ULYSSES OBSERVATIONS OF LATITUDE GRADIENTS IN THE HELIOSPHERIC MAGNETIC FIELD

E. J. Smith,[1] A. Balogh,[2] R.P. Lepping,[3] M. Neugebauer,[1] J. Phillips,[4] and B. T. Tsurutani[1]

[1]*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099*
[2]*The Blackett Laboratory, Imperial College, London SW72BZ*
[3]*Goddard Space Flight Center, Greenbelt, MD 20771*
[4]*Los Alamos National Laboratory, Los Alamos, New Mexico 87.54.5*

ABSTRACT

Several parameters measured by Ulysses as it traveled southward to heliographic latitudes of -50° are presented and analyzed. The radial component of the magnetic field, averaged over 5° latitude increments and extrapolated back to 1 AU, is found to agree with baseline measurements provided by IMP-8, There is little, if any, evidence of a latitude gradient, a result consistent with the dominance of the magnetic field associated with the heliospheric current sheet and with recent models which include the effect of the current sheet as well as of source surface fields. Thus far, the spiral angle agrees with the Parker spiral assuming a rate of rotation of the field lines at the Sun equal to the equatorial value. No evidence is seen of either a change in rotation rate with latitude or an unwinding of the spiral as suggested by a recent analysis, Hourly variances in the field magnitude and in the sum of the variances in the components, normalized to the square of the observed field strength, show the former to be independent of latitude while the latter shows a strong increase with latitude. These two observations are shown to be associated with Alfvén waves that are continuously present at high latitudes. The waves have large amplitudes, extend to long periods, and have important implications for galactic cosmic rays and the solar wind,

INTRODUCTION

The measurements to be described were acquired by the magnetometer /1/ and plasma analyzer /2/ on the Ulysses spacecraft. Data were acquired after Ulysses left Jupiter and began traveling southward enroute to 80° idiographic latitude. Recent data taken at latitudes up to -50° are included. Three topics of scientific importance are investigated: (1) the latitude gradient in the radial field component, B_R; (2) the extent of agreement between the observed and Parker spiral angles near -50°; (3) the field variances and their interpretation which chiefly concerns large amplitude Alfvén waves discovered at the highest latitudes sampled. In each case, the observations are compared with theory.

LATITUDE GRADIENTS IN B_R

The measure that we have studied is the average value of B_R in negative sectors only. This choice avoids several problem. over intervals such as a solar rotation, the average value of B_R is relatively small at the radial distance of Ulysses and relatively large fluctuations are superposed on it, especially at high latitudes. Use of the modulus, $/B_R/$, involves the risk of rectifying the power in these fluctuations anti having them contribute to the average. Both sectors are present in the baseline, in-ecliptic data (IMP-8) but, above ≈-30° latitude, only a single negative sector ($P<0$) is observed by Ulysses /3/.

Figure 1 shows the average, $<B_R>$, at Ulysses extrapolated back to 1 AU assuming an r^{-2} dependence. Also shown is $<B_R(P<0)>$ from IMP-8 which provides the baseline against which to compare the higher latitude Ulysses observations. The averages were computed over 5° latitude intervals as shown along the bottom scale. The two sets of averages agree quite well and yield an average value of --3.5 nT.

Another point of comparison is provided by the field strength at the solar wind source surface such as those routinely published in *Solar Geophysical Repot-m* by Stanford University. The data shown are also extrapolated to 1 AU after averaging the source surface fields at the latitude of Ulysses over successive solar rotations, The values so obtained are smaller than the observed values by a factor of -2 even when increased to allow for instrumental effects /4/.

The reason for the absence of a strong latitude gradient is the dominance of the field associated with the current sheet (CS). The simplest model of the source is an interior dipole, the spherical source surface and the exterior current sheet. In Figure 2, due to Wolfson /5/, the contribution designated CS is the field of the current sheet which is independent of latitude and reverses sign at the equator. The source surface currents, assuming as usual that the field is radial at that location, lead to diverging field lines with a null at the equator (a neutral line), and increasing values toward the poles (SS). The third field model is that of Pneuman & Kopp /6/, PK included as a point of reference, which basically agrees with the resultant of the other two as expected. The figure shows that the CS field is dominant over a broad range of latitudes as in Figure 1. Recent models for the source surface field including the effect of the CS have been developed by Wang /7/ /8/ and by Zhao and Hoeksema /9//10/. They confirm that any changes in B_R would still be small at the latitude of Ulysses.

THE SPIRAL ANGLE

The most fundamental aspect of Parker's theory /1 1/ is the spiral angle of the field which derives from a vanishing of the steady electric field in the solar wind frame and is given by

$$\tan\psi_p = B_T/B_R = -\Omega r\cos\delta/V_R. \qquad (1)$$

The field components are expressed in solar heliospheric (R, '1', N) coordinates and Ω, r, δ and V_R are the angular velocity of the Sun, radial distance, heliographic latitude and the radial component of the plasma velocity.

In comparing theory with observation, several considerations need to be taken into account. First, the Ulysses distribution functions for $\psi = \tan^{-1}(B_T/B_R)$ are highly asymmetric and the mean and mode (most probable value) differ by 10°-20°. Second, the inverse tangent is a non-linear function which may influence the distribution of the angles in the presence of fluctuations. Finally, the variations in ψ_P associated with the limited variations in V_R at high latitude are restricted to a narrow range of about ±10°. Thus, Parker's model can only be tested near the peak in the distribution. The deviations in the angle in the wings of the distribution have some other cause, unrelated to the Parker equation, such as waves and discontinuities.

Figure 3 shows the projection of $\vec{B}$ onto the RT plane. The X_p axis is parallel to the Parker spiral, a coordinate transformation that simply involves a rotation through angle, ψ_P, based on Equation 1. The individual points are the tips of the field vector corresponding to one-minute averages of B_{XP}, B_{YP}. The distribution functions viewed from the X_p and Y_p directions are also shown. The field vectors tend to lie on a circle of finite width consistent with nearly constant magnitude. The distribution functions show that the most probable value of B_{YP} is zero, indicating agreement with the Parker equation.

This result is consistent with many years of in-ecliptic observations which also agree with Parker's model, *e.g., /12/,* There is an absence at high latitude of any unwinding of the Parker spiral as suggested by the analysis of Smith & Bieber /13/. There is no evidence of a significant change in Ω with latitude, the equatorial value corresponding to a sidereal period of 25.4 days having been used to compute ψ_P .

FIELD VARIANCES: ALFVÉN WAVES

The variances are a measure of the irregularity in the heliospheric magnetic field. Initially, we have concentrated on two measures, the variance in the field magnitude, σ_B^2, and the sum of the variances in the components, $\sigma_S^2 = \sigma_R^2 + \sigma_T^2 + \sigma_N^2$. The variances have been normalized by dividing by B^2, the square of the field magnitude, since the ratios are remarkably constant in the ecliptic over a large range of radial distances. The variances were computed over intervals of one hour and then averaged over successive latitude intervals of SO. Hourly values are considered to be representative of the background field fluctuations while avoiding large-scale variations associated with solar wind structure or CMEs.

The results appear in Figure 4. The power in the magnitude variations is relatively small as compared to σ_S^2/B^2 and is independent of latitude. By contrast, the power in the directional changes increases markedly with latitude.

The origin of large σ_S^2 values is evident when the data are inspected as in Figure 5. Over this interval of nearly one solar rotation, there are large variations in all three components with little simultaneous variation in /B/. The variations are reminiscent of Alfvén waves such as those commonly seen in the ecliptic and which might be expected as a result of the firehose instability, e.g./14/.

The Alfvén wave hypothesis has been tested by comparing the magnetic field with the solar wind plasma measurements and by comparing both with theory, Figure 5 contains the three components of V superposed on those of $\vec{B}$ in the manner of Belcher & Davis /15/. A good correlation (≈0.8) is evident, particularly in the transverse (T, N) components. The correlograms of the latter yield slopes, $\delta V/\delta B$, of 31 and 42 km/s nT.

This observed value has been compared with theory which implies

$$\frac{\delta V}{\delta B} = \pm(4\pi\rho)^{-1/2}\,\eta \tag{2}$$

where $\eta = 1 - (P_{\parallel} - P_{\perp})\big/\left(B^2/4\pi\right)$.

The effect of the pressure anisotropy has been included, with $P_{\|}, P_{\perp}$ being the plasma pressures parallel and perpendicular to $\vec{B}$, and ρ is the mass density of the protons and alpha particles. The ± sign, the observed positive correlation and the polarity of the magnetic field (inward) imply that the waves are propagating outward. A variance analysis indicates they are propagating principally along the radial direction.

Substitution yields and average value for $(4\pi\rho)^{-1/2}\,\eta$ of 35 km/s nT. The average value of η is 0.7. Since the product is less than 1, the plasma at the point of observation is not subject to the firehose instability. The Alfvén speed, however, is 0.7 times what it would be in the absence of the pressure anisotropy.

As can be seen, the waves have large amplitudes with peak to peak excursions comparable to the average magnitude, i.e. $\delta B/B \approx 1$. The periods (wavelengths) are long extending down to at least 10 hours (0.3 AU). They may be the waves postulated by Jokipii & Kota /16/ and discussed by Hollweg & Lee /17/. They can be expected to resonate with particles having energies between 10 MeV and 1 GeV and may, therefore, exert a strong influence on the motion of incoming galactic cosmic rays /18/. Hollweg /19/ has shown that the Alfvén waves can influence both the linear and angular momentum carried by the solar wind.

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Figure Captions

Fig. 1. Latitude Gradient in B_R. Averages of B_R over 3 solar rotations (77 days) in negative sectors are shown both in the ecliptic at IMP-8 (squares) and at Ulysses (circles) between -8 and -55° heliographic latitude (top scale). Also shown are solar rotation averages of B_R at the solar source surface extrapolated to 1 AU.

Fig. 2. Comparison of Three Models of Solar-Heliospheric Magnetic Fields. The bottom panel shows the field line topology for the three models: CS = dipole plus Current Sheet (solid), SS = Source Surface field for an interior dipole (dots), PK = Pneuman and Kopp model (dashes). The SS field lines diverge radially and do not produce an external current sheet, The upper panel shows the latitude variation associated with each model, The CS field is independent of latitude (except for sign), the SS field changes gradually and the PK field is a superposition of the current sheet and the dipole field deformed by currents in the corona. [From Wolfson /5/].

Fig. 3. Comparison of the Observed and Parker Spiral Angles. The upper left panel contains dots representing one-minute averages of B_R, B_T transformed into a coordinate system with Xp along the Parker spiral (as given by equation (1)). Two histograms for B_{XP} and B_{YP} are shown, the latter (upper right) showing agreement between the observed field direction and the Parker spiral,

Fig. 4. Magnetic Field Variances as a Function of Latitude. The circles show σ_S^2/B^2 (hourly values) averaged over successive latitude intervals of 5°. The squares are corresponding averages of σ_B^2/B^2. The power in the directional field changes increases dramatically with latitude whereas the power in the changes in field magnitude does not.

Fig. 5. Components of Solar Wind Magnetic Field and Velocity at -43° Latitude. The three field components and magnitude (in nT) are shown with the scale to the left. The three velocity components are superposed on the field with the scale (in km/s) on the right. The field magnitude and speed occupy the bottom panel. In the two middle panels it is difficult to distinguish the field from the velocity components because they are highly correlated indicating the variations are attributable to Alfvén waves.

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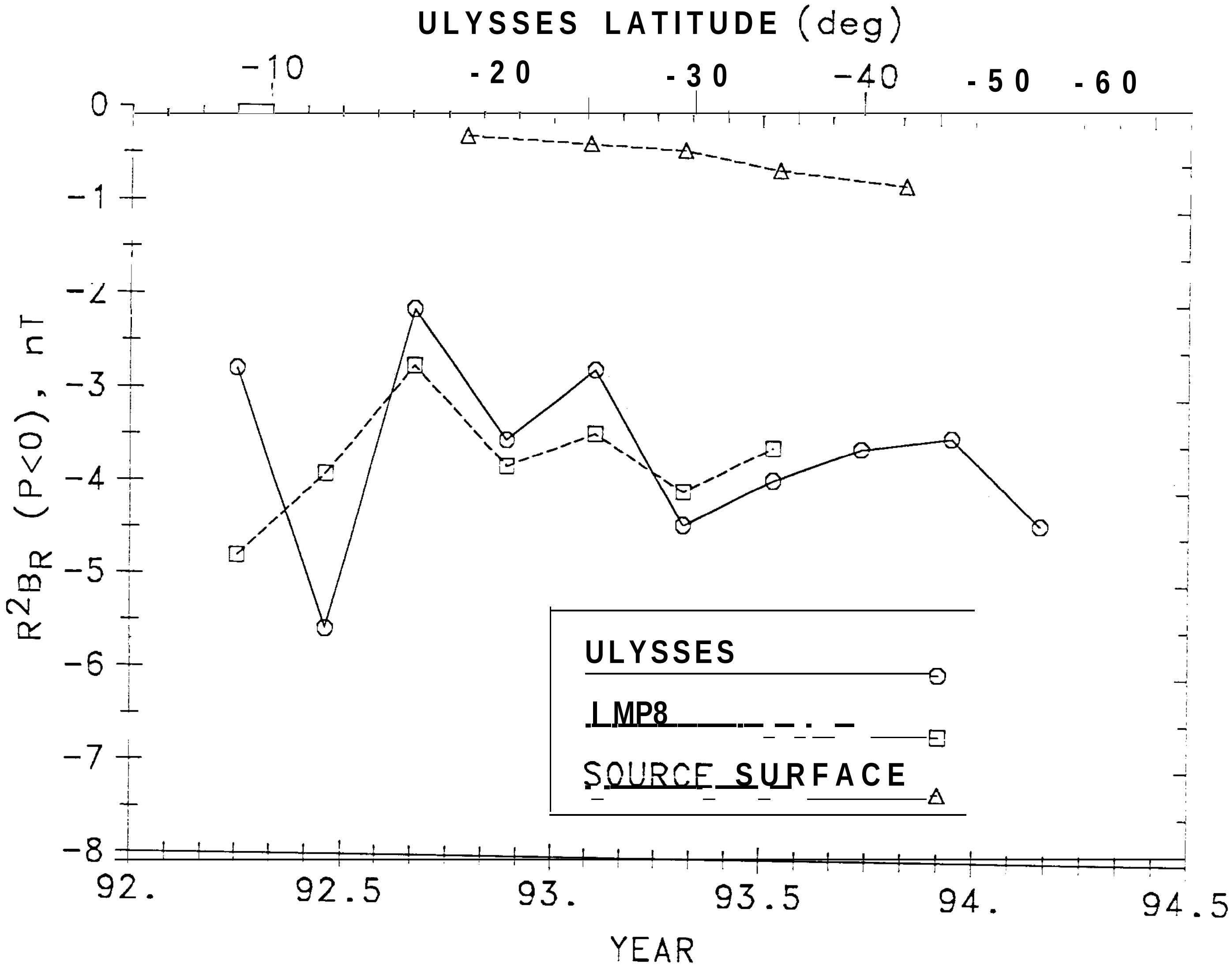
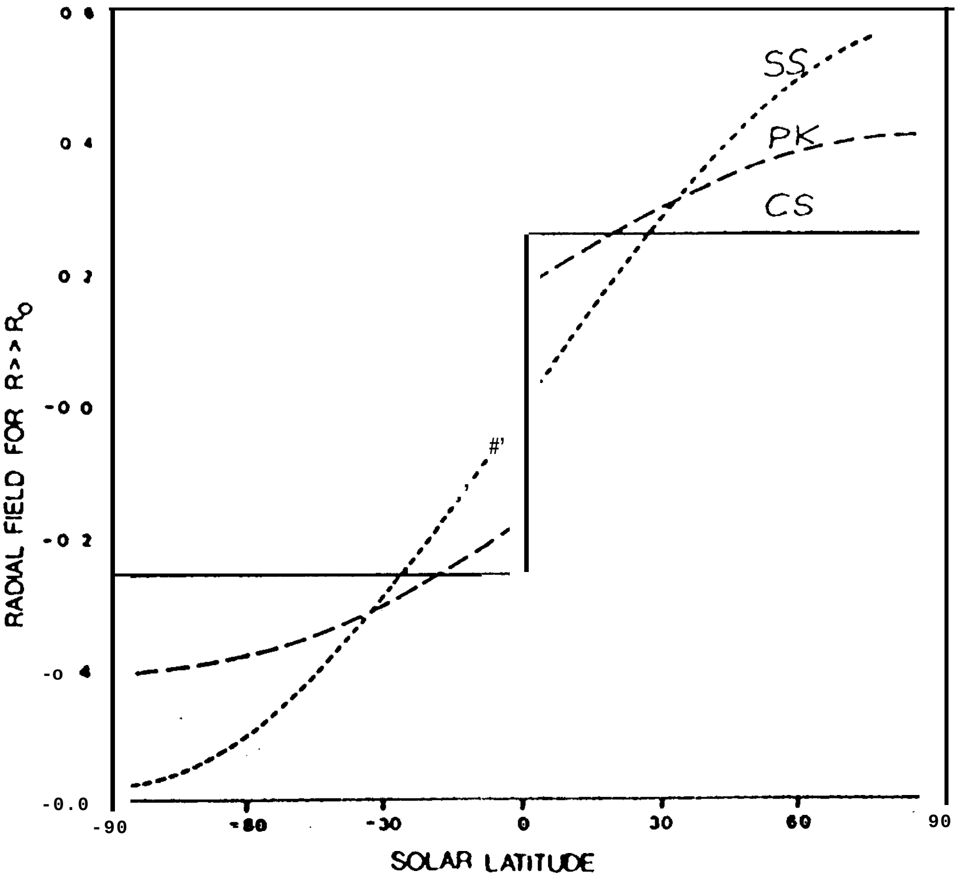

ULYSSES LATITUDE (deg)
-10
-20
-30
-40
-50
-60
0
-1
-2
-3
-4
-5
-6
-7
-8
R^2B_R (P<0), nT
92.
92.5
93.
93.5
94.
94.5
YEAR
ULYSSES
IMP8
SOURCE SURFACE

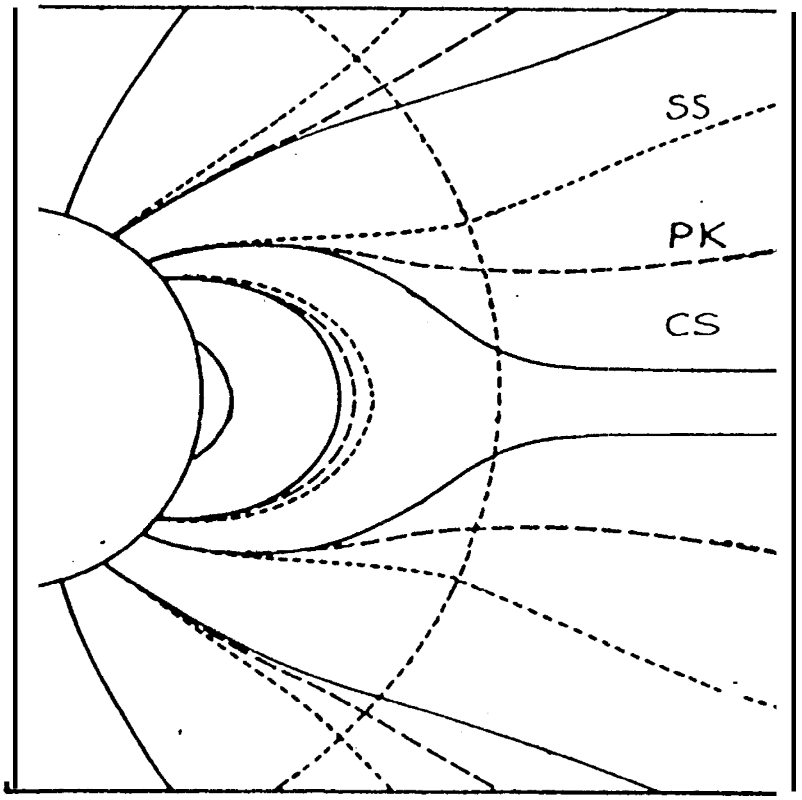
1.



C S ___, Current Sheet

PK ---- Pneuman - Kopp

SS ------- Source Suds.ce



2.

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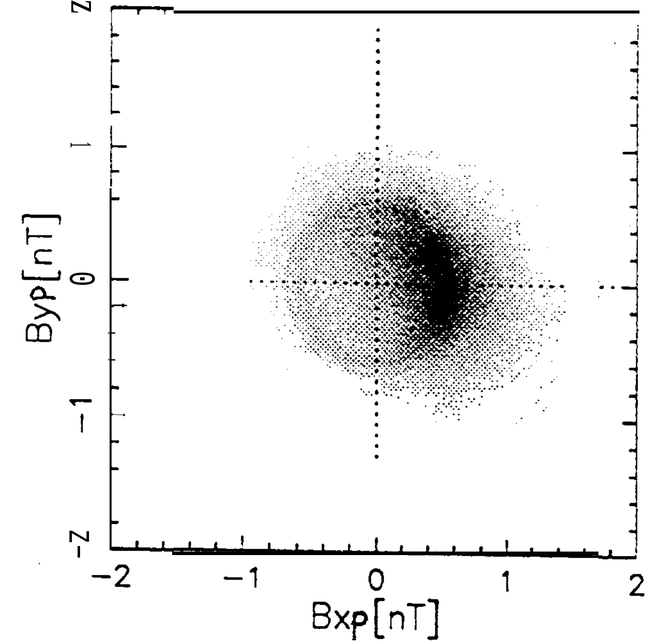
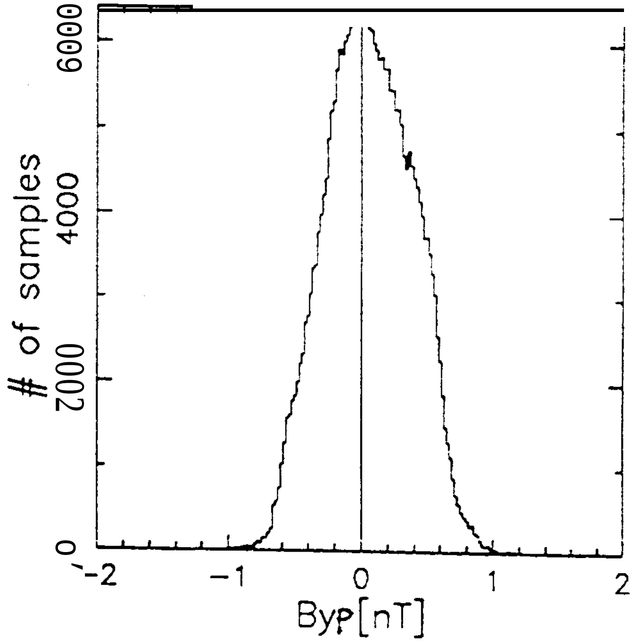


Byp distribution



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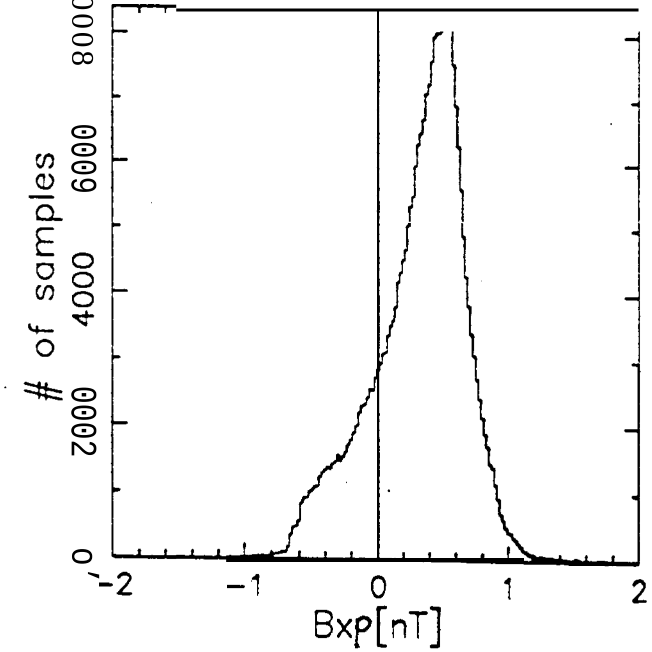

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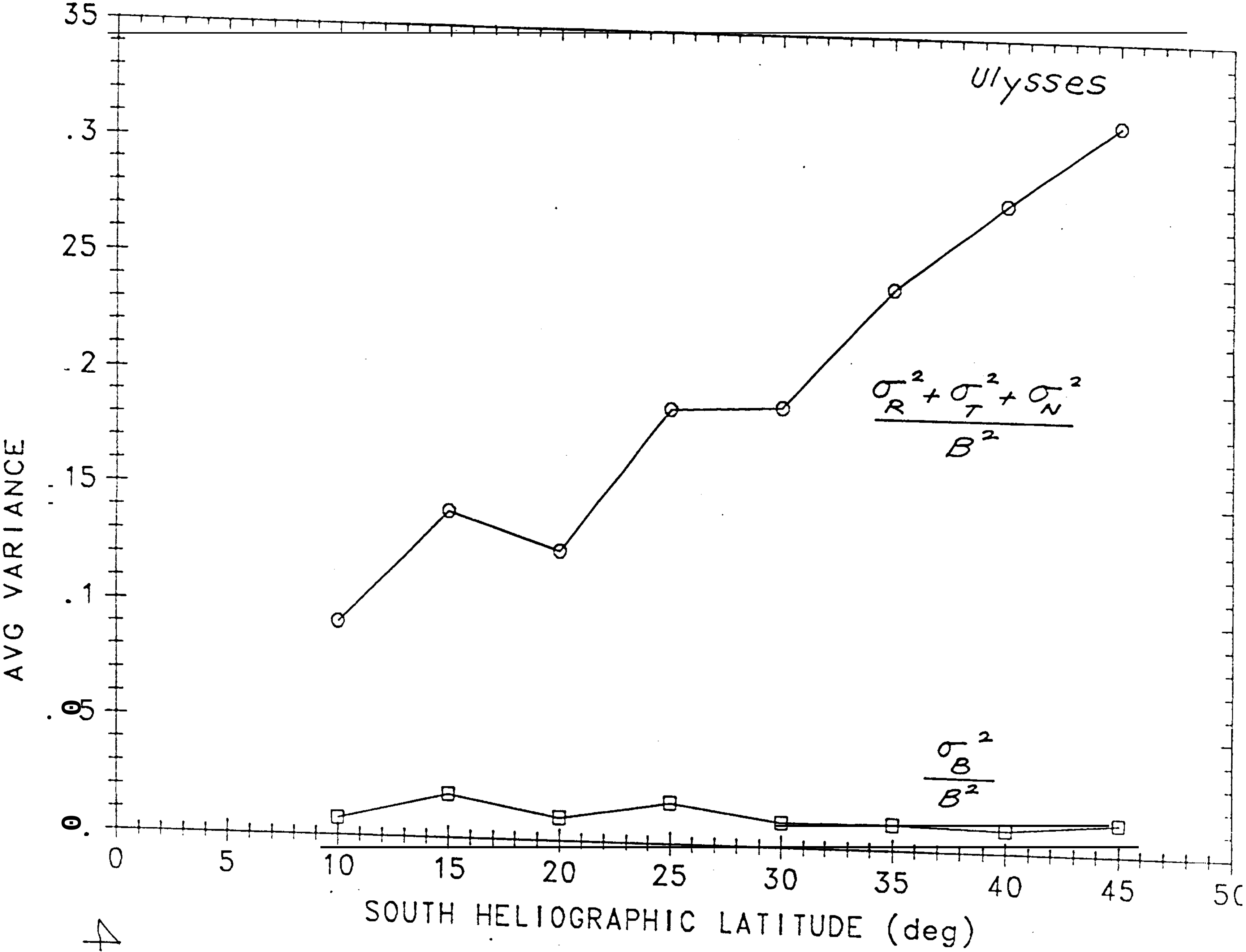
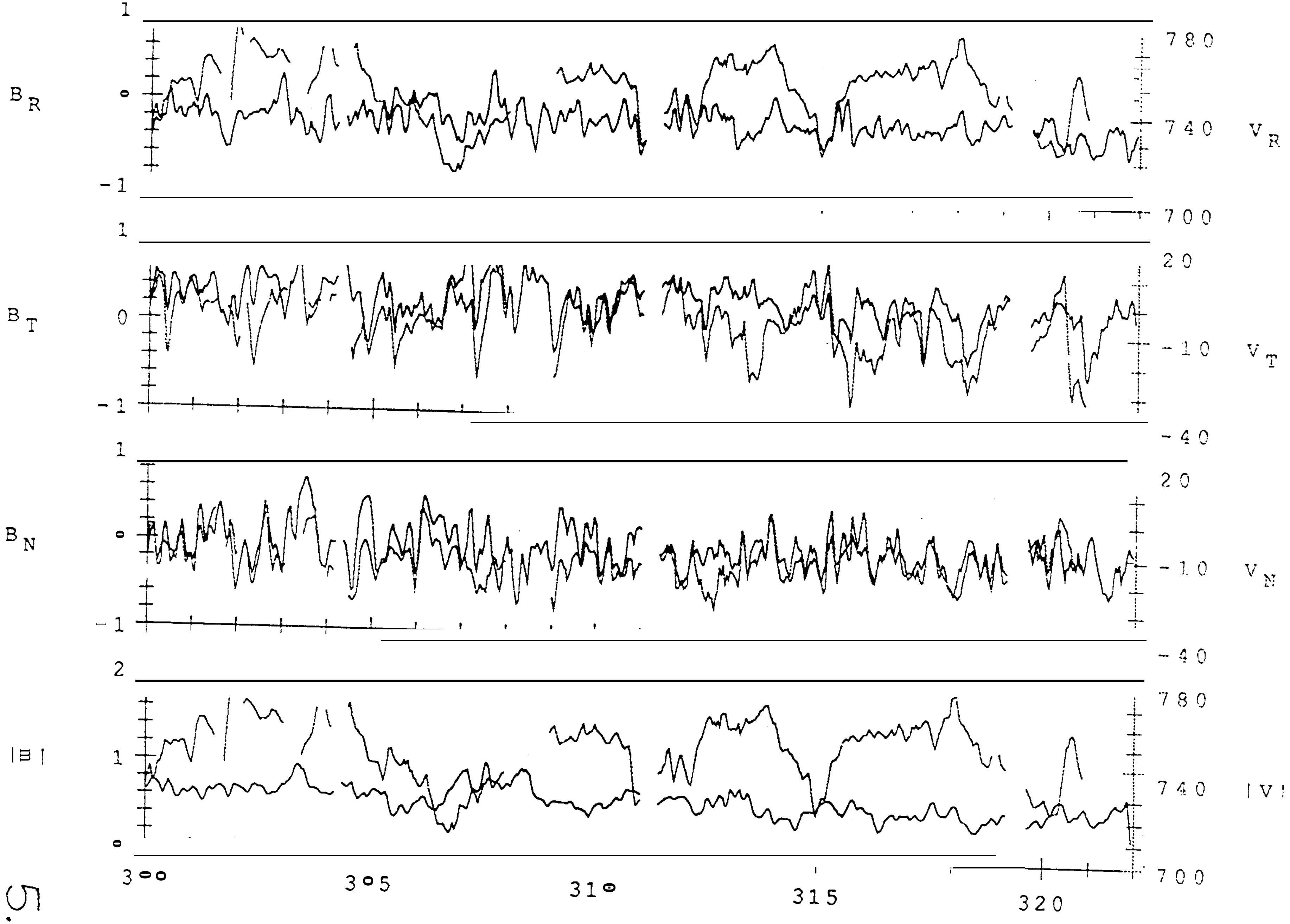

Ulysses
$\frac{\sigma_R^2+\sigma_T^2+\sigma_N^2}{B^2}$
$\frac{\sigma_B^2}{B^2}$
AVG VARIANCE
35
.3
25
.2
.15
.1
.05
0.
0
5
10
15
20
25
30
35
40
45
50
SOUTH HELIOGRAPHIC LATITUDE (deg)

4.

ULYS Hour Avgs SH Coords

Oct 27 - Nov 17, 1993 (300-321)



5.