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LETTER

Letter to the Editor

Emission lines in the spectra of late-B type stars

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Abstract. We report detections of weak emission lines in the red spectral region of sharp-lined chemically normal and peculiar (HgMn) late-B type stars from high spectral resolution and high signal-to-noise data. Most emission lines originate from high-excitation states of the ions Cr II and Mn II, with others likely to be attributed to Ti II and Fe II. The emission is observed to extend over the entire line profile width for rotational velocities up to 18 km s^{-1}, implying that it originates within the same rotational framework as the absorption line spectrum. Within the sample no obvious correlation is noted for the presence of emission with regard to stellar effective temperature or luminosity. A dependence upon element abundance is evident from the absence of Mn II emission for HgMn stars for which the manganese enhancement is greater than 1.3 dex. This trend is mildly reinforced by the chromium emission spectrum being most developed amongst stars richer in chromium. We postulate that the Cr II and Mn II emissions in the red spectral region arise from a selective excitation process involving hydrogen Lyα photon energies.

Key words: stars: abundances – stars: atmospheres – stars: chemically peculiar – stars: emission-line, Be

1. Introduction

Emission lines in the spectra of normal and peculiar B type stars has long been sought in connection with ascertaining whether chromospheric conditions exist for them. The mid-B to mid-A type main sequence stars appeared to reside within an emission gap of the H-R diagram between stars cooler than spectral type A7 that display diagnostics of cool star chromospheres and hot B stars, for which emission lines arise from the photoionization of stellar winds induced by radiation pressure.

The presence of emission lines and mass loss in the chemically peculiar HgMn stars has been presumed to be evidence that velocity fields are present in the photosphere at levels that would disturb the diffusion process that is believed responsible for creating observed spectral anomalies. However, it has been argued that an instability of the atmosphere occurs at a distance from the star that would not disrupt diffusion. Moreover, helium abundances can be modified in the line forming region in the presence of mass loss (Michaud et al 1987), and therefore, the presence of emission lines would not necessarily be detrimental to diffusion theory.

Weak emission lines from Cr II and Fe II have been identified within the hydrogen Lyα absorption line profile for the early-A type stars Vega and Sirius (van Noort et al.1998) but their existence may not require a stellar chromosphere. More recently, weak emission lines originating from highly-excited states of P II, Mn II, and Hg II have been reported in the spectra of the chemically peculiar stars 3 Cen A (B5 III-IVp) and 46 Aql (B9III HgMn) by Sigut, Landstreet & Shorlin (2000). Data of similar high quality were obtained by one of us (S.H.) in connection with observing programs related to HgMn and more chemically normal late-B type stars. In this contribution we present early results from these observations regarding the presence and nature of emission lines.

2. Spectrum analysis

Our search for weak emission lines has been undertaken by comparing observed with synthesized spectra. The observations were made with the 3.6-m CFHT and GECKO spectrograph at a resolving power of R = 125000 and grating settings corresponding to the wavelength intervals 6005 − 6095, and 6105 − 6190 Å. The latter region was obtained for all stars at signal-to-noise levels in excess of 200:1 while the former region was obtained for few stars.

For each star a LTE model atmosphere and synthetic spectra were generated using the ATLAS9 and SYNTHE programs (Kurucz 1993), respectively. The stellar parameters effective temperature and gravity were determined from the uvbyβ photometric colors of Hauck & Mermilliod (1998) and a computer code provided by Napiwotzki (1999, private communication) based on the formalisms of Moon & Dworetsky (1985). Atmospheric parameters for both components of the binary HD 174933 were taken from Ryabchikova, Zakharova & Adelman (1996). For iron-group elements displaying emission lines the abundances were either taken from the literature, having been determined from spectral lines at blue or ultraviolet wavelengths, or as-

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Table 1. Stellar Characteristics and Equivalent Width Data

HD	Sp.Type	T_{eff} (K)	log g	$v \sin i$ ($\mathrm{km\,s^{-1}}$)	W_λ(6106.5) Ti II	W_λ(6182.3) Cr II	[Cr/H][a]	W_λ(6122.4) Mn II	[Mn/H][a]
16727	B7 HgMn	14550	4.19	5		(+0.1)/+1.9		−0.6/+4.4	
174933	B9 HgMn SB2	13100	4.10	2					+1.35
179761	B8 III	13030	3.43	16		(+0.5)/+2.1		−1.6/+10.3	+0.80
196426	B8 III SB2	13010	3.84	5.5		−0.6/+1.8	−0.3	−1.4/+3.5	+0.25
219927	B8 III	12970	3.63	4.5		−1.2/+2.0		−1.2/+1.8	
186122	B9 HgMn	12910	3.74	0	−1.3/+0.1	(−0.1)/+1.8	−1.5	−2.9/+10.7	+0.80
178065	B9 HgMn	12350	3.44	2	−1.8/+0.2	−3.9/+2.8	+0.5		+1.75
175640	B9 HgMn	12080	3.92	2	−5.0/+0.3	−3.9/+3.8	+0.8		+2.10
27295	B9 HgMn	12000	4.19	5		−1.4/+1.7	+0.4		+1.96
186568	B8 III	11700	3.50	18		(−0.1)/+1.5		−0.9/+2.5	
193452	B9 HgMn	10700	4.12	2		(+0.3)/+2.0	+0.8		+0.60
209459	B9.5 V	10350	3.48	4	−0.8/+0.6	−1.0/+0.9	+0.0	+1.4/+4.7	+0.25

[a][X/H] = $\log(N_X/N_H)_{star} - \log(N_X/N_H)_{sun}$ with stellar abundances from Adelman & Pintado (2000), Jomaron et al. (1999), Smith & Dworetsky (1993), Wahlgren et al. (2000)

sumed to have solar values if no such information was available. The turbulent velocities were assumed to be zero. The projected equatorial rotational velocity, $v \sin i$, was determined for each star by synthetically fitting the b ^{4}D - z ^{4}P^o Fe II lines at λ6147.736 and λ6149.248 as well as the O I multiplet (10) triplet.

Overall, we have identified weak emission lines, as characterised by equivalent widths of a few mÅ, associated with some high-excitation levels in Mn II and Cr II. The Mn II emission is from the transition 4d ^{5}D - 4f ^{5}F (multiplet 13). This multiplet has been discussed by Johansson et al.(1995) in the context of emission lines in the spectrum of η Car and their excitation by fluorescent processes. The Cr II emissions are observed between several upper (^{4}D^o, ^{4}F^o, ^{6}G^o, ^{4}H^o, 105000−106000 cm^{-1}) and lower (e ^{4}P, f ^{4}D, e ^{4}G, 89000−90000 cm^{-1}) terms which are rather restricted in energy. In addition, we attribute an emission feature at 6106.5 Å in several stars to the line 3d^2 (3F)4d f ^{2}F$_{2.5}$ - 3d^2 (3F)4f ^{2}G$^o{}_{3.5}$ Ti II λ6106.477 (wavelength from Zapadlik 1996). However, confirmation of this identification would be strengthened by the detection of the other line from this upper level at λ6102.544, which is not included in our observed spectral intervals. The possibility that the λ6106.5 feature is due to Si I λ6106.416 is not likely since other emissions from Si I lines ($\lambda\lambda$6112.928, 6124.494) arising from the same upper level and of comparable strength (gf value) are not observed. For only one star (HD 219927) is there an identification that corresponds to Fe II (λ6165.893), and for HD 175640 there are several unidentified emission features in the spectrum ($\lambda\lambda$6138.2, 6146.1, 6177.5). With perhaps one exception the emission lines do not appear P Cygni in nature and we have not detected a wavelength shift greater than the uncertainties of the observation and known wavelengths. For no star in our sample do we detect Hg II or P II emission, as had been noted by Sigut et al. for the *hotter* star 3 Cen A. Emission can go undetected if present as a filling-in of the absorption line or, as in the case of spectroscopic binaries such as HD 174933, where the observed flux of one star is diluted by that of its companion and orbital radial velocity variations can mask weak emission lines within the companion's absorption spectrum.

Table 1 presents equivalent width measurements for the typically strongest emission line of Ti II, Cr II, and Mn II in our data. Each W_λ entry has the form x/y, where x is the observed equivalent width (positive below the continuum, negative above), and y is the equivalent width calculated by spectrum synthesis. An indication of the total emission requires accounting for filling-in of the absorption line. Numbers in parentheses for Cr II indicate that the line is at the continuum level to within the signal-to-noise level of the observation. For these stars errors in the transition oscillator strength and abundance may influence the interpretation.

While most emission lines are obvious in their presence, others are revealed through subtle effects, such as their influence on absorption lines of other species. A clear example of this is the influence of high-excitation lines 4d e ^{4}G - 4f ^{4}H Cr II $\lambda\lambda$6158.108, 6158.181 upon the long wavelength components of the 3p ^{5}P$_3$ - 4d ^{5}D$^o{}_{3,4,5}$ O I λ6158.1 transition for HD 175640 and HD 178065. A third line of the Cr II multiplet (λ6158.621) is more easily seen to be in emission since it is unblended. From a comparison of the observations with best fit synthetic spectra for the O I 6156 and 6157 Å lines the effect of the Cr II emission is to reduce the equivalent width of the O I 6158 (absorption) line by 14% and 11%, respectively, for these two stars and to redshift this O I line by about 15 mÅ. From Table 1 we see that HD 175640 and HD 178065 show the strongest emission of 4d e ^{4}P$_{2.5}$ - 4f ^{4}D$_{3.5}$ Cr II λ6182.340.

Irregularities in the relative line strengths of the Mn II multiplet (13) emission lines from those expected from the known gf values were noted for 46 Aql by Sigut et al. From our larger number of stars we are fortunate enough to sample the behaviour of Mn II line strength irregularities from absorption through emission, as highlighted by Fig. 1. For the Mn-rich HgMn star HD 27295 (and HD 175640, not depicted in figure) the Mn II

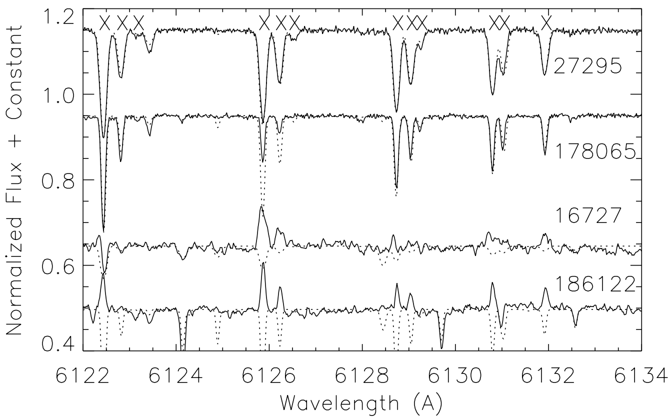

Fig. 1. Mn II multiplet(13). For four HD stars are plotted the observation (solid) and synthetic spectrum (dotted) for the 12 components of the Mn II multiplet (13). Component wavelengths are from Johansson et al. and their locations are denoted by the symbol 'X'. The flux scale for the lower two spectra has been magnified by a factor of three.

multiplet (13) spectrum is in absorption with the relative line strengths well matched by the synthetic spectrum. Deviations from the relative strengths of the gf values first appear to be evident in the λ6125.8 line as a filling of the absorption line trough (HD 193452, as well as HD 78316 in Sigut et al.) and then becomes evident in the λ6126.2 line. These two lines share the same lower level (J = 3), along with λ6126.8 which can be too weak to study. As displayed by the spectrum of HD 178065 this anomaly is well developed. The λ6125.8 line may also be the first within the multiplet to display emission above the continuum level, in close connection with the λ6126.2 line (HD 16727). The Mn II λ6122.4 line appears to show a P Cygni profile unless this is the result of an unknown absorption line. An example of a spectrum in which all Mn II lines are in emission is given by HD 186122, although all lines are not in proportion to the gf values. The spectra for HD 219927, HD 196426, HD 186568 and HD 179761 all display very weak emission for the three strongest components in rough proportion to their gf values. As opposed to the case for O I we have been unable to identify candidate blending lines that if present in emission would account for the weakening of the Mn II $\lambda\lambda$6125.8, 6126.2 lines. We must therefore consider whether this upper energy level is being selectively depopulated since thermal or Doppler effects would affect the other levels (J values).

3. Discussion

Evidence exists in our observations that a selective excitation process is present. The emission lines all originate from high-excitation states, yet not all such high-excitation states are involved in producing emission. One example involves Cr II for HD 175640, for which the emission line spectrum is the most developed amongst our stellar sample. Some lines involving upper terms with the highly-excited states, such as (5D) 4d e $^4G_{7/2}$ - (5D) 4f $^6D^o{}_{9/2}$ Cr II λ6161.931 (log gf = -1.03) and (5D) 4d f $^4D_{7/2}$ - (5D) 4f $^4G^o{}_{9/2}$ Cr II λ6186.315 (log gf = +0.34), might be expected to be viewed in emission by virtue of their gf values if a mechanism was at work that populated all highly-excited states, but they do not appear to be. Another example may be the many high-excitation Fe II absorption lines found in our spectra, yet only one line in one star is suspected of being in emission.

In the case of Mn II selective excitation can be further investigated through observations of the high excitation e ^{7}D - z $^7F^o$ Mn II multiplet (11) near 5300 Å. Since this multiplet's upper term lies within 0.005 eV of that for Mn II multiplet (13), with the multiplet (11) lines possessing slightly higher gf values, their presence in absorption simultaneously with multiplet (13) emission would be a strong argument for selective excitation of the multiplet (13) upper term. Although our dataset did not include the lines of Mn II multiplet (11) it had been noted by Hartoog & Cowley (1979) that weak (absorption) features, presumably attributed to Mn II near 5300 Å, are seen in the spectrum of HD 16727. If these features are Mn II multiplet (11), then our observation of emission lines for Mn II multiplet (13) in this star would indicate that selective excitation is a possibility. As a test of this possibility we obtained a high resolution (R = 110,000) spectrum of HD 186122 using the VLT UVES. The Mn II multiplet (11) lines are all found to be in absorption, although there are slight irregularities amongst the multiplet lines which may be related to line blending. The multiplet (13) lines are all found to be in emission and therefore a selective excitation process is suspected, as opposed to their being recombination lines from radiative electron capture from the Mn III ground term.

A common trait of the emission lines appears to be that transition levels can be populated by photon energies in the vicinity of hydrogen Lyα. In the case of Mn II multiplet (13) the lower level lies 10.14 eV above the ground level and can be directly populated by absorption of Lyα photons. Subsequent excitation would be required to populate the upper level at 12.16 eV, which may be accomplished through absorption of continuum radiation or collisions. In the case where the density of particles is low enough to support a collisionally populated metastable level (a ^{5}D, E = 1.8 eV) absorption of Lyα photons or photons from Si II UV5 (10.37 eV) would populate the Mn II multiplet (13) upper level. From Table 2 of van Noort et al. and the wavelengths for Mn II multiplet (13) listed by Johansson et al. it can be seen that emission lines of Fe II in the Lyα profile are located within a couple tenths of an angstrom of that required to pump the multiplet (13) upper level from the ^{5}D metastable level and offers a possibility for creating intensity anomalies within Mn II multiplet (13). Likewise, the Cr II spectrum can also be excited by hydrogen Lyα. For example, the high excitation 4f $^4D_{7/2}$ state at 105507 cm^{-1} can be populated by the transition Cr II λ1194.958, which leads to producing Cr II λ6182.34 fluorescence, the strongest Cr II emission line in our spectra. As not all the observed emission lines are fully explainable in terms of this scenario we must remain open to the possibility that more than one type of excitation process may be acting. Wavelength coincidences exist between Si I and Ti II as well as Ti II and Mn II in our observed spectral region. Thus, photoexcitation by accidental coincidence (PAR) may be present to some extent. A more complete mapping of all weak emission lines is required to acquire a fuller understanding of the excitation process(es) involved.

One importance of detecting emission lines in late B type stars lies in its possible relevance to diffusion theory and the development of spectrum peculiarities. From the data presented in Table 1 several insights can be drawn regarding emission lines in general and their nature in normal and chemically peculair (HgMn) stars. (1) Essentially all stars in our sample show evidence for weak emission lines. This is particularly true for Cr II. No obvious correlations are noted for emission in terms of stellar parameters (T_{eff}, luminosity). The non-detection of emission for HD 174933 may result from its SB2 nature. As the binary nature for our stellar sample is not firmly established we can not say whether the emission lines are a consequence of binarity. More likely, the mechanism for generating emission lines exists for all late-B main-sequence stars. (2) The Cr II emission appears to be correlated with chromium abundance in the sense that the most Cr-enhanced stars display the largest emission equivalent widths for the Cr II λ6182.3 line and they show the most developed Cr II emission spectra. An exception may be the cooler peculiar star HD 193452, which might imply a temperature effect (reduced flux at Lyα). (3) There is an anti-correlation of Mn II λ6122 emission with manganese abundance enhancement. Those HgMn stars with the largest values of [Mn/H], perhaps placed at a threshold value near [Mn/H] $\geq$ 1 dex, do not show the emission. However, we do notice an anomaly of absorption line strengths within the Mn II multiplet (13) lines for HD 178065. (This trend is strengthened by consideration of spectra for the HgMn stars HD 35548, HD 78316, and HD 141556, for which we have lower resolution NTT spectra not previously included in this discussion). (4) We have not detected emission lines from P II or Hg II in our sample of HgMn stars despite their enhanced line strengths and presumably enhanced abundances. This stands in contrast to their detection by Sigut et al. for 3 Cen A (B5p) and warrants further investigation into the occurrence of emission line formation as a function of T_{eff} through observations of additional mid-B type stars. (5) The widths of emission lines appear to be the same as for the associated underlying absorption lines.

It may eventually be shown that all main sequence B star atmospheres produce emission lines. The emission appears to be formed near the photosphere since the line widths correspond to those of the underlying rotationally broadened absorption lines with little or no detectable wavelength shift. In the cooler B stars of our sample it is the more chemically normal stars that show Mn II emission lines. This leads us to postulate that Mn II emission lines are being quenched in HgMn stars, perhaps by a higher number density for Mn^{+} ions resulting from diffusion, and thus the atmospheric structure for chemically normal and peculiar stars may be different for various ions.

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