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Chandra Spectra of Three Very Active Stars: AB Dor, 44i Boo, and σ^2 CrB

Jeffrey L. Linsky and Steve Skinner

JILA, University of Colorado and NIST, Boulder, CO 80309-0440

Rachel Osten

CASA, University of Colorado, Boulder, CO 80309-0389

Marc Gagné

West Chester University, West Chester, PA 19383-2130

Abstract. We show Chandra HETG spectra of a short-period RS CVn-type binary system (σ^2 CrB), a contact binary system (44i Boo), and a Pleiades-age K0 dwarf (AB Dor). The fourth active star in our program, the dM1e star AU Mic, will be observed in November 2000. We show the rich X-ray spectra of these stars and preliminary analyses concerning the coronal densities, abundances, and emission measure distributions.

1. Introduction

For many years we have dreamed of analyzing high resolution spectra of stellar coronae. The spectral energy distributions of stellar coronae observed by Einstein, EXOSAT, ROSAT, and ASCA stimulated enormous progress in identifying which types of stars are X-ray emitters, the dependence of the X-ray luminosity on stellar parameters (e.g., age, rotation, spectral type), properties of flares, and rough measures of coronal temperatures and metal abundances. Such important questions as coronal electron densities, accurate metal abundances, detailed emission measure distributions, and bulk flows could not be addressed without high resolution spectroscopy. Also, the basic questions of what mechanisms heat coronae, the geometrical properties of the emitting plasmas, and the important processes that control the ionization of metals required observations of spectra that could resolve individual lines and even measure line profile shapes and Doppler shifts.

The long awaited era of X-ray spectroscopy is now upon us. Chandra and XMM-Newton are now providing excellent quality spectra. Here we would like to present our observations of three active stars, each representing a different class of star. Table 1 summarizes the properties of these stars and the observations with the Chandra HETG. Since these spectra are now in an early stage of analysis, here we will present the data and comment on its importance.

Table 1. Summary of stellar properties and Chandra observations.

Star	σ^2 CrB	44i Boo	AB Dor	AU Mic
HD	146361	133640	36705	197481
Sp. Type	F6V + G0V	G0V + G8V	K0 V	dM1e
Class	RS CVn	W UMa	Pleiades m.g.	active dMe
m_V	5.7	4.76	6.93	8.61
Period (d)	1.14	0.27	0.514	4.865
Mass	1.12/1.14		0.9	0.59
Radius	1.22/1.21		1.3	0.6
Distance (pc)	21	12.8	14.9	9.94
Chandra	HETG	HETG	HETG	HETG
When observed	6/19/00	4/25/00	10/09/99	(11/00)
Exposure (ks)	86	59.8	60	(60)
log Lx (ROSAT)	30.5	29.7	30.9	29.7

2. AB Doradus

The nearby K0 V star AB Doradus is a kinematic member of the Pleiades moving group (Innis et al. 1986), with an age of 30–100 million years. Its rapid rotation ($P_{\rm rot}$ = 12.4 hours) is consistent with its young age and high X-ray luminosity. The star shows hydrogen Hα absorption features traversing the stellar disk at about 3 stellar radii above the photosphere, indicating that long-lived cool gas structures (perhaps stellar analogs of solar prominences) exist within the hot coronal plasma (Collier Cameron et al. 1990). During the 60 ks Chandra HETG observation, no large coronal flares were seen. The 4–24 Å MEG spectrum of AB Dor is shown in Figures 1 and 2. In this spectral interval the highest ionization stage detected is Fe XXIV. Also shown in the MEG spectrum are the bright Lyman-α lines of hydrogen-like Si XIV (6.2 Å), Mg XII (8.4 Å), Ne X (10.2 Å), and O VIII (19.0 Å). This rich spectrum shows lines of many ionization stages of Fe and other elements.

The helium-like triplets of Si XIII, Mg XI, Ne IX, and O VII are shown in detail in Figure 3. The triplets are well resolved and are useful electron density indicators. The shortest wavelength line in each triplet is the 2 ^{1}P $\rightarrow$ 1 ^{1}S resonance line, the longest wavelength line is the 2 ^{3}S $\rightarrow$ 1 ^{1}S forbidden line, and the 2 ^{3}P $\rightarrow$ 1 ^{1}S intersystem line lies in between. Since the intersystem and forbidden lines have very different Einstein A values, there is a range in electron density where one of these lines is collisionally de-excited while the other is radiatively de-excited. Thus the F/I line ratio is density sensitive in this range of electron density, provided the upper levels are populated by collisions rather than recombination. Using the calculations of Doschek (1990), we find that the coronal electron density of AB Dor, determined from the F/I ratio of O VII, is $\log n_e = 10.68^{+0.22}_{-0.33}$ (cm^{-3}). The F/I ratios for Ne IX and Mg XI only provide upper limits of < 11.0 and < 12.7. The temperature-sensitive ratio G=(F+I)/R for O VII indicates $T > 2 \times 10^6$ K. Thus, a typical coronal pressure

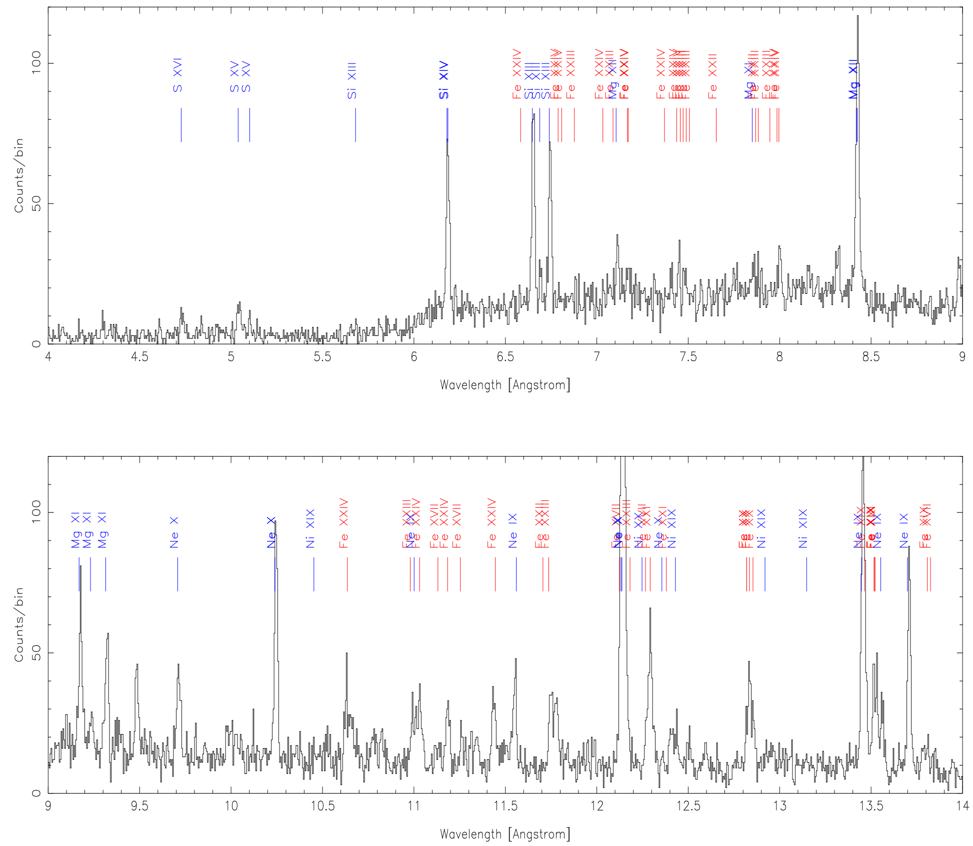

Figure 1. The short wavelength portion of the MEG spectrum of AB Dor with the main emission lines identified.

is $n_e T \approx 10^{17}$ cm^{-3}K, at least an order of magnitude higher than for solar coronal active regions.

The APEC v1.0.1 (see Smith, et al. 1999) and Chianti v3.01 (Dere, et al. 2000) codes were used to generate synthetic X-ray spectra. A solar-abundance APEC model using an emission-measure distribution with peaks at $\log T \approx 6.7$ and 7.4 K (e.g., Mewe et al. 1996) matches the MEG continuum, but the Fe lines in the model are too strong while the Ne lines are too weak, suggesting low Fe and high Ne abundances. However, the same emission-measure distribution using the Chianti code produces an X-ray continuum that is too strong.

3. 44i Bootis

This remarkable system is a visual binary consisting of the main sequence star 44i Boo A ($\approx$G1V) and a fainter companion that is itself a close binary, 44i Boo BC. The separation between the G1V star and 44i Boo BC varies considerably but has been less than $1''$ at recent epochs (Hill et al. 1989). The eclipsing system 44i Boo BC is of primary interest since it is the nearest W UMa contact binary known. The contact binary components are thought to be G-type stars

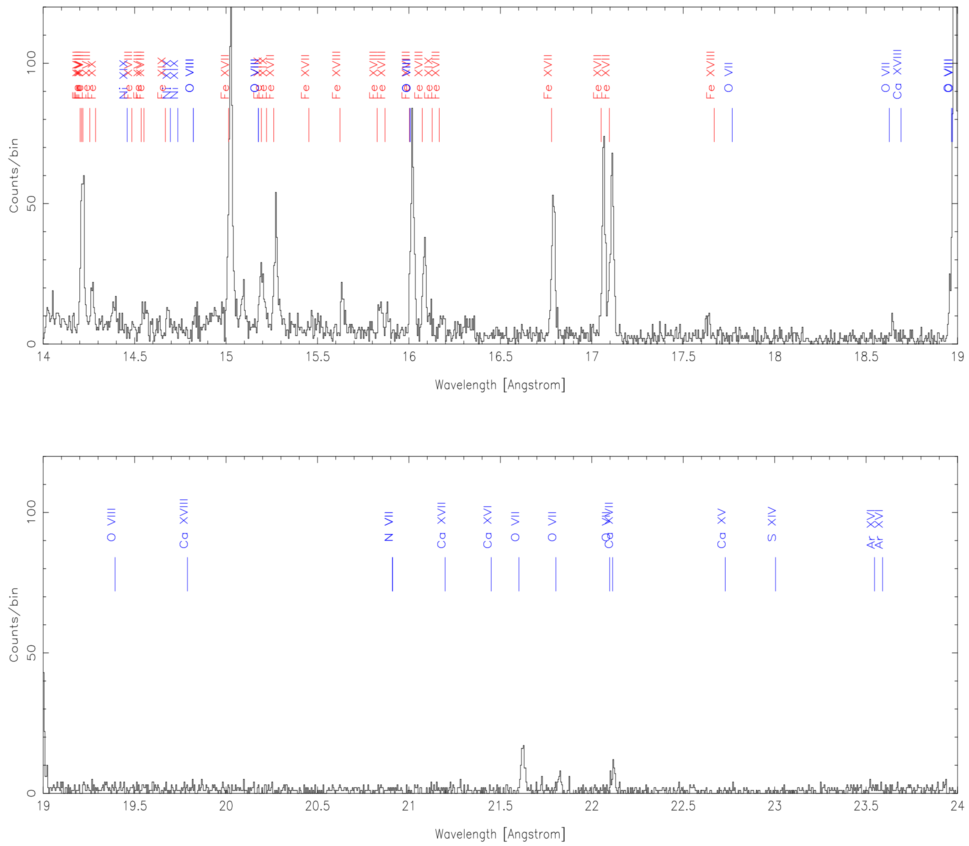

Figure 2. The long wavelength portion of the MEG spectrum of AB Dor with the main emission lines identified.

but this classification is uncertain due to spectral contamination from the tertiary G1V star (Rucinski 1998). X-ray emission from 44i Boo has been studied with EXOSAT, Einstein, and ROSAT and is thought to originate in the rapidly rotating components of the contact binary.

Figure 4 shows the Chandra first order MEG spectrum of 44i Boo. The line-dominated spectrum shows definitive evidence for plasma over a range of temperatures and includes cleanly resolved density diagnostics such as the He-like O VII triplet at 22.7 Å. Our preliminary spectral analysis shows that continuous emission measure models can reproduce the MEG spectrum just as accurately as discrete-temperature models. Continuous emission measure models show a moderately broad peak in the emission measure distribution near 0.7 – 0.8 keV ($\sim$8 – 9 million K), similar to results obtained from EUVE spectra (Brickhouse & Dupree 1998).

Previous studies have reported periodicity in the optical and EUVE light curves with a period of $\sim$0.27 days, but no definite phase modulation has been detected in X-rays (cf. Vilhu & Heise 1986; McGale et al. 1996). The Chandra light curve spans 17.1 hours of elapsed time and shows no large-amplitude flare-like variability. Low-level count rate fluctuations of $\approx$8% (2.6 σ) about the mean are present, but an initial period search does not provide compelling evidence

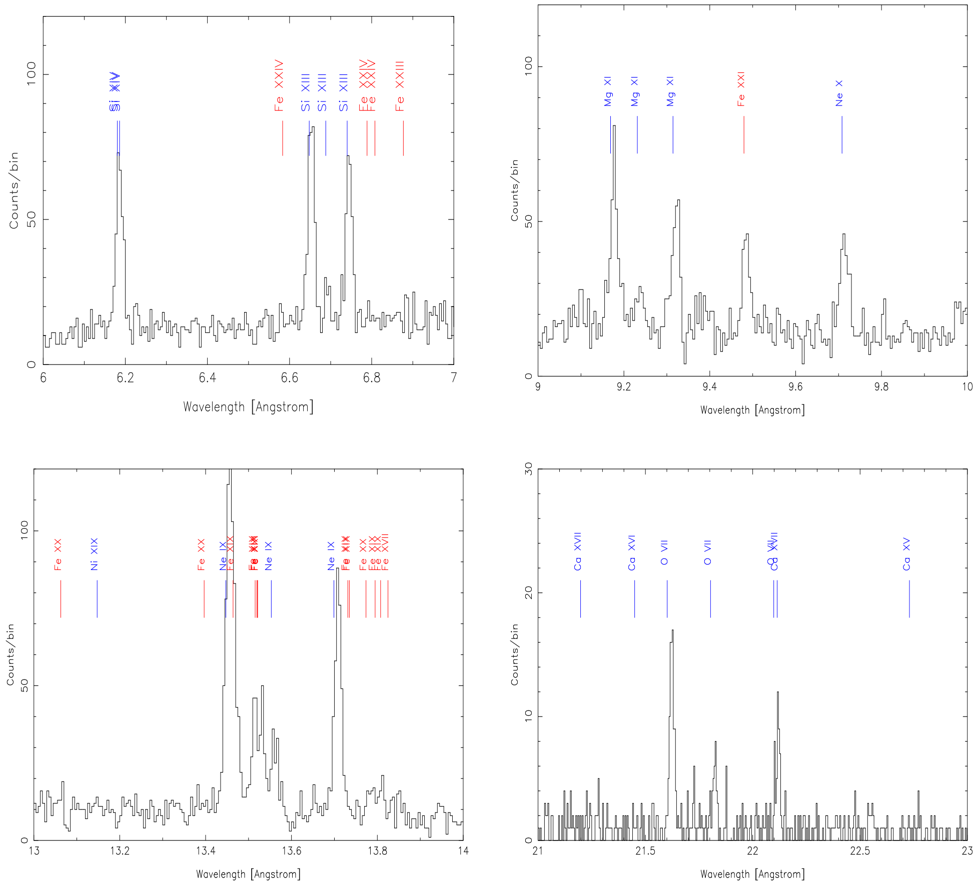

Figure 3. Portions of the MEG spectrum of AB Dor showing the helium-like triplets of Si XIII, Mg XI, Ne IX, and O VII. For each ion the resonance line is to the left, the intersystem line is in the middle, and the forbidden line is to the right.

for X-ray periodicity. Further timing analysis and line-based spectral analysis are in progress.

4. σ^2 Coronae Borealis

We observed the short-period active binary σ^2 CrB with the HETG on Chandra, coordinated with the Extreme Ultraviolet Explorer and the Very Large Array. During the nine day EUVE pointing, numerous flares were observed. One flare was observed during the 86 ks ACIS-S+HETG observation, providing 78 ks of quiescence at 2 cts s^{-1} in the MEG arm and 8 ks of flaring activity which peaked at 6.6 cts s^{-1} in the MEG arm of the spectrometer (see Fig. 5). Many emission lines were detected in the MEG and HEG spectra during quiescence and flares, and a brightening of the hot lines during the flare is evident. Density-sensitive helium-like triplet lines are detected during both quiescent and flare conditions. Preliminary evidence indicates the existence of hot material up to 100 MK during

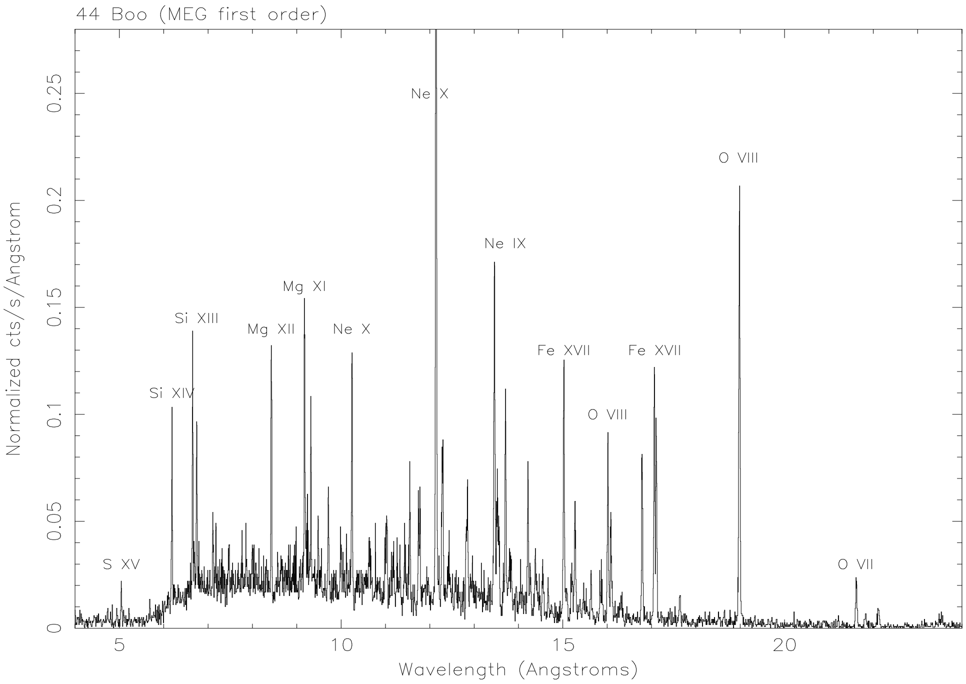

Figure 4. The first order MEG spectrum 44i Boo with the main emission lines identified.

quiescence. We are now studying the coronal density and abundances, the reality of the 100 MK plasma in quiescence, and are searching for flare-related Doppler shifts.

Towards the end of the Chandra observation, the rise, peak and initial decline of a moderately large flare was observed. Simultaneous EUVE observations displayed the same behavior. We extracted a quiescent spectrum from June 18.57–19.47 and a flare spectrum for the remainder (June 19.47–19.55). We used an iterative process to estimate and subtract the continuum flux from the spectra for line fitting. Initial results indicate the continuum flux increased by a factor of 4 during the flare compared with the quiescent continuum flux.

We used the emissivities from the SPEX line list for emission lines in the quiescent spectrum with $S/N > 20$ to construct emission measures (EM) for all bright lines of a given element, along with the EM distribution determined from the minimum values of the line EMs at each temperature (Fig. 6). The EM distribution has a power-law trend that appears to be increasing with temperature up to 100 MK. This trend is being heavily weighted by the emissivities of a few hydrogenic and helium-like lines that have significant emissivity at high temperature. The reality of this increase towards high temperatures needs to be investigated with careful attention to the background.

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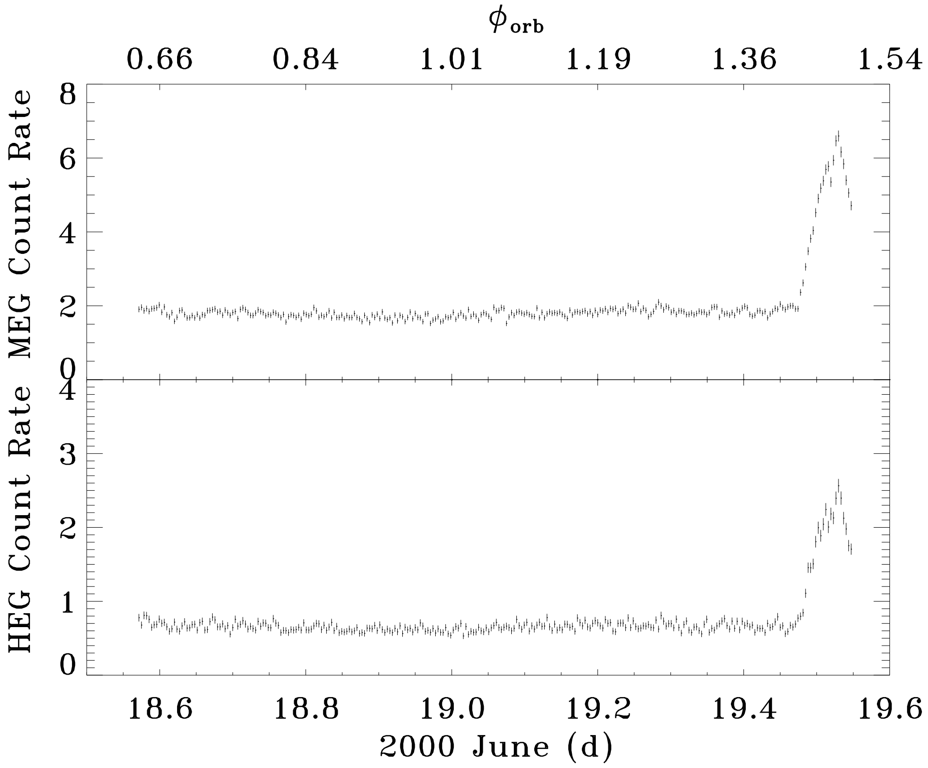

Figure 5. A light curve of the total flux in the MEG (upper) and HEG (lower) spectral intervals as a function of time and orbital phase for σ^2 CrB.

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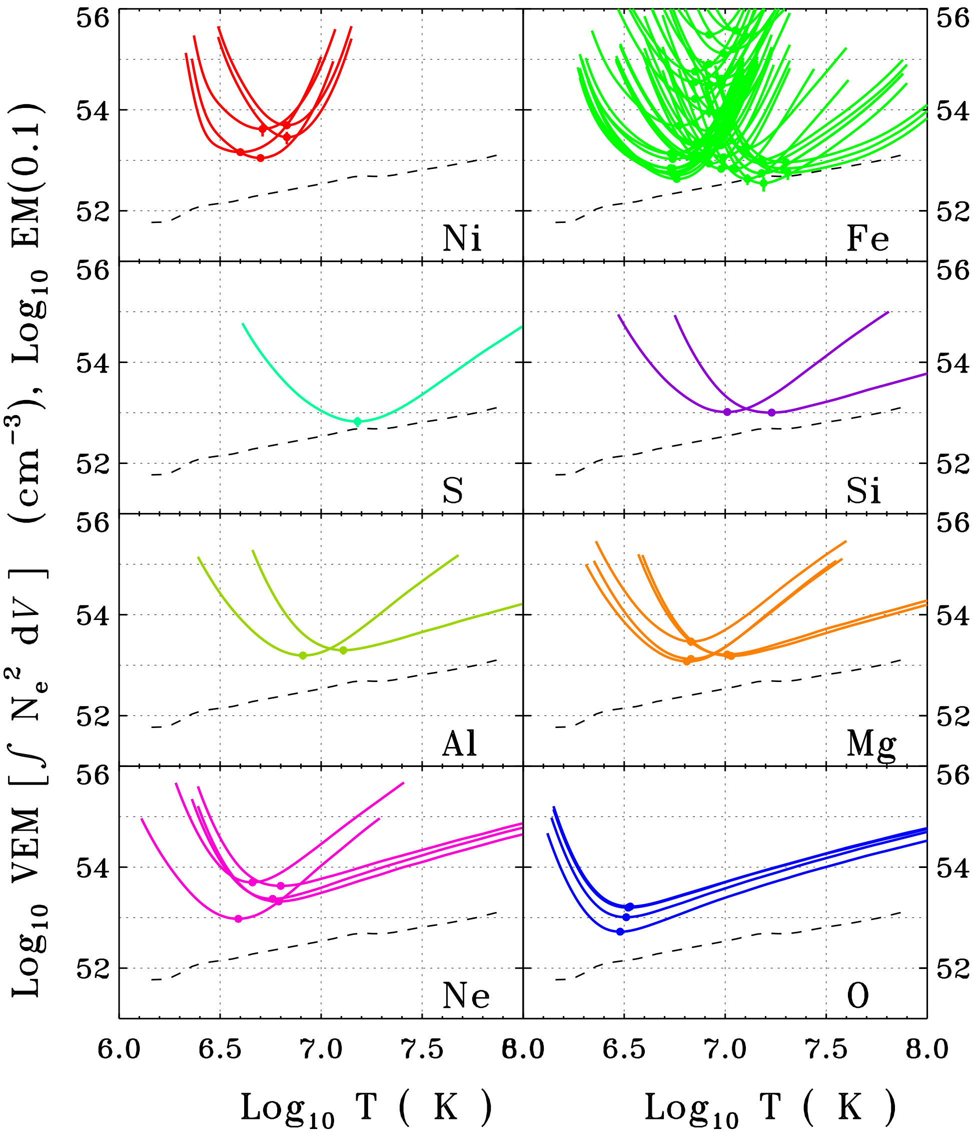

Figure 6. Emission measure loci (solid lines) for all emission lines of eight elements detected in the quiescent spectrum of σ^2 CrB. The dashed line is the emission measure distribution determined from the minima of emission measure loci of lines with S/N > 20.