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Coronal properties of active M dwarfs

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Abstract

We investigate the dependence of coronal properties on spectral type for all M dwarfs observed so far with the *Chandra* HETGS, namely YY Gem, AU Mic, EQ Peg A and B, EV Lac, AD Leo, and Proxima Cen. We use two methods which are suitable also for spectra with low signal and may thus also be applied to later M dwarfs not observed so far with X-ray gratings: First, the slope of the cumulative spectrum traces the continuum level and therefore the average coronal temperature. We find very similar steep slopes for spectral types M0.5 to M4, and a decay for later spectral types. Second, linear combinations of line fluxes of the strongest emission lines with a similar temperature dependence can be used to obtain coronal abundance ratios that are independent of the underlying emission measure distribution. For all M dwarfs in our sample, we find abundance anomalies compared to the solar photosphere. The ratios sensitive to a FIP bias, i. e. Mg/Ne and Ne/Fe, show a clear trend with increasing spectral type to approach the solar photospheric level, while ratios insensitive to such a bias like Si/Mg and Ne/O stay at a constant level. These trends seem to be independent of the age of the stars.

Cumulative Spectra

Active M dwarfs of spectral types M0–M4 are strong coronal X-ray sources with X-ray luminosities often close to a saturation limit of $\log L_X/L_{\mathrm{bol}} \sim -3.3$. During quiescence, their emission measure distributions peak around 6–8 MK (Robrade & Schmitt 2005), thus their average coronal temperatures are much higher than solar values(1–2 MK). At a spectral type of ≈ M5, M dwarf coronae start to cool down rapidly (Fuhrmeister et al. 2007) and their X-ray luminosity leaves the saturated regime. Late M dwarfs with spectral types M7–M9 are only hardly to detect in X-rays during quiescence at all.

We use the cumulative spectra of our sample stars as a proxy for the average coronal temperature: The slope of the cumulative spectrum basically represents the continuum, with a steep rise indicating a harder spectrum and thus higher temperatures. Strong emission lines turn up as steps in the cumulative distribution.

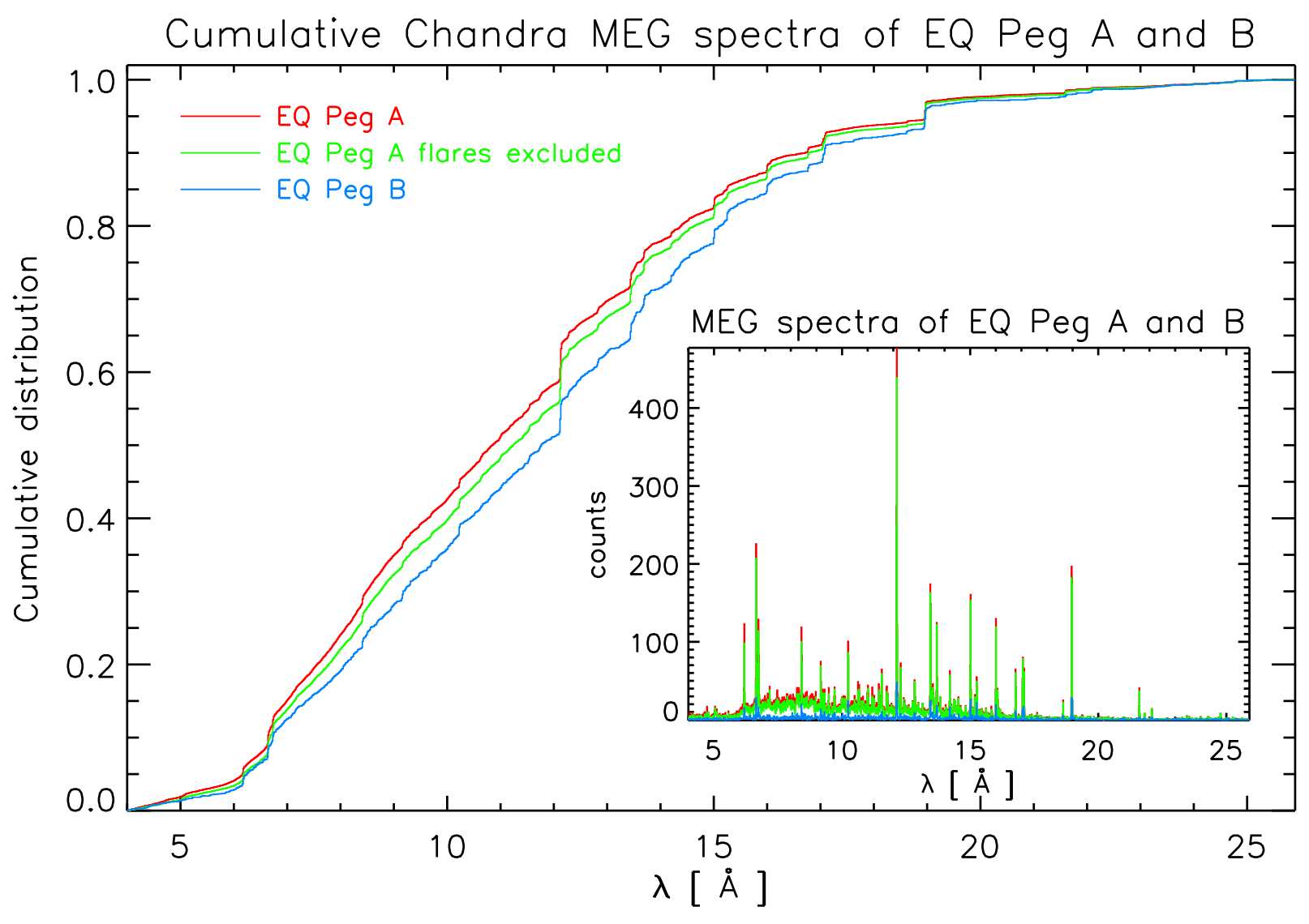

Figure 1: *Chandra* MEG spectra of EQ Peg A and B (M3.5/M4.5) and their cumulative distribution

Figure 1 shows that the difference between the two components of the EQ Peg binary system is rather small, but EQ Peg A appears slightly harder than the B component. When two larger flares on the A component are excluded from the data, EQ Peg A and B become even more similar.

A differential emission measure analysis shows that the emission measure distributions of two stars have indeed a very similar shape, while the fact that EQ Peg A is by about a factor of 6 more luminous than B during quiescence can be attributed to a fairly reduced overall level of emission measure. L_X/L_{bol} however is in the saturation regime for both stars.

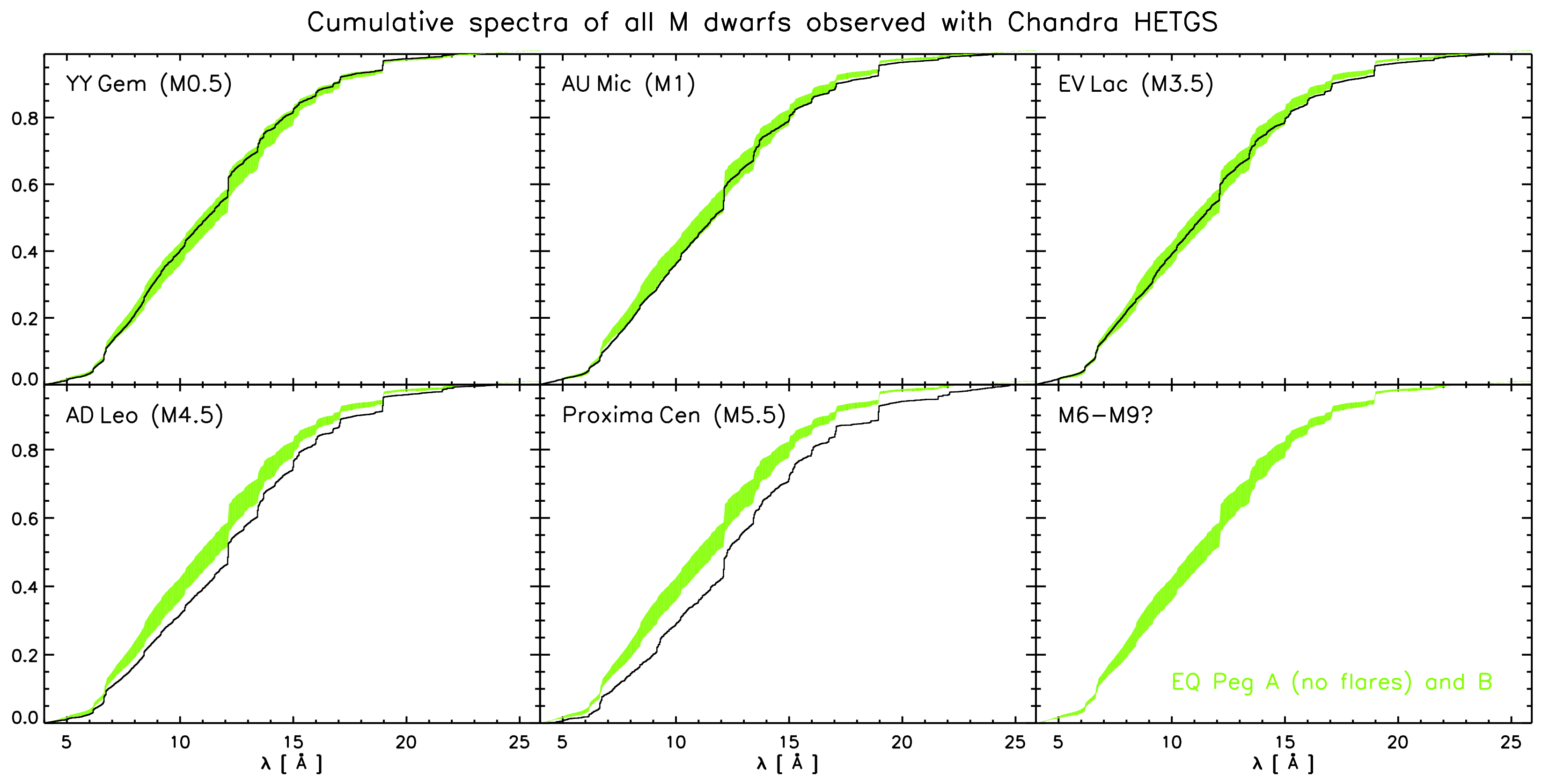

Figure 2: The cumulative spectra for the quiescent states of the other five M dwarfs in comparison to the cumulative spectra of EQ Peg A and B, bracketing the green-shaded areas.

Figure 2 shows that the spectra of AU Mic and EV Lac are similar to the EQ Peg system, with YY Gem very similar to EQ Peg A, and EV Lac just between the two components of the EQ peg binary. AU Mic has stronger neon lines than EQ Peg, leading to somewhat larger steps in the cumulative distribution. AD Leo is more similar to EQ Peg B, but somewhat softer, and Proxima Cen shows a rather soft spectrum. The five stars YY Gem, AU Mic, EQ Peg A and B, and EV Lac thus show very similar coronal temperatures, while a cooling sets in for the M4.5 star AD Leo, and the M5.5 star Proxima Cen is clearly cooler.

Emission-measure independent abundance ratios

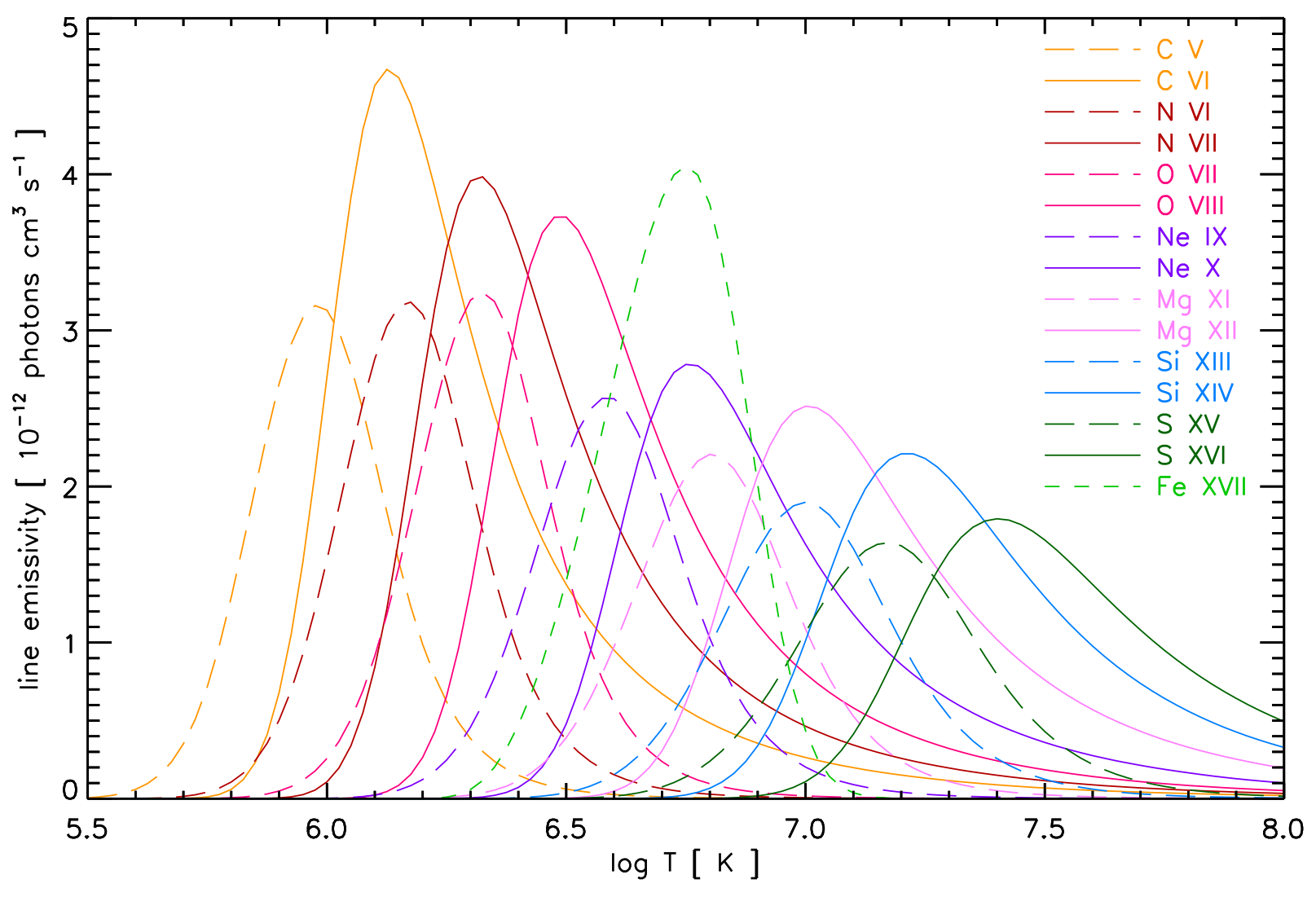

Figure 3: Line emissivities for different H-like and He-like ions, and Fe XVII at 15.01 Å (scaled down by a factor of 10).

The strongest lines in stellar coronal X-ray spectra are the H-like and He-like lines of carbon, nitrogen, oxygen, neon, magnesium, and silicon, as well as Ne-like Fe XVII. These lines are formed over a broad temperature range, but their emissivity peaks are relatively narrow, as shown in Fig. 3. Lines with a similar peak formation temperatures yield a similar temperature dependence, thus ratios of their line fluxes depend only weakly on the temperature structure of the emitting plasma, but strongly on the abundance ratio of the respective elements. For a given element, the peak formation temperature of the H-like ion always exceeds that of the corresponding He-like ion, and the peak formation temperatures of the H-like and He-like ions shift to higher temperature with increasing atomic mass. Pairs of H-like and He-like ions of elements with different atomic mass yield similar peak formation temperatures, and their contribution functions have similar shapes. Acton et al. (1975) proposed to determine the solar coronal Ne/O abundance ratio from the ratio of the measured fluxes of the Ne IX resonance and O VIII Ly α lines.

Drake & Testa (2005) reduced the residuals for this ratio by computing a linear combination of Ne X Ly α and the Ne IX resonance line in order to construct a new contribution function of Ne lines that is more similar in shape to the O VIII Ly α line.

We searched for linear combinations of strong lines without significant blends (i. e. hydrogen- and helium-like lines and the strongest lines of Fe XVII as mentioned above) of two certain elements yield the smallest temperature residuals in their normalized contribution functions. We thus write for the abundance ratio of two elements with respective abundances A_1 and A_2

$$\frac{\mathrm{A}_1}{\mathrm{A}_2} = \frac{f(\mathrm{A}_1^{\mathrm{Z}-1}) + C_1\cdot f(\mathrm{A}_1^{\mathrm{Z}})}{C_2\cdot f(\mathrm{A}_2^{\mathrm{Z}-1}) + C_3\cdot f(\mathrm{A}_2^{\mathrm{Z}})}, \qquad (1)$$

with $f(\mathrm{A}_1^{\mathrm{Z}-1})$ and $f(\mathrm{A}_2^{\mathrm{Z}-1})$ denoting the measured line fluxes f of the He-like resonance lines and $f(\mathrm{A}_1^{\mathrm{Z}})$, and $f(\mathrm{A}_2^{\mathrm{Z}})$ the corresponding H-like Lyα lines of two elements A$_1$ and A$_2$, respectively, and

$$\frac{\mathrm{A}}{\mathrm{A}_{\mathrm{Fe}}} = \frac{C_4\cdot(f(\mathrm{A}^{\mathrm{Z}-1}) + C_5\cdot f(\mathrm{A}^{\mathrm{Z}}))}{\sum f(\mathrm{Fe\,XVII})} \qquad (2)$$

where $\sum f(Fe\,\mathrm{XVII})$ corresponds to $f(Fe\,\mathrm{XVII}$ 15.01 Å$) + f(Fe\,\mathrm{XVII}$ 16.78 Å$) + f(Fe\,\mathrm{XVII}$ 17.05 Å$) + f(Fe\,\mathrm{XVII}$ 17.09 Å$)$, to determine relative abundance ratios.

We performed a minimization of the temperature residuals of the corresponding linear combination of the theoretical emissivities ε (from CHIANTI 5.2, Landi et al. 2006) for the involved lines over a given temperature range to obtain the coefficients C_1, C_2, C_3, C_4, and C_5 listed in Table 1.

There are still residuals in temperature for these linear combinations, and their amplitudes differ for each ratio. We found the lowest residuals for the Si/Mg ratio and the largest ones for the Ne/O ratio, both are illustrated in Fig. 4.

Table 1: Coefficients for Eqns 1 and 2 to convert the measured line fluxes in photon flux units to absolute abundance ratios (independent from any set of solar photospheric abundances).

ratio	C_1	C_2	C_3	C_4	C_5
N / C	+0.13	−0.07	+0.73	—	—
O / N	+0.30	+0.01	+0.93	—	—
Ne / O	+0.02	−0.17	+0.69	—	—
Mg / Ne	+0.18	−0.08	+0.87	—	—
Si / Mg	+0.32	+0.05	+0.86	—	—
S / Si	+0.42	+0.15	+0.85	—	—
Ne / Fe	—	—	—	+34.71	+0.46
Mg / Fe	—	—	—	+67.73	−0.30

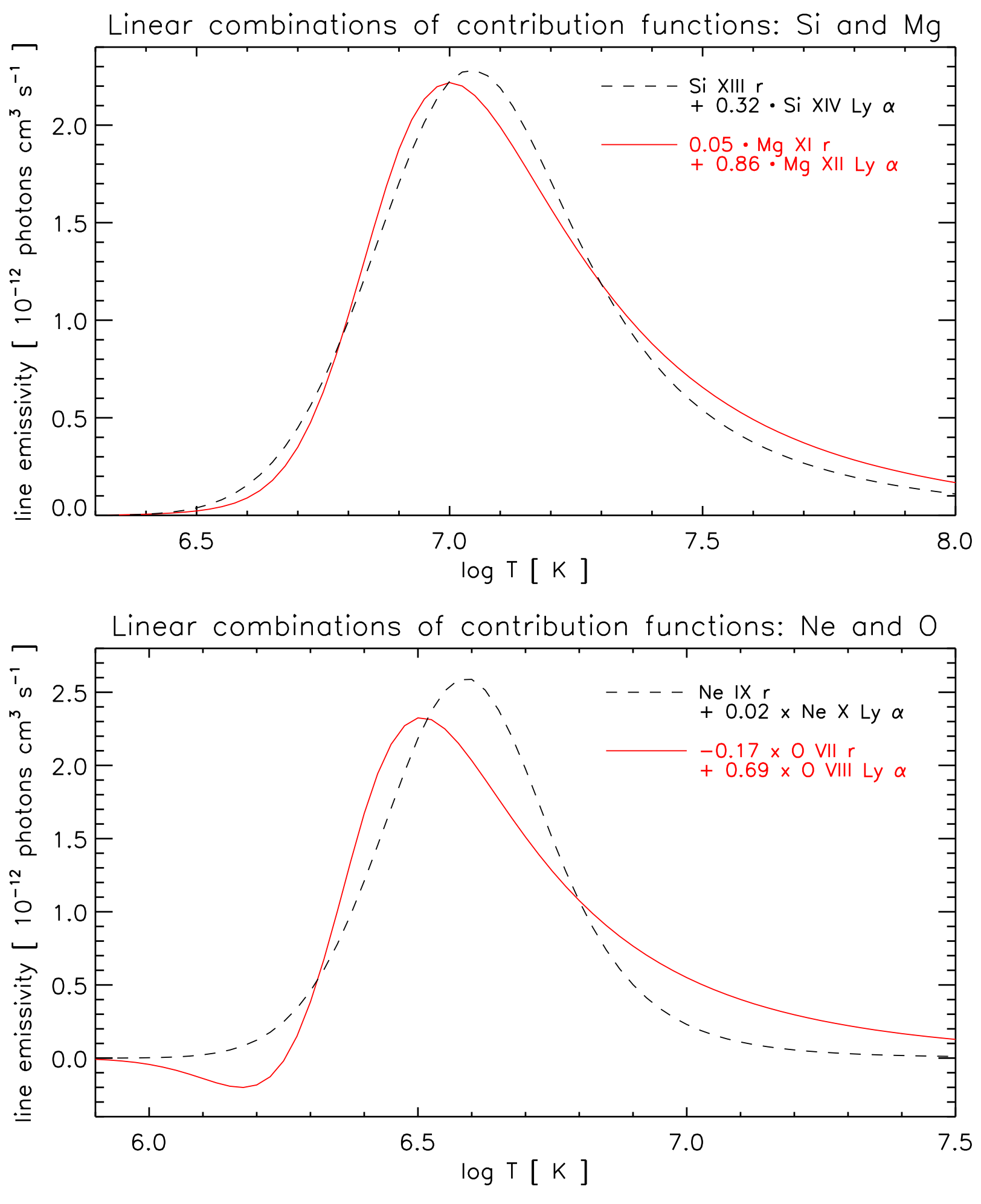

Figure 4: Linear combination of the contribution functions of the H-like Ly α and He-like resonance lines of silicon and magnesium (top) and neon and oxygen (bottom).

We applied Eqns 1 and 2, with the coefficients from Table 1 multiplied by the solar photospheric abundances of Asplund et al. (2005), to the line fluxes measured from the *Chandra* MEG spectra of the seven M dwarfs, periods of flare activity were excluded from the data. As shown in Fig. 5, the Ne/O ratio is enhanced by a factor of 2 for all our sample stars. Si/Mg is also enhanced by a factor of about 2, while Mg/Ne is depleted by factors from 3 (EQ Peg B and Proxima Cen) up to 10 (AU Mic). The values for O/N range from 0.3–1.0 times the solar level, partly with large uncertainties. The Ne/Fe ratio is clearly increased, by factors ranging from 4.5 (Proxima Cen) to 9 (AU Mic), while the Mg/Fe ratio is about solar. O/N and Ne/O can be considered as high FIP/high FIP ratios, and within the errors, these ratios do not change with spectral type. No trends can also be identified for the low FIP/low FIP ratios Mg/Fe and Si/Mg. The low FIP/high FIP ratio Mg/Ne on the other hand clearly increases towards later spectral type, while the high FIP/low FIP ratio Ne/Fe decreases. The trends observed for Ne/Fe and Mg/Ne are roughly independent of the occurrence of flares. This confirms previous findings that strength of the inverse FIP effect scales with the general activity level of a star (Güdel et al. 2002; Telleschi et al. 2005), as activity decreases with increasing spectral type. While the behavior of the Ne/Fe and Mg/Ne ratios in our M dwarf sample implies an absolute decrease of neon with later spectral type, the constant Ne/O ratio does not fit that picture. This indicates that not only a single element like neon causes this effect, but that the inverse FIP effect in general diminishes for later M dwarfs.

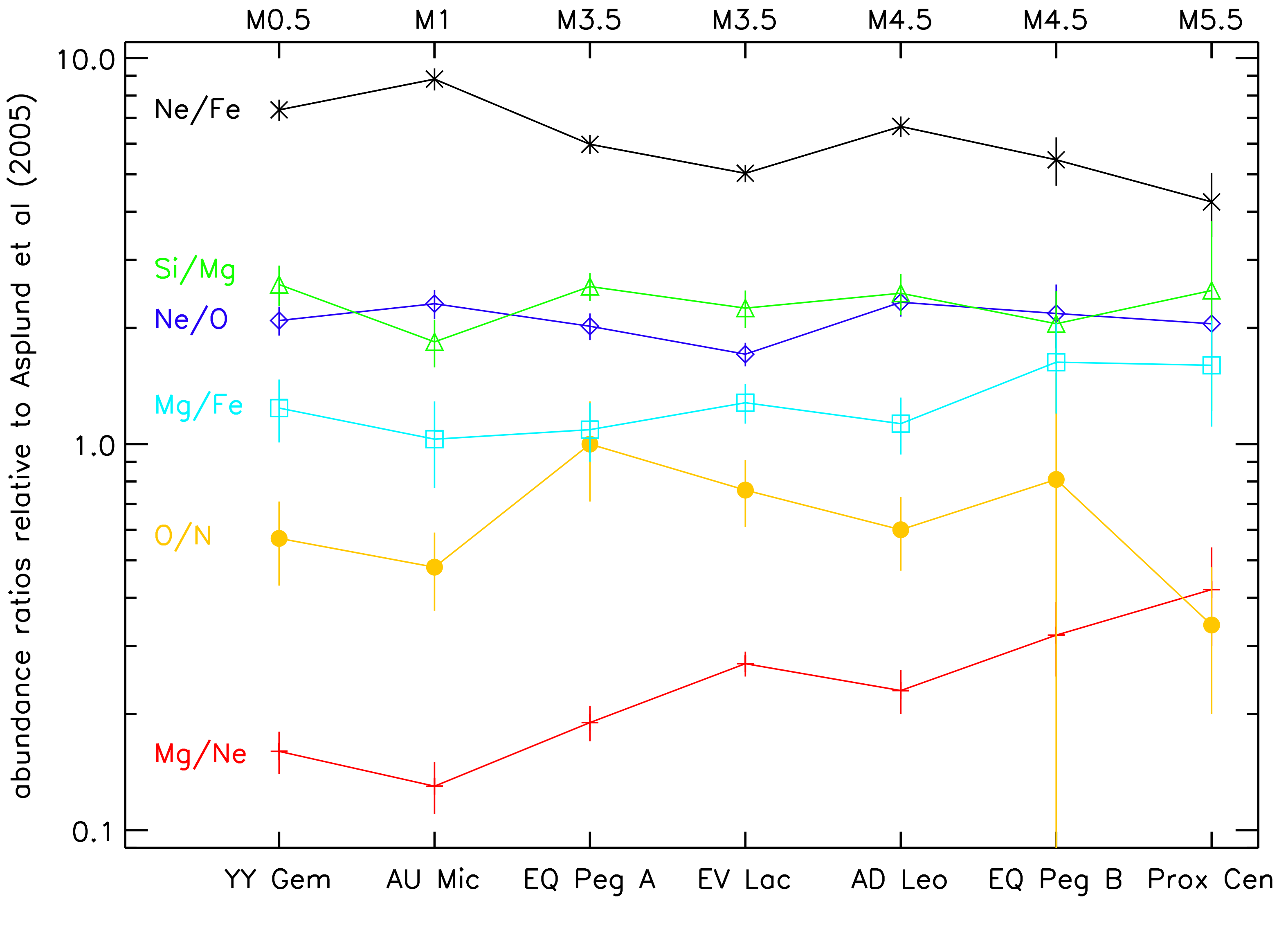

Figure 5: Coronal abundance ratios of active M dwarfs as a function of spectral type.

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