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Temperature Determination and Emission Measure Modeling of the Coronae of α Centauri and Procyon

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Abstract.
We have obtained the spectra of the coronae of α Centauri and Procyon using the Reflection Grating Spectrometer (RGS) on board XMM-Newton and the Low Energy Transmission Grating Spectrometer (LETGS) on board Chandra. From measured line fluxes of H- and He-like lines of Carbon, Nitrogen and Oxygen and of strong lines of Fe IX and Fe X temperature estimates and emission measures EM have been obtained. For all three stars (Procyon, α Cen (G2V), and α Cen (K1V)) the temperatures are in the regime of 1-2 MK. The emission measure for Procyon is about 1×10^{50} cm^{-3} and for both components of α Cen about 8×10^{48} cm^{-3}. Global fits to the total spectrum using SPEX show significant temperature components around 1 and 2 MK. Self-consistent continuous emission measures have been constructed. The α Cen (K1V) is somewhat hotter than its G2V companion.

1. Introduction

Solar-type stars of spectral classes F-M show considerable hot outer atmospheres (coronae). From the solar corona we know that there is a variety of processes with rich details, different temperatures, abundances, densities, and surface structures (see TRACE observations by Schrijver et al. CS12, 2001). Also stellar coronae show a large variety and appear in quiescent, active and flaring states with temperatures from 1 MK up to 50 MK during flares and densities in the regime from 10^9 upto 10^{13}. The abundances obtained for these hot plasma's depend on activity states and differ from the photospheric abundances of the stars. No clear explanation for this deviation from stellar photospheric abundance is known neither for the heating mechanism of the corona. Although the stellar coronae are not spatially resolved, valuable information about the temperature and density structure can be obtained from spectroscopy. High-resolution X-ray spectra of stellar coronae are available now produced by RGS on board XMM-Newton (Brinkman et al. 2001; Audard et al. 2001ab; Güdel et al. 2001ab) and by

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LETGS on board Chandra (Brinkman et al. 2000; Ayres et al. 2001; Behar et al. 2001; Canizares et al. 2000; Drake et al. 2001; Mewe et al. 2001a; Ness et al. 2001a). Many of the observed sources are hotter and more active than the Sun. Here we present the spectral analysis of two nearby solar-type stars Procyon and α Centauri. Procyon was observed by LETGS on board Chandra and by RGS on board XMM-Newton, α Centauri was observed by LETGS only. Both objects have been studied by Drake using EUVE (Drake, Laming & Widing 1995; Drake, Laming & Widing 1997). They obtain for both objects temperatures at $\log T \sim 6.3$. However, they were not able to resolve α Cen into its two components, G2V and K1V. The two components of α Cen are separated by $16''$. By positioning the dispersion axis perpendicular to the axis between the two stars separated spectra of the two α Cen stars could be obtained (Fig 1). Based on these observations the spectra, shown in Fig 2 and Fig 3 have been obtained. The three spectra look very similar with a strong Fe IX line around 171 Å and its isoelectronic twin of Ni XI around 148 Å. Strong H- and He-lines of C, N, and O dominate the spectrum below 40 Å (see also Fig 3). In between many L-shell lines of Ne, Mg, and Si appear. From these figures it might be seen that the "cool" Fe IX line is somewhat stronger relative to the "hotter" O VIII line at 18.969 Å for the G2V star (middle) than for the two other stars (Fig 2). The same is true for the "cooler" C VI line at 33.74 Å compared to the "hot" O VIII line for the G2V star (Fig 3). The Procyon spectrum shown in Fig. 3 is from RGS, the two other spectra are from LETGS.

2. Individual Lines Fluxes

Based on the spectra, shown in Fig 2 and 3, we have measured the fluxes of a number of individual lines to obtain temperature indications and emission measures. These lines have been selected on the base of their strength, resulting in a low signal-to-noise inaccuracy, and on the fact that their data in the atomic data bases are expected to be most accurate. The fluxes have been measured by convolving a δ-function with the instrumental Line-Spread-Function. In Table 1 the selected lines are given with their fluxes (in 10^{-4} photons/cm^2/s) and identification for the three stars. For the stronger lines the error bars are 5% or below, while for the weakest lines the error bars go up to 25%. From this Table 1 we notice that the hotter lines (O VIII, O VII and N VII) are weaker in the G2V star compared to the K1V star, while this is just the opposite for the cooler lines (C V and Fe IX). This indicates that the K1V star is more intense in the hotter plasma.

		Procyon	α Centauri	
Ions	λ(Å)	F5IV-V	G2V	K1V
O VIII	18.969	1.83	0.27	0.53
O VII	21.602	3.01	0.84	1.09
N VII	24.781	0.80	0.10	0.20
N VI	28.787	0.73	0.24	0.23
C VI	33.736	4.02	1.21	1.22
C V	40.268	2.09	0.77	0.45
Fe IX	171.075	114	71	47
Fe X	174.530	118	52	50

Table 1. Line fluxes in 10^{-4} photons/cm^2/s of strong selected individual lines

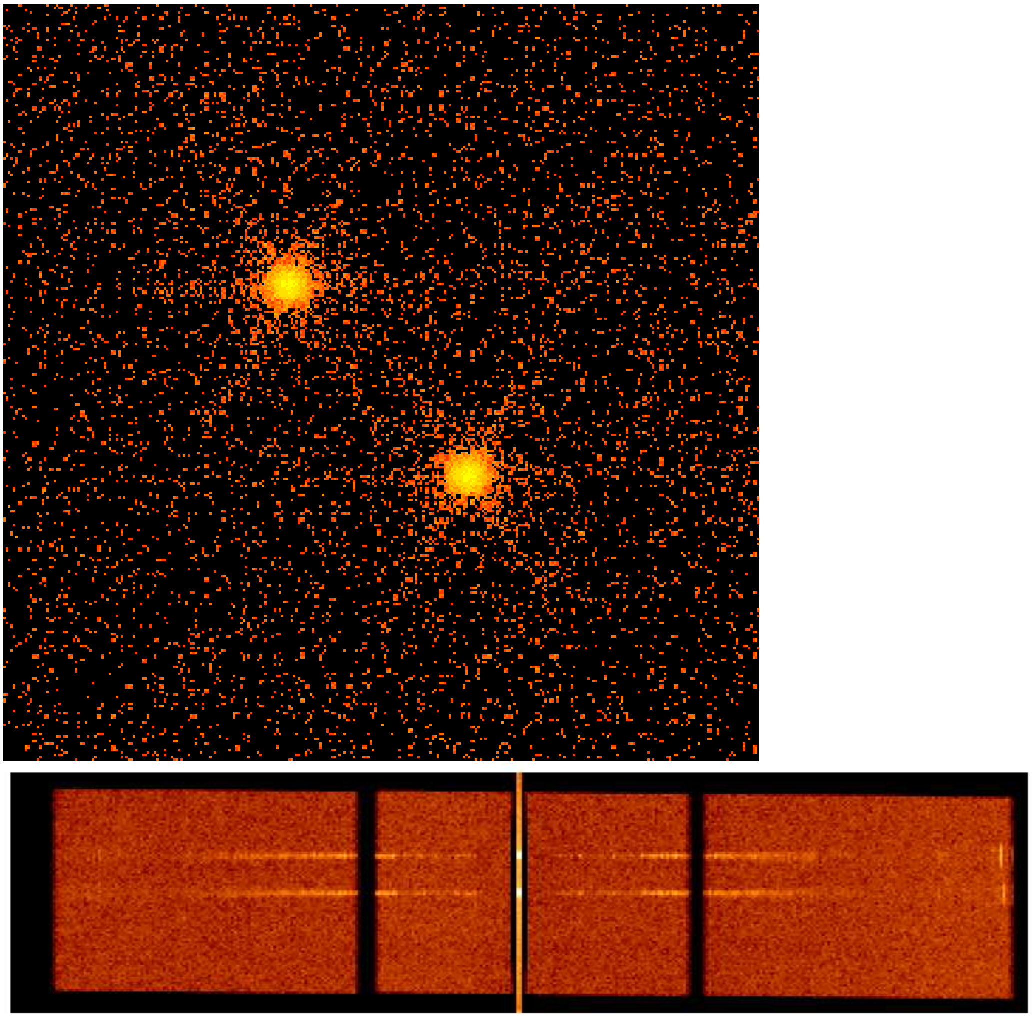

Figure 1. The images and spectra of α Cen G2V (top) and α Cen K1V (bottom) observed by LETGS on board Chandra.

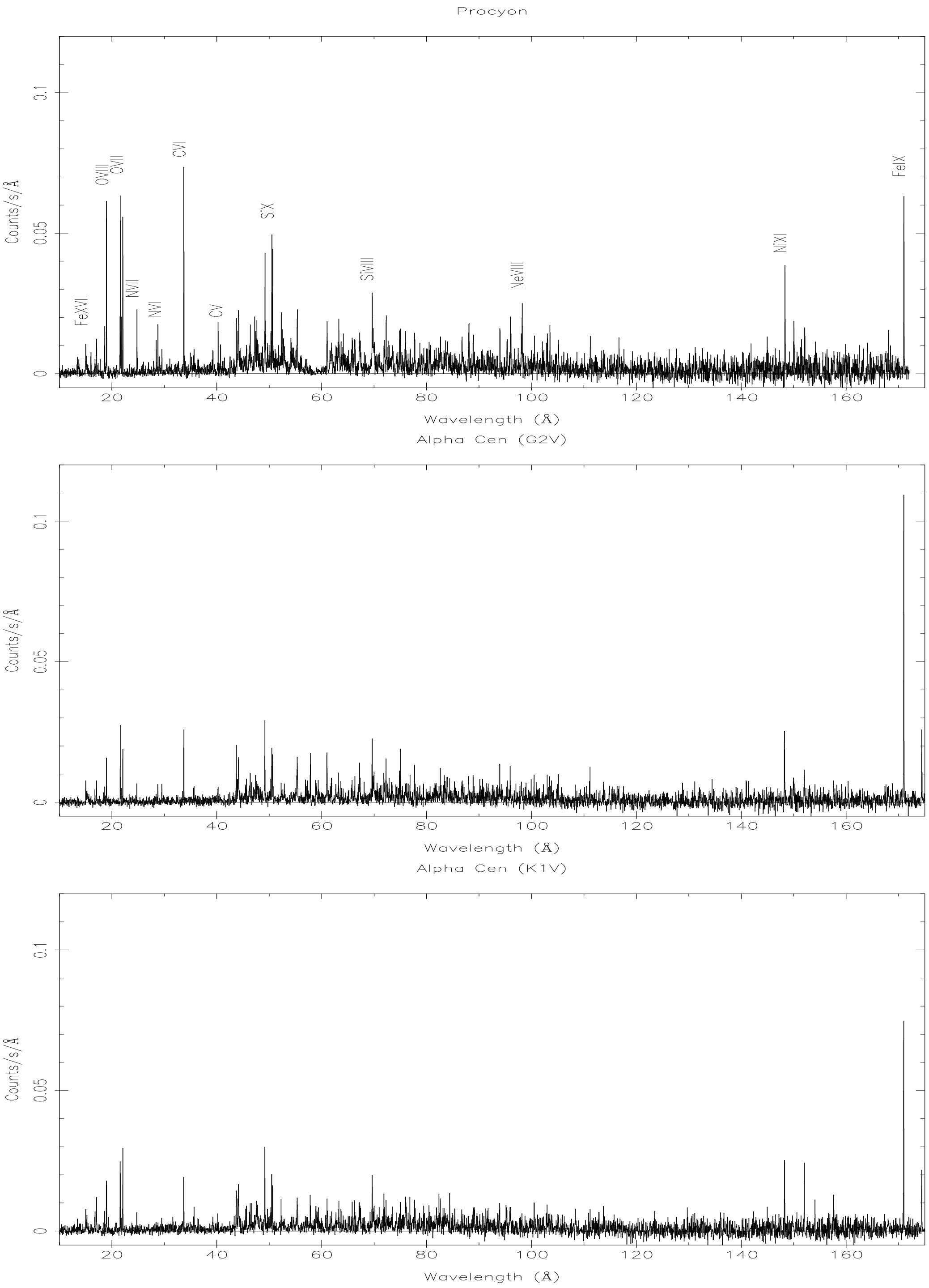

Figure 2. The spectra of Procyon (top), α Cen G2V (middle), and α Cen K1V (bottom) observed by LETGS on board Chandra. Notice the strong Fe IX line around 171 Å and the H- and He-like lines of Carbon, Nitrogen and Oxygen between 18 and 42 Å.

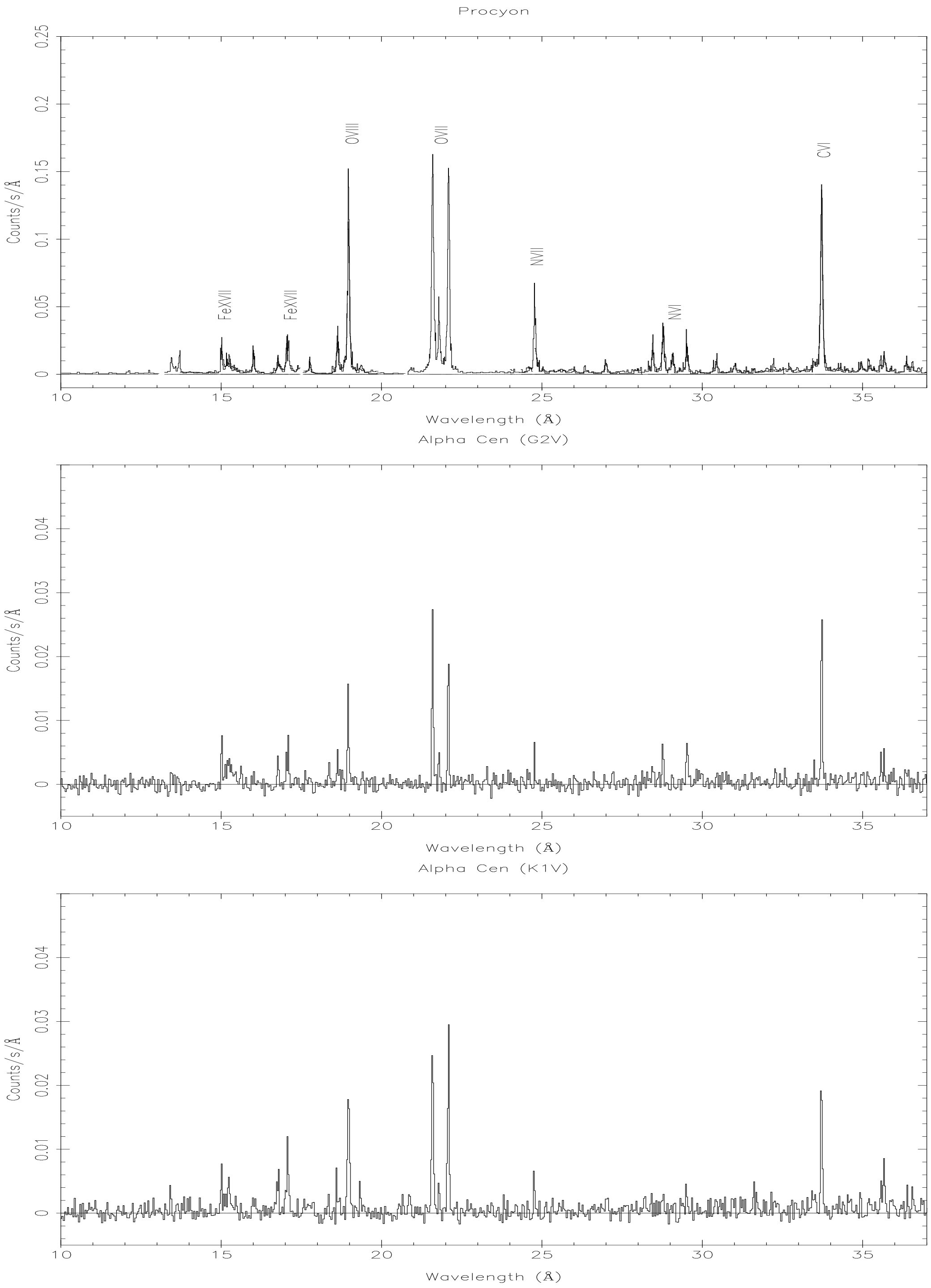

Figure 3. The spectra of Procyon (top) by RGS, α Cen G2V (middle), and α Cen K1V (bottom) by LETGS. Notice the strong H- and He-like lines of Carbon, Nitrogen and Oxygen. The He-like resonance line (r), intercombination line (i) and forbidden line (f) are temperature and density sensitive.

Based on the ratios of the resonance lines of two succeeding ions we have obtained estimates of the temperature. These estimates are based on the assumption of an iso-thermal plasma. The O VII ratio, which is based on the resonance line (r), the intercombination line (i) and the forbidden line (f), shows a temperature more representative for the region where O VII is formed (Mewe et al. 2001b and Ness et al. 2001b). In Table 2 we notice that for all three sources the obtained temperatures are in the region between 1 and 2 MK. From the values shown in Table 2 we see that the temperature for the G2V star is a bit lower than that of the two other stars. Especially the comparison with the K1V star is of interest.

	Procyon	α Centauri	
Ions	F5IV-V	G2V	K1V
OVII(i+f)/r	1.1	0.8	1.1
OVII/OVIII	2.1	1.8	2.0
NVI/NVII	1.5	1.3	1.7
CV/VI	1.1	1.1	1.2
FeIX/X	1.3	1.1	1.3

Table 2. Temperatures (MK) derived from individual line flux ratios

Based on the same line fluxes as shown in Table 3 an emission measure (EM) has been constructed. The EM is defined as

$$EM = n_e n_H V, \tag{1}$$

where n_e is the electron density, n_H is the hydrogen density (n_H = 0.85n_e), and V is the emitting volume.
The relation between individual line fluxes and the EM is given by the following formula for Procyon:

$$F = 0.3435 \times A \times \lambda \times 10^{-s} \times EM_{50}, \tag{2}$$

and for α Cen by

$$F = 2.3434 \times A \times \lambda \times 10^{-s} \times EM_{50}. \tag{3}$$

Here F is the measured line flux (in 10^{-4} photons/cm^2/s) from Table 1, the forefactor is calculated for the distances of Procyon (3.5 pc) and α Cen (1.34 pc), A is the abundance, relative (fixed at a value of 1.0) to the solar photospheric abundances taken from Anders and Grevesse (1989) (except for Fe for which we used log $A_{Fe} = 7.51$), s is the $\log_{10}$ of the normalized line power output, as described by Mewe, Gronenschild and van den Oord (1985) in their Table IV, and later modified in the more recent flux table of the MEKAL code [1]. The parameter s is taken at the optimum temperature for the formation of a particular line of a specific ion, λ is the wavelength (in Å) of the considered transition, EM_{50} is the emission measure in 10^{50} cm^{-3}. In this calculation also the two neighbouring temperature bins have been taken into account, i.e. the emission measure is obtained for Δ log T_e=0.3. From Fig 3 we also may see that the abundances

[1] http://www.sron.nl/divisions/hea/spex/

differ from solar photospheric, especially for Fe compared to O in the K1V star of α Cen.

3. Global Fitting

Apart from the temperature determination and emission measure modeling based on individual lines we have modeled the total spectrum using the SPEX software package (Kaastra et al. 1996a) in combination with MEKAL (Mewe et al. 1995). Based on these packages we have made a multi-temperature fit to the spectrum as a whole. However, due to the inaccuracy or lack of a number of L-shell data of Ne, Mg, Si etc, bins have been removed, only leaving those with lines of better accuracy. A multi-temperature fit results in two significant temperature components for all three sources, all in the range of 1-2 MK. Their values have been collected in Table 3 together with the obtaines EM. The total EM is $\sim 3.6 \times 10^{50}\mathrm{cm}^{-3}$, $\sim 1.7 \times 10^{49}\mathrm{cm}^{-3}$, and $\sim 2.0 \times 10^{49}\mathrm{cm}^{-3}$ for Procyon, α Cen G2V, and K1V respectively. The difference between the G2V and K1V star is caused by the difference in emission measure for the hotter component. Also from Table 3 it is seen that the K1V star is hotter than the G2V star.

Parameters	Procyon F5IV-V	α Centauri G2V	K1V
log N_{H} [cm^{-2}]	18.07	18.00	18.00
T_1 [MK]	1.17(.04)	1.14(.05)	1.18(.02)
T_2 [MK]	2.34(.08)	1.88(.07)	2.12(.07)
EM_1 [$10^{49}\mathrm{cm}^{-3}$]	22(2)	1.11(.04)	1.11(.10)
EM_2 [$10^{49}\mathrm{cm}^{-3}$]	14(2)	0.64(.09)	0.90(.05)

Table 3. Temperatures and emission measures based on global fitting using SPEX and MEKAL. Values of Procyon are from Raassen et al. 2001.

The SPEX software package contains a variety of matrix inversion techniques to construct a self-consistent EM (Kaastra et al. 1996b). We used the "regularization method", because it produces a smoothed EM over a large temperature range. The EMs are shown in Fig. 5. The significant region (low error bars) streches for Procyon from .7 to 4 MK, and for α Cen from .8 to 2.5 MK and from .8 to 3.5 MK for the G2V and K1V star respectively. The total EM of Procyon is about 15 times the EM of α Cen G2V and K1V. This is mainly due to the larger stellar radius of Procyon, compared to α Cen G2V and K1V (R_* is $2.1R_\odot$, $1.24R_\odot$, and $.84R_\odot$ respectively). At the hotter part ($\sim$2 MK) of the spectrum the EM of the K1V star is about 50% higher than that of the G2V star.

4. Conclusions

The X-ray spectra of Procyon, α Centauri G2V and K1V are line rich, especially in case of moderate stages of ionization.
The temperatures for Procyon and α Cen are about 1-2 MK. No significance is found for the presence of hot plasma ($T \gtrsim 4$ MK).
The EM of Procyon is about 15 times that of α Cen G2V and K1V, mainly due to difference in stellar radii. The EM of the K1V star is higher than that of the G2V star

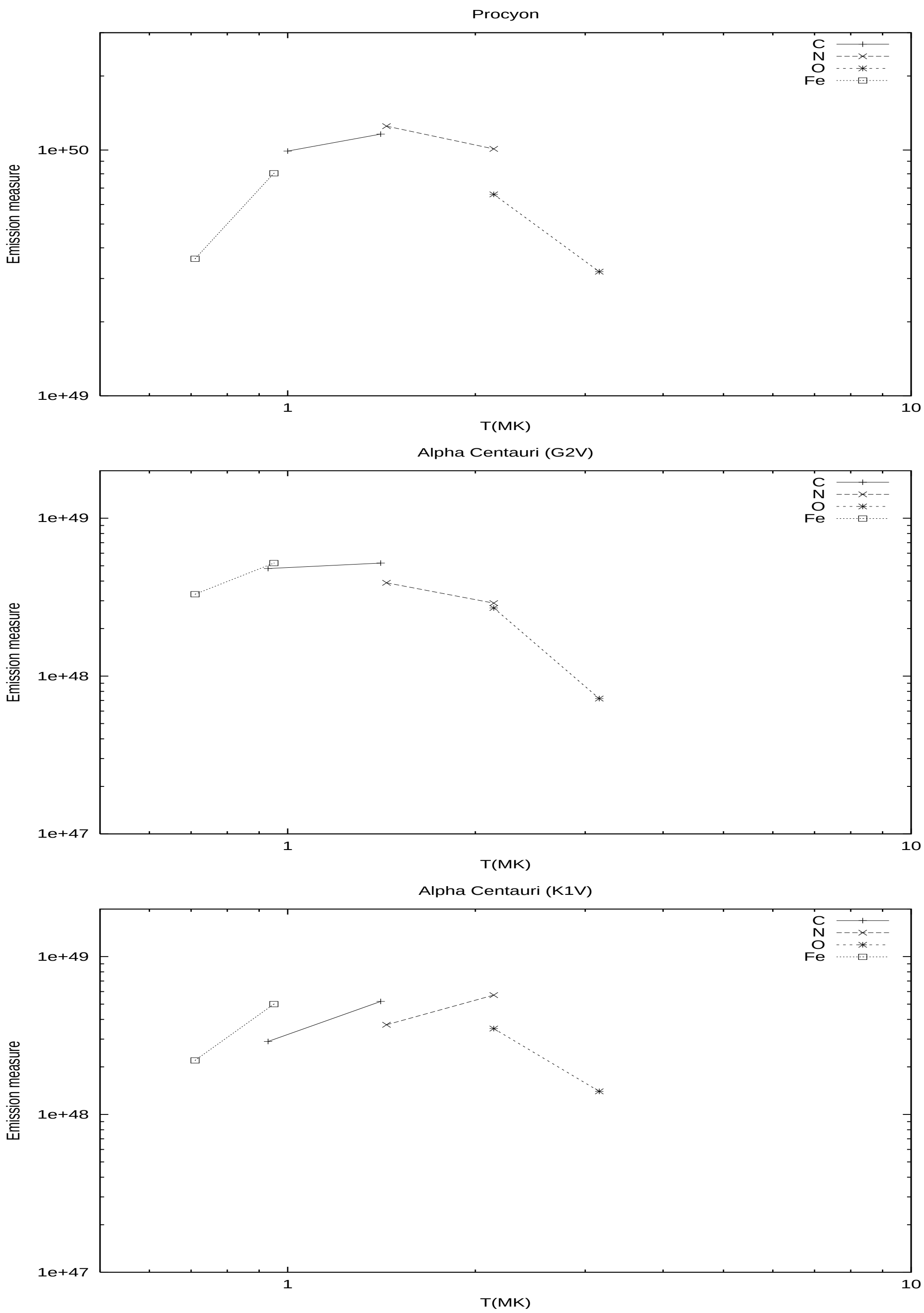

Figure 4. Emission measures of Procyon (top), α Cen G2V (middle), and α Cen K1V (bottom) based on individual line fluxes. The scale for Procyon is about 20 times higher than the scale for the α Cen stars. Notice the higher emission measure for the hotter temperatures of K1V compared to the G2V star.

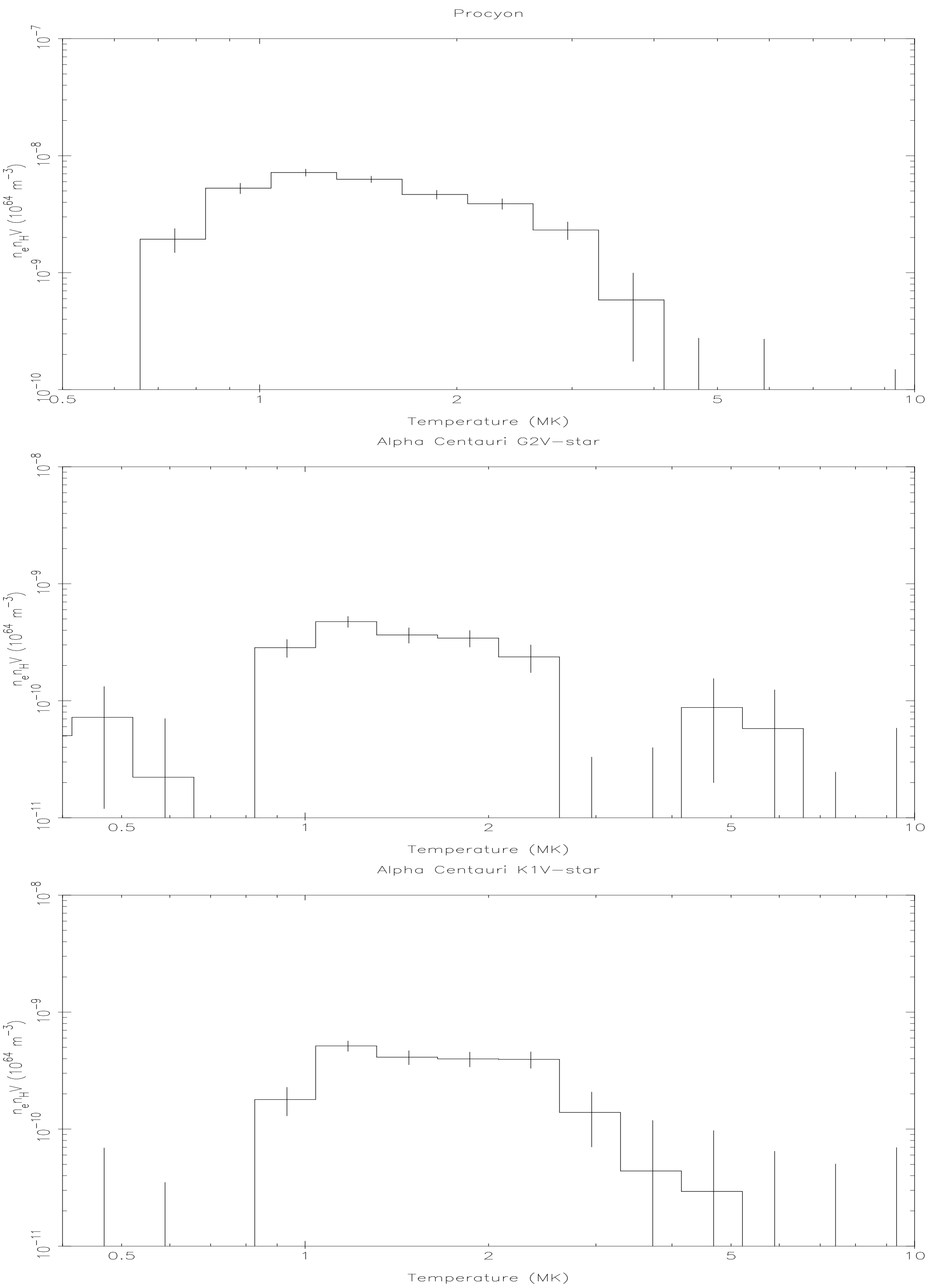

Figure 5. Self-consistent EM of Procyon (top), α Cen G2V (middle), and α Cen K1V (bottom), obtained from the regularisation inversion method in SPEX.

for the hotter part of the spectrum ($T \sim 2$ MK).
The Fe-abundance relative to O seems a bit higher, compared to solar photospheric abundances, for the K1V star.

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