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(NASA-TM-84955) DYNAMICAL EVOLUTION OF INTERPLANETARY MAGNETIC FIELDS AND FLOWS BETWEEN 0.3 AU AND 8.5 AU: ENTRAINMENT (NASA) 20 p HC A02/MF A01 CSCL 03B

N83-19667

Unclas G3/90 08905

NASA

Technical Memorandum 84955

DYNAMICAL EVOLUTION OF INTERPLANETARY MAGNETIC FIELDS AND FLOWS BETWEEN 0.3 AU AND 8.5 AU: ENTRAINMENT

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JANUARY 1983

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Space Administration

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1. Introduction

The radial evolution of interplanetary flows in the outer heliosphere has been discussed by Burlaga (1982), Burlaga and Behannon (1982), Burlaga *et al.* (1980), Collard and Wolfe (1974), Collard *et al.* (1982), Dryer *et al.* (1978), Goldstein and Jokipii (1977), Gosling (1981), Gosling *et al.* (1976), Hundhausen (1973a,b), Hundhausen and Gosling (1976), Pizzo (1980, 1982), Schubert and Cummings (1967), Simon and Axford (1966), Smith (1979), and Smith and Wolfe (1977, 1979). The emphasis in most of these papers is on the processes related to the steepening of a corotating stream, particularly: 1) the development of shock pairs, and 2) the acceleration of slow material and deceleration of fast material. Akasofu (1982) has investigated the overtaking of a corotating flow by a transient disturbance using the kinematic model described by Hakamada and Akasofu (1982). The purpose of this work is to investigate the radial evolution of a system of flows and magnetic fields between 0.3 AU and 8.5 AU using data from Helios and Voyager. The principal new phenomena are 1) the entrainment of slow streams (transient and corotating streams) and shocks by fast corotating flows, and 2) the associated growth of large-scale pressure waves. These results suggest a new picture of heliospheric structure between the sun and $\sim$ 30 AU which is discussed in Section 4.

2. Observation of the Radial Evolution of Flow Systems

We shall discuss the radial evolution of flows and magnetic fields observed by Helios 1 (H1) between 0.3 and 1 AU and by Voyager 1 (V1) between 8.0 AU and 8.5 AU. The principal period of interest is the 70-day interval May 9 to July 18, 1980 in the V1 data, i.e., just over two solar rotations. The corresponding interval in the H1 data set is approximately April 11 to June 22 1980. The solar equatorial plane projection of the spacecraft trajectories is shown in the left panel of Figure 1. Note that a parcel of plasma detected at H1 on day 133 and moving at V $\sim$ 500 km/s would have passed near V1 on day 160 after a propagation time of $\sim$ 27 days, (the propagation time would be $\sim$ 45 days if V = 300 km/s and $\sim$ 19 days if V = 700 km/s). At this time the latitudinal separation of the spacecraft was $\lesssim 1^\circ$, as shown by

ABSTRACT

The radial evolution of interplanetary flows and associated magnetic fields between 0.3 AU and 8.5 AU was analyzed using data from Helios 1 and Voyager 1, respectively. During a 70-day interval in 1980 Voyager 1 observed two streams which appeared to be recurrent and which had little fine structure. The corresponding flows observed by Helios 1 were much more complex, showing numerous small streams, transient flows and shocks as well as a few large corotating streams. It is suggested that in moving to 8 AU the largest corotating streams swept up the slower flows (transient and/or corotating streams) and shocks into a relatively thin region in which they coalesced to form a single large-amplitude compression wave. We refer to this combined process of sweeping and coalescence as "entrainment". The resulting large-amplitude compression wave is different from that formed by the steepening of a corotating stream from a coronal hole, because different flows from distinct sources, with possibly different composition and magnetic polarity, are brought together to form a single new structure. As a result of entrainment, memory of the sources and flow configurations near the sun is lost. Small-scale features are erased as the flows move outward and energy is transferred from small scales to large scales by entrainment. Thus in the outer solar system the structure of the solar wind may be dominated by large scale pressure waves (compressions followed by rarefactions) separated by several AU. Beyond several AU most of the compression waves are no longer driven by streams, and the compression waves expand freely. At large distances ($\gtrsim$ 25 AU) they will have interacted extensively with one another producing yet another state of the solar wind, with fewer large-scale non-uniformities and more small-scale non-uniformities.

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The speed profile observed by the MIT plasma instrument on V1 is shown in the top panel of Figure 1. There are two large streams, one per solar rotation, separated by ~ 27 days; a similar stream was observed one solar rotation before the first stream and one solar rotation after the second stream. Thus, it appears that V1 observed a single large corotating stream twice in the interval under consideration. Two other characteristics of the V1 speed profile should be noted: 1) the amplitude of the stream is relatively small (~ 150 km/s), the speed ranging from ~ 350 km/s to ~ 500 km/s, and 2) the duration is relatively long, > 15 days.

If the stream observed by V1 were corotating, then the stream steepening models and previous observations imply that H1 should likewise have observed a single corotating stream, twice in the interval under consideration, with possibly somewhat larger amplitudes than seen by V1. However, the speed profile observed by the plasma instrument on H1 is surprisingly different from this expection (Figure 2, middle panel). Instead of two streams, there are many streams; instead of small amplitudes (~ 150 km/s), the amplitudes are large (up to 500 km/s); and instead of long-lasting streams, the flows at H1 are of relatively short duration. There is another difference between the H1 and V1 observations which we do not show explicitly owing to lack of space: The major streams at H1 (with maxima on days 141, 150, 153, 165 and 179 in the middle panel of Figure 2) have the usual signature of a corotating stream, viz. low density, high temperature and a well-defined stream interface, whereas in the streams at V1 the density and temperature profiles are complex and it is difficult to identify a stream interface. How can one account for these great differences among the V1 and H1 observations?

To facilitate comparison of the H1 and V1 speed profiles, the Helios speeds were plotted in the middle panel of Figure 2 with a time delay corresonding to a corotating flow with a constant speed of 500 km/s. Despite the many differences discussed in the preceding paragraph, there is a correspondence among the largest streams. The first stream in the V1 profile corresponds to a closely spaced pair of streams at H1, and the second stream in the V1 profile corresponds to a single very large and very steep stream at H1. Thus, it appears that the corotating streams observed by V1 are related to the largest corotating streams at H1, but their structure is very different at the two spacecraft, and the disappearance of the slow streams and shocks at H1 must still be accounted for.

To compare the H1 and V1 flow systems in more detail, the H1 speeds were plotted at the bottom of Figure 2 with a time delay for each hour equal to the corotation delay corresponding to the speed measured at H1 in that hour. Thus, the time delay is different for each hour, depending on the speed, and fast plasma arrives earlier than shown in the middle panel of Figure 2 while slow plasma arrives later. At first glance, the kinematic projection seems nonsensical, because it gives a multiple-valued speed profile. However, closer inspection shows that this projection provides significant insight, provided that one understands the limitations of the approach. The declining speed profiles of the projections of the two largest streams at H1 agree reasonably well with the corresponding profiles of the trailing part of the two streams at V1 (A tracing of the V1 speed profile is shown in the bottom panel of Figure 2 to facilitate this comparison). The steep trailing part of a corotating stream at H1 becomes a broad trailing flow at V1 because the fast plasma moves ahead relative to the slow plasma behind it during the transit to V1.

The multi-valued speed profile in the bottom panel of Figure 2 is the result of fast flows overtaking slower flows ahead. For example, the second (faster) of the pair of streams seen at H1 (shown at days 150 and 153 in the middle panel of Figure 2) overtakes the first stream, and they coalesce to form a single stream. Such an interaction between two corotating streams was discussed implicitly by Hundhausen and Gosling (1976), using a gas dynamic code (B = 0). This pair of streams similarly overtakes and coalesces with part of the corotating stream ahead. The net result is a "compound stream" at V1, in the classification of Burlaga and Ogilvie (1973) and Burlaga (1975), in which only vestiges of the original streams can be seen. This process of interacting corotating flows is a special case of a more general process that we shall call "entrainment" in which slow streams and/or shocks are swept-up and assimilated by a faster flow.

The entrainment process is suggested by the evolution of the flows observed by H1 between "corotated days" 160 and 190 shown in the middle panel of Figure 2. The large fast corotating stream near day 18) apparently overtakes and coalesces with a whole series of flows, observed as much as 20 days earlier by H1 as it moved rapidly in longitude near perihelion. Thus, several streams with possibly different compositions and magnetic polarities, originating from perhaps several sources were swept-up into a small region ahead of the large corotating stream. Most of the small streams were transients and shocks associated with two active regions preceding the coronal hole that produced the large corotating stream, so we cannot attribute much significance to the individual projections obtained by corotating each profile. Nevertheless, the active regions were recurrent, and we may assume that similar, albeit different, short lived streams were continually emitted and swept-up by the corotating stream. The essential result is not the detailed pattern of the particular flows described here, but the idea of entrainment suggested by those observations, which is probably a general process in the interplanetary medium.

3. Entrainment and Pressure Waves

The entrainment process that we have been discussing is the result of two processes: 1) sweeping of slow flows (corotating and/or transient streams) by a fast corotating flow, and 2) coalescence of all those flows. Sweeping is, of course, basically a kinematic process. Note that it is different from the kinematic steepening process associated with an isolated corotating flow (see, e.g., the discussion of Burlaga and Barouch, 1976, and Gosling, 1981). Sweeping involes the overtaking of several streams and shocks ahead of a different fast corotating flow, whereas stream steepening involves the overtaking of slow material at the leading edge of a stream by faster material in the same stream. Coalescence is a dynamical process in which several streams, interaction regions and possibly shocks, brought close together kinematically, interact via pressure gradients to form a new pressure profile and stream profile. The process of entrainment, involving both sweeping and coalescence, produces a significant restructuring of the heliospheric plasmas and magnetic fields, in which the signatures of individual sources and smaller scale features are lost and a large "pressure wave" profile is produced.

The entrainment process concentrates a great deal of energy into a small volume, resulting in the creation of a large, non-linear compression wave. Figure 3 shows the total pressure, $P = NkT_p + B^2/8\pi$ divided by the pressure P_o for a hypothetical structureless solar wind. The total pressure was computed from the plasma data discussed above, and from the GSFC magnetometer on V1 and the University of Rome/GSFC magnetometer on H1. The pressure P_o was computed from the formula P_o (10^{-10} dyn/cm^2) = 0.345 $[R(AU)]^{-2.7} + (2/\pi)$ [1 + $R(AU)^2]/R(AU)^4$. In the absence of streams and shocks, one expects that P/P_o should be close to 1. The H1 data in Figure 3 show several small spikes in P/Po, corresponding to shocks and interaction regions associated with the corotating streams, as discussed by Burlaga and Ogilvie (1970), Siscoe (1972) and Smith and Wolfe (1976). At V1, the pressure profile is very different, the amplitude and width of the compression waves being very large, much larger than those at H1. (Strictly speaking, one should include contributions due to electrons in P and P_o; using plausible electron temperature profiles, we found only a small decrease in the amplitude of the P/P_o profiles due to electrons). The difference between the H1 and V1 pressure profiles is obviously not due simply to the steepening of isolated streams, but rather it is due to the entrainment of flows as discussed above.

The compression waves in Figure 3 are followed by rarefaction waves in which the pressure is so low that it appears to be zero. The regions of the rarefaction waves correspond to the trailing part of the speed profile at V1. The low pressure in this part of the flow explains why the kinematic method (which neglects pressure) was able to give a reasonable fit to the trailing speed profiles by projecting the Helios stream profiles.

Hundhausen (1982) has suggested another way in which small-scale structure in the solar wind can be lost. Using a gas-dynamic code (β = 0), he modeled a single sinusoidal velocity perturbation (stream) near the sun on which was superimposed a smaller amplitude, shorter wave length sinusoidal perturbation, and he found that the smaller scale features tended to disappear by the time the stream reached 1 AU. Thus, this is a model of the fine structure of streams, corresponding to the "irregular variations" in the classification of Burlaga and Ogilvie (1973). It is distinctly different from the process of entrainment suggested here, which involves the interaction of different streams particularly beyond 1 AU. The two processes are not mutually exclusive, however. Hundhausen suggests that the solar wind acts as a low pass filter which, strictly speaking, means that the power at high frequencies is lost. In our concept of entrainment, the power at high frequencies is transferred to low frequencies, and in particular to the large-scale nonlinear pressure waves as we now describe.

4. Conceptual Model of the Heliosphere

The results derived above from a relatively small set of data support and augment the conceptual model of the heliosphere discussed by Burlaga (1982) for the region between the sun and $\sim$ 30 AU and for times when it is dominated by corotating streams and pressure waves (see Figure 4). Near the sun, say within a few AU, heliospheric structure is determined by streams, and the V, N, T profiles are closely related to conditions in the corona. Farther from the sun, entrainment and stream steepening lead to the formation of large, corotating, non-linear pressure waves. These pressure waves react on the solar wind, accelerating slow plasma and decelerating fast plasma. The growth of pressure waves is thus associated with the decay of streams, and at $\sim$ 10 AU heliospheric structure may be governed by large-scale pressure waves rather than by streams. As a result of entrainment, a new ordering of the interplanetary parameters is produced. The N, T, V, B profiles at large distances have an organization appropriate to large-scale, non-linear pressure waves, and details concerning the source conditions which are carried by streams near the sun are lost.

At still larger distances, say $\gtrsim$ 25 AU, the pressure waves will interact with one another, and these wave-wave interactions will produce a third zone in the solar wind. In this wave interaction zone, large-scale inhomogeneities associated with the waves will be reduced, small-grained structure will develop, and entropy will increase. It might be necessary to describe the wave interaction zone in statistical terms rather than the deterministic models used until now.

5. Cosmic Ray Effects

Our original motivation for investigating the flow systems discussed above was the observation that the "corotating" stream observed by Voyager 1 on approximately day 180, 1980 (see Figure 2) caused an abrupt, permanent, step-like decrease in the galactic cosmic ray intensity (Mc Donald et al., 1982; Burlaga et al., 1982). The problem was to explain why this stream was so effective in modulating cosmic rays while the stream seen 27 days earlier was not. The answer seems to be that the stream on day 180 entrained several different flows, including transients and shocks, and the complex mangetic field configuration in the resulting compression wave formed an effective barrier to cosmic rays. In contrast, the stream on the preceding solar rotation was formed from the interaction of more ordered, quasi-stationary corotating flows. The details of the cosmic ray modulation will be discussed in a subsequent paper.

6. Summary

We have described the evolution of a system of flows between 0.3 AU and 8.5 AU for two solar rotations in 1980. Whereas two broad, small-amplitude corotating streams (one per solar rotation) were observed by Voyager 1 near 8 AU, many narrow, large-amplitude streams, both corotating and transient streams were observed by Helios 1 inside of 1 AU. It is suggested that small streams and shocks were "entrained" by the largest corotating streams, i.e., they were swept-up owing to the kinematic tendency of fast plasma to overtake slow plasma and coalesced to form a single flow system owing to dynamical interactions. As a result, large non-linear "corotating" pressure waves were formed. It is suggested that between ~ 10 AU and ~ 25 AU heliospheric structure may be dominated by such pressure waves, which carry little memory of the source conditions; only vestiges of streams remain in the pressure wave zone.

It is conjectured that beyond ~ 25 AU extensive wave-wave interactions can occur, giving rise to another state of the solar wind, more homogeneous on a large scale than the pressure wave zone, but possibly more inhomogeneous on a smaller scale. A statistical description and model may be more appropriate in this wave-interaction zone than a deterministic description and model. We stress that this conceptual model is applicable when one or a few fast flows are dominant. A different model may be more appropriate when systems of transient flows are dominant (Burlaga *et al*., 1982).

Acknowledgments

We are grateful to Drs. F. Mariani and N. Ness for allowing us to use their data from Helios 1, to Drs. H. Bridge and A. Lazarus for plasma data from Voyager 1, to Dr. N. Ness for magnetic field data from Voyager 1, and to Mr. L. Klein for programming assistance. Dr. Lazarus also contributed helpful comments on the manuscript. The need to understand the structure and dynamics of the flows discussed in this paper arose from studies of cosmic ray modulation, and one of us (L. B.) is indebted to Dr. F. B. Mc Donald for directing his attention to this problem.

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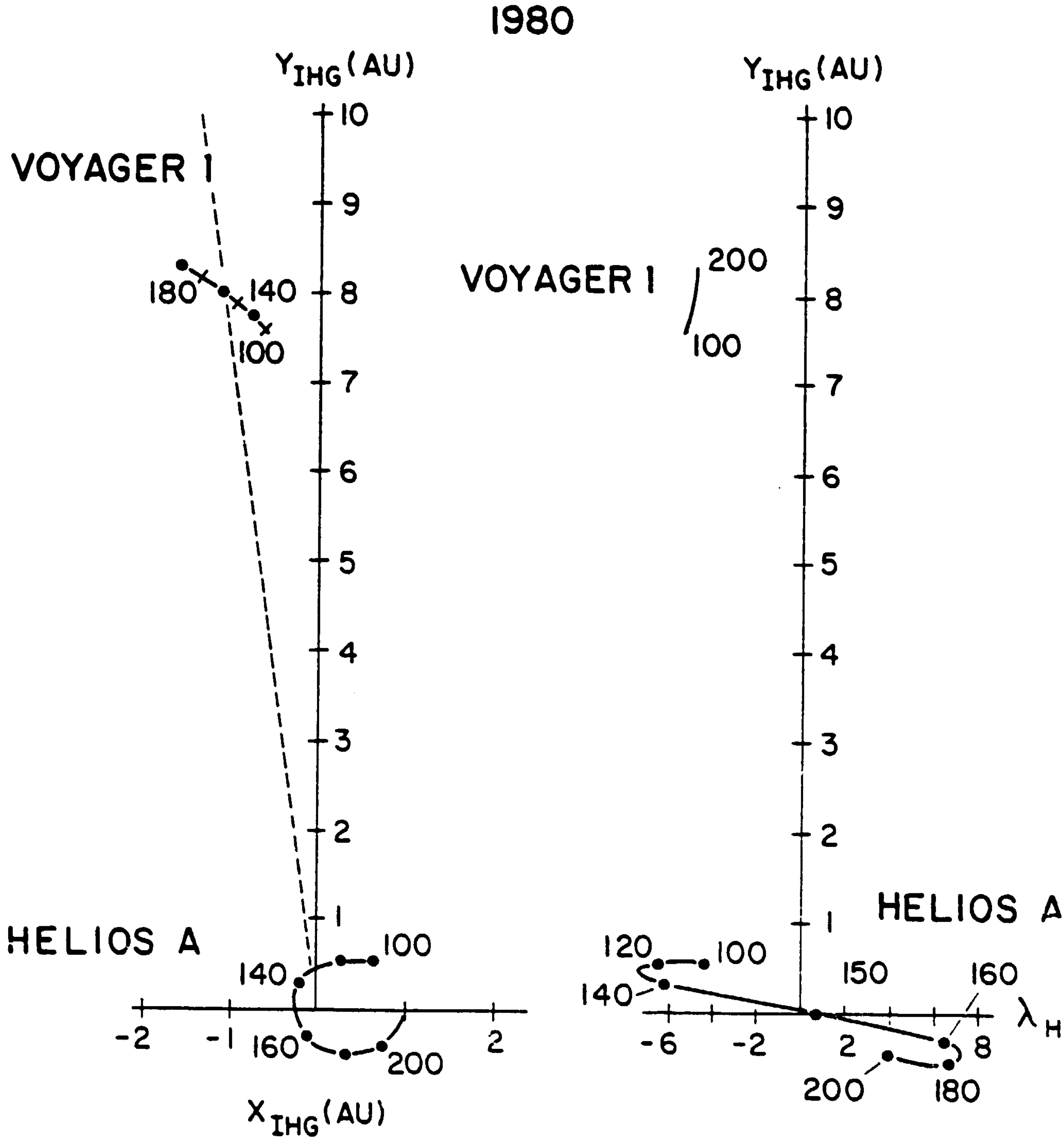
Figure Captions

Figure 1 — Helios and Voyager trajectories. The solar equatorial plane projection in inertial heliographic coordinates is shown at the left. On the right is shown the solar latitude of the spacecraft in degrees, relative to the equatorial plane.

Figure 2 — Helios and Voyager speed profiles. Top: Voyager 1 hour-averages of the speed versus time. Middle: Helios 1 hour-averages of speed versus time plotted with a time delay assuming corotation and a constant speed of 500 km/s. Bottom: Helios 1 hour-averages of speed versus time plotted with a time delay assuming corotation and a radial speed equal to the measured speed for each hour.

Figure 3 — Pressure profile. P is the sum of the magnetic and ion pressure P_o is a nominal pressure profile versus distance for a structureless solar wind.

Figure 4 — A schematic conceptual model of the outer heliosphere for times when corotating systems are dominant.


1980
YIHG (AU)
VOYAGER 1
180
140
100
HELIOS A
140
100
160
200
-2
-1
2
XIHG (AU)
YIHG (AU)
VOYAGER 1
200
100
HELIOS A
120
100
140
150
160
-6
-2
2
8
200
180
λH
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9
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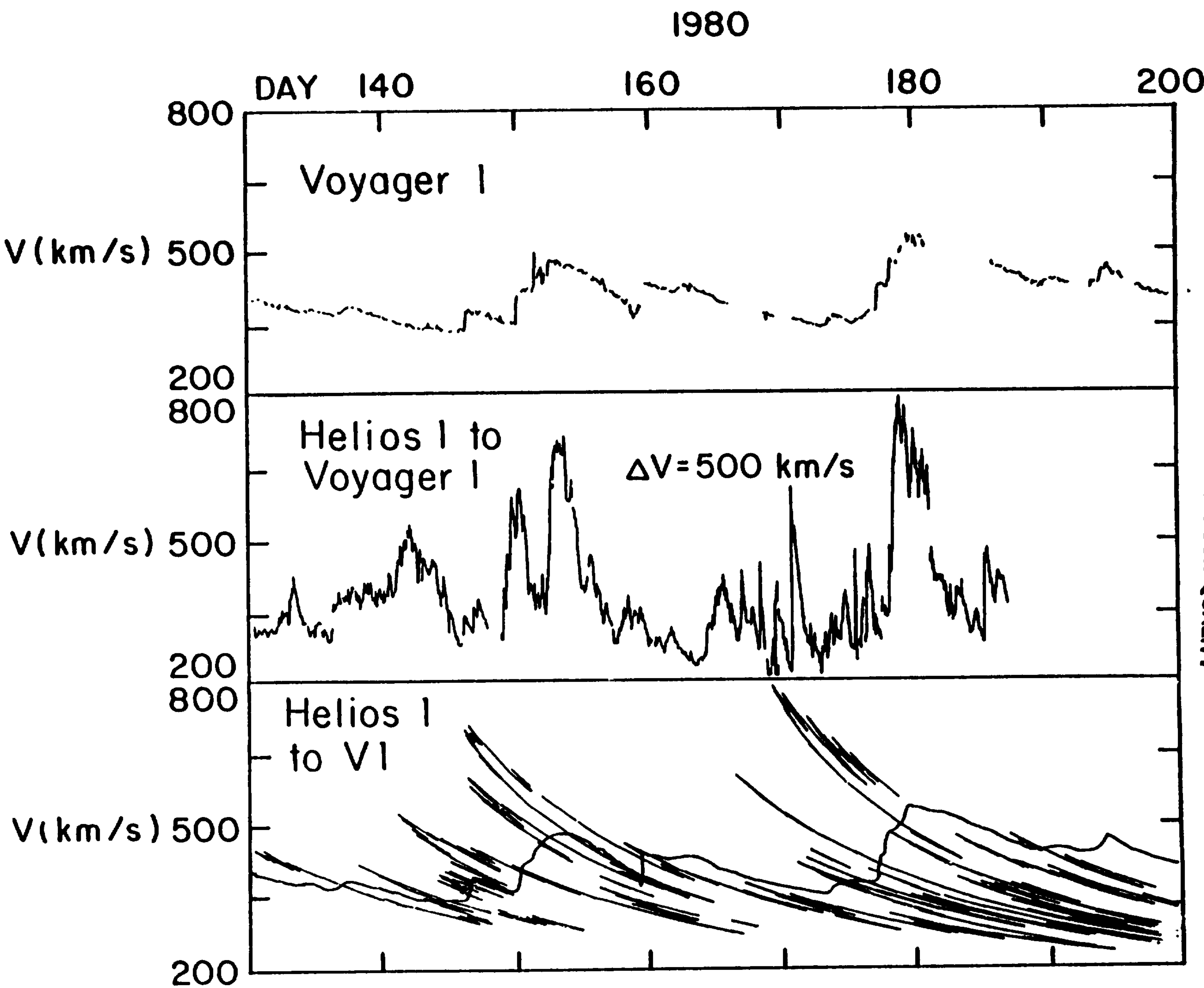
7
6
5
4
3
2
1

Figure 1



1980
DAY
140
160
180
200
800
500
200
V(km/s)
Voyager 1
Helios 1 to Voyager 1
ΔV=500 km/s
Helios 1 to V1

Figure 2

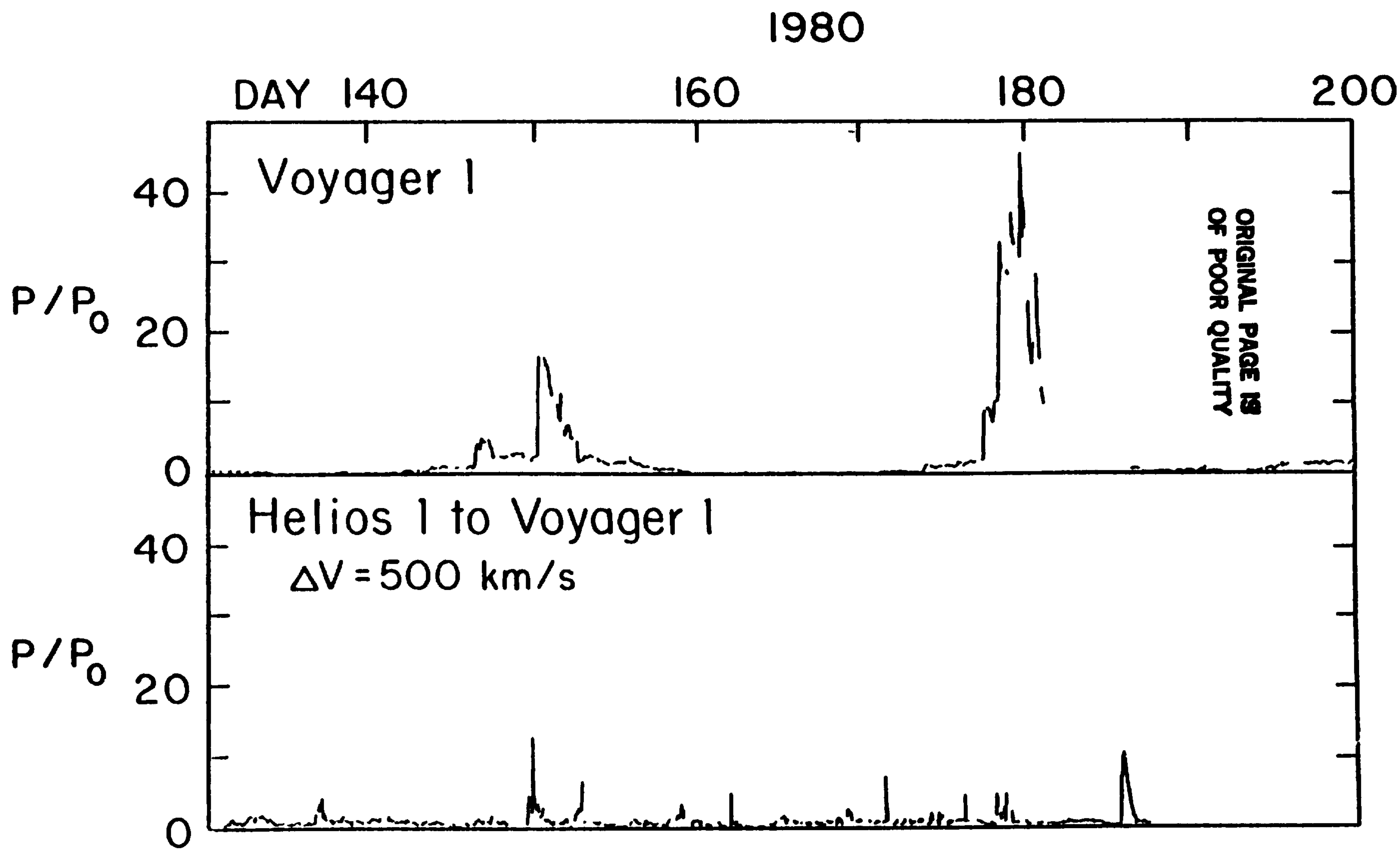

1980
DAY 140
160
180
200
Voyager 1
ORIGINAL PAGE IS
OF POOR QUALITY
P / P0
40
20
0
Helios 1 to Voyager 1
ΔV = 500 km/s
P / P0
40
20
0

Figure 3

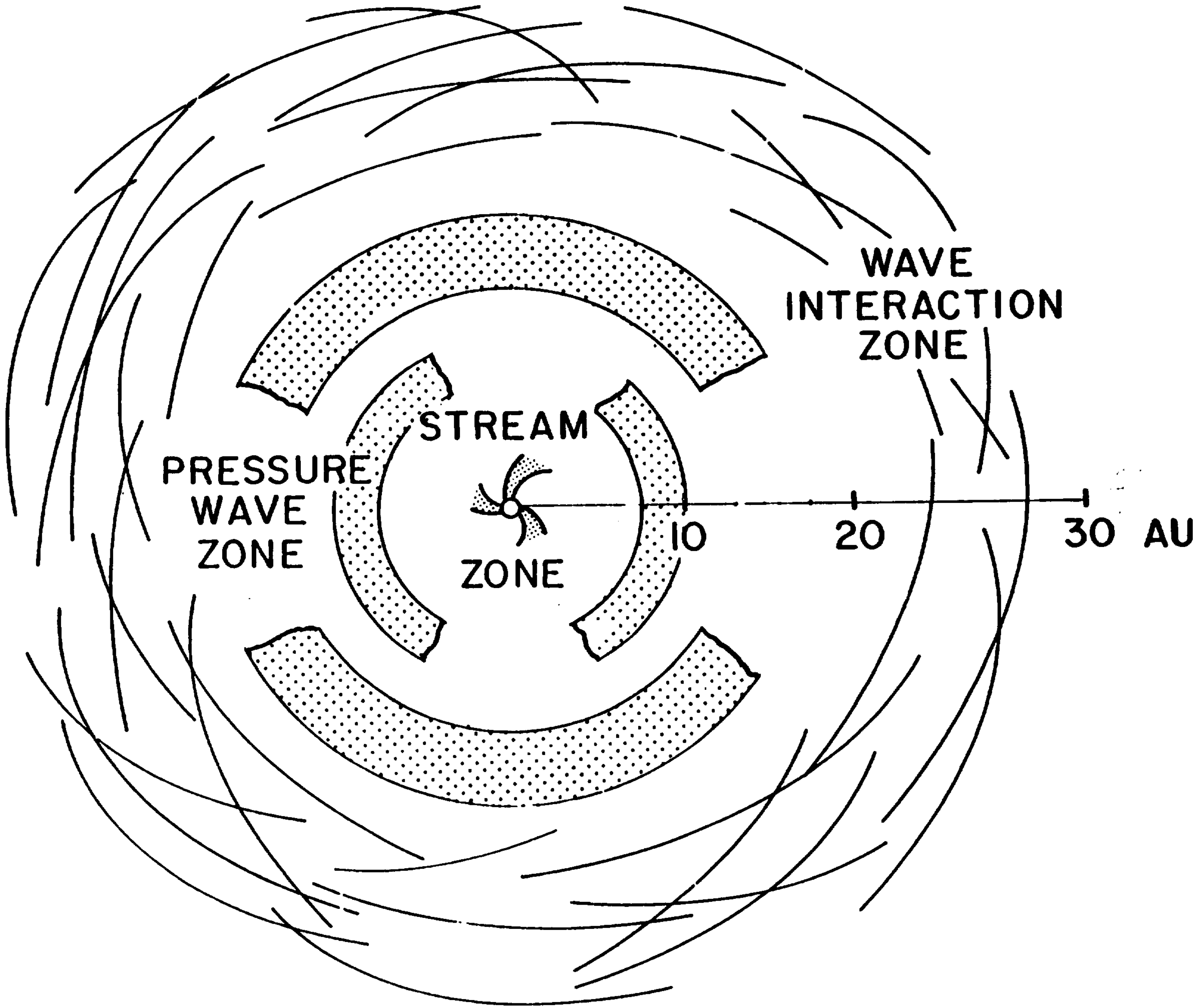

WAVE
INTERACTION
ZONE
STREAM
ZONE
PRESSURE
WAVE
ZONE
10
20
30 AU

Figure 4