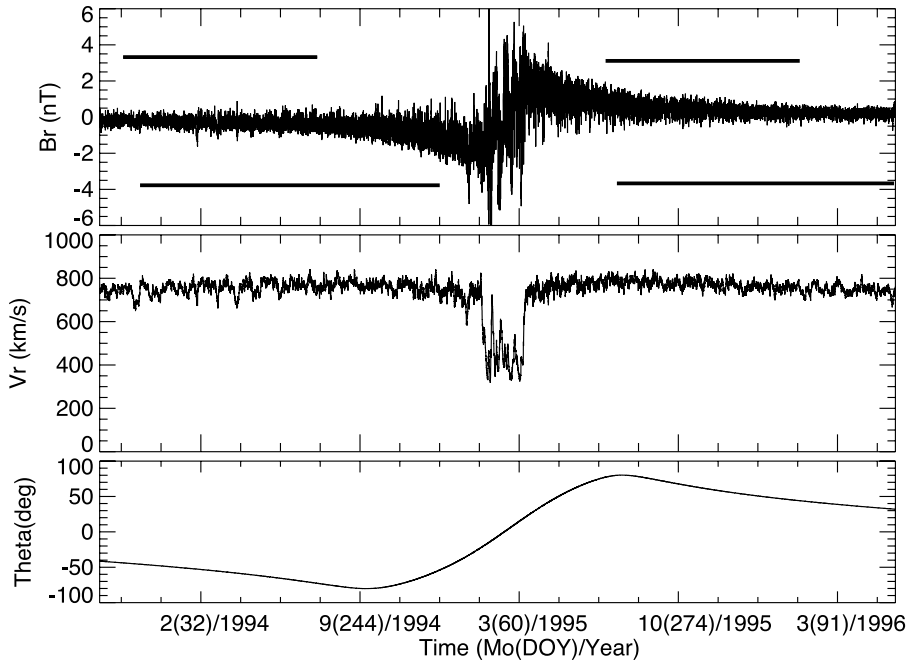

Figure 1. The latitude of Ulysses along with measurements of the radial components of the magnetic field and velocity for the interval of interest here. We use time series from the southern (left) and northern (right) hemispheres, well away from the region of the "fast latitude scan" current sheet crossing and slow flow in the middle of the graph. Approximate intervals for Figure 3 are shown below the B_r trace and for Figures 4 and 6 by the lines above the B_r trace.

find new peaks, but it determines peaks more precisely, as shown, e.g., by *Marple* [1987].)

[6] Figure 2 shows a spectrum of 30 years of the normal component of the magnetic field using OMNI2 data, from 1985 to 2005. This spectrum will be discussed in another paper in more detail, but here we note only that there is very little evidence of any mode structure and that the spectrum through the range that includes solar rotation frequencies (a few tenths of microHertz) is quite flat. Thus in the ecliptic, the normal component of the magnetic field is seen to be quite insensitive to solar rotation or any other periodic effects. In what follows, we test this for high-latitude measurements where complications due to nonuniform flows and sector structure do not enter.

3. Test of Predicted Latitudinal Fields

[7] *Zurbuchen et al.* [1997] used the ideas of the Fisk et al. model to derive expressions for the heliospheric magnetic field. The most striking difference between these predictions and those of Parker is the presence of a field in the N direction in RTN coordinates. The prediction is

$$B_N = \frac{B_0 r_0^2}{Vr}\omega \sin(\beta)\sin\left(\phi(t) + \frac{\Omega r}{V} - \phi_0\right)$$

where B_0 is the magnetic field strength at a reference position r_0, V is the solar wind speed, r is its radial distance from the Sun, and Ω is the equatorial rotation rate of the Sun. As expected, this field vanishes in the absence of superradial expansion, parameterized by β, the angle of the field line from the heliographic pole at the source surface and the rotation axis, and differential rotation, given by ω, the difference between the equatorial and higher latitude rotation rates. We ignore ϕ_0 since it does not affect spectra or our other conclusions. Here we use Ulysses data to test the prediction for B_N due to the simplicity of the flows seen

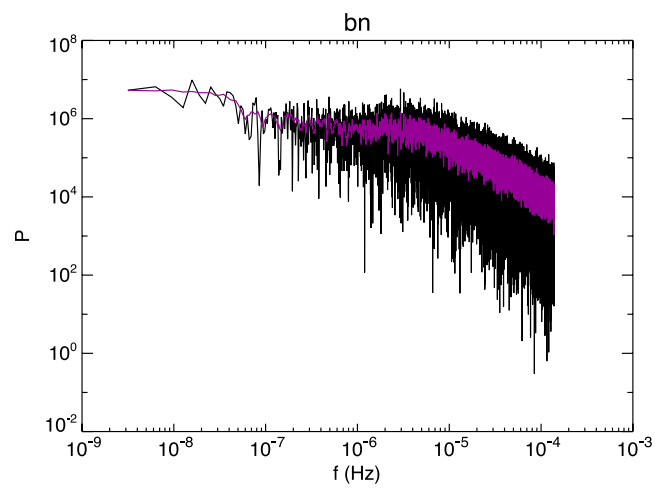

Figure 2. A reference spectrum of B_N in the ecliptic from the OMNI dataset for 30 years of data from 1975 to 2005. The black line is the unsmoothed spectrum, and the colored line in the middle is the spectrum smoothed with a 50-point running window that has been phased in at the ends by including successively more points. Note that there is no evidence of solar rotation, annual, or solar cycle effects, as are seen in other field components.

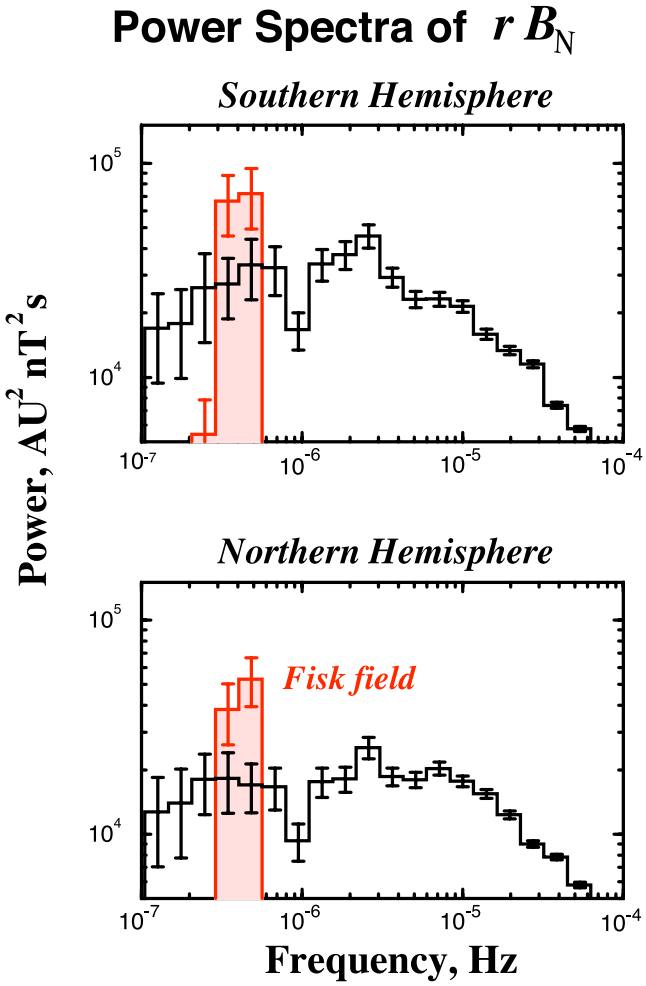

Figure 3. Spectra of the normal ("θ") component of the magnetic field for both hemispheres, compared to the predictions from equation (1) along the Ulysses trajectory. The interval for the southern pass covers 1993, day 292 through 1995, day 1. The northern pass covers the period 1995, day 180 through 1996, day 179.

there, although in principle the predicted normal field should also be seen in the ecliptic. We use direct measurements for the product at the beginning of this expression through:

$$B_0 r_0^2 = B_R r^2$$

where B_R is the measured radial field at the distance r from the Sun. The other quantities in B_N are given by Zurbuchen et al., except for ϕ which is the spacecraft longitude in Carrington coordinates. Thus following Zurbuchen et al., we use a value of 30° for β and of 0.068 radians/day for ω. The value of ϕ is very nearly equal to Ωt since the inertial motion of the spacecraft in longitude is small, so the primary predicted frequency for B_N is that of the equatorial rotation rate. We use the spacecraft longitude for ϕ, thus taking into account the spacecraft motion.

[8] Figure 3 shows a conventional spectrogram of rB_N for northern and southern polar fields (weighted by r to remove possible radial evolution effects, although they are small), compared to the predictions of the above formula, where, to remove effects of the spacecraft motion, the power spectrum of the model is also taken along the trajectory of Ulysses. We compute power spectral density by first determining the autocorrelation function, R of a time series of $x = rB_N$ for the interval of interest, and then taking a Fourier transform of R. (See equations (7.32), (7.49), and (7.50) of *Bendat and Piersol* [1966].) We then sum the power spectrum into bins that are equally spaced on logarithmic scale to reduce the uncertainty in the estimate, leading to the error bars shown. The predicted spectral peak is broad due to the binning, but the main point is that the predicted peak is not observed. We show spectra for northern and southern Ulysses passes in Figure 3, but using halves of the time intervals for the analysis leads to the same conclusions. The ratio of predicted power to observed power at the peak of the predicted spectrum is in the range of 3 to 5. In general we find that the spectrum of the normal component over the poles of the Sun is very similar to that shown in Figure 2 for the ecliptic,

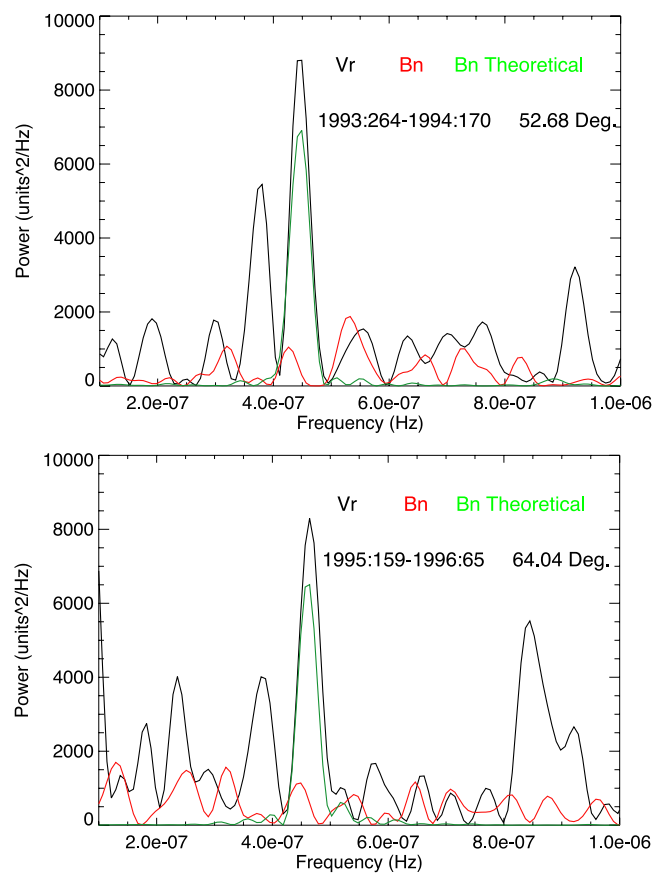

Figure 4. Spectra on a linear scale from northern (bottom) and southern (top) regions for the radial component of the velocity and for theoretical and measured normal components of the magnetic field. The radial velocity shows peaks for both the coronal hole rotation with a period of 27 days (0.45 μHz) and the differential rotation period of about 33 days (0.35 μHz). The time series have been zero-padded to increase the accuracy of the peak determination. The vertical scales are arbitrary but consistent for all the magnetic fields.

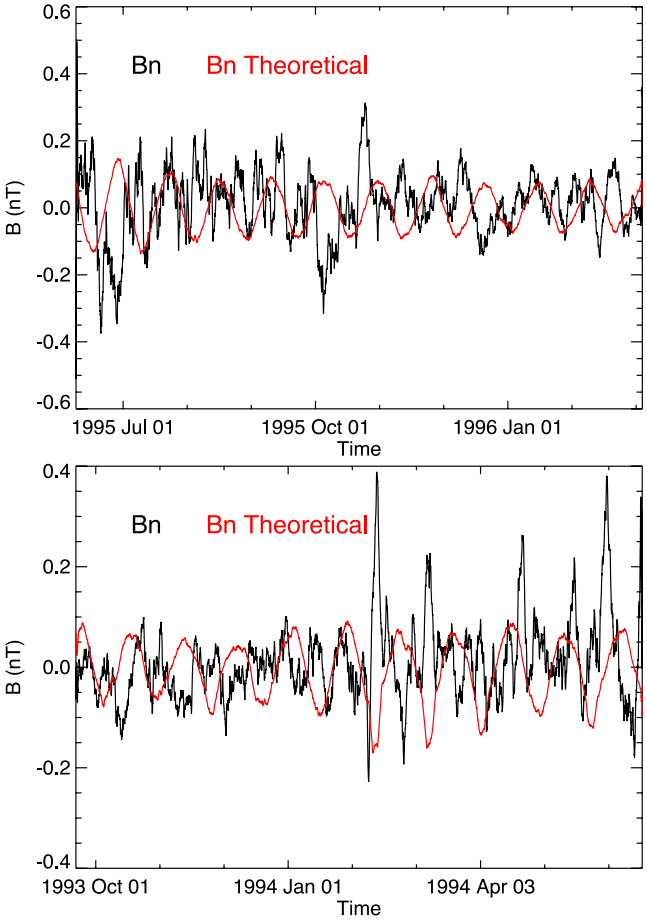

Figure 5. Theoretical and measured time series of B_N based on hour-averaged values, both smoothed by 101 points (≈4 days). Note that changing the relative phase of the series would not improve the comparison.

with no prominent features. Subintervals of the current intervals yield the same basic results.

[9] Results of other ways of looking at the data are shown in the next two figures. For Figure 4, time series from intervals similar to that in Figure 3 have been zero-padded (the total series length was doubled) to increase the accuracy of the spectral peaks [see *Marple*, 1987], and no binning or smoothing has been done. The resulting spectra have larger error bars (roughly a factor of two), but peaks are sharper and qualitative results are clear. The theoretical spectrum is seen to have a peak near the equatorial solar rotation frequency, whereas the measured spectrum (in the same units) has no significant power at that frequency, similar to that in the ecliptic. A peak of comparable significance and essentially the same period as that in Figure 7 of *Zurbuchen et al.* [1997] can be seen at 0.53 μHz (21.3 days). The 20 day peak could possibly be due to the mechanism suggested by Zurbuchen et al., although we note that this peak is less prominent in the the northern hemisphere, and there are a number of other peaks that are of comparable significance that are not easily explained in the same way. For comparison, the spectrum of the radial velocity (arbitrarily scaled) shows very strong peaks at both the equatorial and higher-latitude slower rotation rate presumably indicative of the region of origin of the wind [*Roberts et al.*, 1987]. Note that the peaks in the velocity spectrum, while interesting, are not directly related to the Fisk model; the peak at the equatorial rotation frequency simply reflects the fairly rigid coronal hole rotation.

[10] Figure 5 offers a direct comparison of the N-component time series from the formula above compared to the observations. Here we have not performed the projection and averaging procedures of *Zurbuchen et al.* [1997], except to smooth the series with a 101-hour window to eliminated higher-frequency fluctuations. The overall amplitude of the curves is comparable, but the phases shift over the time interval, and the measured curve is much less sinusoidal, consistent with the spectrum. The lagged correlation between the two time series varies between −0.2 and +0.2, which shows that no phase shift significantly improves the result. While our method is simpler than that of Zurbuchen et al., we believe it offers some insight. The predictions should hold for this case, in that the smoothing removes random effects. The analysis here in the time domain was approached in this and other ways by *Forsyth et al.* [2002] who concluded that the likely cause of most of

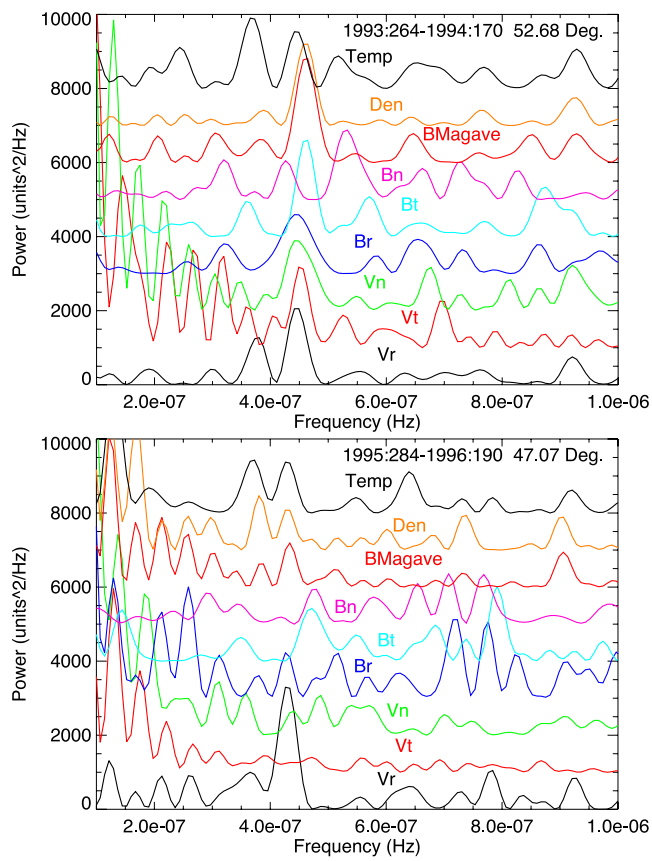

Figure 6. Spectra similar to Figure 4 with the southern hemisphere spectra on the top, but for many quantities. The zeros are offset by 1000 units per spectrum for clarity. Note that the "compressive" quantities such as density, temperature, and the radial velocity are the ones showing the clearest signs of a differential rotation peak at approximately 0.35 μHz.

the variations of the polar fields seen by Ulysses were due to Alfvén waves, although they could not rule out a small contribution from the effects suggested by Fisk.

4. A Search for Further Evidence of Photospheric Differential Rotation

[11] The spectra shown thus far show evidence for both the coronal hole rotation rate and, in the radial flow speed, the slower differential rotation rate of the source region of the wind. It is useful to look for similar evidence in other variables. Figure 6 shows spectra for nine variables using the same zero padding as in Figure 4. The density, temperature, magnetic field magnitude, and radial velocity all show double peaks either side of 0.4 μHz, indicative of the coronal and differential rotation periods. For the southern (top) pass, all the fields except for B_N show a peak at the coronal hole period, whereas for the northern pass this peak also is absent in V_N and B_T. The northern pass shows a possible differential rotation peak for B_R in addition to the above-mentioned variables. Most of the transverse quantities, including B_N, show no peak near that of the "compressive" quantities such as V_R.

5. Discussion and Conclusions

[12] The primary results of this paper are that (1) the evidence for differential rotation in fields likely to have their origin in polar coronal holes is primarily confined to "compressive" quantities (temperature, density, radial velocity), and (2) the predictions of a quantitative realization of the Fisk model for B_N produces predictions not seen in the observations at 2–4 AU in Ulysses data. The polar N-component spectrum looks very much like the very long time average spectrum of the equatorial field shown in Figure 2; both are essentially featureless, consistent with stochastic variations about a mean Parker field of zero.

[13] The three assumptions underlying the derivation of the Fisk field are most clearly and succinctly stated by *Fisk et al.* [1999]. Of these, the assumption of frozen-in magnetic field and differential rotation and nonradial flow are almost certainly true. This leaves open assumption 3, which states essentially that the nonradial expansion is about the magnetic axis, which rotates rigidly. The consequences follow from these assumptions. These assumptions, while based on sound physics, oversimplify a highly complex and variable coronal boundary condition. During the southern polar pass of Ulysses, which occurs well before solar minimum, the coronal holes have many extensions and they evolve considerably over the multiple rotations included in the analysis to find correlation functions and spectra. The situation may not be sufficiently stationary to produce the expected effects coherently. Even during the northern pass, when the Sun is at its lowest activity level, discrepancies from the model assumptions exist. A preliminary examination of the LASCO coronal images from SOHO leads us to suggest that the value of β in the model equations used above may be too large; a factor of two would produce a factor of four in the spectrum which would make the prediction statistically consistent with the observation, although so small as to make it hard to distinguish from noise. Also, the coronal holes (which are still not simple in Yohkoh soft X-ray images) do not align with the perpendicular to the current sheet, represented by the streamer belt, and thus it is not clear what the magnetic axis should be for this case. In this instance, the flows from the coronal holes look fairly symmetrical about the rotation axis in SOHO EIT images, which would further weaken the effect. In short, the results obtained in this paper constrain the global magnetic field models, but not yet in such a way as to rule out the physics of the Fisk scenario, which we still find plausible.

[14] Another possible interpretation of the difference between the predicted and observed differential rotation results is that the boundary conditions at the Sun that determine flow speed, such as pressure and density, depend on the local thermodynamic conditions at the solar surface. The speed variations will produce other compressive variations, and these will be reflected in signatures at the differential rotation frequency. Magnetic field signatures, and transverse velocity perturbations that might be associated with them, depend more on the lower-order moments of the solar field that lead to rigid coronal hole rotation. This could lead to the observed lack of differential rotation signature for magnetic components. The normal component of the magnetic field, in the conventional picture, would not be affected by sector structure and would be independent of the radial flow speed since it is nonexistent in the Parker model.

[15] In addition to the above considerations, there is at least one other concern about testing predictions of the Fisk model. The heliospheric fields are known to be dynamically evolving at all scales [e.g., *Roberts et al.*, 1987], and thus it could be that signatures near the Sun have been modified by nonlinear interactions in passage to the point of observation. We do not currently understand the large-scale dynamics of the field sufficiently well to rule out this possibility. A significant difficulty with this is that the primary predicted peak, namely at the equatorial rotation frequency, is well-preserved in many quantities but is not present at a significant level in B_N. Further modeling will be needed to fully resolve this issue.

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