SINGLY-IONIZED IRON EMISSION LINES IN THE SPECTRA OF EARLY TYPE STARS

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(Paper read by D. G. Hummer)

Abstract. The appearance of singly ionized iron emission lines in the spectra of early type stars is studied, and the results of a spectroscopic investigation of EW Lac and other Be stars are given. We also discuss the atomic processes of excitation of Fe II in the stellar envelopes using a two-parameter diagram W, $N_eT_e^{-1/2}$.

1. Introduction

This paper is concerned with a systematic investigation of singly ionized iron emission lines in the spectra of early type stars. This study is justified by some important facts. First, in the spectra of Be and shell stars the strongest lines of singly ionized iron – notably λ 4233, 4583, 6238 Å, etc. – often have emission components, such as in the 1937–39 spectra of γ Cas (Wellmann 1952), and in EW Lac (see later). Lesh (1968) classified the extreme Be stars, characterized by spectra with prominent Fe II lines, as Be_3–Be_4. These stars are most probably surrounded by very extended atmospheric envelopes. Actually, as we shall show later, infrared observations confirm that stars with more extended envelopes have stronger emission lines, as also suggested by simple theoretical computations.

Forbidden lines of [Fe II] have been observed in HD 200775, the central star of NGC 7023 (Weston, 1949; Viotti, 1969), and in some peculiar B-type stars like XX Oph, BD+61°154, HK Ori and HD 45677. It is worth remembering that ionized metal emission lines frequently appear in superluminous B- and A-type stars, including several stars in the Magellanic Clouds, and in many peculiar objects (η Car, symbiotic stars, etc.). A further argument for this study is that the presence of Fe II in emission in early type stars provides evidence for cool extended atmospheric envelopes. Finally, the conditions of excitation of the ionized metal lines in stellar envelopes are different from those of hydrogen and helium. In addition, the line opacity is obviously much smaller so that in many cases the emitting regions are optically thin to ionized metal lines. Thus their study could be faced in a different and a somewhat simpler way.

In the following we describe (Section 2) the appearance of Fe II emission lines in the spectra of some Be stars, in particular of EW Lac. In Section 3 we discuss the

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physical processes populating the Fe II levels and compare spectroscopic observations with infrared photometry.

2. Fe II Emission Lines in Be Stars

EW Lac (HD 217050) is a typical shell star with many sharp Fe II absorption lines. P. Koubsky analysed a spectrogram of this star taken at the Ondřejov Observatory (Plate number 1287, October 8, 1972; original dispersion 8.5 Å mm^{-1}). The following ionized iron lines show, or probably show, emission components: λ 4178.85, 4233.17 (s), 4351.76, 4385.38 (?), 4472.92 (?), 4491.40, 4508.28 (?), 4515.34 (?), 4520.22, 4522.63, 4549.47, 4555.89 (?), 4583.83 (s; see Figure 1), 4629.34, 4923.92, 5018.43 (s), 5169.03 (?), 5275.99, 5316.61 (s), 5534.86 (?), 6238.38, 6247.56 (?), 6318.0 (s) and 6385.5 Å (s). The identification of this last line is questionable, but it is also present in ζ Tau, 48 Lib, in MV Sgr (Herbig, 1975), in η Car and probably in RR Tel.

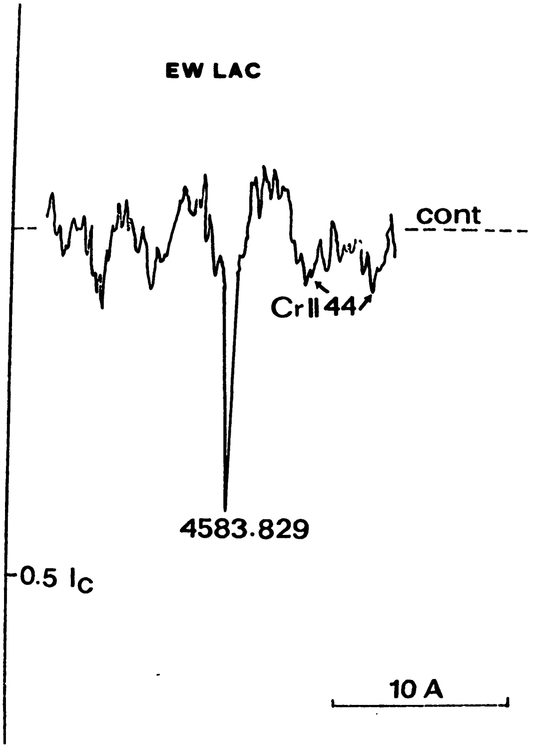

Fig. 1. The spectrum of EW Lac near the Fe II line at λ 4584 Å showing the shell absorption and the broad emission components (plate N.1287, original dispersion 8.5 Å mm^{-1}).

The intensity tracing near λ 4584 Å is shown in Figure 1. The Fe II emission is double with a strong central shell absorption. In a few cases the Fe II lines present a very broad absorption.

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The following equivalent widths have been estimated from the spectrograms for the emission components of seven lines: λ 4233, 0.34 Å; 4520, 0.26 Å; 4583, 0.44 Å; 4628, 0.32 Å; 6238, 0.59 Å; 6318, 0.68 Å; 6385, 0.60 Å. The intensities are comparable to those of γ Cas given by Wellmann (1952). In both stars and in MV Sgr we found that their intensity, normalized to gf λ^{-3} exp $(-E_u/kT_{ex})$ (E_u = energy of the upper level of the transition, T_{ex} = mean excitation temperature of Fe II lines), increases with wavelength as a consequence of the decreasing stellar continuum. γ Cas and EW Lac are classified by Lesh (1968) as Be_1, that is with weak H emission and no Fe II in emission, and this gives an example of the large variability of the intensity of the emission lines in Be stars. In AX Mon according to the profiles published by Peton (1974) the emission at λ 4233 Å is variable in time with an equivalent width ranging from 0.3 to 0.52 Å. A search for emission at this line failed for the stars φ Per, ψ Per, Pleione (28 Tau) and 1 Del, while the line has a V emission peak in the 1968 spectrum of ζ Tau and at all times in the spectrum of HD 218393 during the years 1972–74.

3. Atomic Processes

The problem is how to relate the observed line intensities with the physical properties of the emitting envelopes. An earlier attempt to study the processes of formation of Fe II and [Fe II] emission lines in the stellar spectra was made by Wurm in 1937. Wellmann (1952) applied the curve-of-growth method to hydrogen, He I and Fe II emission lines in the spectrum of γ Cas. Recently Viotti (1976) analysed the problem of excitation of Fe II and [Fe II] in the envelopes of hot stars, and discussed the dominant processes of excitation in some early type stars mostly on the basis of the infrared observations of Gehrz *et al.* (1974). The physical parameters for the envelopes of some early type stars are illustrated in Figure 2, where W is the geometrical dilution factor, and N_e and T_e the electron density and temperature. Actually, in the figure the abscissa is a measure of the rate of electron collisions, while the ordinate is a measure of the stellar radiation in the envelope. By comparing the rate of collisional excitation of the upper levels of the Fe II transitions (E.P. about 5–6 eV) with photoexcitation through the ultraviolet resonance lines, one finds that the latter dominates when $W \gg 10^{-12} N_e T_e^{-1/2}$ ('radiative' regime of excitation). This boundary is represented in Figure 2 by a dashed line. A competitive process populating the upper levels of Fe II is radiative recombination from Fe III followed by cascade. A precise estimate of its rate is at present impossible, but it seems to be negligible with respect to photoexcitation from the ground level as long as the photospheric temperature is below 30 000 K. These considerations regarding the excitation processes of Fe II are obviously valid for all the ions having similar Grotrian diagrams.

Let us now compare the above considerations with observations. Figure 2 shows the representative points (derived from the infrared observations of Gehrz *et al.* 1974) for the envelopes of 9 Be stars (γ Cas, π Aqr, χ Oph, ω Ori, φ Per, ζ Tau, EW Lac, 48 Lib and β Psc), of P Cyg and the O 7.5 supergiant ξ Per. For ζ Ori we used the results of the recent study of its Hα profile made by Hearn (1975). All the

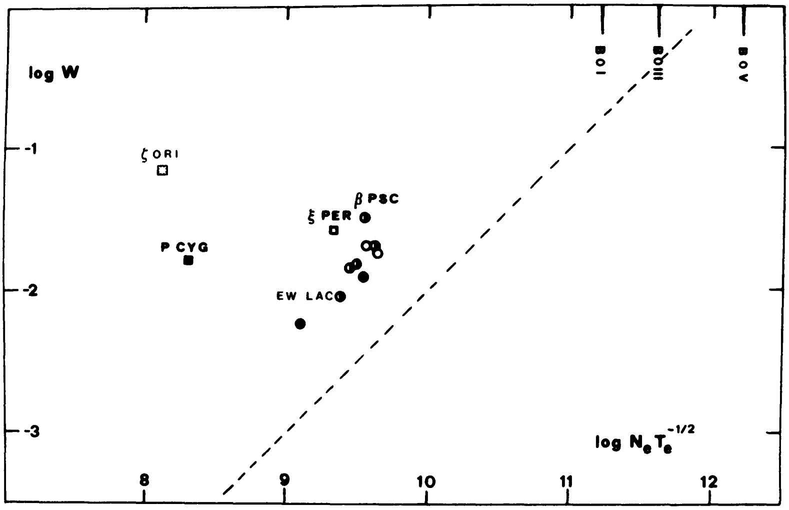

Fig. 2. Physical conditions in the envelopes of some Be stars (circles), of P Cyg and ξ Per (Viotti 1976), and of ζ Ori (Hearn, 1975). The emission character of each Be star is indicated according to Lesh (1968). Open circles: no emission. Half-filled circles: stars with weak emission (Be_1). Filled circles: stars with strong emission (Be_4). EW Lac classified Be_1 by Lesh in 1972 showed many Fe II emission lines. The dashed line ($N_eT_e^{-1/2} = 10^{12}\ W$) is the boundary between the 'radiative' region (upper left) and the region where electron collision is the dominating process of excitation of the emission lines of Fe II. The value of $N_eT_e^{-1/2}$ in the photospheres of B-type stars is also indicated.

representative points of the Be stars, except perhaps β Psc, apparently form a linear sequence with $N_eT_e^{-1/2}$ proportional to the dilution factor W, that is to R_E^{-2}, where R_E is the radius of the envelope. This suggests that the same physical process of mass loss is acting in these stars and that probably the rate of mass loss is similar. In Figure 2 the representative points of the Be stars fall on the left side of the dashed line, implying that in their envelopes the rate of collisional excitation of the upper levels of metallic ions is very low. Under these conditions the lower (metastable) Fe II levels are in LTE with the ground level, while the upper levels of the permitted transitions are depopulated with respect to LTE roughly by a factor W (Viotti, 1976), so that the intensity of the Fe II emission lines is proportional to the number density of the Fe^+ ions and to R_E. As a matter of fact, in Figure 2 the stars with more extended envelopes have the stronger emission character (filled circles and EW Lac). This result is of particular importance for the study of some peculiar variables, namely of the spectral variations of the novae. Taking $R_E = 2 \times 10^{12}$ cm, $N(Fe^+) = 10^7\ cm^{-3}$, and $T_{star} = 20\,000$ K we find that for an optically thin envelope the strongest Fe II lines should have an emission equivalent width of a few 0.1 Å, in agreement with the intensities observed in EW Lac and γ Cas.

Many Be stars have an infrared excess produced by free-free emission in an extended envelope, and we have shown that in these stars the Fe II lines are, or should be according to elementary theoretical computations, in emission with an intensity increasing with the radius of the envelope. Thus, *there is a physical connection between the presence of singly ionized iron emission lines and an infrared* *excess in Be stars.* These lines are excited by the ultraviolet stellar radiation, and it would be of great importance to make a systematic investigation of the ultraviolet flux of the Be stars with Fe II in emission near the ionized iron resonance lines. Forbidden ionized iron emission lines should appear when the envelopes are much more extended (W smaller than 10^{-3}, Viotti, 1976), in a more favourable condition for dust grain formation. *We therefore expect that* [Fe II] *emission lines are more likely related to infrared excesses by dust emission.*

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