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Chromospheric Modelling in Late-Type Dwarfs: 1. Quiescent Objects

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1. The Purpose of Chromospheric Modelling

Observational facts about chromospheres are now well established. The existence of a layer at a higher temperature than the underlying photosphere in a star like the Sun gives rise to "superthermal" emission features of relatively low excitation which are strong and easily recorded. Nevertheless, there are many unanswered basic questions about chromospheres which still merit the attention of observers and theorists alike. In a recent article in the *Messenger* (No. 35) Pallavicini described some of the observations which go into producing a picture of a typical chromosphere. He dwelled in particular on two types of observations which can be made with the CES (Coudé Echelle Spectrograph) which operates with either the 3.6 m or the CAT at La Silla. These were the use of high spectral resolution to try to derive the rotational velocities of slowly rotating objects via Gray's asymmetry method, and close examination of the cores of the Ca II H and K emission lines. He also picked out X-ray luminosity, measured by the Einstein satellite, as a parameter strongly correlated with rotation, and hence with the existence and strength of chromospheres.

In this article we will be dealing more directly with some of the problems which arise when trying to use observational material to clarify the mechanisms which heat the chromosphere of a late-type star, in order to obtain a clear physical picture of what a chromosphere is like, how it is related to the underlying photosphere, and to the overlying corona. It is usually said that the chromospheres of late-type stars are heated by mechanical deposition of energy from the convective zone of the upper photosphere, or alternatively by magneto-acoustic energy. To what extent can we distinguish in practice between these two mechanisms, and is either of them the same as that which heats coronae? How directly can we translate information given to us in the form of high resolution line profiles of, say, the H and K resonance lines of Ca II, or their Mg II h and k analogues into a semi-empirical model which incorporates energy sources and their distribution with depth. We will illustrate our points with observations taken with the CES and also with the IUE satellite long wavelength spectrograph.

2. Reliable Data and Reliable Interpretation

The cool star observer has an apparently major asset compared with those who are trying to interpret the spectra of other stars, which is his ability to make comparisons with the Sun. This can, however, be misleading, and as an example we can cite our experience with IUE spectra in the h and k resonance lines of Mg II. Thanks to some careful and beautiful balloon-borne solar spectroscopy by Lemaire and Skumanich (*Astronomy and Astrophysics,* **22**, 61), it was clear as early as 1973 that a chromospheric emission line would have a significantly different appearance and strength depending on whether it came from the quiet chromosphere or from a plage "active" region; its strength varies from one chromospheric regime to another, from plages, to supergranular cells, to cell boundaries. To some degree also the shape changes, so that the central self-absorption appears differentially shifted with respect to the chromospheric emission core. Clearly, even from this small sample of information we can see that it will not be easy to interpret the spectra of other stars, which are of course the integrated products of all the regions of their chromospheres. In a star which may have stronger velocity fields than the Sun, it will be hard to take out the line structure imposed by the combination of velocity fields, leaving only the dependence of density, electron density and temperature with height, which must typify the model. In fact the Mg II spectra of G dwarfs taken with IUE, of which four examples are shown in Fig. 1, appear to give striking evidence for the widespread existence of such velocity fields. The central self-absorption is displaced by several km s^{-1} with respect to the emission core, sometimes to the red, sometimes to the blue. Most papers dealing with Mg II until 1983 (with the notable exception of one by Bohm-Vitense) dealt with such line profiles as showing evidence for chromospheric motions, although few attempts were seriously made to provide physical explanations. The values for the red-shifts or blue-shifts were from a few km s^{-1} to ten or even twenty. It is inconceivable that whole chromospheres could be moving outwards or inwards at those kinds of speeds, but one problem was that accurate absolute velocity data with IUE were hard to derive (typical precision was of order $\pm$ 10 km s^{-1}), so it was never wholly clear whether the emission or the self-absorption at the centre was shifted with respect to the photospheric radial velocity. Circumstellar shells, either in expansion, or even in collapse, could be ruled out as the mass-losses or mass accretions implied were orders of magnitude too large. Finally, after several years of effort in improving the wavelength and photometric fidelity of the spectra, it could be ascertained that the whole story was a "red herring" (or a blue herring as the case may be) in that most

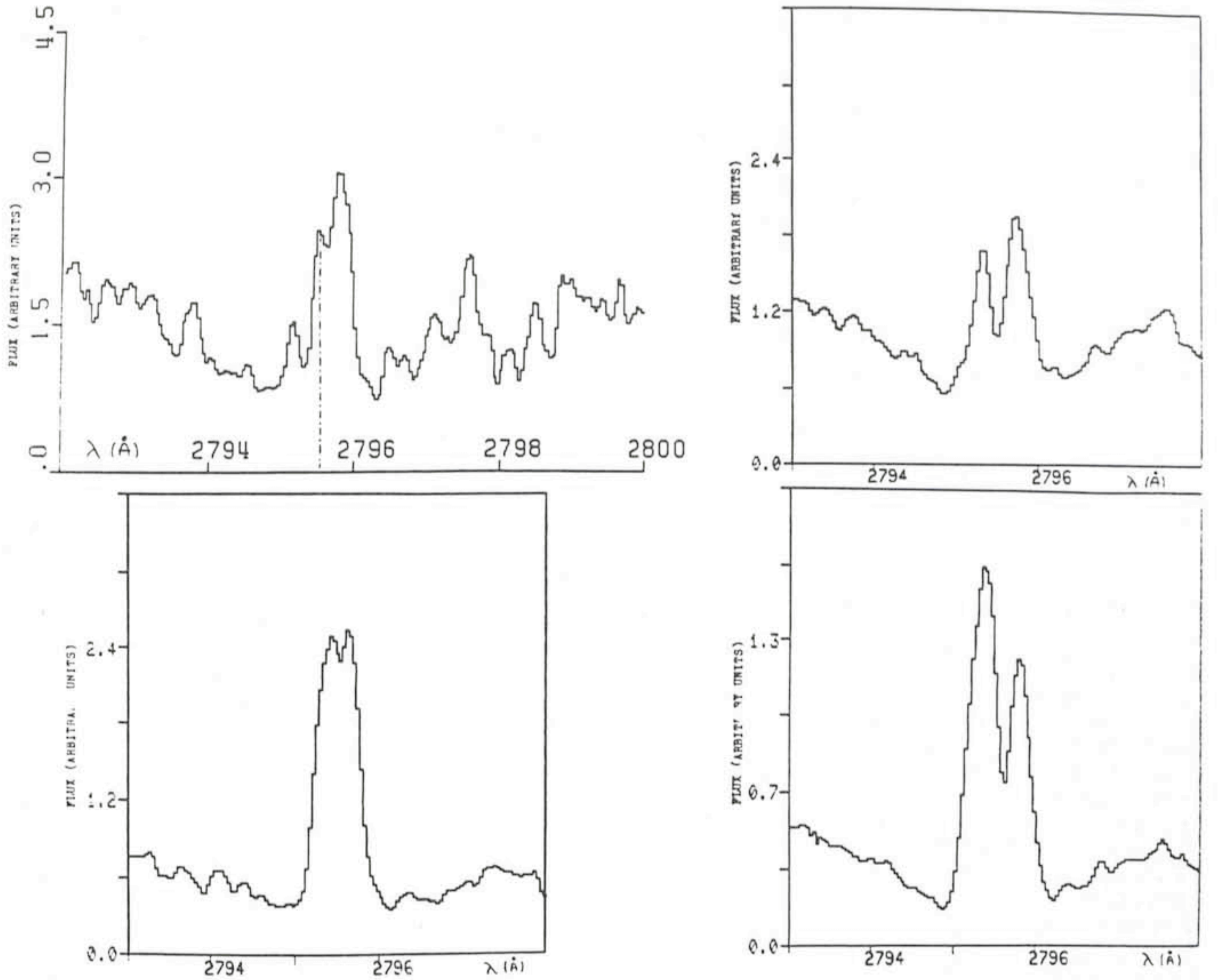

Fig. 1: *Mg II k lines from the chromospheres of four late-type stars: (a) β Hya (G2 IV); (b) ζ Tuc (G2 V); (c) τ Cet (G8 V); (d) δ Pav (G8 IV). The strikingly different central self-absorptions within the chromospheric emission cores are due to the LISM (local interstellar medium).*

of the absorptions could be identified with the local interstellar medium (LISM).

Fig. 2 gives the vital clue to the separation of chromospheric from LISM components. We can see the spectrum of β Hya taken with the CAT+CES compared with an IUE high resolution spectrum, and hence a comparison of Ca II K with Mg II k. The Mg II emission core, as well as exhibiting a different profile, shows two absorption features, while the Ca II core shows only one. With our improved velocity resolution (± 4 km s^{-1}) we were able to identify the blue-shifted feature with a cloud in the ISM, because its velocity coincides with that predicted by Crutcher from Lyα data using Copernicus. We could then go on to identify LISM features in many nearby late-type stars, and thereby map the LISM down to 3 pc from the Sun, so intense are the Mg II absorptions. The reason for the absence of any equivalent features in the Ca II spectra is simply one of lower abundance, and slightly less favourable IS excitation conditions for Ca II. We now know that the best way to avoid LISM effects is either to choose a line of sight where its radial velocity is large enough to take the absorption feature right outside the chromospheric core, or to observe in the direction of a "hole" in the LISM. This work has now brought us to the point where we can make serious use of IUE spectra to examine the effects of both velocity and intensity fields in the chromospheres of stars, with signal-to-noise ratios of the order of 30 : 1 in the h1 and k1 intensity minima.

3. Why Simple Models Cannot Predict Line Shapes

Fig. 3 shows the full panoply of chromospheric lines which we can now use: Hα, Ca II K, and the Ca II infrared triplet, all taken with the CES, and Mg II h and k taken with IUE. These profiles relate to different but overlapping depths in the chromosphere. Can we use them to derive meaningful models? Such models normally comprise the run of temperature and total pressure with depth above a reference level (typically the photospheric level where the optical depth in the continuum at 5000 Å is unity), together with the depth dependence of electron density, and the atomic and ionic densities of the more important components. Once such a model has been established, the problem of providing a consistent set of energy sources as a function of depth becomes much more tractable. Of course, the arguments are going to be somewhat circular, because there is always some degree of model dependence in the allocation of depth to flux within a line profile, and this means that the use of line profiles to predict energy sources and sinks is itself model-dependent. The ideal situation would be that a particular depth in the chromosphere

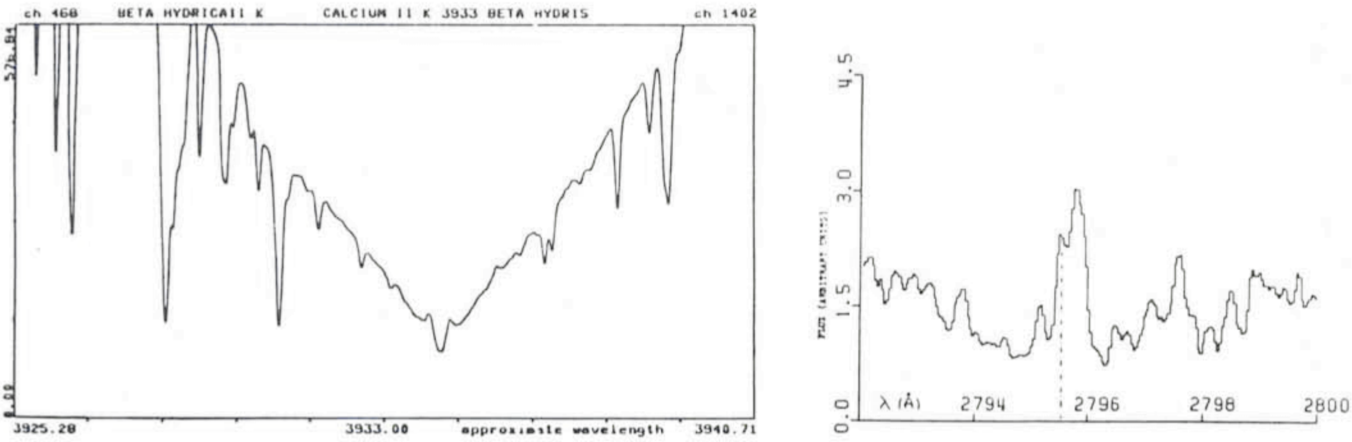

Fig. 2: *Comparison of the K line of Ca II, formed in the chromosphere of β Hya, and measured with the ESO CAT+CES with the k line of Mg II from the same star observed with IUE. Note the extra absorption feature in Mg II which is due to the LISM.*

would be cross-referenced by several different lines, by the wings of the lines in the IR triplet, for example, and by the core of the Mg II doublet, so that a self-consistent model could be built up.

Theoretical progress in relating line profiles to model atmospheres has been considerable, especially since the introduction of the techniques of partial redistribution to the formation of resonance lines in the chromosphere, in the 1960s and 1970s, which has transformed our ability to reproduce profiles from one of near failure to one of near success (the number of excellent theorists involved is too great to single out anyone here. Essentially this type of analysis is an attempt to specify what happens to any and every photon which goes to produce a spectral line in the atmosphere of a star, or indeed in any plasma. In grossly oversimplified terms, the theory attempts to compromise between the case of resonant scattering, in which a photon is absorbed and re-emitted coherently, and the case of complete redistribution in which the photons emerging from a particular layer of the atmosphere preserve no "memory" of those that entered, but are redistributed according to the prevailing temperature in the layer. The detailed dependence of the photon flux at any frequency on angle and on velocity is not yet wholly under the control of the modeller, though within a few years, and with the increasing use of computers, the solution of what can be reduced to a multidimensional set of matrix tranformations becomes imaginable. Of course, chromospheres are far from being in a state of LTE, and are not even in a state of hydrostatic equilibrium, so that line modelling presents more challenges there than in a photosphere.

4. Chromospheric Inhomogeneities

Another set of problems comes from the fact that the atmosphere itself is by no means a set of spherically symmetric static uniform layers. Firstly, there is the obvious fact, as seen on the Sun, that structure exists on many scales: typically on the scale of the granulation (1,000 km in diameter) and the supergranulation (100,000 km in diameter) dictated by magnetic fields. Secondly, there are the well-known phenomena associated with the temperature minimum, and the onset of a positive temperature gradient, and the presence of a rapid transition to the corona, all within 10,000 km of the photospheric surface, and with the presence within that layer of one or more "plateaux" where the temperature does not rise with height. In sum, there is structure both horizontally and vertically. Thirdly, there is the set of phenomena associated with activity, which, on the Sun, means the proportion of the chromospheric disk covered with "plages" which appear brighter in Hα and in Ca II H and K spectroheliograms. Finally there is the less well-known presence of more than one set of temperatures as a function of height, the presence of two co-existing "streams".

5. Two-Stream Modelling

This latter phenomenon might have been recognized as long ago as the early 1970s, when attempts to build reliable chromospheric models by combining data from the UV (both line and continuum), and the submillimetre continuum, which should in theory come from the same layers of the chromosphere, showed strange discrepancies. These could be resolved in principle if it was assumed that we are dealing with two streams of plasma, one much hotter than the other. The submillimetre continuum appears to be coming from the cooler stream, and the UV Lyman continuum and Lyα from the hotter. The observations receive a more or less rational explanation if we assume that the cooler stream occupies a greater fractional area of the disk, and can thus dominate the submillimetre radiation, whereas the hotter stream can dominate the UV because of a "Wien averaging" effect. The two streams could be thought of as occupying the super-granular cells, and the cell boundaries respectively. The difference between these appears to be a greater concentration of magnetic flux tubes along the boundaries.

This apparently dichotomic structure has been interestingly confirmed in recent years by measurements of the different temperature structures implied by different lines. One of the first pieces of deduction possible with a good quality spectrum of a late-type star in either the Ca II or Mg II resonance lines is to derive the temperature minimum, using the residual intensity at K3 or k3 (or their H and h equivalents), the points of minimum intensity in the combined chromospheric-photospheric line. Temperatures derived in this way for the Sun are of order 4,500 K. On the other hand, temperature minima derived from the infrared overtone, and fundamental vibration-rotation systems of carbon monoxide are of order 4,000 K or even lower.

In a recent article (preprint), Ayres has offered a persuasive physical scenario for this two-stream temperature structure. He starts by identifying the principal cooling agents in the hotter upper chromosphere which are in fact the Mg II and Ca II resonance lines, the Ca II infrared triplet, and the chief emission lines of hydrogen. Not only do these lines offer the best diagnostics for measuring the temperature structure via their profiles, but they also indicate, via their fluxes, the quantities of energy radiated to space, and the "only" remaining problem is to apportion these losses as functions of height.

It is usually assumed that the negative hydrogen ion H^- is a key chromospheric coolant by recombination, but Ayres points out that at temperatures below a critical value of 4,900 K, H^- is in fact heating the chromosphere this way. It is very difficult to find alternative cooling agents in the critical height region where the temperature lies between 4,000 K and 4,900 K. Below 4,000 K the CO can act as an effective coolant. Its radiative de-excitation rate is rather small, while collision rates are large, since the molecular vibrational-rotational states are excitable by collisions with neutral atoms and molecules, whereas in the case of ionic or atomic transitions only electron excitation is effective, and these states are far away from LTE in chromospheric conditions; CO can be in LTE at the same place in the chromosphere. The basis of the reasoning is that the cooling (or for that matter the heating) rate in any spectral line is proportional to the factor C/(C+A), where C and A are respectively the collisional and radiative transition probabilities. Where this factor approaches unity, the line can act as a strong net coolant, and at the same time the species will be in a state of LTE, in the sense that the distribution of its members among the possible energy levels available will follow Boltzmann statistics. Above the 4,000 K temperature limit, CO can no longer act as a coolant, since it dissociates.

6. How Two Temperature Structures Can Co-Exist

The interesting point about the dual cooling mechanism is that in a good part of the chromosphere, that is to say between the temperature minimum of around 4,000 K and a value just below 5,000 K where H^- cooling can take over, there is a range which is unstable, in the sense that the higher the temperature the less efficient the cooling. Below 4,000 K there is, as we have seen, a most efficient mechanism via CO. It is known that the chromosphere contains many small-scale magnetic structures, the "flux-tubes", and that the rate of deposition of

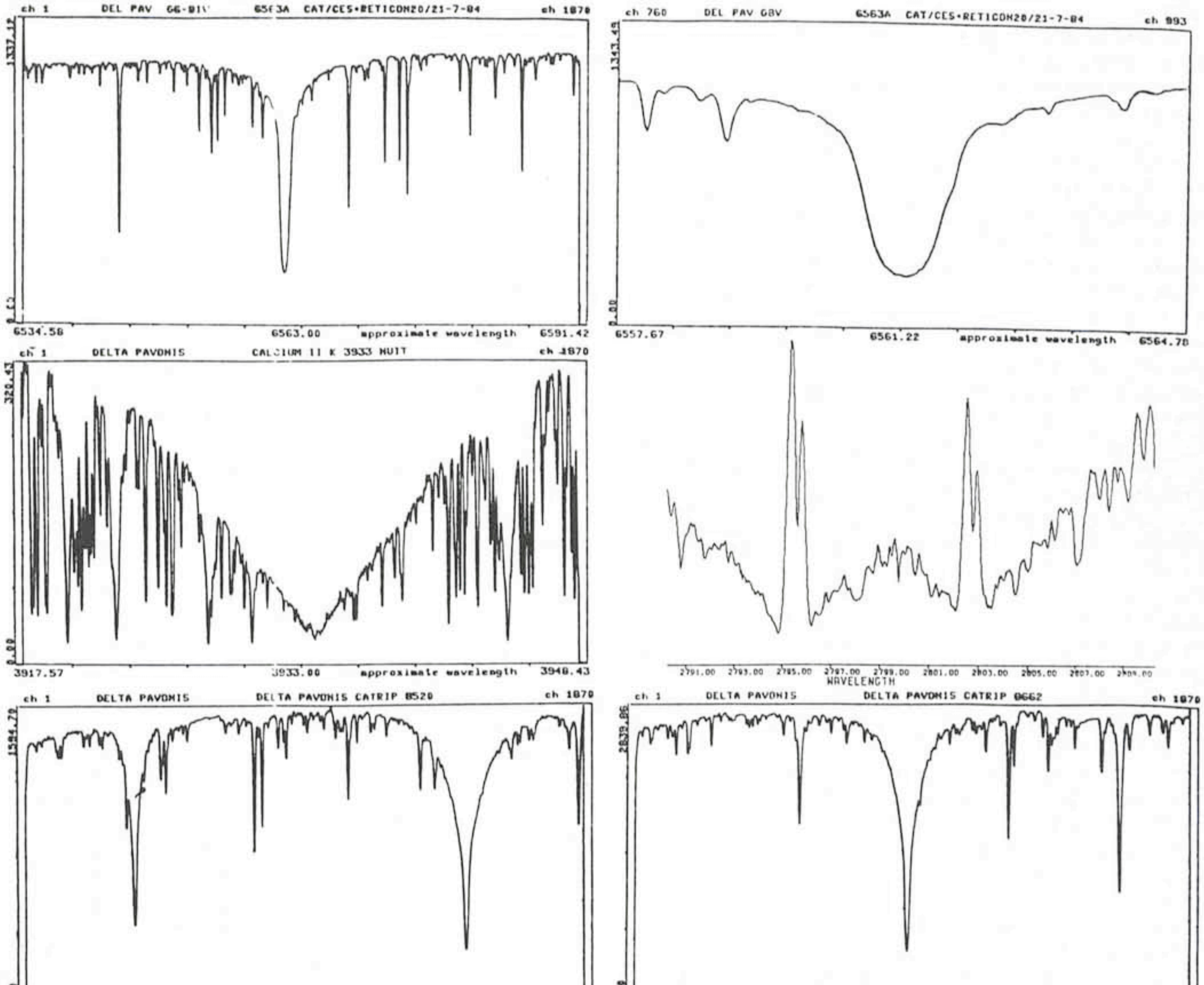

Fig. 3: *A compilation of lines accumulated from δ Pav giving chromospheric diagnostics. The Hα, Ca II K and the Ca II IR triplet come from the ESO CES; the Mg II k is from IUE. Note the considerably different line shapes, implying different strengths and formation regimes, and permitting exploration of the chromosphere in depth. These lines are the most potent in cooling the upper chromosphere, while CO rotation-vibration lines cool the lower regions (see text for details).*

energy within a flux tube should be significantly enhanced compared with the surrounding field-free regions. This would provide a mechanism for a two-stream radiative model, because the flux-tubes would reach the critical temperature of 4,000K, and then tend to higher temperatures, while the surrounding plasma could remain comparatively cool, essentially below 4,000K.

If this mechanism is indeed important, the consequences for those trying to model chromospheric lines either from the Sun itself or from solar-type stars, are certainly significant. As far as the Ca II and Mg II resonance lines are concerned, the part of the line formed in the "chromosphere", which is essentially the emission core, will be diluted by a purely "photospheric" absorption line, essentially the very broad surrounding feature, which in fact comes from the rather large bulk of cool material which co-exists outside the flux tubes but at the same height. The emission cores will come principally from those regions where the flux tubes are most concentrated, which, in the case of the Sun, implies the supergranular boundaries and the plage regions, and the broad absorption wings will come from an entirely different pressure and temperature regime. One way to test the idea on the Sun, is by careful centre-to-limb measurements of the Ca II profiles, since near the limb the cooler more opaque regions will have a greater effect, and the absorption trough should deepen relative to the emission core. Such a test will be necessary before serious attempts to apply two-stream modelling to stars can be contemplated, but solar measurements of this type are not exceptionally difficult.

7. The Use of Observations at High Spectral Resolution

According to the "classical" method of dealing with high resolution profiles, one starts by using the K1 and H1 minima in intensity to determine the stellar chromospheric temperature minima, the widths of the emission core to establish a microturbulence parameter to insert within the model, and the emission fluxes to compute the distribution of heating and cooling rates. A simple combination of the photospheric and chromospheric components (not neglecting the effects of non-LTE and partial redistribution) then sets up the line profile. By combining information from lines formed at different heights, one can then hope for self-consistent models. Now we are faced with a situation in which not only we must take into account the unknown (and almost unknowable) field of microturbulence with height, but also the streaming velocity fields inside the structures that produce the lines. We must take into account the role played by inhomogeneities, which appears to be dominant, and we must be sure that any interstellar effects in the line profile data from the star are well and truly eliminated. We can then begin to apply models which allow for non-LTE and partial redistribution effects. Only at that point can we begin to realize our goal, which is to parametrize those factors which lead to the deposition of energy within chromospheres, before going on to show how they vary with the mass, age, chemical composition, and rotation rate of a star.

CASPEC and IUE: A Perfect Match

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As not all readers of the *Messenger* may be familiar with the lingo of today's astronomers, we shall first try to explain the acronyms used in the title: CASPEC stands for "Cassegrain Echelle Spectrograph", IUE for "International Ultraviolet Explorer". Both are modern and very successful instruments for high resolution spectroscopy of astronomical objects. In both devices the high resolution is achieved using an echelle design, i.e. by dispersing the light with two perpendicularly oriented diffraction gratings, one of which is operated at high ($\sim 10^2$) orders. (For more technical details see the articles by D'Odorico et al. in *Messenger* No. 33 and by Le Luyer et al. in *Messenger* No. 17.) There are also some differences between CASPEC and IUE: CASPEC was developed as an auxiliary instrument for the ESO 3.6 metre telescope at La Silla. It can be used in the spectral range ~3500 Å to 9500 Å. The IUE spectrograph circles the earth as an artificial satellite at a mean distance of about 36,000 km above the equator and is fed by a telescope of only 0.45 metres aperture. As its name implies, IUE is used at UV wavelengths (about 1100 Å to 3200 Å) where ground-based observations are impossible because of the strong UV absorption in the earth's atmosphere.

During the past six years our group has been using IUE for investigations of a variety of different astronomical objects. During this time we found the IUE satellite to be particularly valuable for studies of distant blue supergiant stars. There are several reasons to investigate extreme blue supergiants: First, these stars are at the upper limit of stellar luminosities and their properties allow important insights into the problems of stellar stability. Secondly, because of their extreme brightness such stars are easily observed in nearby extragalactic stellar systems and therefore can be used to probe the physical conditions in other galaxies. The potential of these objects is illustrated by the fact that the absolute brightness of a single extreme blue supergiant typically exceeds that of a globular cluster or even that of a dwarf galaxy containing millions of stars.

IUE is particularly useful for studying blue supergiants as these stars emit most of their radiation just in the IUE spectral range. Hence, these objects can be observed at high spectral resolution even at the distance of the Magellanic Cloud galaxies. In fact, in spite of the much larger telescopes at La Silla, before 1983 we were often unable to match the high resolution of IUE spectrograms of bright Large Magellanic Cloud (LMC) stars with ground-based spectroscopic observations at longer wavelengths. This was unfortunate since at different wavelengths we observe different layers of these objects and only observations over a large spectral range allow to deduce a complete picture of their physical structure: In most cases the UV observations result in information on the dense and hot parts of the expanding envelope, while measurements in the visual and red provide data on the deeper, more static, layers, but also (using forbidden-line profiles) on the rarified outermost regions. CASPEC therefore greatly improved the efficiency of spectroscopic studies of such stars. In the following we shall describe in a few examples how CASPEC and IUE can be combined for obtaining a maximum of physical information.

The "Star" HDE 269599

This object derives its name from its number in the **H**enry **D**raper **E**xtension star catalog, where its position was pub-