RESONANCE LINE TRANSFER WITH PARTIAL REDISTRIBUTION. III.
Mg II RESONANCE LINES IN SOLAR-TYPE STARS

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ABSTRACT
We discuss the gravity dependence of the Mg ii resonance lines calculated including effects of partial redistribution in frequency. Using chromospheric models scaled from a solar model, we demonstrate the increased decoupling of the radiation temperature of the kλ feature from the minimum electron temperature in lower-gravity models. The limb darkening of the λ-line in the main-sequence model is also discussed.

Subject headings: chromospheres, stellar — line formation — radiative transfer

I. INTRODUCTION
This paper is the third in a series describing the effects of partial frequency redistribution on the profiles of strong resonance lines which appear in stellar spectra and which may be used as indicators of chromospheric structure. In Paper I (Milkey and Mihalas 1973a) we described the fundamental theory for computational treatment of these problems and applied the technique to the problem of the solar λλ line (Milkey and Mihalas 1973b). In Paper II (Milkey and Mihalas 1974) we extended the treatment to the solar Mg ii resonance lines at 2800 Å (h and k). In this paper we use a formalism identical to that developed in Paper II to discuss the effects of partial frequency redistribution on solutions for the h and k lines in stars of the same spectral type as the Sun but differing surface gravity. On the basis of the results reported in Paper II, we would expect that the lower-gravity stars would show more pronounced differences between the partial (PRD) and complete redistribution (CRD) solutions—a result, in part, of the decrease in redistribution by the van der Waals interaction. In making these comparisons we will be primarily interested in the changes which take place outside of the line core, i.e., outside the h2 or k2 emission peaks. The core of the line is too sensitive to the details of the microturbulence model to give a clear-cut indication of the size of the redistribution effects in the absence of some independent means of determining the non-thermal broadening appropriate for each model.

II. COMPUTATIONS
a) Model Atom
The atomic model chosen to represent the Mg ii atom is identical to that described in Paper II and

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consists of the 3s 2S ground state, the two 3p 2P excited states, and the Mg iii ionization continuum. The Mg i-Mg ii ionization equilibrium is treated in LTE, but is of little consequence because of the low abundance of Mg i at solar temperature. The total Mg abundance is chosen as solar, the collision rates are those used in Paper II, and the photoionization rates are computed in a manner identical to that used in Paper II. The important van der Waals broadening width is adopted at 10 times the value given by a statistical hydrogenic treatment of the Mg ii ion (see Paper II). The radiative transfer–statistical equilibrium solutions were accomplished in a manner identical to those reported in Paper II except for the minor difference that we used a much faster algorithm to generate the scaling relation between the Rij and g as computed in a manner identical to that reported in Paper II except for the minor difference that we used a much faster algorithm to generate Rij, based partly on the original Adams, Hummer, and Rybicki (1971) code, and a trapezoidal frequency quadrature scheme instead of the spline quadrature used for previous calculations.

b) Model Stellar Atmospheres
For these illustrative calculations we consider a simple grid of stellar models having similar T(τ5000) relations but different gravities. The effect of changing the gravity for a given [T(τ5000), g0] model is to multiplicatively shift the mass column density scale (g cm⁻²) by an amount (g/g0)⁻¹/², where g is the new surface gravity. This particular scaling relation arises from the essentially quadratic pressure dependence of H⁻ opacity and is clearly demonstrated in the Carbon and Gingerich (1969) grid of models. The T(τ5000) relation for our grid of models is based on the semiempirical upper solar photosphere of Mount and Linsky (1974) and a schematic chromospheric temperature rise. This chromospheric temperature rise is linear in log (mass) with a slope similar to that in the Linsky and Avrett (1970) or Gingerich et al. (1971) models. Above 10,000 K we assume that the temperature rises so rapidly that Mg ii is ionized to Mg iii or higher.

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states in a distance much less than one optical depth so that the material above 10,000 K does not participate in the line formation process. We adopt a temperature minimum of 4200 K at $T_{\text{min}} = 10^{-4}$ and a depth-independent microturbulent velocity of 4 km s$^{-1}$. Once the temperature distribution has been established, the densities are found by a hydrostatic equilibrium solution allowing for departures from LTE in the hydrogen ionization equilibrium.

Although these models are based on a set of ad hoc scaling rules, it is interesting to note that they do give a good representation of the Ca I wing broadening discussed by Lutz, Furenlid, and Lutz (1973) and probably represent a reasonable first guess at the outer atmospheric structure of the solar-type stars. At least, these scaled models are adequate for achieving our goal of describing the differential effects between the partial and complete redistribution solutions for stars of differing gravity.

III. RESULTS AND CONCLUSIONS

a) Gravity Dependence

The results of profile calculations for the k-line in scaled solar-type models with log $g = 2.0$ and log $g = 4.44$ are shown in figure 1; in each case both the complete redistribution (CRD) and partial redistribution (PRD) profiles are shown. It should be noted that while the CRD calculations for stars with the same $T_{\text{min}}$ yield values of $F_\lambda$ at $k_1$ that are essentially identical, the calculations including PRD effects indicate considerable darkening of $k_1$ with decreasing gravity. This may be understood as a combination of the greater thickness of the line in the lower-gravity models and the decrease of the collisional redistribution coupling the wing source function to the saturated core source function. It is also significant that for both gravities the $k_1$ minimum lies closer to the line center for the PRD solution than for the CRD solution, this effect being somewhat greater for the log $g = 2$ model than for the main-sequence model. Furthermore, the complete redistribution solution predicts $k_2$ about equally bright for both gravities, while the partial redistribution solution for the log $g = 2$ model predicts $k_2$ about 50 percent brighter than for the log $g = 4.44$ model. In both the PRD and CRD solutions the line for the lower-gravity model is broader than for the main-sequence model. We have not discussed in detail the cores of the lines because of their sensitivity to microturbulence. Although we have not explicitly discussed the behavior of the h-line, it behaves virtually identically to the k-line, and the relative behavior of the h- and k-lines is similar to that described in Paper II.

The significant departures of the PRD solution from the CRD solution can be understood physically in terms of the frequency dependent source functions discussed in Paper II, and the well-known phenomenon that, because the line opacity is linearly dependent on the density, while the dominant source of continuum opacity, H$^-$, is quadratically dependent on the density, in models of lower density the line is thicker compared to the continuum. In the giant model the increased line-center optical depth of the upper photosphere causes the $k_1$ feature to appear farther from line center than in the main-sequence model; consequently the line scattering is more nearly coherent (see Paper II). Furthermore, the lower collision rates increase the monochromatic thermalization lengths in the inner wings. These two effects combine to produce the decrease in $k_1$ intensity with decreasing gravity.

b) Limb Darkening in the Solar-Type Model

Figure 2 illustrates the center-to-limb variation of the k-line wing in the solar-type model (the $\mu$-values shown are the quadrature points for the calculation of the flux profile). The important feature of this calculation is that $k_1$ not only shifts to greater $\Delta \lambda$ but also

![Fig. 1.—Flux profiles (in ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$) for the wing of k-line for complete redistribution, CRD (log $g$), and partial redistribution, PRD (log $g$). $\Delta \lambda$ is the distance from line center.](image-url)
darkens toward the limb. This behavior is in qualitative agreement with Lemaire and Blamont's (1967) center-to-limb observation and is virtually impossible to reproduce with a frequency-independent source function in a homogeneous atmosphere. CRD calculations do show the \( k_1 \) shift toward the limb, but the \( k_1 \) intensity is generally constant. The limb darkening of the \( k_1 \) feature results from the fact that the frequency-dependent line source function is nearly decoupled from the chromospheric temperature rise at the frequency of \( k_1 \) and decreases monotonically outward from the photosphere as a coherent scattering source function would. The better studied H and K lines of Ca ii show a similar behavior toward the limb (Zirker 1967), and considerable effort has been devoted to explaining these observations (Linsky and Avrett 1970). Although the Ca ii problem is complicated by the metastable 3D levels, it seems likely that a PRD treatment of the Ca ii system would show some of the behavior of our Mg ii calculations. Inhomogeneities also undoubtedly play a role in determining the center-to-limb behavior of both the Ca ii and Mg ii (e.g., Beebe 1971), but partial redistribution effects are probably more important.

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**REFERENCES**


