Space Weather of the Heliosphere: Processes and Forecasts
Proceedings IAU Symposium No. 335, 2017
C. Foullon & O.E. Malandraki, eds.

doi:10.1017/S1743921317007268

Testing Models of the Fast Solar Wind using Spectroscopic and In Situ Observations

Andrzej Fludra[1] **and Enrico Landi**[2]
[1]RAL Space, STFC Rutherford Appleton Laboratory, Didcot, UK
email: `andrzej.fludra@stfc.ac.uk`
[2]University of Michigan, Ann Arbor, USA
email: `elandi@umich.edu`

Abstract. We present a new technique to study joint observations of EUV spectral line intensities and in situ charge states of the fast solar wind. We solve the time-dependent equation for ionization and recombination for a chosen element and calculate the charge state evolution along the open magnetic fields for elements such as C, O, Ne, Mg, Si and Fe. Comparing predicted spectral lines intensities above the limb and in situ charge states to observations from SOHO/SUMER and Ulysses/SWICS, we test how well the modelled thermodynamic parameters of the solar wind reproduce observations. We outline the application of this method to Solar Orbiter data.

Keywords. Sun: solar wind, Sun: UV radiation, methods: numerical

1. Introduction

Understanding the sources and acceleration mechanisms of the solar wind remains one of the major unsolved problems in solar physics. Further progress can be achieved by making joint observations with high-resolution EUV spectrometers and in situ heavy ion sensors that provide measurements of several ionization stages of heavy ions observed near the solar surface and in the heliosphere. The combination of these two different observables provides means of testing solar wind model predictions. In this paper we present a method of combining spectroscopic and in situ data sets, summarize results obtained from the application of this method to SOHO/SUMER and Ulysses/SWICS data and three solar wind models, and outline its application to future observations from the Solar Orbiter SPICE and SWA/HIS instruments.

2. Method

The method, developed by Landi *et al.* (2012a), consists of 5 steps:

Step 1: Obtain joint observations of high resolution EUV spectral line intensities measured in the low corona and in situ solar wind charge state distribution of the same solar wind plasma parcels.

Step 2: Establish the magnetic connectivity between the solar surface and the location of the in situ sensor. The magnetic field lines are tracked from the spacecraft to the Suns surface using 3D MHD global models (e.g. AWSoM, van der Holst *et al.* 2014) to determine the exact location of the source region of the wind plasma measured in-situ.

Step 3: Select the solar wind models to be tested and extract from them the solar wind parameters along the open magnetic field line: electron temperature, electron density, and the solar wind velocity.

Step 4: Solve ionization balance equations and calculate evolution of charge states. We use the Michigan Ionization Code (MIC - Landi *et al.* 2012b):

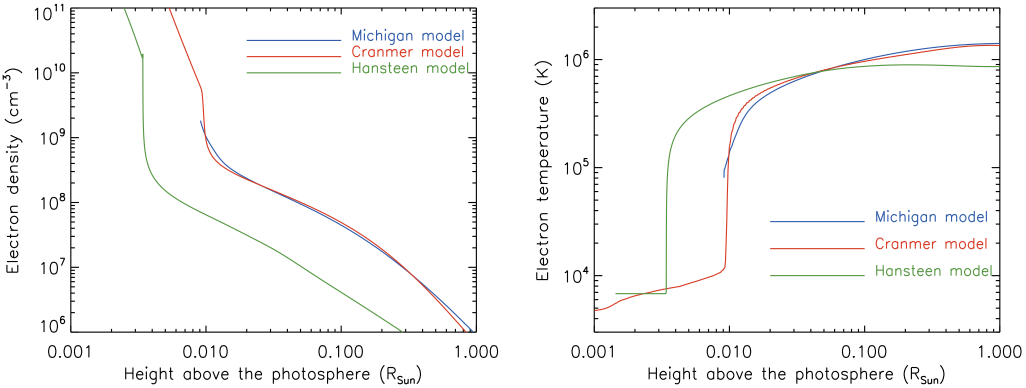

Figure 1. Electron density (left) and temperature (right) from the three models.

$$\frac{\partial y_m}{\partial t} = n_e(y_{m-1}C_{m-1}(T_e) + y_{m+1}R_{m+1}(T_e) - y_m(C_m(T_e) + R_m(T_e))) \qquad (2.1)$$

where y_i is the fractional abundance of ionization stage i, and $C_i(T)$ and $R_i(T)$ are ionization and recombination rates from stage i, taken from CHIANTI.

Step 5: Calculate the local spectral line intensities using non-equilibrium MIC ion fractions and electron density and temperatures from the solar wind models; then integrate intensities along the line of sight. Results are compared with observations.

This procedure can also be used to build empirical models of the solar wind. In this case, all 5 steps of the procedure are repeated, except that in step 3, rather than using a theoretical model, we adopt user-selected wind parameters as a function of position along the magnetic field line. The comparison with observations provides information on what needs to be changed in the solar wind parameters: these are modified, and fed again into the procedure at step 4 until satisfactory agreement with observations is obtained.

3. Application to SOHO and Ulysses data

Landi *et al.* (2014) applied this procedure to compare predictions from three models of the fast solar wind to high resolution spectra recorded by SOHO/SUMER at the north polar limb and Ulysses/SWICS fast wind charge states. They considered the following models: (a) Hansteen and Leer (1995) - 1D, single temperature, ad-hoc heating function; (b) Cranmer *et al.* 2007 (coronal hole) - 1D, single temperature, wave-based plasma heating and wind acceleration; and (c) the AWSoM model (van der Holst *et al.* 2014) - 3D, 2-temperature, Alfven-wave plasma heating and wind acceleration. Predicted electron temperature and density are shown in Figure 1.

Results of steps 3, 4 and 5 in Figure 2 show that none of the models can fully reproduce observations. The Cranmer and Michigan models provide the best fit, with similar levels of disagreement. Possible sources of discrepancies include: (a) solar wind source region located in the corona rather than in the chromosphere, (b) presence of photoionization, (c) presence of supra-thermal electrons, (d) geometrical effects in the line-of-sight integration.

4. Application to Solar Orbiter

An unprecedented opportunity to extend this study to new data will become available after the launch of the Solar Orbiter mission (Müller *et al.* 2013). The spacecraft will travel close to the Sun (0.28 R$_s$ at perihelion), climb out of the ecliptic up to 32 degrees, and carry out remote observations of the Sun and in situ measurements of fields and

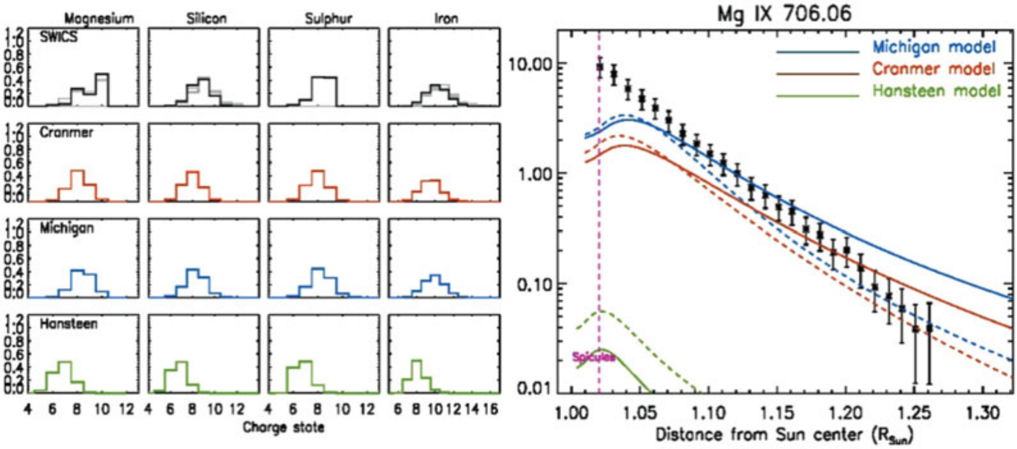

Figure 2. (a) Left: measured (SWICS, upper panel) and predicted charge state distributions. (b) Right: Full lines are intensities (phot cm^{-2} s^{-1} $arcsec^{-2}$) predicted using non-equilibrium ion fractions from MIC. Dashed lines: intensities predicted assuming ionization equilibrium. Error bars are observations from SUMER.

particles. The two instruments important for the extension of this study are the SPICE spectrometer (Fludra *et al.* 2013) and SWA/HIS ion sensor.

SPICE will measure 2D high resolution spectra and spectral images in the 70.4 - 79.0 nm and 97.3 - 104.9 nm ranges, which include emission lines from ions of H, C, O, N, Ne, S, Mg, Si and Fe, formed at temperatures from 10,000 K to 10 MK. SPICE will obtain the first ever out-of-ecliptic spectral observations of polar regions.

The SWA Heavy Ion Sensor (HIS) will measure the properties of ions heavier than He in the solar wind and interplanetary CMEs. The HIS instrument is a top-hat mass spectrometer capable of measuring energy, energy per charge, time-of-flight, azimuth angle, and elevation angle. The ions measured by HIS are He^{1-2+}, C^{2-6+}, N^{2-7+}, O^{2-8+}, Ne^{6-9+}, Mg^{6-12+}, Si^{6-12+}, S^{6-14+}, Fe^{3-24+}.

Several elements and ions will be observed jointly by both instruments. Therefore, when SPICE and SWA/HIS are used together, SPICE intensities will test the solar wind model predictions in the transition region and low corona, while HIS will test predictions of charge states in situ as described in Section 2 and 3. In addition, SPICE and HIS can measure the low-FIP/high-FIP abundance ratios (e.g., Si/C, Fe/O, S/N, Mg/Ne). Comparing SPICE abundance ratio maps with in situ SWA/HIS abundances may help confirm the magnetic connectivity of the solar wind observed at the location of the spacecraft to the wind sources on the Sun.

References

Cranmer, S. R., van Ballegooijen, A. A. & Edgar, R. J. 2007, *ApJS*, 171, 520
Fludra, A., *et al.* 2013, Proceedings of the SPIE Optical Engineering conference: Solar Physics and Space Weather Instrumentation V, Vol. 8862, 88620F
Hansteen, V. H. & Leer, E. 1995, *JGR*, 100, 21577
Landi, E., *et al.* 2012a, *ApJ*, 750, 159
Landi, E., *et al.* 2012b, *ApJ*, 744, 100
Landi, E., *et al.* 2014, *ApJ*, 790, 111
Müller, D., *et al.* 2013, *Sol. Phys.*, 285, 25
van der Holst, B., Sokolov, I. V., Meng, X., *et al.* 2014, *ApJ*, 782, 81