FORMATION OF THE INFRARED EMISSION LINES OF Mg I IN THE SOLAR ATMOSPHERE

E. S. Chang, E. H. Avrett, P. J. Mauas, R. W. Noyes, and R. Loeser

ABSTRACT

The Mg I emission lines at 7 and 12 μm provide a sensitive measure of the magnetic and electric field strengths in the layers of the solar atmosphere where the observed emission originates. Hence it is important to know how and where these lines are formed. Their strong limb brightening suggests a chromospheric origin; however, theoretical studies by Lemke and Holweger and by Hoang-Binh, and observations by Deming et al., suggest an origin at or below the temperature minimum, with the emission being produced by the underpopulation of lower atomic levels relative to the upper ones. Such underpopulations are caused by radiative depopulation of lower levels, together with collisional coupling of higher levels with the Mg I continuum.

We investigate these effects with a 41 level atomic model, including collisions with hydrogen atoms as well as with electrons, and including the charge exchange process Mg$^+$ + H(n) → Mg(n) + H$^+$ between magnesium and hydrogen. Using an average quiet Sun atmospheric model, we calculate emission-line profiles that resemble the observed ones, that is, broad absorption troughs with narrow central emission, and significant limb brightening. The charge exchange rates are significant, but the effects of high-n coupling between Mg and Mg$^+$ (due to collisions with electrons and with hydrogen atoms) together with radiative losses between low-n transitions are of greater importance.

We confirm that the emission cores are formed no higher than the temperature minimum region, and that the emission is caused by off-LTE effects rather than by the chromospheric temperature rise. This photoionospheric origin explains why the brightness temperature of the trough, or minimum intensity in the line wings, is unrelated to the temperature minimum between the photosphere and chromosphere.

The model calculations indicate that the line core is sensitive to magnetic fields located almost 400 km above those measured in ordinary magnetograms; the gas pressure decreases 20-fold between these two heights. The electron density decreases by a factor of 8 between the heights at which the trough and emission core originate, consistent with observed Stark shifts.

The behavior of the emission lines as seen during a total solar eclipse should provide a strong test of these model calculations and inferred formation mechanisms.

Subject headings: line formation — Sun: atmosphere — Sun: eclipses — Sun: magnetic fields

1. INTRODUCTION

Emission lines in the infrared solar spectrum were first reported by Muralray et al. (1981). The 7 μm line, observed during a balloon flight, and the 12 μm lines, observed from the ground, were thought to be likely though not necessarily solar in origin. The solar origin of the 12 μm lines was confirmed by Brault & Noyes (1983) who used the McMath telescope to carry out observations with improved angular and spectral resolution. With an instrumental width of 5 mK (1 mK = 10$^{-3}$ cm$^{-1}$), the FWHM of the strongest two lines were found to be 17 mK at disk center, and thus too narrow to be formed in the corona. Moreover, the emission lines showed pronounced limb brightening, suggesting a chromospheric origin. At disk center, each emission line was observed to sit in a broad trough with FWHM of about 165 mK. The troughs had a depth relative to the continuum of about 3%, and one trough was seen to be displaced relative to the central emission core. These features were confirmed by the ATMOS satellite data of Farmer & Norton (1989; see Kurucz 1991) which included similar information on the 7 μm line. Other observations of these emissions have been described by Deming et al. (1988, 1991).

The 7 and the 12 μm lines were identified from theory as the 5g–6h, 6g–7h, and 6h–7i transitions of neutral magnesium (Chang & Noyes 1983). The identifications of the 12 μm lines were confirmed by laboratory diode laser absorption spectroscopy (Lemoine, Demynk, & Destombes 1988). Additional midinfrared lines of Mg I have also been noted in the solar spectrum (Chang & Noyes 1983; Chang 1987; Glenar et al. 1988; Jefferies 1991) and confirmed in laboratory spectra (Lemoine et al. 1990). The higher precision laboratory line positions were found to agree very well with the emission components of the 12 μm lines. Thus, Chang & Schoenfeld (1991) were led to conclude that the emission components were formed in a region of negligible Stark shift while the absorption troughs were measurably Stark-shifted. Based on the electron densities implied by the shifts, the absorption troughs were found to be formed in the lower to middle photosphere. However, the emission cores had to be formed at least as high as the upper photosphere, if not the chromosphere.

The exact mechanism and height of formation may be determined from a detailed non–LTE radiative transfer calculation using a model atmosphere. An earlier attempt by Lemke & Holweger (1987, hereafter LH) used an atomic model without sufficiently high energy levels, which led to an inconclusive interpretation. Focusing on the 6g–7h line, they neglected all
levels higher than the ones with $n = 7$. Several radiative transitions had been deleted (e.g., $4f$–$6g$, $5g$–$7h$), while the rates for others (the $3p^3{}^3P$–$nd{}^1D$ series) were too large by orders of magnitude. Their calculated departure coefficients $b_s$ for the $6g$ and the $7h$ levels were virtually identical, resulting in an absorption profile without any hint of emission. With just radiative and van der Waals damping, the computed absorption profile was narrower and almost 5 times deeper than the absorption part of the observed profile. Only by using ad hoc values of $b_s$ and $b_\gamma$ were they able to generate a peak-on- trough line profile similar to the observed one. A preliminary report by Carlsson, Rutten, & Shechukina (1990) confirmed these results based on model calculations with a larger number of Rydberg levels.

Some of the LH deficiencies were removed by Hoang-Binh (1991, hereafter HB). He argued that the levels of interest were hydrogen-like and performed a non–LTE calculation for a hydrogen atom with $n$ ranging from 3 to 30. However, his computation was based on an isothermal, constant-density atmosphere, so it is difficult to assess the effect of temperature and density variations. Nevertheless, both LH and HB concluded that the $12$ $\mu$m lines were caused by non–LTE effects in the upper photosphere, and not by the chromospheric rise as suggested by Brault & Noyes (1983) and Zirin & Popp (1989).

Deming et al. (1988) found that time series observations of the $12$ $\mu$m lines imply an origin at or below the temperature minimum region rather than in the chromosphere.

We have attempted to combine the best features of the LH and HB atomic models, using a quiet Sun atmospheric model. In addition, we include the quasi-resonance charge exchange process between Rydberg states of Mg $^+\,$ and H $^+$ described by Chang (1987). We present results for the $7$ and $12$ $\mu$m lines, and compare our computed profiles with the available ground-based and satellite data.

2. MODELING AND ATOMIC DATA

The atmospheric model in our calculations is the average quiet Sun model given by Maltby et al. (1986, Appendix A). We use the Pandora computer program described by Vernazza, Avrett, & Loeser (1981). For the Mg atom, we combine the low-$l$ ($l \leq 2$) levels considered by LH with the hydrogen-like high-$l$ ($l \geq 3$) levels used by HB. Thus for $n = 7$, the levels consist of $1S$, $3S$, $3P$, $3D$, $1D$, $3D$, and a high-$l$ level which encompasses $7f$, $7g$, $7h$, and $7i$. For $n \geq 8$, each level is taken to be hydrogenic as in HB. The result is a 41 level model atom which is both realistic and complete in its essentials up to the $n = 15$ level. (The last level has an ionization wavelength of $20$ $\mu$m, substantially longer than that of any lines of interest.) Photoinitiation cross sections are adopted from Hosfaess (1979; 1990 private communication) for low-$l$ levels, while hydrogen cross sections (Storey & Hummer 1991) are used for the remaining levels. Some 200 Einstein $A$-coefficients taken from a recent calculation (Mocchia & Spizzo 1988) are included.

For the first nine energy levels we use the rates and cross sections compiled by Mauas, Avrett, & Loeser (1988). Electron impact ionization rates are calculated from the formula of House (1964). For the collisional excitation of allowed transitions, we use the van Regemorter (1962) formula. For forbidden transitions the cross sections measured by Aleksakhim et al. (1973) are typically one order of magnitude smaller than those for allowed transitions. Therefore, we simulate these results by using the van Regemorter formula for these forbidden transitions with the oscillator strengths chosen to be $0.1$. In the cases of transitions between two hydrogenic levels, we calculate the cross sections according to Gee et al. (1976).

Collisions with neutral hydrogen are treated according to Kaulakys (1985) for both ionization and excitation. His formulation assumes that the magnesium atom is in a hydrogen-like Rydberg level. Thus we have applied his formulas only to the high-$l$ or high-$n$ hydrogenic levels. For most of these transitions, collisions with hydrogen typically increase the total rate by 10% over the electron collision rates. However for certain $l$-changing transitions (with $\Delta n = 0$), collisions with hydrogen may increase the total rate by an order of magnitude as noted by HB.

It has been suggested by Chang (1987) that charge exchange with hydrogen, that is,

$$\text{Mg}^+ + \text{H}(n) \leftrightarrow \text{Mg}(nl) + \text{H}^+$$

may be responsible for the emission mechanism. Indeed, rate coefficients as large as $10^{-7}$ cm$^3$ s$^{-1}$ have been calculated (Chang 1991) for the emission-line levels. We find that this process introduces substantial changes in the departure coefficients in the chromosphere but has a much smaller effect in the upper photosphere where the fractional densities of H$(n)$ are very low.

We treat the emission levels of the $7$ and $12$ $\mu$m lines as sublevels of a hydrogen-like manifold. Each emission line is then separated out according to its statistical weight $g$, Einstein $A$-coefficient, and frequency in the same way as C 1 multiplet lines were treated by Mauas et al. (1989). Radiative and van der Waals damping are treated in the usual way. We also include Stark broadening by electrons (Chang & Schoenfeld 1991) which was found to be proportional to $n^2$. Since van der Waals damping varies as $n^4$, Stark broadening is the dominant broadening mechanism for the high-$n$ emission-line levels. For the $12$ $\mu$m lines, Stark broadening is 3 times larger than van der Waals broadening.

3. RESULTS AND DISCUSSION

Our calculated departure coefficients $b_s$ for our hydrogenic levels $n = 4$–$8$ are shown in Figure 1. Our curve for $n = 6$ resembles LH’s ad hoc model 1 with a value of approximately 0.91 at $\tau_{5000} = 10^{-3.4}$. This value is substantially closer to unity than the value of 0.7 in LH’s standard calculation or the HB value of 0.83. Figure 1 shows that very large collision and recombinations rates keep $b_s$ for $n \geq 8$ close to unity almost out to the temperature minimum ($\tau_{5000} \approx 2 \times 10^{-4}$). Starting with $n = 7$ and lower, systematic departures of a few percent occur in the upper photospheric region, causing a small underpopulation of the lower level relative to the upper level. This translates into a rapidly rising source function $S$ in a region where the Planck function $B$ is very flat. For small values of $(hv/kT)$, the ratio $S/B$ for the $n$ to $n - 1$ transition is given by

$$S = \frac{hv}{kT} \left[ b_{s-1} \left( 1 + \frac{hv}{kT} \right)^{-1} - 1 \right]^{-1}.$$  

(2)

Figure 1 also shows the variation of $B$ and $S$ for the $n = 7$–$6$ lines at 12 $\mu$m. For 12 $\mu$m and $T = 4500$ K, $hv/kT = 0.27$. Thus, when $b_s/b_n = 1.03$ and 1.06, we get $S/B = 1.16$ and 1.36, so that a small overpopulation of the upper level gives a much larger increase of $S$ relative to $B$. From this figure it can be seen that at $\tau_{5000} = 10^{-3.4}$, $b_b/b_n = 1.03$, so that the corresponding line source function $= 1.16B$. The rapidly rising non–LTE source function in these upper photospheric layers is
FORMATION OF Mg i INFRARED EMISSION LINES

The curves C(1.0) and C(0.2) in Figure 1 show the relative contributions per unit log $\tau_{5000}$ to the peak intensities at $\mu = 1.0$ and 0.2 plotted on a linear vertical scale (in arbitrary units). The arrows indicate the intensity values of the $\mu = 1.0$ continuum, trough, and peak, and the $\mu = 0.2$ continuum and peak, at the heights where the source function equals these values. Clearly the peaks are formed in the upper photosphere rather than in the chromosphere. While the calculated peak intensities are smaller than observed (see below), the calculated and observed peak intensity ratios $I(0.2)/I(1.0)$ are in good agreement, both being about 1.2. The calculated ratio 

$$[I(0.2) - I_c(0.2)]/[I(1.0) - I_c(1.0)],$$

where $I_c$ is the continuum intensity, is roughly 5, as expected in the optically thin limit. This is similar to the observed ratio inferred by Brault & Noyes (1983).

The troughs in the $\mu = 1$ profile are formed at around $\tau_{5000} = 2 \times 10^{-2}$ (This is the depth where $I = S$; the contribution function extends over the region where $S$ has a minimum.) At this optical depth, the electron density in the model atmosphere is $2.7 \times 10^{12}$ cm$^{-3}$. This value is in good agreement with the electron densities inferred by Chang & Schoenfeld (1991) from the Stark shifts, namely $2.4 \times 10^{12}$ cm$^{-3}$ for the 811 cm$^{-1}$ and $1.4 \times 10^{12}$ cm$^{-3}$ for the 818 cm$^{-1}$ lines. We obtain similar results for the 7 $\mu$m line.

Our computed profiles at disk center for the 7I-6h, 7h-6g, and 6h-5g lines at 811, 818, and 1356 cm$^{-1}$, respectively, are displayed in Figure 2 (panels a, c, and e, respectively). Also shown, as dashed lines, are the ATOMS satellite disk-center spectra (Kurucz 1991) and, as solid lines, the $\mu = 1$ profiles of Brault & Noyes (1983). The peak-on-trough shapes are in good agreement, but the computed emission peaks are not as strong as observed. Figures 2b, 2d, and 2f show the computed profiles at $\mu = 0.2$ compared with the 12 $\mu$m profiles observed from the ground by Brault & Noyes. (The 7.34 $\mu$m profile at $\mu = 0.2$ has not been observed.) The agreement is better at the limb, but the computed central emission is still insufficient. Unlike the 12 $\mu$m lines at the limb, our computed 7 $\mu$m line in Figure 2f shows that the emission line sits on a broad absorption trough of depth 2% below the continuum. This predicted feature could be tested in a future satellite observation of the solar limb at 7 $\mu$m. From Figure 2 there is little doubt that the computed line profiles provide a good representation of the observed data. Further adjustments of the uncertain cross section data may increase the computed peak heights to be closer to the observed values.

The peak heights also depend on the photoionization rates for the lowest levels of Mg i, since decreasing the low-level values of $b_n$ causes $b_6/b_7$, for example, to decrease. The photoionization rate depends on the run of $J_\nu$ throughout the visible and ultraviolet, which in turn is affected by the complex spectrum of line opacity throughout this region. We have found that when only continuum opacities are used, the calculated 7 and 12 $\mu$m Mg i emission tends to exceed the observed emission.

Because the line source function increases sharply with height in the upper photosphere, and because there is considerable line opacity well above unit optical depth in the local continuum, we expect the line emission to extend above the continuum limb (see Deming et al. 1991). This is illustrated in Figure 3, which shows the computed distribution of line center emission with height above the limb, in comparison with a similar profile for the continuum. Eclipse observations at 12 $\mu$m should show a relative displacement of the line and continuum limbs by about 300 km, and in addition should provide evidence for the sharp peak in line center intensity just above...
Fig. 3.—Height profiles of emission near and above the extreme limb, in the 12.32 µm line center and adjacent continuum, and at 5000 Å. Height scale is relative to radial optical depth unity at 5000 Å.

the continuum limb. On the other hand, if the emission core were formed in the chromosphere, with a line source function at most equal to the local Planck function, then the emission would have to rise at least 1500 km above \( \tau_{5000} = 1 \), the height in our model where the Planck function first exceeds the line intensity at \( \mu = 0.2 \) as observed by Brault & Noyes (1983). This height in our model is about 1000 km above the 12 µm continuum limb. The height difference of at least 700 km between the limb inferred from a photospheric or chromospheric formation of this line should be easily distinguishable in eclipse data.

4. CONCLUSIONS

We have conducted a non–LTE radiative transfer investigation of the emission lines at 7 and 12 µm using a realistic atomic model for neutral magnesium. The computed \( b_6 \) and \( b_7 \) departure coefficients are much closer to unity than those computed by LH who did not include levels higher than \( n = 7 \), and by HB who used a hydrogen atom with \( n \geq 3 \) and an isothermal, constant density atmosphere. Nevertheless these small departures from LTE are sufficient to form emission lines in the upper photosphere for the 6–5 and 7–6 lines. This is because small departures are strongly amplified by the stimulated-emission term in the line source function (see eq. [2]). Our computed widths for both the emission and the absorption components agree well with observations, without any ad hoc enhancement of line broadening parameters. We attribute the low values of our computed line emission to uncertainties in the electron and hydrogen collision data, and in the photoionization rates for the lowest levels of Mg i.

Two predictions arising from this work remain to be tested. The 7 µm line at \( \mu = 0.2 \), when or if observed (from space), should sit in a trough with a depth of 2%, unlike the 12 µm lines which show no troughs at \( \mu = 0.2 \). Eclipse observations of the 12 µm lines should show the line center limb to be located about 300 km above the continuum limb, with a sharp peak in line-center intensity just above the continuum limb, as illustrated in Figure 3.

This work was supported by NASA grant NSG-7054 and by a grant from the National Science Foundation to the Institute for Theoretical Atomic and Molecular Physics at Harvard University and the Smithsonian Astrophysical Observatory. We thank Robert L. Kurucz for providing the ATMOS profiles shown in Figure 2.

REFERENCES

Aleksakhim, J. S., Zapesoschnyi, I. P., Garga, I. I., & Starodub, V. P. 1973, Optics Spectrosc., 34, 1053
Carlsson, M., Rutten, R. J., & Shchukina, N. G. 1990, Publ. Debrecen Obs., 7, 260
Chang, E. S. 1987, Phys. Scripta, 35, 792
—, 1991, in preparation
Hofaess, D. 1979, Atomic Data Nucl. Data., 24, 285