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INTERPRETATION OF SOLAR WIND ION COMPOSITION MEASUREMENTS FROM ULYSSES

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Final Report

For the period 1 March 1995 through 30 September 1997

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1. Summary

1.1 Scope of the Investigation

The ion compositions measured in situ in the solar wind are important since the ion fractions carry information on the plasma conditions in the inner corona. The conditions in the inner corona define the properties of the solar wind plasma flow. Thus, if the ion fraction measurements can be used to unravel some of the plasma parameters in the inner corona, they will provide a valuable contribution to solving the heating and acceleration problem of the solar wind.

The ion charge states in the solar wind carry information on electron temperature, electron density and ion flow speed. They are also sensitive to the shape of the electron distribution function. Through carefully modeling the solar wind and calculating the ion fractions predicted for different solar wind conditions, constraints on the electron temperature and ion flow speeds can be placed if the electron density is measured using polarization brightness measurements.

1.2 Progress Made

Over the past few years we have re-evaluated the atomic physics inherent in the interpretation of ion charge states, and we have estimated the possible effects of non-Maxwellian distribution functions. The results of these investigations were used to carry out a parameter study on the effect of high ion outflow speeds on the charge state distribution.

Flow speeds recently derived from chromospheric/transition region and coronal observations indicate that the solar wind acceleration process takes place at heights in the solar atmosphere much lower than previously imagined. Doppler dimming observations of the O VI 1032/1037 Å spectral lines show that this is not only true for the background electron-proton solar wind but also for minor ions. The limits that these observations place on the flow speed of the O^{+5} ions are at least a factor of 3 to 4 higher than the highest flow speeds expected from earlier minor ion studies It is likely that other ions reach similar speeds in the inner corona.

The interpretation of in situ charge state observations was re-examined in light of these new velocity measurements. Large flow speeds imply that some species are not close to equilibrium in the inner corona at any distance. Given a large deviation from equilibrium the use of charge state ratios to determine equilibrium temperatures is no longer appropriate.

Using the newest available atomic data together with the most recent observational constraints on electron temperatures, electron densities and flow speeds, we found models with high minor ion outflow speeds of the order of the O^{+5} outflow speed (about 130 to 230 km s^{-1} below 3 R_S) that are consistent with charge state observations.

The solar wind models that where used to match the observed charge states of O, C, Fe, and Si are shown in Figure 1 (dashed and solid lines) together with all the observational constraints presently available in the inner corona. These constraints are derived from very different observational techniques such as IPS, spectral line measurements and polarization brightness measurements.

We were able to show that if the ion flow speeds in the inner corona are larger than previously expected, also the electron temperature at which these charge states are produced has to be higher. The traditional models used in charge state interpretation underestimate the electron temperature (Figure 2). The electron temperatures derived from the studies are shown in Figure 1c. Figure 3 shows the calculated ion fractions together with the observed values from ULYSSES.

The model study also showed that the interpretation of charge states should be complemented by measurements of minor ion spectral lines in the inner corona if possible since this is the only way one can constrain the ion flow speed. We therefore designed an observational study of minor ions ion the inner corona using the UVCS instrument on SOHO supplemented by other SOHO instruments such as LASCO, SUMER and CDS. We are currently analyzing the data, and a paper on the UVCS observations is currently been written. This study shows that the minor ions in the inner corona are not necessarily heated in the same way. We find that O^{+5} is heated much more than Mg^{+9}. The discrepancy between the two ions is much larger than expected from any theory. This also implies that the two ion species will not be accelerated in the same way. This result agrees with the results from a parameter study comparing O and Mg ion charge states which showed that it is easy to fit the observed O charge states assuming high coronal flow speeds, but the same is not true for the Mg ions. The Mg ions that we studied showed a tendency to better fit the lower flow speeds.

Figure 1. Summary of observationally constraint plasma parameters in the inner corona. a) flow speeds are constraint by in situ ULYSSES measurements (upper dashed and solid lines), flow speeds derived from ULYSSES measurements and the assumption of constant particle flux (solid dots), Ly-α Doppler dimming observations (solid triangles and squares), O^{+5} Doppler dimming (open triangels) and He 10830 Å line asymmetry (stars). c) Electron densities are constraint by polarization brightness measurements (dots) and spectral line intensity measurements (stars). c) Electron temperatures are constraint by intensity ratio measurements of different spectral lines. The dashed and solid lines are the values calculated from the models.

Figure 2. Figures a and be demonstrates that an increase in the O flow speed has to be matched by an increase in the electron temperature if the ion ratio of O^{+7} to O^{+5} is constant. c) shows the condition very close to the coronal base where an equilibrium situation is approached.

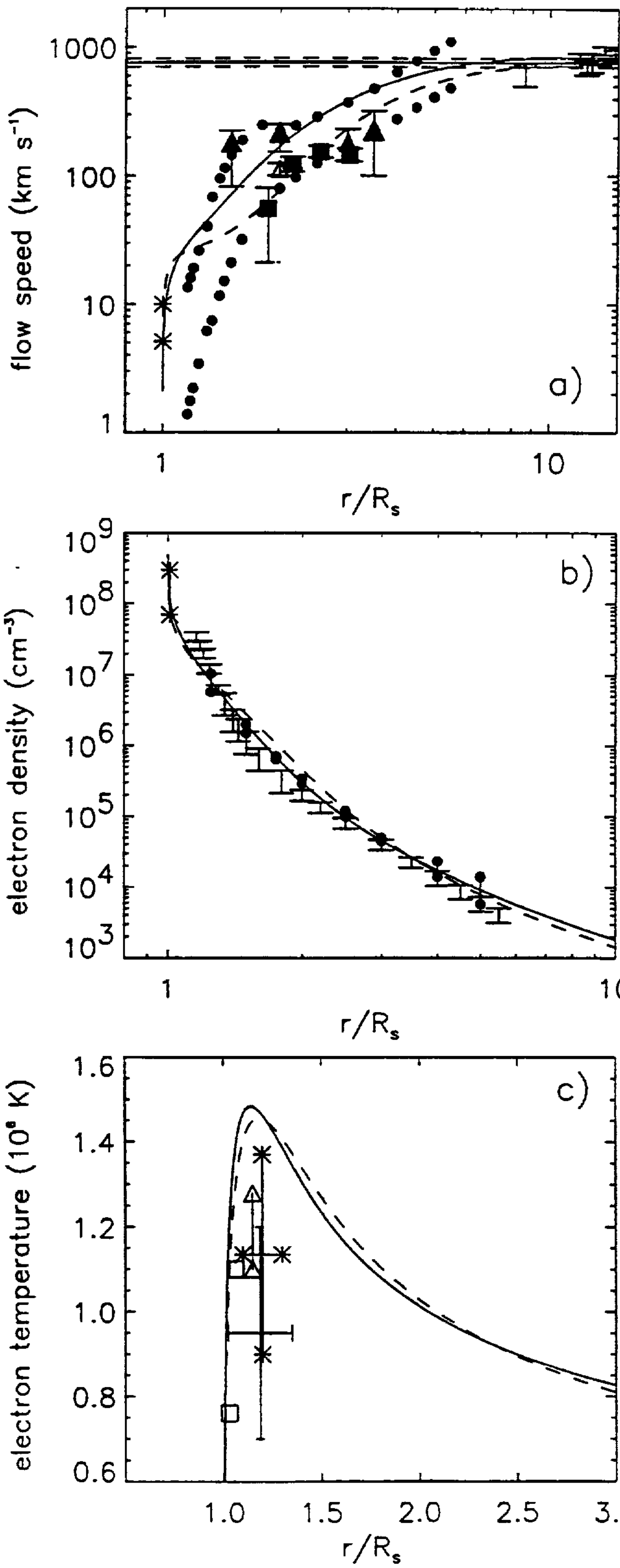

Figure 1

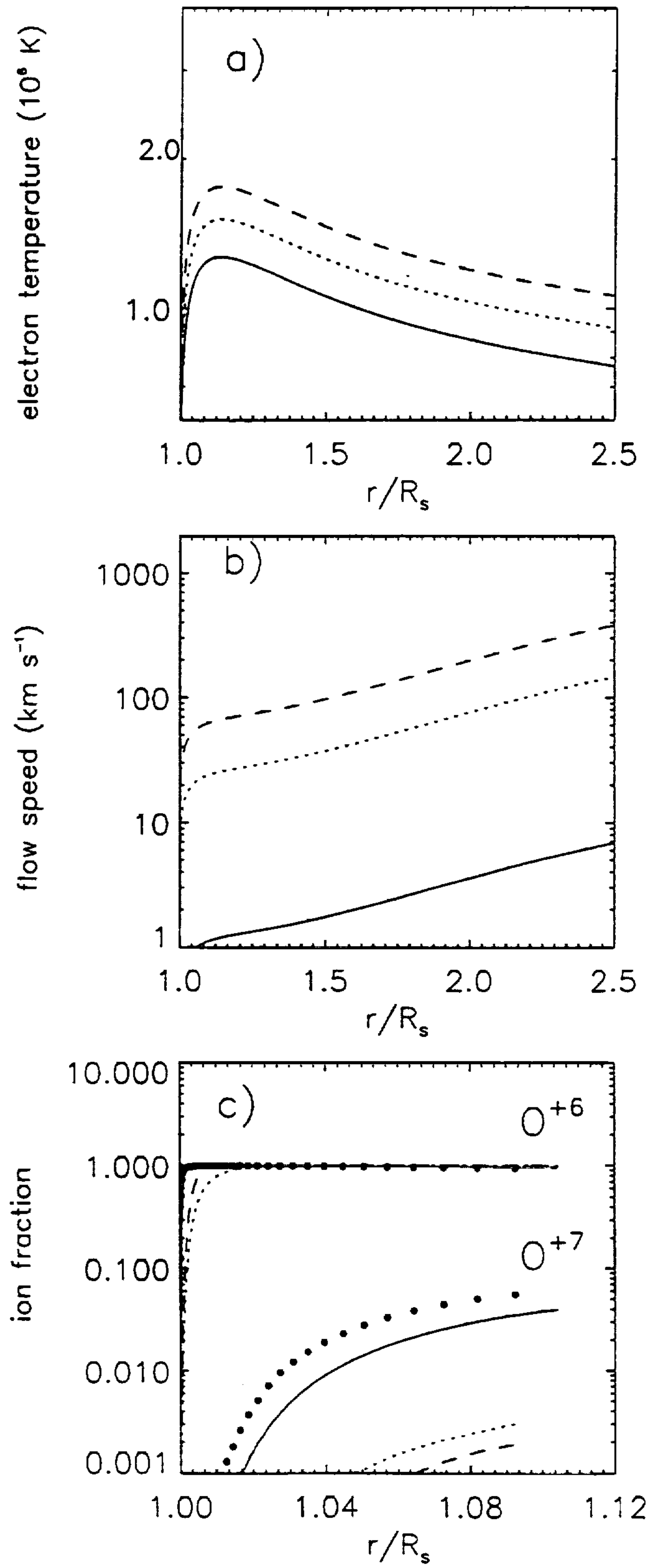

Figure 2

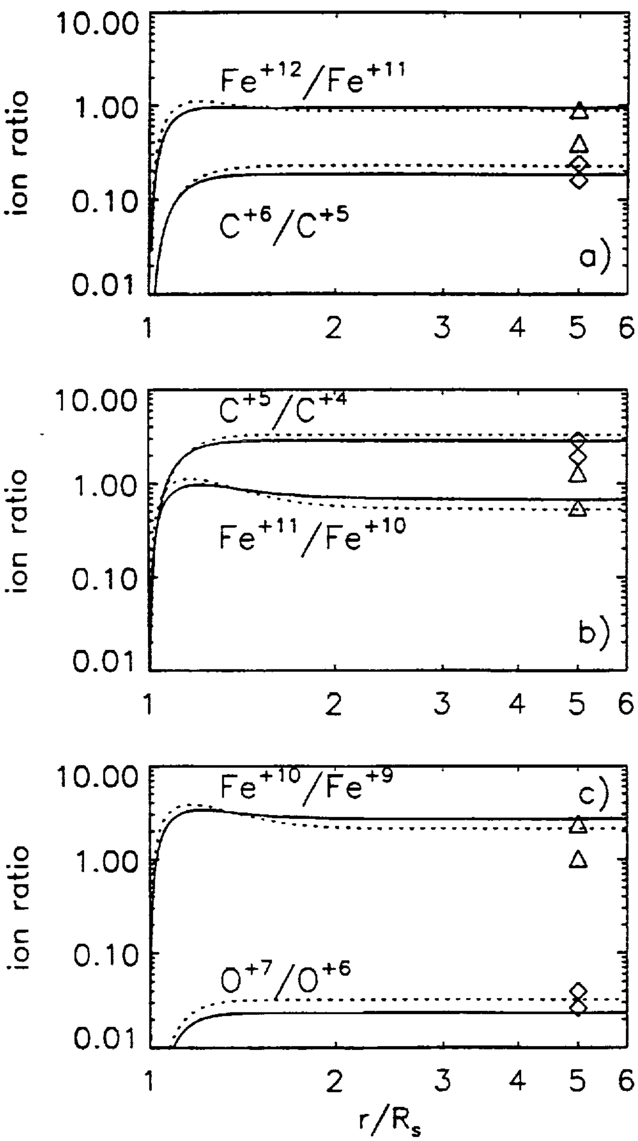

Figure 3

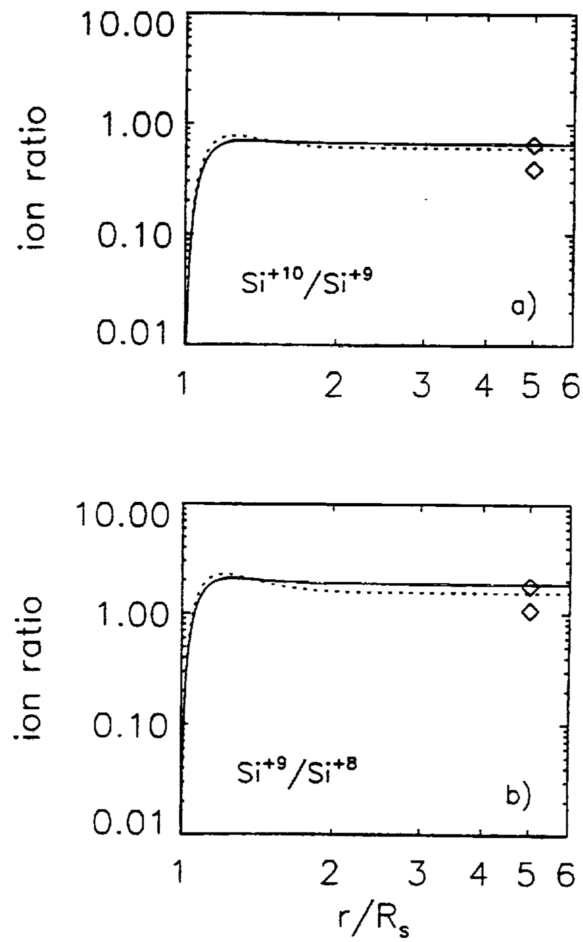

Figure 4

Figures 3 and 4. Ion fractions calculated with the models in Figure 1 and the ratios observed in situ by ULYSSES.

2. Publications in Journals and Proceedings Funded or Partially Funded by Grant NAGW-4379

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.

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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.

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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.

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

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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.

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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.

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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.

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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.

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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.*, in press 1997.

26. X. Li, R. Esser, and S. R. Habbal, Influence of heavy ions on the high-speed solar wind, *J. Geophys. Res.*, **102**, 17,419, 1997.

27. R. Esser, S. Fineschi, D. Dobrezycka, S. R. Habbal, J. Raymond, J. Kohl, and M. Guhathakurta, Plasma properties in coronal holes derived from measurements of coronal minor ion lines and polarization brightness, to be submitted to *Astrophys. J. Let*, 1998.

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.