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THE RESONANCE LINES OF MG II AS DIAGNOSTICS OF THE UPPER SOLAR CHROMOSPHERE

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Final Report

For the period 1 November 1991 through 30 April 1993

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The Resonance Lines of Mg II as Diagnostics of the upper solar Chromosphere

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1 Introduction

The resonance lines of singly ionized magnesium, the Mg II h&k lines at about 280 nm, are two of the small number of lines in the solar spectrum that are optically thick in the chromospheric part of the solar atmosphere. Potentially these lines contain information on the initial temperature rise that occurs at the top of the photosphere. Unfortunately, few good observations of the lines exist due to their wavelength near 280 nm the ultraviolet. However, a fair number of observations (on the order of 200) are available from the data base of the UltraViolet Polarimeter and Spectrometer (UVSP) instrument that flew on board of NASA's Solar Maximum Mission (SMM) satellite.

In addition, this data base contains a number of spectra that include the Mg I resonance line at λ285.2nm, just longward of the h&k lines. The neutral magnesium line is not as strong as its ionic counterparts and samples slightly lower parts of the atmosphere. Its width is a sensitive diagnostic of the ionization balance between neutral and singly ionized magnesium, which determines the opacity scale (and formation height) of other diagnostically important Mg I lines like the 457.1 nm intercombination line, the magnesium *b* lines and the infrared Mg I emission lines near 12μm. Analysis of the observed line profiles shows that it is necessary to include the effects of partial frequency redistribution (PRD) in the formation of the line as in the case of the h&k lines. This implies that the core of the line is very sensitive to the way scattering is treated in the modeling of the line, and in turn this allows us to separate the uncertain effects in the atomic data (viz. the Van der Waals broadening) from the uncertainties in the underlying atmospheric model.

The main objective of this research was to compare observed spectra of the magnesium resonance lines against theoretical line profiles calculated from recent models of the solar atmosphere by Fontenla *et al.* (1993), hereafter called FAL. These models extend earlier solar models by Avrett et al. (Vernazza *et al.* 1981, Maltby *et al.* 1986) and provide yet a better match between observed and calculated spectra, in particular of the hydrogen Lyman α line, by including the effects of ambipolar diffusion of hydrogen and helium in the mass and energy transport equations for the chromosphere–corona transition region. Although the transition region models can be built self-consistently (without additional observational input) once the proper boundary conditions are given at the top of the chromosphere, there are uncertainties in the models precisely because these boundary conditions are not well-known. With the analysis of UVSP magnesium observations we strive to constrain these uncertainties.

2 Observations and calibration

We have extracted most of the observations that were done with UVSP in the light of the magnesium lines at 279.6, 280.3 and 285.2 nm. They could in principle be observed with three entrance–exit slit combinations: slits 10, 12 and 20. In practice only the latter two combinations were used. Combination 20 with a long ($1\times180'$) entrance slit and a narrow exit slit (0.002 nm) was mostly used for spectral atlas scans. Slit combination 12, with a small entrance (3×3′) and a wider exit slit (0.006 nm) was used for high spatial resolution spectra of specific solar features. In addition, it was employed to make so called rastergrams where the solar surface was scanned pixel by pixel at one specific wavelength. We are especially interested in spectral scans with slit combination 12 that were directly preceded or followed by a rastergram, since these in principle allow us to determine from what kind of solar features such as a network elements, a plage area or a dark supergranulation cell interior the particular spectrum has been obtained. We did not include in our analysis spectra that were taken from sunspot umbrae or penumbrae. Neither did we include observations that were obtained during a flare or other high energy event (as judged from the SMM event list). In this way 19 atlas scans and about 150 high spatial resolution spectra and rastergrams of the Mg II h&k lines were found. We only found three atlas scans that covered the Mg I resonance line at 285.2 nm, two at disk center and one at the limb.

The photo detector counts provided by the data base of UVSP experiments need to be calibrated onto absolute intensity and wavelength scales to make a direct comparison between spectrograms and calculated line profiles possible. We calibrated the intensity by fitting a spectrogram obtained with a long slit (1×180′) onto a well–calibrated rocket spectrum from the Harvard experiment (Kohl *et al.* 1978) which was obtained with a similar field of view (7×130′). Comparing spectra with such a large field of view has the advantage that the calibration is mostly independent of the exact instrument pointing as long as the slit does not cover an active region.

Both slit combinations 12 and 20 in the UVSP telescope and spectrograph used the same light path, without additional refracting or reflecting elements, and the same detector (No. 5) so that a calibration for the long (1×180′) slit (20) could also be used for the slit with the smaller entrance (12). The number of photons $\Phi(\lambda_0;\mathrm{S})$ at wavelength λ_0 counted with slit S is related to the measured intensity $\bar{I}_{\lambda_0}$ within the aperture $\Delta\Omega$ of the entrance slit, and the width of the exit slit $\Delta\lambda$ as follows:

$$\Phi(\lambda_0;\mathrm{S}) = At\eta(\lambda_0;\mathrm{S}) \int_{\Delta\Omega_\mathrm{S}} \int_{\Delta\lambda_0} \frac{\lambda}{hc} I_\lambda \,\mathrm{d}\lambda \mathrm{d}\Omega \approx \frac{At\eta\lambda_0}{hc} \Delta\Omega_\mathrm{S} \Delta\lambda_0 \bar{I}_{\lambda_0},$$

where A is the telescope area (66.4 cm^2), t the gate time, η the efficiency of the spectrometer–detector combination. For small enough aperture and wavelength interval we find:

$$\bar{I}_{\lambda_0} \approx C(\lambda_0;\mathrm{S})\Phi(\lambda_0;\mathrm{S})/t,$$

with $C(\lambda_0;\mathrm{S}) = hc/(\lambda_0 A\eta\Delta\Omega_\mathrm{S}\Delta\lambda_0)$. For slit 20 and $\lambda_0 = 280$ nm we find $C(280;20) = 375$ erg cm^{-2} ster^{-1} nm^{-1}. Using the different aperture and exit slit width of slit 12 we find $C(280;12) = 2.5\,10^3$ erg cm^{-2} ster^{-1} nm^{-1}. A problem with the intensity calibration that we did not address is the deterioration of the optical surfaces in the telescope and spectrometer with time. However, we mainly used spectra from the second period of operation of the SMM satellite (after November 1984 when its pointing system was replaced by Shuttle astronauts). Of the observations we show in this report only experiment # 11148 is from the first period. We find the best match between profiles from the different periods when we assume that the instrument transparency degraded by a factor of 2.5 from the first to the second period at the wavelength of the h&k lines. In the second period the deterioration rate had slowed down considerably so that we can safely assume that all other spectra can be calibrated with the factor that is derived above.

We did not attempt to make an absolute calibration of the wavelength scale. Relative wavelengths were obtained from the experiment headers that specified wavelength drive positions. these could be converted, apart from Doppler shifts due to orbital velocity and skips in the drive mechanism, with the dispersion coefficients provided in the UVSP user's manual. The observed spectrograms were then shifted in wavelength so that the centers of the lines best fitted those of the calculated profiles.

3 Theoretical modeling

Both the Mg I λ285.21 nm line and the Mg II h&k lines are so opaque that their cores form at densities where natural line broadening dominates over collisional deexcitation. Thus, effects of partial frequency redistribution (PRD) are important. This was already well-known for the Mg II resonance lines (eg. Milkey and Mihalas 1974), but was still controversial for the Mg I line (Canfield and Cram 1977, Heasley and Allen 1980). Our calculations show that the latter line indeed displays emission reversals in standard plane–parallel solar models when treated with PRD while no such emission arises in CRD. The observed UVSP spectra (see Fig. 3) show only a suggestion of such emission.

To compute line profiles from the FAL models including the effects partial redistribution we used Uitenbroek's (1989) version of the versatile radiative transfer code MULTI developed by Carlsson (1986). We used an atomic model for magnesium with 11 levels in the neutral stage, 7 levels in the singly ionized states plus the doubly ionized continuum. The model included 15 Mg I lines and 7 Mg II lines. Radiative bound-free transitions were explicitly solved for in the neutral stage, but were treated with fixed radiation temperatures in the ionized stage.

The outer wings of the Mg II h&k lines overlap in the solar spectrum. MULTI does not take account of this overlapping. However, the line separation is large enough so that the opacity of one line does not influence the radiative rates in the other line significantly (these rates are determined by the line integrated radiation field but are strongly weighted by the line absorption profile centered on the core). The proper line shape is computed afterwards by solving the radiative transfer equation with the combined line opacities and source functions determined from the population numbers found without accounting for the line overlap.

4 Results

We now turn to a brief discussion of the comparison between computed profiles and observed spectra from the UVSP experiment data base. We plan to present a more detailed discussion with conclusions in two forthcoming papers; one on the PRD effects in the Mg I λ285.21 nm line, and one on the Mg II resonance lines. Figure 1 shows the theoretical h&k profiles from FAL model C compared with three UVSP experiments 11148, 25343, and 22481. All three observations were obtained with the small aperture slit 12. Model C was constructed to reproduce the average quiet Sun spectrum. The theoretical spectrum from this model shows good agreement with observations in the top two panels, but does not match with measured intensities in the bottom panel. The rastergram preceding this latter spectrum was taken in the inner wing of the h line and shows little detail unfortunately. However, from the height of the emission peaks it can be inferred that the slit was at least partly overlying a network element, while that is not evidently the case in experiments 11148 and 25343. Notice that the width of the central emission reversals increases with the height of the emission. In all three cases the k_3 self absorption minimum is deeper in the theoretical profiles than in the observed ones. This is a general trend that still eludes a satisfying explanation. The wing intensities agree well indicating that the photospheric temperature gradient in the FAL model is realistic, and that it is not very different from the quiet Sun in the network.

Figure 2 compares the computed spectrum of the Mg II h&k lines from FAL model F (upper panel) and the XCO model discussed below (lower panel) with observed spectra from UVSP experiments 22481 and 22887 respectively. Model F is representative of the magnetic network. The width of the emission reversals now fits the observed profile better than in the bottom panel of Fig. 1. However, the wings of the theoretical profile clearly lie above the observed spectrum, indicating that the photospheric temperature is overestimated in model F. Model XCO has been constructed by Avrett and Loeser to fit a large number of first overtone rotation–vibration lines of the CO molecule observed with the ATLAS instrument (Farmer and Norton 1989). The model has a very cool temperature minimum of 3850 K that occurs at lower densities than in the standard FAL models. Clearly, the intensities in the wings of the h&k lines, which form at similar heights in the atmosphere as the stronger CO line cores are very well reproduced by this model. Model XCO does have a chromospheric temperature rise, but it occurs at too low densities to give sufficient emission in the core of the resonance lines. Together the results from models F and XCO suggest that a two-component model with a cool component similar to model XCO and a hot component similar to model F may be very succesful in explaining the Mg II h&k line profiles and their variation over the surface in quiet areas.

Finally, in Fig. 3 we show two theoretical line profiles of the Mg I λ285.21 nm line from FAL models A (upper panel) and C (lower panel) compared with the spectrum from experiment 21579 which was taken with the large aperture ($1 \times 180''$) slit 20. Neutral magnesium is a minority ionization stage in the solar atmosphere; most magnesium is in the singly ionized stage. This makes the population of Mg I levels very sensitive to the ionization equilibrium between the neutral and singly ionized stages. Ionization takes place mainly from the singlet and triplet P levels with edges at 375.5 and 251.1 nm respectively). The radiation field in these wavelength regions is difficult to model due presence of a large number of atomic lines (mostly of iron) there. This makes the wings of the Mg I resonance line a less reliable indicator of photospheric temperature than its h&k line counterparts. However, in combination with these latter it can be employed as a diagnostic of the Mg I/Mg II equilibrium, since the Mg II resonance lines can be used to fix the photospheric temperature. Other choices of some of the uncertain atomic parameters can bring the calculated line profiles in Fig. 3 into better agreement with the observations.

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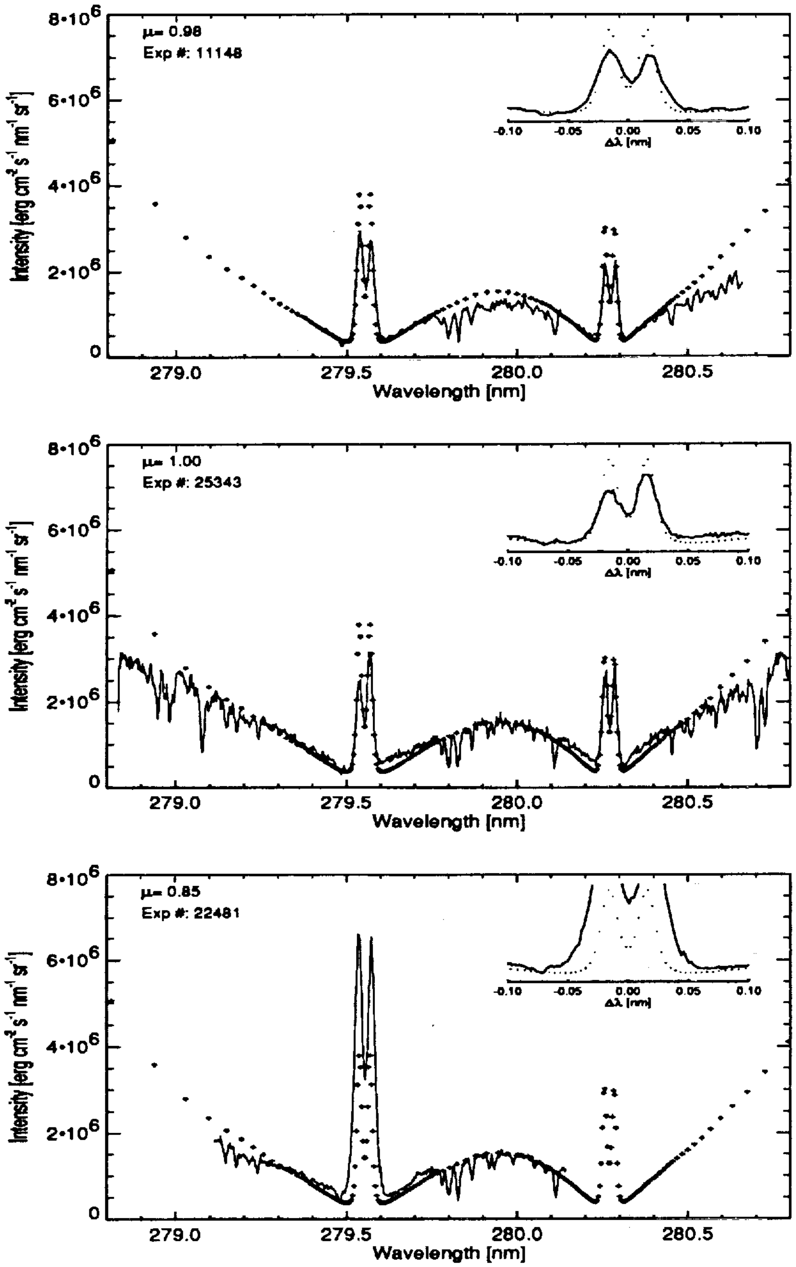

Figure 1: Comparison of the theoretical line profile of the Mg II h&k lines (plus signs) from FAL model C with observed spectra (solid lines) from SMM/UVSP experiments 11148 (upper Panel), 25343 (middle Panel) and 22481 (lower Panel). Each panel separately displays the inner two Ångstrom in the core of the k line where the theoretical profiles are represented by dotted curves. The value of μ denotes the cosine of the viewing angle.

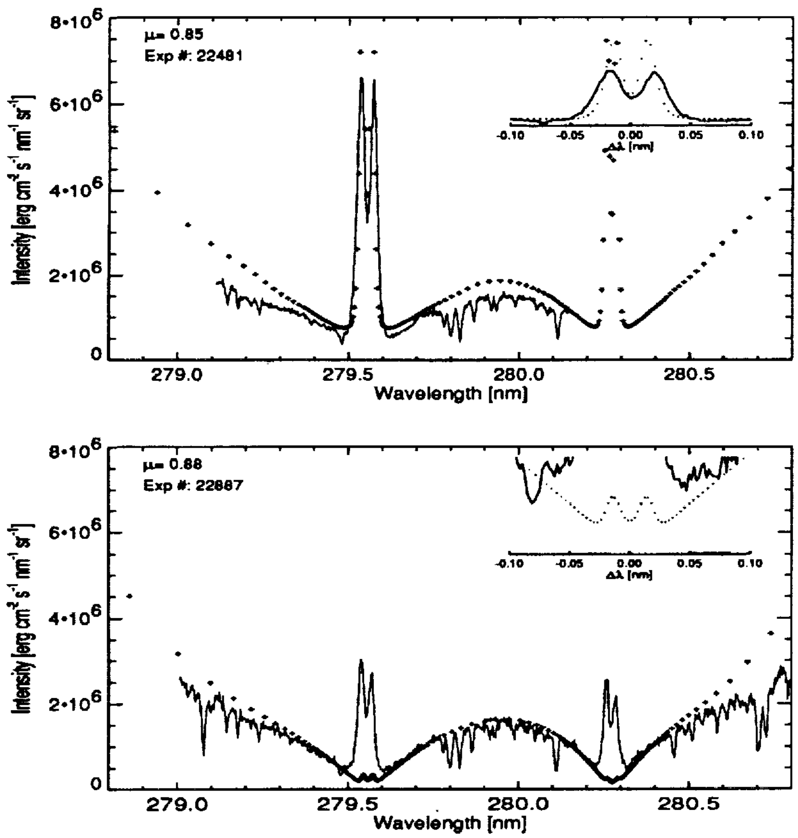

Figure 2: Comparison of the theoretical line profile of the Mg II h&k lines (plus signs) from FAL model F (upper panel) and model XCO with observed spectra (solid lines) from SMM/UVSP experiments 22481 (upper Panel), 22887 (lower Panel). Each panel separately displays the inner two Ångstrom in the core of the k line where the theoretical profiles are represented by dotted curves.

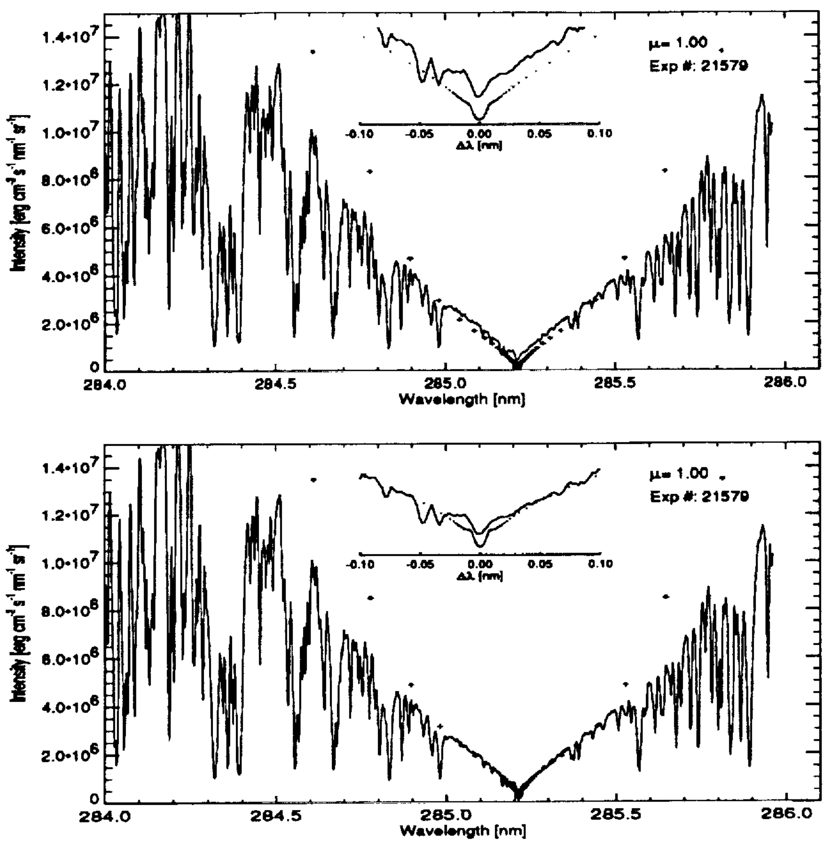

Figure 3: Comparison of the theoretical line profile of the Mg I λ 285.21 nm line from FAL models A (plus signs, upper panel) and C (lower panel) with the observed spectrum from UVSP experiment 21579 (solid line). Each panel separately displays the inner two Ångstrom in the core of the line where the theoretical profiles are represented by dotted curves.

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