MODELS OF CORONAL HOLE FLOWS*

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Abstract. Models of plasma flow in a coronal hole fall naturally into four classes. These are: (i) radial flow on a streamline along which the divergence is assumed to vary differently than as the square of the radial distance from the Sun; (ii) global flow along streamlines determined in some independent manner; (iii) empirical models originating in, or based strongly on observation; (iv) dynamic models using magnetic and plasma boundary conditions low in the corona to find both the geometry of streamlines and the flow field.

To date, models both of ideal coronal holes and of specific observed coronal holes indicate that flow velocities above 100 km s\(^{-1}\), and temperatures of perhaps \(2 \times 10^6\) K are possible at \(2R_\odot\) heliocentric distance, where densities of \(2 \times 10^5\) cm\(^{-3}\) have been reported. These velocities are at, or just above the sound speed, although still sub-Alfvénic. There is also general agreement among models of large polar holes that conversion of mechanical wave energy flux into solar wind kinetic energy is occurring in the \(2R_\odot\) to \(5R_\odot\) range, perhaps occurs even further outwards, and that the magnitude and extent of this energy deposition depends on the size and on the geometrical divergence of the hole.

However, each model exhibits distinct weaknesses counteracted only by the complimentary nature of the various types of models. Models in class (i) are simply not global representations, but are tractable when dealing with complex forms of the energy equation or with several ion species. Class (ii) models lack any geometrical information beyond the \textit{ad hoc} assumption of known streamline geometry, but have the same advantages as those in class (i). Class (iii) models cannot determine streamline geometry within a hole and do not extend further from the Sun than the available data -- although they place important constraints on models in the other classes. Class (iv) models are limited to simple forms of the energy equation and/or to quasi-radial flow, but are the only models producing self-consistent streamline geometries through inclusion of transverse magnetic stresses in the momentum equation.

Most limitations in coronal hole flow models can be eliminated by using known numerical techniques to combine models in classes (i), (ii), and (iv). This would allow detailed models of coronal holes and corresponding interplanetary conditions to be developed for specific time periods, at the cost of flexibility and possibly also general conceptual understanding. Nevertheless, the concept of a coronal hole is now reasonably well established, and acceptable modelling approaches are rapidly filling the literature. It can be anticipated that the evolution of these models, together with present and future observations, will bring us much nearer to understanding coronal energetics and dynamics.

1. Introduction

Coronal holes are regions of the corona which appear dark when viewed in soft X-ray images, in white light coronagraphs, and in eclipse photographs of the solar corona. They are also detectable with the \(K\)-coronameter and in some EUV and XUV measurements, and their presence can be inferred with the high resolution potential field maps made from photospheric magnetic field measurements. Apparently the first person to discover coronal holes was Waldmeier (1957), who notices regions of low intensity on synoptic maps of the emission line (generally 5303 Å) corona. However, it was not until recently, when solar observations from space, and especially Skylab, became possible, that the morphology, internal geometry, and evolutionary characteristics of coronal holes could be studied. At the same time, it

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has been discovered that in all cases where it can be proved or disproven, a coronal hole is always a source of high speed solar wind stream (Krieger et al., 1973; Zirker, 1977b). Because coronal holes tend to last longer than one solar rotation, there is thus a 27-day recurrence period for high speed streams at the Earth, producing a natural explanation for the same well known recurrence period in geomagnetic activity (Bartels, 1934) and the associated source at the Sun—which has up until this discovery been known as the ‘\textit{M}-region’.

The history of the study of \textit{M}-regions has been long and interesting, with many erroneous ideas, and \textit{M}-regions have been the source of a continuing interest in coronal structure as the source of solar wind inhomogeneities. Now, with the identification of the \textit{M}-regions, together with quantitative measurements and modeling of coronal structure, the study of inhomogeneous coronal flow has come of age. Experimental discovery has led quite naturally to vigorous theoretical activity and to the resultant publication of a variety of models dealing with these interesting problems. The various models usually approach one or a few specific aspects of coronal hole flows, such as the energy balance, flow geometry, density, and so on.

A general review of coronal holes and high speed wind streams has been written by Zirker (1977a). In addition, a collection of papers resulting from a series of Skylab/NASA/HAO workshops has been published as a book (Zirker, 1977b), and Holzer (1978) has written a review of the solar wind and related phenomena, which has conveniently been cast in the context of coronal holes, and which examines many important aspects of theoretical modeling. The purpose of the present review can then be narrowly defined: to describe only, and in some detail the approaches which have been taken to modeling coronal hole flow, to give some of the results, and to point the way for future efforts. Chromosphere and transition region models, magnetic field models which do not interact with the flow field, and models of flow in the interplanetary medium will not be emphasized, as these topics either are not \textit{flow} models, or are reviewed elsewhere in this volume (Harvey and Sheeley, 1979; Burlaga, 1979).

In Section 2, a brief synopsis of general observational results for coronal holes will be given, setting the stage for theoretical models—which fall naturally into four classes. These classes are: (i) one-dimensional radial flow on a streamline whose divergence is specified to vary differently than as the square of the radial distance from the Sun; (ii) flow along streamlines whose geometry has been predetermined in some independent manner; (iii) empirical models originating in or based strongly on observation; (iv) dynamic models using magnetic and plasma boundary conditions low in the corona to find both the geometry of streamlines and the flow field. These models will be described in Sections 3 through 6, corresponding to classes (i) through (iv), respectively. The review is summarized in Section 7, and results from the models are gathered together in Section 8 in an attempt to offer an explanation for a few of the observed characteristics of coronal holes, and to define specific approaches necessary to further our understanding. It should be recalled that the philosophical purpose of the theoretical modeling is to investigate the consequences of the various