A&A 376, 154–157 (2001)
DOI: 10.1051/0004-6361:20010957

Astronomy
&
Astrophysics

Research Note

What can HST-GHRS Fe II observations of α Orionis (M2 Iab) tell us about short-period heating?*

M. Cuntz[1], G. M. Harper[2], and P. D. Bennett[2,3]

[1] Department of Physics, University of Texas at Arlington, Arlington, TX 76019-0059, USA
[2] Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309-0389, USA
e-mail: `gmh@casa.colorado.edu`; `pbennett@casa.colorado.edu`
[3] Department of Astronomy and Physics, Saint Mary's University, Halifax, N.S. B3H 3C3, Canada
e-mail: `pbennett@ap.stmarys.ca`

Received 29 January 2001 / Accepted 21 May 2001

Abstract. Cuntz (1997) suggested that apparent velocity shifts in Fe II emission lines observed in Betelgeuse (α Orionis: M2 Iab) indicate that non-magnetic wave modes are relevant for the heating and dynamics of α Ori's chromosphere. This claim was based on the similarity of computed stochastic velocities in 1-D short-period acoustic wave models and velocity shifts in profile fits to Fe II emission lines (Carpenter & Robinson 1997), which is now identified as coincidental. While acoustic waves may indeed be important for the heating and dynamics of α Ori's chromosphere, the interpretation of the Fe II emission line profiles does not provide evidence for this possibility. The line formation of optically thick scattering lines in an extended outflow makes Fe II emission lines poorly suited as a diagnostic for small-scale structure in hydrodynamical models. Better diagnostics include electron density sensitive, low opacity lines such as C II]. In the view of these findings, we discuss directions of future research.

Key words. hydrodynamics – waves – stars: chromospheres – stars: individual: α Ori – stars: supergiants

1. Introduction

The mechanisms which heat chromospheres and drive stellar winds from evolved late-type stars are outstanding problems in stellar astrophysics. While there is no consensus on the origin of mass loss, a relatively simple picture has emerged concerning chromospheric heating. There appears to be a magnetic component, which is related to rotation and convection, and a "basal" component, which is independent of stellar rotation and possibly related to acoustic wave heating (e.g., Schrijver 1995; Buchholz et al. 1998). Although not a basal flux star per se because of the presence of chromospheric variability at different time-scales (e.g., Carpenter 1984; Dupree et al. 1987) and the existence of large-scale dynamic surface structure (Buscher et al. 1990; Klückers et al. 1997), resulting in episodic heating and emission (Toussaint & Reimers 1989), α Ori is considered relatively inactive. This result is also supported by a study of Judge & Stencel (1991), who provided a statistical analysis of mass-loss energetics, heating rates, and Mg II emission of α Ori in comparison with other evolved stars.

In the view of this result, Cuntz (1997) calculated a set of stochastic acoustic heating models assuming 1-D short-period shock waves. These models were time-dependent, fully nonlinear, and also considered the height-evolution of the photospheric wave frequency spectrum. The time-scale of variability associated with chromospheric heating was $\lesssim 5 \times 10^6$ s, which is distinctly different from the longer time-scales given by the irregular variability of photospheric absorption lines (Goldberg 1984, and references therein) or pulsation (Dupree et al. 1987; Smith et al. 1989). Due to the mechanical energy dissipation by the shocks, episodic chromospheric heating occurred leading to temperatures of $\gtrsim$8000 K in the Ca II and Mg II line formation region. Cuntz also compared the flow velocities from his models with velocity information contained within α Ori's (M2 Iab) Fe II emission profiles and suggested that the agreement provides evidence for the existence of nonmagnetic heating. In this paper we examine this claim. In Sect. 2 we describe the Fe II emission line

---

Send offprint requests to: M. Cuntz, e-mail: `cuntz@uta.edu`

* Based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

data presented by Carpenter & Robinson (1997). In Sect. 3 we discuss the implications of the observational data in conjunction with the theoretical models. The conclusions are given in Sect. 4.

2. Fe II profiles of α Orionis

2.1. Fe II profiles

Fe II emission line spectra of α Orionis (M2 Iab) have been obtained with the Goddard High Resolution Spectrograph (GHRS) on-board the *Hubble Space Telescope* (Carpenter & Robinson 1997). These data were obtained on two days, 1992 September 22 and 1992 September 24, through the Small Science Aperture with moderate resolution $R \sim 15$ km s^{-1}. The typical exposure times were 10 min. Carpenter & Robinson presented multi-Gaussian fits for the Fe II line profiles in order to allow a cursory empirical analysis of their large dataset. This form of data compression has its limitations in that a direct physical interpretation of the line fit parameters is not always possible and the systematic uncertainties are extremely difficult to evaluate. The fits for α Ori take the assumed form of a Gaussian emission profile, with two superimposed saturated Gaussian absorption features, but do not include the spectrograph line spread function.

Carpenter & Robinson (1997) also found the velocity centroids of the Gaussian emission component of Fe II lines, which span a range of relative optical depths, show significant scatter about a mean velocity which is close to the photospheric value. The mean and standard deviation of these velocity centroids are 18 ± 6 km s^{-1}, compared to the optically determined heliocentric photospheric velocity of 21 km s^{-1} (Dupree, communication to Carpenter & Robinson 1997). The mean velocity of Fe I absorption features in the GHRS spectra is also 18 km s^{-1}.

2.2. Line formation processes

The formation of Fe II lines in late-type stellar chromospheres has been discussed by Judge & Jordan (1991), Judge et al. (1992), and Johansson & Jordan (1984). The rich UV Fe II spectrum is found to be excited by three main processes: direct collisional excitation, collisional excitation followed by photoexcitation by the photospheric radiation field, and selective photo-excitation, e.g. by H Lyα.

A simple picture for the formation of these chromospheric emission lines in evolved late-type stars with partially ionized winds can described as follows: in the dynamic chromosphere which has little or no discernible mean outflow velocity, Fe II is the dominant ionization stage and the pool of Fe II line photons are excited by collisions and photo-excitation. Photons in optically thin lines which escape in the direction of the observer directly reflect velocity fields integrated over the stellar disk, while photons in the cores of optically thick lines undergo repeated scattering. The strongest lines show wind absorption features and are optically thick in the wind. For these lines the observed profile is a complicated combination of the underlying emission feature with P-Cygni line scattering. The important difference between classical P-Cygni scattering and that in the winds of evolved late-type stars is that in the latter case the turbulence is comparable to the wind flow over a wide region and there may be significant geometric occultation by the stellar disk. The shaping of the line profiles by scattering and line-interlocking presents a substantial challenge for quantitative spectral interpretation. The repeated scattering of line photons in the wind, as well as averaging of the line formation regions over the stellar disk, results in loss of information about the small-scale chromospheric velocity fields. Although the information present in the rich Fe II spectra has been used to construct quantitative wind acceleration models (large scales) for several evolved late-type stars (e.g., Carpenter et al. 1999), these lines are probably not suitable diagnostics of small-scale density or velocity structure in the chromosphere.

3. Evaluation of 1-D short-period heating models

3.1. Fe II line formation

We now consider the suggestion by Cuntz (1997) that apparent velocity shifts in Fe II emission lines indicate that non-magnetic wave modes are relevant for the heating and dynamics of α Ori's chromosphere. The basis of this claim has been the similarity of the scatter in the centroid velocities of fits to the Fe II emission lines and the calculated velocity structure of the 1-D acoustic shock models. In Fig. 1 we present the emission velocity data of Carpenter & Robinson (1997). In the top panel we show the centroid velocity of the Gaussian emission features as a function of the energy of the upper level. In the bottom panel we show the same lines plotted against an estimate of the relative line center optical depth. If the passage of shock waves through the atmosphere were to lead to differences in emission velocity as implied by Cuntz, then one would expect that these differences would be related to their excitation, and their height in the chromosphere. There is no evidence in these figures that shows that selected lines behave differently from the sample.

Since the excitation energy of the bulk of the lines is similar, most of the Fe II photons will be created in plasma where the line contribution functions are high. Collisionally excited optically thin lines formed in these regions would have the same velocities. Multiple scattering in strong lines can lead to pumping of weaker lines which share a common upper level, and Doppler induced shifts can alter the apparent velocity centroid. Lines with different opacity would scatter of different regions potentially leading to differences in velocity centroid. The lower panel shows no clear trend with line opacity. It is more likely that multiple scattering will average out the

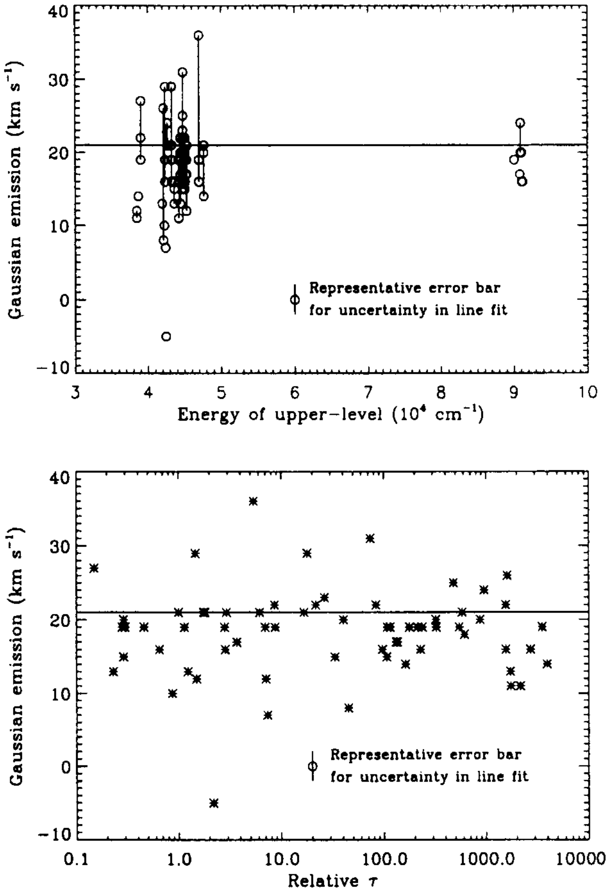

Fig. 1. The centroid velocity of the Gaussian emission features for Fe II lines in α Ori from Carpenter & Robinson (1997). The velocities are heliocentric and the stellar photospheric velocity (21 km s^{-1}) is shown in both panels. Top panel: velocity plotted against energy of upper level, where lines from a common upper level are joined by a solid line. This shows there is considerable scatter for lines from a given level. Bottom panel: Velocity plotted against relative optical depth (see text for details). These scatter plots provide no indication that selective Fe II lines are formed at different velocities.

velocity differences. So even in cases with small-scale shocks with discrete velocities existing, we would not expect to see different lines with different velocities, especially when the disk integrated spectrum is considered.

Potential sources of the actual scatter of the Fe II emission centroids are (a) absolute uncertainties in the wavelengths of each GHRS spectra region ($1\sigma \sim 2$ km s^{-1}), (b) emission line blends (0.5–3 km s^{-1}), (c) unknown overlying absorption sources, (d) optical depth effects, such as line interlocking, (e) uncertainties in the fitting procedure, and (f) biasing from the assumed form of the schematic line fits. Carpenter & Robinson (1997) themselves suggested that the scatter may result from sources (a)–(d); sources (e)–(f) are likely to be important for some lines but hard to quantify. There is no evidence here that the underlying Fe II emission features are differentially shifted by any dynamical process.

3.2. Chromospheric extent

There is substantial observational evidence that the scattering region for Fe II in evolved stars extends far into the winds, which is beyond the region where most of the energy in short-period wave models is dissipated. In ζ Aur systems, the strong lines of Fe II are known to scatter in extended regions (e.g., Baade et al. 1996). The partially ionized wind of α Ori has been mapped through semi-empirical models which satisfy radio free-free continuum observations (Newell & Hjellming 1982), cf., Skinner & Whitmore (1987), Skinner et al. (1997). Hα emission in α Ori is observed out to 4 R_* (Hebden et al. 1987). On the other hand, short-period wave models are typically restricted to $\lesssim 1.2\ R_*$ (Cuntz 1992, 1997). This atmospheric extent is similar to that of the semi-empirical chromosphere model by Basri et al. (1981), which has been constructed to account for Mg II *k* and Ca II K line observations. Even though the majority of the photon creation may occur within 1.2 R_*, the optically thick Fe II line profiles are shaped by the scattering in a much more extended region, which point to the need of a unified chromosphere and wind model as well as the necessity of considering long-period wave modes.

3.3. Non-radial velocity fields and turbulence

A major shortcoming of 1-D wave models (both acoustic and magnetic) is the absence of non-radial motions. The large line widths of the low opacity lines suggest supersonic motions well in excess of those in the heating model calculated. These have important effects on the predicted disk integrated spectrum. If such non-radial motions are driven by acoustic waves, the discrepancy between synthetic and observed line widths can possibly be reduced.

Another drawback to 1-D models is the difficulty of representing turbulence, which is closely related to the scale of dissipation in comparison with 3-D models. In 1-D models the shocks "cannabalize" each other and grow to a small number of large-amplitude shocks (Cuntz 1992). In 3-D models, however, this effect is likely largely suppressed, which may allow the mechanical energy to cascade down to small-scale motions resulting in the generation of turbulence (e.g., Tennekes & Lumley 1987; Frisch 1995). This may also explain why 1-D heating models commonly fail to reproduce the observed chromospheric turbulence inferred from the line widths of the C II] 2325 Å multiplet, which is ~35 km s^{-1} *FWHM* in α Ori (Carpenter & Robinson 1997). The C II] multiplet is expected to be excited in the same chromospheric region as the Fe II lines.

Another method of determining chromospheric turbulence is the analysis of optically thick (and effectively thin) lines such as Mg II *h*+*k* (Robinson & Carpenter 1995; Carpenter & Robinson 1997), which form over a large depth range. In this case, the deduced turbulence is strongly model dependent and the interpretation of the results is much less clear. Lobel & Dupree (2001) analyzed the Si I λ2516 (UV 1) line, among other lines, and deduced a “macrobroadening” velocity of 9 ± 1 km s^{-1} required to derive the correct line width from the predicted (NLTE) profile after considering instrumental corrections. This value appears to be commensurate with the velocity range of the Cuntz (1992, 1997) models. Clearly, more detailed studies are needed to relate turbulent velocities from observations and semi-empirical models to time-dependent ab-initio simulations in an appropriate manner.

4. Conclusions and outlook

The purpose of this paper is twofold. First, we want to pointed out the limitations of using Fe II as a diagnostic of the small-scale inflow and outflow of dynamical shock wave models. Line-interlocking and the presence of wind scattering make Fe II a less than optimum choice for comparing observational results with those predicted by theoretical models. The similarity of computed stochastic velocities in 1-D short-period acoustic wave models (Cuntz 1997) and velocity shifts in profile fits to Fe II emission lines (Carpenter & Robinson 1997) is found to be coincidental. Second, we want to emphasize the intrinsic limitations of 1-D chromospheric heating models in representing the observed tangential turbulence. Although these models often describe the height-dependent heating rates sufficiently well (e.g., Buchholz et al. 1998), they are apparently dynamically incomplete – a result also found in a study for α Tau (K5 III) based on the analysis of C II] 2325 Å intersystem lines (Judge & Cuntz 1993).

This type of incompleteness is, however, also encountered in existing *magnetic* α Ori chromosphere/wind models as e.g. the Alfvén wave wind model by Hartmann & Avrett (1984). Although this model does a tolerable job in reproducing a broad range of spectral features, it is insufficient to account for the GHRS Fe II observations as it assumes a constant energy damping length in time-independent approximation, and does also not account for the interaction between the wind flow and the waves (see Charbonneau & MacGregor 1995 for details). Future chromospheric models should thus include 2-D or 3-D velocity fields, which are essential for a more realistic representation of the atmospheric dynamics in evolved late-type stars. While this is currently a very demanding computational task, it is nevertheless required from recent observations, e.g., the high S/N and spectral resolution optical and UV observations obtained by HST/GHRS and STIS, as well as from line profile modeling.

Multi-dimensional magnetohydrodynamic models for the stellar parameters of α Ori have recently been computed assuming a constant temperature profile (Airapetian et al. 2000). We look forward to the inclusion of a detailed energy equation in these models, so that emission line profiles can be compared with observations. Another important task would be to calculate 2-D or 3-D non-magnetic chromospheric heating models and to consider effects of gravity modes and semi-regular pulsation. These models should also take into account improved computations of nonmagnetic energy generation, including realistic photospheric frequency spectra.

Acknowledgements. We are thankful for numerous discussions with colleagues and the encouragement to pursue the problem of complex velocity fields in cool star atmospheres. In particular, we would like to thank Dr. A. Brown. This research was funded in part by the NASA LTSA grant NASA-GODD (NAG5-4804) to the University of Colorado (G.M.H.). Support for this work was also provided by NASA through grant numbers AR-5285.02-93A, AR-06383.01-95A and AR-06369.01-95A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555 (M.C., G.M.H., P.D.B.).

References

Airapetian, V. S., Ofman, L., Robinson, R. D., et al. 2000, ApJ, 528, 965
Baade, R., Kirsch, T., Reimers, D., et al. 1996, ApJ, 466, 979
Basri, G. S., Linsky, J. L., & Eriksson, K. 1981, ApJ, 251, 162
Buchholz, B., Ulmschneider, P., & Cuntz, M. 1998, ApJ, 494, 700
Buscher, D. F., Haniff, C. A., Baldwin, J. E., & Warner, P. J. 1990, MNRAS, 245, 7p
Carpenter, K. G. 1984, ApJ, 285, 181
Carpenter, K. G., & Robinson, R. D. 1997, ApJ, 479, 970
Carpenter, K. G., Robinson, R. D., Harper, G. M., et al. 1999, ApJ, 521, 382
Charbonneau, P., & MacGregor, K. B. 1995, ApJ, 454, 901
Cuntz, M. 1992, in Cool Stars, Stellar Systems, and the Sun, Seventh Cambridge Workshop, San Francisco, ASPCS 26, ed. M. S. Giampapa, & J. A. Bookbinder, 383
Cuntz, M. 1997, A&A, 325, 709
Dupree, A. K., Baliunas, S. L., Guinan, E. F., et al. 1987, ApJ, 317, L85
Frisch, U. 1995, Turbulence (Cambridge University Press, Cambridge, UK)
Goldberg, L. 1984, PASP, 96, 366
Hartmann, L., & Avrett, E. H. 1984, ApJ, 284, 238
Hebden, J. C., Eckart, A., & Hege, E. K. 1987, ApJ, 314, 690
Johansson, S., & Jordan, C. 1984, MNRAS, 210, 239
Judge, P. G., & Cuntz, M. 1993, ApJ, 409, 776
Judge, P. G., & Jordan, C. 1991, ApJS, 77, 75
Judge, P. G., Jordan, C., & Feldman, U. 1992, ApJ, 384, 613
Judge, P. G., & Stencel, R. E. 1991, ApJ, 371, 357
Klückers, V. A., Edmunds, M. G., Morris, R. H., & Wooder, N. 1997, MNRAS, 284, 711
Lobel, A., & Dupree, A. K. 2001, ApJ, in press
Newell, R. T., & Hjellming, R. M. 1982, ApJ, 263, L85
Robinson, R. D., & Carpenter, K. G. 1995, ApJ, 442, 328
Schrijver, C. J. 1995, A&AR, 6, 181
Skinner, C. J., Dougherty, S. M., Meixner, M., et al. 1997, MNRAS, 288, 295
Skinner, C. J., & Whitmore, B. 1987, MNRAS, 224, 335
Smith, M. A., Patten, B. M., & Goldberg, L. 1989, AJ, 98, 2233
Tennekes, H., & Lumley, J. L. 1987, A First Course in Turbulence (MIT Press, Cambridge, MA)
Toussaint, F., & Reimers, D. 1989, A&A, 226, L17