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Detection of variable Si II, Mn II, and Fe II emission lines in the magnetic Bp star a Centauri*

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ABSTRACT

Context. The nature of non-variable high-excitation emission lines detected in the optical spectra of normal late-B type and chemically peculiar HgMn and PGa stars is still poorly understood.
Aims. To better understand the origin of the weak emission lines in B type stars it is especially important to investigate the spectra of a variety of stars to search for correlations between the emergence of these lines and fundamental stellar parameters.
Methods. We have acquired high resolution UVES spectra for the sharp-lined magnetic helium-variable star a Cen over the rotation period of 8.82 d to search for the presence of weak emission lines.
Results. For the first time we present observational evidence for the appearance of variable high-excitation Si II, Mn II and Fe II emission lines in a magnetic Bp star. Si II emissions are the strongest at the phase corresponding to the maximum strength of He I lines. Mn II and Fe II emissions vary in antiphase to the He I lines. A correlation is found between the probable location of Mn and Fe surface spots and the strength of the emission lines. On the basis of the currently available data it seems possible that the same kind of selective excitation process is working in the atmospheres of objects within a broad parameter space which could be defined by age, effective temperature, chemical composition, rotational velocity, and magnetic field. Neutral iron lines previously reported to appear broad and shallow at certain phases are not detected in our spectra, although two of them are identified as He I forbidden lines, showing maximum strength at the phase of the passage of the He rich region across the visible disk.

Key words. stars: chemically peculiar – stars: emission-line, Be – stars: abundances – line: identification – stars: individual: HD 125823

1. Introduction

A considerable fraction of main-sequence stars of spectral types A and B exhibits atmospheric chemical peculiarities that, apparently, do not have an evolutionary origin, but result from the segregation of chemical elements in the stellar outer layers under the competing actions of various physical processes. The chemically peculiar (CP) stars are distributed into three main categories: the magnetic CP stars (Ap, He weak, Si and Sr-Ti, He strong), the Am stars, and the Bp stars of HgMn and PGa peculiarity. PGa stars are usually considered as hotter analogs of HgMn stars. The spectra of these stars exhibit deficient He and strongly overabundant P and Ga. Although very weak magnetic fields have recently been detected in a few HgMn and one PGa star (Hubrig et al. 2006a) this group of CP stars is usually regarded as non-magnetic.

The presence of weak high-excitation emission lines in the optical spectra of late-B type chemically normal and peculiar HgMn and PGa stars has been reported by various authors (Sigut et al. 2000; Wahlgren & Hubrig 2000, 2004; Castelli & Hubrig 2004). The observed emission lines do not show any detectable variation and originate from high-excitation states of a number of elements. The spectra of P II, Mn II, Fe II, Ni II, Cu II, Cr II and Ti II are particularly rich in their number of emission lines. The mechanism for populating the highly-excited states is under investigation and the results may have a significant bearing upon our understanding of the outermost atmospheric regions of B type stars and the formation of spectrum anomalies generally attributed to diffusion processes. To date, explanations of the phenomenon have been put forward in the context of non-LTE line formation (Sigut 2001) and possible fluorescence mechanisms (Wahlgren & Hubrig 2000).

It may be an essential clue for the understanding of the origin of weak emission lines that they have recently been discovered in the spectrum of the very young massive object LkHα 101 which illuminates the central part of the dark cloud L1482 in the main Taurus-Aurigae cloud complex (Herbig et al. 2004). Interestingly, although a very early B type star was suggested for LkHα 101, no sign of its absorption spectrum could be found in the optical region. To better understand the nature and origin of weak emission lines in mid- to late-B type stars it is especially important to investigate the spectra of a variety of stars to search for correlations between the emergence of these lines and effective temperature, log g (as an indicator of the stellar age), membership in binary and multiple systems, chemical composition, peculiarity type and magnetic field. In spite of the high resolution studies of Bp stars carried out in the last decade (e.g. Wade et al. (2006) and the numerous references therein), no detection of emission lines originating from high-excitation states of various elements has ever been reported for magnetic variable helium-strong and helium-weak stars, and the qualitative

* Based on observations collected at the European Southern Observatory, Paranal, Chile (ESO programmes 65.L-0316(A) and 073.D-0504(A)).

Table 1. Emission lines detected in the spectrum of a Cen.

λ [Å]	Identification	λ [Å]	Identification
6122.43	Mn II	8769.16	Mn II
6239.80	unidentified	8774.57	unidentified
7513.14	Fe II	8813.33	Fe II
7848.75	Si II	8825.54	unidentified
7849.76	Si II	8834.01	Fe II
8490.05	Fe II	8910.39	unidentified
8767.63	unidentified		

and quantitative assessment of the spectra of B type stars seemed to link the appearance of diverse emission lines exclusively to the non-magnetic PGa and HgMn groups. Here, we present the first detection of variable Si II, Mn II and Fe II emission lines in the slowly rotating magnetic helium strong/weak variable star a Cen (=HD 125823).

2. Observations and spectrum analysis

The 5.9 $M_\odot$ star a Cen with $T_{\rm eff}$ = 18 400 K (Hunger & Groote 1999) is a striking helium variable, ranging in helium spectral type from He-strong B2 to He-weak B8 with a period of 8.82 d (e.g., Norris 1968). The magnetic field observations reported in the literature indicate that the negative extremum coincides closely in phase with the maximum helium strength (Wolff & Morrison 1974; Borra et al. 1983). The positive magnetic pole shows a He-deficient cap, so that the two magnetic poles are associated with very different helium abundances.

The observations reported here have been carried out at the European Southern Observatory. a Cen was observed by us on two consecutive nights in May 2000 with the echelle spectrograph FEROS on the 1.52 m telescope at La Silla at a resolving power of 48 000. Rather unexpectedly, we detected in the FEROS spectra a few very weak emission lines of Mn II and Fe II. Some other lines offered suspicions that they could also be in emission, but our data were of too low spectral resolution and too scant in phase to be definitive. In May 2004 we were able to obtain much higher resolution and higher signal-to-noise ratio UVES spectra on nine consecutive nights to cover the rotation period of 8.82 d. We used the UVES DIC1 and DIC2 standard settings to cover the spectral range from 3030 Å to 10 000 Å. The slit width was set to 0."3 for the red arm, corresponding to a resolving power of $\lambda/\Delta\lambda \approx$ 110 000. For the blue arm, we used a slit width of 0."4 to achieve a resolving power of ≈80 000. The spectra were reduced by the UVES pipeline Data Reduction Software (version 2.5; Ballester et al. 2000) and using standard IRAF routines. The signal-to-noise ratio of the obtained UVES spectra is very high, ranging from 350 in the near UV to 600 in the visual region. The measured $v \sin i$ value for a Cen is only about 15 km s^{-1} and high signal-to-noise ratio and high spectral resolution are critical to precisely define line profile shapes.

In our spectra, weak emission lines are clearly seen at the locations of several Si II, Mn II and Fe II lines. A number of He-rich and He-weak magnetic stars appear to possess comparatively dense magnetospheres which are observed via Balmer or helium emission line variations, or anomalously strong and variable UV resonance lines (e.g. Shore et al. 2004). We note that no emissions are detected in the H I and He I lines, which means that we do not detect any evidence for an extended atmosphere. The list of observed emission lines is presented in Table 1. The

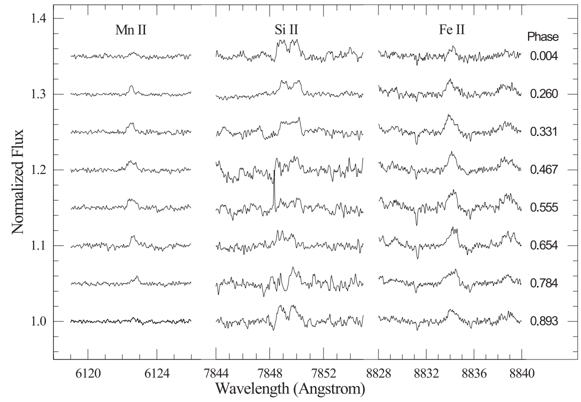

Fig. 1. Variations of Mn II, Si II and Fe II emissions over the rotation period.

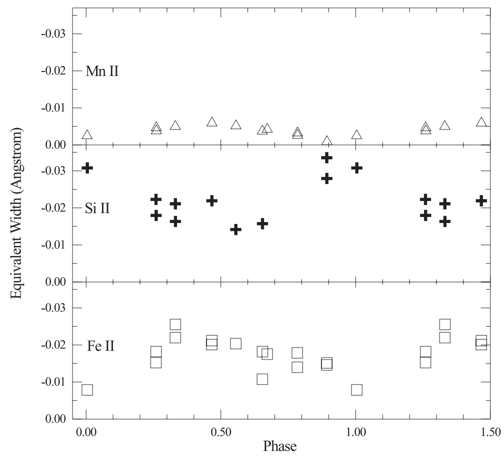

Fig. 2. Variations of the equivalent widths with phase.

detected emission lines are definitely variable over the star's rotation period. The Si II emission reaches the largest intensity at the phase corresponding to the maximum strength of the helium lines. Mn II and Fe II emissions vary in antiphase to the He I lines. This is the first time that the variability of emission lines is detected in B type stars. The variations of the line profiles of the emission lines of Si II, Mn II and Fe II are presented in Fig. 1. In Fig. 2 we show the variation of their equivalent widths over the rotation period. Although the Mn II line at λ6122.4 of multiplet 13 (transition 4d ^{5}D–4f ^{5}F) is observed in emission, the strongest line of multiplet 11 at λ5302.32, with a comparable upper excitation potential, appears in absorption. This observation suggests that a selective excitation process might be at work populating the multiplet 13 upper term. The same anomaly has been observed in η Car by Johansson et al. (1995) and in HgMn and normal late-B type stars by Wahlgren & Hubrig (2000). Among the detected emission lines only the unidentified line at λ6239.8 shows a P Cygni profile. The character of the intensity variations of the Mn II and Fe II absorption lines in the spectra of a Cen is very similar to that of the emission lines, reaching the maximum intensity at the phase corresponding to the minimum strength of the He I lines. However, Si II emissions vary in antiphase to the Si II absorption lines. Due to the inhomogeneous surface distribution of Mn II and Fe II the absorption line profiles of these elements appear split at phases 0.47–0.78, indicating that two or more areas of enhanced Mn and Fe are crossing the visible disk at these phases (Fig. 3, upper panel). The Si II lines do not appear split, but the phase variation of the Si II line profile at λ4128

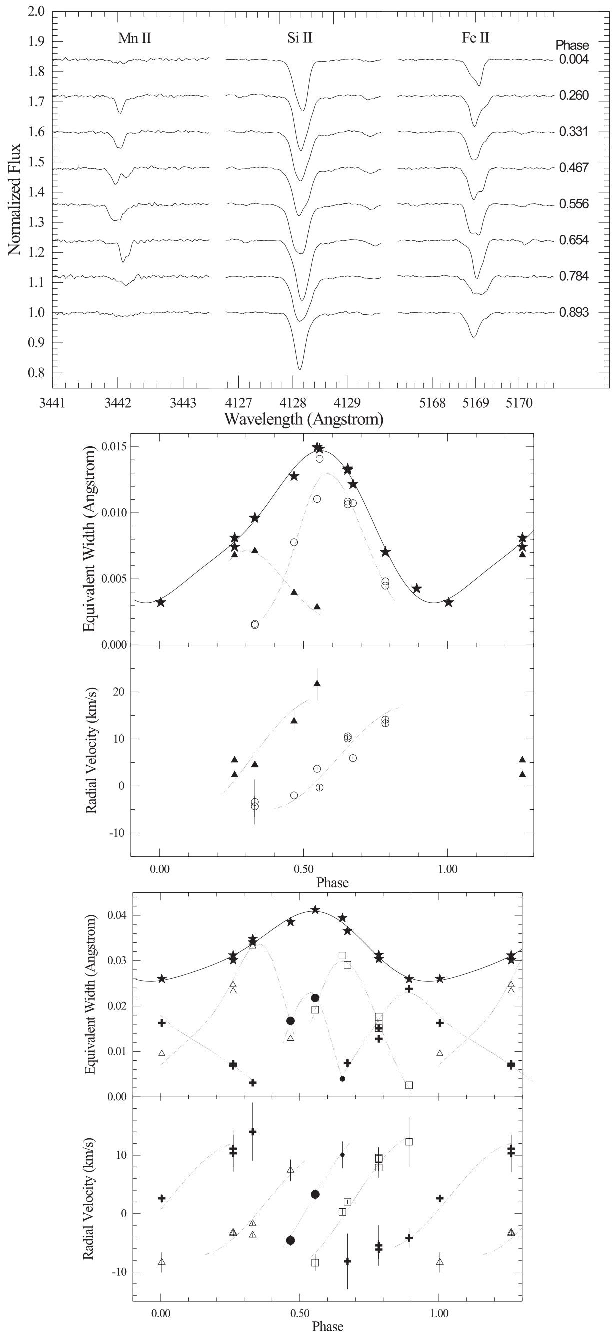

Fig. 3. *Upper panel*: variations of line profiles of Mn II λ3442, Si II λ4128 and Fe II λ5169 over the rotation period. *Middle panel*: phase dependencies of the equivalent width measured by direct integration of the whole profile of the Mn II line at λ3442 (filled stars), and of the equivalent widths measured for split line components (filled triangles and open circles) by fitting multiple Gaussians. The radial velocities corresponding to two Mn II spots are presented in the lower half. *Lower panel*: the equivalent widths and radial velocities for Fe II λ5169 measured in the same way as for Mn II λ3442. The surface distribution of Fe II can be represented by four spots crossing the center of the visual disk at the phases 0.35, 0.55, 0.7 and 0.95.

indicates that Si II is also distributed inhomogeneously over the stellar surface. The measurements of equivalent width and radial velocity of the Mn II line at λ3442 and the Fe II line at λ5169 are presented in Fig. 3 in the middle and lower panels. At the phases of splitting, the radial velocities and equivalent widths of the split components have been measured by fitting multiple Gaussians. The variations of the Mn II line at λ3442 can be presented by two spots of enhanced Mn II crossing the center of the visual disk at phases 0.3 and 0.6. Fe II is likely enhanced in four spots crossing the center of the visual disk at phases 0.35, 0.55, 0.7 and 0.95.

Inspecting the behaviour of the spectral lines of other elements at different rotation phases we conclude that all elements show a spectral variability. The equivalent widths of lines of C II, N II, O II, Si II, Cl II, Mn II and Fe II appear variable, showing their maximum in the phase corresponding to the minimum strength of He I, O I, Ne I, Mg II, Al III, S II, Ar II and Ca II. We present the behaviour of the line profiles of various elements over the rotation period in Fig. 4. The variations of the equivalent widths are shown in Fig. 5. It is interesting that for some elements the equivalent widths of neutral and ionised lines vary in antiphase. This phenomenon has already been mentioned in previous studies by Underhill et al. (1975) and Norris & Baschek (1972). An example of this opposite behaviour of equivalent widths of O I and O II is presented in Fig. 5.

The appearance of broad shallow Fe I lines in the spectrum of a Cen at certain phases has previously been reported by Underhill & Klinglesmith (1973). However, the existence of these lines could not be confirmed by our observations. It is interesting that at least two of the observed Fe I lines appear at the wavelength positions of He I forbidden lines, at $\lambda\lambda$4045.2 and 4383.5, which become significantly stronger at phases of maximum strength of the helium lines (Fig. 6).

Previous studies of a Cen suggest that this star is seen from an inclination $i \gtrsim 30°$ and has an angle β between the magnetic and rotation axes of nearly 90° (Borra et al. 1983). The line profile variations as well as the variations of the equivalent width and of the radial velocity of the He lines observed in our spectra support the models of a surface distribution with He-rich and He-weak hemispheres (Borra et al. 1983; Vetö et al. 1991). It is remarkable that the He I lines show some hint of splitting around the rotational phase 0.5. Such an appearance can be explained by a He-weak spot passing the center of the visible disk at this phase. The lines of N II, O I, Al III, Cl II, Ar II, S II, N II, Ca II, Mn II and Fe II show a similar splitting at the same phase as the He I lines. This behaviour could possibly be explained by an inhomogeneous surface distribution of these elements involving several spots in the transition region between the He-rich and He-weak spots, or by a continuous ring around the positive magnetic pole with a He-deficient cap. The detailed geometry of the surface distribution of He and the other elements still has to be determined. However, since the measured $v \sin i$ value for a Cen is only about 15 km s^{-1}, it is rather hopeless to apply the standard Doppler Imaging technique. As a future task we plan to use the so-called direct Doppler Imaging method allowing to compute spectral line profiles from test images created by varying the local element abundances (Savanov & Strassmeier 2005; Hubrig et al. 2006b).

3. Discussion

The fact that large-scale organized magnetic fields of Ap and Bp stars are more readily observable than those of any other type of non-degenerate stars makes them a privileged laboratory for the study of phenomena related to stellar magnetism. The rather bright slowly rotating star a Cen combines a well measured magnetic field with remarkable spectrum variations and thus deserves further detailed studies to clarify the relationship between the appearance of weak high-excitation emissions, vertical and horizontal abundance gradients and magnetic field geometry.

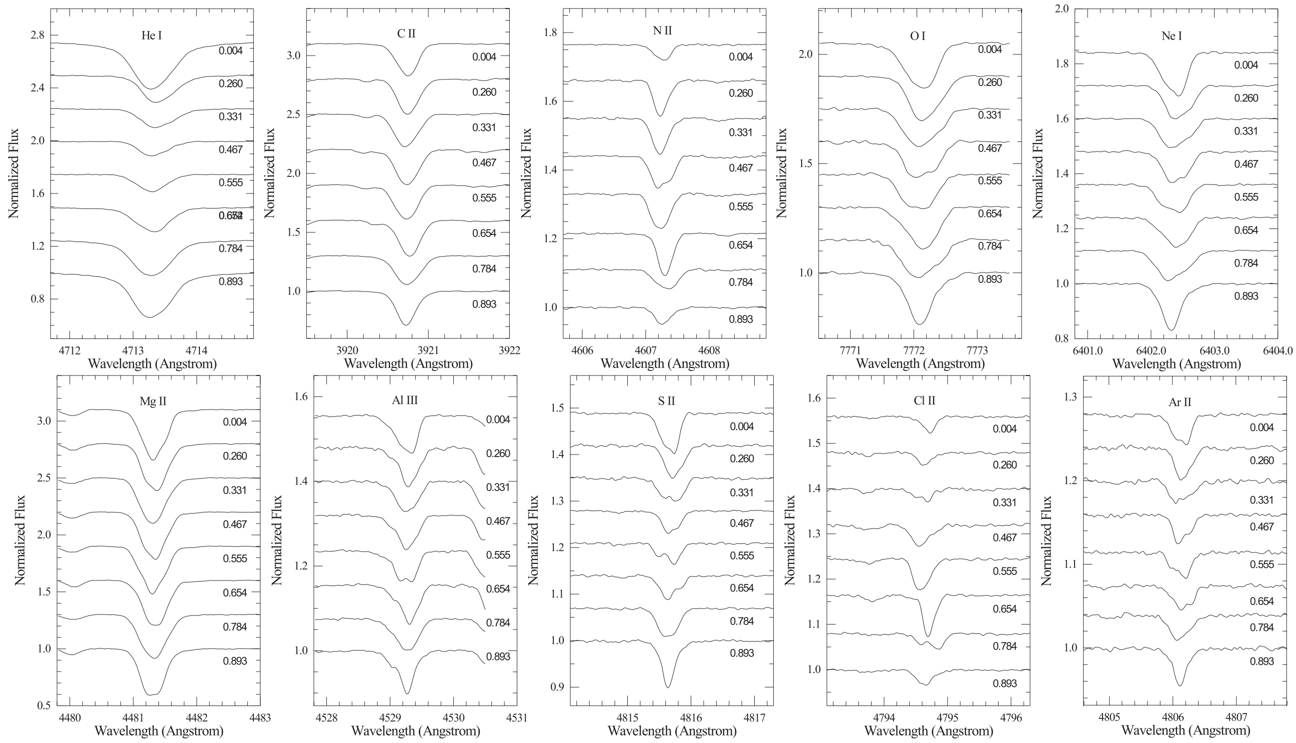

Fig. 4. Variations of line profiles of various elements phased with the rotation period.

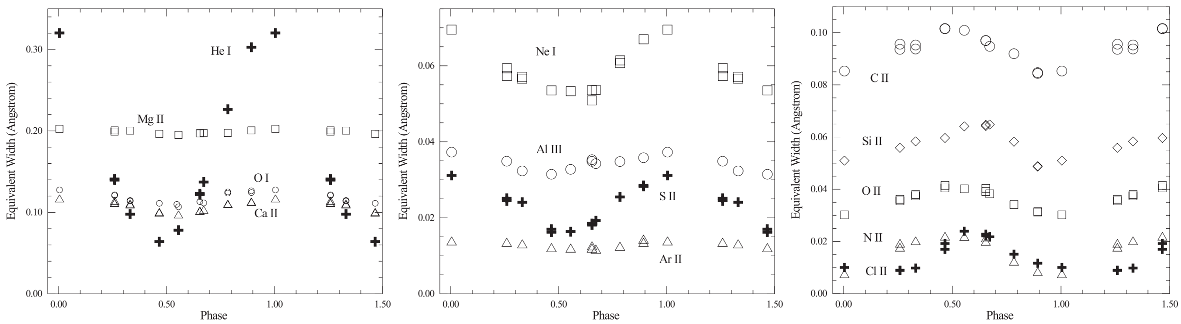

Fig. 5. Variations of the equivalent width of various elements phased with the rotation period.

The origin of weak high-excitation emission lines in various B type stars is still rather poorly understood. Theoretical modelling involving non-LTE photospheric models and a simplistic two level inverse stratification of abundance has been tested for certain multiplets of Mn II (Sigut 2001). This modelling requires a photospheric origin for the emission and made specific predictions regarding the strength of Mn II emission lines. A second approach has been put forward by Wahlgren & Hubrig (2000) that postulates a connection between atomic metastable states with absorption lines found in the vicinity of hydrogen Lyα and Lyβ and emission lines observed in the red spectral region.

The importance of detecting emission lines in different groups of B type stars lies in its possible relevance to diffusion theory and the development of spectrum variability. It is the first time that emission lines and their variability are definitely identified in the spectra of a magnetic star. Although a number of members of the PGa or HgMn groups occur at the same effective temperature as a Cen, this star has never been reported to show the distinctive abundance anomalies of either the PGa or HgMn stars. This fact implies that a Cen presents a particularly interesting case for forging connections between different chemically peculiar star classes. The detection of emission lines in this star alters our perception of distinctions between the various chemically peculiar star classes and should provide a basis for a more unified picture of the physical processes that may be responsible for the observed spectral anomalies.

The non-detection of weak emissions in other magnetic Bp stars could be related to the rather large $v \sin i$ values of the stars previously studied by other authors. In our study of emission lines in the spectra of late-B type stars (Wahlgren & Hubrig 2000) we noted that the emission appears to be formed near the photosphere, since the emission line widths correspond to those of the underlying rotationally broadened absorption lines. Thus it is possible that other magnetic Bp star atmospheres produce emission lines that are difficult to detect in broad-lined rapidly rotating stars.

Previous studies of stars with emission lines have shown that the determination of element abundances is especially important to establish correlations between the presence of emission and abundance patterns. For example, the HgMn stars do not display Mn II emissions if the abundance enhancement of Mn is greater than about a factor of 10 above the solar value (Wahlgren & Hubrig 2000). The Cr II emission appears to be correlated with the Cr abundance in the sense that the most Cr-enhanced stars

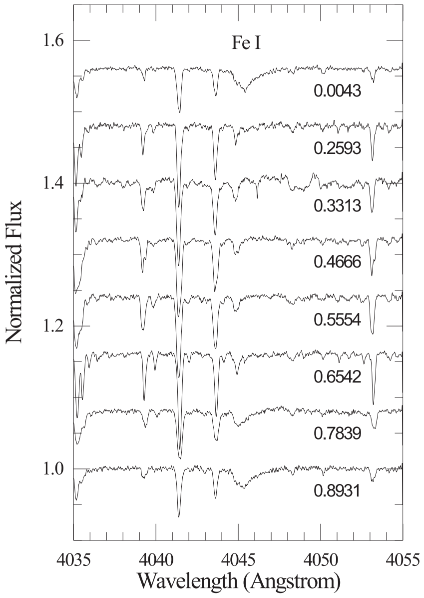

Fig. 6. The behaviour of the λ4045 line over the rotation period.

display the largest emission equivalent widths and they show the most developed Cr II emission spectra. The study of the dependence of the emission line variations on the distribution of the surface abundance over the stellar surface in a Cen must therefore give us clues to the structure of the stellar atmosphere and whether diffusion and/or stellar winds may be present.

It has been shown that the Mn II and Fe II high-excitation emissions also appear in the spectra of objects of completely different evolutionary states. As mentioned in the introduction, apart from the detection of these lines in the spectra of main-sequence B type stars, they have also been discovered in the spectra of the luminous blue variable η Car and of the young massive star LkHα 101 in a massive star forming region. The Mn II and Fe II emissions, which have been identified in a Cen, have also been detected in our UVES spectrum of the Population II star Feige 86 with the atmospheric parameters $T_{\rm eff}$ = 16 430 K and $\log g$ = 4.20 (Castelli et al., in preparation). Right now, on the basis of the currently available data, it seems possible that the same kind of selective excitation process is working in the atmospheres of objects within a broad parameter space defined by age, effective temperature, chemical composition, rotation velocity, and magnetic field.

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