Hourly variances of fluctuations in the heliospheric magnetic field out of the ecliptic plane

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Abstract

Magnetic field fluctuations at high heliographic latitudes are discussed in terms of the latitude and radial dependence of their variances, as observed by the Ulysses spacecraft. The increased level of transverse fluctuations in fast solar wind flows from the polar coronal holes is similar to that found in high speed streams near the ecliptic. However, continuous observations in the fast solar wind both southward and northward of the solar equatorial plane. has allowed the determination of the radial dependence of fluctuations on hourly and shorter timescales, free from additional energy input from stream-stream interactions or from coronal mass ejections and in the presence of a slowly evolving, low frequency Alfvénic population. The conclusion is that fluctuations in the inert i al range in the homogeneous polar coronal flows decay faster than predicted by the WKB approximation. However, even minor compression effects can increase the energy in these fluctuations.

introduction

Magnetic field observations made by the Ulysses space probe at high solar latitudes [Smith *et al.*, 1995a, Balogh *et u/.*, 1995, Horbury *et al.*, 1995a], in fast solar wind flows originating in the southern polar corona] hole [Phillips *et* al., 1995] were characterized by a significant increase in the average level of magnetic fluctuations when compared to in-ecliptic observations (see, e.g., Denskat and Neubauer [1982], Roberts *et al. [1990]*, Mariani and Neubauer [1990]). Fluctuations at high latitudes present some of the characteristics identified previously near the ecliptic, but there arc also significant differences. In this paper, we use hourly estimates of the magnetic field variances to describe and discuss some of the spatial dependence of magnetic fluctuations along the orbit of Ulysses. The longer time-scale characteristics of the fluctuations, and more specifically their dependence on heliocentric distance arc described by Balogh *et al.*, [in preparation].

Structure function analysis of the fluctuations in the solar polar flows [Horbury *et al., 1995b*, 1995c] has shown that there are fundamentally two populations of fluctuations, one at high frequencies (above about 10-3 Hz) the other at low frequencies (below 10^{-4} Hz) in the frame of the observations. The. variations seen in the magnetic field in the frequency range below about 10-5 Hz are. likely to be the. signatures of larger scale spatial structures [e.g. Jokipii and Kota, 1989]. The high frequency fluctuations appear to be. caused by intermittent, inertial range turbulence operating in the solar wind, similar to that observed near the. ecliptic plane [Roberts *et al.*, 1987, Tu *et al.*, 1989a], with a power spectral exponent close to, but not necessarily equal to -5/3. The lower frequency fluctuations are characterised by a power spectral exponent close to -1, and arc mainly transverse to the radial direction in the polar flows [Smith *et* al., 1995a]. The transition between the two populations occurs at a frequency which depends on radial distance [Horbury *et al.*, 1995c], but once Ulysses is in the polar flows, almost certainly not on heliolatitude. In the solar wind originating in the. polar coronal hole, the low frequency fluctuations appear to be slowly evolving and arc of solar or coronal origin [Horbury *et al.* 1995c, Smith *et al.*, 1995a]. These lower frequency, 1/f fluctuations are similar to those found in high speed solar wind streams in the Helios observations at 0.3 AU [Denskat and Neubauer, 1982]. Similar results concerning the existence of two populations in in-ecliptic observations have. been described and discussed, among others, by Bavassano *et al., [1982]* and Klein *et al.*, [1992]. The break between the 1/f population and that with a higher power spectral exponent, near -5/3, occurs at frequencies about an order of magnitude lower in the. ecliptic (in high speed streams at 1 AU) than at high latitudes (at 2 to 3 AU) [Horbury *et* al., 1995c]. The lower frequency fluctuation in the ecliptic have timescales of the order of a day and longer which necessarily include dynamic effects due to the stream structure of the solar wind,

Given that the existence and principal characteristics of the fluctuations have been established by both spectral and structure function analysis, an alternative view of the hourly scale fluctuations can be obtained by analysing the variance of the magnetic field, in particular to establish spatial dependences based on observations along the out-of-ecliptic orbit of U] ysses. Variances used in this paper (see below) are effectively sensitive above the break-point in the spectrum at about 10-4 Hz, i.e. in the inertial range, where energy transfer processes are most significant.

Observations

The orbit of the Ulysses spacecraft Smith *et* al., 1995b] has been characterised by a slow climb to high southern latitudes from the ecliptic plane, starting in February 1992 and reaching a maximum heliolatitude of 80.20 south in September 1994. Since then, the spacecraft has moved relatively fast back through the ecliptic, crossed it on March 13, 1995, and reached 800 north latitude on July 31, 1995. The heliocentric distance range covered during the ascent to high latitudes was from 5.4 AU to 2.2 AU, and during the descent from 2.2 AU to 1.4 AU. Thus the Ulysses observations represent, during the first phase, a sample of the heliospheric magnetic field as a function of a slowly varying heliolatitude and heliocentric distance, while, during the second phase, the change in heliolatitude was rapid, but restricted to a small range of heliocentric distances. The observations were carried out during the late declining phase of the solar cycle, in relatively stable solar conditions. The two phases therefore allow a good separation of temporal, latitudinal and radial dependences.

Two sample periods of magnetic field observations are shown in Fig. 1. The two 8-day intervals were selected to illustrate the change in the nature of the fluctuations between equatorial and polar flows. The abrupt changes seen on day 34 (February 3) and day 87 (March 22) 1995, in the general appearance of the fluctuations in the components of the magnetic field were observed during the fast latitude scan of Ulysses. The first occured as the spacecraft travelled towards the ecliptic, at a heliolatitude of 23° south, the second at 19° north, as the spacecraft travelled northward following its ecliptic passage on 5 March 1995. The transition in the first case was accompanied by a Coronal Mass Ejection, and in the second case by a compressive feature, as the solar wind from the northern polar coronal hole compressed the preceding equatorial flow. As discussed below, the transition from equatorial to polar characteristics was considerably less abrupt in the earlier climb to high latitudes in 1992-93. As shown by Smith *et al. [1995a],* fluctuations in the polar flows at low frequencies were mostly transverse to the radial direction rather than to the average magnet ic field. At higher time resolutions, not discussed in this paper, the picture is considerably more complex, not just in spectral terms [Horbury *et al.,* 1995b], but also because of the very high rate of occurence of discontinuities [Tsurutani *et al.*, 1994]. For the frequency range considered in this paper, the anisotropy of the fluctuations can be best understood in terms of radially transverse. fluctuations at the. lower end of the range with the higher frequency fluctuations transverse to the local magnetic field, superimposed on the longer wavelength fluctuations [Horbury *et* al., 1995d].

'he. normalised variances of the magnetic field components and magnitude calculated along the Ulysses orbit are shown in Fig. 2. as a function of heliolatitude. The input data set for this study is the highest resolution magnetic field data obtained from the magnetic field experiment on Ulysses [Balogh *et* al., 1992]. These are. vector samples of the magnetic field at either one or two vectors per second, depending on telemetry rate. Vectors arc defined in the heliospheric RTN coordinate system, a right hand cartesian system in which the. R (radial) axis is defined radially anti-sunward along the sun-spacecraft line, the T (tangential) axis is defined by the cross-product of the solar rotation axis with the R direction, and the N (normal) axis is defined completing the right handed system.

Variances of the components B_R, B_T and B_N of the magnetic field field vector and of its magnitude $|\mathbf{B}|$ have been calculated over hourly intervals; given that we have n samples per hour (with n = 1800 to 3600, depending on data rate), the variance in the radial component of the magnetic field is

$$\sigma_R^2 = \frac{1}{n}\sum_{i=1}^{n}\left(B_{Ri} - \bar{B}_R\right)^2$$

with similar definitions for σ_T^2, σ_N^2 and σ_B^2. This produces un-normalised variances, and will obvious sly give different results depending on the strength of the magnetic field at the time and place of the measurements. This field strength dependence can be removed, as was done for Fig. 2, by dividing all the variances by B^2 to produce normalised variances which are dimensionless. In Fig. 2, these. normalised hourly variances were further averaged into successive 20 latitude bins; the spread of the values increased as the time spent in each bin decreased with the spacecraft moving nearer to the sun.

At heliolatitudes up to about 25° south, normalised variances in the components were nearly equal and of similar magnitude to that seen in the ecliptic [e.g. Mariani *et al.*, 1978], with the normalised variance in the magnitude of the field considerably smaller than those of the component S. However, in the. polar solar wind flows, the normalised variances of the two transverse components of the magnetic field increased to a high level, about a factor 4 or so above the equatorial values. The normalised variance. of the radial component of the field also increased, but by a smaller factor. On the. scale shown in Fig. 2, there is little change in the variance in the magnitude. of the field throughout the high latitude orbit of Ulysses. During the. poleward-bound part of the orbit, the increase in the variance of the transverse components was apparently gradual, spread over from about 300 to almost 500 in heliolatitude. As discussed below, this gradual increase is the result of averaging over the gradually disappearing stream-stream interaction regions. The observations during the high latitude pass show that normalised variances were approximately constant as a function of heliolatitude in the fast solar wind stream from the polar coronal hole. The apparently small variation in the data when plotted against heliolatitude can be explained by the radial dependence of the variances as discussed below. The abrupt change in the level and nature of the variances around the equatorial scan of Ulysses can be clearly seen in Fig. 2, as already referred to in connection with the observations shown in Fig. 1. The change between the polar and equatorial characteristics occured, both south and north of the ecliptic, at approximately the highest latitude reached by the Heliospheric Current Sheet in the two hemispheres, as estimated from the solar source surface neutral line.

The differing behaviour of hourly magnetic field variances during the mid-latitude southbound and subsequent equatorward northbound passes can be explained by the averaging of equatorial-like and polar-like values of variances in the interval between 300 and 450 latitudes during the southbound pass. The same interval was marked in the solar wind velocity by large scale oscillations between fast solar wind originating in the developing southern polar coronal hole and slow streams from the more equatorial regions still sampled by Ulysses [Phillips et al., 1995]. The magnetic field, simultaneously, showed the compression regions which periodically recurred as a result of the stream-stream interaction between polar and equatorial flows [Balogh et *al.*, 1995]. As shown on the expanded time scale in Fig. 3, the representative hourly variance σ_N^2 in the solar meridional component, averaged over successive two-day intervals, fluctuated significantly during this period. The figure also shows the strength of the magnetic field for the same interval. The large fluctuations in the variances were due to the succession of CIRs observed in this heliolatitude range, with fast wind streams from the equatorward extension of the then developing southern polar corona] hole periodically compressing slower wind streams originating closer to the equator. As can be seen in Fig. 3, σ_N^2 was smallest just ahead of the. CIRs (in the slow solar wind), and highest just behind the compressed magnetic field regions, where the solar wind velocity was the highest. The slowest solar wind associated with near-ecliptic flows disappeared [Phillips *et al., 1995]* at the same time as the magnetic sectors [Smith *et* al., 1993] at about 30° heliolatitude, although compressive si gnat ures continued to be observed for another three solar rotations. Transverse variances track this evolution, and when the pure polar flows were reached, the high levels were maintained, as seen in Fig. 2, over both southern and northern polar coronal regions.

Discussion

In the fast, polar streams, transverse variances had consistently higher values than near the ecliptic. In the mid-latitude range at large distances (up to 5 AU), the transverse variances were also high, close to values reached in the pure coronal hole flows, in the high speed solar wind originating in the equatorward extension of the polar coronal hole. In the more equatorial flows, during the fast latitude scan by Ulysses, variances in the components fell back to the average low-latitude values. This distinction in the power in fluctuations between slow and high speed solar wind streams is the consequence, as in the ecliptic, of the presence of long wavelength (i.e. several hours in the spacecraft frame) Alfvénic fluctuations in the high speed solar wind in the trailing (rarefaction) edges of CIRs. Such waves were observed in the inner solar system [Bruno *et al.*, 1985], but become less prominent due to stream-stream interaction effects with heliocentric distance [Bavassano *et al.*, 1982]. At the medium latitudes explored by Ulysses, these long-wavelength fluctuations were observed to 4 AU and beyond in the fast solar wind associated with the polar coronal hole [Smith *et al., 1995a]*.

However, the estimates of variances described and discussed in this paper are sensitive to fluctuations which have timescales shorter than the regime. for the 1/f Alfvénic fluctuations identified by Smith *et al. [1995a]*. The question therefore. arises as to the origin of the high relative power in what are in fact fluctuations in and above the frequency range corresponding to the spectral transition between the. 1/f and $f^{-5/3}$ populations. in the absence of large scale velocity shears, the energy source is ultimately the lower frequency Alfvénic population and its (slow) evolution and break-up and the transfer of power into the turbulent cascade in the frequency range above 1()-~ Hz [l'u, 1988]. The high relative power levels are therefore the consequence of the very high levels of power in the 1/f fluctuations of the magnetic field in solar wind flows from the polar coronal hole.

Fluctuations on time scales considered in this paper have been extensively discussed using the WKB framework (for a recent review, see Tu and Marsch [1995] and references therein). Results in the ecliptic (e.g. Bavassano *et al.* [1982], Burlaga *et al.* [1982], Bavassano and Smith [1986]) have concluded that, on the whole, the radial dependence of fluctuations remained close to a power law with an exponent close to -3, predicted by the WKB approximation. Roberts *et al.* [1990] found that the radial dependence of fluctuations at the. intermediate to long wavelengths also followed the WKB approximation, even when the stream-stream interaction effects were not taken into account. Similarly, the exponent was found to be relatively independent of solar wind speed by Tu *et al.* [1989b], although the power levels normalized to 1 AU increased strongly with solar wind speed. As pointed out by Roberts *et al. [1990],* there may be a number of different reasons for the apparent validity of WKB approximation near the ecliptic, where energy provided at long wavelengths by shears in the flow due to stream-stream interaction can balance the dissipation at higher wave numbers. Polar flows are relative] y free from stream-stream and other compressional interaction effects [Phillips *et al.*, 1995]; these cannot therefore be considered to contribute significantly to the distribution of fluctuations in the high latitude Ulysses observations. However, as shown below, the radial dependence of the power in the higher frequency fluctuations is sensitive to even relatively small compressional effects.

The radial dependence of the hourly un-normalised variances presented in this paper is shown in Fig. 4. Fitting a radial dependence of the form r^{-n} to the complete data set from 1.5 to 4 AU gives n = 3.00 ± 0.07, 3.00 ± 0.08, 2.89 ± 0.09 and 2.30 ± 0.08 for $\sigma_R^2, \sigma_T^2, \sigma_N^2$ and σ_B^2, respect ivel y, apparently confirming a very good match to the value expected from WKB. However, a number of compressional features were present in the magnetic field observations between 3 an 4 AU, due to high latitude CMEs and corotating features. As can be seen in Fig. 4, the variance data in this distance range shows a slower decrease than in the 1.5 to 3 AU range, when such compressional features were absent. Fitting the same r-n law to the data set between 1.5 and 3 AU (as shown in the figure), the best fit values are n = 3.39 ± 0.07, 3.45 ± 0.09, 3.37 ± 0.09 and 2.48 ± 0.14 for $\sigma_R^2, \sigma_T^2, \sigma_N^2$ and σ_B^2, respectivel y. These results provide a strong indication that the expected dissipation at high frequencies is counteracted by additional energy fed into this range by compressional and/or shear effects, as proposed by Roberts *et* al. [1990], to mimic a WKB-like radial dependence. Power in the fluctuations, when lower frequencies are included, decays at a rate slower than r^{-3} [Balogh *et al.*, in preparation] even when only uniformly high solar wind flows are considered; this implies that, at the radial distances covered in this study, the WKB approximation can be valid at most for a relative] y restricted frequency range, just below the break between the 1/f and the inertial range populations.

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FIGURE CAPTIONS

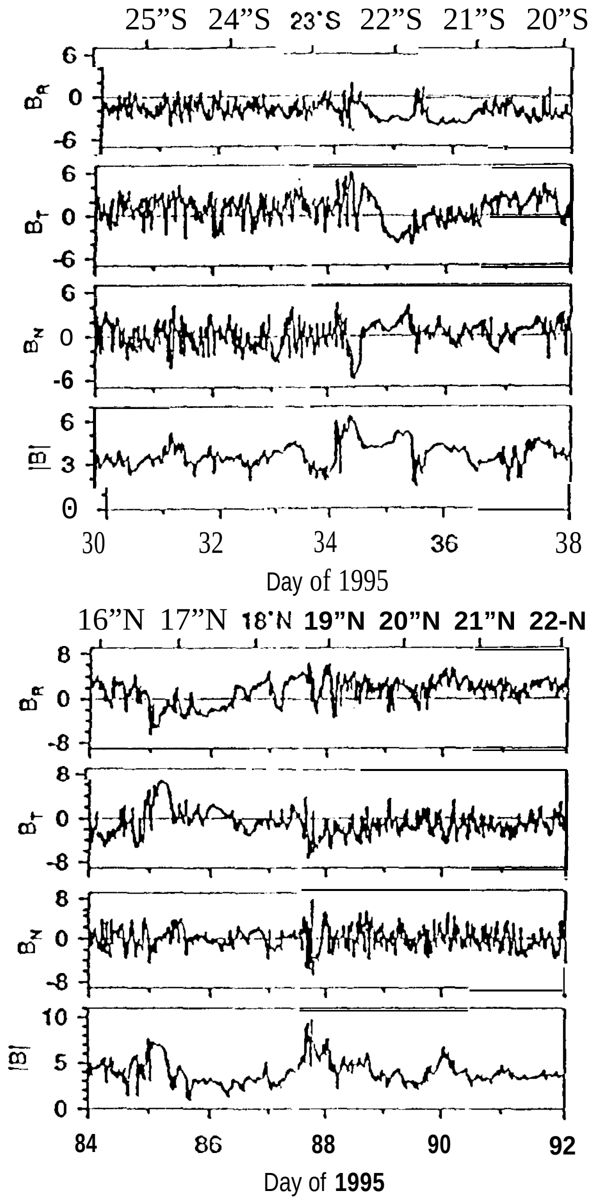
Fig. 1: Ulysses magnetic field observations showing the change in characteristic fluctuations in the components of the field between southern fast solar wind flows and equatorial flows (upper panel), and between equatorial flows and northern fast solar wind flows (lower panel). The magnetic field is given in the RTN coordinate. system (see text), the upper horizontal scale in the two panels shows the heliographic latitude of Ulysses.

Fig. 2: Normalized variances of the high time resolution magnetic field components and magnitude calculated over one hour intervals and averaged in 2° latitude bins for the complete latitude survey of Ulysses from the ecliptic to close. the. sun's south pole and then through the ecliptic to close to the north pole. The high values of the variances in the transverse components in polar coronal holes can be clearly observed, as well as the abrupt return of the variances to in-cc] iptic values during the fast latitude scan of Ulysses. Error bars at the top of the figure correspond to the numerical uncertainty ($\pm 1\sigma$) in the N-component of the relative variances.

Fig. 3: The magnitude of the magnetic field and the normalized variance of the N (meridional) component of the field during the ascent of Ulysses to high solar latitudes. During the series of CIRs, variances were high behind the peak compressions in the field, in the rarefaction regions following the CIRs (as shown enlarged in the lower panel). As the magnetic field became less compressive, the normalized variance increased, on average, towards values observed in pure polar flows. The epochs marked *a, b* and c re.present, respectively, the onset of the CIRs associated with the polar coronal hole; the disappearance of the sector structure; and the immersion of Ulysses in purely coronal solar wind flows.

Fig. 4: Log-log plot of the un-normalized hourly variances of the components and the magnitude of the magnetic field as a function of heliocentric distance. Best fit lines are shown for data

between 1.5 and 3 AU, avoiding the compressive effects in the variances between 3 and 4 AU. Values for the best fits to the r-n power law are given in the text.



25"S 24"S 23'S 22"S 21"S 20"S
B_R
B_T
B_N
|B|
6
0
-6
3
30
32
34
36
38
Day of 1995
16"N 17"N 18'N 19"N 20"N 21"N 22-N
8
0
-8
10
5
84
86
88
90
92
Day of 1995

Figure 1

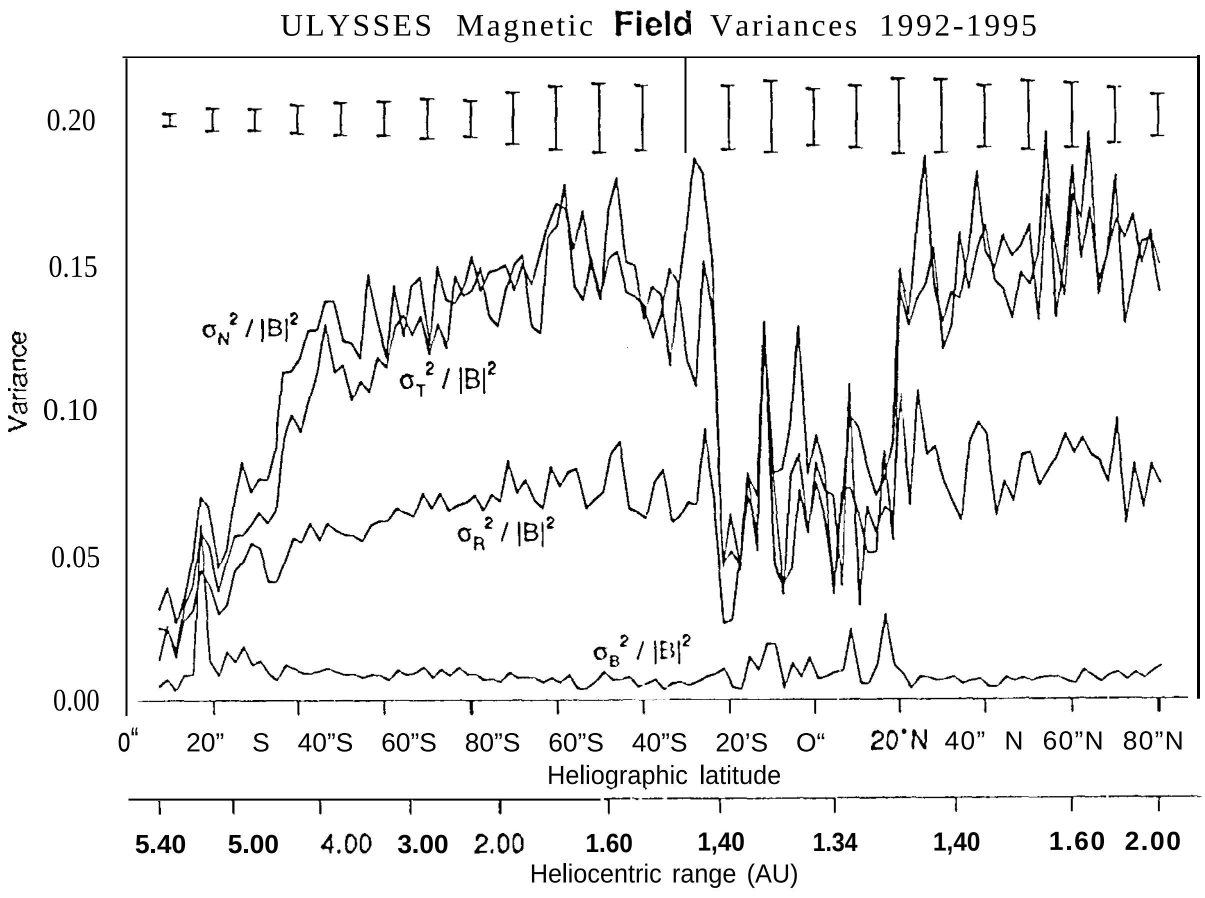

ULYSSES Magnetic Field Variances 1992-1995
0.20
0.15
0.10
0.05
0.00
Variance
σN² / |B|²
σT² / |B|²
σR² / |B|²
σB² / |B|²
0" 20" S 40"S 60"S 80"S 60"S 40"S 20'S O" 20°N 40" N 60"N 80"N
Heliographic latitude
5.40 5.00 4.00 3.00 2.00 1.60 1,40 1.34 1,40 1.60 2.00
Heliocentric range (AU)

Figure 2

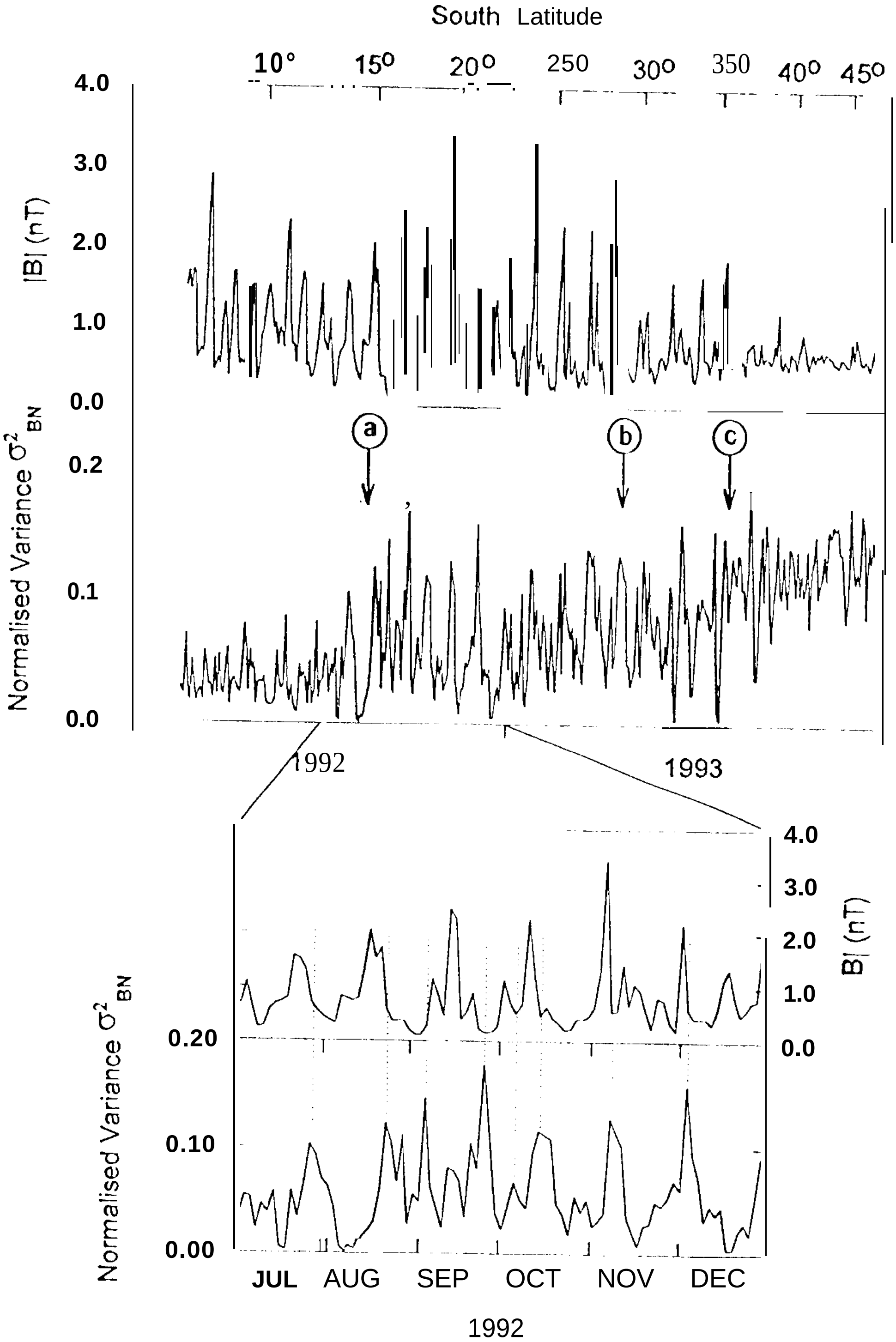

South Latitude
10°
15°
20°
25°
30°
35°
40°
45°
4.0
3.0
2.0
1.0
0.0
|B| (nT)
a
b
c
0.2
0.1
0.0
Normalised Variance σ^2_{BN}
1992
1993
4.0
3.0
2.0
1.0
0.0
B| (nT)
0.20
0.10
0.00
Normalised Variance σ^2_{BN}
JUL
AUG
SEP
OCT
NOV
DEC
1992

Figure 3

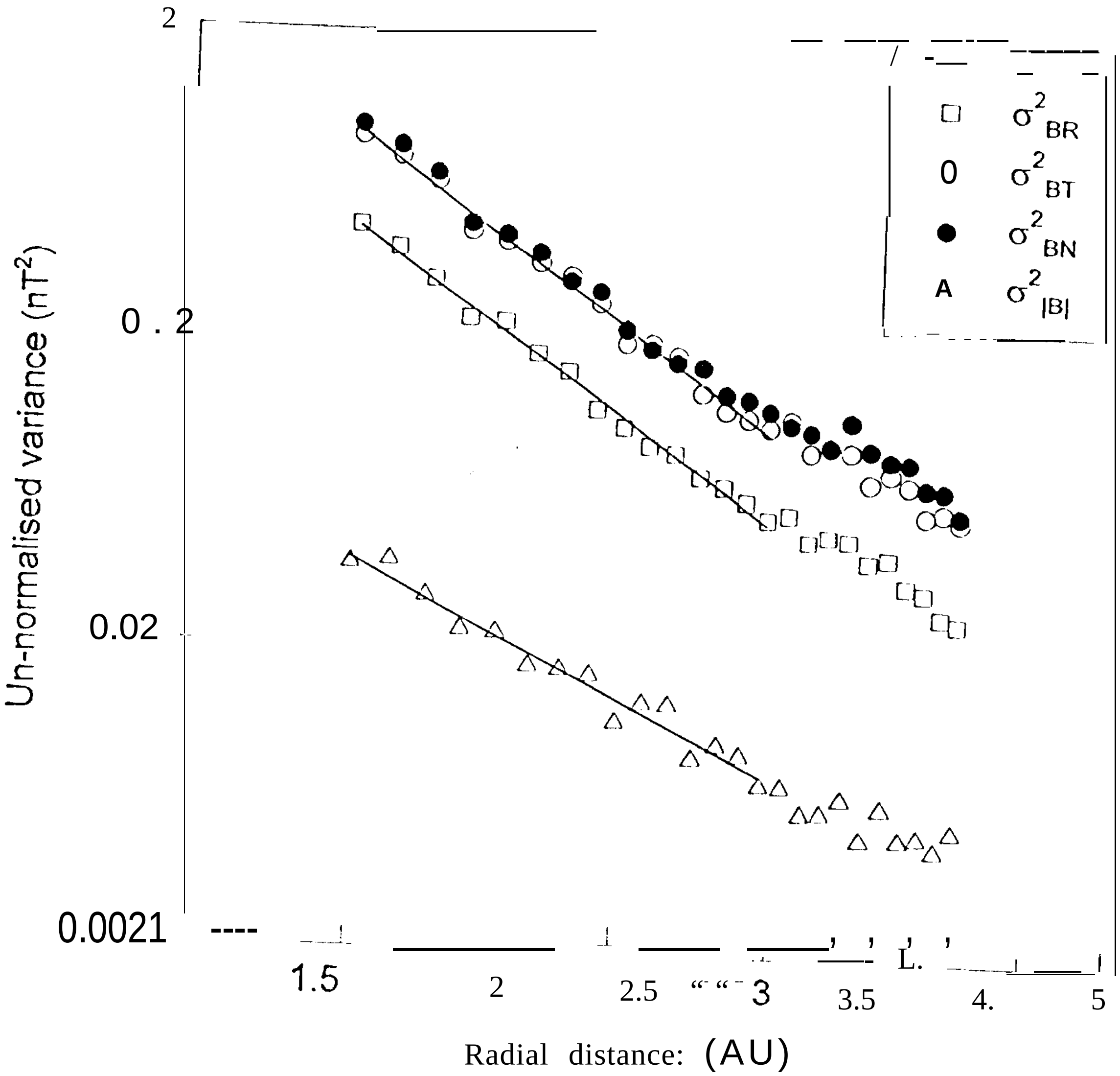

2
0 . 2
0.02
0.0021
Un-normalised variance (nT^2)
σ^2_{BR}
σ^2_{BT}
σ^2_{BN}
$\sigma^2_{|B|}$
1.5
2
2.5
3
3.5
4.
5
Radial distance: (AU)

Figure 4