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EVIDENCE FOR EXTENDED CHROMOSPHERES SURROUNDING RED GIANT STARS

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There is now an increasing amount of both observational evidence and theoretical arguments that regions of partially ionized hydrogen extending several stellar radii are an important feature of red giant and supergiant stars. The purpose of this paper is to summarize this evidence and to examine the implications of the existence of extended chromospheres in terms of the nature of the outer atmospheres of, and mass loss from, cool stars.

1. Spectroscopic Evidence

1.1. Emission measure in the mid-UV lines of C^+

A marvelous marriage between observational astrophysics and theoretical atomic physics recently occurred when the density-sensitive variation of line ratios within the five-lined 2325 Å multiplet (UV 0.01) of C II was studied in the spectra of red giants (Stencel et al. 1981). The sensitivity of the boron isoelectronic sequence to the electron density of lines in the $2s^2 2p\,^2P$ - $2s2p^2\,^4P$ multiplet has been known for some years. Previous work has concentrated on N III, O IV and higher sequence members in the context of the solar atmosphere. The C II features are sensitive to densities in the 10^7-10^9 cm^{-3} regime, inappropriate for the dense solar chromosphere, but valuable in measuring densities in low gravity cool stars. Observations of the C II 2325 Å multiplet in the Sun and in the planetary nebula NGC 6572 fix the high and low density ratios for three pairs of lines. By iteratively adjusting collision strengths and A-values, Stencel et al. achieved an optimum fit to the density extremes, reducing the spread in N_e as derived from three line ratios for individual red giants. The line ratios are relatively insensitive to changes in T_e over the 7000–20,000 K range. More accurate collision strength calculations are needed, however, and observations of objects nearer the low and high density limits are being requested, but such observations require long exposures even with the IUE satellite. The implied electron densities for α Boo and α Tau are 2-3 × 10^8 cm^{-3}, in reasonable agreement with upper chromospheric values in models by Kelch et al. (1978) and Ayres and Linsky (1975).

In addition to the valuable density diagnostic, the ratio of total flux in the 2325 Å multiplet to that in the 1335 Å resonance line multiplet provides an independent measurement of T_e. This information combined with ionization equilibrium estimates and abundances can lead to estimates of the hydrogen column density, $\int N_H dh$, which is $\sim 6 \times 10^{20}$ cm^{-2} for α Boo. Then assuming the carbon ionization fractions and the value of N_e/N_H, we derive a lower limit to the (C II) chromospheric thickness for α Boo of $\sim 2 \times 10^{12}$ cm, which is at minimum comparable to the stellar radius. More precise calculations for the hydrogen and carbon ionization equilibria and line formation, including collisional excitation would be valuable. Preliminary calculations assuming a two-level C^+ ion and optically thin line, and the observed values, suggest that chromospheric thicknesses range from about 6R_* in α Boo to 10-15 R_* in M giants and supergiants, like β Peg and α Ori. It is encouraging that this same technique predicts a very thin (0.01 R_*) chromosphere for the Sun. Recent C II observations of the KO III star β Gem indicate $N_e \sim 10^{9.1}$ and a chromospheric thickness of 0.06 R_*. This result is encouraging, because β Gem exhibits soft X-ray emission transition region emission lines, indicative of an outer atmospheric structure similar to the Sun, including a geometrically thin chromosphere. It seems physically appealing that among the red giants which show no evidence for hot coronae, the chromosphere occupies a volume homologous to that of coronae in warmer, higher gravity stars.

1.2. Other estimates of chromospheric extent and inner CS radius

The coolest and most luminous red giants are known to be surrounded by an extensive, cold circumstellar (CS) gas and dust envelope, extending possibly hundreds of stellar radii (for α Ori several arc-minutes in apparent extent -- Honeycutt et al. 1980). The radius of the inner edge of this CS shell is referred to as R_{min} and its value is important in estimating mass loss rates, but it also provides an outer limit to the extent of warm, chromospheric material near the star. Sutton et al. (1977) employed optical heterodyne interferometry on the 10 μm silicate feature in α Ori and α Sco, and found that dust emission ceases within 12 R_*, implying an extended warm interior region. Less direct techniques have inferred R_{min} for α Ori to lie in the 8-12 R_* range, cf. Bernat and Lambert (1975), Knapp et al. (1980), van der Hucht et al. (1980), Castor (1981). The radio spectrum reported by Altenhoff et al. (1979) is consistent with free-free emission from a 2-3 R_* warm region around α Ori.

1.3. Variable He I 10830 Å emission

The appearance of variable He I 10830 Å emission and absorption among red giant stars (O'Brien 1980; Zirin 1976) for which upper limits on coronal X-ray emissions are very small (Ayres et al. 1981a) poses the difficult problem of line formation that perhaps can be resolved by recognizing that the chromospheres of these stars are probably extended. The existence of emission in 10830 Å is easier to understand if it is formed over a region large compared to the photosphere. This is in contrast to thin chromosphere dwarfs where

10830 Å appears consistently in absorption. More importantly, the nature of the 10830 Å variations themselves has been used by O'Brien to argue for moving prominence-like material at large distances from red giants. The nature of these events is far from established, but they strongly imply the existence of chromospheric material at large distances above the stellar photosphere. Evidence for episodic mass ejections among red giants has also been found by Bernat (1981).

1.4. Atmospheric structure in 32 Cyg

High resolution ultraviolet spectra obtained during the recent eclipse of 32 Cyg by Stencel et al. (1982) provide direct measurement of the chromospheric temperature rise with height above the supergiant's photosphere as a result of the different lines of sight through the K5Ib stellar atmosphere to the partially eclipsed B5V companion star. Preliminary analysis using Fe I and Fe II curve of growth indicates an excitation temperature that appears to plateau at 7200 K above approximately 2 R_K.

1.5. Ionization anomalies

Ramsey (1981) has reported on the ionization balance in G5-M2 giants and supergiants, using Ca I 6573 Å and [Ca I] 7324 Å lines. He found an increasing discrepancy between observed and LTE line strengths for $T_{eff} < 4250$ K, which he interpreted in terms of increased overionization. This effect highlights the inadequacy of radiative equilibrium, LTE atmospheres for such stars, which could be due in part to a lack of collisional deexcitation in low density and extended material, or subtle filling of the line core by chromospheric emission. The NLTE effect and core filling both could have substantial impact on attempts to perform abundance analyses of these objects (see below).

1.6. Ca II K and Mg II k

Chromospheric temperatures and velocity fields can be derived from profiles of the emission cores of the resonance doublets of Ca^+ and Mg^+. Reimers (1977) has delineated that portion of the HR diagram where cool stars typically show CS (K_4) features in their K line cores, thus indicating the presence of outflowing 3000-7000 K material well above the low chromosphere. Stencel (1978) and Stencel and Mullan (1980a,b) have studied the statistics of asymmetries in the doubly reversed emission cores. They find that the Ca II K line changes from a solar-like ($K_2V > K_2R$) asymmetry to an outflow ($K_2V < K_2R$) type of asymmetry along a locus in the H-R diagram similar to that proposed by Reimers for the presence of K4 features, whereas the Mg II k line undergoes a similar asymmetry change several spectral subtypes earlier, nearly coincident with the division between stars with and without detected soft X-ray emission (Ayres et al. 1981a). Effects of interstellar Mg II absorption can affect the apparent asymmetry (Bohm-Vitense 1981) although to first order, the impact can be judged by comparing the stellar radial velocity against the "expected" asymmetry for the stars' location in the H-R diagram.

Several bona-fide "discrepant asymmetry" (Ca II K ≠ Mg II k) stars have been isolated by Mullan and Stencel (1982), including α Boo (K2 III), α Tuc (K3 III), σ Oph (K_3 II), π Her (K_3 II), 56 Peg (K_0 II + wd). Several others are suspected of having discrepant asymmetries (e.g., 56 UMa, G8 II), although interstellar Mg II absorption may interfere. In contrast, the G giants and M giants tend to have asymmetry agreement. It is significant that when the discrepancy is found, it is always in the sense that Ca II shows V > R while Mg II k shows the opposite asymmetry. This "preferred parity" must be physically meaningful, unless a reliable counter example can be found.

At the time of this writing there is no definitive explanation for this phenomenon, although several hypotheses have been advanced. Our attempts to simulate discrepant asymmetries numerically using plane parallel, hydrostatic equilibrium (HSE) model atmospheres and comoving frame multilevel NLTE calculations including PRD have not been successful; the formation regions of Ca II K and Mg II k overlap to a great extent (cf. Fig. 1 of Vernazza et al. 1981) and unphysically steep velocity gradients would be required to produce the discrepant asymmetries. There is no reason to believe that the high pressure chromosphere models of Baliunas et al. (1979) would do any better. There are two possible solutions: we could adopt very nonsolar Ca/Mg abundance ratios to separate the Ca II and Mg II formation regions; or we could assume that the chromosphere is extended and inhomogeneous. The latter option seems preferable. Spectral synthesis calculations are needed for the following models: (1) one component, geometrically extended chromospheres (T_{max} ~ 8000 K); (2) extended chromospheres, including stellar prominences (T_{max} ~ 10,000 K), and (3) "double valued" chromospheres (T_{max} initially rising to 10^5 K, then dropping back to ~8000 K). None of these models can assume HSE, a point we'll return to later.

For a one-component chromosphere without a high temperature corona at its upper bounds the Mg II k formation region will extend well above that of Ca II K, such that it should be possible to produce discrepant asymmetries, with plausible radial velocity gradients. In the stellar prominence model an upward moving layer, which is optically thick in Mg II k but thin in Ca II K, overlies a static chromosphere, and adds absorption and emission components to the symmetric underlying profile in any desired proportions. Such models are highly nonunique however. Finally, the model based on temperature distributions proposed for other reasons by Hartmann and MacGregor (1980) may have merit in the present case. Above an initial chromospheric rise is a high temperature (10^5 K) transition region (TR) above which lies an extended, cooler chromosphere. For this model the Ca II K core emission could be primarily formed in an interior deceleration zone, while most of the Mg II k could be formed exterior to the TR, in an expansion zone. Again, radiative transfer calculations in spherical geometry need to be carried out to demonstrate the feasibility of this appealing idea. This model does predict that TR emission lines would exist in proportion to T_{max}, and the TR thickness. Stringent limits to the emission measure of TR features must be borne in mind (e.g., α Boo), despite the existence of "hybrids" and their possible TR line variability. Actual differences in the amount of TR material in K giants and bright giants may relate to intrinsic age and evolutionary differences, much as may be the case for the G-type giants whose range of X-ray luminosities suggests this possibility (Simon et al. 1982). Finally, it should be remembered that a complete statistical sample based on simultaneous observations is far from complete, although the suggestion of discrepant asymmetries must mean either extreme variability or unique physical circumstances for such chromospheres.

1.7. Additional spectroscopic indicators

Subordinate emission lines, such as those appearing in the wings of the Ca II H and K lines (Stencel 1977) and those in the mid-UV spectra of many red giants (Stencel et al. 1980), tend to lack counterparts in warmer, high gravity, coronal-type stars. In part this could be a matter of contrast with the photospheric continuum distribution, but their appearance in stars only above the asymmetry dividing line for Ca II K (Stencel 1978; Hagen et al., this volume) suggests that they maybe useful in studying extended chromospheres.

2. Direct Evidence

2.1. Narrow-band speckle spectroscopy

A very significant advance in the study of red giants and supergiants occurred with the discovery of a large increase in the apparent diameter of α Ori when viewed in the light of Hα (see Hege et al., this volume). They report that the diameter increases from about 50 milliarsec (mas) in continuum light to over 250 mas in the Hα ± 3 Å core, suggesting chromospheric emission extending to at least 5 R_{*}, consistent with the previous discussion. In principle, it should be possible to resolve time-dependent chromospheric structures and possibly stellar rotation. Several groups are busy planning how best to exploit this technique; narrow band observations are being planned for a variety of strong lines. The results are guaranteed to be exciting and fundamental.

2.2. Narrow band observations of occultations

Similar efforts involving narrow band occultation observations have also indicated extended chromospheric emission among red giants. White et al.

(1981) found that 119 Tau (M2 Ib) is at least twice its continuum diameter in Hα light. Similarly, Radick and Africano (1981) found suggestions of a small increase in angular diameter of α Tau (K5 III) when viewed in a 7 Å FWHM filter that had the Ca II 8542 Å line near one edge of the bandpass. Estimates that correct for light loss, etc., suggest a larger angular diameter would be found with the filter centered on the chromospheric line. White et al. suggest that several bright cool stars, and all M supergiants with I(104) < 2^m, may be suitable targets for such observations.

3. Discussion

3.1. Failure of hydrostatic equilibrium (HSE)

Dimensional arguments indicate that extended chromospheres are orders of magnitude larger than their isothermal pressure scale heights ($RT/\mu g$). The average chromospheric densities implied by the C II diagnostics for α Boo and α Ori are 10^8 and 10^7 cm^{-3} respectively. The isothermal pressure scale heights in 10^4 K chromospheres are 10^{11} and 10^{12} cm. These are 50 and 250 times smaller than the dimensions implied by 5 R_* chromospheres for these stars. It appears that hydrostatic pressure alone is incapable of supporting these chromospheric extents.

Another source of pressure in red giant atmospheres is due to turbulent and expansion velocities. The averaged pressure, P_{chr}, implied by $\rho g R_{chr}$ is sufficiently large that rms turbulent velocities of 70 and 50 km s^{-1} would be required for α Boo and α Ori, respectively, to support it. While for α Boo, 70 km s^{-1} is consistent with the transient Ca II K_4 feature displacements reported by Reimers (1977) for similar stars, 50 km s^{-1} seems a factor of 3 or more above chromospheric or expansion velocities derived for α Ori (Bernat 1981). A plausible alternative to hypersonic velocites would be the support due to a modest magnetic field energy density ($B^2/8\pi$). Assuming an r^2 divergence, the surface (1 R_*) field required is only 9 and 2 gauss, respectively. These field strengths are comparable to those assumed by Hartmann and MacGregor (1980) in their Alfvén wave heating model for red giants. However, the magnetodynamic support arises in the <u>tangential</u> component of the field ($\underline{B} \times \nabla \times \underline{B}$), and if small Alfvénic perturbations on a stronger, fixed radial field are required, the total energy in the support field over large dimensions must be enormous. The Alfven wave heating theory is probably appropriate to describe the stellar wind in the far-field limit, but an alternative may be necessary in the near-field. Mullan (1981) has discussed the stability of emerging flux loops in stellar atmospheres, and argues from analogy with solar helmet streamers that below a certain mass-to-radius ratio (i.e. log g ~ 2), such loops will not find stable configurations, and must evolve to open topology. Reconnection near the base may pinch off magnetically confined plasma bullets which are propelled upwards, in effect driving the mass loss (see comments by Mariska and Boris in this volume). The idea is appealing in that it explains the observed episodic nature of mass loss, but it has not yet been supported by realistic calculations (Pneuman 1981).

3.2. Energy balance and the hybrid stars.

It has been noted by R. Hammer (private communication) that the intensity distribution across the extended chromospheres will be indicative of radiative loss and hence of the heating mechanism. Although the details of the dissipation remain preliminary, compressional wave heating modes (e.g. acoustic and slow mode with field equipartition) are much more closely tied to the density distribution than the noncompressional wave heating modes (e.g. Alfven-waves). The radiative loss rate as a function of radius then indicates the heating mode, assuming an exponential density falloff. Considering that if the number of isothermal pressure scale heights involved is large, the radiative losses in Hα then appear essentially insensitive to density, as there is detectable signal from the extended material. This points toward noncompressional wave heating as the important mechanism, although the details of its dissipation await further clarification. The spatial variation of chromospheric line emission provides an important clue, and needs more careful measurement.

If Alfvénic wave heating is an appropriate description of the outer atmospheres of noncoronal stars, the thickness and density of their transition regions determine the visibility of their 10^5 K emission features in the far ultraviolet. Again, the statistics are incomplete, but perhaps as many as one in four of the K giants and bright giants so far sampled are hybrid (Reimers, this volume; Simon et al. 1982). It is particularly dangerous to draw premature conclusions for this region of the H-R diagram because it is also occupied by the Ba II stars, many of which are thought to have white dwarf companions and thereby enhanced transition region emission (Schindler et al. this volume). If the transition regions of such stars are also extended (2-3 R_* in the MacGregor-Hartmann models), they might be spatially resolved near the star in speckle spectroscopy of helium or other lines. The suggestions of variability in TR emission lines (e.g. comparing the Iota Aur and Theta Her at different epochs) indicate changes in the energy input responsible for the TR formation, and the mass loss. This may be important in the formation of the variable He I 10830 Å absorption and emission seen among such stars.

3.3. Future prospects.

The concept of a geometrically thick chromosphere surrounding noncoronal type stars is appealing in that a wide range of observed properties of red giant stars can be more easily understood. One characteristic of extended chromospheres that distinguishes them from the thin chromospheres of the Sun and G giants, is the fluorescent line pumping that can occur: e.g. O I (pumped by Ly-β, Haisch et al. 1977), numerous lines of S I (Brown and Jordan 1980) and CO (Ayres et al. 1981b). Note that these fluorescent features can be confused with important TR lines due to wavelength coincidences, and any hybrid candidate must be carefully scrutinized with respect to this possibility. Further, abundance estimates may be suspect if the filling in of line cores by chromospheric emission, which reduces line equivalent widths, is overlooked (e.g. O I and metal lines, Sneden et al. 1979).

Among the high priority observations in the next few years should be simultaneous X-ray (EXOSAT), far ultraviolet and Mg II (IUE), Ca II, Hα and He I 10830 Å observations of red giants, as well as a thorough exploration of the immense potential of speckle spectroscopy (section 2.1 above) of such objects. In terms of calculations, models for line formation and radiative losses in extended, spherical chromospheres should receive first attention. Any attempts to comprehensively interpret the outer atmospheres of red giant stars must take into account the evidence for the extended chromospheres, their variability and large scale asymmetries (as suggested by the speckle data — Hege et al. this volume — and by linear polarization work — Hayes 1980).

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