Studies of Cool Giant Stars using GHRS Spectra

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Abstract. Observations with the GHRS have made a considerable impact on the study of cool stars. Observations with the International Ultraviolet Explorer established the overall nature of the UV spectra of cool evolved stars, but only strong sources could be observed at high resolution and measurements of line widths were impeded by the lower signal-to-noise. The greater sensitivity of the GHRS has allowed many more emission lines to be observed, in particular, weak lines of C IV and fluorescent lines of Fe II, H$_2$ and CO in α Tau (K5 III). These and other examples of how GHRS observations have led to improvements in spectroscopy and understanding cool giant atmospheres are discussed.

1. Introduction

The general properties of the ultraviolet emission line spectra of cool stars were established from observations with the International Ultraviolet Explorer (IUE). The identifications of relatively strong unblended lines in the wavelength range from 1200 Å to 3000 Å were made from low resolution ($\delta \lambda \sim 6$ Å) spectra, while the high resolution mode ($\delta \lambda \sim 0.07$ Å) was used to study the profiles or widths of the strongest lines. The fluxes of emission lines have been used to make models of the chromospheres and transition regions of a variety of main sequence and evolved stars, which together with the line widths, have been used to investigate the radiative losses and the energy which could be carried in acoustic and MHD waves. Work on cool evolved stars based on IUE spectra has been reviewed (for example) by Jordan & Linsky (1987) and Jordan (1997).

The use of the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope has led to significant improvements in all aspects of the above types of observations. The low resolution spectra ($\delta \lambda \sim 0.7$ Å) allow a good coverage of the spectra, the medium resolution spectra ($\delta \lambda \sim 0.06$ Å) cover a restricted range of wavelengths in one exposure, but with a greater sensitivity and signal-to-noise than the IUE high resolution mode. The echelle mode can be used to study the profiles of individual strong lines with a resolution equivalent to 3 km s$^{-1}$. The new observations have led to advances in understanding the spectra of cool evolved stars, in modelling through the inclusion of weaker lines and improved measurement of flux ratios sensitive to the electron density ($N_e$), and in determining the important line widths. Work using line profiles for studies of stellar winds is discussed by Harper in these proceedings.
2. Basic spectroscopy

Observations with IUE showed that the spectra of main-sequence stars and of giants with hot coronae are all similar to that of the Sun, although some line flux ratios vary with $N_e$ or the chromospheric opacity. The majority of the lines are formed by ion-electron collisions. However, the spectra of cool giants and supergiants are quite different in nature. In the cooler giants, as the surface gravity ($g_*$) and $N_e$ decrease from early K-type stars to mid-M stars, the line opacities tend to increase and lines formed by radiative excitation through accidental wavelength overlap with strong lines become stronger relative to the collisionally excited lines of the high chromosphere and low transition region. For example, the strong emission in the O I (mult. uv2) lines around 1304 Å, observed in α Boo (K2 III) from an early rocket flight, was shown to be caused by pumping by the H Lyman β line to the 3d level in O I, which decays through mult. UV 2 (Haisch et al. 1977). These strong O I lines then pump levels in S I (uv 9) (Brown & Jordan 1980), Si II (uv 3) around 1309 Å (Jordan & Judge 1984) and levels of CO in the fourth positive system (Ayres, Moos & Linsky 1981; Ayres et al. 1986). Pumping by H Lyman α excites many lines of Fe II (Johansson & Jordan 1984) and high levels in S I (Brown & Jordan 1980; Judge 1988). Pumping of H2 by H Lyman α was first discovered in solar sunspot spectra observed with the Naval Research Laboratory’s High Resolution Telescope and Spectrograph (HRTS) (Jordan et al. 1978) and was observed with IUE around the pre-main sequence star T Tauri (Brown et al. 1981). Other examples of fluorescence occur including pumping of Fe I (uv 44) by Mg II (Harper 1990) and pumping of other ions by H Lyman α and by Fe II (Carpenter et al. 1988). Examples of pumping within a given species where an optically thick line shares a common upper level with an optically thin line are also found in O I, C I and Fe II. The reviews by Jordan (1988, 1997) give details of this earlier work.

Given the improved sensitivity and spectral resolution of the GHRS medium resolution mode it is not surprising that there have been significant discoveries and advances from the new spectra obtained. One of the most exciting was the discovery of emission in the resonance lines of C IV in the cool “non-coronal” giant α Tau (K5 III) (Carpenter, Robinson & Judge 1994; Robinson et al. 1998). The same region of the spectrum also showed further weak lines of Fe II pumped by H Lyman α (Carpenter et al. 1994a) and recombination lines of Ca II following photoionization from the metastable 3d levels (McMurry, Jordan & Carpenter 1999). This photoionization route was recognized by Linsky & Avrett (1970) and many resulting recombination lines were identified by Sandlin et al. (1986) in solar sunspot spectra observed with the HRTS. The same GHRS spectrum showed lines of H2 pumped by H Lyman α, the first discovery of these lines within the atmosphere of a star other than the Sun. This spectrum is shown in Fig. 1, taken from McMurry et al. (1999). Observations of the spectrum around 1289–1310 Å revealed many more of these fluorescent lines of Fe II than could be observed with IUE. (See Fig. 1 in McMurry et al. 1999.) Subsequent observations of α Tau showed further lines of Fe II and H2, as can be seen from Fig. 2, taken from McMurry & Jordan (2000).

Although observations with IUE showed that the CO lines pumped by the O I resonance lines are present in a number of cool giants, the spectral resolution
Figure 1. GHRS spectrum of $\alpha$ Tau obtained by Carpenter (P.I.), showing weak, broad emission in C IV and fluorescent lines of Fe II, H$_2$ and Ca II. From McMurry et al. (1999).

Figure 2. GHRS spectra of $\alpha$ Tau showing fluorescent lines of Fe II, H$_2$ and CO, and other lines as indicated. From McMurry & Jordan (2000).

did not allow individual lines to be identified. This became possible in the GHRS spectra obtained of $\alpha$ Tau (McMurry et al. 1998, McMurry & Jordan 2000) and
Figure 3. GHRS spectra of K giants showing CO fluorescent lines and CO absorption in $\alpha$ Boo and $\gamma$ Dra. From Ayres et al. (1997).

the CO lines are indicated in Fig. 2. (See also the poster by McMurry & Jordan in these proceedings.) Figure 3 shows GHRS spectra of four K-type giants, from Ayres et al. (1997), illustrating the strength of the CO fluorescent lines in $\alpha$ Boo (K2 III) and $\gamma$ Dra (K5 III), and their absence in $\beta$ Gem (K0 III) and $\beta$ Cet (K0 III). Our line identifications and calculations for $\alpha$ Tau (McMurry & Jordan 2000) show that in this region the strongest five CO emission lines are due to the Q8, Q9 transitions from the excited $v' = 9$ level (1378.52 Å and 1378.69 Å), the Q25 transition from the $v' = 11$ level (1380.23 Å) and the Q19 and Q22 transitions from the $v' = 9$ level (1381.44 Å and 1382.64 Å). Ayres et al. (1997) suggest that CO absorption in the 5 to 0 band is present in the profiles of the Si IV lines and that this is caused within a two component atmosphere, where CO overlies the Si IV forming region rather than by pumping of CO by Si IV, which was discovered in the HRTS solar sunspot spectra (Jordan et al. 1979).
Absorption by CO bands was first discovered in GHRS spectra of α Ori (M2 Iab) by Carpenter et al. (1994b), although with hindsight the band heads are detectable in spectra obtained with IUE. The CO absorption is shown in Fig. 4, taken from Carpenter et al. (1994b) and is consistent with a circumstellar origin. This discovery explains the behaviour of the O I resonance lines in giants and supergiants, as observed at low resolution with IUE. Carpenter et al. (1990) noticed that in M supergiants the surface flux in the O I resonance lines is much weaker than in the K giants, although the chromospheric lines of S I + Si II around 1810 Å are stronger. It is now clear that in at least α Ori this decrease is caused by absorption by the CO bands. There must be strong O I (uv 2) emission present within the atmosphere because the intersystem line at 1641 Å (uv 146), from a common upper level, is present.

3. Flux ratios and line widths

3.1. Density sensitive flux ratios

While the fluxes in the stronger lines observed with IUE are reliable, the GHRS spectra have allowed improved measurements of the fluxes in lines whose ratios can be used to determine $N_e$. Such measurements are needed to make models of the atmosphere from emission measures ($\int N_e^2 dh$) derived from transition region lines, and to constrain semi-empirical models of chromospheres constructed to fit observed line fluxes and profiles. The intersystem lines of C II around 2326 Å provide the best method of measuring $N_e$ in cool evolved stars. The
lines of interest can be blended with lines of Fe II and the flux measurements have benefited from the higher spectral resolution and signal-to-noise of the GHRS. (E.g. compare the IUE spectrum of α Tau shown in Stencil et al. 1981 with the GHRS spectrum shown in Robinson et al. 1998).

3.2. Line widths

The emission measure distribution derived from line fluxes can be used together with the radiative power loss function to find the spatially averaged radiation losses from a stellar transition region as a function of temperature ($T_e$). If the emission line widths of optically thin (usually intersystem) lines can be measured with sufficient accuracy and the electron densities are known, then the radiative losses can be compared with the energy carried by acoustic or MHD waves passing through the atmosphere as a function of $T_e$. For example, in the low solar transition region the energy flux appears to be almost constant with $T_e$, since $\xi$, the most probable speed increases according to $T_e^{0.25}$ (Jordan 1991). (This assumes that the magnetic flux is constant with $T_e$). This behaviour is consistent with the small radiative losses from the low transition region. In the Sun, the observed values of $\xi$ are about half the sound speed. The IUE spectrum of the giant β Gem shows transition region lines and the values of $\xi$ measured from the line widths tend to exceed the local sound speed. GHRS spectra of β Gem obtained from the archive have been analyzed by an Oxford undergraduate project student (S. Sim). With the improved resolution of the GHRS the line widths are all smaller than those derived from the IUE spectra. This is particularly true for the narrowest optically thin intersystem lines formed below $2 \times 10^4$ K which could not be resolved with IUE. Although comparable with the sound speed to within the measurement errors, the speeds derived from such line widths are now all subsonic. A new model of the atmosphere and a discussion of the energy fluxes will be given in a forthcoming paper.

4. Modelling from the GHRS spectra of α Tau

For many years the standard model of the chromosphere of α Tau has been that by Kelch et al. (1978), which was based mainly on the lines of Ca II and Mg II. Judge (1986, 1988) used IUE observations to extend our understanding of the emission line spectrum. More recently, McMurry (1999) has used the GHRS spectra to make a new model of the high chromosphere, extending to a transition region at $10^5$ K to reproduce the C IV emission. This model is based on collisionally excited lines, plus the O I lines excited by H Lyman β. Although the model by Kelch et al. (1978) is still appropriate in the low chromosphere, the new model gives an improved fit to the resonance lines of C II and O I.

This model was then used to calculate the fluxes in the fluorescent lines of Fe II, Ca II and H$_2$ (McMurry et al. 1999). The lines of Fe II (and Ca II) are on average reproduced to within a factor of two. However, there are sufficient lines of Fe II pumped at different wavelengths within the H Lyman α profile to deduce that where the pumping occurs, the profile is narrower than computed in the model. The situation for H$_2$ is more dramatic; the chromospheric model fails to reproduce the observed fluxes by several orders of magnitude.
The model has also been used to calculate the fluxes in the recently identified lines of CO. Depending on the transition, there are large differences between many of the observed and predicted fluxes, again in the sense that the model gives insufficient flux. There are sufficient lines pumped from different lower levels of CO to deduce the excitation temperature in the region where the pumping occurs (see also Ayres 1986). This is \( \sim 2000 \) K, significantly lower than the minimum value of 2700 K in the model. Inhomogeneous models of the outer atmospheres of giant stars have been proposed by Wiedemann et al. (1994) based on modelling of the infrared absorption lines of CO. In addition to a normal chromosphere they suggest that there are regions in radiative equilibrium, where the temperature continues to decrease outwards, down to about 2400 K.

From our work on all the fluorescent lines it is clear that the one component (plane parallel) model which reproduces the collisionally excited lines cannot also account for the fluorescent lines. There must be more cool material present in close proximity to the pumping radiation. We suggest that the model which reproduces the collisionally excited lines describes regions heated by shocks, averaged over space and time. Shock heated models have been investigated by a number of authors (see e.g. Carlsson & Stein 1995; Buchholz et al. 1998; Ulmschneider 1999). The strong pumping lines then excite the fluorescent lines in the cooler surrounding regions which may resemble a radiative equilibrium atmosphere. The details of the evidence for this picture are given in McMurry & Jordan (2000) and our poster in these proceedings.

References

Carpenter, K. G., Robinson, R. D., Judge, P. G. 1994a, BAAS, 26, 1380
Jordan, C. 1988, JOSA B5, 2252
Jordan, C., Judge, P. G. 1984, Phys. Scripta, T8, 43