The complex XMM–RGS spectrum of the hot star sigma Orionis

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We present a preliminary analysis of an *XMM-Newton* observation of the σ Orionis cluster centered on the O9.5V star σ Ori. In addition to the EPIC image, which shows the presence of about 240 sources, mostly low-mass PMS stars belonging to the cluster, a high statistics RGS spectrum is obtained for the central source. The EPIC image shows the presence of nearby sources, including a flaring one, which, although weaker, may contaminate the RGS spectrum of the central star. We present an analysis of the RGS and EPIC spectra of σ Ori and of the EPIC spectra of the nearby sources and we discuss the possible contamination of the hot star RGS spectrum by the other sources.

1. Introduction

The σ Ori cluster, discovered by *ROSAT* [1, 2] around the O9.5V star σ Ori, belongs to the OB1b association and is located at a distance of 352 pc; in addition to several hot stars, it is known to contain $\sim$ 100 likely pre-main sequence late-type stars within $30'$ of σ Ori, as well as some brown dwarfs and planetary-mass objects [3–5]. The estimated age of the cluster is $2-5$ Myr.

X-ray emission from O and B stars is usually explained with the presence of winds. X-ray observations of the stars ζ Pup (O4If) and ζ Ori (O9Ib) have shown the presence of such winds, with velocity widths of order 600–1500 km s^{-1} and blueshifted centroids [6–8]. However, some conflicting results have been found, like high-densities close to the stellar surface in ζ Ori [6], raising the question on whether coronal loops could be present in some of these stars. High-resolution spectroscopic observations of the hot star σ Ori were expected to shed some light on these issues.

The EPIC imaging data of our *XMM-Newton* observation of the σ Ori cluster have been discussed by [9]. The merged dataset has an equivalent MOS exposure time of 217 ksec. The sensitivity in the center of the field is $L_{\rm X} \sim 2.5 \times 10^{28}$ erg sec^{-1}. Fig. 1 shows the central part of the composite EPIC image. RGS spectra were obtained from the center of the field, with an exposure time of $\sim$42 ks. Three sources in addition to σ Ori itself contribute to the flux in the RGS spectra. They are listed in Table 1. The EPIC/PN light curves of these four sources are shown in Fig. 2. σ Ori AB is by far the strongest source and its emission is steady; σ Ori E instead appears to undergo a strong flare, which is unusual for a B2V star and could be due to an unseen late type companion. Some contribution from nearby K dwarfs is also present.

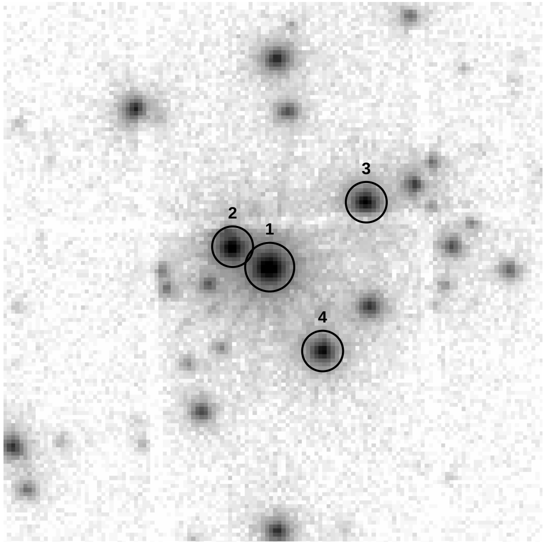

Figure 1. Central part of the composite *EPIC* image of the σ Ori field. Encircled are the sources falling in the RGS field of view and contributing more than 10% of the total flux. Numbers identify the sources listed in Table 1.

2. RGS spectra

XMM/RGS spectra have been analized with the software provided by the *Interactive Spectral Interpretation System* (ISIS) [10]. Surprisingly, the preliminary analysis of the XMM/RGS spec-

Table 1
Sources falling in the RGS field of view contributing more than 10% of the total flux. Identified stars are all members or candidate members of the σ Ori cluster

N_x	RA_x	DEC_x	count rate	$\log L_X$	Opt. ID	offset	V	$B-V$	Sp.type
	(2000)		(10^{-3} cts/s)			($''$)			
1	5 38 44.82	−2 35 59.2	381.78 ± 1.48	31.56	σ Ori AB	1.34	3.80	−0.24	O9.5V
2	5 38 47.24	−2 35 39.2	180.64 ± 1.13	31.23	σ Ori E	1.52	6.68	−0.18	B2Vp
3	5 38 38.52	−2 34 55.1	110.78 ± 0.89	31.02	r053838-0234	0.47	12.24	1.18	K5
					GSC 4771-1147	2.55	13.71	1.18	K0
4	5 38 41.37	−2 37 22.2	88.93 ± 0.75	30.92	r053841-0237	1.22			K3

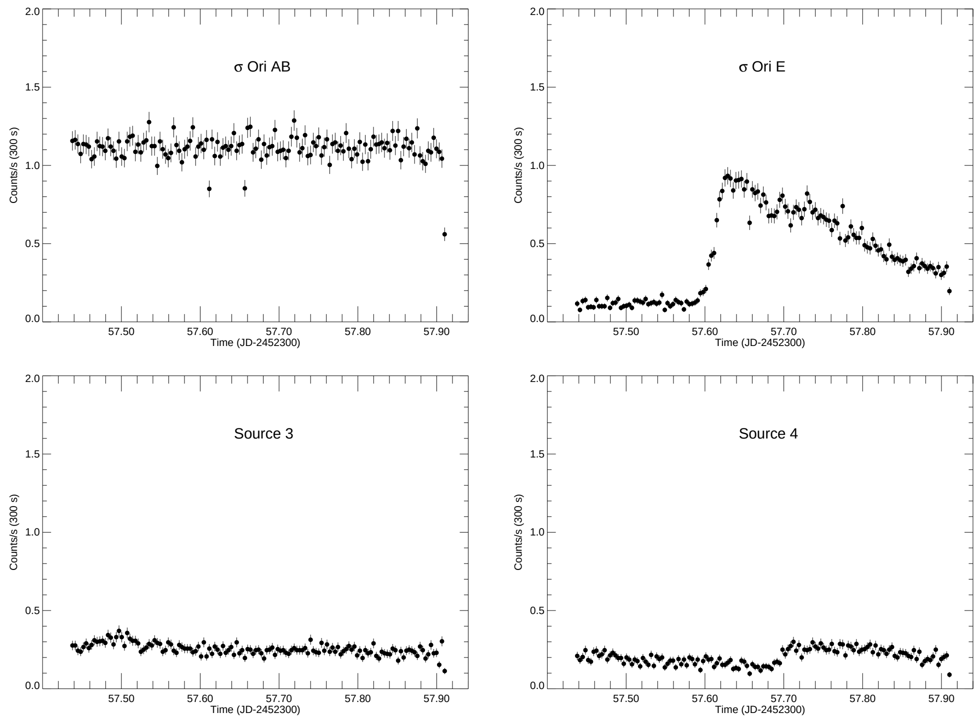

Figure 2. EPIC/PN light curves corresponding to the 4 main sources listed in Table 1.

trum of σ Ori has shown no substantial blueshifts, as it would be expected if winds were responsible for the emission. Some characteristics observed in the composite spectra (Fig. 3) are:

- No substantial blueshifts or Doppler-broadening of lines.
- The ratio O VII $F_{22.1}/F_{21.8}$ (f/i) shows a remarkably low value ($\sim$0). In a collisionally excited plasma this would mean an electron density $\log n_e \geq 12$ cm^{-3}. However, the UV radiation field of the hot star conditions the formation of the intercombination line, and the O VII triplet is no longer valid as a density diagnostics in the same range. In this case the observed ratio puts only a lower limit of $\log n_e \geq 8$ cm^{-3}.
- The presence of small lines redwards of O VIII 18.97 Å indicates the contamination by O VIII 18.97 Å lines from other sources in the field. Since the dispersion angles of RGS 1 and 2 are perpendicular to each other, it is possible to associate these lines to their individual sources in the RGS field of view.
- We found higher than solar abundances of C, N, and O with respect to

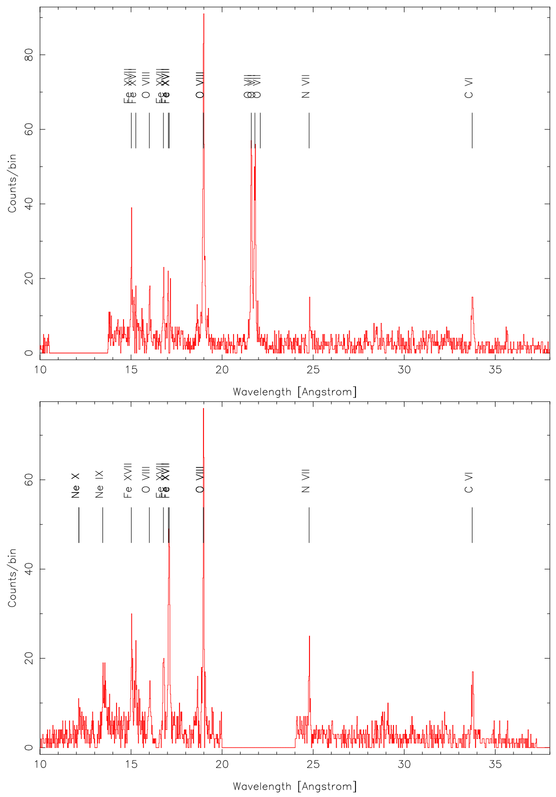

Figure 3. RGS 1 & 2 spectra of the central area of the σ Ori cluster (RGS exposure time ~42 ks). The most intense lines identified are marked.

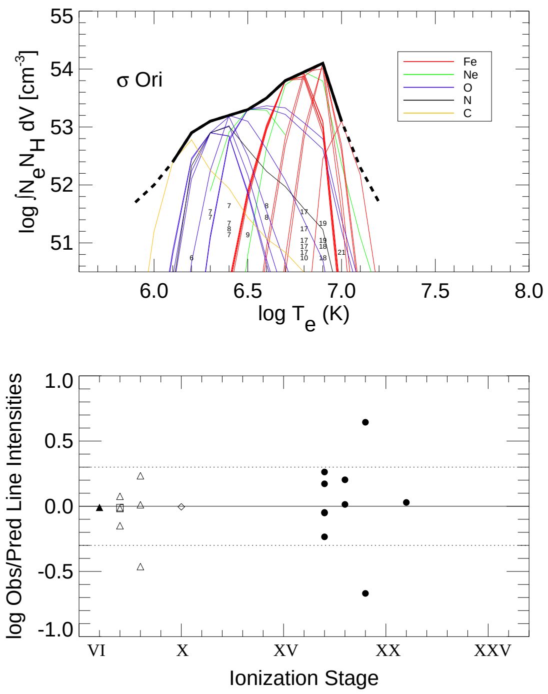

Figure 4. Emission Measure (EM) distribution of σ Ori (RGS spectrum). The *upper panel* shows the EM distribution (thick line) and the contributions of each spectral line, weighted by the EM distribution (thin colored lines). *Lower panel*: ratio of observed to predicted lines intensities from different elements: Fe (filled circles), Ne (diamonds), O (open triangles), C (filled triangles) and N (squares).

Fe ([C/Fe]=0.44±0.12, [O/Fe]=0.64±0.14, [N/Fe]=0.58±0.11), which could indicate a possible mixture of CNO-burned material with the rest of the X-ray emitting material, an unexpected result for a young star. Ne abundance, instead, is almost solar [Ne/Fe]=0.12±0.09 rejecting an inverse FIP-like effect.

- The Emission Measure distribution built from the RGS spectra (using a line-based method and the atomic database APED), is dominated by material in the range 1–10 MK (see Fig. 4).

3. EPIC spectra

Fig. 5 shows the EPIC spectra of the four sources contributing to the RGS spectrum. Is is evident from the figure that σ Ori AB is significantly cooler than the other sources. Spectral fits using 2-temperature APEC models yield temperatures of $\sim$ 2 and 5 MK for σ Ori AB, with emission measures of 7 and 2×10^{54} cm^{-3}, respectively. For σ Ori E we find $T \sim 7.5$ and 35 MK, with $EM \sim 4 \times 10^{53}$ and $\sim 1.5 \times 10^{54}$ cm^{-3}, respectively; the high temperatures and emission measures are attributable to the strong flare. However even during the pre-flare phase the star is significantly hotter than σ Ori AB, having T = 5 and 17 MK with similar emission measures. These high temperatures further support the idea that the X-ray emission might be due to an unseen late-type companion rather than to the B2V star itself.

The other two sources, identified with K-type dwarfs, have similar coronae, with temperatures in the range $5-10$ MK and $25-30$ MK and

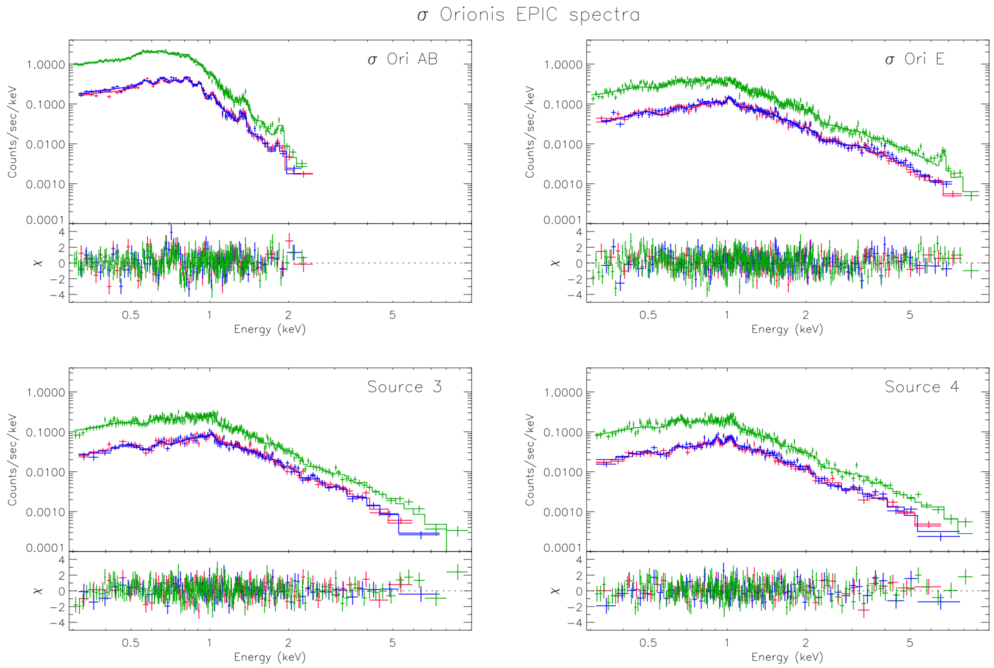

Figure 5. EPIC MOS1 (*blue*), MOS2 (*red*) and PN (*green*) spectra of the 4 main sources listed in Table 1. The best-fit models are also shown. The spectrum of σ Ori AB is dominated by background above 2.5 keV

with the hotter component dominating the X-ray emission ($EM_2/EM_1 \simeq 2-3$).

4. Conclusions

The RGS spectra of σ Ori that we have obtained are clearly complex. Although the pointed O9.5V star is the dominant source, other sources in the field, including a flaring one, contribute to the observed spectra. A detailed analysis of the different contributions of individual sources, by using the wavelength shifts in the dispersion direction associated with each source, as well as the spectral information derived from the simultaneous EPIC spectra, is needed in order to quantify the flux from the different sources. The preliminary analysis presented in this paper shows that the X-ray emission from σ Ori itself is steady and much softer than the one associated with the other sources. It also does not show the presence of strong winds contrary to what could be expected from current models of hot stars. The observed presence of large amounts of C, N and O is intriguing but needs to be further investigated once the possible effects of instrumental or analysis uncertainties are removed.

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