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Identification of the 4486, 4504Å emission lines in O-type spectra

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Abstract. Inspired by an appeal to the community from Walborn (these proceedings) we decided to solve the long-standing problem concerning the nature of the 4486, 4504Å emission lines, which are frequently observed in O-type spectra and which are particularly prominent in supergiants. We claim that these lines emerge from sulfur, namely by de-excitation of a highly excited S IV doublet state. We prove this by an exploratory NLTE calculation with a detailed model atom.

1. Introduction

In his paper, Walborn (these proceedings) emphasizes that two prominent emission lines occurring in O-type spectra remain unidentified 37 years after being documented by Wolff (1963). In fact, as pointed out by Wolff, these lines were reported even earlier by Swings & Struve (1940) in a spectrum they have taken of 9 Sge, O7.5 Iaf, hence this problem remains unsolved over 60 years. Walborn furthermore states that despite several contrary suggestions in the literature, these lines are unlikely to be due to CNO ions, because they show no preference for ON or OC spectral types. Because of their possible role as selective emission lines with potential diagnostic power he concludes that "we should not sleep well until these lines are identified". The prospect of many sleepless nights, though not too frightening to astronomers, prompted us to attack this problem.

2. NLTE calculations

We calculated plane-parallel static NLTE model atmospheres composed of hydrogen, helium, and sulfur. The code used is based on an Accelerated Lambda Iteration (ALI) technique and is described in detail by Werner & Dreizler (1999). The sulfur model atom consists of ionization stages S II–VI. Figure 1 displays our model atom for S IV, which has 27 NLTE levels linked by 70 radiative transitions. Energy levels were obtained from the NIST database (http://www.nist.gov/), oscillator strengths and bound-free cross-sections from the Opacity Project database (Seaton et al. 1994). Line broadening and collisional rates are computed by standard approximate expressions due to the lack of reliable data. In the following we exclusively describe results from a single model calculation ($T_{\rm eff}$=35 500 K, $\log g$ =3.7, solar abundances). Systematic investigations covering the O spectral sequence and all luminosity classes are the subject of future work.

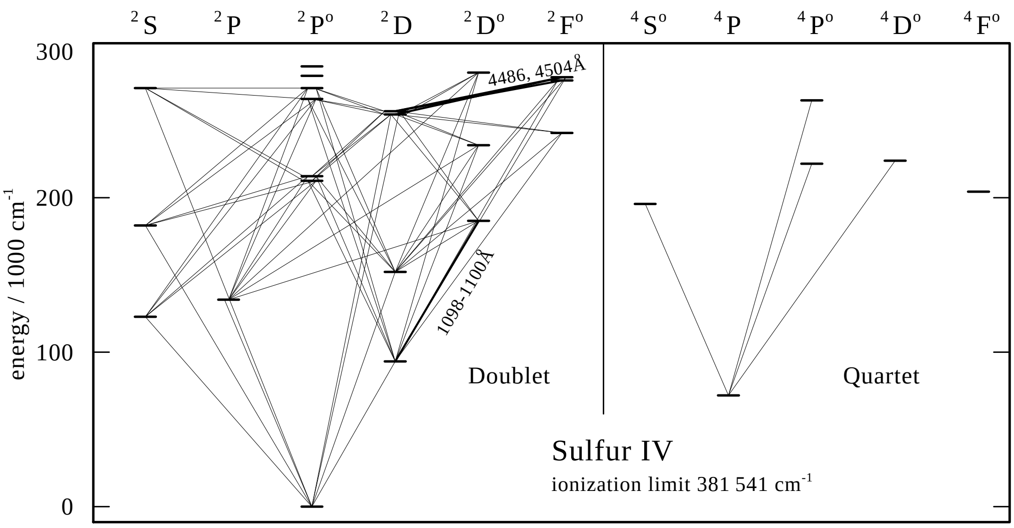

Figure 1. Model atom for S IV. The transitions in the doublet system responsible for the observed emission are marked by thick lines and wavelength labels. A FUV line discussed in the text is also marked.

Figure 2 shows the sulfur ionization structure throughout the atmosphere. It can be seen that S V is the dominant stage in the line formation region ($\log m = 0 ... -0.4$), followed by S IV. This situation favors recombination from S V into highly excited S IV levels which then de-excite radiatively by photon emission. In fact this turns out to be the mechanism responsible for the emission lines under discussion. The observed emission line pair stems from the transition $3s^24d$ ^2D–$3s^24f$ $^2F^o$, which in detail is composed of three lines. In all observed spectra we have inspected in the literature, the two blue components at 4486Å are too close to be resolved because of stellar rotation (Fig. 2).

Table 1. Atomic data for the newly identified S IV emission lines, taken from NIST and Opacity Project databases

Wavelength Air (Å)	Rel. Int.	Oscillator Strength	E_i (cm^{-1})	E_k (cm^{-1})	$J_i - J_k$	$g_i - g_k$
4485.662	16	0.407	255 395.8 –	277 682.8	3/2 – 5/2	4 – 6
4486.568	12	0.019	255 400.3 –	277 682.8	5/2 – 5/2	6 – 6
4504.093	14	0.388	255 400.3 –	277 596.1	5/2 – 7/2	6 – 8

Figure 3 compares the computed model spectrum with observations of 15 Mon, O7 V((f)), and HD 105056, ON9.7 Iae. The model is convolved with rotation profiles with $v \sin i$=67 km/s and 68 km/s, respectively (from Howarth et al. 1997). It has parameters appropriate for 15 Mon (see above), being somewhat cooler than the temperature obtained by Herrero et al. (1992, $T_{\rm eff}$=39 500 K). The S IV emission lines match the observation very well, both in wavelength and in strength. The supergiant HD 105056 requires a much cooler model with much lower gravity ($T_{\rm eff}$=31 600 K, $\log g$ =3.1, Pauldrach et al. 1990), but nevertheless we show the spectrum of this star with the same model in order to emphasize the relative

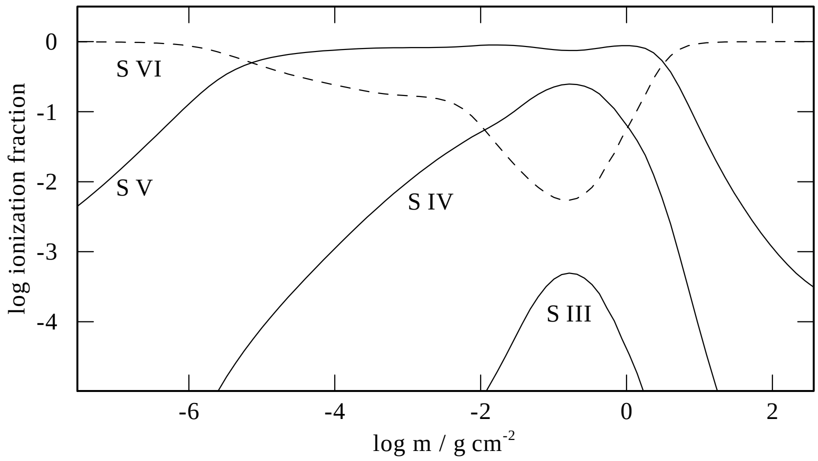

Figure 2. Ionization of sulfur as a function of depth in the model atmosphere. Depth parameter is the column mass measured inward from the top of the atmosphere.

strength of the S IV emissions as compared to the main sequence star 15 Mon. The relative strength of the two emission lines is not matched by the model. This can be caused by subtle details, like treatment of collisional rates among the levels, and deserves further investigation.

Our models also include S IV and S V lines in the UV and FUV spectral regions. They show an S V absorption line at 1502Å which supports the identification first suggested by Howarth (1987). In addition, the models predict an absorption line of S IV at 1099Å. It is a multiplet with four components between 1098.4Å and 1100.05Å arising from transitions between the lowest ^{2}D and ^{2}D^o terms in the Grotrian diagram (Fig. 1). A hitherto unidentified line at this wavelength has been observed in COPERNICUS spectra of O-stars (Walborn & Bohlin 1996) and we suggest the identification with S IV.

3. Conclusion

Finally, sixty years after the first documentation of the 4486, 4504Å emission lines in O-star spectra, their origin has been revealed; by using model calculations, we have shown that they are attributable to S IV. Since the models are of plane-parallel atmospheres, neither sphericity effects nor stellar winds need to be invoked for this emission line phenomenon. Future work may explain the observed strength of these lines as a function of effective temperature and luminosity class so that, in turn, these selective emission lines may henceforth be used as a diagnostic tool.

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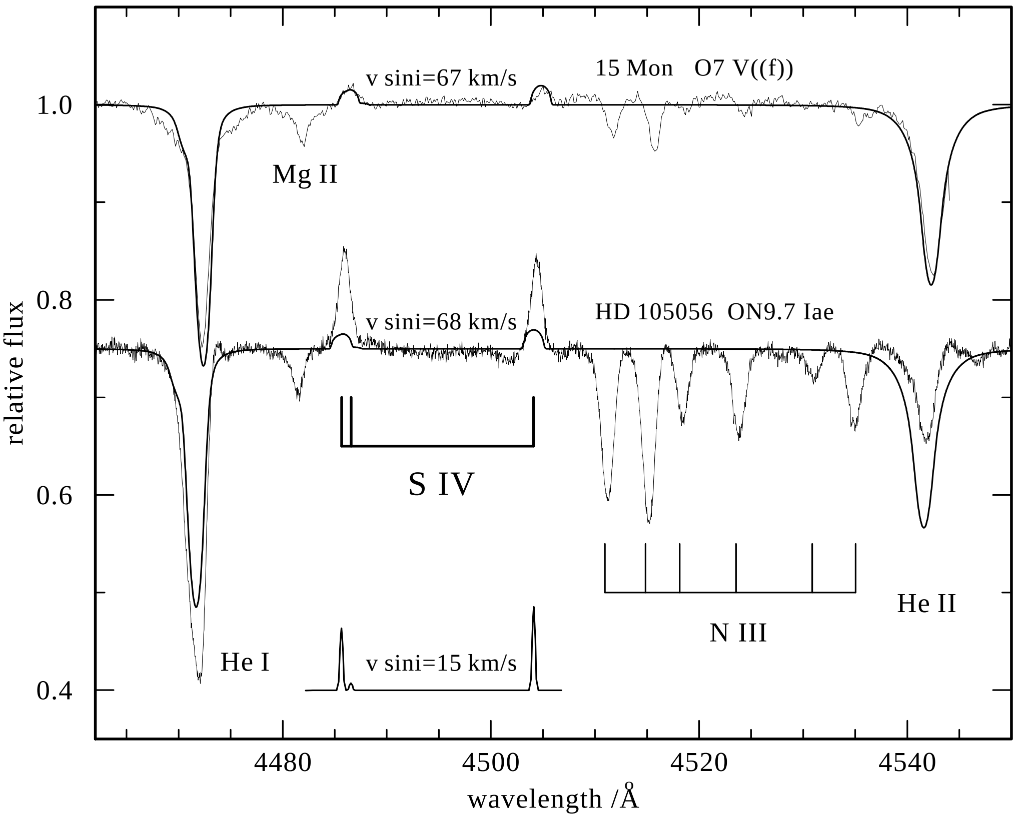

Figure 3. Comparison of the synthetic spectrum with 15 Mon and HD 105056. The model is folded according to the stellar rotation velocity and redshifted for 15 Mon in order to match He I 4471Å. The computed spectrum with reduced rotation velocity and, thus, resolved blue components is shown at the bottom.

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