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Weak emission lines and peculiar stars

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Abstract. Weak emission lines (WELs) of metals are observed in sharp-lined spectra of mid- to late-B type stars. The WELs are detected over a range of element abundance and are found among both chemically-normal and chemically-peculiar stars. The characteristics of this ubiquitous phenomenon are reviewed and their potential for the study of inhomogeneous stellar atmospheres is presented.

Key words: stars: B-type – stars: chemically peculiar – spectral lines: emission

1. Defining weak emission lines

The spectra of main-sequence B stars can be broadly categorized as either nondescript or strangely peculiar. For the majority of main sequence B-type stars, rapid rotation produces broad absorption features and mundane spectra. At the other extreme, stars of low apparent rotation velocity display sharp-lined spectra, and are often immediately recognized to include a variety of spectrum anomalies that have been interpreted as abundance anomalies. The low- and moderate-resolution spectra (resolving power $R < 30\,000$) typical of earlier epochs revealed only absorption line spectra. Even after spectrographs capable of much higher resolution became available, the study of line profiles failed to reveal emission lines from single, B-type stars until only less than a decade ago (Sigut *et al.*, 2000; Wahlgren, Hubrig 2000; Wahlgren, Hubrig, 2001 a; Wahlgren, Hubrig 2001 b; Wahlgren *et al.*, 2003; Wahlgren, Hubrig 2004; Castelli, Hubrig 2007), when observations were being taken at high signal-to-noise ratios ($S/N > 200$). The phenomenon of the weak emission lines (WELs) discussed here is the result of detections made at both high spectral resolution and high signal-to-noise.

From currently available observation of mid- to late-type main sequence B stars, a simple working definition of WELs can be established.

- They have a small equivalent width, typically less than 30 mÅ.
- The identified lines are associated with the second spectrum; the majority appear to be from iron-group elements (Fe, Cr, Mn, Ti, Co, Ni) although other elements (for example Si, P, Hg) have been identified.
- They originate from high-excitation states. From the identifications of red and near-IR emission lines it is noted that the lower energy level of the transition is above $60\,000$ cm^{-1}.

These traits suggest that atomic structure plays a crucial role in whether an ion will produce WELs. The above-mentioned elements have extensive systems of meta-stable energy levels for their first ion. The on-going task of identification and characterization of WELs may therefore benefit from first considering ions having meta-stable levels. If the formation of emission lines is tied to atomic structure, in addition to properties of the stellar atmosphere, then we would expect that all main-sequence stars in this effective temperature domain are capable of producing weak emission lines.

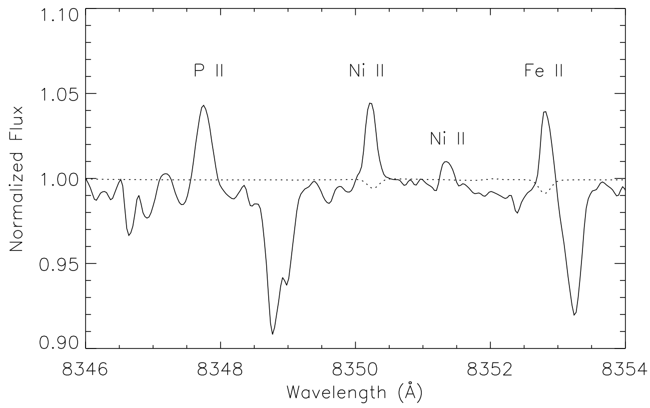

Figure 1. Examples of WELs in the spectrum of 3 Cen A (B5 IVp). Spectrum obtained with the European Southern Observatory 1.5 m telescope and FEROS spectrograph ($R = 48\,000$).

2. Observations

The WELs are evident in the spectrum in three ways: 1) direct detection of an emission line above the continuum level, 2) alteration of absorption line depth for the line in which emission is occurring, which in a sense makes them appear to be *filled-in* absorption lines, and 3) alteration of the profile of an absorption line that is blended with the emission line. Fig. 1 presents examples of emission lines above the continuum level in the spectrum of 3 Cen A. The reference to a spectral line being *filled-in* is based on the difference between the observed depth of an absorption line and the predicted line depth, typically deeper, from a synthetic spectrum calculation that takes into account its elemental abundance as determined from other lines of the species. Since the emission lines are associated with high-excitation states, one can be suspicious of the transition oscillator strength (f-value). However, the difference between observed and synthetic line profiles for these lines is not the same for different stars, which indicates that stellar conditions are an important contributor to line depth. An example of alteration of an observed absorption line by blending with an emission line is afforded by the O I triplet at $\lambda\,6156$ (Wahlgren, Hubrig 2001b), where two weak emission lines of Cr II are blended with the $\lambda\,6158$ line of an O I triplet.

The presence of a stellar companion, in particular the relative flux of the two stars at the wavelength of the emission line, will act to dilute the line spectrum of each star and introduce line blending effects that hinder the detection of WELs. Stellar rotation velocity ($v \sin i$) is another important consideration to emission line detection. The WELs are best observed for stars displaying sharp-lined spectra. The intrinsically strongest emission lines are no longer detected when $v \sin i$ is as high as 30 $\mathrm{km\,s^{-1}}$. This is a critical observation, since the non-detection of WELs for rapidly rotating B stars implies that the material creating them is not circumstellar; it is within the rotation frame of the star.

Finally, element abundance influences observed line strength, and thereby, whether specific emission lines will be detected. This facet of WELs is of particular relevance to testing segregation of elements in peculiar-star atmospheres, as briefly discussed below.

Precise measurement of line profiles for wavelength shift, breadth, and intensity are invaluable for probing the atmospheric location and dynamics in the region of line formation. These observations require high spectral resolution and high S/N, beyond the typical levels that are obtained for chemical abundance analysis. The detection of a blue or red-shifted emission line would indicate motion relative to the photosphere of the plasma responsible for the emission lines. Measurement of emission line widths and their comparison with those from the absorption line spectrum has the potential for diagnosing temperature gradients and turbulent motions. Each of these three measurements, when carried out for a series of observations over time, is capable of probing longitudinal structure of the line-emitting region as the star rotates. Therefore, rotation periods can potentially be measured independently of absorption-line fitting, and an estimate for the inclination angle can be made.

Wavelength shifts, intensity, and profile variations were reported by Hubrig and González (2007) for the magnetic Bp star a Cen, which may be indicative of rotation. Additional spectra at a higher S/N will be needed for this star for confirmation and quantitative analysis. Possible variations in line intensity for Mn II multiplet 13 lines in the HgMn star 46 Aql are presented in the spectra of Fig. 2 obtained by the author on two occasions with the 2.5 m Nordic Optical Telescope and SOFIN echelle spectrograph ($R = 75\,000$).

An interesting observation related to the optical/near-IR detection of WELs, which has received very little attention, is the many Fe II emission lines detected in the H Lyα profile for both Sirius and Vega (van Noort *et al.*,1998). Many of these lines originate from excited states that also serve as the upper levels for WELs observed at red wavelengths in HgMn stars. No comparable high-quality observations of HgMn stars exist that include the H Lyα line. This serves to remind us that there are many transitions originating from high-excitation states that are recorded as absorption lines, but which are not recognized as affected by non-Boltzman level populations.

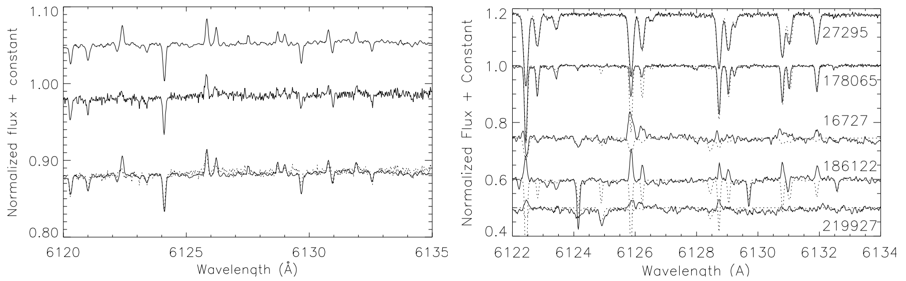

Figure 2. Left: Lines of Mn II multiplet 13 in the spectrum of 46 Aql on two occasions (top and middle) and a comparison of these two spectra (bottom). Variations in the emission lines are suggestive from these data. **Right:** Mn II multiplet 13 lines in stars, as [Mn/H] increases from bottom to top.

2.1. Mn II abundance and peculiarity

The most intriguing WELs detected to date are those from the Mn II spectrum, both for reasons of abundance effects and spectrum peculiarities. It is the appearance of the Mn II spectrum that leads one to ponder the nature of chemically peculiar star atmospheres regarding element segregation. For chemically normal main sequence late-B stars, Mn II multiplet 13 appears to be ubiquitous in its presentation of WELs that might only barely be discerned above the continuum. It is only through comparison with synthetic spectra that one can be convinced that small undulations in the observed spectrum are indeed protrusions above the continuum at the positions of multiplet 13 lines.

From the analysis of Mn II lines originating at low energy levels, the manganese photospheric abundance can be derived, and applied to creating synthetic profiles for higher excitation lines, such as those from multiplet 13. It is then that one discovers the influence of element abundance on WELs and the peculiarities that herald a non-homologous solar model composition. The spectra in Fig. 3 are arranged from bottom to top in order of increasing photospheric manganese abundance. HD 219927 is closely solar-like in (Mn/H) and displays the characteristically weak hyperfine-component emission lines which appear in strengths relative to their respective oscillator strengths. Increasing the manganese abundance in the upper atmosphere causes the emission lines to strengthen and start to display anomalous relative line strengths, at first between the strongest two components at $\lambda\,6125.8$ and $\lambda\,6121.9$ Å. With the exception of the $J = 2$ hyperfine components, the remainder of the lines begin to recede in strength as (Mn/H) is further enhanced. Eventually, when the manganese abundance is approximately 100 times the solar level, the entire multiplet displays absorption profiles with relative strengths dictated by their oscillator strengths. Thus, the intensity of WELs for an element is related to the atmospheric abundance of that element.

The above prescription appears to be followed by the cooler B stars: the chemically-normal and HgMn stars. For the hotter He-weak stars, the P-Ga subclass, the stars 3 Cen A and HD 185330 display very strong Mn II multiplet 13 lines, while the He-weak stars HD 37043B and HD 202671 show weak emission for Mn II. The latter two stars are significantly cooler ($T_{\rm eff} = 14\,000$ K) relative to the former two ($T_{\rm eff} = 16\,500$ to $17\,500$ K), which potentially introduces $T_{\rm eff}$ as a variable for WELs. One must also consider the relationship between He-weak and HgMn peculiarity classes and whether improper classifications have been assigned to those particular stars.

3. Origins

The variety of catalogued emission lines (Wahlgren, Hubrig 2004) leaves open the possibility that multiple excitation mechanisms may be at work to populate excited levels. Here we mention several sources of excitation that have been or can be considered.

The presence of emission lines implies atmospheric particle densities low enough to allow radiative de-excitation processes to dominate over collisional de-excitation. The appropriate physical conditions are those of classical non-LTE. Sigut *et al.* (2000) and Sigut (2001 a, b) discuss non-LTE calculations for Mn II. Those calculations show that non-LTE can be a significant mechanism for the production of WELs. Improvements to model atoms, especially for high excitation states, are required before calculations can be properly interpreted.

Wahlgren and Hubrig (2000; 2004) discussed the possibility that the population of highly excited states can be due to excitation from far-UV continuum radiation. The Mn II multiplet 13 lines have been shown by Johansson *et al.* (1995) to be pumped by H Lyα in the nebula environment of η Carinae. The ability of far-UV radiation to excite first ions from their metastable levels will depend on the effective temperature, or spectral type, of the B star. For spectral type B5, such as 3 Cen A, far-UV radiation is abundant down to shortward of H Lyβ, whereas for the coolest B stars, the UV radiation is extremely weak shortward of H Lyα and therefore less likely to overpopulate excited states.

For early- to mid-B stars, emission lines have been detected from classic indicators of magnetospheres or what might be labeled chromospheres. Emission lines have been detected in hot-star spectra for C IV (Shore, Brown 1990), Mg II k (Lanz, Hubeny 1993), and He I (Leone et al. 1995), and their presence raises questions of how the temperature gradient in the outer atmosphere of a B star is established and maintained. Are magnetic fields a necessary ingredient?

X-ray companions of B-type stars have been studied (Golub *et al.* 1983; Hubrig *et al.*, 2007; Stelzer *et al.*, 2006) in order to account for x-ray emission detected by satellites. Most x-ray B stars with excess x-ray luminosity have cool companions with active atmospheres capable of producing x-rays. However, a few x-ray emitting B stars have not as yet been shown to have companions.

4. Summary

The weak emission lines found in the spectra of mid- to late-type main sequence B stars have the potential to provide diagnostics of the outer regions of the stellar atmosphere and insight into both vertical stratification and horizontal inhomogeneity.

Further observations are required to increase the sample of B stars from which the nature and peculiarities of WELs can be better characterized. It is likely that the variety of WELs will mimic the variety in spectrum peculiarity, since the formation of WELs is dependent on the stellar atmosphere in the same way that element abnormalities are dependent on it. Theoretical testing of model atmospheres, atomic models, and excitation mechanisms are underway by the author and collaborators.

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