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Three Dimensional Aspects of Interplanetary Shock Waves

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Abstract

Initially spherical blast waves are systematically distorted due to persistent latitudinal solar wind structure. This is to be distinguished from the non-systematic (random) distortion due to varying structure in longitude which introduces an $\simeq 30^{\circ}$ average deflection of shock normals from radial. The systematic latitudinal effect should be at least 25° at mid-latitudes, and observable in the 30° noise level with 14 or more shocks for statistics. The observed occurrence rate of shocks during solar maximum is sufficient to detect the effect. Corotating shocks should become detectable between 1 and 5 AU. Identification could be a problem because of the 30° noise level becoming greater beyond 1 AU. However, the three-dimensional geometry of corotating shocks show a strong latitudinal structure which can be used in an out-of-the-ecliptic mission for a statistical identification based on shock occurrence rates.

Introduction

Most of the interplanetary shock waves observed with 1 AU of the sun originate from some short lived solar event, such as a solar flare, and then propagate out as a more-or-less spherical shock wave until they leave the solar system. Beyond 1 AU another class of interplanetary shock wave becomes common-- the cortating shock pair formed by the interaction of long lived solar wind streams. We discuss here the three dimensional geometry of these two classes of interplanetary shocks and how these geometries can be studied with an out-of-the-ecliptic mission.

Out-of-the-Ecliptic Distortion of Solar Blast Waves

Lack of spherical symmetry in the solar wind distorts the surface of a shock wave as it propagates away from its solar origin into interplanetary space. This phenomenon is observed near the solar equatorial plane at 1 AU, where the inhomogeneities associated with solar wind streams produce typically a 30° deflection of the shock wave normal away from the radial direction (Heinemann and Siscoe, 1974; Hirshberg et al., 1974). The distortion results from differential advection of the shock front due to solar wind speed variations and from differential propagation speed of the shock in the solar wind due to density variations--the shock propagates more slowly in high density regions. In spite of the large distortion of individual shocks, the averaged shock normal direction near the equatorial plane at 1 AU is radial from the sun (Chao and Lepping, 1974; Heinemann and Siscoe, 1974).

A systematic variation in latitude of the solar wind speed and density produces a systematic distortion in latitude of the surfaces of solar produced shock waves. That is, the averaged shock normal direction $(\bar{\underset{\sim}{n}}_s)$ in general will not be radial from the sun. The angle between $\bar{\underset{\sim}{n}}_s$ and the radial direction will depend on latitude in a manner which reflects the average latitudinal dependence of the solar wind speed and density.

A lower limit on the deviation of $\bar{\underset{\sim}{n}}_s$ from radial is shown in Figure 1. Here a shock wave that was spherical at 20 solar radii becomes distorted into a quasi-ellipse at 1 AU by the action of a differential advection of 400 km sec^{-1} at the equator increasing smoothly to 600 km sec^{-1} at the poles. This latitudinal gradient of solar wind speed, approximately 2 km sec^{-1} deg^{-1}, is at the lower end of the range of gradients suggested in the literature (see reviews by Gosling, 1975, Hundhausen, 1975, Dobrowolny and Moreno, 1975). The figure probably also underestimates the distortion for the assumed gradient since it neglects the possible latitudinal gradient in density–decreasing toward the poles (Hundhausen et al., 1971)--causing the shock to propagate faster in the solar wind at higher latitudes.

The maximum deviation of $\bar{n}_s$ from radial ($\Delta\theta_{max}$) occurs at mid-latitude and is about 25° at 1 AU. In order to observed this effect, enough solar generated shock waves must be measured while a spacecraft is in the mid-latitude region to obtain a value for the polar angle ($\bar{\theta}_s$) of $\bar{n}_s$ with a statistical error considerably less than $\Delta\theta_{max}$. For the sake of having a numerical example, we take the requirement that the expected standard deviation of $\bar{\theta}_s$ be less than or equal to 1/3 of the conservative value obtained above for $\Delta\theta_{max}$, i.e. S. D. $(\bar{\theta}_s) \le 8°$.

Near the equatorial plane the distortions produced by solar wind streams cause approximately a 30° standard deviation in the angle between individual shocks and their average, radial direction. The standard deviation of the average angle of N shocks is $30°/\sqrt{N}$. For N = 14, this is $\sim 8°$. Thus in a 30° background noise level in the angle of individual shocks due to stream structure, it takes 14 shocks to obtain a value of $\bar{\theta}_s$ with an expected standard deviation of 8° from the true value. It is likely that the noise level at mid-latitudes is less than 30° since the effect of streams in producing solar wind inhomogeneities as measured by enhanced radio scintillations is apparently confined to within 40° of the equator (Houminer, 1973). Thus the requirement of 14 shocks is probably more than necessary.

To estimate the time needed to observe 14 solar generated shocks, we use the 100 years of SSC statistics compiled by Mayaud (1975). The validity of this procedure is based on the study of Chao and Lepping (1974) showing that at least 87% of SSC's can be associated with solar activity such as solar flares and type 2 and type 4 radio bursts. There are on average about 10 SSC's per year during solar minimum and about 35 SSC's per year during solar maximum. Thus about 17 months are required in the first case and 5 months in the second of mid-latitude observations to observe 14 shock waves originating from a solar surface source. We conclude that an out-of-the-ecliptic mission scheduled for solar maximum would have high probability of observing systematic shock wave distortion even if the worst-case example discussed above should apply.

The importance of measuring the systematic distortion of the shock shape lies in its use in determining the systematic latitudinal dependence of solar wind parameters. This method is independent of all other methods. It does not involve unravelling separate space and time variations. In the case of an out-of-the-ecliptic mission via Jupiter, the space dependence involves both radial distance and latitude angle which can give independent contributions to any variations observed in *in situ* measurements. Knowledge of the three dimensional shape of blast waves is important also for determining the flow of flare energy into interplanetary space. A non-spherical shock shape implies that energy is not distributed uniformly but converges in some places--relative to a purely radial flow--and diverges in others. In the case considered, energy would diverge away from the equator causing the shock strength to decrease faster in the equatorial plane than would be expected on the basis of spherical symmetry.

Three Dimensional Structure of Corotating Shocks

Near the equatorial plane the border between contiguous solar wind streams is a spiral (Sarabhai, 1963; Dessler, 1967). If the trailing stream--in the sense determined by the direction of the solar rotation--is faster, a pair of shock waves will form at some distance from the sun (Hundhausen, 1973 a,b). Such shock wave pairs have apparently been observed between 1 and 5 AU by the Pioneers 10 and 11 spacecraft (Hundhausen and Gosling, 1975; Smith and Wolfe, 1975). In a steady state situation, the streams, their spiral border, and the shock pair all corotate with the sun. In this section we estimate the heliocentric distance of shock formation in the equatorial plane as a function of the speed differential between the streams and give a qualitative description of the three dimensional shape of the shock surfaces. For the latter we assume that the stream border is perpendicular to the equatorial plane. This example illustrates the essential aspects of the geometry and possibly represents the typical case as indicated by radio scintillation observations (Houminer, 1973) and the north-south alignment of coronal holes which might be the sources of fast streams (Krieger et al., 1973; Noyes, 1975).

Figure 2 shows the relevant geometry in the equatorial plane. The figure also illustrates one argument for expecting the existence of shock pairs which at the same time suggests a simple calculation for the approximate heliocentric distance to their point of formation. The spiral labeled stream interface is the border between the streams. Sample flow streamlines--labeled fast and slow--are shown in the corotating reference frame in which all geometrical features are time independent. With the fast stream trailing, the pitches of the spiral streamlines in both streams are such that they would intersect the spiral interface unless prevented from doing so by forces that act to deflect the flows away. The build up of pressure at the interface resulting from the convergence of the flow there produces such a force (Siscoe, 1972). Relative to the flows in the two streams, the interface looks, like a curving wall and the flows are forced to follow the curve because of the increased pressure. The compressive deflection of a supersonic flow by a curving wall is known to produce a detached shock wave in the flow (Landau and Lifschitz, 1959, p. 429). Streamlines intersecting the shock waves are deflected parallel to the interface spiral, bringing to an end the compressive interaction between the streams.

The approximate location of the origin of the shock waves can be found by considering the characteristics of the flow eminating from a point, A, on the interface close enough to the sun that the streamlines are essentially radial but far enough from the sun to be in the supersonic region. The characteristics are generated by following the progress of a sound wave starting at A and subsequently expanding and being convected with the flow, as illustrated in the figure. However, before the shocks are formed, the flow converges on the interface; thus the sound speed must be greater than the speed characterizing the convergence in order for the sound wave to expand. As the wave moves out from point A, the sound speed decreases because the solar wind cools as it expands, and the speed of convergence increases because of the relative pitches of the spirals. A distance is reached when convergence exceeds the speed of sound and the wave begins to shrink.

From the point of view of an observer moving with the flow along a streamline, and looking at the wall represented by the interface, he sees the wall approach him—that is, convergence in his frame of reference. If we think of the wall as a piston moving into the flow, at the point where the sound wave begins to shrink, the piston is moving faster than the local speed of sound, and a shock wave will form upstream from the piston. Thus, the origins of the shock waves will be approximately at points B in the slow stream and C in the fast stream marking where the sound wave stops expanding away from the interface.

To find the approximate locations of these points and their dependence on the speed difference between the streams, we consider an idealized case in which the slow stream has constant speed V_s, the fast stream has constant speed V_f, the speed at the interface is $V_o = (V_s+V_f)/2$, and the Mach number, M, is constant throughout. Using the procedure given in Heinemann and Siscoe (1974), we find the equations of the characteristics to be

$$\eta_s = \frac{1}{M}\left(1 + \ln r/r_s - r/r_s\right)$$
$$\eta_f = \frac{1}{M}\left(1 - \ln r/r_f - r/r_f\right) \qquad (1)$$

where η is the azimuthal angle in the corotating reference frame, r is the heliocentric distance, and $r_s = V_s/M\Omega$, $r_f = V_f/M\Omega$. Without the $\ln$ terms, these are the equations of Parker's solar wind spirals (Parker, 1963, p. 138). The ℓn terms represent the movement of the sound wave away from the spiral. The equation of the interface is

$$\eta_o = \frac{1}{M}(1 - r/r_o) \tag{2}$$

with $r_o = V_o/M\Omega$. To estimate where the shocks form we determine where the radial separation between the characteristics and the interface begins to decrease, i.e. set $d\Delta r/d\eta = 0$. The result is shown in Table 1 for different speed differentials, $V_f - V_s$ with $V_o = 400$ km sec^{-1} and $M = 4$.

As expected, the bigger the differential, the nearer the sun the shocks form. In the biggest case considered 160 km sec^{-1}, they form near the orbit of Mars. Any differential bigger than approximately 50 km sec^{-1} produces shocks inside the orbit of Jupiter. Although this example is idealized, it gives a fair test of the argument based on characteristics to predict qualitatively the essential geometrical aspects of the formation of corotating shocks. The prediction that typical solar wind streams, which have differentials bigger than 50 km sec^{-1}, should form shocks between the orbits of Earth and Jupiter is apparently confirmed by the Pioneer 10 and 11 observations. This justifies applying the argument to determine the out-of-the-ecliptic shape of corotating shock waves.

The application is straightforeward, and the result is immediate if we consider the situation at the poles. Here the border between the streams is a radial line--the polar axis. The pitches of the streams lines are essentially zero and, hence, so is the speed of convergence of the streams. A sound wave starting here will expand forever, although it will slow down because of the radial decrease in sound speed. Thus corotating shocks will not form over the poles. At intermediate latitudes, the pitches of the streamlines and the border are not zero, but they are less than at the equator. A sound wave must travel further before the convergence speed overtakes the sound speed and shocks form. Thus, the distance to the formation of the shocks increases with latitude.

The three dimensional geometry of the stream interface and the shock pair is sketched in Figure 3. The interface is generated by an expanding meridian circle that rotates about the polar axis as it expands so that its intersection with the equatorial plane moves along the border spiral. The leading points of the shocks are in the equatorial plane and the leading edges spiral outward as they move away from the equator, maintaining a proximity to the interface. A sketch on an expanded scale of a single corotating shock surface is shown in Figure 4. The motion of this surface is analogous to that of a tapered paper banner attached to a stick that is being twirled around the polo· axis. The length of the banner is determined by the lifetime of the solar wind stream.

To study these structures an out-of-the-ecliptic mission is needed that covers the radial range between Earth and Jupiter. Knowledge of the three dimensional nature of these shock waves is essential for the interpretation of cosmic ray data and for applications to other astrophysical situations. The distortion of solar shock waves as described earlier and the highly structured geometry of corotating shocked waves illustrate the complexity of the problems faced by galactic cosmic rays as they try to enter the inner solar system. Three dimensional probing of the interplanetary medium is required to obtain a complete picture of the extended stellar envelope of a representative from a major population of main sequence stars. The interaction of such stars with the interstellar medium in various galactic situations can they be treated with a fuller understanding of the stellar parameters. Comprehension of the three dimensional aspects of structures generated because a star rotates has application to contemporary astrophysical problems such as the interaction of the Crab pulsar with the Crab nebula.

Acknowledgments

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$V_f - V_s$	$d\Delta r/d\eta = 0$
16 (km/sec)	12.5 (AU)
32	6.2
48	4.2
64	3.1
80	2.5
96	2.1
112	1.8
128	1.6
144	1.4
160	1.3

Table 1. Approximate heolcentric distances in the equatorial plane to the formation of shock pairs due to interacting streams with various speed differentials. In this example the average speed is 400 km sec^{-1} and the Mach number is 4 throughout.

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Figure Captions

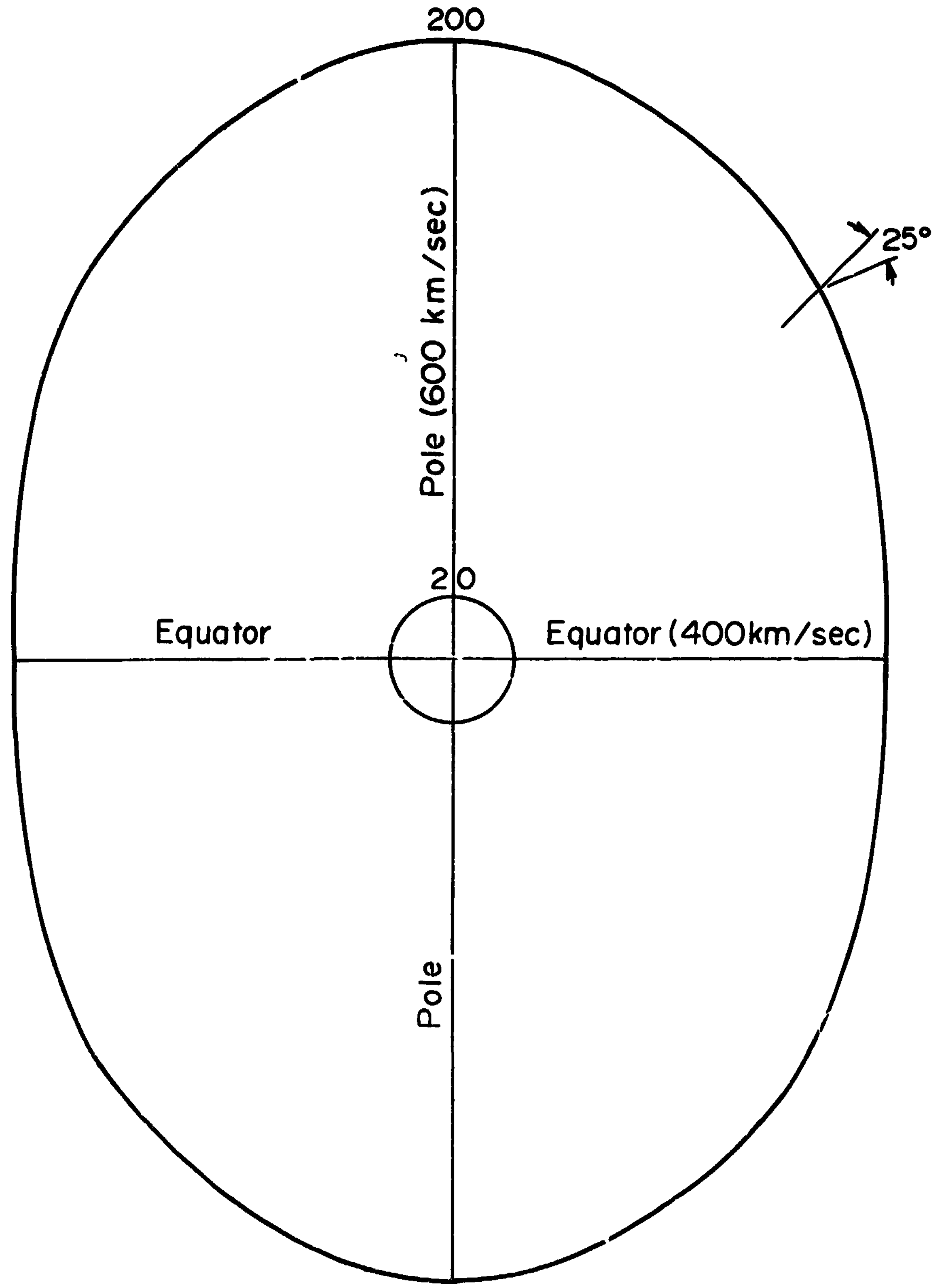
Figure 1. A meridian plane cross section through a solar origin shock surface assumed to be circular at 20 solar radii and distorted into a quasi-ellipse at 200 solar radii by the action of equator to pole solar wind speed differential of 200 km sec^{-1}.

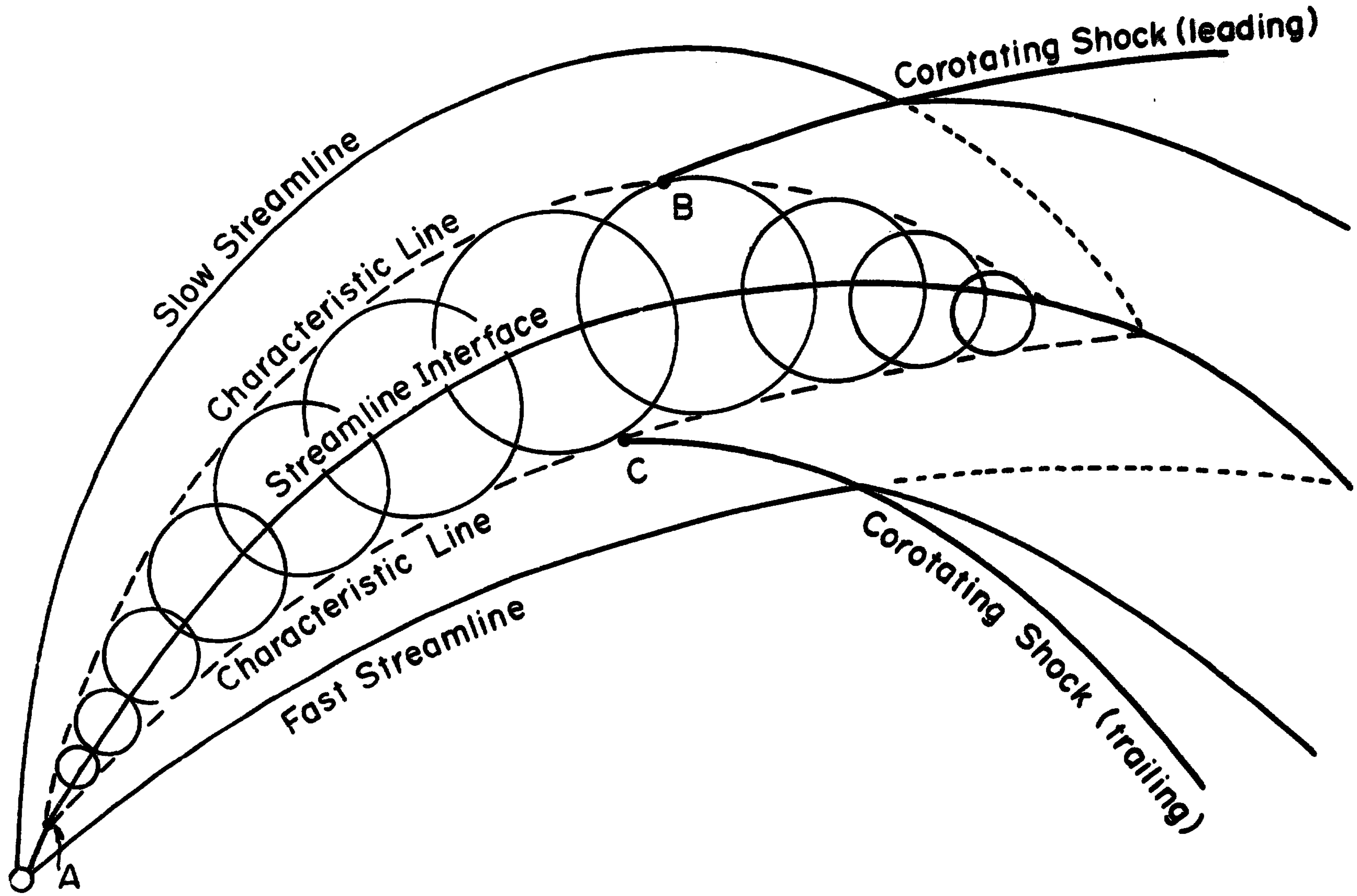
Figure 2. A sketch of geometrical features of the flow in the equatorial plane and in the corotating reference frame. The stream interface separates a slow stream (leading) and a fast stream (trailing). Sample streamlines and corotating shocks in both streams are shown. The shocks deflect the streamlines parallel to the stream interface--with no deflection they would intersect the interface. The circles are sequential snapshots of a sound wave starting at A and expanding while being convected with the flow (distortion due to the flow speed differential is neglected). Shocks form where the sound wave begins to shrink which happens when the speed of convergence of the streams toward the interface (due to the differences in the pitches of the various spirals) becomes bigger than the local sound speed.

Figure 3. A sketch of the three dimensional geometry in the northern hemisphere of the stream interface and associated shock pair. The interface is generated by an expanding meridian circle that rotates about the polar axis as it expands so that its intersection with the equatorial plane follows the interface spiral, like

a needle in the groove of a record. The interface separates the shock pair. Their leading point is in the equatorial plane and their leading edges spiral away from the sun as they move away from the equatorial plane, maintaining a proximity to the interface.

Figure 4. A sketch on an expanded scale of a single shock surface. The location of the equatorial plane is indicated by lines radiating from the sun. The motion of the surface is similar to that of a tappered paper banner attached at its point to a stick that is being twirled around the polar axis. The length of the banner is determined by the lifetime of the streams.


200
Pole (600 km/sec)
25°
20
Equator
Equator (400km/sec)
Pole



C 3
Corotating Shock (leading)
Slow Streamline
Characteristic Line
Streamline Interface
B
C
Characteristic Line
Fast Streamline
Corotating Shock (trailing)
A