WAVE SPEEDS IN THE CORONA AND THE DYNAMICS OF MASS EJECTIONS

Steven T. Suess and Ronald L. Moore

Space Science Laboratory, NASA Marshall Space Flight Center
Huntsville, Alabama 35812

ABSTRACT

A disturbance or coronal mass ejection being advected by the solar wind will expand at the fastest local characteristic speed – typically approximately the fast-mode speed. To estimate this characteristic wave speed and the velocity field in the ambient corona, it is necessary to know the magnetic field, temperature, and density. Only the density is known from coronal observations. The temperature, magnetic field, and velocity are not yet directly measured in the outer corona and must be estimated from a model.

In this study, we estimate the magnetic field, solar wind velocity, and characteristic speeds using an MHD model of coronal expansion between 1 and 5 solar radii ($R_\odot$) with a dipole magnetic field at the base. This model, for a field strength of about 2 gauss at the base, gives flow speeds at low latitudes (near the heliospheric current sheet) of <250 km/s at 5 $R_\odot$ and, <50 km/s at 2 $R_\odot$, and fast-mode speeds to 400 to 500 km/s everywhere between 2 and 5 $R_\odot$. This suggests that the outer edge of a mass ejection will appear to move at a nearly constant rate of 400 to 500 km/s between 2 and 5 $R_\odot$. This result is in agreement with the observed velocity of mass ejections reported by MacQueen and Fisher (1983) and implies that the acceleration mechanism for coronal mass ejections is other than simple entrainment in the solar wind.

INTRODUCTION

The kinematics of coronal transients have been well described elsewhere. It is not our intent to review this research or to put forth a new or original hypothesis for the origin of coronal mass ejections. Rather, what we propose is to offer a deeper physical insight into the dynamics of coronal transients in a way that relates to physical parameters of the corona. The motivation for our study comes from the velocity data reported by MacQueen and Fisher (1983). They examined the kinematic properties of several "loop-like" coronal transients over the range 1.2 to 2.4 $R_\odot$ from Sun center. Their results are partially summarized in Figure 1(a). In this figure, velocity profiles for all of the transients analyzed are reproduced. In Figures 1(c) and 1(d), the results are split into transients observed in the inner corona with the Mauna Loa K-coronameter system and transients observed in the outer corona with the coronagraphs on Skylab and the SMM. Radial expansion speeds are seen to range from 60 to 900 km/s – except for the anomalous 6 September 1973 event. Flare-associated events were found to exhibit high speeds and little acceleration with height. Eruptive-associated events exhibited large accelerations. MacQueen and Fisher conjectured that the pressure gradient forces responsible for the generation of the solar wind may play an important role in accelerating the eruptive-associated events.

Here, we examine the behavior of an isolated blob of gas riding upon the background solar wind and suggest that this behavior is very much like the behavior of coronal mass ejections. The distinction between the hypothesis made by MacQueen and Fisher and what we are describing is that rather than riding passively on the solar wind, the expansion of the mass ejection into the ambient medium is the main cause of the observed motion of the leading edge of the mass ejection.

RESULTS

The model that we use for our computation of characteristic wave speeds in and near streamers is that published by Steinolfson, Suess, and Wu (1982) (hereafter referred to as SSW). In that calculation, a model was developed for the formation of a steady coronal streamer through numerical solution for the time-dependent, dissipationless MHD equations of motion in a meridional phase, for axisymmetric flow. The flow is polytropic and the atmosphere is stationary in magnetically closed regions and flowing outward in open regions. The solution is found through a relaxation in time in a domain extending from 1 to 5 $R_\odot$ and from pole to pole. The flow and magnetic fields, density, and temperature are thus known everywhere in the corona.

CMEs never occur in coronal holes. Therefore, in using the results of SSW, we limit ourselves to results in the neighborhood of the global streamer – polar angles of 90 degrees to 140 degrees (the equator lies at 90 degrees and the polar hole is centered at 180 degrees). The region of interest is shown in Figure 2, modified from SSW. The closed field lines near 90 degrees are in magnetostatic equilibrium – the flow speed there is effectively zero. In Figure 2, the shaded portion is coronal hole-like and therefore excluded from consideration; three radial cuts through the topology are indicated at 100, 120, and 140 degrees. Figure 3 shows the flow speed, sound speed, and Alfvén speed along these radii. A profile is not given for 90 degrees because that is the magnetic neutral sheet, the field strength is zero there, and hence the Alfvén speed is also zero.

Also shown in Figure 3 is the flow + fast-mode speed, where we have used the term "fast-mode" for the sum of the sound speed and the Alfvén speed – strictly only a correct terminology for propagation perpendicular to the magnetic field. We will ignore this distinction because the propagation of a transient through the corona seems to strongly deform the ambient field and hence almost certainly have its motion dominated by the Alfvén speed.

Figure 3 shows that the flow speed is never very large in the vicinity of the streamer, that the Alfvén speed is quite large near the Sun, and – most striking of all – the sum of fast mode and flow speed is both nearly constant in radius and on the order of 400 km/s. The sound speed between 1 and 5 $R_\odot$ is so small as to be unimportant in this sum.

These results apply only to the streamer vicinity. The Alfvén speed is quite different in coronal holes and will be the subject of a separate study. However, near streamers, we feel the tendency shown in Figure 3, for the flow speed + Alfvén speed sum to be nearly constant in radius, is representative of the corona in the vicinity of real streamers. The difference between individual streamers will be dominated by field strength and density – the sum will be larger for higher field strength streamers because the density does not rise as fast as the field strength (SSW). For geometrically more compact streamers, there should be no qualitative difference – the characteristic speeds will still be of the same order of magnitude.

DISCUSSION

The results shown in Figure 3 are relevant to mass ejections because the front edge of a disturbance moving through the corona will always move at the fastest local characteristic speed (Steinolfson, 1985). Thus, if we imagine a blob of plasma injected into the corona and having a finite overpressure, then its center of mass will move upwards with the solar wind expansion speed. In addition, its front edge (and back edge as well) will expand outwards away from the center of mass with the fastest local characteristic speed in the solar wind moving frame of reference.

An obvious question is why should the front edge necessarily be the same as the visible front edge of a transient. It is true that it does not necessarily have to be the visible front edge. However, if the front edge is initially visible at the beginning of the transient, then under normal circumstances, we believe it will only get more visible. This is because a compressive disturbance in the corona always steepens (Steinolfson, 1985; Zel'dovich and Razier, 1966; Montgomery, 1959; Cohen and Kulsrud, 1974; Steinolfson, 1981; Kantrowitz and Petschek, 1966).

It is also obvious that the sum of speeds shown in Figure 3(d) is a lower bound. After a shock is formed, the front edge of the disturbance moves at the shock speed. Thus, no freely expanding CME can move less rapidly through the corona than with the sum of speeds shown here – about 400 km/s. This is the reason for the result quoted in a study of the numerical simulation transients by Steinolfson (1982). There, he used the steamer model shown in Figure 2 and introduced a perturbation in pressure at the base. He found that, depending on the magnitude and character of the perturbation, he could generate a variety of propagating disturbances, but that these disturbances never traveled outward more slowly than about 400 km/s in the neighborhood of the streamer.

By the time a CME reaches a height of 2.0 solar radii, it should be almost free of whatever initiated the transient or restrained it from freely moving outwards. Thus, on the order of the time it would take for information to propagate across the transient with the local characteristic speed, the front edge of CME will appear to be moving at the sum of the solar wind flow speed + fast-mode speed.

Returning to the data shown in Figure 1, we also offer a hypothesis for why some CMEs are moving slowly at heights of 2.0 $R_\odot$ and accelerating rapidly. Since the time for information to propagate across the CME is short with respect to the time it takes the CME to reach these heights, the CME cannot be moving outwards freely. Apparently the CMEs are being restrained from moving outwards and the rapid acceleration reflects the release of this restraint. These considerations suggest that the restraint is due to the linkage of the magnetic field in a CME back to the surface and that this connection is not completely broken at distances below about 2 $R_\odot$. These events may therefore more accurately be called "coronal mass releases" rather than mass ejections.

REFERENCES

Cohen, R. H. and Kulsrud, R. M., 1974, *Phys. Fluids, 17,* 2215.

Kantrowitz, A. R. and Petschek, H. E., 1966, in *Plasma Physics in Theory and Application* (W. B. Kunkel, ed.), McGraw-Hill, New York.

MacQueen, R. M. and Fisher, R. R., 1983, *Solar Phys., 89,* 89.

Montgomery, D., 1959, *Phys. Rev. Letters, 2,* 36.

Steinolfson, R. S., 1981, *J. Geophys. Res., 86,* 535.

Steinolfson, R. A., 1982, *Astron. Astrophys., 115,* 39.

Steinolfson, R. S., 1985, in the proceedings of the AGU Chapman Conference on Collisionless Shock Waves in the Heliosphere, Napa Valley, California, 20-24 February 1984, in press.

Steinolfson, R. S., Suess, S. T., and Wu, S. T., 1982, *Astrophys. J., 255,* 730.

Zel'dovich, Ya. B. and Razier, Yu. P., 1966, *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena,* Academic Press, New York.

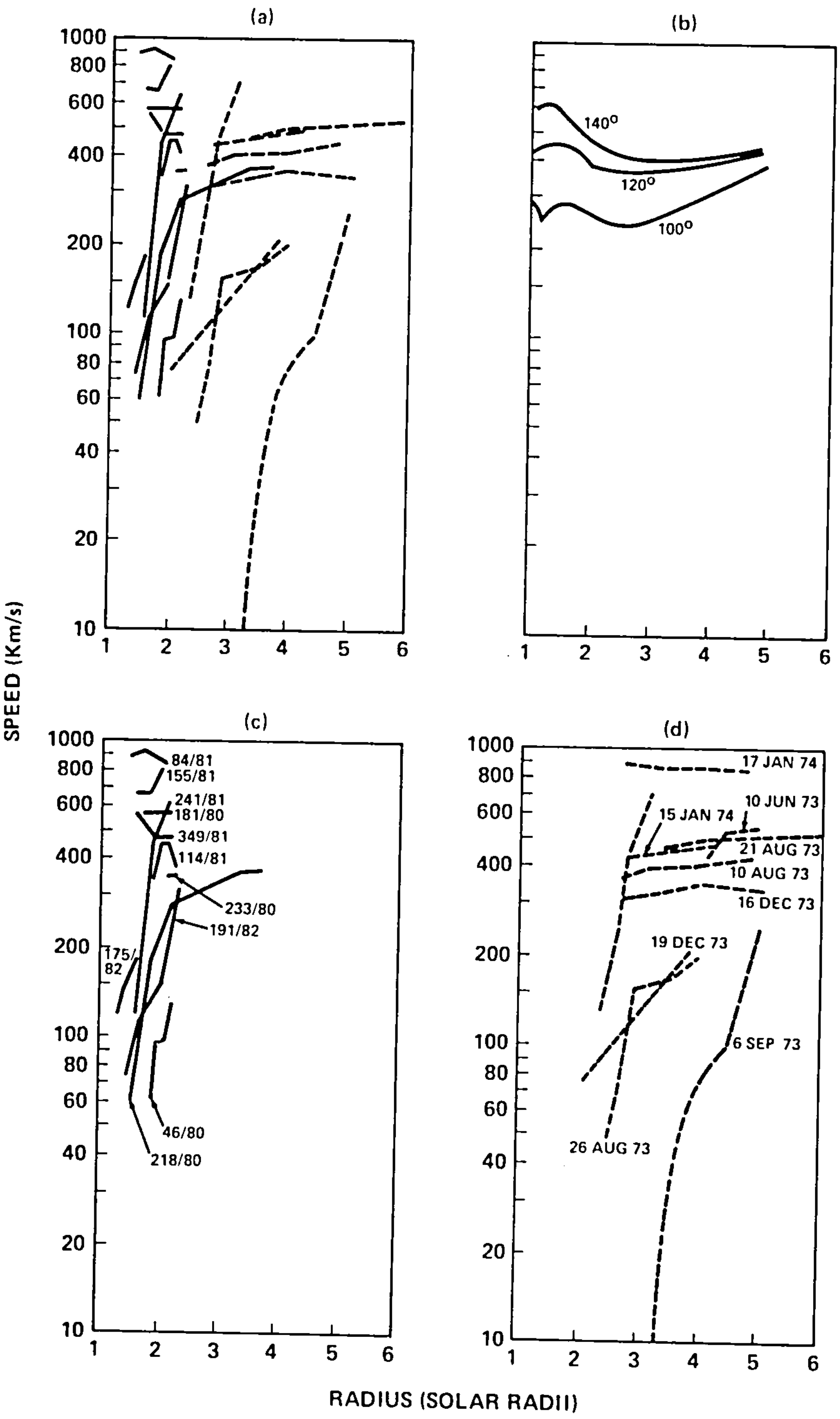

Figure 1. (a) Radial speed of transients, including measurements from the Mauna Loa K-coronameter, Skylab coronagraph, and the SMM coronagraph/polarimeter. (From MacQueen and Fisher, 1983.) (b) Sum of flow speed and fast-mode speed for three positions in and near an MHD model coronal streamer. (From Steinolfson, Suess, and Wu, 1982.) (c) Data from panel (a) that were taken only with the Mauna Loa K-coronameter, with the date the observations were made. (d) Data from panel (a) that were taken only from the Skylab coronagraph and SMM coronagraph/polarimeter, with the date the observations were made.

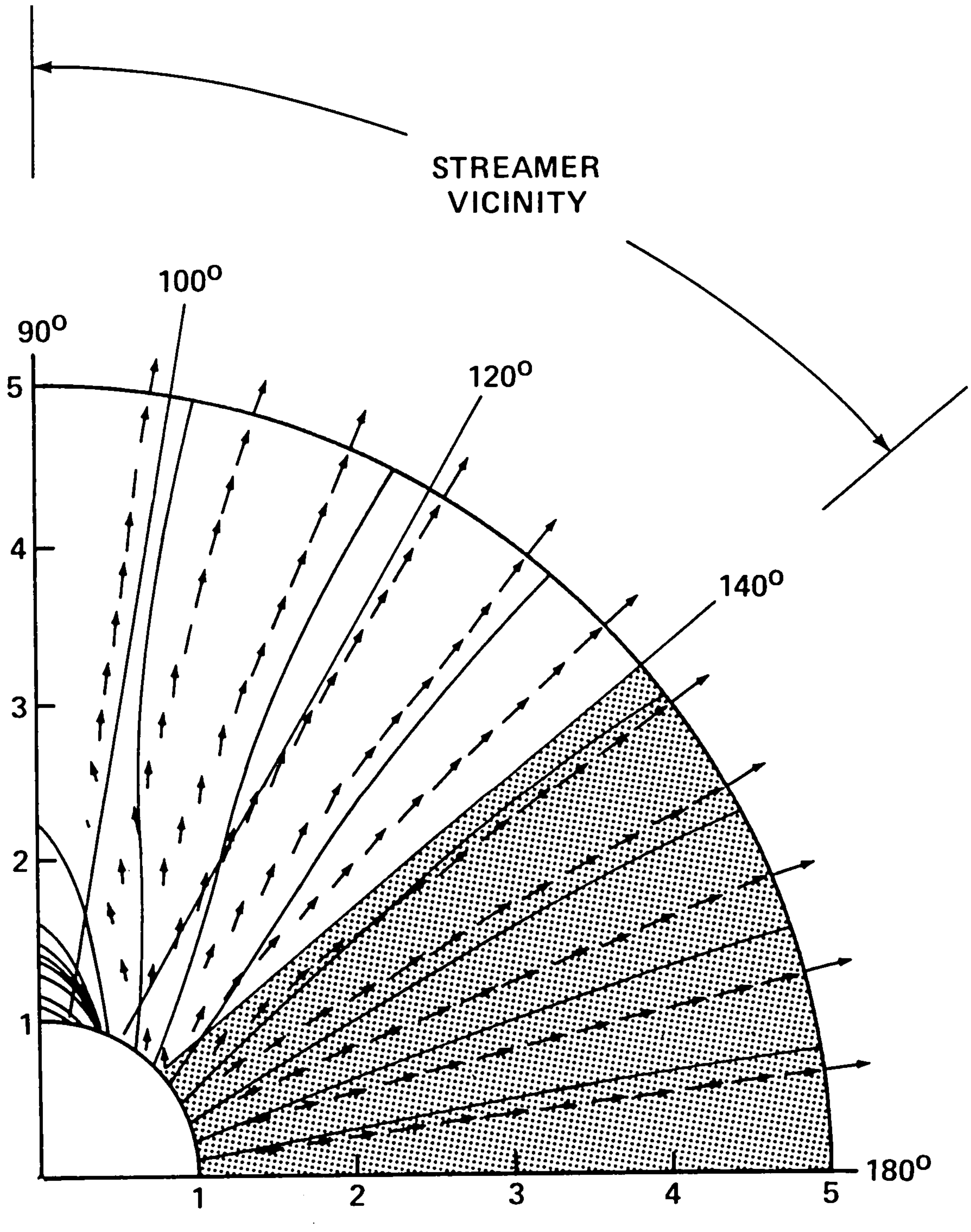

Figure 2. Magnetic field lines and flow speed vectors for the MHD streamer model of Steinolfson, Suess, and Wu (1982). The three radial cuts marked at 100, 120, and 140 degrees are where the data shown in Figure 1(b) and Figure 3 were taken from.

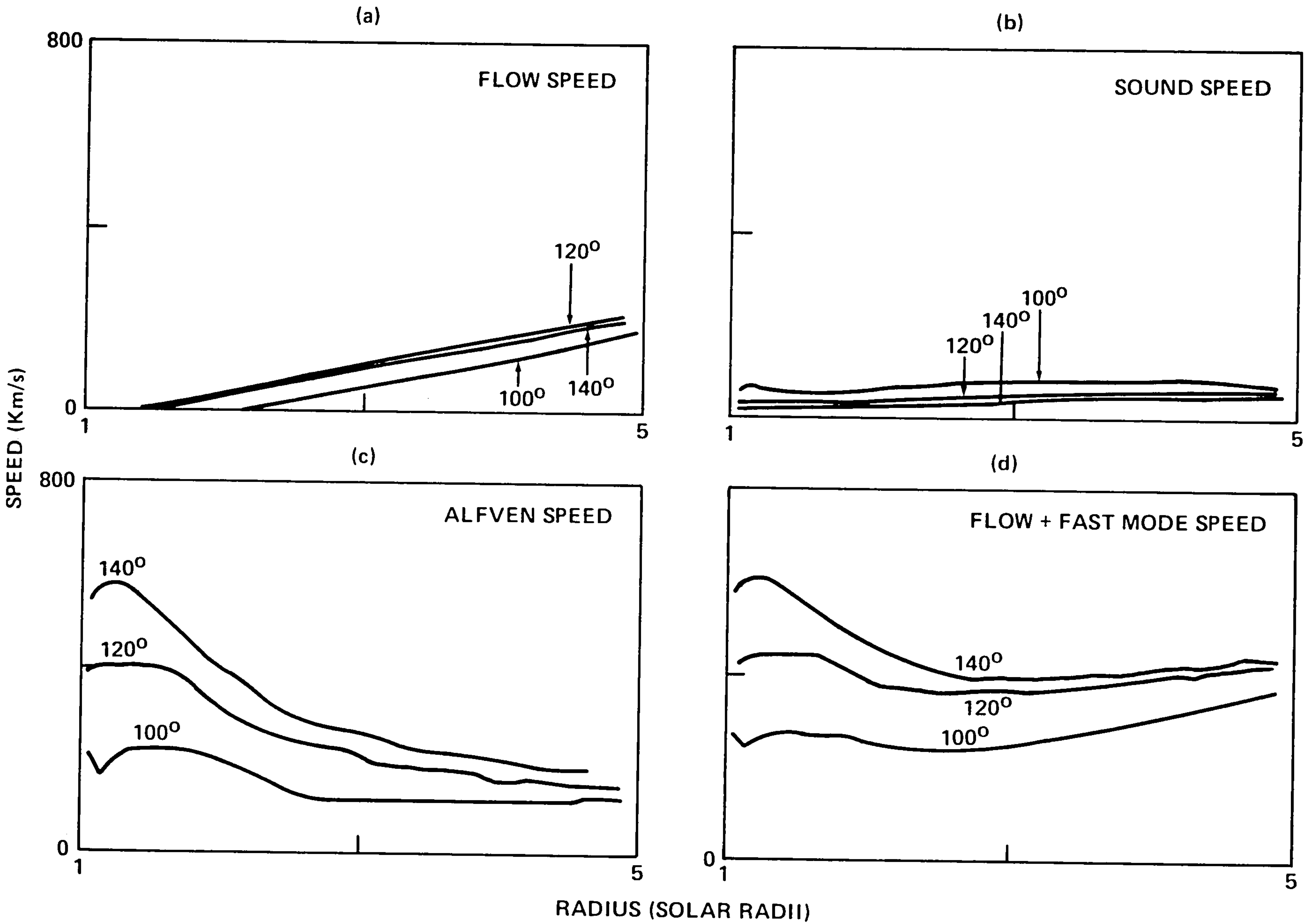

Figure 3. (a) Flow speed, (b) sound speed, (c) Alfvén speed, and (d) sum of the flow speed, Alfvén ("fast-mode") speed, and sound speed along the three radial cuts through the streamer model shown in Figure 2.