MICROSCOPIC STRUCTURE OF THE SOLAR WIND*

FREDERICK L. SCARF
Space Sciences Laboratory, TRW Systems Group, Redondo Beach, Calif., U.S.A.

(Received 1 May, 1970)

Abstract. As the solar wind flows out from the coronal base the coulomb collision frequencies rapidly become small and particle-particle collisions can no longer maintain local statistical equilibrium. At 1 AU the particle distribution functions have important non-Maxwellian characteristics and the firehose instability, a cyclotron resonance whistler-mode instability, and several heat flux current instabilities should be operative. Superthermal particle populations also provide large wave levels, and other forms of enhanced plasma turbulence develop at shock fronts and discontinuities. This report contains a review of the theoretical concepts and a progress report on the experimental study of interplanetary wave-particle interactions.

1. Introduction

To a large extent our understanding of the local properties of the solar wind is based on analytical studies carried out using the formalism of fluid dynamics. The original Parker model (Parker, 1958; 1963) and several more complex hydrodynamic computations (Noble and Scarf, 1963; Scarf and Noble, 1965; Whang and Chang, 1965; Whang et al., 1966) have provided reasonably accurate predictions of the bulk or average flow properties near the Earth. The computed values for the mean velocity, density, magnetic field strength and field orientation are close to those observed, and even the temperature prediction can be correct in a rough sense (Hundhausen, 1968). However, it was always known that the fluid description could not be justified in terms of ordinary coulomb collision effects alone. In Parker's earliest papers he pointed out that when the gas streams away from the Sun into the supersonic region \( r \gtrsim 0.1 \text{ AU} \) the collisional mean free path \( l \) must rapidly increase so that near the Earth we find \( l \) comparable to the scale height \( l(1 \text{ AU}) \approx 1 \text{ AU} \). Nevertheless, in these initial discussions Parker also provided a general justification for the use of fluid equations beyond the dense collisional region; he pointed out that some microscopic plasma instabilities must naturally develop and that associated wave-particle scattering then produces a thermalization mechanism leading to a finite mean free path and effective fluid transport characteristics.

It is now quite clear that plasma turbulence generates partial thermalization at 1 AU. The microscopic scattering effects are important in the study of the solar wind, but these phenomena apparently do produce negligible viscous forces so that hydrodynamic continuity and momentum conservation equations remain appropriate for descriptions of the main flow properties \( (N, u \text{ and associated } B_x, B_y) \), at least out to 1-2 AU. However, present analysis shows that microscopic interactions must be

* Prepared for Space Science Reviews.
extremely significant with respect to energy transport and energy balance in the wind. Moreover, the microscopic processes play an important role in allowing interplanetary shocks, discontinuities and other non-uniformities to persist as the fluid expands. Collisionless dissipation phenomena also determine the forms of interaction of the solar wind with planetary objects and comets, with cosmic rays and with the interstellar medium. Analysis of these wave-particle interactions also has general value because the solar wind provides a unique natural laboratory for study of wave propagation, plasma instabilities, stochastic acceleration and diffusion processes, collisionless energy loss mechanisms, anomalous conductivity, field annihilation and related phenomena.

Although the importance of wave-particle interaction studies was anticipated in some of the initial discussions of the solar wind, little attention was paid to wave phenomena during the early years of direct interplanetary exploration. In 1959, 1960 and 1961 the first intermittent measurements of wind particles were made on Lunik 2, 3, Venus 3 and Explorer 10, and the first verification of continuous solar wind flow came from the flight of Mariner 2, in 1962 (Snyder et al., 1963). For several years thereafter theoreticians concerned themselves primarily with re-examinations of the fluid models. The roles of coulomb heat conduction and viscosity, solar rotation and the imbedded interplanetary magnetic field were studied in detail. Experimental investigations were largely directed toward the analysis of very long period time variations (M-regions, persistence of fast and slow streams, sector structure), although some studies of interplanetary Alfvén waves were conducted.

In 1966 several related theoretical and experimental developments began to reveal the basic inadequacies of the fluid models and provided new impetus to study of wave-particle interactions in the solar wind. This paper contains a review of some of the relatively recent experimental advances that contributed to this change in emphasis (Section 2). We then discuss the general wave propagation characteristics of the wind (Section 3) and describe various possibilities for wave-particle interactions or plasma instabilities (Section 4). Section 5 includes a progress report on observations of these instabilities and related phenomena, and some outstanding problems are discussed in Section 6.


The characteristics of a dense neutral gas dominated by energy- and momentum-conserving two-body collisions are given by the Navier-Stokes fluid equations, which can readily be derived from the Boltzmann equation. It is assumed that the actual one-particle distribution function, \( f(r, v, t) \), can be represented by a slightly perturbed Maxwellian,

\[
f(r, v, t) = f_0(r, v, t) \left[ 1 + \phi \right],
\]

where

\[
f_0(r, v, t) = N \left( \frac{m}{2\pi\kappa T} \right)^{3/2} \exp \left[ -m(v - u)^2/2\kappa T \right],
\]