Letter to the Editor

Infrared line emission in 10 Lacertae

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Abstract. We report the presence of Brα and Brγ emission features in the infrared spectrum of the O9V MK standard star 10 Lac. Waters et al. (1993) have reported similar emission in the spectrum of the B0.2V star τ Sco and have suggested that the emission is from a low-density disk and that τ Sco is a mild, pole-on member of the Be class of stars. We argue that such emission features arise as a natural consequence of the structure of these stars' outer atmospheres, thus eliminating the need to introduce departures from spherical symmetry. Indeed, theoretical Brα and Brγ line profiles calculated using stellar parameters derived for 10 Lac by Grigsby et al. (1992) show a striking similarity to our observations.

Key words: Infrared: stars; stars: atmospheres – Be

1. Introduction

It is only recently that advances in instrument technology have enabled the acquisition of good-quality infrared spectra of high dispersion. Already such spectra have revealed line profiles that are in surprising contrast with those of lines at other wavelengths. Waters et al. (1993) (hereafter WMGOZ) have reported emission in the Brα and Brγ lines of the B0.2V MK standard star τ Sco which was unexpected as the star does not exhibit emission in the Balmer lines. They proposed that their observations were consistent with emission from a low-density disk and that τ Sco could be a mild, pole-on, member of the Be class.

As part of a programme of characterizing the infrared spectral line morphology of normal O and B stars, we have obtained infrared line profiles of the O9V MK standard star, 10 Lac, that show emission which is very similar to that observed in τ Sco by WMGOZ. In this paper we present these results as well as our own observations of τ Sco. We investigate the extent to which it is possible

to explain these observations as a natural consequence of the atmospheric structure of hot stars rather than as an aspect of the Be phenomenon.

2. Observations

10 Lac and τ Sco were observed on the nights of 1993 July 27–29 using the Cooled Grating Spectrometer No. 4 at the United Kingdom Infrared Telescope. The instrument was configured with the 300 mm camera and échelle, to give a sampling of three points per ~ 20 km s^{-1} resolution element and a spectral range per wavelength setting of 1400 km s^{-1}. Observations were made of both stars at Brγ (2.166 μm) and He I 2.058 μm. In addition, 10 Lac was observed at Brα (4.052 μm). Integration times per point were 80 seconds for all settings, giving a continuum signal-to-noise ratio of between 20 (10 Lac Brα) and 150 (τ Sco Brγ).

Wavelength calibration was achieved by the measurement of the positions of atmospheric absorption features which were themselves identified through comparison with arc or nebular emission spectra. The resulting wavelength scale is accurate to better than ± 2 km s^{-1} at Brα and Brγ and better than ± 1 km s^{-1} at He I 2.058 μm.

Spectra of HR 8626 (G3Ib) were used for atmospheric correction of the 10 Lac Brγ and He I observations, HR 6106 (G0IV) for correction of τ Sco Brγ and He I and HR 8718 (F5II) for correction of 10 Lac Brα. The absorption lines in the Brα and Brγ atmospheric standard spectra were removed prior to ratioing. No such correction was necessary for He I 2.058 μm.

Few of the atmospheric standards we observed at these settings had photometry available for the purpose of flux calibration so all spectra presented here were calibrated relative to a single observation at Brγ of the F2IV star τ Cyg (HR 8130), where we assumed $K = 2.70$ and $T_{\rm eff} = 6880$K. As a check, we compared the resulting continuum fluxes with continuum fluxes derived from broadband photometry of 10 Lac (Castor & Simon 1984; Deacon 1992) and τ Sco (Thé, Wesselius & Janssen 1986). They were found to be consistent to within about 8 per cent.
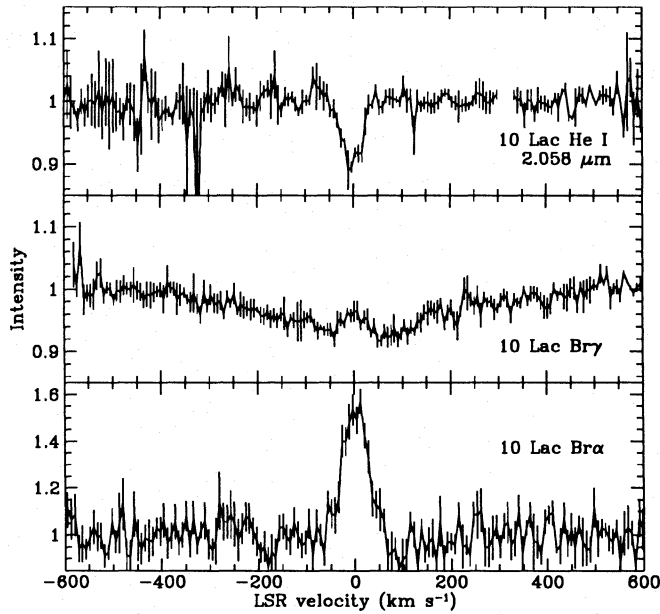

Fig. 1. Observed line profiles of 10 Lac.

Fig. 2. Observed line profiles of τ Sco.

Table 1. Stellar data and estimated parameters of the observed line profiles.

Parameter	units	10 Lac	τ Sco
Spectral type		O9V	B0.2V
$v_{rot} \sin i$	km s^{-1}	25[a]	5[a]
v_{LSR}	km s^{-1}	-1 ± 1[b]	$+11 \pm 1$[c]
		Brα	
FWHM	km s^{-1}	59 ± 9	67[d]
v_{LSR}	km s^{-1}	$+2 \pm 4$	-10[d]
flux	10^{-17} W m^{-2}	16 ± 1	120[d]
		Brγ	
FWHM	km s^{-1}	41 ± 19	37 ± 7
v_{LSR}	km s^{-1}	$+0 \pm 10$	$+6 \pm 3$
flux	10^{-17} W m^{-2}	2.5 ± 0.2	29 ± 1
		He I 2.058 μm	
FWHM	km s^{-1}	44 ± 15	39 ± 8
v_{LSR}	km s^{-1}	-3 ± 7	$+6 \pm 4$
flux	10^{-17} W m^{-2}		80 ± 3
EW	Å	0.35 ± 0.02	-0.33 ± 0.02

[a] Schönberner et al. (1988).
[b] From $v_{helio} = -9.3$ km s^{-1} (Blaauw & van Albada 1963).
[c] From $v_{helio} = +3$ km s^{-1} (Buscombe & Morris 1960).
[d] WMGOZ, where velocity is assumed to be heliocentric.
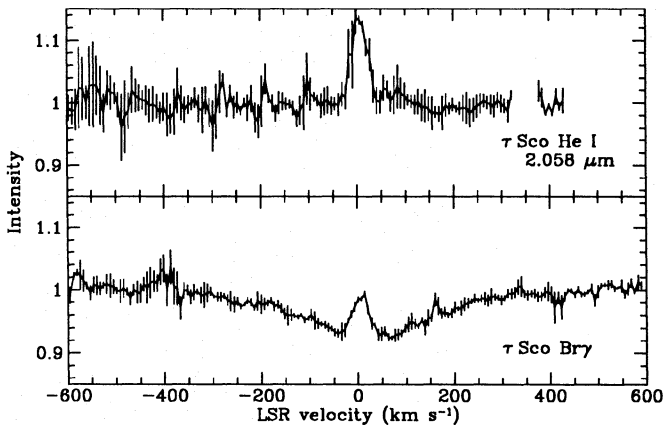
The resulting spectra of 10 Lac and τ Sco are presented in Figs. 1 and 2. In the cases of the He I and Brα lines, the observed flux has been normalized through division by an arbitrary constant. The Brγ profiles have been normalized by the division of a straight line fitted using data at $v_{LSR} < -400$ km s^{-1} and $v_{LSR} > +400$ km s^{-1}. An absorption feature in the atmospheric standards produced artificial peaks at about $+300$ km s^{-1} in the He I 2.058 μm spectra. The gaps in the spectra at this velocity are where these peaks have been removed.

The Brγ profiles in both 10 Lac and τ Sco appear as broad absorption with single-peaked emission cores. Only τ Sco's Brγ emission component was detected in the poorer signal-to-noise spectrum of WMGOZ, although they suspected the presence of the underlying absorption feature. The Brα line in both stars appears as a single-peaked emission feature, with a contrast ratio of about 1.5

in 10 Lac, as opposed to 2.0 (WMGOZ) in τ Sco. There is no obvious evidence for the presence of an underlying absorption feature analogous to that in Brγ in this line. However, it shall be seen that this impression may be false. The He I 2.058 μm line is weakly in emission in τ Sco but is weakly in absorption in 10 Lac. τ Sco thus seems to show a greater tendency towards emission in all three lines.

For each of the Brα and Brγ lines we have calculated the velocity centroid, FWHM and emitted flux of the emission component by fitting a Gaussian profile. In the case of Brγ, first the absorption component was fitted and then the emission component was fitted to the subsequent residuals. For each He I 2.058 μm line, we have estimated the velocity centroid, FWHM and equivalent width also via the fitting of a Gaussian. The resulting parameters are given in Table 1 along with their estimated errors. We caution that the emission flux measurements are sensitive to the assumed form of the underlying absorption profile and in any case become meaningless if there is no physical separation between the absorption and emission line forming regions.

3. Discussion

Some physical parameters of 10 Lac are listed in Table 1. An O9V MK standard, it presents relatively narrow optical photospheric lines, indicative of a low rotational velocity or near-pole-on orientation. Its mass-loss character-

istics are normal for its spectral type (Howarth & Prinja 1987). Historically, there have been problems in assigning 10 Lac a unique effective temperature from atmospheric models. Conti (1973) found that formal spectral classification led to an O8III assignment in contrast to Walborn's (1971) preference for O9V. The model atmosphere studies of Herrero et al. (1992) and Grigsby, Morrison & Anderson (1992) derived effective temperatures of respectively 37,500 K and 30,000 K. The differences here rest on whether or not He II 4686 Å was used in the analysis: where the line was used, the derived effective temperature is higher.

A contrast between τ Sco and 10 Lac, apart from a modest spectral type difference, is that τ Sco's UV spectrum indicates enhanced wind features for its spectral type (Walborn & Panek 1984). It is this along with τ Sco's single-peaked IR emission, small $v_{\rm rot} \sin i$ and B spectral type (Table 1) that are the main arguments behind WMGOZ's pole-on Be star interpretation. WMGOZ noted that Be stars exhibit a similar UV spectral morphology and they modelled τ Sco's infrared emission as due to a low density Be-star-like disk structure around the star, viewed pole-on. 10 Lac's wind appears to be normal but, because of its other similarities to τ Sco, a similar pole-on low-density disk model might be applicable to it as well. 10 Lac would then be a second example of this 'mild' Oe/Be phenomenon.

It has been known for some years that 10 Lac and τ Sco show some predisposition toward emission in the infrared. Lennon & Dufton (1989) considered the empirical relationship between the equivalent width of the triplet He I 1.083 μm line and stellar effective temperature for B and late O main sequence stars. Their data showed a significant trend of decreasing equivalent width (tendency to emission) towards earlier spectral types, with τ Sco and 10 Lac lying at the extreme of their distribution. Just as they found the He I 1.083 μm line weakly in absorption for 10 Lac and weakly in emission for τ Sco, so we also find from our observations of the singlet He I 2.058 μm line (Figs. 1 and 2). If both τ Sco and 10 Lac were Be stars viewed in a special orientation, we might expect to see them stand apart from the trend set by 'normal' B stars rather than continue it. Accordingly, consideration should also be given to the alternative, more prosaic, explanation that Brackett line emission is a normal spectral characteristic of late- B and early- O type stars. If this is a viable option, there would then be no reason to bring in departures from spherical symmetry as proposed by WMGOZ. We show below that it is viable.

The most widely used atmospheric models relevant to these stars are those of Kurucz (1992) using LTE, Auer & Mihalas (1972) and its descendents (including Anderson 1985) using linearization for NLTE, and Werner (1986) using accelerated Λ-iteration for NLTE. The more recent NLTE calculations with realistic line blanketing produce temperature structures similar to LTE line-blanketed

models because the inclusion of a greater number of transitions allows more degrees of freedom in the interaction of gas and radiation. Naively one would predict pure absorption features in the infrared lines we have presented here. Indeed, the monotonic outward decline in temperature characteristic of both LTE and NLTE line-blanketed model atmospheres (see Fig. 3 in Anderson 1985) would necessarily lead to net absorption *were it not that* NLTE effects are strong enough and in the appropriate sense to negate this tendency. In his investigation of the differences in atmospheric structure arising from LTE and NLTE treatments of line-blanketing, Anderson (1985) noted that the infrared α transitions of hydrogen can go into emission. Mihalas & Auer (1970) also found this result, but surmised that it was due to their NLTE temperature structure which shows a chromosphere-like rise at high altitude. In fact, the emission is relatively independent of the temperature structure. The reason for the effect is that ' intermediate (H^0) levels drain to the ground state when the relevant transitions become thin, while upper levels tend to remain collisionally coupled to the ion' (Anderson 1985). For the case of Brα this condition would yield departure coefficients $b_4 < b_5 \lesssim 1$, which increases the line source function above its LTE value.

This is not quite the whole story, however. Continuum opacity has an important role to play here as well. Due to the effects of free-free and bound-free opacity, the depth of formation of the continuum at 4 μm is much shallower than at, say, the wavelengths of lines of the Balmer series. Because of this, Brα necessarily arises from a greatly reduced column, very much higher up in the atmosphere, where departures from LTE will be most pronounced, and where the temperature contrast between the depths of formation of the background continuum and line centre is lower. Brγ is, of course, an intermediate case.

To put flesh onto the bones of these ideas we have calculated ab initio Brα and Brγ line profiles using PAM, the NLTE line-blanketed model atmosphere code described by Anderson (1985), in order to compare them with our observations of 10 Lac. The stellar effective temperature and gravity used were those derived by Grigsby et al. (1992, $T_{\rm eff} = 30000$ K and $\log g = 4.0$) from the fitting of Hα, Hβ, Hγ, He I 4471 Å and He I 4922 Å line profiles. As in Anderson (1985), the model hydrogen atom included 9 NLTE levels. The resultant Brackett line profiles are shown in Fig. 3 along with the observed profiles. It is apparent that theory, without any tailoring, has reproduced the main features present in the data. Given the ambiguity, noted above, in effective temperatures derived from optical fitting, a perfect match could not be expected. The comparison also exposes the inadequate wavelength coverage in the observation of the Brα line: it warns that the Stark width of this transition is so wide that true continuum normalization is not possible. Detailed fitting to these observations is thus unwarranted. We note that Brα is apparently more closely reproduced than Brγ, the core of
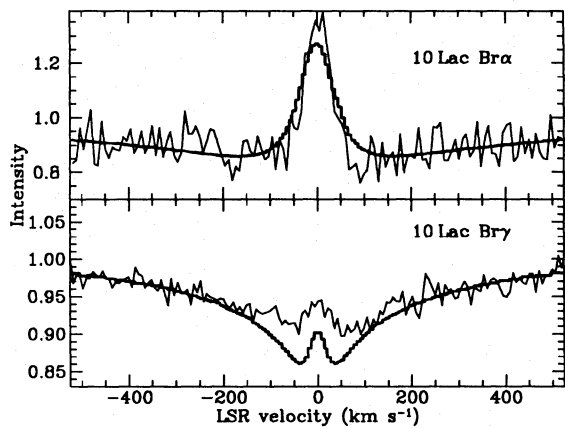
Fig. 3. Theoretical (bold line) and observed Brackett line profiles for 10 Lac. We do not know where the true continuum lies in the observed profiles. The normalization of the data in each case has thus been adjusted to match the model at $v_{LSR} < -400$ km s^{-1} and $v_{LSR} > +400$ km s^{-1}. The theoretical profiles have not been rotationally broadened.

the latter being too deep in comparison with observation. This discrepancy may be improved by a slight increase (decrease) in the model effective temperature (gravity), or by improved Stark profiles for the Brackett series.

The behaviour of the He I 1.083 μm (Lennon & Dufton 1989) and 2.058 μm lines is not yet satisfactorily explained in any atmospheric model. Lennon & Dufton (1989) presented theoretical equivalent width estimates for the triplet line, derived from an updated version of the Auer-Mihalas NLTE code, that implied significantly stronger *emission* than observed. We encounter a milder version of this problem in the case of 10 Lac in that the synthesised 2.058 μm line profile is a very weak, sharp emission feature with an equivalent width of -0.04 Å. The observed profile (Fig. 1) is hardly a strong feature, having an equivalent width of just 0.35 Å, but it is very clearly in absorption. The reason for the continuing discrepancy between model atmosphere theory and observation requires further investigation. Significant population of the $n = 2$ He^0 states is likely to be maintained to still shallower depths than those in which Brα forms. Because of this, transitions among these states may show greater sensitivity either to the onset of departures from hydrostatic equilibrium or to what is strictly a non-zero outer boundary condition in these mass-losing stars.

Bearing in mind that such factors may influence line formation high up in a hot star atmosphere, it would be premature to suppose that the stronger IR emission from τ Sco demands an explanation qualitatively different from that which seems workable for 10 Lac. Much of the appeal of WMGOZ's interpretation derives from τ Sco's well-known mass-loss peculiarities. Care in sorting out cause and effect is essential here. τ Sco's wind may be implicated in the apparently enhanced IR line emis-

sion, but it need not itself be the source of the emission. Perhaps τ Sco, uniquely, is a pole-on Be star (the probability of an inclination of less than 5°, that adopted in the model of WMGOZ, is 1 in 250) but is this a necessary explanation for its unusual mass-loss characteristics? Many subtle questions suggest themselves. In as complex a situation as this may be, a good beginning would be to understand better the observable consequences of the outer atmospheres of 'normal' hot stars.

The corollary to our demonstration of the feasibility of an atmospheric origin for the observed infrared line emission in 10 Lac is that centrally reversed Brα and Brγ line profiles should be the norm among late O and early B stars with weak winds. The central reversal in 10 Lac's Brγ line is a subtle feature that would be missed at lower dispersion or signal-to-noise ratios or indeed in stars with more than a very moderate projected rotational velocity. Accordingly, it is no surprise that similar effects are not seen in the K band classification spectra recently published by Hanson & Conti (1994). To establish unambiguously the true extent of this phenomenon, further observations at resolving powers of 10000 or more are required.

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