SHOCK INTERACTIONS IN THE OUTER HELIOSPHERE

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Abstract. Observations of plasma and magnetic fields by Pioneer 10 and 11 and Voyager 1 and 2 reveal that MHD shocks are an important component of the large-scale solar wind structures in the outer heliosphere. This review discusses recent progress in simulation studies of the nonlinear evolution of the solar wind structures, and in particular concentrates on the theoretical development and applications of the shock interactions model. Various stream propagation models, which do not use the Rankine–Hugoniot relations to calculate the jump conditions at shock crossings, have been used to simulate the essential evolution process of isolated streams and the formation and propagation of corotating and transient shocks. They produce fairly good results in the region up to a few AU. In 1984, the shock interactions model was introduced to study the evolution of large-scale solar wind structures in the region outside 1 AU up to several tens of AU. The model uses the exact Rankine–Hugoniot relations to calculate the shock speed and shock strength at all shock crossings. So that the model can more accurately calculate the shock speeds and the accumulated irreversible shock heating of plasma at several tens of AU. The applications of the shock interactions model are presented in three groups. (a) The first group covers the basic interaction of a shock with the ambient solar wind, the formation and propagation of shock pairs, and the collision and merging of shocks. (b) The second group covers the use of the shock interactions model to simulate the nonlinear evolution of large-scale solar wind structures in the outer heliosphere. These simulation results can provide the detailed evolution process for large-scale solar wind structures in the vast region not directly observed. Two selected studies are reported. (c) Finally, the shock interactions model is applied to studying the heating of the solar wind in the outer heliosphere. The model calculations support shocks being chiefly responsible for the heating of the solar wind plasma in the outer heliosphere at least up to 30 AU.

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1. Introduction

This review concentrates on recent progress in simulation studies for the nonlinear evolution of the solar wind in the outer heliosphere. Observations of plasma and magnetic fields by Pioneer 10 and 11 and Voyager 1 and 2 reveal that MHD shocks are an important component of the solar wind structure. Corotating shocks form near and outside 1 AU. Beyond several AU, shocks may become very strong. Across a strong shock the pressure may jump by a factor of 100 or greater. The shock strength and the shock speed change continuously as the shock interacts with the ambient solar wind. Shocks propagate in a forward or reverse direction in the solar wind frame of reference. Shocks also interact with one another. When a forward and a reverse shock propagate toward each other, a collision of the two shocks can take place. A shock can overtake another shock from behind, and the two merge into a stronger shock. MHD shocks and shock interactions play very significant roles in the nonlinear evolution of the large-scale structures of the solar wind in the outer heliosphere.

The magnetohydrodynamic (MHD) theory that governs the dynamics of the solar wind and the solar wind shocks is well developed and well understood (see review by Burlaga, 1985). The motion of MHD fluid must satisfy the continuity equation, the equation of motion, and the equation of energy conservation. The variation of the magnetic field is governed by Faraday's law of induction and the divergence free condition. The jumps in flow properties across a solar wind shock in a frame of reference attached to the shock can be described by the classical theory of MHD shocks. Its solutions are known as the Rankine–Hugoniot relations. Shock waves described by these relations are sometimes referred to as the Rankine–Hugoniot shocks.

Just like the applications of fluid mechanics to many other scientific and engineering areas, the implementation of MHD theory to simulation study for the evolution of the solar wind structures progresses rather slowly. Several dynamic and kinematic models have been developed to study the nonlinear evolution of streams and the formation and propagation of corotating shocks and transient shocks. Prior to 1984, several models had been developed without using the exact Rankine–Hugoniot relations to calculate jumps in flow properties across shocks. In Section 4, we give a brief summary of the models in this category and their representative results related to large-scale structures in the outer heliosphere. In 1984, a new model was developed using the