MEDIUM RESOLUTION SPECTROSCOPY AT 1-2 MICRONS

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ABSTRACT

The need for establishing classification criteria at long wavelengths is stressed. The usefulness of doing this is illustrated with a discussion of the composite spectra of FU Orionis stars. Spectra of these pre-main-sequence stars from 1.5-2.5μ were obtained with a Fourier Transform Spectrometer. Luminosity criteria in the 1-2μ range are also discussed with application to M stars.

1. INTRODUCTION

Classification of stellar spectra has traditionally been carried out in a very narrow spectral bandpass from 3900-4900 Å. Although this bandpass was originally a practical and convenient choice, it is not necessarily the optimum for all classes of stars. With the advent of new detection techniques, new alternatives are becoming available.

For at least three groups of objects the 1-2μ spectral region has significant advantages, and there is a corresponding need to establish classification criteria there, together with the necessary standards. The three groups are: (1) heavily obscured objects, (2) composite objects, and (3) late-type (M, S and C) stars in general.

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Examples are discussed here from the second and third groups which will serve to stress this need for future classification studies.

2. INSTRUMENTATION

Traditional classification resolution has been $\lambda/\Delta\lambda \simeq 2000$ at 4000 Å. Similar resolution at 2μ (5000 cm^{-1}) is presently best obtained with the Fourier Transform Spectrometer. For this medium resolution such instruments can be built at relatively low cost (e.g., Thompson and Reed 1975). They will remain the most efficient instruments for this purpose until detector noise in solid-state arrays is significantly reduced. Fourier Transform Spectrometers should no longer be considered as specialist instruments and are available or under development as common-user instruments at a number of observatories.

The spectra to be discussed here were obtained with a prototype 10-cm FTS (Hall 1977, Ridgway and Capps 1974) at the Mayall 4-m telescope. Although this instrument is capable of high resolution ($\lambda/\Delta\lambda \approx 10^5$), a programmable reduction in the path length enables considerably lower resolution to be used without loss of efficiency.

3. CLASSIFICATION CRITERIA AND THE RECOGNITION OF COMPOSITE SPECTRA

Features available as classification criteria in the 4000-7000 cm^{-1} region include:

(1) Brackett lines of hydrogen. These are strong, of course, in types A and F, and diminish rapidly in later types.

(2) A number of three to five volt lines of Al I, Si I and Mg I replace the hydrogen lines in G type spectra.

(3) The first overtone CO bands become strong in K giants. Like CN in the optical, and for the same reasons, these bands are positive luminosity criteria (Baldwin, Frogel and Persson 1973). Unlike the CN bands, they increase monotonically through M types.

(4) The 1.9μ band of water vapor appears in middle M types and increases rapidly with decreasing temperature.

(5) The Ballik-Ramsay C_2 bands distinguish carbon stars (Thompson et al. 1973).

A systematic program of observing classification standards would enable these loose criteria to be defined precisely but no such work has yet been attempted.

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Even with such loose criteria, however, a mismatch between optical and infrared classifications can readily identify composite objects. A fine example is provided by the FU Orionis stars (Herbig 1966, 1977). For V 1057 Cygni a hint of a later spectral type in the red (G2 - 5Ib) than in the blue (G0) was already apparent to Herbig. In the infrared, however, a much later type is clearly seen (Fig. 1) from the strong water vapor depression, the presence of CO and the absence of Brackett lines.

Mould et al. (1978) discuss models for the origin of these composite spectra. In the model they favor, gravity darkening of a rapidly rotating protostar produces a strong negative temperature gradient from pole to equator. A quantitative model can be constructed using the geometrical formulation of Collins (1963) and von Zeipel's (1924) gravity darkening theorem. The optical G0 spectrum comes from the hot polar regions and the infrared spectrum from the equator. The 10-20μ infrared excess of FU Ori stars must originate in a circumstellar shell, which is probably flattened in the plane of rotation. This shell may indeed be a disk evolving in the manner envisaged by Lynden-Bell and Pringle (1975). This aspect of the model is subject to dynamical test by comparison of the infrared and optical line profiles at higher resolution.

Further work at classification resolution is required to establish the spectroscopic relationship of these stars to the precursor T Tauri stars.

To conclude on the subject of composite spectra, it is worth recalling that the spectra of galaxies fall into this category. At classification resolution the nuclei of bright galaxies are marginally accessible in the infrared. Information on their stellar populations will be available from infrared spectra.

4. M DWARFS AND SUBDWARFS

For very cool stars in general the infrared has important advantages over the blue for spectral classification. Over a hundred times more flux is one factor; another is the avoidance of confusion due to line blanketing. A very clear-cut luminosity criterion for separating giants and dwarfs is provided by the first overtone CO band. Very good criteria are also available, however, for distinguishing subdwarfs.

In Fig. 2 marked line weakening is apparent in the quite mild subdwarf Gliese 15A, relative to a regular dwarf, Gliese 229, of almost the same temperature. Model atmosphere calculations indicate that this is a result of metal deficiency. The abundance difference

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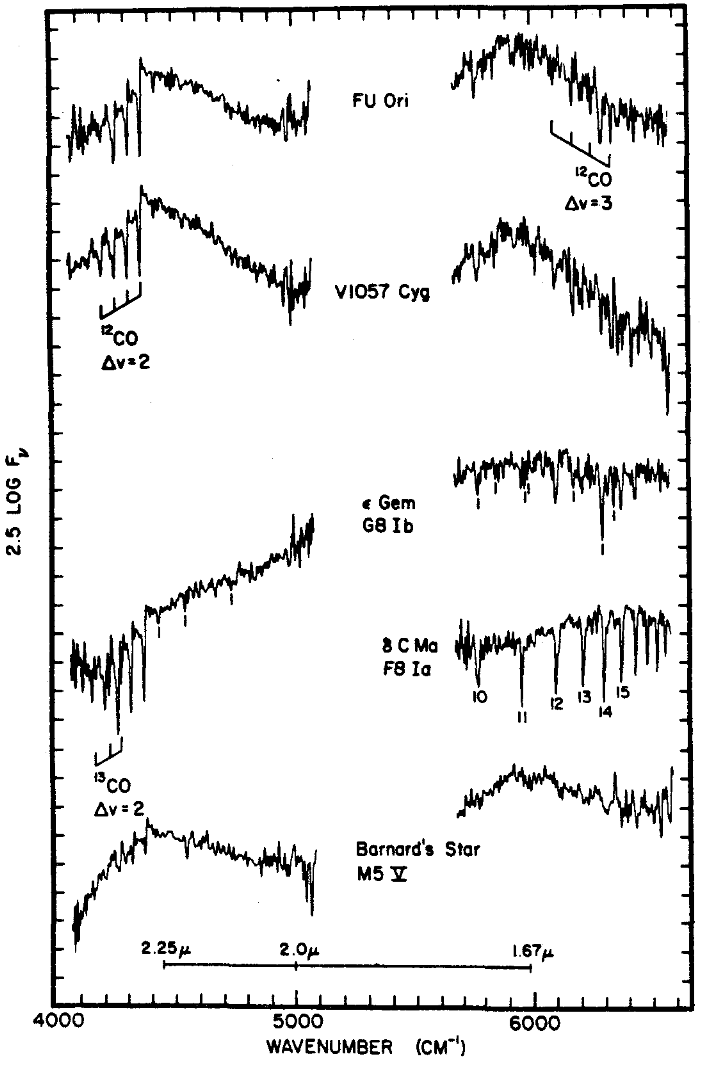

Fig. 1. Spectrophotometry of FU Ori and V1057 Cyg at 5 cm^{-1} resolution. F and G supergiants and a late M star are shown for comparison. Vertical ticks are separated by 0.1 mag. No data are available for the opaque region 5080-5670 cm^{-1}, and only the blue part of the spectrum of δ CMa is shown. The unlabelled vertical lines mark prominent metal lines which could be identified in the sunspot atlas of Hall (1974). In the noisiest spectrum (FU Ori) the rms signal-to-noise ratio is ~130 at 4500 cm^{-1} The noise increases substantially for wavenumbers > 6500.

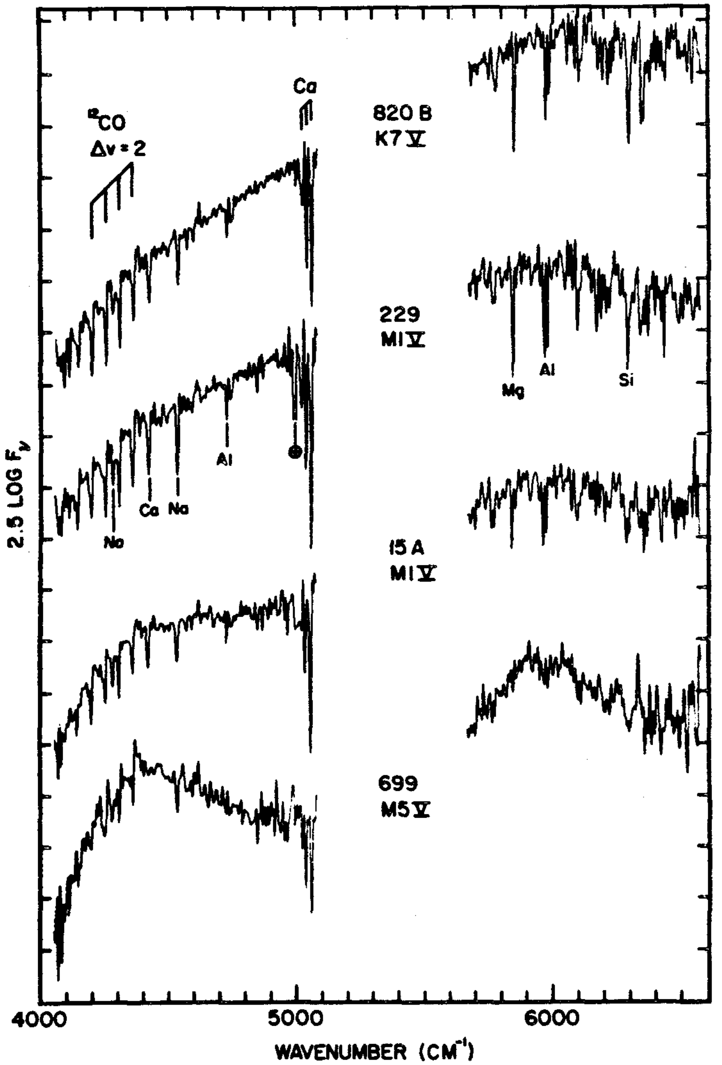

Fig. 2. Spectrophotometry of four M dwarfs. Vertical ticks are separated by 0.1 mag. The first four heads of the first overtone band of ^{12}CO are identified, together with a number of strong neutral metal lines. The terrestrial CO_2 band ⊕ near 50000 cm^{-1} has not been fully corrected out in the spectrum of Gl 229 (air mass 1.7).

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between these stars is estimated by Mould (1978) to be a factor of 3.5. More extreme subdwarfs exist and can be recognized in the blue (see, for example, Kapteyn's star in Keenan and McNeil 1976). But infrared spectra seem more sensitive, and can be expected to yield the most reliable classifications and abundances for these objects.

5. CONCLUSIONS

It is apparent that 2μ spectroscopy has some advantages over the conventional blue spectral region for certain interesting classes of objects. A number of good classification criteria are available, but a disciplined program of observation of MK standards is required to realize their full potential.

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DISCUSSION

Jaschek: Could you please indicate why you reject the binary explanation for the FU Ori stars?

Mould: I do not think the binary hypothesis can be rejected. Three aspects of the binary interpretation, however suggest that it is an ad hoc solution rather than a compelling model: (1) it is not clear whether an over-luminous T Tauri star and an under-luminous M giant ($M_{BOL} \simeq -1$) form a consistent evolutionary pair. One possible suggestion is that the M giant is a low mass star in its Hiyashi contraction phase; (2) no radial velocity variations have been observed. In the edge-on case with both masses approximately solar, a binary separated by less than 10 AU could be detected in Herbig's optical velocity curve. If we suppose a large mass ratio of the hot to cool components, the agreement between the infrared velocities and the molecular cloud velocities places a similar constraint; (3) the 5 mag outbursts remain a mystery. Mass transfer, although an attractive mechanism, is unlikely given the minimum separation derived above and a radius for the cool (larger) component of $\gtrsim$ 0.5 AU.

Welin: How do the observed spectral changes in V1057 Cyg (from A (or even B) to G fit into your model? Is the given rotational velocity for V1057 Cyg v or v sin i? V1057 Cygni has been said on several grounds (each pretty weak, but together maybe of some weight) to be seen almost pole-on. Could the line broadening be due to heavy turbulence instead of rotation?

Mould: Perhaps the star spins up during contraction and, on reaching break-up velocity, throws off a shell. This might explain the observed outburst in the periodic mode Herbig suggests. The optical line widths cannot unequivocally be assigned to rotation. The velocity derived from this hypothesis is, of course, v sin i. However, it would be hard to see how turbulence could give line widths of 65 km s^{-1}, in a spectrum which now looks relatively quiescent.

Cowley: Do you see a difference in the widths of lines that might characteristically arise in the polar region as compared to those lines that might arise in the cooler equatorial regions of the star?

Mould: The resolution of the spectra we have obtained in the infrared is not yet sufficient to tell this. If the star is in solid body rotation, a higher velocity width might be expected in the infrared. If the coolest component of the spectrum arises from a circumstellar (Keplerian?) disk, lower velocities may be possible. This information is dynamically very interesting, and we will go after it as soon as possible.