# Final Report: NASA Grant NAG5-10975 and NNG04GM99G

**L. A. Fisk, Principal Investigator**
**University of Michigan**

The purpose of this grant was to develop a theoretical understanding of the processes by which open magnetic flux undergoes large-scale transport in the solar corona, and to use this understanding to develop a predictive model for the heliospheric magnetic field, the configuration for which is determined by such motions.

**Years One and Two**: The plan for the first and second year of this grant was to identify and quantify the governing processes by which open magnetic flux is transported in the solar corona, to relate this transport to basic solar processes such as the acceleration of the solar wind, and to publish and to make presentations about these results. This plan was successfully followed, with some very interesting related results:

In Fisk and Schwadron [Astrophys. J. 500, 425, 2001] a detailed discussion is provided of the behavior of the open magnetic flux of the Sun, the magnetic flux that opens into the heliosphere. It is pointed out that the open flux should tend to be constant in time since it can be destroyed only if open flux of opposite polarity reconnects, a process that may be unlikely since the open flux is observed to be ordered into large-scale regions of constant polarity throughout the solar cycle. The open magnetic flux should be transported by a diffusive process in which open field lines reconnect with one end of randomly oriented magnetic loops, and undergo a displacement to lie over the other end of the loop with the same magnetic polarity as the open field line. This diffusion process needs to be described by a special form of the diffusion equation, different from the one commonly used in energetic particle transport. Solutions are presented to this special form, which suggest that the reversal in polarity of the open magnetic flux over the solar cycle is accomplished simply by a rotation of the current sheet that separates regions of uniform polarity. The diffusion process can also concentrate open magnetic flux in coronal holes, provide energy and mass into the solar wind, and influence the configuration of the heliospheric magnetic field.

The special form of the diffusion equation excited some debate among specialists in diffusion theory, e.g. Mike Schultz and Gene Parker. A detailed justification of this form was developed. Interestingly, the special form was first noted by Gene Parker in an appendix to his 1963 book on Interplanetary Dynamical Processes, but has largely been forgotten since. The special form is appropriate when the diffusion is caused by an external media, e.g. reconnection with loops, and can have profoundly different properties than standard diffusion, e.g., it can cause open flux to accumulate in coronal holes.

The diffusion process, in which open field lines reconnect with closed magnetic loops, provides a natural source of energy and mass to form the solar wind. The resulting displacements of the open field lines in the overlying corona, and the subsequent relaxation of induced magnetic pressure variations back to equilibrium, deposits energy throughout the corona. The reconnection process releases mass from the loops onto open field lines. In Fisk [J. Geophys. Res., 108 (A4), pp. SSH 7-1, CiteID 1157, DOI 10.1029/2002JA009284, 2003], these simple processes have led to a theory for the solar wind that predicts a specific functional relationship between the final speed of the solar wind and the temperature of material on the loops that reconnect with the open field lines. Gloeckler, Zurbuchen and Geiss [J. Geophys. Res., 108(A4), SSH 8-1, 1158, DOI 10.1029/2002JA009286, 2003] relate the loop temperature to the temperature of coronal electrons, as measured by solar wind ionic charge states. They find that the predicted functional form for the speed of the solar wind holds in all samples of the solar wind: fast and slow, high and low latitudes, and at all times during the solar cycle.

The potential power of this simple theory for the acceleration of the solar wind should not be underestimated. If it is confirmed that certain solar parameters, such as temperatures in loops, or their size, can uniquely determine the final speed of the solar wind, there are important implications for a basic Living with a Star problem. Solar observations can be made of loops, the observed properties fed into the theory for the solar wind, and numerical models can be used to determine the entire heliosphere. This potential coupling should be pursued in detail.

All of these results have been presented in invited presentations at AGU meetings, at the ACE/Voyager Workshop, at the Solar Wind 10 conference, and in several seminars.

**Years Three and Close-Out Year.** The principal thrust of the third year of this grant was to develop a detailed model for how the emergence of magnetic flux on the Sun is related to the formation of coronal loops and the transport of open flux. The model provides a quantitative measure of the parameters that govern the interaction of coronal loops and open field lines, and thus the diffusion coefficients for the transport of open flux. The model also offers an explanation for why coronal holes – accumulations of open flux – form; the location is predicted to coincide with regions where the rate of emergence of new magnetic flux is a local minimum, e.g. at the solar poles during solar minimum conditions. The paper summarizing these results is Fisk, L. A., The open magnetic flux of the Sun. 1. Transport by reconnections with coronal loops, [Astrophysical J., 626, 563-573, 2005].

All of these results have been presented in invited presentations at AGU meetings, and at several seminars, and were the basis for a series of invited talks at Solar Wind 11 and SHINE.

In the development of the second paper in this series, which deals with the interaction of open flux with the canopy of loops on the Sun, it was realized that a prediction of the amount of open flux outside of coronal holes is possible. Open flux outside of coronal holes is important for understanding the escape of energetic particles from impulsive solar flares, the distribution of Type III radio bursts, and the compositional differences between fast and slow solar wind. This paper is more appropriate for JGR than ApJ and will be submitted shortly to this journal.

The final topic funded under this grant, which was considered in the extension year, had been intended for a follow-on grant, which was not funded. It was recognized in the development of models for the diffusion of magnetic fields that this process inherently results in a large-scale electric field, which can be used to accelerate particles. The electric field can be used to heat the solar wind through dissipative heating, and also to accelerate energetic particles through statistical acceleration. The latter acceleration is believed to have wide applications to acceleration in the solar wind and at the Termination Shock of the solar wind, and is being pursued through other funding.