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MAPPING THE SOLAR WIND FROM ITS SOURCE REGION INTO THE OUTER CORONA

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Final Report

For the period 1 February 1993 through 31 July 1997

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Final Report for the grant "Mapping the Solar Wind from Its Source Region into Interplanetary Space", NAGW-3513

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1. Summary

1.1 Scope of the Investigation

Knowledge of the radial variation of the plasma conditions in the coronal source region of the solar wind is essential to exploring coronal heating and solar wind acceleration mechanisms. The goal of the proposal was to determine as many plasma parameters in the solar wind acceleration region and beyond as possible by coordinating different observational techniques, such as Interplanetary Scintillation Observations, spectral line intensity observations, polarization brightness measurements and X-ray observations. The inferred plasma parameters were then used to constrain solar wind models.

1.2 Progress Made

Over the past few years we have carried out, analyzed and made use of a number of different observational techniques to achieve the above goal. The observations include IPS observations from the EISCAT and VLBA antennas (in collaboration with Wm. A. Coles), spectral line intensity observations from the National Solar Observatory at Sacramento Peak (in collaboration with R. C. Altrock), Spartan polarization brightness observations (in collaboration with L. Guhathakurta), spectral line width measurements from the UVCS/SOHO experiment, as well as additional observations from CDS, SUMER and LASCO (also SOHO instruments). These observations were supplemented by YOHKOH soft X-ray images (in collaboration with H. S. Hudson) and results from the SWICS/ULYSSES in situ particle experiment. Most of these observations were devoted to coronal hole studies since the major part of the funding period was close to solar minimum when coronal holes are best visible. A minor part of the study was aimed at coronal hole boundaries (in collaboration with S. Solanki) and coronal conditions preceding and following a coronal mass ejection. For that study we also made use of VLA observations.

The above observations indicate that the solar wind originating in polar coronal holes accelerates much closer to the coronal base than previously assumed. In Figure 1a we have summarized the flow speeds in the inner corona derived using a variety of different observational techniques and assumptions.

Most of the information available on flow speeds in the inner corona pertains to the electron-proton plasma. The values plotted at 1 R_S are derived from line-asymmetries in the He 10830 Å spectral line (Dupree et al. 1996). Flow speed estimates derived from Ly-alpha Doppler dimming are plotted as filled squares (Strachan et al. 1996), and filled triangles (Strachan et al. 1993). Filled dots are derived from polarization brightness measurements (Fisher and Guhathakurta 1995), under the assumption of constant mass flux and a homogeneous solar wind. The lower values are for a radial expansion geometry of the solar wind flow tubes, the upper values for a geometry that expands 11 times faster than radially (see e.g. Esser et al. 1996 for a discussion of expansion geometry in the flow speed estimates).

The error bars around 10 R_S are from Interplanetary Scintillation (IPS) measurements (Grall et al. 1996), and the dashed horizontal lines are upper and lower limits measured from the Ulysses spacecraft south of -60^o. The mean Ulysses speed is plotted as a solid line (e.g. Phillips et al. 1995). The IPS observations below 10 R_S are not included in the figure since the possible bias due to waves increases as the sun is approached, and might be rather large close to the sun. It should be mentioned that these flow speed estimates range from about 400 to 1200 km s^{-1}.

The only estimate of an oxygen ion flow speed derived from the Doppler dimming experiment of the O VI 1032 Å spectral line (Kohl et al. 1996) is plotted in Figure 1a as open triangles. Note that the value they derive for the O^{+5} ion is extremely high, about 200 km s^{-1} at 2 R_S.

Electron densities in the inner corona are plotted in Figure 1b. The innermost value, at 1 R_S, is derived from the line intensities of the Mg VIII λ436.62/λ430.47 spectral line ratio using new atomic models (Brickhouse and Esser, 1996) and measurements obtained during the Skylab mission (Vernazza and Mason, 1978) (a corresponding Soho observation was not yet available to us when we wrote the paper). Upper and lower values of electron densities derived from polarization brightness measurements by Lallement et al. (1986) are shown as filled dots at a few selected distances. The remaining error bars are from the polarization brightness observations by Fisher and Guhathakurta (1995), also used to derive the limits on the flow speeds in Figure 1a. It can be seen from the figure that the range of possible coronal hole densities in the inner corona is still quite large.

Constraints on the electron temperature in that region are even more rare. We have selected some examples from Habbal et al. (1993, and references therein) in Figure 1c. Included in this figure are only measurements which clearly reflect the electron temperature. We have excluded the hydrostatic temperature derived from white light observations, and line broadening observations such as the Ly-α line width, since these observations reflect the temperatures of neutrals, protons, or other ions. Electron temperatures are only derived very close to the solar limb. The bars in Figure 1c represent the distance ranges over which a given measurement has been carried out, and the range of temperatures that are derived. The values shown do not include error bars, and thus realistic limits of the electron temperature are even larger than the figure suggests. The radial profile of T_e becomes increasingly uncertain at larger distances, as the statistical significance of emission line intensities decreases. No measurements at distances above 1.2 - 1.3 R_S have been possible to date (for a more detailed discussion see Habbal et al. 1993).

It was shown (e.g. Esser et al. 1996; Esser and Brickhouse, 1996 and Hollweg and Esser, 1996) that the high flow speeds shown in Figure 1a can be achieved by allowing the ion temperatures to be very high (in agreement with UVCS observations) or by direct momentum addition in the inner corona. Two solar wind models calculated for the high speed wind with the computer code described in Hu, Esser, and Habbal (1997) and Esser et al. (1997) are also plotted in the Figures 1a to 1c (solid and dashed lines). These two models are also in agreement with in situ observations of flow speed and mass flux. The combination of flow speed, electron density and electron temperature shown in the figure (solid and dashed lines) give charge state ratios in agreement with in situ charge state observations. Since the ion ratios depend on both, the ion flow speed and the electron temperature for a given electron density profile, the higher ion outflow speeds observed by the UVCS instrument can be matched with higher electron temperatures (still inside observed limits) to yield the same ion ratios at 1 AU. An example is shown in Figure 2a and b. The combination of the corresponding three flow speed and electron temperature profiles all result in exactly the same ion ratio. Figure 2c shows the condition for the oxygen ions very close to the inner boundary to demonstrate that the ions are close to an equilibrium situation there. In Figure 3a to 3c we show the calculated ion ratios for O, C, and Fe when the two models of Figure 1 are used. The symbols in the Figure show the observed ion ratios in interplanetary space. Figures 4a and b show the corresponding values for the Si ratios.

By comparing the observations carried out in the high speed solar wind at different radial distances from the coronal base with theoretical model predictions, we gained some insight into the requirements that the heating and acceleration mechanism/s have to meet. For example, from the above study we draw the conclusion that the rapid acceleration of the high speed wind in the inner corona is most likely due to direct momentum addition into the protons, since upper limits on the proton temperatures derived from Lyman-alpha Doppler dimming are not high enough to accelerate the solar wind close enough to the coronal base. The high temperatures of the heavy ions which are much higher than the proton temperatures, result in an outflow speed of the heavy ions exceeding that of the protons already in the inner corona. These high ion temperatures can easily result in ions flowing an Alfvén speed faster than the protons at 1 AU.

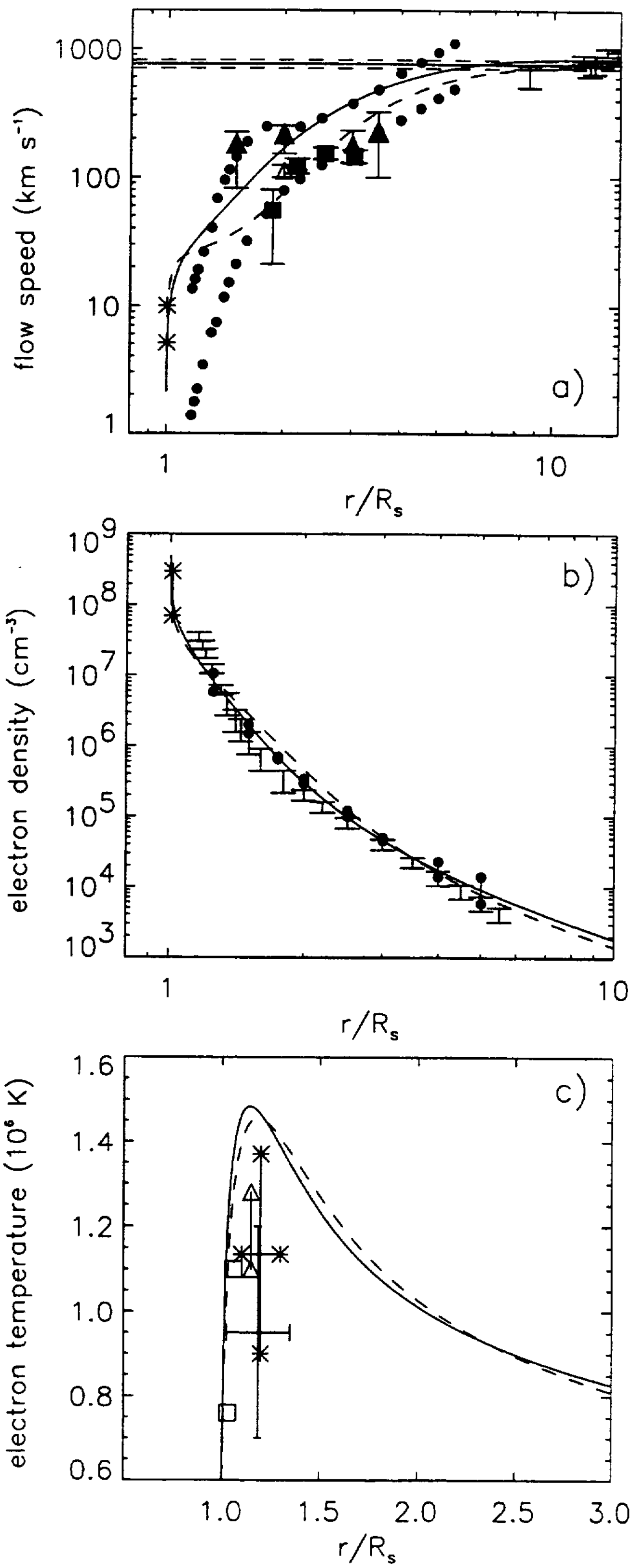

Figure 1

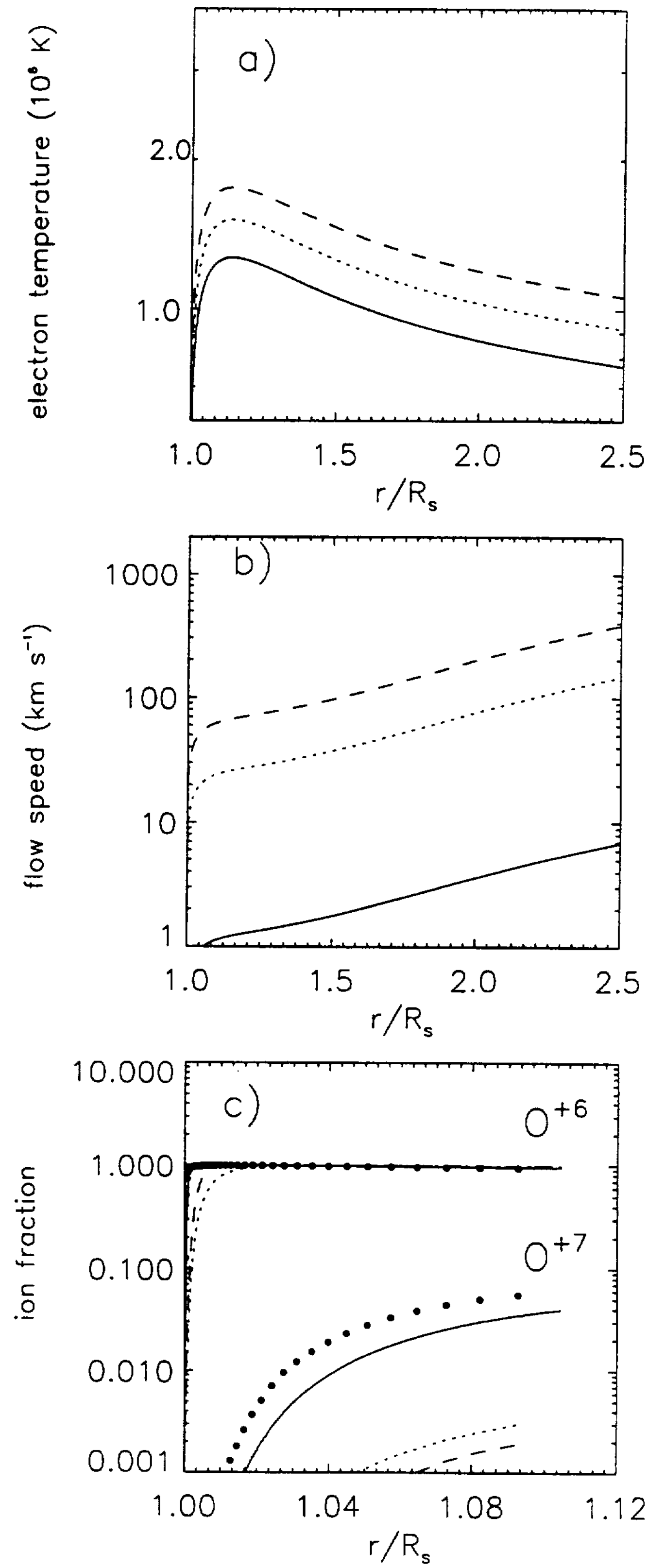

Figure 2

For a description of the Figures see text

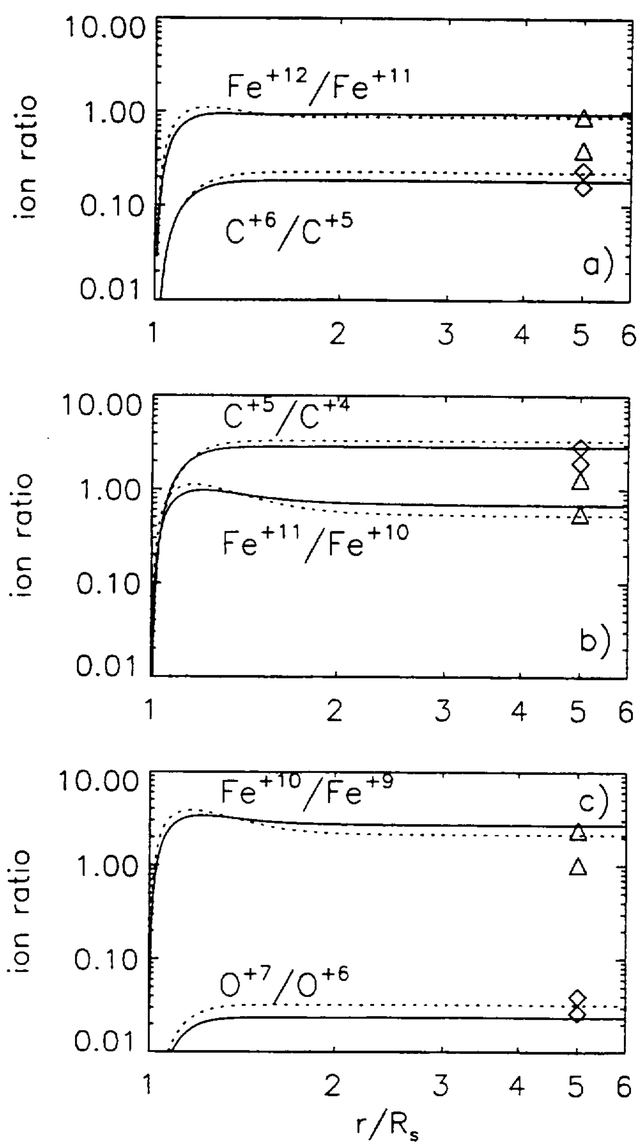

Figure 3

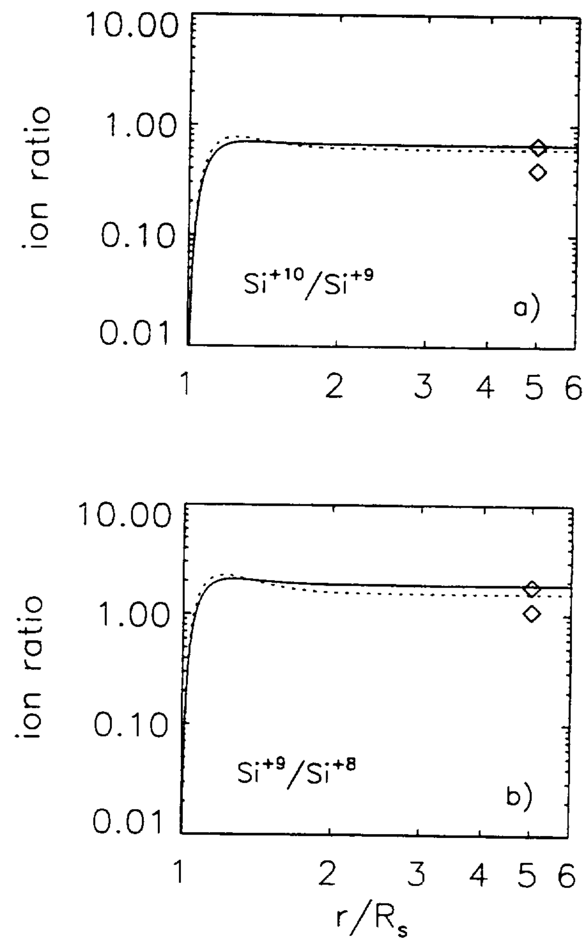

Figure 4

For a description of the Figures see text

2. Publications in Journals and Proceedings Funded or Partially Funded by Grant NAGW-3513

1. R. Esser, S. R. Habbal, and M. B. Arndt, Temperature Measurements in the Inner Corona, in Proceedings of the *First SOHO Workshop, Annapolis*, ESA Sp-**348**, 277, 1993.

2. M. Kojima, K. Asai, R. Esser, Y. Kozuka, H. Misawa, H. Watanabe, and Y. Yamauchi, Solar Wind Observations with Interplanetary Scintillation During the STEP Interval, in Proceedings of the *STEP Symposium*, 1994.

3. S. R. Habbal, R. Esser, M. Guhathakurta, and R. Fisher, Flow Properties of the Solar Wind Obtained from White Light Data And A Two-Fluid Model, in Proceedings of the Third SOHO Workshop, *Solar Dynamic Phenomena and Solar Wind Consequences*, ESA-SP**373**, 1994.

4. S. R. Habbal and R. Esser, On the Derivation of Empirical Limits on the Helium Abundance in Coronal Holes below 1.5 R_S, *Ap. J. Letters*, **421**, L59-L62, 1994.

5. R. Esser, Unsolved Problems of Solar Wind Expansion: Can We Learn Anything from SOHO? *Space Sci. Rev.*, **70**, 331-340, 1994.

6. S. R. Habbal, R. Esser, M. Guhathakurta, and R. Fisher, Flow Properties from a Two-Fluid Model with Constraints from White Light and In-Situ Interplanetary Observations, *Geophys. Res. L.*, **22**, 1465-1468, 1995.

7. R. Esser, N. S. Brickhouse, S. R. Habbal, R. C. Altrock, and H. C. Hudson, Using the Fe X 6374 Å and Fe XIV 5303 Å Spectral Line Intensities to Study the Effect of the Line of Sight on Coronal Temperature Inferences, *J. Geophys. Res.*, **100**, 19829-19838, 1995.

8. R. Esser, and S. R. Habbal, Coronal Heating and Plasma Parameters at 1 AU, *Geophys. Res. L.*, **22**, No 19, 2661-2664, 1995.

9. R. R. Grall, W. A. Coles, M. T. Klinglesmith, A. R. Breen, P. J. S. Williams, J. Markkanen, and R. Esser, Measurements of the Solar Wind Speed in the South Polar Stream Near the Sun, *Nature*, **379**, 429-432, 1995.

10. S. R. Habbal, A. Mossman, R. Gonzalez, and R. Esser, Radio, Visible and X-Ray Emission Preceding and Following a Coronal Mass Ejection, *J. Geophys. Res.*, **101**, 19943, 1996.

11. R. Esser, Recent Development in Solar Wind Modeling, *Astrophys. and Space Sci.*, **243**, 57, 1996.

12. N. S. Brickhouse, and R. Esser, Effects of High Proton Temperatures on Diagnostics for Electron Density and Electron Temperature, *Astrophys. J. Let.*, **479**, 470, 1996.

13. R. Esser, N. S. Brickhouse and S. R. Habbal, Demonstrating the limitations of line ratio temperature diagnostics using Fe X and Fe XIV spectral line intensity observations, in Proceedings of the *Solar Wind Eight Conference*, eds. Winterhalter, D., Gosling, J., Habbal, S. R., Kurth, W. and Neugebauer, M., **AIP 382**, 173, New York, 1996.

14. R. Esser, and S. R. Habbal, Modeling high flow speeds in the inner corona, in Proceedings of the *Solar Wind Eight Conference*, eds. Winterhalter, D., Gosling, J., Habbal, S. R., Kurth, W. and Neugebauer, M., **AIP 382**, 133, New York, 1996.

15. S. R. Habbal, N. S. Brickhouse, and R. Esser, Exploring the temperature structure of coronal

holes with a novel combination of visible Fe lines in Proceedings of the *Solar Wind Eight Conference*, eds. Winterhalter, D., Gosling, J., Habbal, S. R., Kurth, W. and Neugebauer, M., **AIP 382**, 177, New York, 1996.

16. S. R. Habbal, R. Esser, M. Guhathakurta, and R. Fisher, Flow properties of the solar wind obtained from white light data, Ulysses observations and a two-fluid solar wind model, in Proceedings of the *Solar Wind Eight Conference*, eds. Winterhalter, D., Gosling, J., Habbal, S. R., Kurth, W. and Neugebauer, M., **AIP 382**, 129, New York, 1996.

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18. R. Esser, and S. R. Habbal, W. A. Coles, and J. V. Hollweg, Hot Protons in the Inner Corona and Their Effect on the Flow Properties of the Solar Wind, *J. Geophys. Res*, **102**, 7063, 1997.

19. J. V. Hollweg and R. Esser, The Solar Corona and Solar Wind: Theoretical Issues, Review paper in Proceedings of the Workshop *Scientific Basis for Robotic Exploration Close to the Sun*, ed. S. R. Habbal, **AIP 385**, 169, 1997.

20. R. Esser and N. Brickhouse, Interdependence of Solar Wind Modeling and Solar Wind Observations, in Proceedings of the Workshop *Scientific Basis for Robotic Exploration Close to the Sun*, ed. S. R. Habbal, **AIP 385**, 219, 1997.

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23. R. Esser, R. J. Edgar, and N. S. Brickhouse, High Minor Ion Outflow Speeds in the Inner Corona and Observed Ion Charge States in Interplanetary Space, Proceedings of the 5th SOHO Workshop, Oslo, Norway, in press, 1997.

24. R. Esser, R. J. Edgar, and N. S. Brickhouse, High Minor Ion Outflow Speeds in the Inner Corona and Observed Ion Charge States in Interplanetary Space, Proceedings of the 5th SOHO Workshop, Oslo, Norway, 1997.

25. R. Esser, R. J. Edgar, and N. S. Brickhouse, High Minor Ion Outflow Speeds in the Inner Corona and Observed Ion Charge States in Interplanetary Space, *Astrophys. J.*, accepted 1997.

26. Y. Yamauchi, T. Tokumaru, M. Kojima, P. K. Manoharan, and R. Esser, Study of Density Fluctuations in the Solar Wind Acceleration Region, *J. Geophys. Res.*, accepted, 1997.

3. Invited Talks at Meetings:

Models and Observations of Coronal Expansions, *7th IAGA General Assembly*, Buenos Aires, Argentina, August, 1993.

Is it Possible to Solve Current Solar Wind Problems with Observations from SOHO? *II SOHO Workshop*, Elba, Italy, September, 1993.

Coronal Holes and the Solar Wind, *Arizona Workshop on "Cosmic Winds and the Heliosphere*, Tucson, Arizona, USA, October, 1993.

Recent Developments in Solar Wind Modeling, *International Colloquium on "Solar and Interplanetary Transients"*, Pune, India, January, 1995.

Interdependence of Solar Wind Modeling and Solar Wind Observations, Workshop on *Scientific Basis for Robotic Exploration Close to the Sun*, Marlboro, 1996.

High Flow Speeds in the Inner Corona: Implications for Solar Wind Modeling, *AGU Spring Meeting*, Baltimore, 1996.

Acceleration of the Multi-Ion Solar Wind, *Workshop on Minor Ions in the Solar Wind*, Warsaw, 25-28 November, 1996.

Solar Wind Models Constraint by SOHO Observations, UVCS Science Meeting, Monselice, Italy, June, 1997.