HIGH RESOLUTION X-RAY SPECTROSCOPY WITH XMM-NEWTON OF HOT STARS: τ SCORPII

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The spectra of the B0.2V star Tau Scorpii, observed with RGS and EPIC-MOS on board XMM-Newton, are simultaneously fitted to obtain self-consistent temperatures, emission measures, and elemental abundances. The nitrogen lines are relatively very strong: the N/O abundance ratio is about 3 times solar. Multi-temperature fitting yields 4 components at temperatures of 1.6, 5.2, 8.2, and $\gtrsim$ 20 MK which are confirmed by DEM modeling. The X-ray luminosity (0.3-10 keV) is 3.2e31 erg/s at d=132 pc. The sensitivity of the He-like forbidden and intercombination lines to a strong UV stellar radiation field yields upper limits to the radial distances at which the He-like lines of Mg, Ne, O, and N originate. The results suggest that the soft X-rays ($\lesssim$ 8 MK) originate from shocks low in the wind produced by the common mechanism of radiation line-driven instabilities. This is consistent with the observed emission line profiles that are much narrower ($\lesssim$ 500 km/s) than the broad lines (up to 1500 km/s) observed high up in the wind of Zeta Puppis. The hot ($\sim$ 20-40 MK) component may be explained by a model involving dense clumps embedded in a wind which is approaching at high relative velocity ($\sim$ 1400-1700 km/s) and the interaction produces strong shocks.

1. Introduction

Hot stars (O-, B- and WR-stars) are characterized by a strong stellar wind due to the strong radiation field in combination with a resonance line driven mechanism. Upto B1 types these stars show strong X-ray radiation.

In binary systems this emission is caused by the colliding winds of the two stars. Therefore this emission is time dependent due to the excentricity of the system, the density and absorption of the wind, eclipses, or variability due to the inclination-dependent line of sight extinction. In single systems the emission is believed to be the result of instabilities in the wind that produce shocks, or by clumps in the wind that stagnate and fall inward and then collide with the faster wind ([1]). All these mechanisms are reflected in a variety of features in the X-Ray spectra of hot stars.

Fig. 1 shows this variety in the spectra of τ Sco, ζ Pup, and WR25, observed by means of RGS and EPIC-MOS aboard XMM-Newton. The figures are taken from [2–4]. From this figure we notice the many lines in the spectra of τ Sco and ζ Pup. However those in the spectrum of τ Sco are narrow i.e., comparable to the instrumental Line Spread Function (LSF) [2], while the lines in the spectrum of ζ Pup are broadened, due to velocity effects in the wind [3]. In the spectrum of WR25 no lines are present above 15 Å, due to strong absorption in the stellar wind of the Wolf-Rayet star [4].

2. Analysis of He-like lines

In the wavelength range between 5 and 40 Å the X-Ray spectra are dominated by H- and He-like transitions of C, N, O, Ne, Mg, and Si. The He-like spectra show three neighbouring lines: the resonance line $1s^2\ ^1S_0$ - $1s2p\ ^1P_1$ (r), the intercombination line $1s^2\ ^1S_0$ - $1s2p\ ^3P_1$ (i) between the triplet and singlet system, and the forbidden line $1s^2\ ^1S_0$ - $1s2s\ ^3S_1$ (f). These transitions are temperature and density sensitive ([5]). Fig. 2 shows the He-like lines of O VII and N VI together with the two H-like lines of O VIII and N VII in the spectra of Procyon (a cool F-type star) ([6]) and τ Sco. The two lower panels of

Fig. 2 zoom in on the O VII He-like transitions of these ions.

The mechanism of the density sensitivity of the three He-like lines is explained in Fig. 3 a. The forbidden transition ($1s^2\ ^1S_0$ - $1s2s\ ^3S_1$) is not a normal allowed electric dipole transition, for which the parity changes by "1", but a less likely magnetic dipole transition for which the transition probability is about a factor 10^6 lower (depending on the ion) than that of the resonance line. In that lower energy state ($1s2s\ ^3S_1$) the electron is in fact captured, since no other radiative decay is possible, other than by a forbidden transition. The radiative decay to the $1s^2\ ^1S_0$ level will take 10^6 longer, which will increase the lifetime of the $1s2s\ ^3S_1$ state. During that time something might happen. One of the things that might happen is a collisional deexcitation from the $1s2s\ ^3S_1$ level by a passing particle. Every passing particle has enough energy to let the electron jump from the $1s2s\ ^3S_1$ state to the $1s2p\ ^3P_1$ state, which is responsible for the intercombination line (i). This will result in a decrease of the flux in the forbidden line and an increase of the flux in the intercombination line and therewith strongly influence the line flux ratio f/i. Of course this mechanism is strongly depending on the density of the plasma.

In Fig. 2 (first and third) panel we recognize the three transitions in the spectrum of Procyon. In the second and fourth panel of Fig. 2, showing the spectrum of τ Sco the forbidden line has disappeared, while the intercombination line is prominently present. The conclusion might be that we deal with a high density plasma in the stellar wind. This conclusion, however, oversees the effect of the strong UV-radiation field, which can not be neglected in case of hot stars.

Fig. 3b shows the depopulation of the forbidden level $1s2s\ ^3S_1$ by means of a radiative transition to the $1s2p\ ^3P_1$ level, as result of the absorption of a photon from the radiation field around 1638 Å. The radiation field of the hot star τ Sco (32000 Kelvin) is far stronger than that of Procyon (5500 Kelvin) and peaks between 500 and 2000 Å, while the radiation of Procyon peaks around 5000 Å. This is shown in Fig. 4. Due to the wavelength shift the hot wind of τ Sco will affect the f/i ratio for O VII, Ne IX, Mg XI and to a lesser extend Si XIII, while the radiation field of Procyon only affects the f/i value of C V.

The strength of the radiation field depends on the distance to the stellar surface. The relation between the distance and the the line flux ratio (f/i) is given in Fig. 5. The bold lines show the upper limits for our ratios. The fact that the plasma seems to be formed near the stellar surface is in agreement with the narrow line profiles, indicating low wind velocities.

3. Conclusions

The X-ray spectrum of τ Sco is dominated by H-like and He-like transitions. The line width is comparable with the instrumental width, indicating wind-velocities $\lesssim$ 500 km/s.

The enhancement of the intercombination line in combination with the absence of the forbidden line in He-like systems is caused by the UV-radiation field near the stellar surface, where the radiation field is strong, and the wind velocities low. The latter agrees with the observation of narrow lines.

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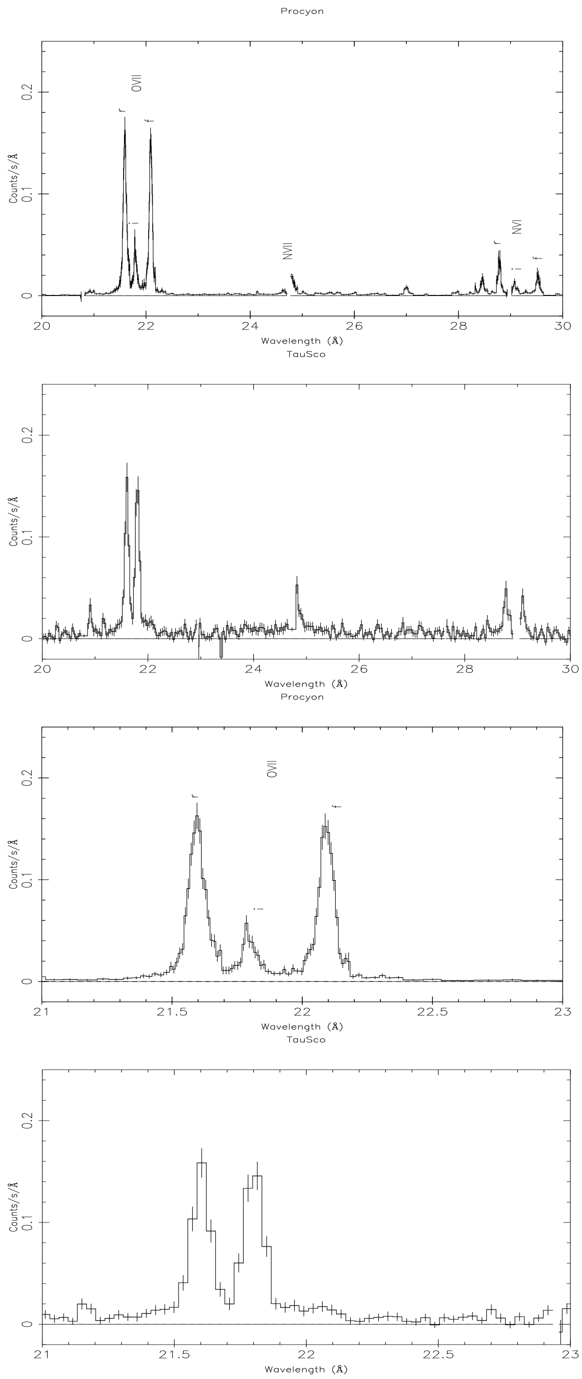

Figure 2. **Top panel**: H- and He-like transition in the spectrum of the cool star Procyon. **Second panel**: The same for the hot star τ Sco. **Third panel**: The He-like transitions of O VII in the spectrum of Procyon. **Fourth panel**: The same for the hot star τ Sco.

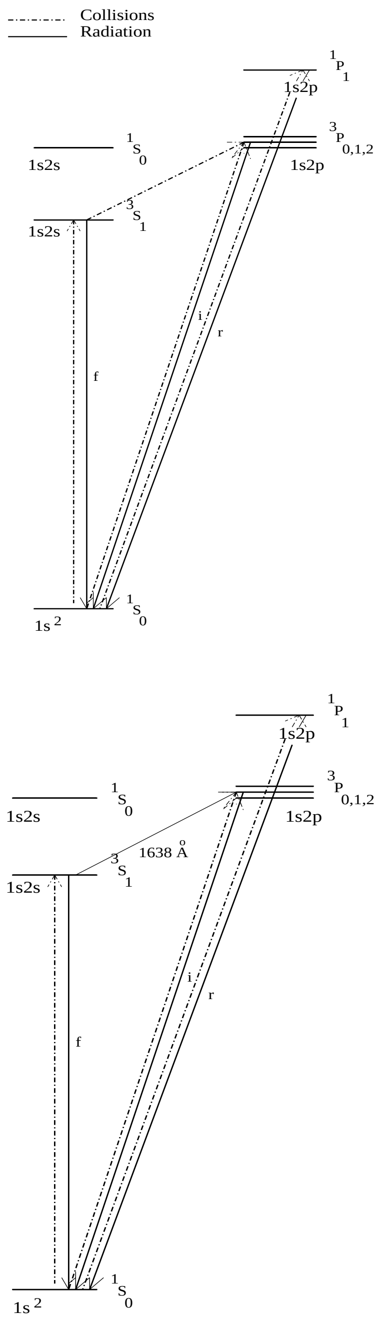

Figure 3. **Top panel**: Illustration of the He-like system in case of collisional depopulation of the forbidden line level (Procyon). **Lower panel**: Illustration of the He-like system in case of radiation depopulation of the forbidden line level (τ Sco).

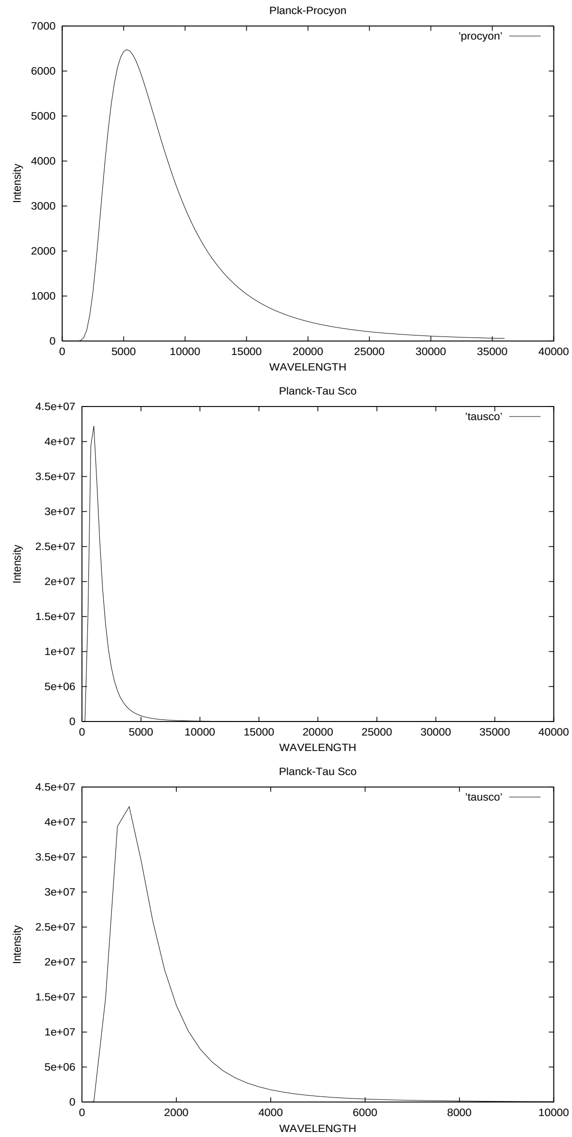

Figure 4. **Top panel**: The Planck radiaton curve for Procyon (5500 K). **Middle panel**: The Planck radiation curve of τ Sco (32000 K). **Bottom panel**: The same as the middle panel but focused on the appropriate wavelength range.

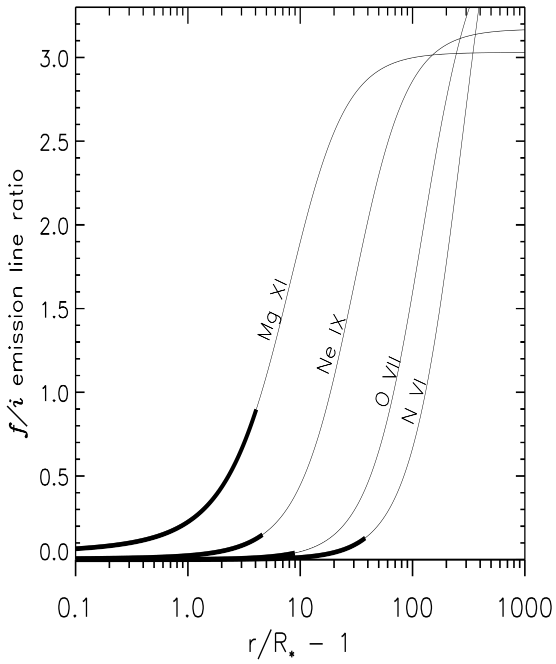

Figure 5. The f/i ratio in He-like ions versus the distance to the stellar surface for the radiation field ofτ Sco.

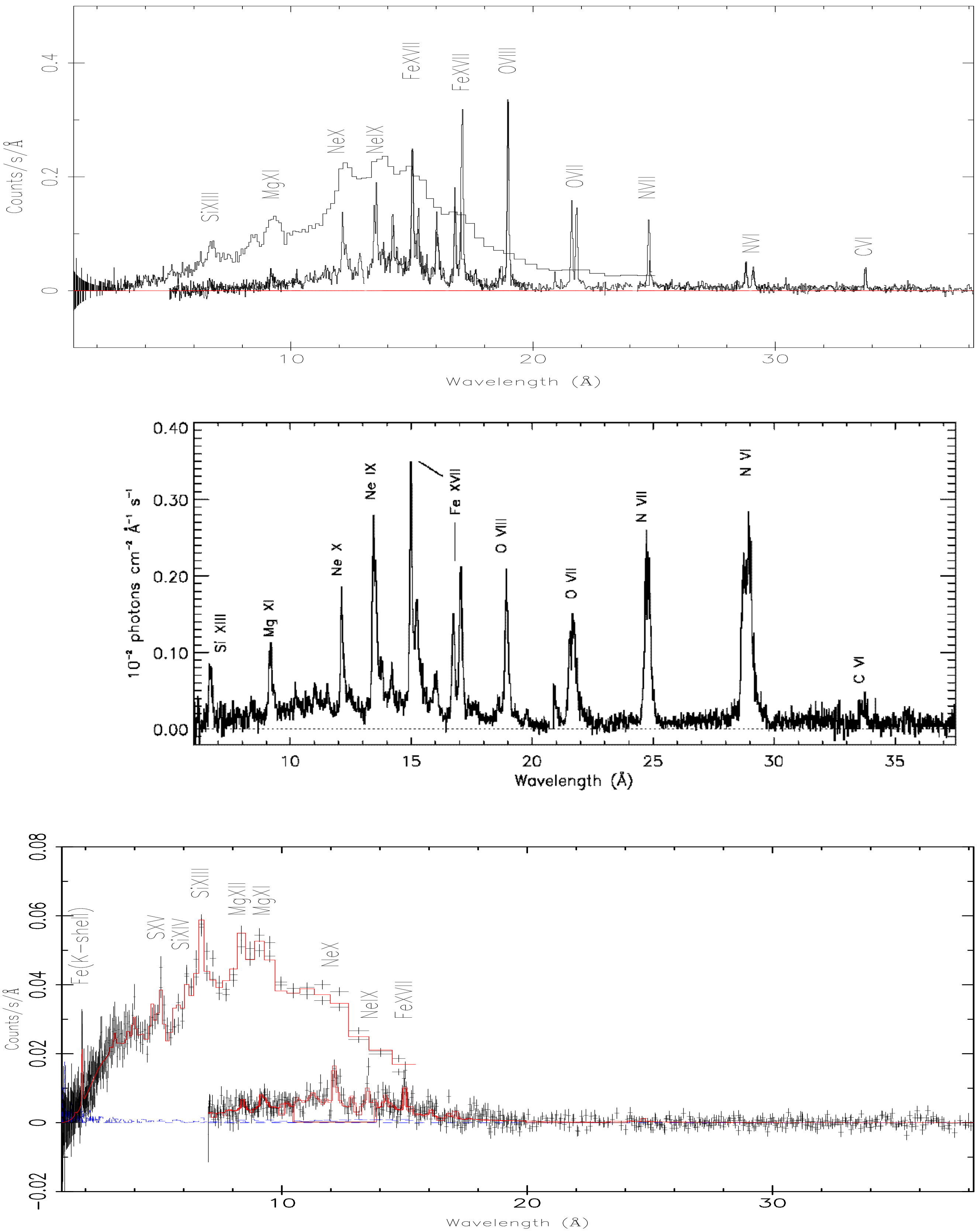

Figure 1. **Top panel**: First-order background-subtracted spectrum of τ Sco (from [2]), observed by RGS (5–37 Å; rebinned by a factor 3 and the spectrum of the EPIC-MOS (1–25 Å). **Middle panel**: ζ Pup *XMM*-RGS spectrum (from [3] for comparison to show the much broader lines. **Bottom panel**: WR25 (from [4])