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Note on Models of the Propagation of
Solar Flare Plasma Through Interplanetary Space

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ABSTRACT

Theoretical treatments of the propagation of a solar flare disturbance in interplanetary space discuss a blast wave expanding from the sun as a center of symmetry. However, recent observations indicate that the solar flare piston often is not expanding in a spherically symmetric manner. In this note we examine some possible causes of the lack of spherical symmetry, assuming the blast models are essentially correct. It is found that failures of different basic assumptions underlying the blast model lead to distinctly different shapes for the propagating flare body. The shapes are sufficiently different so that observations should soon be available that will distinguish between the models.

The purpose of this note is to discuss the way in which a disturbance due to a solar flare propagates through the interplanetary medium. Theoretical treatments of this problem, for example, Parker [1963] and Hundhausen and Gentry [1969], envision a blast wave expanding from the sun as a center of symmetry. The shock in such a sun-centered model will always be perpendicular to the earth-sun line. However, recent observations indicate that flare shocks are often strongly tipped to the plane of the ecliptic [Bame et al., 1968; Hirshberg et al., 1970; Greenstadt et al., 1969], indicating that the flare piston is not expanding in a spherically symmetric manner. In this note we examine some possible causes of the lack of spherical symmetry under the assumption that the blast models are essentially correct. We first briefly review the observational evidence that the shocks are not perpendicular to the earth-sun line. Then we critically evaluate some of the assumptions underlying the blast model and give qualitative arguments as to what would happen if each of these assumptions failed. We find that failures of different assumptions lead to distinctly different shapes for the propagating flare body and consequently to different orientations for the shocks caused by the supersonic propagation of the body through the ambient solar wind. The published data on shock orientation are still too fragmentary to permit definite selection between two of the possible models. However, the distinctions between the shapes are sufficiently great so that observations should soon be available that will make the choice clear.

One source of evidence that flare-produced shocks are not always perpendicular to the earth-sun line comes from geomagnetic storms. Since the sudden commencements of the largest storms are believed to be due to flare-shocks, the orientation of the shocks may be investigated by studying the ssc̲s. Akasofu and Yoshida [1967] found that the strongest sudden commencements are caused by central meridian flares. These data indicated [Hirshberg, 1968] that the shock was expanding on a broad front but with considerable deviation from the sun-centered symmetry of the blast models, as shown in Figure 1. Since flares do not occur at high solar latitudes, the study of sudden commencements essentially yields a two-dimensional picture of the shock front rather than a three-dimensional one. The shape of the shock derived from sscs can be approximated as a circle of radius 0.6 AU centered at 0.4 AU. Fig. 1

A more direct method of testing the spherical symmetry of the flare-produced shock is to observe the direction normal to the shock. Although many interplanetary shocks have been studied since they were first described [Sonett et al., 1964; see also Wilcox, 1969, for a review], there have been very few cases in which a definite flare-shock identification could be made and, for the same event, sufficient data existed to calculate shock normals. However, three events have recently been discussed in the literature in which the flare-shock identification is well established and the shock normal could be determined. On January 11, 1967, a class 3B flare occurred at 26°S, 47°W. The shock was observed on January 13 by Vela's 3A and 3B [Bame et al., 1968]. The intersection of the shock with the ecliptic plane made an angle of about 70° with the earth-sun line instead of the 90° expected for a spherical blast, while the latitude of the outward shock normal was 35°northward instead of the expected 0°. A second interplanetary shock was caused by a flare of importance 2 at 34°N, 45°W. This shock has been the subject of several studies [Van Allen and Ness, 1967; Greenstadt et al., 1969], the most comprehensive of which is that of Greenstadt et al., who concluded that the shock normal lay 16° east of the solar radial line and pointed 65° southward (instead of lying in the ecliptic plane). A third shock was caused by the class 3B flare of February 13, 1967, at 20°N, 10°W. The intersection of the shock with the ecliptic plane made an angle at 80° with the earth-sun line, in reasonable agreement with the 90° expected for spherical models of propagation. However, instead of lying in the ecliptic plane, the normal pointed 60° southward [Hirshberg et al., 1970]. This normal, calculated from magnetic field variations across the shock, was in good agreement with the measured time lag between the appearance of the ssc on the earth's surface and the arrival of the shock at the spacecraft magnetometers. Furthermore, the possibility that the strong tipping of this shock was a local effect could be eliminated by noting that post-shock structure in the solar wind was also tipped at more or less the same angle for many hours after the shock had passed.

These observations of oblique shocks produced by solar flares show that not all flare shocks are expanding with the sun as a center of symmetry as envisioned in the Parker model and its extensions. Although the sun-centered symmetry may be considered an ad hoc assumption, an examination of reasonable justifications of the spherical model is useful in obtaining an understanding of the implications of the findings that the propagation of the blast wave departs significantly from spherical symmetry.

A sun-centered symmetric model would be appropriate if the flare occurred at the origin of coordinates, in a spherically expanding solar wind in which all properties (such as velocity, density, etc.) were functions of r only. Further, it must be assumed that the flare particles are not preferentially accelerated at any angle. For example, the energy of the flare may be assumed to be delivered to the particles in the form of heat. Then the equations describing the propagation of the flare plasma through space will depend on r alone. If, in addition, the energy density of the bulk motion of the flare piston plasma (measured relative to the ambient solar wind) substantially exceeds the magnetic energy density of the interplanetary plasma, the flare plasma will dominate the flow rather than being channeled by the ambient interplanetary field (barring instabilities to be discussed later). Observations indicate that this condition is met for the solar flare piston plasma.

The most obvious point at which these approximations are at variance with the known facts is the assumption that the flare takes place at the origin of a spherically symmetric medium. Instead, the flare occurs in an atmosphere at a point about 1 $R_\odot$ (solar radius) from the origin of coordinates. However, we shall argue that the effects of the sun and its atmosphere on the shape of the blast seen at the earth will be small for flares occurring on the visible disc of the sun. The density of the sun's atmosphere falls off rapidly so that the density at 5 $R_\odot$ is 2×10^{-4} the density at 1 $R_\odot$, while at 10 $R_\odot$, the density is only 2.5×10^{-5} the surface value [Newkirk, 1967]. Thus at 10 $R_\odot$, the flare plasma can be considered free from the direct effects of the atmosphere. Further, since the radius within which the solar atmosphere rotates rigidly with the sun is probably less than 3 $R_\odot$ [Newkirk, 1967], the flare piston plasma can be considered to have emerged into the solar wind and to be propagating according to the various extended blast models by the time it reaches 10 $R_\odot$. Figure 2 is a scale drawing showing the earth at 215 $R_\odot$ and the piston plasma emerged into the solar wind at 10 $R_\odot$. It is seen that 10 $R_\odot$ is Fig.

sufficiently close to the origin so that it is reasonable to expect the effects on the wave shape at 215 $R_\odot$ to be negligible for flares occurring on the visible hemisphere. (The presence of the sun at the origin will, of course, strongly affect that part of the wave that is propagating back toward the sun. Thus, the shock from flares occurring on the far side of the sun would be expected to be highly distorted from the sun-centered symmetric model.)

There are three approximations that must be explored further:

1. The flare particles are not preferentially accelerated at any angle.

2. The ambient solar wind quantities, such as temperature, density, velocity, etc., are functions of $\underline{r}$ alone.

3. The flows are well behaved in the sense that there are no instabilities that cause large scale alterations in the flow.

The possibility of the failure of each of these approximations will be discussed in turn.

1. There is no generally accepted model of flares so that one cannot predict if the flare particles are preferentially accelerated at some angle. In the lower regions of the corona, the solar atmosphere is quite dense; and it might be argued that, however the energy was originally delivered, collisions redistribute it as heat. However, further channeling of the beam may occur as the piston plasma rises

through the corona. If flare plasma leaves the sun with a sizable amount of directed motion, then the analysis that is appropriate to the problem would be that of a supersonic jet propagating through a radially expanding medium. This is a difficult mathematical problem, and no theoretical calculations exist to compare to the present results. However, jets that propagate as bodies of revolution about the solar radial direction cannot produce shock shapes that explain at the same time the obliquity of the shocks observed in space and also the sizes of the sudden commencements of the storms caused by solar flares appearing on the far limbs of the sun. To see this, we note that the sizes of sudden commencements imply that the shock is expanding as shown in Figure 1. If this broad front is considered as representing a body of revolution, then the latitudes of the shock normals should never exceed 20° or 30°, in disagreement with the two observations of latitudes of approximately 60° [Hirshberg et al., 1970; Greenstadt et al., 1969]. In view of these considerations, the acceleration of flare particles with a preferred direction is not a promising model to explain the extreme flare shock obliquities. However, a combination of jet effects and the solar atmosphere effects discussed above may contribute to producing the mild obliquities shown in Figure 1.

2. The approximation that the solar wind parameters, such as velocity, density etc., are independent of angle is at variance with the

sector structure of the solar wind flow in the ecliptic plane. The density, velocity, magnetic field, and temperature vary systematically as the sectors are crossed [Wilcox and Ness, 1965]. Furthermore, it has been suggested [Pneuman, 1966] that the general dipole of the sun will tend to distort the solar wind flow so that the wind speeds in the equatorial plane will be slower than those from the poles. Both of these effects would cause a distortion of the spherical symmetry of the expanding wave. Since observations are made in the ecliptic plane, it is likely that the sector structure would be the more important variable in causing distortions of the observed blast waves.

A sketch of the type of configuration that might result from the variation of plasma properties across a sector is shown in Figure 3. Fig. 3
The inset graphs are from Wilcox [1968] and show the variations of the velocity and density as 8-day-wide sectors were crossed. Note that the velocity of the ambient solar wind is relatively low at the beginning and the end of the sector. The shock propagating in these regions will tend to lag the shock propagating into the faster ambient wind in mid-sector. The density distribution reinforces the same effect. The density was relatively high at both ends of the sector, and was very high near the beginning of the sector shown as crosses, the density and velocity variations both cause the shock to tend to lag near the sector boundaries.

A rough estimate of the magnitude of the distortion due to the density can be made from the work of Hundhausen and Gentry [1969], who show how the transit time of a shock is related to the density of the ambient solar wind. In Figure 3 we have sketched the shock indentation estimates from Hundausen and Gentry for a sector with a density variation as shown by the crosses in the inset graph. Unfortunately, Hundhausen and Gentry do not give the variation of shock transit time as a function of ambient wind velocity, so that velocity effects could not be included. The major distortion consists of an indentation near the sector boundary.

Note that Figure 3 shows the intersection of the shock with the ecliptic plane. In the three cases of experimentally observed flare-shock normals, the projections of the normals onto the ecliptic planes were at most 20° from the direction expected for spherically expanding shock. The major observed disagreements with spherical symmetry were all in the meridional plane where angles of 35°, 60°, and 65° were observed instead of the expected 0°. Since we have no information on the shape of the sectors in the meridional plane, nor on the distribution of density and velocity in that direction, we cannot make any comments on the distortion expected from this model in that plane.

3. The extended blast models neglect the possibility of instabilities in the flow. One interesting possibility is the development

of the flute instability, i.e. the hydromagnetic analog of the Rayleigh-Taylor instability, in which a dense fluid is supported by a light fluid. It can be expected that the instability will occur when the magnetic fields in the two media are parallel [Stix, 1962]. That is, the piston will tend to break through in planes parallel to the magnetic field. It is possible that processes (perhaps nonlinear) will intervene to heal the break. Further analysis of this problem is necessary (see, for example, Byers [1967] and Dnestrovskii [1969]). However, if we assume that the instability grows, then the resultant flare piston shape will be a flat plate-shaped object as shown in Figure 4. Since, near the ecliptic plane, the ambient solar wind Fig. 4 magnetic field usually lies in the ecliptic, the plate plane will most often be parallel to the ecliptic plane. There is no difficulty in reconciling the observations with such a plate (see also Greenstadt et al. [1969]). The broad front of the plate can be approximated from the studies of sudden commencements, i.e. it has a radius of about 0.6 AU centered at 0.4 AU, and is of unknown thickness. If the plate passed above the earth with the plate plane parallel to the ecliptic, it could produce shock normals tipped southward of the ecliptic plane, in agreement with the observations for the two flares occurring in the northern solar hemisphere [Hirshberg et al., 1970; Greenstadt, 1969]; while if it passed below the earth, the shock normal would be tipped northward of the ecliptic plane, as in the case of the shock caused by the flare occurring in the southern hemisphere [Bame et al., 1968]. For plate planes parallel to the ecliptic, the orientation of the intersection of the shock with the ecliptic plane would be within 20° or 30° of that expected from spherical symmetry. This again agrees with the three observations available.

Four possible causes of the failure of the shock to propagate in a spherically symmetric manner have been discussed, each resulting from a different failure of the approximations that ensured spherical symmetry. It was found that the effects of the solar atmosphere would be negligible, while a jet of plasma would not produce the observed shock orientations. The two most promising models to explain the extreme shock obliquities involved indentations due to the sector structure and a flat plate due to the development of the flute instability. The flat plate is favored by the meager data presently available.

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Figure Captions

Fig. 1 The shape of a flare shock as derived from data on the intensity of the sudden commencements of geomagnetic storms is shown as a solid line [from Hirshberg, 1968]. The dashed line, representing a circle of radius 0.6 AU centered at 0.4 AU, is included for comparison.

Fig. 2 A scale drawing showing the relative positions of three points at 10 $R_{\odot}$ from the origin, compared with the earth at 215 $R_{\odot}$, indicating that the effect of the solar atmosphere on a blast wave will be negligible for flares on the visible side of the sun.

Fig. 3 A sketch showing the effect of the sector structure on a flare shock propagating in interplanetary space. The inset graphs [from Wilcox, 1968] show the variation of density and velocity as sectors are crossed. An indentation will appear near the sector boundary due to both the high density and low ambient solar wind velocity in that region. The figure shows an estimate of the magnitude of the effect based on the density variation alone.

Fig. 4 An artist's sketch showing the propagation of a flare piston after the development of a flute instability. The piston, shown crosshatched, has broken through in a plane parallel to the ambient solar wind field and forms a flat plate. The top figure shows the meridional plane. The piston is pushing through the ambient solar wind, which is shocked and flows back along the flanks. The bottom view shows the plate in the ecliptic plane. The magnetic field lines pass through the shock but then leave the ecliptic plane as required by the flow around the plasma body.

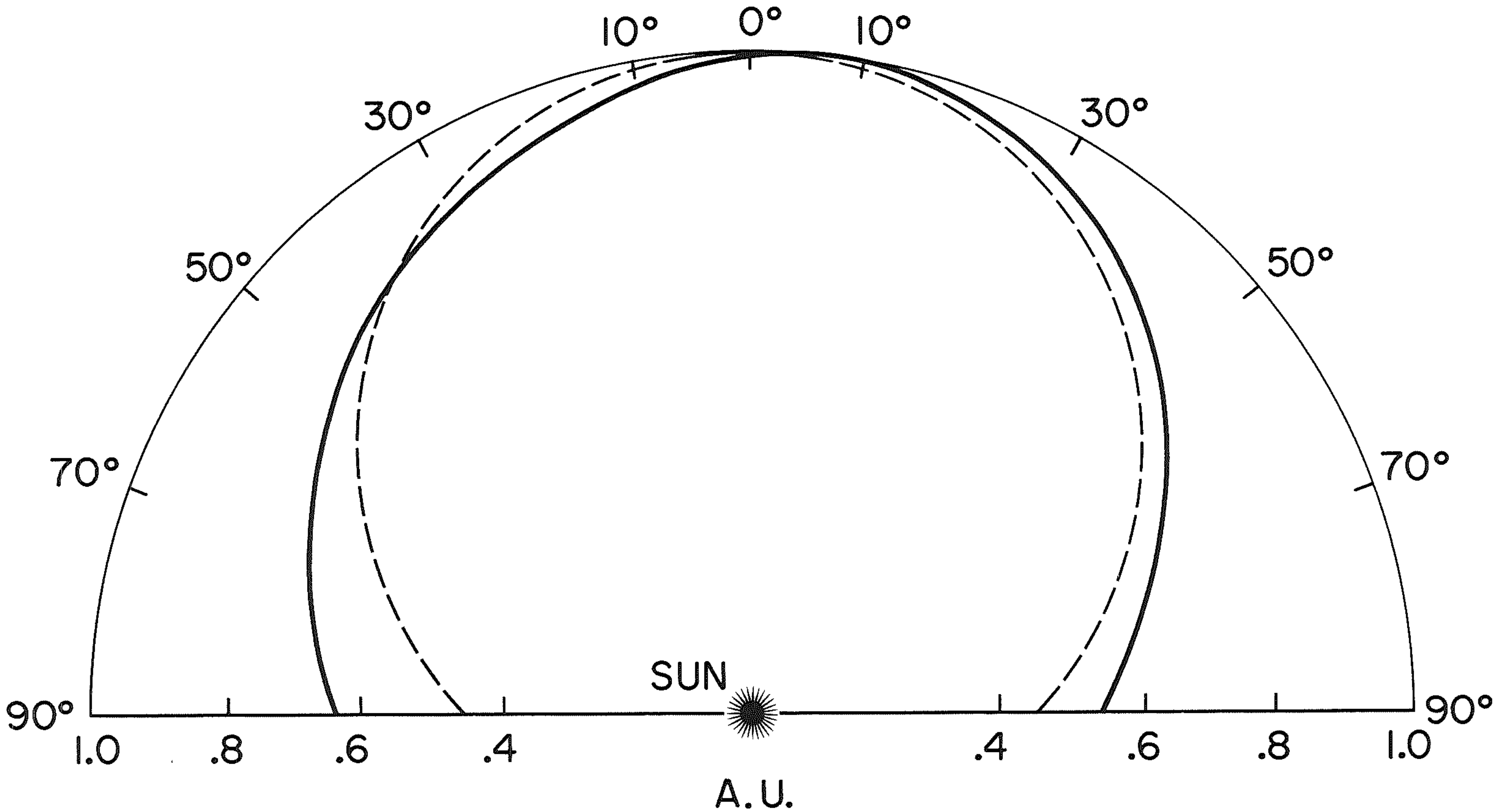


Figure 1.

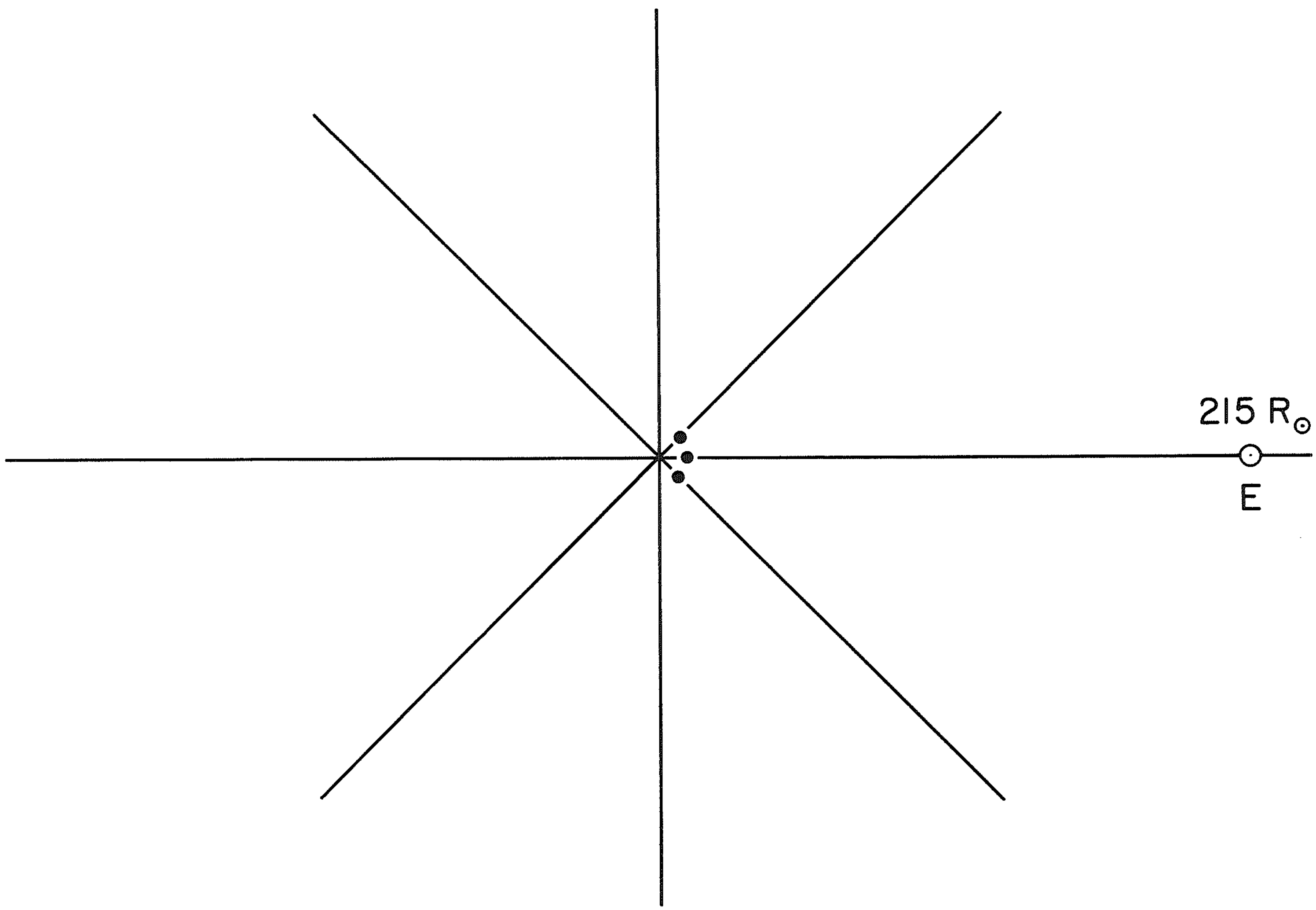
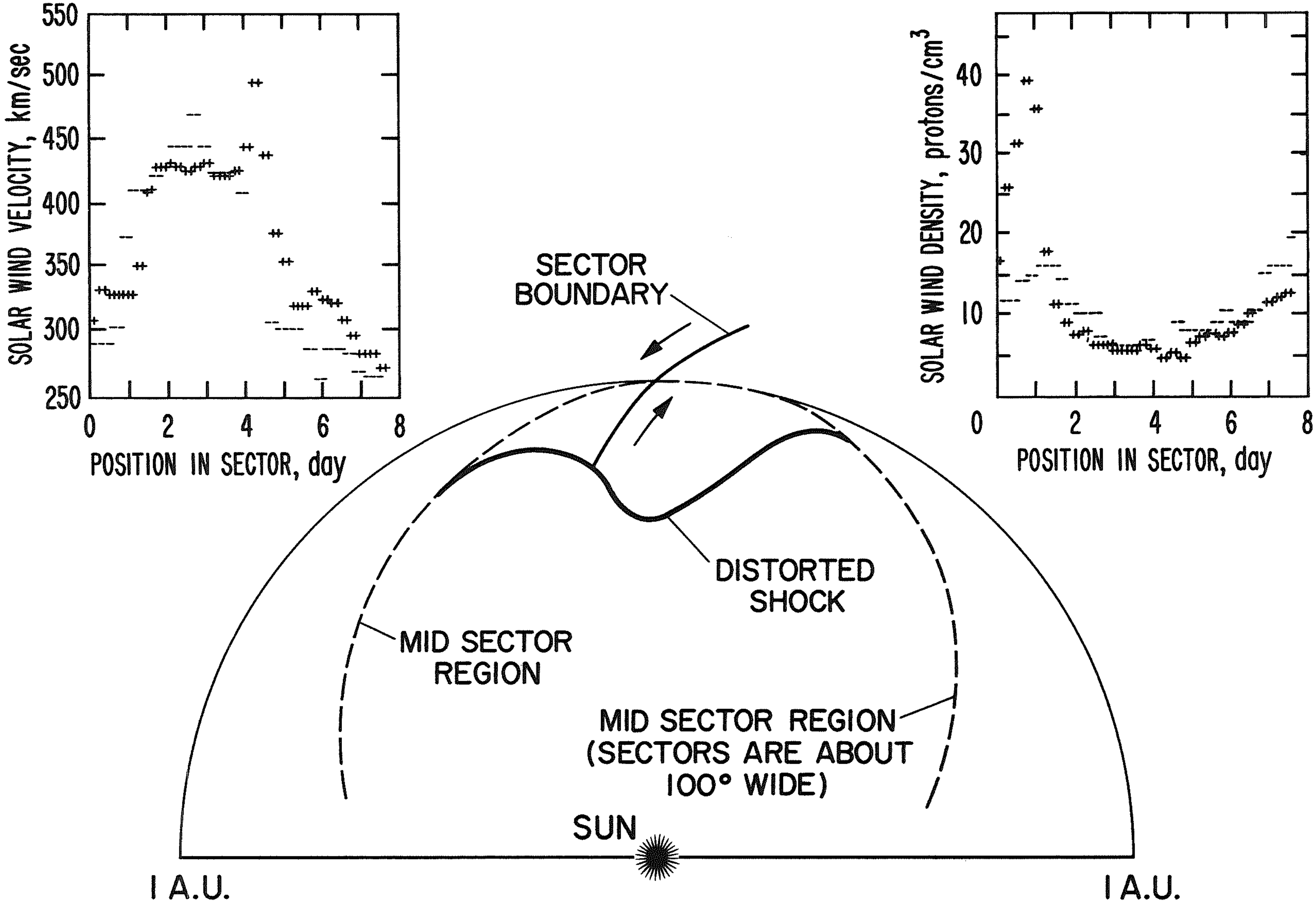


Figure 2.



550
500
450
400
350
300
250
SOLAR WIND VELOCITY, km/sec
0
2
4
6
8
POSITION IN SECTOR, day
40
30
20
10
SOLAR WIND DENSITY, protons/cm^3
0
2
4
6
8
POSITION IN SECTOR, day
SECTOR BOUNDARY
DISTORTED SHOCK
MID SECTOR REGION
MID SECTOR REGION (SECTORS ARE ABOUT 100° WIDE)
SUN
1 A.U.
1 A.U.

Figure 3.

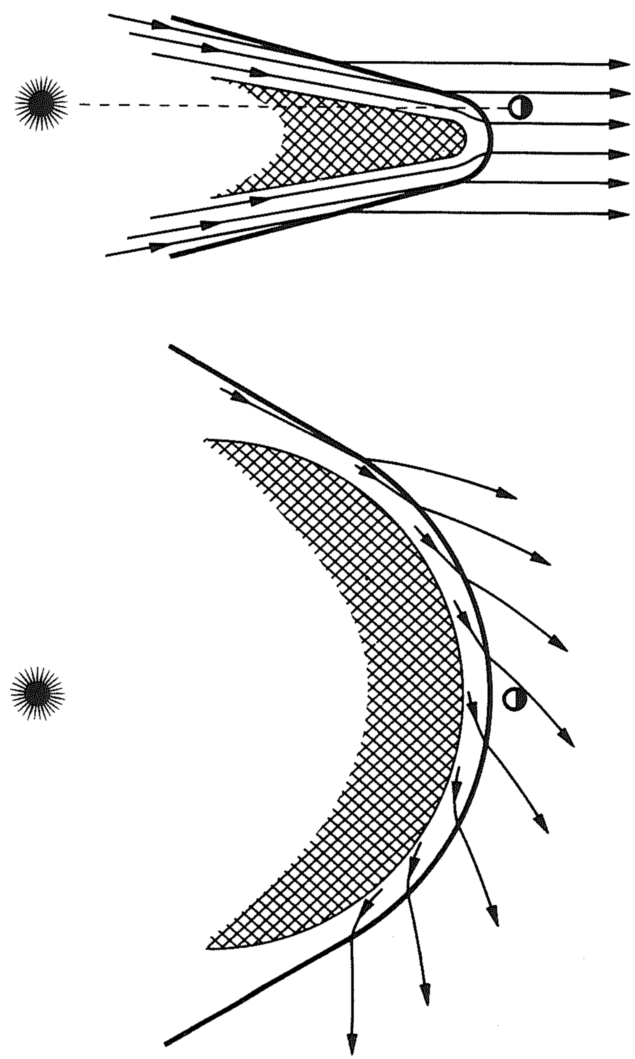


Figure 4.