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ORIGIN AND EVOLUTION OF FLUCTUATIONS IN THE SOLAR WIND: HELIOS OBSERVATIONS AND HELIOS-VOYAGER COMPARISONS

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Abstract. Using hour-averaged data from the Helios and Voyager spacecraft, we have investigated the origin and evolution of low-frequency interplanetary fluctuations from 0.3 to 20 AU. Alfvénic fluctuations in the inner solar system are found to be generally outward traveling from the Sun and at times quite pure, in general agreement with previous work. The correlation between velocity and magnetic field fluctuations can be high even on scales longer than the transit time from the Sun to the spacecraft, indicating a solar origin for the initial outward traveling waves. However, the fluctuations become substantially less Alfvénic by 1 AU, with the larger scales evolving more rapidly, and this evolution continues in the outer heliosphere. Near the Sun it is regions with small velocity gradients, rather than specifically the trailing edges of high-speed streams, that exhibit the purest Alfvénic fluctuations. Density and magnetic field magnitude fluctuations inside 1 AU show the anticorrelation characteristic of pressure balance structures previously found in the outer heliosphere. The lower frequency positive correlation between density and field observed farther out in association with the growth of compression regions is not generally present inside 0.4 AU. Fluctuations have a somewhat higher magnetic than kinetic energy at scales of less than a day, but at lower frequencies, kinetic energy is already dominant by 0.3 AU. These results support the view that outward propagating Alfvénic fluctuations are generated near the Sun and that substantial dynamical evolution, probably involving shear-generated nonlinear couplings, is important at all heliocentric distances examined.

1. Introduction

Since the work of Belcher and Davis [1971], interplanetary fluctuations have often been regarded as originating at or near the Sun, with little evolution thereafter except perhaps at interaction regions at the leading edges of high-speed streams. An alternative point of view, first presented in detail by Coleman [1968], is that the observed fluctuations are generated in situ by stream shear. This idea is often criticized on the grounds that a shear-flow mechanism would not naturally produce the observed preponderance of outward traveling waves. The present work shows that the viewpoints of Coleman and of Belcher and Davis may both be needed to explain solar wind observations from 0.3 to 20 AU.

An excellent review of early work in this area was given by Barnes [1979], and subsequent work is discussed by Roberts et al. [1987] (hereafter Paper 1). We mention briefly a few papers of particular relevance to this study. Denskat and Neubauer [1982, 1983] reported high correlations between all components of the velocity **v** and magnetic field **B** in Helios data, indicating the frequent presence of Alfvénic fluctuations. For 2 intervals of about 2 months each, one near 0.3 AU and the other at about 1 AU, high-speed streams generally had high correlations. To explain earlier, similar results, Dobrowolny et al. [1980a, b] proposed that nonlinear magnetohydrodynamic (MHD) processes tend to produce an alignment of **v** and **B** which in the solar wind would be observed as a purely outward propagating static state. This process is known as "dynamic alignment." In contrast, Matthaeus et al. [1984] showed that in two-dimensional MHD simulations, dynamic alignment proceeds at a relatively slow rate. This study suggested that outward fluctuations might be generated outside the solar Alfvénic critical point if the large-scale solar wind contained a "reservoir" of structures with an inward sense of correlation.

In Paper 1 we showed that in the outer heliosphere there is a definite evolution toward a less purely Alfvénic state with increasing heliocentric distance, and that this evolution is not simply due to the growth of interaction regions. Although reservoirs of "inward propagating" structures, such as hypothesized by Matthaeus et al. [1984], were sometimes present, the magnitude of the normalized cross helicity associated with these structures was generally not large, so that solar generation is still the best candidate for the main source of outward going fluctuations. In a recent study of data from the primary missions of the Helios spacecraft, Bruno et al. [1985] found evidence that Alfvénic fluctuations could have periods as long as 15 hours near 0.3 AU, and that the Alfvénic character of these long period waves did not persist to near 1 AU. In the present work, we extend the analysis of Paper 1 and of Bruno et al. to include observations inside 1 AU using data from the entire Helios mission through late 1980. The evolution in Alfvénicity we previously observed in the outer heliosphere is shown to

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occur more rapidly in the inner heliosphere, and in low-speed as well as high-speed streams. We conclude that outward traveling fluctuations are predominantly generated by the Sun, but that in situ turbulence, most likely due to stream shear, generates fluctuations with both inward and outward senses of correlation.

2. Data and Methods

We used hour-averaged data in this study to facilitate the analysis of the long time intervals required to obtain a high degree of confidence in results showing the evolution of interplanetary fluctuations. Combined magnetic field and plasma data from the Helios 1 and Helios 2 missions were supplied by the National Space Science Data Center (NSSDC), who obtained the plasma and magnetic field data from H. Rosenbauer and F. M. Neubauer, respectively. Data acquired by Voyagers 1 and 2 were used for comparisons. The magnetic field data from the Voyager missions were supplied by N. F. Ness and the plasma data by H. S. Bridge. The periods covered in the analysis are from 1974 to 1986, but the primary focus was on the period from late 1977 to early 1980 when there was good simultaneous data coverage from the inner and outer heliosphere. The range of heliocentric distances covered was 0.3 to 20 AU.

As in Paper 1, the basic methods used involved multiple time scale correlations calculated with 3-, 9-, 27-, 81-, and 243-hour means. The quantities of greatest interest were [cf. Matthaeus and Goldstein, 1982]

$$\sigma_c = \frac{2\langle \delta v \cdot \delta b \rangle}{\langle \delta v^2 + \delta b^2 \rangle} = \frac{2H_c}{E} \qquad (1)$$

$$\sigma_z = \frac{E_k - E_B}{E} \qquad (2)$$

and

$$\rho_{bn} = \frac{\langle \delta b \delta n \rangle}{(\langle \delta b^2 \rangle \langle \delta n^2 \rangle)^{1/2}} \qquad (3)$$

The angle brackets indicate an average over the appropriate interval, n is the proton number density, $\delta v = v - \langle v \rangle$, etc., and the field is normalized using the Alfvén speed v_A and mean magnetic field B_o according to

$$\delta b = \frac{\delta B}{B_o} v_A \qquad (4)$$

H_c is the cross helicity, and E, E_k, and E_B are the fluctuating total, kinetic, and magnetic energies, respectively. The Alfvén speed includes a 5% contribution of He^{++} (by number) and was generally determined using the local hour-averaged value of the density. (Using the average density over the analysis interval produced only small quantitative changes in the Voyager σ_c results of Paper 1, but for Helios data, the large density changes with heliocentric distance had to be taken into account in long data sets.) For pure Alfvén waves, σ_c is equal to ±1 [e.g., Barnes, 1979]. Because negative (positive) values of σ_c indicate propagation along (opposite to) the mean magnetic field, we rectified the sectors in computing σ_c so that positive values of σ_c always indicate outward propagation. Our results were relatively insensitive to the exact criterion for sector boundaries. The Alfvén ratio r_A (the ratio of kinetic to magnetic energy) is related to σ_z by

$$r_A = \frac{1 + \sigma_z}{1 - \sigma_z} \qquad (5)$$

Goldstein et al. [1986] showed that the low Alfvénic Mach number in the inner solar system might affect the computed values of cross helicity due to a breakdown of the Taylor [1935] frozen-in-flow hypothesis, which ignores the finite propagation speed of the fluctuations. We show in the appendix that this effect is not important in this study.

A number of results from Paper 1 can be briefly summarized in terms of the above quantities. First, we performed extensive error analysis on Voyager data to determine the effect that various experimental uncertainties had on the value of σ_c. The net result is that the typical error in percentage distributions of σ_c such as that shown in Figure 6 is ±1% in each point. Both independent analysis of Helios data and comparisons to Voyager data show that Helios results should be at least this accurate; the relative errors in Helios data should generally be even smaller than those in Voyager data due to the larger amplitudes of the fluctuations closer to the Sun. The distributions are well determined because of the accuracy of the data and because a large number of points are used to determine statistics. The accuracy of the data also allowed us to determine that a perfectly aligned Alfvén wave is not likely to have $|\sigma_c| < 0.8$ within measurement uncertainty. This provides a more restrictive but also more physically motivated criterion for Alfvénic fluctuations than has been used previously [cf. Belcher and Davis, 1971; Denskat and Neubauer, 1983]. The interpretation of fluctuations with normalized cross-helicity values less than 0.8 is straightforward only when the assumptions of incompressibility and weakly interacting waves hold, and this is difficult to determine from the data. Thus as in Paper 1, we will refer to "outward," "inward," and "mixed" states of the fluctuations, with the caveat that in the mixed ($|\sigma_c| < 0.8$) case, the wave field may or may not consist of a superposition of Alfvén waves propagating in opposite directions. Similarly, the terms "more inward" or "more mixed" will be sometimes used to indicate an evolution in σ_c, rather than specifically the generation of inward propagating Alfvén waves. Whatever the detailed nature of a "mixed state" may be, it is indicative of in situ generation of fluctuations, since generally only outward traveling waves will escape from the Sun past the trans-Alfvénic point in the solar wind. Evolution from an outward to a mixed state provides stronger evidence for in situ generation.

The methods used here all involve time domain correlations, but in Paper 1 we showed that spectral methods can be used to arrive at similar conclusions both for individual intervals and for

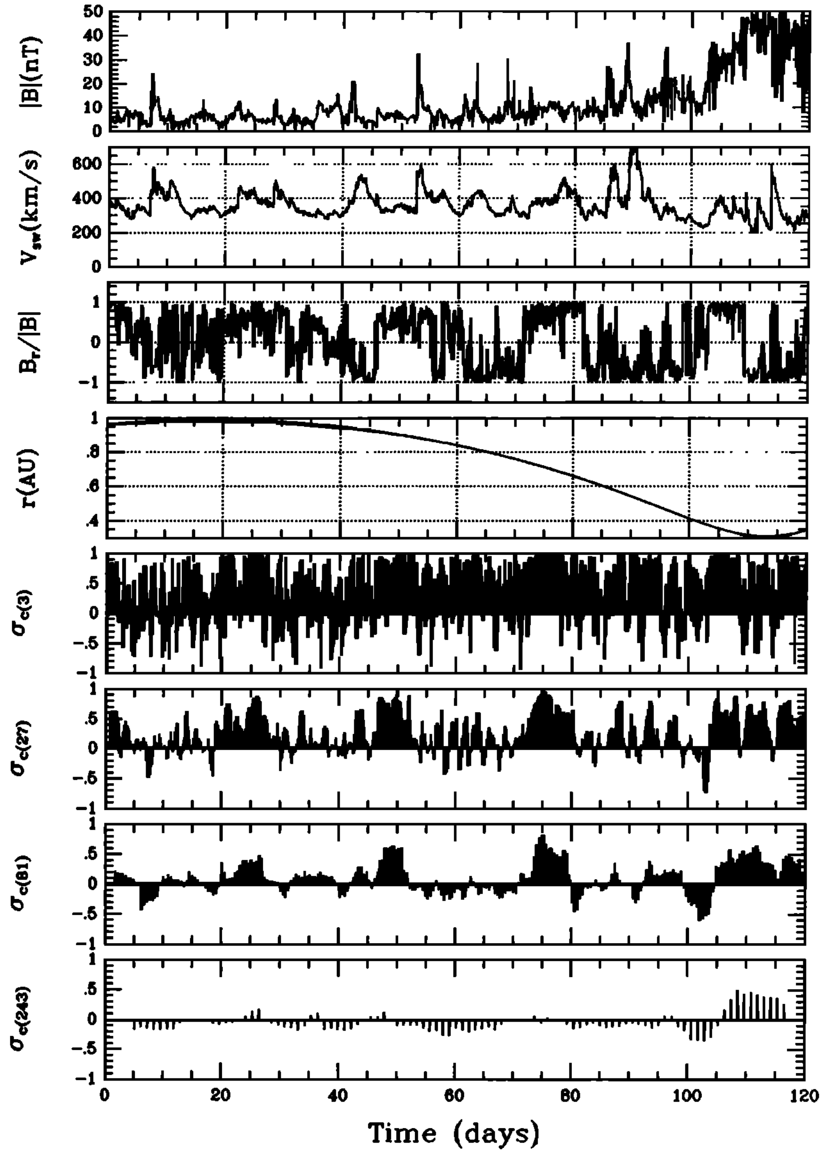

Fig. 1. Panels of (top to bottom) |B|, V_{sw}, B_r, heliocentric distance, and 3-, 27-, 81-, and 243-hour running values of σ_c for Helios 1 data obtained in early 1980. The "spikes" are at each value computed; correlations were only calculated as often as needed to resolve significant changes.

overall statistics. We have verified that spectra of H_c and E also give similar results to those shown here for Helios data, but these spectra are not shown, as they add nothing new to the results. The higher-resolution spectra used in Paper 1, as well as, for example, those shown by Matthaeus and Goldstein [1982], lead us to believe that the 3-hour scale correlations shown here are representative of what happens at smaller scales (down to about 0.5 min). We found some direct evidence for this in the case of Helios data by comparison of our 3-hour scale correlations with the correlations shown by Denskat and Neubauer [1983], which were 1-hour correlations based on 40-s data. While the agreement was quite good, determining the correspondence between 3-hour and shorter scales for Helios data in general will require further comparisons.

3. Alfvénicity in Helios Data

First we consider the purity and direction of Alfvénic fluctuations in Helios data. Figure 1 shows time series of data from the Helios 1 spacecraft acquired during the early part of 1980 (days 38-158). The panels show |B|, V_{sw}, the radial component of the magnetic field divided by the field magnitude, the distance of the spacecraft from the Sun, and σ_c at 3-, 27-, 81-, and 243-hour scales. (The 9-hour scale, not shown here, looks qualitatively the same as the 3-hour scale.) Note that the interval covered includes the entire range of heliocentric distances traversed by the spacecraft. The radial magnetic field is shown to indicate sector structure, but as indicated above, positive values of σ_c imply outward propagation in all cases.

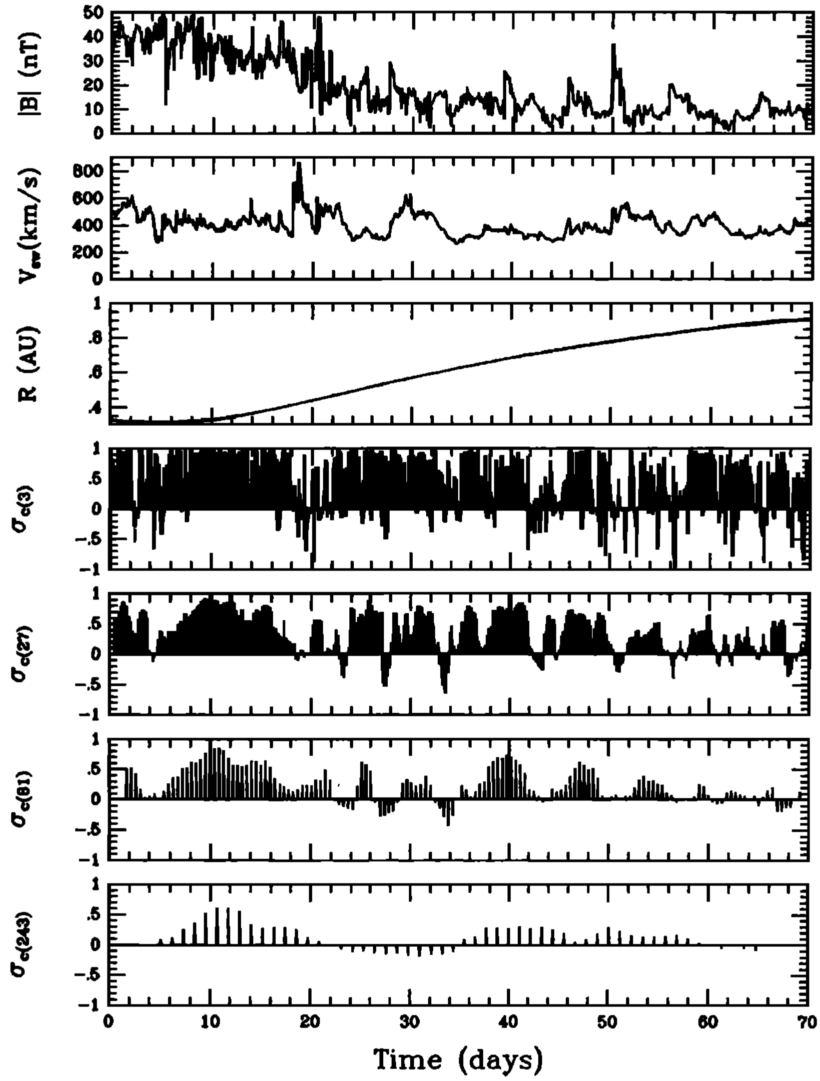

Fig. 2. Similar to Figure 1 (but without the radial component) for an interval of Helios 1 data obtained in early 1978. The bottom panel of Figure 10 shows the sector structure for this case.

The figure illustrates many of the points of this paper. First, note that generally more low and negative values of σ_c occur near 1 AU (days 0-40) than near 0.3 AU (days 105-120). In this case the effect is most clearly seen at the 3-hour scale, but this result is typical of most of the intervals studied, independent of when they occurred in the solar cycle. The few exceptions to this evolution were in cases where σ_c was unusually low near 0.3 AU. As noted above, this evolution in σ_c is clear evidence of the role of in situ generation of fluctuations. The highly mixed state in the first 20 days of data, where the sector structure is changing rapidly and thus the spacecraft is probably near the current sheet, may be indicative of increased generation of fluctuations near the sector boundary. This requires further study, but the example shown in Figure 2 (discussed below) shows that the general evolution seen here is not dependent on the rapid sector changes.

A second significant point apparent in Figure 1 is that the purest (in the sense of the highest correlation) Alfvénic fluctuations are not in the trailing edges of high-speed streams [cf. Denskat et al., 1981]. In fact, the high correlation near day 50 on the plot, which we found to be an example of unusually pure waves at this heliocentric distance, is clearly associated with the low-speed wind. The two main peaks in σ_c nearer 0.3 AU, around days 75 and 107, are also associated with low-speed flow. The considerably lower correlations during the time between these peaks are all associated with the inward directed field magnetic sector, which indicates that conditions either side of the heliospheric current sheet can be quite different. In particular, note that the highest speed streams in the interval are in the sector that has generally low values of σ_c. While the three-dimensional structure of flows cannot be determined from single spacecraft measurements, the above associations suggest that stream shear may be an important source for producing the more mixed state seen more prevalently near 1 AU. This is consistent with what Coleman [1968] first suggested [cf. Rosseland, 1928], but he offered no explanation for why the waves both he and

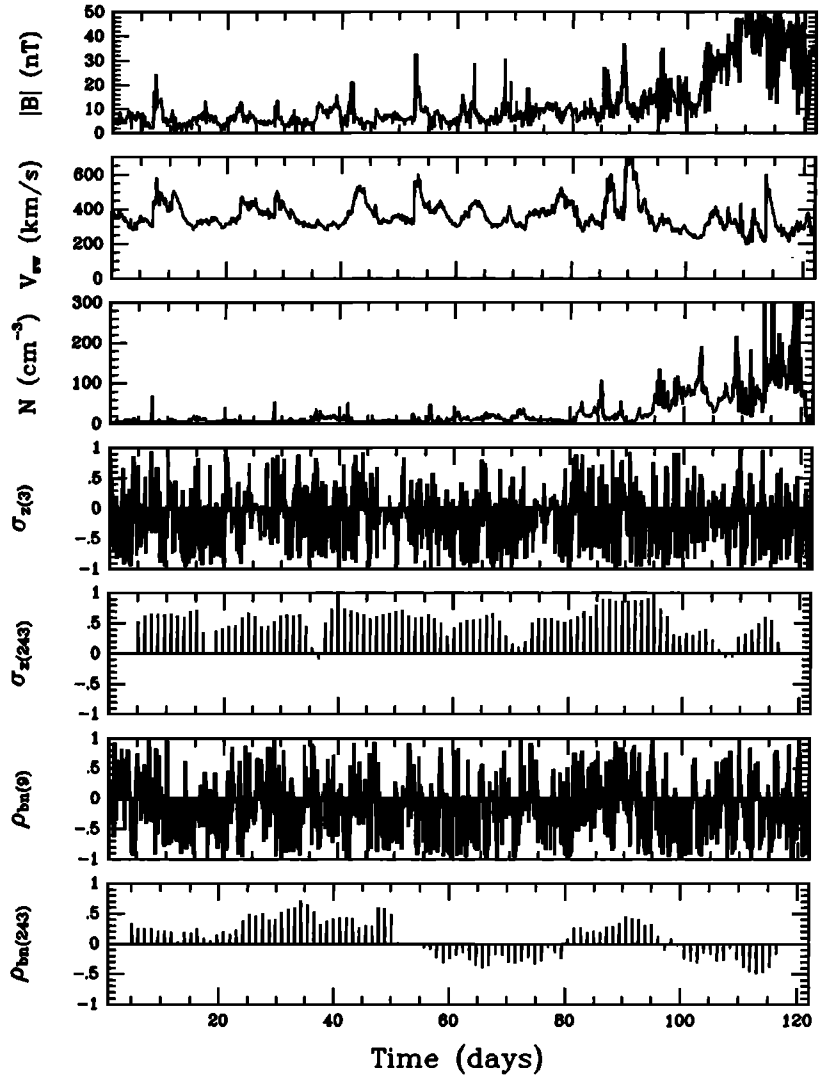

Fig. 3. Multiple-scale (3 and 243 hour) σ_z for the data shown in Figure 1. The values of "σ_z" are related to the Alfvén ratio r_A by (5). The lowest two panels show 9- and 243-hour scale correlations of density with magnetic field strength for the same interval.

Belcher and Davis [1971] observed tended to be outward propagating. The present work suggests a possible solution to this difficulty: stream shear, to the extent that it can generate MHD fluctuations, should not preferentially create fluctuations with only one sign of v-B correlation, and thus its action could result in the observed evolution in σ_c. Although, as shown in Paper 1, the correlation of trailing edges of high-speed streams with more purely outward traveling fluctuations near 1 AU is not very strong, a tendency toward this correlation can be explained as the result of weaker velocity shear in the trailing edges of the streams. This will be discussed further below.

A third striking feature of the time series shown in Figure 1 is that near 0.3 AU, $\delta \mathbf{v}$ and $\delta \mathbf{b}$ are correlated fairly well even at the longest time scales. The 81-hour scale here represents structures that would be about 1 AU in extent if they were truly spatial. When the large-scale correlations are high, the values of σ_c at smaller scales are usually higher still. Near 0.3 AU there is a peak in σ_c even at the "3-AU" (243-hour) scale. Such correlations cannot be produced by an in situ generation process but must arise from motions near the Sun that shake the ends of the field lines very slowly. The spacecraft was in the "near field" of these fluctuations, and although it is impossible to observe a full wavelength, we can tell the sense of propagation from the $\delta \mathbf{v}$, $\delta \mathbf{b}$ correlation. Given that the shorter-scale correlations line up well with those at longer scales, we infer that the Sun is the source of at least most of the outward going flux at small heliocentric distances. Consequently, the "minority species" mechanism proposed by Matthaeus et al. [1984], while possibly important at times in the solar wind, cannot be the major reason for the initial outward flux of Alfvénic fluctuations.

Figure 2 shows an analysis of data from Helios 1 obtained during 1978 days 114-184. It provides a further illustration of high correlation at all scales when the spacecraft is nearer the Sun and in a region with little free energy in streams.

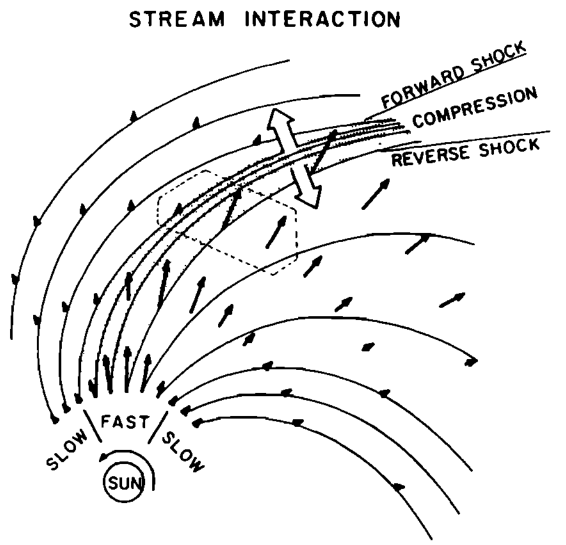

Fig. 4. Schematic view of stream interaction regions showing the compression (shaded) and rarefaction produced as high-velocity plasma overtakes low velocity plasma [after Eviatar and Goldstein, 1980].

The evolution to a more mixed state near 1 AU at all scales is also apparent. The evolution here occurs in regions with well-defined sector structure, as shown, for example, by comparing days 5-18 and days 56-66 which are regions of the same well-defined magnetic polarity. (The sector structure for this data set is shown in the bottom panel of Figure 10.) The most mixed state near perihelion is around day 20 of the plot, in a region containing a high-speed stream. A statistical study of the evolution seen in Helios data will be presented below in conjunction with Voyager data.

Denskat et al. [1981] conducted a similar study of Alfvén wave evolution using data from the primary missions of the Helios spacecraft (December 1974 to March 1975 for Helios 1, and January to April 1976 for Helios 2). Their conclusions are consistent with ours when the differences in methods and intervals are considered. For example, they found no evidence for evolution in the **v**-**b** correlations of the waves in the Helios 1 data, using 1-hour correlations of individual components. Using a 3-hour scale and vector correlations, we found the same apparent lack of evolution for this data set, due to unusually low values of σ_c near 0.3 AU. However, a clear evolution is evident at our longest scales (81 and 243 hours). Their result that about 75% of the interval was Alfvénic was based on a less strict definition than we have used (Paper 1). If "Alfvénic" is restricted to mean that the waves observed could be purely outward propagating Alfvén waves to within measurement errors, then according to the criterion of Paper 1 ($\sigma_c > 0.8$ using (1)), this occurred only about 22% of the time at the 3-hour scale in the primary mission of Helios 1. The more strict criterion indicates that 78% of the time for this interval there were fluctuations present that probably were not generated in the solar atmosphere.

Bruno et al. [1985] found an evolution similar to that shown in Figures 1 and 2 for waves near the 15-hour scale in the high-speed streams of the primary missions of Helios. We concur with their conclusions but have found that during other time periods the same evolution can be seen outside of high-speed steams and their trailing edges. Also, the analysis of a larger set of Helios intervals and the results of Paper 1 make it clear that evolution occurs at both longer and shorter time scales as well, as is evident, for example, in Figure 2. As noted above, we expect that an analysis of higher-resolution Helios data for the intervals analyzed here would show that the 3-hour scale is indicative of what happens at shorter time scales.

4. The Alfvén Ratio and Compressive Effects

In Paper 1 we showed that the magnetic fluctuation energy typically exceeded the kinetic fluctuation energy in the outer heliosphere, especially in compression regions. The main exception to this was at large scales at the smaller heliocentric distances in the study where the stream kinetic energy dominated. The situation in the inner heliosphere is essentially similar, as illustrated in Figure 3, which shows σ_z at a small and a large scale for the same data as in Figure 1. Negative values of this quantity, which indicate the dominance of magnetic energy, again predominate at the small scales [cf. Bruno et al., 1985], while kinetic energy dominates at large scales. The large-scale kinetic energy should become relatively less important closer to the Sun since the magnetic field rapidly increases with decreasing heliocentric distance, due to magnetic flux conservation. Therefore the rapid disappearance of the large-scale outward sense of σ_c between 0.3 and 1.0 AU is quite possibly associated with dynamical processes driven by kinetic energy which generally dominates the flow at distances greater than 0.3 AU.

Compression regions are associated with a positive correlation between density and magnetic field magnitude changes [Burlaga, 1984]. Burlaga and Ogilvie [1970], Vellante and Lazarus [1987], and Paper 1 all showed that at shorter scales the solar wind at 1 AU and beyond is often characterized by the negative n, b correlations indicative of pressure balance structures. The bottom panels of Figure 3 show the situation in the inner heliosphere. We again see a tendency for strong negative correlations at small scales, but inside about 0.8 AU (days 55-120), this tendency extends to large scales as well. The middle of this period (days 80-100) includes two large streams which have already produced strong compressions as indicated by the positive values of $\rho_{bn(243)}$ at that time. The two flanking intervals (days 55-80 and 100-120) contain comparatively low flow speeds. In those cases, compression regions are insignificant, and pressure balance structures may dominate the compressive part of the fluctuations at all scales.

The relation between shear and compression in the spiral geometry of the heliosphere is illustrated in Figure 4, which is adapted from Eviatar and Goldstein [1980]. The figure shows velocity vectors and lines of constant solar wind speed for a situation that starts at the Sun with a symmetrical high-speed stream. Initially the stream has equal shear on both sides of the

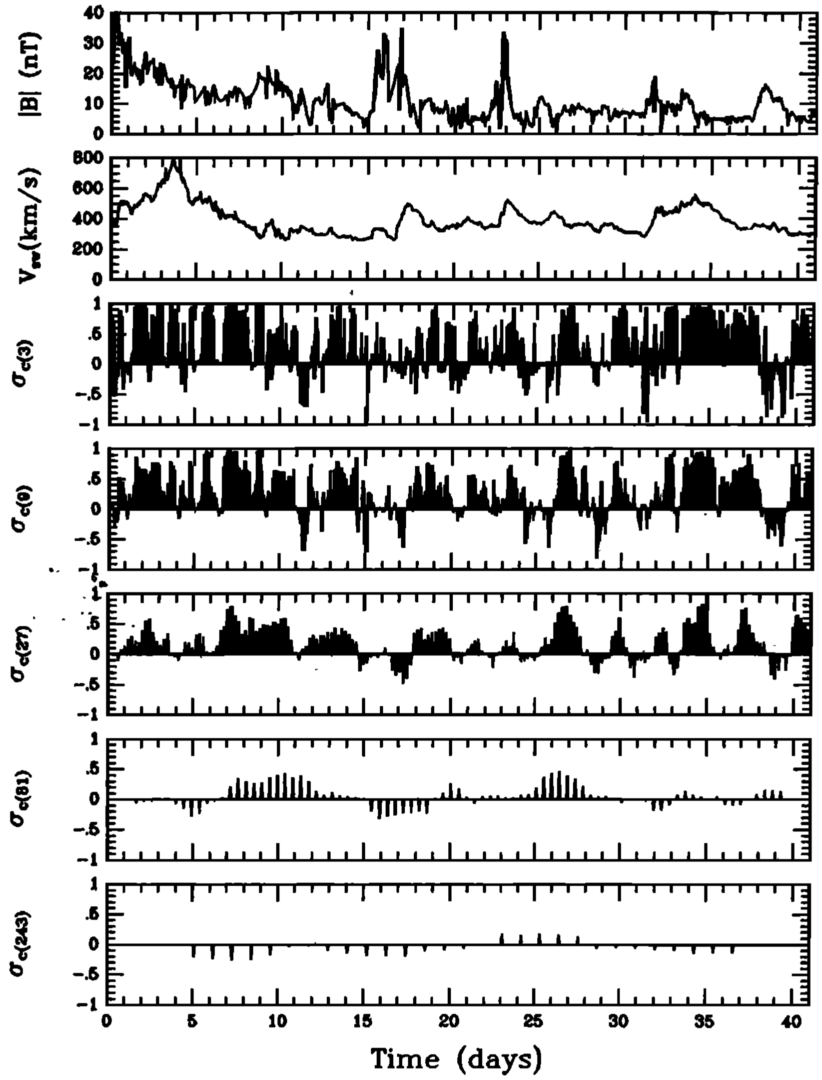

Fig. 5a

Fig. 5. Multiple-scale plots of σ_c comparing (a) Helios 2 near 0.7 AU to (b) Voyager 1 near 1.7 AU for the same plasma region.

velocity maximum and little compression or rarefaction. Further from the Sun, the leading edge of the stream has increasingly greater shear and compression, while the trailing edge has lower shear. This is illustrated in the dotted box where the shaded compression region has higher shear than the rarefaction region. Thus the generation of fluctuations by stream shear can explain the observed mild correlation found between compression regions and more mixed wave propagation [Paper 1; Belcher and Davis, 1971], and it may provide a better description of the observations than generation by compressions. Local generation of fluctuations driven by compressions alone would produce a strong correlation of mixed cross helicity with stream compressions. However, the observed evolution does not differ greatly in rarefactions compared with compressions (Paper 1), consistent with generation in the nearly symmetrical shear present near the Sun and the evolution toward stronger shear in compression regions at greater heliocentric distances.

5. Helios-Voyager Comparisons

In this section we present two instances where the same plasma was observed by both Helios and Voyager spacecraft. In one case the spacecraft were separated by about 1 AU, and in the other by almost 8 AU. Time series of |B|, V_{sw}, and σ_c at various scales are shown for the first comparison case in Figure 5. Figure 5a is based on data from Helios 2 when the spacecraft was near 0.7 AU in late 1977 (days 312-354), and Figure 5b is based on Voyager 1 data from an interval at about 1.7 AU that starts a few days later than the Helios interval (days 317-358). The field and speed time series are generally very similar, except for expected changes such as the growth of a compression region at the leading edge of a steepening stream toward the right of the figure. The trailing edge of the first high-speed stream, which also is a region of relatively mild speed gradients, is generally outward traveling at both spacecraft at all scales except the largest. The relatively mild evolution observed here is

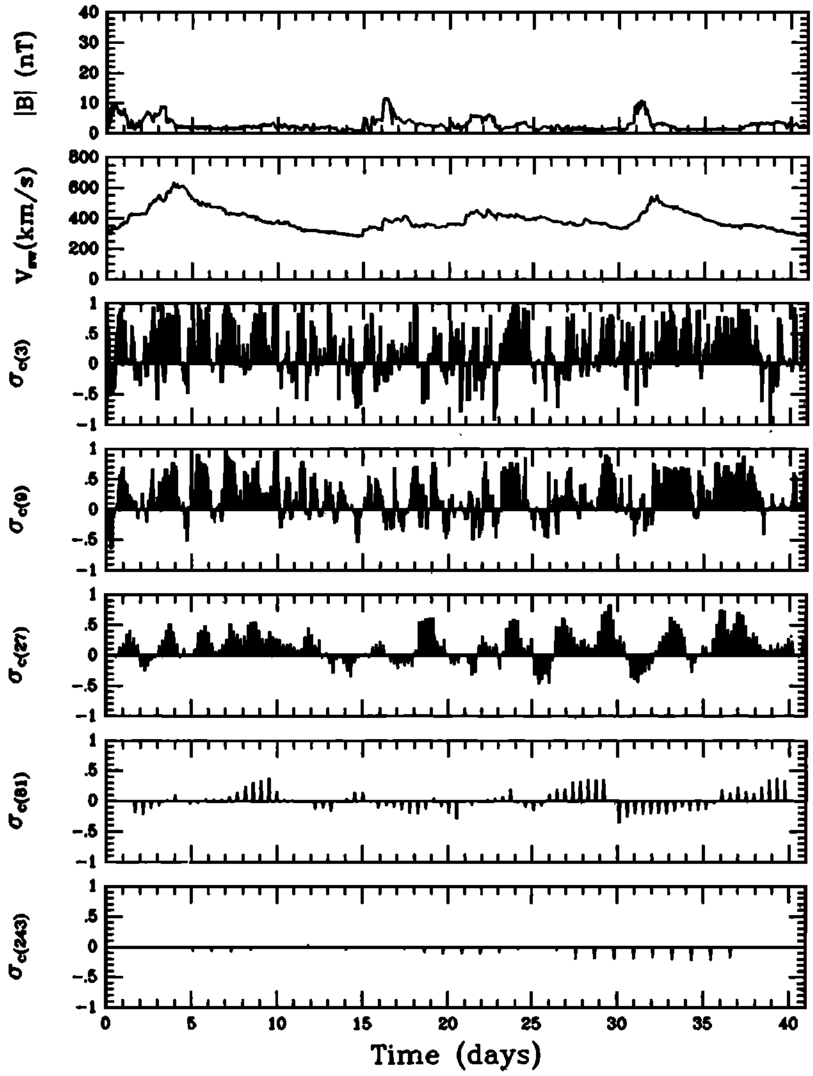

Fig. 5b

consistent with the result in Paper 1 that near and beyond 1 AU the evolution in σ_c is small. That there is evolution here is shown in Figures 6a and 6b, which show percentage distributions of σ_c in bins of 0.2 for the entire interval at the 3- and 27-hour scales. The circles are for the Helios data, and the triangles are for the Voyager data. The 3-hour time scale shows a small but statistically significant (see the discussion of errors above) evolution toward a more mixed state farther out in the heliosphere. The evolution in the initially quite mixed 27-hour scale is less evident, but still in the direction of more mixed farther out. The general agreement in regions of outward and mixed propagation in Figure 5, as well as in the statistical distributions in Figure 6, provides a consistency check on the methods used here by showing that similar results are obtained from two spacecraft. Also, the double-peaked distribution for Helios in Figure 6 is typical and represents the presence of regions of relatively pure Alfvén waves (e.g. days 34-36 in Figure 5a) along with other regions that have already become mixed (e.g. days 15-18).

A second example is particularly instructive because it was studied in detail by Whang and Burlaga [1985], so that the evolution of the large-scale structure is well understood. The

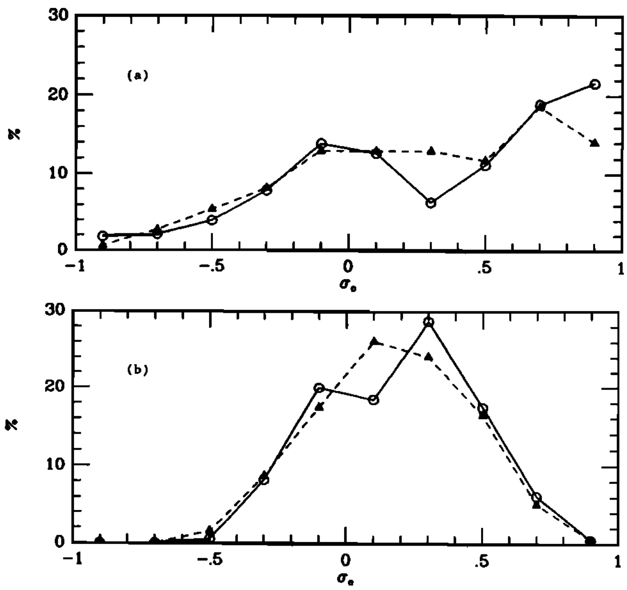

Fig. 6. Evolution of distributions of σ_c as given by percentages in bins 0.2 wide at (a) 3-hour and (b) 27-hour scales from the Helios (circles) and Voyager (triangles) spacecraft data in Figure 5.

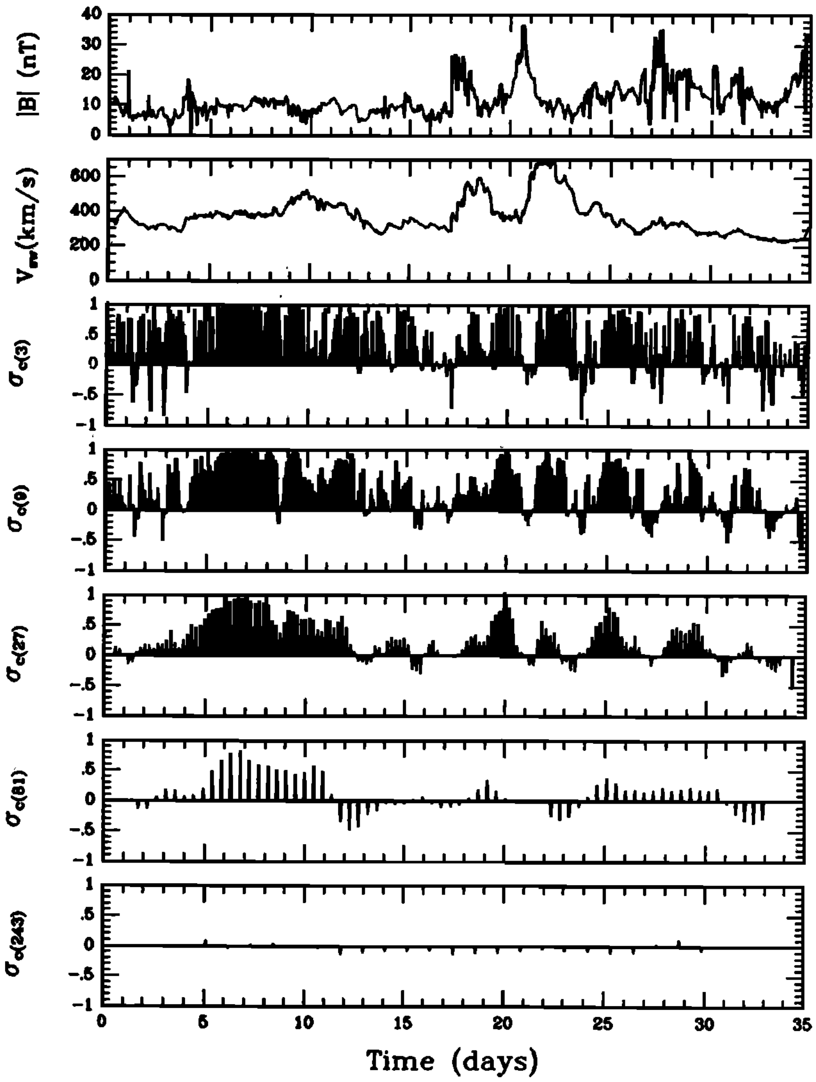

Fig. 7a

Fig. 7. Multiple-scale plots of σ_c comparing (a) Helios 1 near 0.6 AU to (b) Voyager 1 near 8 AU for the same plasma region.

interval (Helios 1, 1980 days 105-140) also corresponds to a subset of that shown in Figure 1 (days 67-102), but it is reproduced in Figure 7a for easier comparison. The Voyager 1 interval (Figure 7b, 1980 days 136-171) comes from the same plasma region, which is now at about 8 AU. The overall evolution in σ_c is stronger than in the previous comparison, as is apparent both visually and from the distribution shown in Figure 8, which shows the 3-hour scale correlations (Helios data are again represented by circles, and Voyager data by triangles). This is consistent with a continuing evolution with increasing heliocentric distance.

There is only one region in the Voyager data in Figure 7b (days 23-30) that shows consistent outward sense of correlation at all scales (although the 243 hour correlations are too small to rule out chance). According to Whang and Burlaga [1985] this region had not interacted with any neighboring material, at least along the radial direction. (It is impossible to eliminate all interactions, especially with streams above or below the ecliptic.) Moreover, all other regions in the interval had undergone stream-stream interactions. The probably undisturbed region also shows outward propagation in the Helios data. Thus it seems likely that the region of coherent outward fluctuations observed in the Voyager data is a remnant of solar generated fluctuations. Note that the trailing edge region has expanded, and thus the long time scale panels in the Voyager plots correspond to higher time scales in Helios plots. Other intervals showing coherent correlation at many scales have been observed in Voyager data (see Paper 1), although they are relatively rare compared with their frequency near 0.3 AU. Such coherent intervals are never as long or as purely Alfvénic in the outer heliosphere as they are closer to the Sun.

The overall evolution of σ_c with heliocentric distance is summarized in Figure 9. Here we show distributions of σ_c at three distances from the Sun (near 0.3 AU, Helios 1, 1978 days 106-131; 2 AU, Voyager 1, 1979 days 120-220; and 20 AU, Voyager 2, 1985 days 300-360), and at three time scales (3, 9, and 81 hours). The distribution near 0.3 AU represents a case that is more purely Alfvénic than any we have observed beyond about

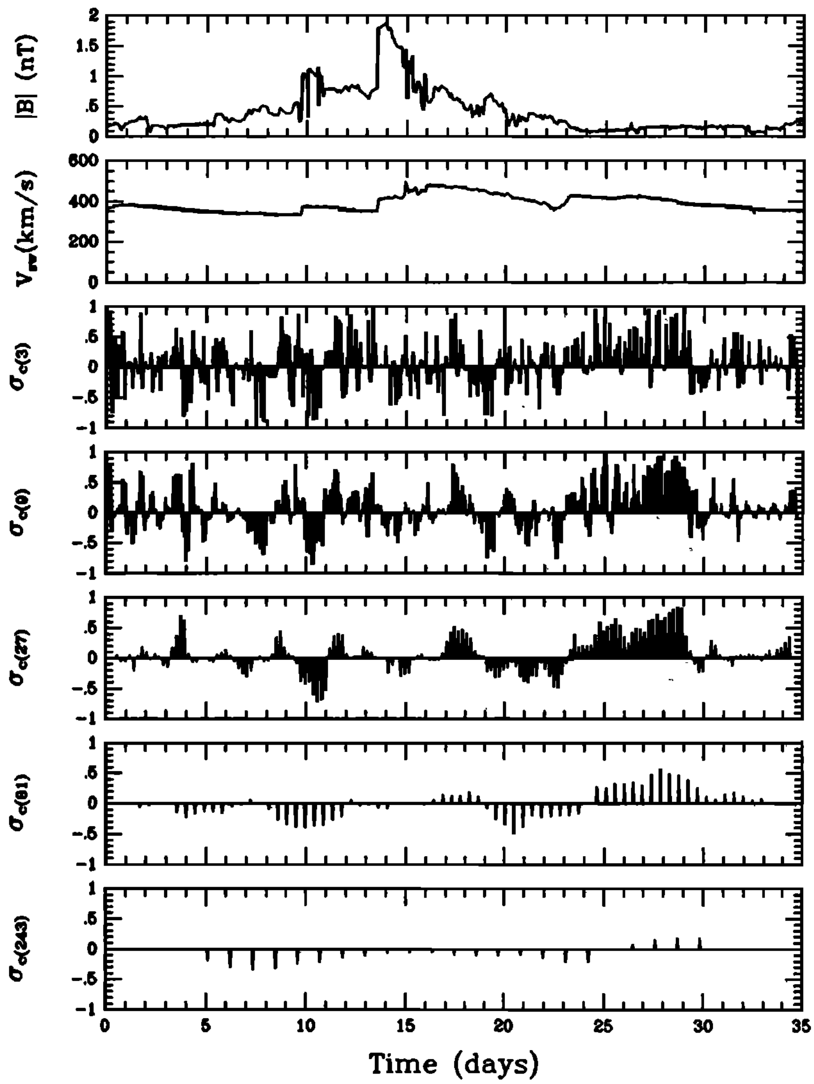

Fig. 7b

0.5 AU, but even here the fluctuations are not purely outward propagating. If the Sun produces purely outward traveling waves, then Figure 9 provides evidence that substantial evolution can occur at small heliocentric distances. The data set used for the most distant case is noisy and thus not completely reliable (L. Burlaga, private communication, 1986), but comparison with the 8 AU distribution in Figure 8, taken in a region of relatively good data, suggests that the 20-AU distribution is a natural end point of the evolution of the cross-helicity spectrum. The solar wind in the outer heliosphere thus appears to have little memory of the fluctuations produced by the Sun, just as it has little memory of the original stream structure [Burlaga, 1984].

6. Discussion

A simple picture emerges from the above discussion which will be investigated in detail in future work: The Sun generates outward propagating fluctuations over a wide range of scales. Stream shear then generates fluctuations with mixed sign of cross helicity wherever the kinetic energy is dominant and the shear sufficiently large. As the large-scale magnetic field decreases, the kinetic energy becomes dominant first at the large scales, and thus the large-scale δ**v**, δ**b** correlations are the first to disappear. A turbulent cascade then sends fluctuations of mixed σ_c to higher wave numbers, leading to mixed distributions even at scales where the velocity is not dominant. Only in

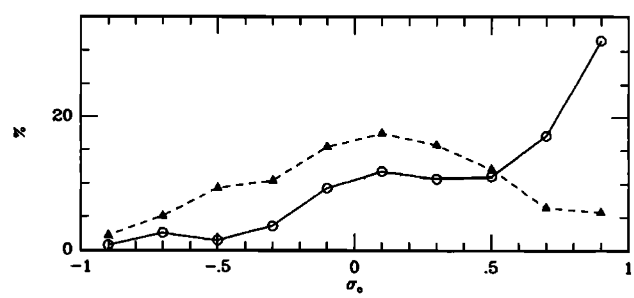

Fig. 8. Evolution of σ_c as given by percentage distributions at the 3-hour scale from the Helios (circles) and Voyager (triangles) spacecraft data in Figure 7.

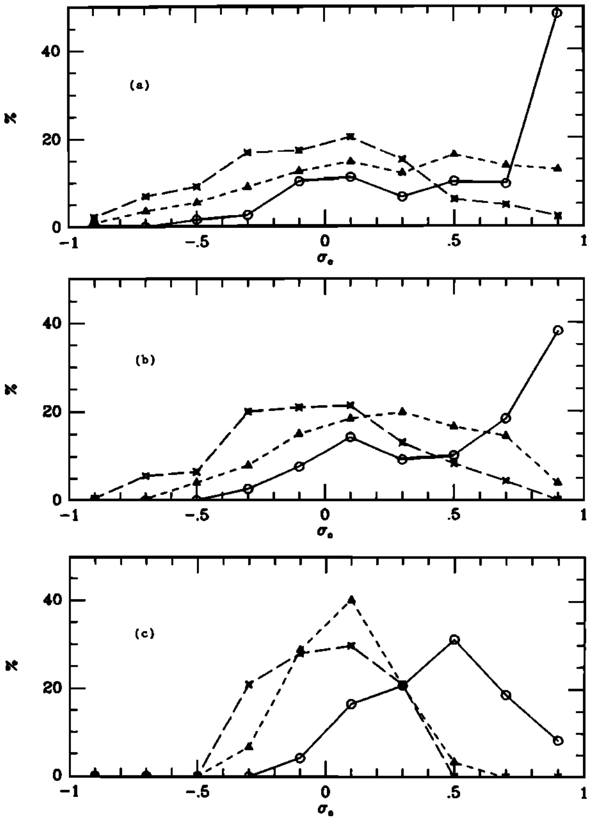

Fig. 9. Evolution of σ_c from 0.3 to 20 AU as given by percentage distributions from both Helios and Voyager spacecraft. Curves shown are for 0.3 (circles), 2 (triangles) and 20 AU (crosses), and are at (a) 3-hour, (b) 9-hour, and (c) 81-hour scales.

regions of low shear will the original outward solar-generated fluctuations persist to large distances. The evolution of σ_c occurs most strongly in the inner solar system, where both the kinetic energy and the associated shear of the streams are the largest. There is some correlation between the regions where compressions grow ($\nabla\cdot\mathbf{v}$ is large) and where in situ fluctuations are generated ($\nabla\times\mathbf{v}$ is large) [cf. Korzhov et al., 1984]. Both effects are expected where the velocity is rapidly increasing. Trailing edges of high-speed streams will not be readily overtaken by other plasma, thus allowing the persistence of more purely Alfvénic intervals in these regions.

This picture unifies the suggestions of Coleman [1968], who maintained that stream shear generates the interplanetary fluctuations, and of Belcher and Davis [1971], who said that the predominance of outward propagation argues for solar generation. Belcher and Davis went on to suggest that the streams might affect the evolution of the fluctuations, but they thought that this would happen farther out in the heliosphere. The change in focus in the present work is primarily from the frequent occurrence of a high outward sense of correlation to the even more frequent occurrence of a lack of perfect correlation. The need for this change was pointed out in the work of Burlaga and Turner [1976], Denskat and Burlaga [1977], and Matthaeus and Goldstein [1982], among others. Bavassano et al. [1982] also showed that spectral evolution occurs in the inner solar system that is not consistent with the WKB prediction for wave amplitudes [Hollweg, 1974, 1978; Whang, 1973] which is based on a simple superposition of MHD waves.

It appears difficult to account for the current observations using a model in which compressions are the source of in situ generation of fluctuations. It was suggested in Paper 1 that interaction regions and the associated shocks do not in themselves produce significant levels of low-frequency fluctuations, since there was little change observed in σ_c across shocks, and compression regions did not produce a mixed state much more quickly than other regions. As Belcher and Davis [1971] pointed out, waves generated in interaction regions will generally be confined by the flow either side of the compression region. If interaction regions

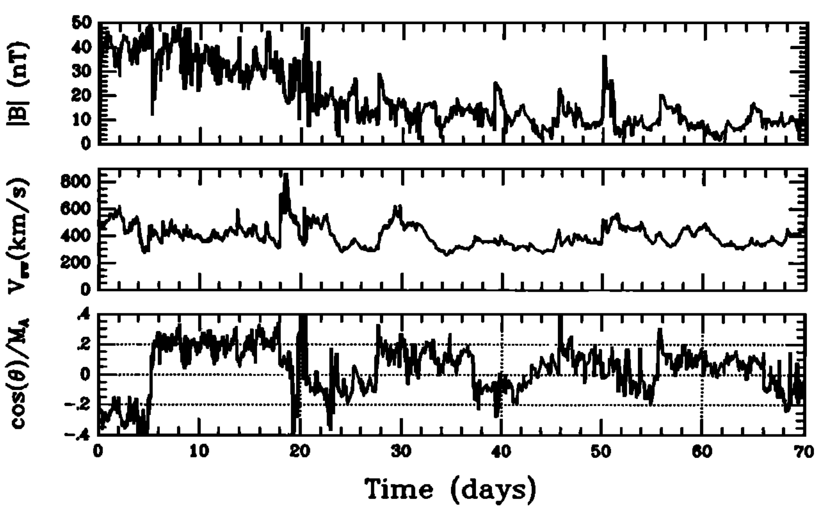

Fig. 10. The magnetic field magnitude, solar wind speed, and the parameter $\cos\theta/M_A$ for Helios data from near perihelion (left) to near aphelion. (The distance scale is shown in Figure 2.)

primarily generated fluctuations, we would not expect to see any significant evolution in the waves elsewhere. In fact the evolution toward a mixed state is almost as strong in rarefaction regions. It is rare by 1 AU to find any region that is as Alfvénic as is commonly the case near 0.3 AU. Moreover, the evolution is strongest where the compression regions are least evident, namely, inside about 0.7 AU.

Stream shear is the most natural source for generating fluctuations besides compression. Korzhov et al. [1984] have shown that the large values of stream shear expected in interaction regions can be strong enough to forestall the steepening of compressions. The nonlinear evolution of velocity shear in a magnetofluid is currently being studied quantitatively in two-dimensional simulations of the Kelvin-Helmholtz instability (D. A. Roberts, M. L. Goldstein, and W. H. Matthaeus, manuscript in preparation, 1987). This study should help answer the question of whether velocity shear can generate high wave number fluctuations similar to those described here.

The present work implies that what we see at 1 AU is not generally representative of phenomena occurring near the Sun. The observed rapid evolution of the cross helicity in the inner heliosphere is indicative of strong in situ nonlinear dynamical processes. These processes may affect the amplitudes of the fluctuations as well as their propagation directions. Regions that are relatively purely Alfvénic may provide some insight into solar processes, but the above results suggest that a full understanding of all 1 AU observations in terms of solar processes must await a more complete theory of the evolution of interplanetary fluctuations.

Appendix

Frozen-in-flow assumes that frequency ω in the spacecraft frame of reference and solar wind wave number k are related by $k = \omega/V_{sw}$ [Taylor, 1935]. In a low Mach number regime, one may have to take into account the speed of the propagating structures [Goldstein et al., 1986]. In the limit that this correction is small (as will be shown to be the case), the new relation can be written

$$\kappa = \frac{k}{1 \pm \beta} \qquad \text{(A1)}$$

where κ is the corrected wave number, k is the wave number without the correction, and

$$\beta = \frac{\cos\theta}{M_A} \qquad \text{(A2)}$$

where M_A is the Alfvénic Mach number and θ is the angle between the mean magnetic field and the solar wind velocity. The sign is positive for waves traveling outward, and negative for inward. It can be shown that for power law spectra with spectral index $-\alpha$, the corrected value of σ_c is related to the uncorrected value by

$$\sigma_c' = \frac{\sigma_c - (\alpha - 1)\beta}{1 - (\alpha - 1)\sigma_c\beta} \qquad \text{(A3)}$$

As illustrated in Figure 10, which covers the same interval shown in Figure 2, the value of $\beta = \cos\theta/M_A$ increases to ~0.2 near 0.3 AU, with occasional excursions to 0.4. Using a value of 0.2, and $\alpha = 5/3$ gives a maximum correction to σ_c of about -0.13, which would in general be significant. However, the correction for values of σ_c greater than 0.8 is less that 0.05. For both small values of σ_c ($\simeq 0$) and $\beta \simeq 0.4$, the error in σ_c is approximately 0.27, decreasing to less than 0.12 for $\sigma_c \gtrsim 0.8$. When the spectrum is closer to $\alpha = 1$, the corrections are even smaller. Both our studies and those of Bavassano et al. [1982] show that power spectra near 0.3 AU at scales longer than a few hours have spectral indices close to $\alpha = 1$, and we show in this work that σ_c tends to be high near the Sun. This means that the above effect will be small in all cases of interest here. For detailed studies of high-resolution data, where spectra are generally steeper, this effect could be more important.

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