Astron. Astrophys. 316, 333–341 (1996)

ASTRONOMY AND ASTROPHYSICS

The rate of turbulent evolution over the Sun's poles

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Received 7 March 1996 / Accepted 4 June 1996

Abstract. Ulysses magnetic field observations in the polar heliosphere have revealed the presence of a population of turbulent fluctuations on small scales with a power spectral index near 5/3 and its extension to progressively larger scales with solar distance. Using the spectral index – calculated from the second order structure function – as a tracer of the turbulent nature of the fluctuations, the rate of extension of the turbulent regime with distance is measured for both the Northern and Southern polar heliosphere. The evolution is similar in both hemispheres: the exponent of the rate of extension of the turbulent regime with solar distance is $+1.1 \pm 0.1$. By comparing of the extent of the turbulent regime in the polar heliosphere with previous measurements of fluctuations near the ecliptic, polar fluctuations are shown to evolve more slowly than those in high speed streams at lower heliolatitudes beyond 0.3 Astronomical Units. Within this distance, however, fluctuations in high speed streams at high and low latitudes probably evolve at the same rate.

Key words: interplanetary medium – solar wind – turbulence

1. Introduction

In-situ spacecraft magnetic field and plasma observations in the low latitude heliosphere have revealed the presence of pervasive fluctuations, some of which appear to be indicative of inertial range turbulence – see Roberts & Goldstein (1991) and Tu & Marsch (1995) for recent reviews of this subject. In general the inertial range fluctuations have a spectral index – that is, fluctuation energy densities of the form $P(f) \propto f^{-\alpha}$ – near 5/3, the Kolmogorov (1941) value, and extend to dissipation scales. At larger scales, however, the fluctuations vary with solar wind stream structure and solar distance. Slow speed streams generally have values of the spectral index $\alpha \sim 5/3$ on all scales and at all distances. Fluctuations in high speed streams tend to have $\alpha \sim 1$ at low frequencies. The transition, or breakpoint, scale between the small scale $\alpha \sim 5/3$ regime and the large scale $\alpha \sim 1$ regime moves to progressively larger scales with solar distance in high speed streams (Bavassano et al. 1982; Feynman et al. 1996). This is strong evidence for energy transfer between scales, and is usually interpreted as being due to the decay of the low frequency $1/f$ fluctuations, which probably originate close to the Sun (e.g. Matthaeus & Goldstein 1986). Energy from the decaying fluctuations is injected into the inertial range, which extends to larger scales as progressively lower frequency $1/f$ fluctuations decay.

An unanswered question regarding this evolutionary process is whether it is driven by the inhomogeneous environment at low latitudes, or is largely unaffected by it. The extremely large velocity shears between fast and slow streams near the ecliptic produce compression and rarefaction regions, leading to the formation of co-rotating interaction regions (CIRs) and eventually shocks. CIRs are usually well developed by 1 Astronomical Unit (AU), but not at 0.3 AU, the closest in situ measurement of the solar wind (see, for example, Tu & Marsch, 1995). The evolution of fluctuations, reflected in the extension of the $f^{-5/3}$ regime to progressively larger scales, is rapid between 0.3 and 1 AU in high speed streams (Bavassano et al. 1982). This evolution may reflect an inherent process in magnetohydrodynamic (MHD) fluctuations, or be the result of the remarkably disturbed near-ecliptic environment. It has been suggested that fluctuations in high speed streams may reflect a genuinely different type of turbulence (Grappin et al. 1991) and evolve differently if undisturbed. On the other hand, theoretical models of turbulent evolution between 0.3 and 1 AU are in fair agreement with observations (e.g., Tu 1988; Zhou & Matthaeus 1990; Schmidt 1995), assuming no forcing by stream structure. Modelling of stream shears (e.g., Roberts et al. 1992) suggests that they could be responsible for generating turbulence, consistent with forced evolution. It would, therefore, clearly be desirable to observe fluctuations in high speed streams which are undisturbed by stream shears and inhomogeneities to help to understand the observed near-ecliptic evolution. Ulysses magnetic field observations at high latitudes (Balogh et al. 1995, 1996) offer just such data: the high latitude heliosphere has proved to be remarkably homogeneous, with high speed (700–800 km s^{-1}) wind emanating from the Sun's polar coronal holes (Phillips et al. 1995). Fluctuations in this undisturbed environment have $\alpha \sim 1$ at large scales and $\alpha \sim 5/3$ at smaller scales, as in high speed

Send offprint requests to: T.S. Horbury streams near the ecliptic (Horbury et al. 1995a, 1996). However, while the transition between the two regimes moves to larger scales with solar distance as is the case near the ecliptic, Horbury et al. (1995b) suggested that this movement is slower at high latitudes than at comparable distances near the ecliptic. Since polar fluctuations out to several AU are effectively undisturbed compared to those near the ecliptic, Ulysses observations suggest that low latitude fluctuations are indeed affected by their environment. Previous measurements of polar evolution by Horbury et al. (1995b) did not produce a value for the rate of this process. Such a measurement is useful in comparing observations with theory. In addition, a quantitative comparison of polar and near-ecliptic measurements of turbulent evolution is required to establish unequivocally that polar evolution is slower than that at low latitudes. In this work, we calculate the rate of evolution of polar fluctuations; establish that the evolution occurs at a similar rate in both hemispheres; and quantitatively compare polar and low latitude evolution.

2. The power spectrum of polar fluctuations

In this paper, the spectral index of magnetic field fluctuations is used as a tracer for the presence of inertial range turbulence. Values of the spectral index (denoted in this work by α) near 5/3 will be taken as "turbulent" while considerably larger or smaller values will not. In practice, the approximate extent of the inertial range is rather simple to detect and the precise value of α for inertial range fluctuations is not important. Our interest in this work is in the range of scales over which the inertial range extends, not in its precise nature: we will not attempt to distinguish between Kolmogorov ("hydrodynamic") or Kraichnan ("MHD") turbulence, for example.

Rather than calculate power spectra directly, we follow the method of several authors (e.g. Burlaga 1992; Marsch & Liu 1993; Ruzmaikin et al. 1995; Horbury et al. 1995b, 1996) and estimate the spectral index from the scaling of the second order structure function. For a given time series $x(t)$ – in this work, time series of measurements of a component of the Heliospheric Magnetic Field (HMF) are used – the second order structure function is calculated as

$$s(\tau) = \langle |x(t+\tau) - x(t)|^2 \rangle \tag{1}$$

where $\langle \cdot \rangle$ denotes an average. The variation of s with time scale τ gives information on the scaling properties of the fluctuations: $s(\tau)$ can be considered to be, in an approximate way, the "variance" of the fluctuations at the scale τ. Values of s often scale with τ as

$$s(\tau) \propto \tau^g \tag{2}$$

over a range of τ. In this case, g is simply related to α on the same scale,

$$\alpha = g + 1 \tag{3}$$

This is essentially because the variance over a range of scales is the integral of the corresponding power spectrum over these scales: see Batchelor (1953) and Monin & Yaglom (1975) for discussions of the relationship between structure functions and power spectra.

Horbury et al. (1995b, 1996) used second order structure functions to estimate the spectral index of polar magnetic field fluctuations. By considering the scaling properties of s over several ranges of scales, they calculated the variation of α with spacecraft scale or frequency. In this paper, we use the same method as Horbury et al. (1995b), where it is described in some detail. The most important difference between the method used by Horbury et al. (1995b) and that used by most other authors (including Horbury et al. 1996) is that values of s were calculated for many values of time lag τ rather than a restricted set of lags $\tau_i = t_{\text{average}} \cdot 2^i$, $i = 0, 1, 2, \ldots$ As a result, more accurate estimates of $g(\tau)$ can be made, but at a considerably increased computational cost.

To place the following results in context, we first present measurements of the variation of spectral index with spacecraft frequency for polar fluctuations in Fig. 1. Each value of α was calculated as the gradient of a least-squares linear fit to values of $\log(s(\tau))$ versus $\log \tau$ over a range of τ. Values of α are plotted in the centre of the range of frequency (in log space) over which they were calculated: these ranges touched but did not overlap. Figure 1 therefore shows how α varies with spacecraft scale. Magnetic field data for the normal component were used. The normal direction unit vector $\boldsymbol{n}$ is calculated from the direction radially away from the Sun $\boldsymbol{r}$ and the Sun's rotation vector $\boldsymbol{\Omega}$ as

$$\boldsymbol{n} = \boldsymbol{r} \times (\boldsymbol{\Omega} \times \boldsymbol{r}) \tag{4}$$

Figure 1 is actually a composite of three results. To reduce the computational cost of structure function calculations, values of s for large time lags are calculated from averaged data, and in this case also from longer intervals of data. Values of α in Fig. 1 calculated from lags of 1 s to around 10^3 s are results from high resolution (1 or 2 seconds between vectors) data from a five day interval of data, 1994 days 245–250: this interval is also discussed in Horbury et al. (1995b). Values of α for lags of 10^3 to 10^4 s are from values of s calculated from 10 s averaged data over the same interval. Values of α for time lags over 10^4 s are calculated from a 50 day interval of 5 minute averaged data. This interval, from 1994 day 225 to day 275, includes the interval for the smaller lags. Between 1994 days 225 and 275, Ulysses travelled from 2.5 AU to 2.2 AU from the Sun, and from 77.5°S to 80.2°S and back to 78.9°S. As such, the data in this interval cannot be considered to be stationary. However, the fluctuations of interest here, on scales up to around 1 day, did not change significantly over the interval.

The results in Fig. 1 show that there are two ranges of scales where the spectral index is rather steady. The first, between around 10 and 100 s on the spacecraft scale ($\sim 8 \times 10^3$–8×10^4 km in the solar wind frame), is where $\alpha \sim 5/3$; the second, on scales around 10^4 s ($\sim 8 \times 10^6$ km) and above, has $\alpha \sim 1$. Horbury et al. (1995a,b, 1996) and Ruzmaikin et al. (1995) identified the smaller of these scales as inertial range turbulence, while Horbury et al. (1995b, 1996) pointed out that the larger scale is that on which Smith et al. (1995) identified the

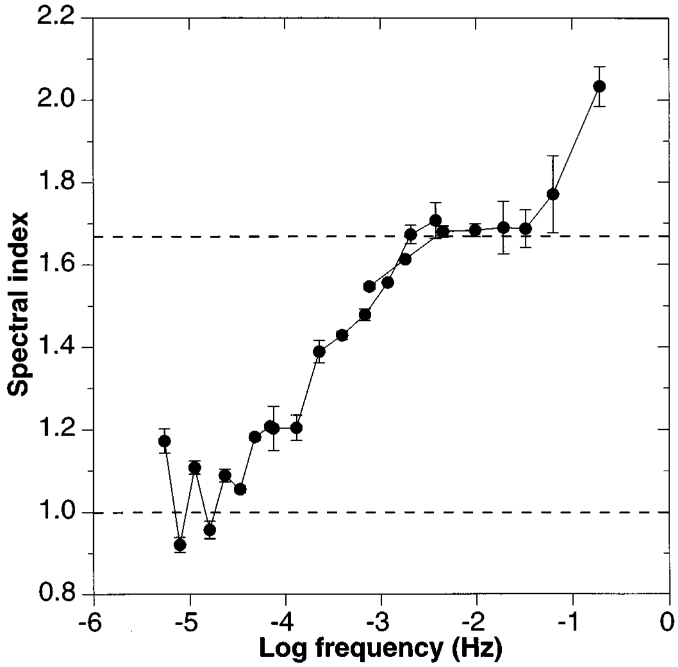

Fig. 1. Variation of spectral index with spacecraft frequency for polar turbulence around 80°S and 2.4 AU solar distance, as measured by Ulysses in 1994. Values of 5/3 and 1 are marked with horizontal dashed lines

presence of large amplitude, rather pure outward-propagating Alfvén waves in the polar heliosphere. Goldstein et al. (1995) discussed frequencies below 10^{-3} Hz using Elsässer variables, normalised cross helicity and the Alfvén ratio, showing that the $1/f$ regime was indeed highly Alfvénic with an outward sense of propagation, and an Alfvén ratio (ratio of kinetic to magnetic energy) $r_A \sim 1/2$. Goldstein et al. (1995) also discussed fluctuations on frequencies below 10^{-5} Hz: these large scales are not of interest in this work. The smallest scales in Fig. 1, below around 10 s, are affected by filtering within the magnetometer itself (Balogh et al. 1992), resulting in the higher values of α: the results in Fig. 1 do not place a lower limit on the extent of the inertial range in the polar heliosphere. The transition scale between the $\alpha \sim 5/3$ and $\alpha \sim 1$ regimes is real, and is the subject of this paper.

The general impression to be gained from these studies of polar fluctuations is of $1/f$ Alfvénic fluctuations at large scales and $f^{-5/3}$ turbulence at smaller scales. This is qualitatively similar to the observations by Helios in the trailing edges of high speed streams between 0.3 and 1 AU (Tu & Marsch 1995 is a recent comprehensive review of Helios observations of fluctuations). In particular, the presence of $1/f$ and $f^{-5/3}$ regimes in high speed wind near 0.3 AU was shown by Bavassano et al. (1982). Several authors (Horbury et al. 1995a,b, 1996; Goldstein et al. 1995) have compared results of Helios and Ulysses observations of fluctuations within high speed streams in terms of their comparative evolution.

3. Polar turbulent evolution

The evolution of polar magnetic field fluctuations was established by Horbury et al. (1995b). This evolution can be seen as an extension of the inertial range to progressively lower frequencies with solar distance. Changes in the fluctuations along the orbit of Ulysses within polar flows could be explained simply by a radial dependence: there does not appear to be a heliolatitude dependence within undisturbed polar flows. However, it was not possible to measure the rate of this evolution from the results of Horbury et al. (1995b). An accurate measurement of the rate of polar evolution is important in understanding the nature of this process. With the completion of both Southern and Northern polar passes by Ulysses, it is possible to measure the evolution rate in both hemispheres to establish the consistency of the earlier Southern hemisphere results. In this paper, we measure the evolution rate in both hemispheres. Several intervals of data, each of 20 days duration, have been studied. These intervals were all taken when Ulysses was wholly within high speed polar solar wind flows.

We have chosen to measure the movement of the "transition" scale with distance rather than the extent of the inertial range directly. This is because of the difficulty of accurately measuring the large scale limit of the inertial range. The slow rate of polar turbulent evolution results in subtle changes in the fluctuations over the range of distances sampled by Ulysses – consequently, precise measurements of the breakpoint movement are necessary. The movement of the transition scale accurately reflects the extension of the inertial range and as such is a good 'proxy' for the inertial range extension.

The precise definition of the transition scale is of necessity somewhat arbitrary, given the extended nature of the transition region between the $1/f$ and $f^{-5/3}$ regimes. We have chosen the breakpoint scale to be that where the spectral index α = 1.4, which typically lies near the middle of the transition regime. This particular value of α was chosen so as to be easy and accurate to identify: higher values (say, 1.5 or 1.6) can occur more than once due to statistical fluctuations in estimates of α, and the slow variations of α with τ make accurate determinations of the value of τ at which a given α occurs rather difficult. Similarly, lower values of α, with rather large errors in α and slow variations of α with τ, make the accurate determination of a precise scale difficult.

To reduce the effect of statistical fluctuations in estimates of α on the determination of the breakpoint scale, a third order polynomial was fitted in a least-squares sense to α-τ curves: Fig. 2 is a typical example of the variation of α with τ through the transition regime with the cubic fit. A third order polynomial was chosen so as to be able to reflect the general shape of the α-τ curve through the transition, where a quadratic for example would not. The transition scale is taken to be the value of τ where the cubic has the value of 1.4. The cubic fit does not take into account error estimates in α, but these are usually rather constant across the transition, as can be seen from Fig. 2. The fit algorithm returns a value of τ at which α = 1.4, along with

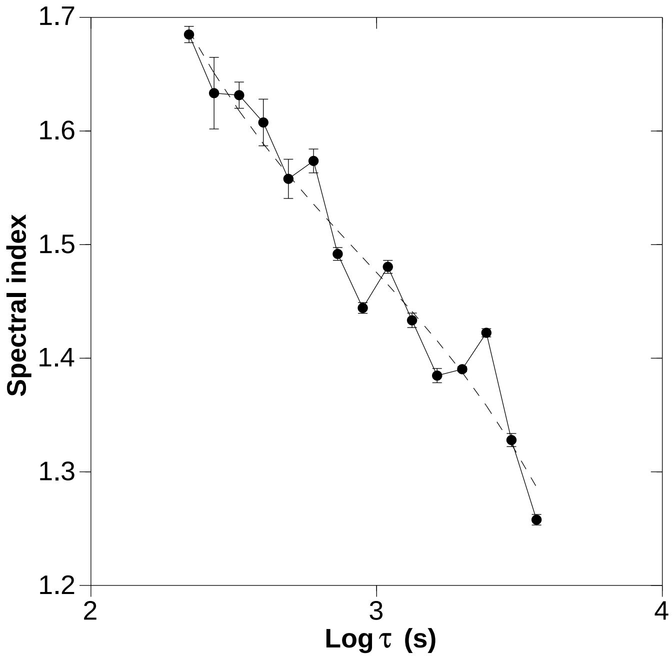

Fig. 2. A typical example of the variation of spectral index α with spacecraft scale τ through the transition scale of polar fluctuations, estimated from the scaling of the second order structure function. A cubic least-squares fit is shown with a dashed line. The breakpoint scale is defined in this paper as the value of τ where the cubic fit has the value 1.4

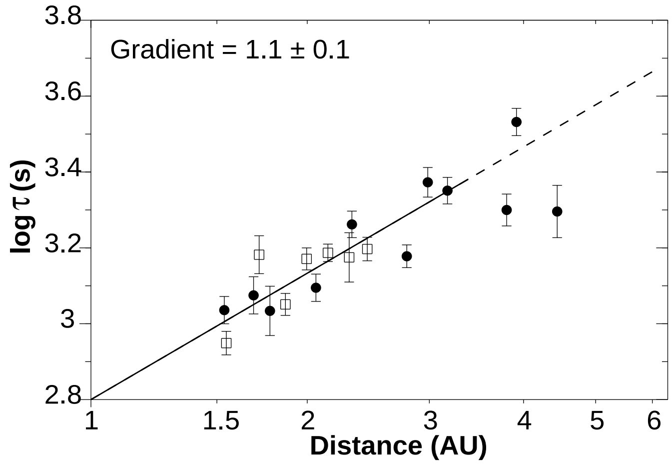

Fig. 3. Variation of the polar transition scale with solar distance, on a log-log scale. Circles denote measurements taken during the Southern pass, squares those during the Northern pass. All data was taken in undisturbed, high speed polar flows apart from the rightmost three circles, which were taken in the trailing edges of high speed polar streams at lower latitudes. A least-squares linear fit to all but the rightmost three circles is shown as a solid line: it is extended to larger distances as a dashed line. The gradient of the least-squares linear fit is 1.1 ± 0.1

a 50% error estimate. We will use this uncertainty value as an estimate of the uncertainty in values of τ.

The value of the breakpoint scale has been measured for the normal magnetic field component for 18 intervals of data. Of these, 15 contained data taken entirely from undisturbed polar flows (8 from the Southern polar flow, 7 from the Northern) while 3 were selected to lie in the trailing edges of the high speed Southern polar solar wind flow. The latter were chosen to extend the survey of the breakpoint in high speed streams to larger solar distances than is possible in undisturbed polar wind. However, the significantly different environment of a trailing edge compared to steady fast flow has a significant effect on the fluctuations, so the breakpoint measurements for these three intervals are not representative of undisturbed fluctuations.

The solar latitudes and distances of the undisturbed intervals in the Southern heliosphere range from 3.12 AU to 1.53 AU and 63°S to 80°S then back to 42°S, while those in the Northern heliosphere range from 1.54 AU to 2.42 AU and 55°N to 80°N then back to 71°N. The furthest interval in the trailing edge of the Southern polar flow was taken at 4.43 AU and 36°S, between days 210 and 230 of 1993.

Horbury et al. (1995b) established that there was essentially no latitudinal trend in the evolution of fluctuations in undisturbed polar flows. The results presented here also show no latitudinal variation, and confirm the radial evolutionary trends identified by Horbury et al. (1995b). The variation of the breakpoint scale with solar distance, shown in Fig. 3, reflects the evolution of the fluctuations and the consequent movement of the breakpoint to larger scales as a result of the extension of the inertial range. Results from both the Southern (circles) and Northern (squares) passes are shown: the consistency of results from the two hemispheres confirms that the evolution is a spatial rather than temporal effect, and that it is not a feature of the Southern polar flow. The rightmost three circles are the data taken in trailing edges of the Southern polar stream, at lower latitudes. These three points seem to exhibit more variation than those from undisturbed flows: indeed, two seem to be significantly "less evolved" than would be expected on the basis of the trend in the undisturbed flows.

As discussed earlier, the advantage of the analysis method used here over that of Horbury et al. (1995b) is that the rate of evolution can now be measured. A least-squares linear fit to the log-log values of τ against r, using the errors in τ, is also shown in Fig. 3. The fit was made to both North and South hemisphere points (fits to each hemisphere separately did not produce significantly different results), but not the three points from trailing edges of the Southern polar flow. The gradient of this line is 1.1 ± 0.1 and we conclude that the transition scale between the inertial range and $1/f$ fluctuations in undisturbed high speed polar flows increases with solar distance r as $\tau \propto r^{1.1\pm0.1}$, or equivalently the transition frequency scales as $f \propto r^{-1.1\pm0.1}$. This measure of the "evolution rate" is also likely to be the rate of extension of the inertial range, because the general shape of the transition region in log-τ space (for example, the α-log τ curve in Fig. 1 for scales above the inertial range) appears to be independent of solar distance: the transition scale simply "moves" to progressively larger scales with distance. This effect can be seen in Fig. 2 of Horbury et al. (1995b), where α-log τ curves from different solar distances in polar flows can effectively be superimposed by shifting them in τ. This behaviour is not particularly surprising: if the evolution is governed by a process which acts on progressively larger scales with distance and this is reflected in the shape of the power spectrum, then this shape should move to larger scales with distance, as seen here.

A complementary analysis of polar magnetic field fluctuations has been performed by Forsyth et al. (1996) and Balogh et al. (manuscript in preparation), who considered the radial scaling of magnetic field variances, σ^2, on different scales. These scales were selected by varying the data averaging period to remove high frequencies and using varying interval lengths to include lower frequencies. By considering the radial variation of the variances of the field components and magnitude with different averaging periods and interval lengths, Balogh et al. demonstrated that fluctuations on different scales varied differently with solar distance in undisturbed polar flows. In general, power law variations of the form $\sigma^2 \propto r^{-\beta}$ were found, where β was a function of the range of scales studied. Using 1 h intervals of 1 or 2 s data, $\beta \sim 3.4 \pm 0.1$ for all three field components (Forsyth et al. 1996). The scaling of longer intervals gave values of β near 3, and even lower values for very long intervals which are not of interest here. The $\sigma^2 \sim r^{-3}$ scaling was found for fluctuations where the spectral index $\alpha \sim 1$. Balogh et al. have discussed the significance of the $\sigma^2 \sim r^{-3}$ scaling of the $1/f$ fluctuations, which is consistent with the WKB approximation: the $1/f$ fluctuations are likely to be non-interacting waves, purely convected by the solar wind and unchanged in character since leaving the upper corona.

The analyses of Forsyth et al. (1996) and Balogh et al. can be compared to the results presented here in a simple way. If we take the polar fluctuations to have a spectrum consisting of two regimes on different scales, with low frequency $1/f$ fluctuations scaling as $\sigma^2 \sim r^{-3}$ and high frequency $f^{-\alpha}$ fluctuations scaling as $\sigma^2 \sim r^{-\beta}$ then we can estimate the transition scale movement rate as a function of α and β. The rate ρ can be shown to be given by

$$\rho = (3 - \beta)/(\alpha - 1) \quad (5)$$

For $\alpha = 5/3$ and $\beta = 3.4$ (the value found by Forsyth et al. 1996 for hourly fluctuations), we have $\rho = -0.6$, rather smaller than the value $\rho = -1$ found in this work. If, however, this calculation is performed in reverse, we can recover β for the high frequency fluctuations from α and ρ. Using $\rho = 1$ and $\alpha = 5/3$, we have $\beta = 3.7$, significantly higher than that found by Forsyth et al. (1996). This apparent contradiction may be resolved by considering the range of scales to which the Forsyth et al. (1996) results are sensitive. This range of scales selects the inertial range, but also some of the transition region. Because the power spectrum has a spectral index $\alpha > 1$ on this range of scales, the variance is most sensitive to the lowest frequency fluctuations, and indeed can be sensitive even to those of periods over 1 h. Therefore, the scaling of variances on these scales may not be a reliable measurement of the variance scaling of the inertial range. Measurements of the scaling of just the inertial range are required before a firm conclusion can be reached about the consistency of these two approaches.

4. Comparison with near-ecliptic evolution

Several authors have studied the evolution of solar wind fluctuations near the ecliptic. The extension of the $f^{-5/3}$ inertial range to lower frequencies with solar distance in high speed flows between 0.3 and 1 AU was demonstrated by Bavassano et al. (1982). However, it is difficult to estimate the breakpoint and its movement from their results. Marsch & Tu (1990) revisited the Helios data and estimated the breakpoint frequency in high speed flows between 0.3 and 1 AU for the Elsässer variables e^+ and e^-. Polar fluctuations are largely Alfvénic with an outward sense of propagation (Goldstein et al. 1995), in common with the near-ecliptic fluctuations observed by Helios in high speed streams. Consequently the e^+ spectra calculated by Marsch & Tu (1990), representing outward-propagating Alfvénic fluctuations, are most pertinent to the observations presented here. Marsch & Tu studied 3 day intervals of data, some of which were chosen so as to lie entirely in the trailing edges of a high speed stream at various heliocentric distances: they reported the e^+ breakpoint frequency and the mean solar wind speed, among other parameters.

Klein et al. (1992) discussed power spectra of magnetic field data from Voyager 1 over a range of solar distances. Using six month intervals of data, they found the breakpoint frequency of the fluctuations by calculating the intersection of straight line fits to the low and high frequency sections of the magnetic field spectra on log-log plots. Klein et al. (1992) give the times of two intervals as 1979.08–1979.55 and 1980.48–1980.95, quoting heliocentric distances of 4 and 10 AU for Voyager 1 respectively. Long time averaged Voyager 1 data is available at the NSSDC archive at the Goddard Space Flight Center. The data available for these intervals (the COHOWeb service was used) shows that the mean solar wind speeds over these intervals were around 450 and 400 km s^{-1} respectively: these values will be used later. It is interesting to note that the distances of Voyager 1 in the middle of these two intervals was actually nearer 5.4 and 9 AU: these values will be used here, although the results are not sensitive to such differences. The six month intervals used by Klein et al. (1992) contain a considerable amount of stream structure: their results are not of course representative of conditions in a single stream at these distances.

Matthaeus & Goldstein (1986) used long intervals of magnetic field data taken at 1 AU and found a breakpoint from $1/f$ behaviour to a steeper spectral slope at a frequency of around 8×10^{-5} Hz, although this varied considerably with the particular data set used. Again, by using long intervals Matthaeus & Goldstein could not identify differences between fluctuations in particular streams.

More recently, Feynman et al. (1996) calculated the breakpoint scale in approximately the same region of plasma (the trailing edge of a single high speed stream) at three different solar distances using 3 day intervals of data from IMP 8, Pioneer 11 and Pioneer 10. In agreement with earlier work, they found that the breakpoint moved to lower frequencies with distance. Velocity data from NSSDC indicate that the particular stream that Feynman et al. (1996) studied was travelling at around 500 km s^{-1}. In fact, Feynman et al. (1996) used the second order structure function to estimate the spectral breakpoint: as such, their method is most similar to that presented here. However, they calculated values of the structure function at lags of powers of 2 times their sampling period. As such, their estimates of the breakpoint could only be made to within half this difference.

We wish to compare the breakpoint scale between the low frequency $1/f$ and higher frequency $f^{-5/3}$ fluctuations as reported in the papers above with the values measured by Ulysses in polar flows. All the results reported here are measurements of the breakpoint scale in the spacecraft frame. This is not, of course, a physically relevant frame for considering the fluctuations. The high speed of the solar wind compared to both the spacecraft velocity relative to the Sun and the MHD wave speeds in the plasma mean that a time series of data from a spacecraft is essentially a radial measurement of the fluctuations. As a result, spacecraft frequencies can be converted to spatial scales in the solar wind in a simple way when the solar wind velocity is known. Taylor (1938) discussed this conversion in the context of laboratory flow measurements – Matthaeus & Goldstein (1982) discussed the subject, known as Taylor's hypothesis, in some detail for spacecraft data. We can regard a spacecraft time series as a radial "snapshot" if fluctuations on a particular spatial scale are sampled much faster than their characteristic period. For a wave of characteristic scale λ propagating with a wave speed ν with respect to the plasma, which is in turn propagating at a speed V_{SW} with respect to the spacecraft, these vary in a time $t_{SC} = \lambda/V_{SW}$ in the spacecraft frame. In the solar wind frame, they vary in a time $t_P = \lambda/\nu$. If $t_{SC} \ll t_P$ or equivalently $V_{SW} \gg \nu$ (which is the case in the solar wind), then the fluctuations can be regarded as "frozen in" to the plasma on the time scale over which they are measured and Taylor's hypothesis is valid. In this case, we can use the dispersion relation $\omega_{SC} = V_{SW} k_P$ to relate a spacecraft frequency ω_{SC} to a solar wind plasma frame wavenumber k_P. It is valid to compare Ulysses measurements from different parts of the polar heliosphere without transforming into the plasma frame since the polar solar wind is rather constant (Phillips et al. 1995) at around 700–800 km s^{-1}. To compare fluctuations recorded in solar wind streams at different speeds, however, we must transform into the solar wind frame.

The estimated breakpoint frequencies and derived wavenumbers of fluctuations as measured in previous work are shown in Table 1. These data, along with breakpoint wavenumbers for Ulysses polar data assuming V_{SW} = 750 km s^{-1}, are plotted against solar distance in Fig. 4. The Ulysses data are separated into undisturbed Southern (circles) and Northern (squares) data, along with the three intervals taken in the trailing edges of the Southern polar high speed stream (triangles).

While the uncertainties associated with the near-ecliptic data are difficult to estimate, and the inconsistencies between different techniques make a precise quantitative comparison difficult, it is clear from Fig. 4 that the polar breakpoint wavenumber is smaller than that at similar distances near the ecliptic over the range of distances covered by Ulysses. We note, however, that because both the IMP and Voyager results are derived from long time series, including stream structure, the meaning of this result is not entirely obvious. A comparison with the Helios data taken in high speed streams is more meaningful: the Helios data near 1 AU (which show consistency with the IMP results) show clearly that the near-ecliptic breakpoint is at a larger scale by 1 AU than the extrapolated polar data. On this basis, we conclude that polar fluctuations are significantly less evolved than

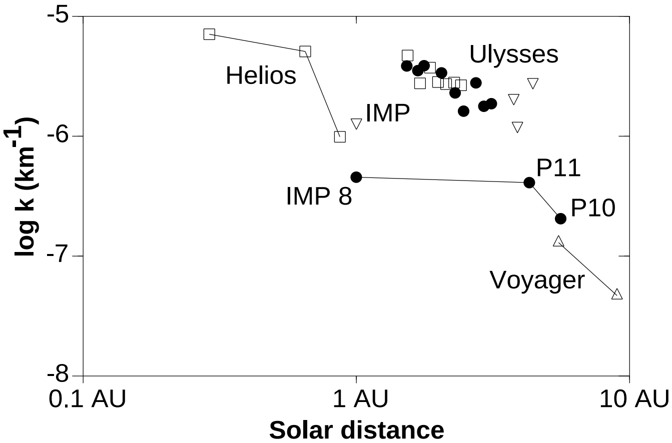

Fig. 4. Variation of spectral breakpoint with solar distance in and out of the ecliptic. Ulysses measurements in polar flows are marked by circles (Southern pass), squares (Northern pass) and triangles (3 high speed velocity declines). Data are also shown from Helios (squares: Marsch & Tu 1990); IMP (triangle: Matthaeus & Goldstein 1986); Voyager (joined triangles: Klein et al. 1992) and a 3 spacecraft study of the same plasma region at different solar distances (joined circles: Feynman et al. 1996)

Table 1. Previous measurements of breakpoint frequencies and wavenumbers from throughout the near-ecliptic heliosphere. The Helios data are from Marsch and Tu (1990); the unified IMP data are from Matthaeus and Goldstein (1986); the Voyager data are from Klein et al. (1992); the IMP 8 and Pioneer data are from Feynman et al. (1996). Velocities are estimated for the IMP, Voyager and Pioneer data; all wavenumbers have been calculated in this work

Spacecraft	Distance (AU)	Velocity (km s^{-1})	Breakpoint frequency (Hz)	Breakpoint wavenumber (m^{-1})
Helios 2	0.29	708	8×10^{-4}	7×10^{-6}
Helios 2	0.65	621	5×10^{-4}	5×10^{-6}
Helios 2	0.87	632	1×10^{-4}	9×10^{-7}
IMP (unified)	1.0	~ 400	8×10^{-5}	1×10^{-6}
Voyager 1	5.5	~ 450	9×10^{-6}	1×10^{-7}
Voyager 1	9	~ 400	3×10^{-6}	5×10^{-8}
IMP 8	1.0	~ 500	5.2×10^{-5}	6.5×10^{-7}
Pioneer 11	4.3	~ 500	3.3×10^{-5}	4.1×10^{-7}
Pioneer 10	5.6	~ 500	1.6×10^{-5}	2.0×10^{-7}

those near the ecliptic at 1 AU and beyond, as was suggested by Horbury et al. (1995a). This is the first quantitative Helios-Ulysses comparison that takes into account the evolution of both polar and near-ecliptic fluctuations.

An extrapolation of the Ulysses data in Fig. 4 to smaller radial distances suggests that the polar and near-ecliptic high speed stream breakpoints might be similar at some distance less than 1 AU. This would not be an unexpected result: close to the Sun, fluctuations in high speed flows from coronal holes are likely to be similar whether the coronal holes are polar or at lower latitudes, and indeed the Ulysses results have shown that flows from polar coronal holes extend to rather low latitudes, at least near solar minimum. The more rapid evolution observed in near-ecliptic fluctuations compared to that in undisturbed polar flows is probably due to the presence of stream structure at low latitudes. However, at small solar distances where fast and slow streams have yet to interact significantly, the fluctuations in fast streams are probably not affected by the presence of slow streams. The high speed streams measured by Helios near 0.3 AU tended to be of uniform speed, while by 1 AU these streams were seen as velocity declines, indicative of a significantly different environment. Therefore, Helios measurements of the breakpoint scale at 0.3 AU may be similar to those in polar data at the same distance. Ulysses has observed undisturbed polar fluctuations at around 1.4 AU and beyond: we cannot, therefore, compare the polar and near-ecliptic fluctuations at 0.3 AU directly. However, it is possible to compare the Helios observations at 0.3 AU with those taken by Ulysses at several AU, assuming a $r^{1.1}$ variation of the breakpoint scale. That is, we can take measurements of the variations of the spectral index α with scale made by Helios in steady high speed streams at 0.3 AU, "normalise" them to a larger solar distance assuming a $r^{1.1}$ movement of the spectrum to lower frequencies, and compare the resulting normalised variation with direct measurements of α at the same solar distance in high speed polar flows. The observation that the α-log τ variation is essentially invariant with solar distance, simply shifting to larger τ with distance, suggests that by shifting Helios observations in the same way, the two sets of observations would coincide.

Bavassano et al. (1982) listed observations of the spectral index α in various spacecraft frequency bands for magnetic field fluctuations at several solar distances, as measured by Helios, in their Table 2. One set of observations was taken at 0.29 AU by Helios 2 in 1976, on days 105 00:00 to 108 21:00 in a high speed stream. We can use this data to plot a α-f curve for high speed solar wind at this distance. We use data for the Z component of their coordinate system, being closest to the N component data used in this study. We will compare this data to α-f data calculated from structure functions for the 5 day interval discussed earlier, taken at 2.4 AU and 80° S. We normalise the Helios data to 2.4 AU: the spacecraft frequencies were multiplied by $1.1 \times (0.29/2.4)$ – this is equivalent to shifting them in log space by $1.1 \times (0.29–2.4)$. Helios velocity data at the NSSDC show that the solar wind velocity was rather constant at around 750 km s^{-1} during the Helios interval: as a result, conversion into the solar wind frame is not necessary since the solar wind velocity was approximately the same for both Ulysses and Helios intervals. Figure 5 shows the α-f curves for both the Ulysses (circles) and Helios (triangles) data. Clearly, the breakpoint at 0.3 AU is at a much smaller scale than at 2.4 AU in polar data. However, the Helios data normalised to 2.4 AU (squares) align closely with the Ulysses observations, reproducing the transition scale rather well, despite the different techniques used to estimate the α-f dependence in each case. We conclude that the Helios and Ulysses observations presented here are consistent with fluctuations in a similar state of evolution at 0.3 AU in both polar and near-ecliptic high speed streams. However, a similar comparison with Helios data taken at larger distances in high speed streams does not result in good agreement with Ulysses polar data. This suggests that the evolution of near-ecliptic fluctuations is more rapid past 0.3 AU, but not before this distance, and raises the question why 0.3 AU is the distance where the more rapid evolution may start. In fact, there is a clear observational difference between Helios data at 0.3 AU and that at larger distances in high speed streams: in general, such observations are of "trailing edges" or velocity declines rather than steady, high speed streams. The exception is at 0.3 AU, where observations of high speed streams show constant velocity streams for several days. In addition, co-rotating interaction regions (CIRs) are only beginning to form by 0.3 AU, while they are well developed by 1 AU. Therefore, the observed consistency of Helios observations at 0.3 AU with those in polar flows is not inconsistent with the driving of near-ecliptic turbulence by stream structure: such structure has yet to influence the fluctuations at such small solar distances.

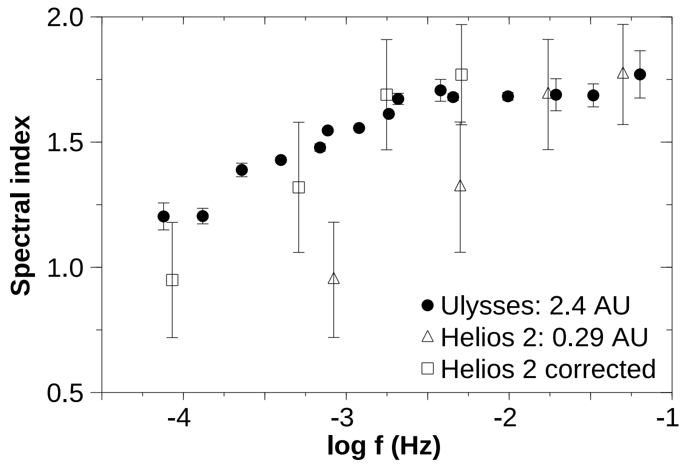

Fig. 5. A comparison of the scale-dependence of spectral index in the polar heliosphere with that in high speed wind at 0.3 AU near the ecliptic. Circles are Ulysses measurements of spectral index variation with spacecraft frequency. Triangles show measurements from Helios 2, taken at 0.3 AU in a high speed stream, as reported by Bavassano et al. (1982). Using the evolution rate measured in polar flows, the Helios data can be "corrected" to that which would be seen at the distance of Ulysses if the same evolution occurred. The corrected data is shown as squares, and agrees well with the Ulysses observations. This agreement suggests that polar and near-ecliptic fluctuations in high speed streams may be similar at 0.3 AU

5. Discussion

The results presented in this paper have provided, for the first time, a quantitative measurement of the turbulent evolution of polar fluctuations in coronal hole streams. The consistency of Northern and Southern measurements confirms that the effect is indeed a radial trend, and not a temporal effect. We conclude that such an evolution probably occurs in all such undisturbed coronal hole streams.

The accurate determination of the breakpoint scale, and its radial variation, allows a comparison with models of turbulent evolution. Such a comparison is left to a later paper – however, we note that the markedly different evolutionary rates observed at high and low latitudes in high speed streams are a strong test of models of turbulent evolution. The quantitative results presented here make an accurate test of models possible. We hope that such tests will be made in the near future. For now, however, we note that the measured polar evolution rate is 1 within errors. An evolution rate of value unity can be explained in a simple way without recourse to MHD turbulence models. In fact, it is perhaps the simplest conceivable rate.

We have seen that energy is transferred into the inertial range fluctuations from the larger scale $1/f$ waves. The breakpoint scale as measured in this work is proportional to the scale of the smallest waves which have yet to transfer significant energy to smaller scales. If the waves decay in a time proportional to their wave period, then the scale of the smallest undecayed waves would increase linearly with travel time, and hence with solar distance. Therefore, the breakpoint scale should also increase linearly with solar distance, leading to an evolution rate of 1. This is indeed the rate observed for polar fluctuations. It is important to note that this measurement of the evolution rate is a function of the decay of the initial $1/f$ fluctuations – and not of the turbulent cascade – in this interpretation. The cascade is simply a consequence of the decay of the low frequency fluctuations. Since in the standard Kolmogorov and Kraichnan views of the inertial range cascade the energy transfer time at a given frequency is proportional to that frequency, the condition that the energy transfer rate be constant is a progressively less stringent condition at higher frequencies. Therefore, one expects to see a $f^{-\alpha}$ power spectrum at higher frequencies when a cascade is occurring, regardless of changes in the energy transfer rate at large scales. The value of α in this case is not a function of the initial decay process but the energy transfer process in the inertial range, which may of course be essentially of the same nature as the decay process.

It is possible to compare Ulysses results with predictions made before the high latitude observations were taken. In particular, we note that the lack of large scale stream shear and the high cross helicity of polar fluctuations (Goldstein et al. 1995) does not prevent the development of turbulence. Dynamic alignment (Dobrowolny et al. 1980) does not appear to occur, and the high cross helicity does not prevent the development of the turbulence as was conjectured by Grappin et al. (1982). Despite the very large amplitude of polar fluctuations relative to the background field (Forsyth et al. 1996), they are not isotropic and do not evolve rapidly towards fully developed turbulence (Roberts 1990). Indeed, the slower rate of evolution at high latitudes compared to that near the ecliptic suggests that this process will probably not occur, at least before they reach the distant heliosphere. The observed evolution appears to agree with "middle of the road" qualitative predictions (Grappin et al. 1991; Bruno 1992) of high latitude fluctuations. Grappin et al. (1991) and Bruno (1992) suggested that the lack of large scale stream shear at high latitudes would cause fluctuations in polar flows to evolve less rapidly than those at low latitudes, as is indeed the case.

There is much in the Ulysses data that is not well understood. In particular, we note a few areas of study for the future, which should prove useful in understanding developing turbulence. Firstly, the interaction of fluctuations with structures – in particular microstreams (Neugebauer et al. 1995) and discontinuities (Tsurutani et al. 1995) – is likely to be important in the initial energy transfer from $1/f$ fluctuations. Secondly, the interaction of fluctuations with stream structure can be studied using Ulysses data at middle latitudes: the polar high speed stream interacts with low speed streams at such latitudes. By tracking in latitude, Ulysses effectively moved from highly evolved to progressively less evolved turbulence as stream structure effects became less important. A careful study of these transition regions is already underway and should help to elucidate stream structure effects. Thirdly, the undisturbed nature of polar turbulence allows the study of the inertial range in a simple homogeneous environment and at a level of detail that is often not possible at low latitudes. Large amplitude, high Reynolds' number MHD turbulence is considerably more complex than turbulence in an unmagnetised fluid: Ulysses data may prove to be some of the most important in studying this important process.

Acknowledgements. The authors wish to thank R. Grappin for helpful comments and suggestions regarding this paper. Support for the magnetic field investigation on Ulysses at Imperial College is provided by the U.K. Particle Physics and Astronomy Research Council. T. S. Horbury is supported by a P.P.A.R.C. fellowship. Portions of this manuscript present work done by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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