Theoretical Studies of Chromospheres

and Winds in Cool Stars

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I. Atmospheres of Hot Pre-Main Sequence Stars

In collaboration with R. Wehrse and P. Hofflich of the University of Heidelberg, we have calculated the properties of hydrogen emission lines in the extended atmospheres of hot pre-main sequence stars. This work is particularly aimed at understanding the infrared hydrogen line emission from luminous, heavily extincted stars like the Becklin-Neugebauer object in Orion. The Brackett and Paschen emission from these objects is much higher than expected from case B recombination in an H II region (Simon et al. 1983; Thompson 1984). Krolik and Smith (1981) have attributed this excess to thermal emission in a dense stellar wind, and used isothermal LTE models to derive the necessary mass loss rates. Simon et al. (1983) also constructed isothermal LTE models with Sobolev calculations of line profiles to estimate the mass loss rates for these stars.

In order to investigate the emission envelopes of these stars, we have constructed spherically extended, non-LTE radiative equilibrium models. We find that non-LTE effects can significantly reduce the mass loss rates estimated from LTE models, and that the Sobolev approximation may not be adequate for calculating line emission arising in these slowly expanding envelopes. Our results also show that both photoionization from the Balmer continuum radiation field and collisional excitation are responsible for the excess infrared emission relative to case B recombination.

We intend to pursue two further lines of research in this area. Line profiles will be calculated for comparison with observations. We expect to find that substantial turbulent velocities are required to fit the profiles, which may be an important clue to the reason why these stars have such low-velocity winds, in contrast to most early-type stars. The detailed temperature structure and ionization balance from our models will also be used to investigate the problem of O I fluorescence in these atmospheres (cf. Persson 1984).

II. FU Orionis Winds

The FU Orionis stars exhibit powerful winds (Bastian and Mundt 1984), and it has been suggested that these winds may significantly affect the dynamics of the interstellar material surrounding T Tauri stars (Mundt and Hartmann 1983). For this reason, it is of interest to derive the mass loss rates of these stars.

Ken Croswell, a graduate student, has been exploring the limits that can be placed on mass loss from FU Ori from comparisons with the Hα and Na I D lines. A relationship has been derived between the mass loss rate and the wind temperature that must be satisfied in order to account for the observed line profiles. Croswell has found that the minimum mass loss rate that can account for the Hα line is $\sim 10^{-7}\ M_{\odot}\,yr^{-1}$. The Na lines are much harder to model, but mass loss rates in the range $\sim 10^{-6}$ - $10^{-5}\ M_{\odot}\,yr^{-1}$ are indicated. It is clear from this work that the winds from FU Ori stars must have a profound effect on neighboring material.

III. Hα Emission from M Dwarfs

A large body of data on the Hα emission of M dwarfs is now available (Stauffer et al., in preparation). The data show that most M dwarfs exhibit a narrow range of Hα absorption equivalent widths, with a sprinkling of stars having Hα in emission. Cram and Mullan (1979) investigated the formation of this line in the chromospheres of M stars. We intend to calculate the behavior of Hα

not as a function of chromospheric column density but as a function of Ca II and Mg II radiative losses. We suspect that the Hα equivalent width is relatively constant for a wide range of radiative losses, producing the observed narrow range. At some critical, large value of Ca II and/or Mg II emission, we expect that Hα thermalizes and goes into emission. Thus, we predict that Hα emission is produced by only a few stars with large amounts of mechanical energy deposition. Finally, we will investigate Hα emission at very large heating rates. We expect that it will be very hard to get equivalent widths of emission greater than about 10A from a plane-parallel chromosphere. This result will explain why it has been so difficult to find the "post-T Tauri" stars from Hα emission surveys. T Tauri stars probably have extended Hα-emitting regions, and this extension increases the emitted flux considerably over a plane-parallel model with comparable emissivity. We hope to show that Hα emission collapses rapidly at a critical extended envelope density.

IV. Envelopes of T Tauri Stars

Our work on FU Ori and the results from the M dwarf chromospheric emission calculations will provide the basis for our continuing modelling of T Tauri spectra. We intend to calculate a small grid of models for two effective temperatures and a few different mass loss rates. From these calculations we hope to make quantitative estimates of mass loss rates, or at least quantify our ignorance, and to assess the relative importance of turbulent and expansion velocities in the envelopes of these stars. One model has been completed for a mass loss rate of 7 x 10^{-9} $M_{\odot} yr^{-1}$ from a star with an effective temperature of 4000K.

V. Extended Chromospheres of M Supergiants: α Ori

In a recent paper (Hartmann and Avrett 1984), we produced a theoretical model of the extended chromosphere of α Ori which produced a reasonable fit to the average electron density profile indicated by radio observations, but was less successful in explaining line ratios and profiles. Shock models calculated by John Raymond indicate that the emission produced by pulsational shock waves can explain the emission line ratios much better. We are beginning simple hydrodynamic calculations of pulsational waves for physical conditions appropriate to α Ori. Our intent is to use these simple models to estimate shock velocities, and then apply the shock calculations of Raymond to predict the emergent line emission. The shock structure will then be averaged over time in order to compare the predicted free-free emission with the radio observations.

VI. Chromospheres of Metal-Deficient Giants

Also published during this reporting period were the results of semi-empirical atmospheric modelling that indicated the emission seen in the Hα wings of Population II giant stars can arise naturally from static chromospheres, requiring no mass loss (Dupree, Hartmann, and Avrett 1984).

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