DEPTH-DEPENDENCE OF TURBULENCE IN STELLAR ATMOSPHERES

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I am very pleased to have this opportunity to present some recent observational work bearing on the depth dependence of motions in stellar atmospheres. I thank Dr. Gray for this invitation and also wish to acknowledge the patronage of the NAS-NRC.

Photospheres

The bulk of the work published on the depth dependence of turbulence, v(h) in stellar photospheres has tended to concern microturbulence alone. The solar case is perhaps the most well studied as both horizontal and vertical components of both micro- and macro-turbulence can be examined with depth. The recent summaries by Beckers (1975) and Canfield (1975) disclose a nearly constant 1 - 2 km/s turbulence through the solar photosphere, possibly rising slightly into the upper chromosphere. Other late type stars can be compared against this best case.

Arcturus is probably the next best studied case. Figure 1 collects several of the efforts to determine depth dependence of turbulence in its photosphere. A distinction among the types of motions measured should be noted: some techniques deliver microturbulence, while others deliver a total non-thermal velocity (including micro, meso and macro-velocities). Classical curve of growth studies, such as that by Griffin and Griffin (1967), yield a mean microturbulence, a depth-averaged value probably applicable to around log optical depth (5000A) of -1, as deduced from moderate strength metal lines. The Goldberg-Unno (1958, 1959), which uses pairs of lines in multiplets, has been applied by Sikorski (1976) and Stenholm (1977) to deduce the variation in v(h). Curiously, despite the similarity of spectroscopic materials and method, these solutions diverge somewhat. This may suggest a limitation of the Goldberg-Unno method in non-solar cases. A thoughrough discussion of the accuracy

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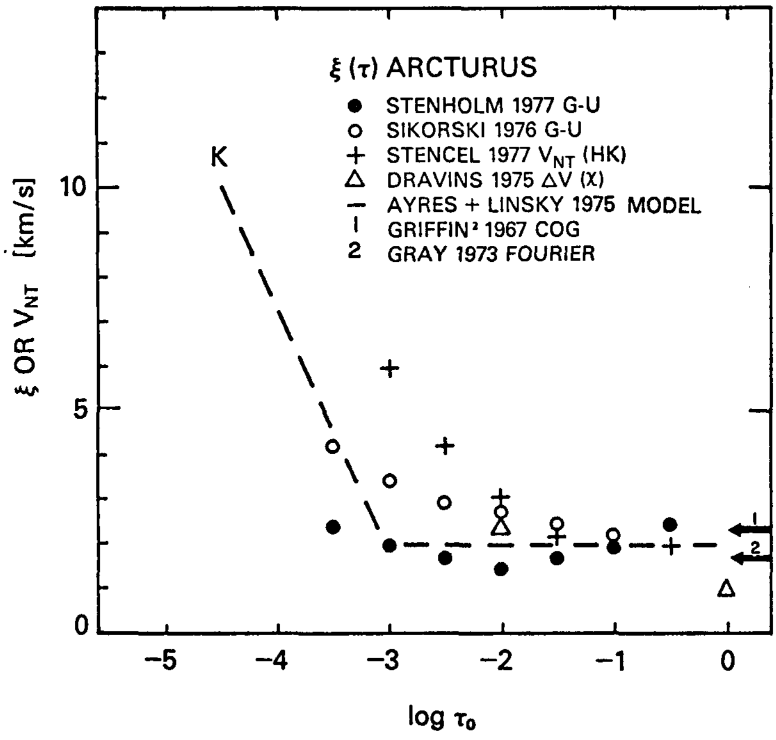

Figure 1. Turbulence variations in the photosphere of Arcturus.

to be expected with this method has been given by Teplitskaja and Efendieva (1975), and the conclude that uncertainties of 10 to 40 percent are likely. Thus the differences may be largely due to the inherent accuracy of the method. Dravins (1974) found, by an entirely different technique, that differential Doppler shifts of 2 km/s were typical of the Arcturan photosphere. If convective cells dominate, higher excitation lines will be formed in the hotter, rising (blueshifted) convective regions, while lower excitation lines will be formed in cooler, sinking (redshifted) elements. Thus, systematic wavelength shifts, similar to those known for the Sun (Glebocki and Stawikowski, 1971) should be observable. Dravins finds evidence for this, which reveals a macro-motion. Another technique, developed for the solar case by Canfield (1971) and applied to Arcturus in my own work (Stencel, 1977) uses the widths of weak emission lines occuring in the wings of the Ca II H & K lines. Their formation against the H & K line wings enables a probe of the total non-thermal line broadening

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to be evaluated with depth in the stellar photosphere. The result is again an indication for increasing motions with height through the photosphere. As new equipment for high resolution and improved signal-to-noise spectroscopy becomes available, application of Gray's (1976) Fourier techniques for deconvolution of line broadening mechanisms will help to reduce the discepancies. Gray's analysis of photospheric lines in the Arcturus spectrum leads to a mean microturbulence in agreement with curve of growth results, plus a small contribution due to stellar rotation. Finally, progress has been made in modeling of the upper photosphere of cool giant stars via spectral synthesis of the H & K lines. The statistical equilibrium methods of Ayres and Linsky (1975) seem to require a microturbulence which rises from 2 km/s in the photosphere, to 10 km/s in the upper chromosphere, which is again in the sense of the previous results.

In summary, to the extent that Arcturus can be considered typical of cool giants and comparable to the Sun, it seems that: 1. both the Sun and Arcturus show evidence for an increase in the total micro- plus macro-velocities with height, starting at mid-photospheric levels, and, 2. no single technique appears to possess an inherent lack of uncertainty, be it due to limitations of the data or the physical approximations and simplifications. Thus, only in the agreement of independent determinations of v(h) can we find hope that we have an idea of the atmospheric state.

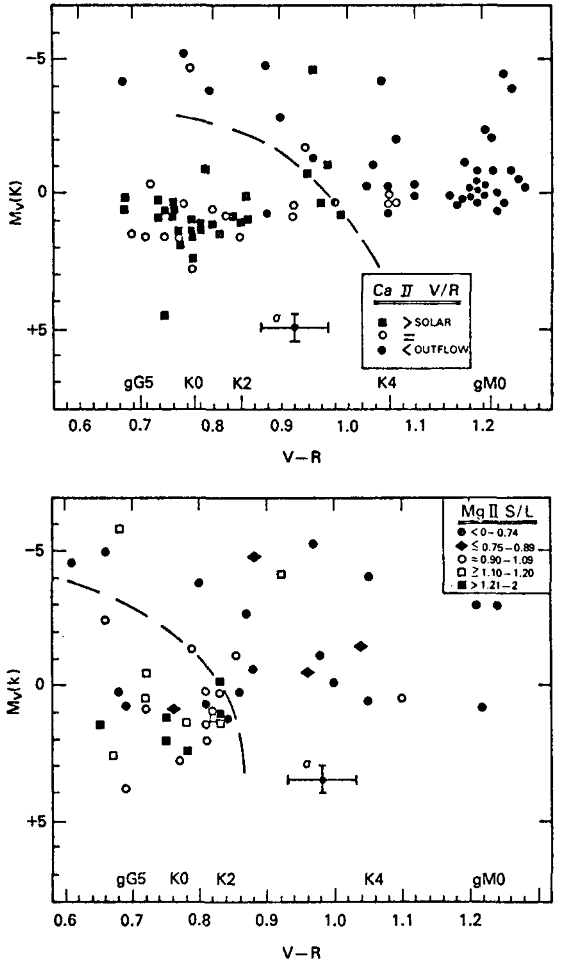
Chromospheres

Of the few diagnostics of stellar chromospheric velocity fields available in the visible region, the Ca II K line may be the most valuable. In G, K and M stars, the central emission is formed over heights covering the low to mid-chromosphere. This maps the temperature rise until collisional coupling of the source function is diminished by the low density in the upper chromosphere. Historically, the influence of velocity fields on the emission width to absolute magnitude correlation (Wilson-Bappu effect) has been the subject of a healthy debate. However, recent compelling theoretical arguments by Ayres (1979) strongly suggest that Wilson-Bappu operates more as a barometer (pressure sensitive) than a tachometer (velocity sensitive).

Although the effects of velocity fields may not appear in the emission core width of the K line directly, they might be strongly visible in the gross asymmetry of the doubly reversed emission profile, characteristic of the line in cool giants and supergiants (cf, Wilson and Bappu, 1957; Linsky, et al., 1979). As first shown by Hummer and Rybicki (1967) and subsequently verified in more general cases, differential atmospheric motions can shift the self-absorbed core (K3) and change the ratio of the peak fluxes of K2V to K2R ("V/R"). An outflow which increases with height would blueshift K3 relative to K2 and diminish the K2V peak, resulting in V/R less than one. This situation is as observed among the late K giants, where blueshifted K4 (circumstellar) concurs with this interpretation. The opposite, as seen in the solar flux spectrum, can be intrepreted as an inflow, probably due to cooler downward motions as part of convective circulation. We must note that some have questioned whether a velocity field uniquely determines a particular asymmetry.

The extensive observational efforts of O.C. Wilson have provided us with an extensive sample of V/R measures (Wilson, 1976). Previous work lead me to examine this data as a function of effective temperature among the cool giant stars. The result (Stencel, 1978) was the quantization of the asymmetries in the HRD: the G and early K giants exhibit the solar asymmetry, while late K and M giants show the outflow pattern. The K1 to K3 giants comprise the transition objects, as is shown in Figure 2. Note the uncertainty of 0.5 magnitude in M_V and 0.06 magnitude in the V - R color, which could distort the sharpness of the transition.

Is this same asymmetry transition seen in the analogous Mg II 2800A resonance doublet which also shows strong chromospheric emission cores? Due to its larger oscillator strength and abundance, the Mg II emission cores are formed about three scale heights above the Ca II H & K lines, into the upper chromosphere. Any differences in v(h) might be expected to show up as a displacement in the asymmetry transition line. Dermott Mullan and I have started to investigate this question with a survey of cool giants with the IUE, and some preliminary results are seen in Figure 3. While the Ca II survey contained over 500 stars, our present survey has but 50. Again, considering the smaller sample and the unfortunate choice of symbols selected by the draftsman,



Figures 2 & 3. **Ca II and Mg II asymmetry transitions. See text for details.**

if you examine the overall trend, you find the Mg II asymmetry changes sense, much as does the Ca II. Our semi-objective judgement of the transition line is indicated and it is clearly shifted to smaller V-R color compared with the Ca II line. The addition of more data will help clarify the transition locus. It is plausible too that the upper chromosphere may be more 'volatile' than the Ca II line forming layers, so that the transition locus may be broadened by the number of stars undergoing asymmetry fluctuations due to upper atmospheric inhomogeneities. Overall, the G giants show the solar circulation pattern while the late K and M giants clearly exhibit outflow.

I also suspect some additional variations among the early G subgiants which should be

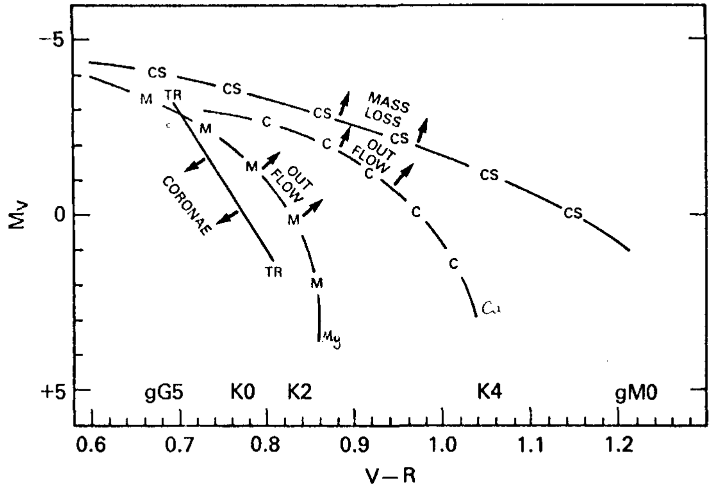


Figure 4. Collected transition loci in the HRD. See text.

explored. This Mg II data has been prepared for the Astrophysical Journal (Stencel and Mullan, 1979). In addition, we find very satisfactory agreement between the Wilson-Bappu M_V(Ca II K) and the Weiler and Oegerle (1979) M_V(Mg II k), except for a few peculiar objects like 56 Peg (cf, Basri, et al., 1980). In summary, the Mg II data points to changes once again in the hydrodynamic structure of the upper atmosphere. This fact should be considered in the current debate over the upper chromospheric pressure and velocity structure of cool evolved stellar atmospheres.

Coronae and Circumstellar (CS) Envelopes

The Ca II and Mg II asymmetry observations can be combined with additional studies to reveal an interesting description of the upper atmospheric structure of cool evolved stars. Reimers (1977) has delineated the occurance in the HRD of stars exhibiting either permanent or transient CS absorption (K4). This locus parallels the Ca II asymmetry transition (Figure 4). In addition, UV spectra of the presence or absence of high excitation lines (10^5K) in cool giants obtained by Linsky and Haisch (1979) lead them to postulate the existence of a thermal transition among the early K giants, such that warmer stars possess hot upper atmospheres (coronae, by implication), while slightly cooler stars do not have such coronae. This transition needs more observations in both UV and X-ray regions to be verified, but if it is correct, placing the proposed transition locus in the HRD leads to an interesting speculation: as a star evolves through the K giants en route to its helium flash, some hydrodynamic mechanism first dissipates the corona and uses the available energy to drive a stellar wind, as is seen in solar coronal holes. Initially the wind influences the upper chromosphere where Mg II emission is formed, and later penetrates to the Ca II line forming region and affects that emission asymmetry. Ultimately, as a consequence of the wind containing enhanced densities, CS features begin to become visible. The timescale necessary for crossing these transitions may position some stars "on the brink" such that patches of corona and of coronal holes alternately dominate the outer atmosphere. This is seen in flux as variable Ca II and Mg II emission core asymmetry changes, and collectively as a broadening of the transition loci. Variable far UV and X-ray flux might be expected. High resolution profiles of the far UV high excitation lines for a sample of stars would help reveal upper atmospheric motions as well, but these will be difficult to obtain even with the IUE.

Mullan's (1978) expanation for this involves the changing height at which motions become supersonic. This supersonic transition locus (STL) is assumed to occur in the coronae of G stars, and to impinge on a discontinuity between hot thin coronae and cooler denser chromospheres among the early K giants. This disrupts the corona and increases the mass loss rate. The Mg II asymmetry is first affected, then the Ca II asymmetry as the STL drops deeper into the atmosphere. While this theory is appealing, it does rely on a strict solar analogy, whereas a steadilly increasing mass loss rate <u>might</u> produce comparable observed effects without requiring a chromosphere-corona discontinuity (Dupree, private communication). Resolution of this will require some sophisticated transfer calculations, but regardless of which theory one favors, the observations reveal a depth dependent effect of velocity fields among a wide range of cool evolved stars. A crucial test of the STL would be made if a non-transient case of Mg II level inflow with Ca II level outflow could be found in a flux observation.

Theoretical work on waves and inhomogeneities is crucial in this context. Recent work by MacGregor and Hartmann (1979) and by Haisch, et al. (1979) and Basri (1979) which consider mechanical and radiative fluxes, are excellent beginnings. This work combined with observations of the depth dependence of turbulence and winds will enable us to come to grips with details of atmospheric structure. At this point, observational advances in the visual wavelengths will come with application of the newest detectors to very high dispersion spectroscopy. Further improvement of statistics and resolution in the UV and X-ray regions will help. Finally, solar studies where the inter-relation of the velocity fields and the line formation can be examined in detail, are vital.

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