HIGH RESOLUTION ABSOLUTE FLUX PROFILES OF THE MG II h & k LINES IN EVOLVED F8 TO M5 STARS

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"One in Five Stars is Remarkable" -- O. Struve

INTRODUCTION

We present the central results of a survey of the Mg II resonance line emission in a sample of over 50 evolved late-type stars, including spectral-luminosity types F8-M5 and Ia-IV. Observed and surface fluxes have been derived and correlations noted. The major findings include: a) Mg II k emission core asymmetry transition near K1 III, analogous to that known for Ca II K; b) a small gravity and temperature dependence of the Mg II chromospheric radiative loss rate. These results and others are fully discussed in a report in press in the Astrophysical Journal Supplement Series [Stencel et al. (1)], encompassing IUE second year programs CCBDM, CMBRS and LFBSW.

MESSAGES IN THE MG II PROFILES

We posit that asymmetry in the doubly-reversed emission core of collisionally-dominated resonance lines (e.g. Mg II k, Ca II K) can be used to infer chromospheric velocity fields, once the interstellar component is accounted for. We recognize the uniqueness problems of inhomogeneous atmospheres with arbitrary relative motions. However, the thrust of the observed asymmetry transitions and Occam's Razor provide us with some degree of confidence in the interpretation we choose.

A SHORT HISTORY LESSON

A fascinating observational connection between chromospheric velocity fields, mass loss and the existence of stellar coronae has developed over the past few years. The extensive high dispersion work on cool stars by Olin

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Wilson has been re-surveyed by Reimers (2) and Stencel (3) who discussed evidence for mass loss in Ca II K_4 features and the occurrence of Ca II "wing emission" features, respectively, in the Hertzsprung-Russell Diagram (HRD). Both found evidence for mass loss above a locus in the HRD running between mid-K giants and early-G supergiants. Stencel (4) also pointed out that the Ca II K core emission asymmetry was K_2R^* dominated above a similar locus. Contemporaneously, Mullan (5) described his seminal STL (supersonic transition locus) theory which predicts a significant increase in mass loss rate for stars above a locus similar to that just described observationally. In addition to velocity information, temperature information has been added by Linsky and Haisch (6) and Vaiana et al. (7) who looked for high excitation (100,000 K) UV lines, and soft X-ray flux, respectively, and found that stars cooler and more luminous than K1 III rarely exhibit evidence for outer atmosphere material much hotter than about 20,000 K. The anti-correlation of coronae and strong mass loss seemed established. The analogy with solar coronal holes and active region loops was irresistible. But the simplicity of the scenario may also prove to be its downfall, as we shall see shortly.

STUDY OF THE MG II EMISSION ASYMMETRY

We undertook a survey of cool stars to establish whether Mg II might exhibit an asymmetry bifurcation in the HRD comparable to that known for Ca II K. Our initial sample of over 40 late-type stars (G and K, luminosity classes II, III and IV) showed that a rough segregation does exist along the lines of that seen for Ca II [Stencel and Mullan (8)]. However, the asymmetry locus was "fuzzy" with several discrepant stars on either side of the dividing line. Initially we considered these discrepancies as due to small number statistics, but careful analysis of the strength of interstellar (IS) Mg II absorption by Böhm-Vitense has clarified the situation. IS Mg II column densities are much larger than Ca II and result in superposition of non-negligible IS absorption features on the intrinsic chromospheric Mg II emission profile, even for stars closer than 100 pc. When we screen our asymmetry data to remove IS effects (accept only $S/L > 1$ for $v_r > 0$, and $S/L < 1$ for $v_r < 0$) the resulting 19 stars show a very clear asymmetry segregation as is seen for Ca II K, but now occurring among slightly warmer stars (K1 III rather than K3 III). See Figure 1a. We compare these transition loci in Figure 1b and note a plausible scenario emerging vis-a-vis the STL theory; as a star evolves from the main sequence, it retains a corona until it reaches the early K giants where it crosses the temperature dividing line (TDL) due to the encroachment of the sonic point of the stellar wind into the upper chromosphere, disrupting the global corona. As stellar evolution to the right in the HRD continues, the stellar wind appears first as outflow in the Mg II core-forming regions, and then in the deeper Ca II core-forming layers. Finally as the mass loss becomes substantial and sustained, circumstellar (CS) features begin to appear in the cores of neutral optical lines.

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*We adopt the conventions that K_2R or R refers to the K line long wavelength peak and K_2V or V refers to the K line short wavelength peak. The corresponding features in the Mg II k line are L and S, respectively.

CORONA - MASS LOSS ANTI-CORRELATION?

Despite the appeal of such scenarios, re-evaluation of theory and new data give us pause. The foundations of the STL theory have been challenged by Holzer (9). A larger sample of IS effect-free Mg II profiles would be desirable. Recent correlation studies between Mg II and C IV 1550 Å flux by Ayres and Marstad (10) -- see paper by Ayres in these proceedings -- reveal a strong functional dependence between fluxes in these two lines. The sense of the correlation is that for a ten-fold decrease in Mg II surface flux for a given T_{eff}, a 30-40 fold decrease occurs in C IV surface flux in normal cool stars. Since, as we will shortly discuss, Mg II surface flux ratioed to bolometric flux decreases with decreasing T_{eff} across the TDL of Figure 1b (cf. Fig. 2), C IV flux would rapidly vary across a similar range in T_{eff}. Given detection sensitivities, C IV *might* appear to be present on one side of the TDL and absent on the other. In addition, hotter material might be confined to magnetic flux tubes in the chromosphere and corona, while the cooler outflowing matter might follow magnetic open regions between loop structures (analogous to coronal holes). The point is that for different T_{eff}, log g combinations, as well as age, rotation, chemical composition, pulsation and whatever, the filling factors for either temperature regime could vary significantly, as is evidenced by the observations. Thus, cool stars showing strong mass loss might also possess small patches of coronal plasma. This surface detail study may prove to be the major use for UV spectra of cool stars. Hartmann et al. (11) argue that Alpha Aqr (G2 Ib) may be a good example of this, as C IV is bright but obvious CS absorption features are seen in Ca II K and Mg II k. The lack of soft X-rays in this case could be due to self-absorption in the CS envelope (10). Additional "hybrid" stars like Alpha Aqr are also found among the K giants, and possibly all along the STL locus (third year *IUE* work in progress). If the Mg II-C IV-soft X-ray correlations are valid, then all stars are "hybrid" in possessing both coronal and mass loss features to varying degrees, and the usefulness of the term "hybrid" becomes very limited.

TALES FROM THE SUPERGIANTS

Late-type supergiants are too often considered in aggregate as cool mass losing stars with few other individualizing characteristics. Our Mg II survey has revealed some differences in kind between stars with T_{eff} differences as small as a few hundred degrees K. Also, we find a 3 to 4 times greater chromospheric radiative loss rate in Mg II emission for cool supergiants than is typical for higher gravity cool giants of similar T_{eff}.

MG II PROFILE DIFFERENCES

At least four distinct profile types are seen among F8-M5 Ib supergiants. F8 supergiants like Gamma Cyg and Alpha UMi show weak doubly-reversed Mg II emission cores. G0-G5 supergiants (Beta Aqr, Alpha Aqr, 9 Peg) exhibit very strong emission with S>>L and substantial CS absorption at -125 km/sec. The G5-K5 supergiants also show strong emission with S>L but with more moderate strength CS absorption shifted generally less than -50 km/sec (Xi Pup, Epsilon Peg, Lambda Vel). Finally, the coolest supergiants we have surveyed

(M2-M5: Alpha Ori and Alpha Her) again show strong Mg II emission with a strong CS or selective absorption (Fe, Mn?) feature superimposed on the k_2 emission component. The Mg II surface flux ratioed to bolometric flux (σT_{eff}^4) appears to peak at spectral type G0 and fall off steeply toward F8, and only gradually toward M5 (Fig. 2).

EVIDENCE FOR ACOUSTIC HEATING?

Following Linsky and Ayres (13), we define the chromospheric radiative loss rate in Mg II h & k, R_{hk}, as the ratio between integrated surface flux of the h & k emission, divided by bolometric flux of the star (see also Ayres, proceedings of this conference). In Figure 2 we present derived R_{hk} values for the sample of cool stars we obtained during second year IUE programs and note that the supergiants tend to lie a factor 3 or 4 above giants and bright giants with comparable T_{eff}. Proponents of acoustic wave heating of stellar chromospheres have computed several orders of magnitude difference in acoustic flux over a similar range of gravity and temperature, in contrast to our observational findings. However, Ulmschneider (private communication) notes that first-order corrections to the acoustic heating theory greatly reduce this predicted gravity dependence, toward the observed amount. This matter deserves further attention. We were able to find the small gravity dependence in R_{hk} because of the uniformity of the data used, in contrast to previous studies by Linsky and Ayres (13) and Basri and Linsky (14), which relied on UV data of varying resolution and signal-to-noise.

THE PROBLEM WITH 56 PEG

Our survey has defined observationally a subgroup of stars falling between Mg II and Ca II asymmetry dividing lines that challenges our supposed understanding of emission line formation and chromospheric velocity fields. 56 Peg-type stars have the unique defining property of discrepant asymmetries between Ca II K ($V/R > 1$) and Mg II k ($S/L < 1$). 56 Peg (K0 Ib-IIp) is the archetype, and Sigma Oph (K3 II), Alpha Boo (K2 III) and Gamma Aql (K3 II) are examples. Stencel and Mullan (8) first called attention to 56 Peg by virtue of the nearly 4 magnitude discrepancy between M_v(Ca K) = −1.6, and M_v(Mg k) = −5.3. SWP spectra of some of these show substantial C IV emission line flux, indicative of a hot outer atmosphere. A more complete report on 56 Peg itself is in preparation [Basri et al. (15)], but we wished to provide a status report at this time.

SEMI-EMPIRICAL MODELING

In terms of the STL theory, 56 Peg-type stars have outer atmospheres in which the supersonic stellar wind penetrates only into the upper chromosphere where Mg II is formed, but not as deep as where Ca II is formed. We have begun to derive semi-empirical models to match the surface flux and asymmetries in various UV lines, using the computation methods of Basri and Linsky (16) for Ca II and Mg II, and of Lites and Cook (17) for C II, III and IV. To date, experiments with meso-scale waves [Basri and Linsky (16)] are promising, but far from adequate. To produce the asymmetries observed, we need to increase the physical segregation in height of formation between the k_3 and K_3 features. One way of accomplishing this spread in the respective optical depth scales is to assume a Mg/Ca abundance ratio much different from solar. Alternately, CS Mg II could be more pronounced than for Ca II due to STL effects in the upper chromosphere.

INTERPRETATIONS

Waves or global pulsations remain a possible mechanism for production of the discrepant asymmetries in this portion of the HRD, since the Pop. II Cepheid-like RV Tau irregular variables frequently are assigned spectral types like early K, class II. For 56 Peg itself, profile variability has not yet been observed in the Ca II K line over several years of monitoring, but additional Mg II k observations are being pursued. Photospheric analysis does not support an unusual Mg/Ca ratio. If the asymmetry loci are as statistically significant as we believe they are, then a non-negligible fraction of the HRD, early to mid K giants and early K bright giants, exhibit an unusual atmospheric structure characterized by fine structure in chromospheric velocity fields, and selective CS absorption. These might be expected to show Ca II K variability and sporadic mass loss as reported by Chiu et al. (18) for Arcturus.

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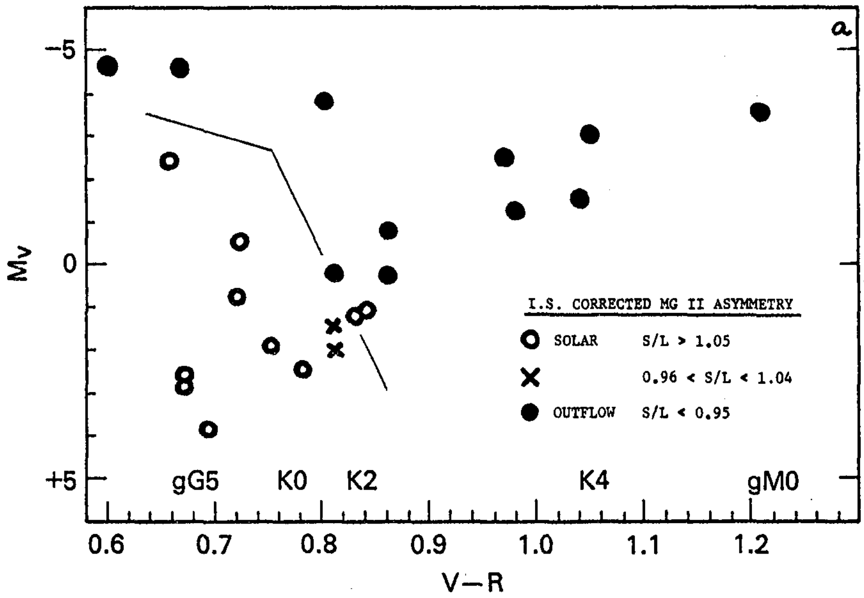

Fig. 1a. Mg II core emission asymmetry, k_2-/k_2+, or S/L, on a color-magnitude diagram for late-type stars. This sample accounts for the effect of overlying interstellar Mg II.

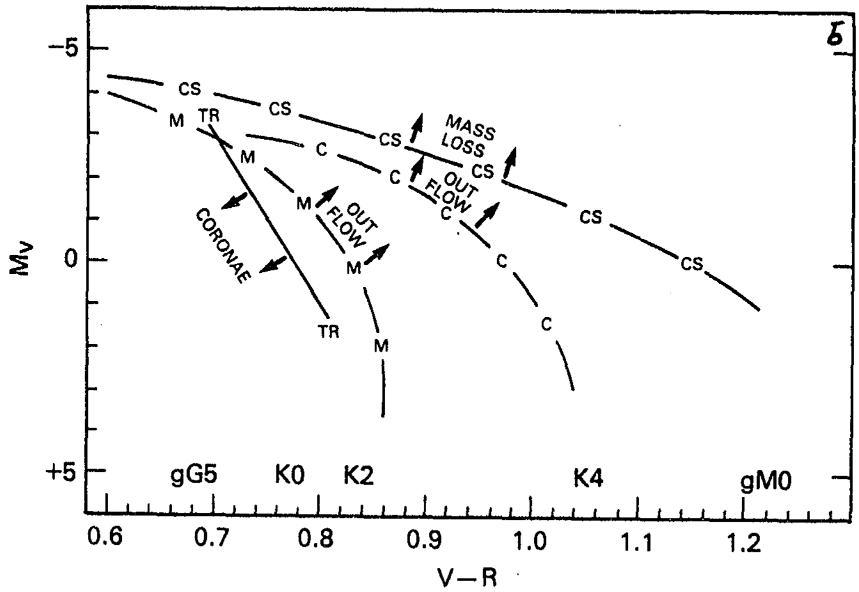

Fig. 1b. Collected transition loci in the HRD. Cf. reference 8.

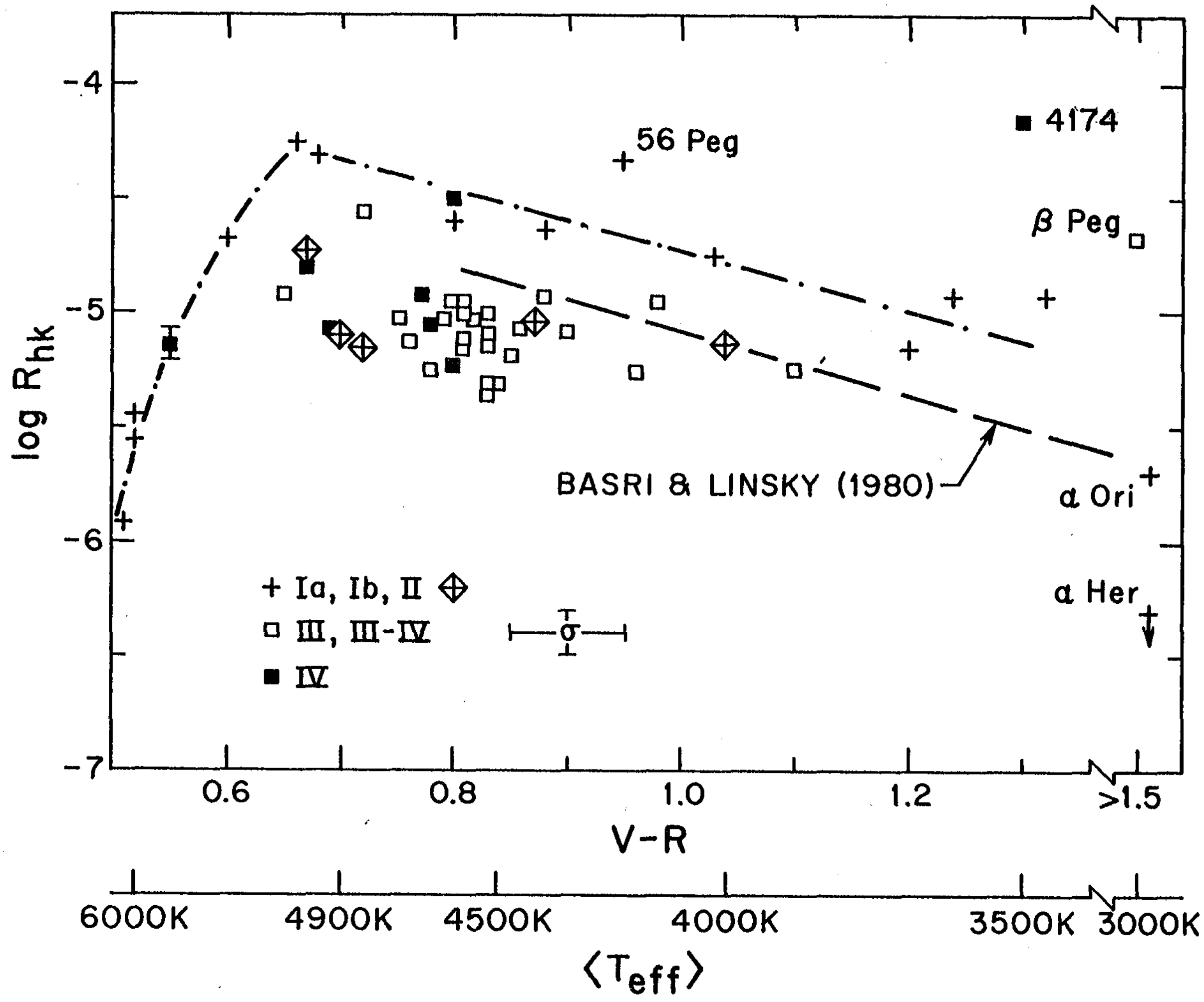

Fig. 2. Chromospheric radiative loss rate in Mg II, R_{hk}, which is the ratio of integrated Mg II h and k surface flux to total bolometric luminosity, as a function of V-R photometric color. See text for discussion.