THE SOLAR WIND IN THE OUTER SOLAR SYSTEM

MICHAEL D. MONTGOMERY
University of California, Los Alamos Scientific Laboratory, Los Alamos, N.M. 87544, U.S.A.

Abstract. The properties of the solar wind including magnetic fields, plasma, and plasma waves are briefly reviewed with emphasis on conditions near and beyond the orbit of Jupiter. An extrapolation of the steady-state wind to large distances, evolution of disturbances and structure, modulation of cosmic rays, interactions with planetary bodies (bow shocks and magnetosheaths), and interactions with interstellar neutral helium and hydrogen are briefly discussed. Some comments on instrumentation requirements to observationally define the above phenomena are also included.

1. Introduction

Although numerous measurements of the solar wind near 1 AU have been carried out since the flight of Mariner 2 (Snyder and Neugebauer, 1964), almost nothing is known concerning the properties of the interplanetary medium either inside the orbit of Venus (0.7 AU) or outside the orbit of Mars (1.5 AU). However, missions are either planned or already underway which should extend the range of observations inward to the orbit of Mercury (Mariner, 1973) and outward to the orbit of Jupiter or somewhat beyond (Pioneer, 1972). While questions concerning the source of the solar wind and the detailed nature of its expansion are best answered by measurements from inward-going spacecrafts, a wide range of topics of considerable scientific interest can be investigated only by measurements beyond the orbit of Jupiter.

The purpose of this paper is to briefly describe the steady solar wind and some of the phenomena that may become important in determining its characteristics as it expands to large heliocentric distances. From this discussion some of the relevant questions emerge that may be answered by in situ measurements. In addition, an outline of measurement requirements necessary to answer these questions is developed.

It must be realized, however, that knowledge at this time is severely limited, and it is difficult to even ask the right questions. It is likely that initial investigations will yield more unexpected results than confirmations of theories. The paper will be limited to only a brief consideration of each subject and should not be regarded as an adequate review. In addition, although the references given here should themselves provide access to most pertinent publications, we have not attempted to provide an exhaustive list. This paper will touch on the following topics: the structureless solar wind at large distances, evolution of large-scale solar wind disturbances, solar wind modulation of galactic cosmic rays, the interaction of the solar wind with planetary bodies, and the interaction of the solar wind with interstellar neutral hydrogen and helium. The reader will note that some of these topics overlap to some extent those covered by some other papers in this collection, but the intent here is to emphasize the solar wind aspect of each of the topics. Solar wind observa-

Note: This is one of the publications by The Science Advisory Group.
tions near 1 AU and various aspects of the interpretation of these observations have been extensively reviewed by Hundhausen (1968, 1970, 1972a), Axford (1968, 1972), Lüst (1967), Wilcox (1969), Parker (1969), and Holzer and Axford (1970). The term ‘solar wind observations’ as used in this paper is defined to mean a comprehensive set of magnetic field, plasma, and plasma-wave observations.

2. A Featureless Solar Wind

To begin our discussion, let us first consider the simplest case - a steady, spherically symmetric solar wind. Numerous theoretical models (see reviews of Parker (1969), Hundhausen (1970, 1972a) and Holzer and Axford (1970)) have been constructed for this case which are in reasonable agreement with observations near 1 AU and, lacking any observations beyond 1.5 AU, represent the only way of obtaining an extrapolation of the solar wind to large heliocentric distances. Although the temperature profiles of the various models vary somewhat depending on the nature of the outer boundary conditions assumed and the nature of the resulting solutions, the radial dependence of velocity and density at large distances is insensitive to these effects if the interstellar medium is neglected. That is, the speed is nearly constant and the density varies as \( r^{-2} \). Further, if one restricts himself to models where the thermal conduction energy flux is required to vanish at large distances, as it must, even the temperature profiles are not greatly different. Thus, since we are here only concerned with providing an approximate description of the medium, any of several models would be quite adequate. The results of one model (Leer and Axford, 1972), are shown in Figure 1 (from Axford, 1972). It was assumed in this model that nonthermal heating of the protons takes place within 5 solar radii, that the solar magnetic field is simply frozen in and does not influence the dynamics, and that energy transport by heat conduction becomes negligible at large distances near the ecliptic plane for both electrons and protons.

This model, while probably too simple to provide a detailed description of the solar wind at large distances is, as was pointed out above, sufficient, at least near the ecliptic plane, to provide a basis for discussion and to give a rough idea of the magnitude and radial dependence of the parameters to be studied. The interplanetary magnetic field lines under the combined influence of an outward-flowing wind and a rotating Sun form the familiar Archimedean spiral pattern near the plane of the ecliptic (Parker, 1963) and become progressively more radial at higher heliocentric latitudes and progressively more azimuthal at larger heliocentric distances. The resulting field magnitudes are shown in Figure 1a.

The model takes into account the reduction in heat flux near the ecliptic plane as the field lines become more azimuthal far from the Sun. Since the electron temperature is dominated by heat conduction at smaller hose angles (heliocentric distances), one expects (and the model indicates in Figure 1b) an \( r^{-2/7} \) temperature dependence close to the Sun. At larger heliocentric distances, the relation is ultimately \( T_e \sim r^{-4/3} \) as the expansion becomes adiabatic. There are other processes, such as heat flux...