Coronal X-Ray Spectroscopy of Solar Analogs

Alessandra Telleschi\(^1\), Manuel Güdel\(^1\), Kaspar Arzner\(^1\), Kevin Briggs\(^1\), Marc Audard\(^2\), Jan-Uwe Ness\(^3\), Rolf Mewe\(^4\), Anton J. Raassen\(^4\), Stephen L. Skinner\(^5\), Manfred Cuntz\(^6\), Steven Saar\(^7\)

\(^1\) Paul Scherrer Institut, Villigen PSI, Switzerland, \(^2\) Columbia University, New York, USA, \(^3\) Universität Hamburg, Hamburg, Germany, \(^4\) SRON, Utrecht, Netherlands, \(^5\) CASA, University of Colorado, Boulder, CO, USA, \(^6\) University of Texas at Arlington, Arlington, TX, USA, \(^7\) Harvard-Smithsonian CfA, Cambridge, MA, USA

Abstract. We present an X-ray study of young solar analog stars of different ages (0.1-0.75 Gyr), based on data from XMM-Newton. An abundance analysis shows a significant change from an inverse FIP-trend to a solar-like FIP dependence during the stellar evolution. He-like O\(^{\text{vii}}\) line triplets indicate electron densities \(> 10^{10}\) cm\(^{-3}\) in the youngest stars.

1. Introduction

The study of main-sequence solar analogs is of outstanding interest not only for general stellar evolution theory, but also because it provides first-hand information on the probable past conditions in our solar system, the influence of the Sun on the planetary atmospheres in time, the climatic conditions on Earth, and, for very young solar analogs, the possible role of ionizing solar radiation in the dispersal of the remnants of the solar accretion disk. Previous programs to study the “Sun in Time” (Dorren & Guinan 1993, Güdel et al. 1997) included optical, radio, and EUV/X-ray studies. XMM-Newton and Chandra add a new dimension by providing high-resolution X-ray spectroscopy, allowing us to determine the temperature structure (differential emission measure distribution, DEM), the characteristic coronal densities, and elemental abundances.

Our targets are described in Table 1 (see Güdel et al. 1997, Dorren & Guinan 1993 for further information and references). The observations (Fig. 1)

<table>
<thead>
<tr>
<th>Star</th>
<th>Spec.</th>
<th>Distance(^a) [pc]</th>
<th>(P_{\text{rot}}) [d]</th>
<th>(\log L_X) [erg/s]</th>
<th>age [Gyr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>47 Cas B</td>
<td>G0-2 V</td>
<td>33.54</td>
<td>(~1.0)</td>
<td>30.31</td>
<td>0.1</td>
</tr>
<tr>
<td>EK Dra</td>
<td>G0 V</td>
<td>33.94</td>
<td>2.75</td>
<td>29.93</td>
<td>0.1</td>
</tr>
<tr>
<td>(\pi^1) UMa</td>
<td>G1 V</td>
<td>14.27</td>
<td>4.7</td>
<td>29.10</td>
<td>0.3</td>
</tr>
<tr>
<td>(\chi^1) Ori</td>
<td>G1 V</td>
<td>8.66</td>
<td>5.1</td>
<td>28.99</td>
<td>0.3</td>
</tr>
<tr>
<td>(\kappa^1) Cet</td>
<td>G5 V</td>
<td>9.16</td>
<td>9.2</td>
<td>28.79</td>
<td>0.75</td>
</tr>
<tr>
<td>Sun</td>
<td>G2 V</td>
<td>(5 \times 10^{-6})</td>
<td>25.4</td>
<td>27.3</td>
<td>4.6</td>
</tr>
</tbody>
</table>

\(^a\)distances from Perryman et al. (1997); \(^b\) ROSAT 0.1–2.4 keV band

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Figure 1. Fluxed RGS spectra of the five solar analogs, ordered from high (top) to low (bottom) activity.

were obtained with XMM-Newton. For details on our data reduction (using SAS vers. 5.4) and analysis, see Audard et al. (2003). In short, we used RGS data only longward of 8.3˚Å and one EPIC MOS spectrum shortward of 9.35˚Å.

2. Coronal Densities

We determined characteristic electron densities using the He-like triplet of O VII in RGS1 spectra (Ness et al. 2003 for details). For EK Dra, Chandra LETGS measurements are also reported. While a clear trend is not detected in Table 2 (considering the errors and upper limits), the electron densities of up to a few times $10^{10}$ cm$^{-3}$ set at least the youngest examples apart from older, less active stars such as α Cen or our Sun ($n_e$ of few times $10^9$ cm$^{-3}$; Raassen et al. 2002).

<table>
<thead>
<tr>
<th>Star</th>
<th>47 Cas</th>
<th>EK Dra</th>
<th>π¹ UMα</th>
<th>χ¹ Ori</th>
<th>κ¹ Cet</th>
</tr>
</thead>
<tbody>
<tr>
<td>log($n_e$) RGS</td>
<td>10.5 ± 0.26</td>
<td>10.5 ± 0.29</td>
<td>&lt; 10.9</td>
<td>&lt; 10.6</td>
<td>10.3 ± 0.28</td>
</tr>
<tr>
<td>log($n_e$) LETGS</td>
<td>...</td>
<td>10.8 ± 0.28</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
3. Coronal Structure and Abundances

We used two different methods to interpret the stellar spectra:

**A**) *Multi-temperature spectral fit to the combined RGS1+RGS2+EPIC spectra in SPEX* (Kaastra et al. 1996; "global fit" with imposed restrictions as described in Audard et al. 2003). Selected wavelength regions of the spectra are used in order to obtain a best-fit emission measure distribution and elemental abundances simultaneously. A smooth DEM is obtained from fitting with Chebychev polynomials of order 6 and 8 (Fig. 2).

**B**) "*Single-line analysis*". An ad-hoc construction of a DEM is iterated reproducing measured fluxes contained in selected lines and line blends. The calculation of the line fluxes from the DEM is done by use of emissivities extracted from the SPEX database. We use only Fe lines (Fe xvii to Fe xxv, where detected, or blend systems of Fe lines for which we calculated combined emissivities) in order to be independent of relative abundances. The iteration also optimized the DEM in order to yield the measured O viii/O vii line flux ratio. From the best-fit DEM, covering log\(T\) = 5.5 – 8.0, we are able to determine abundance ratios A/Fe for all elements represented by well detected emission lines. The input fluxes were then varied according to their errors (assumed to be at least 10% to account for uncertainties in the atomic physics) in order to estimate the errors of the DEM and the abundance ratios. Our results (DEMs, abundances) are the averages of \(\approx 20\) such realisations per star. (A comprehensive description including additional methods will be given in a future paper.)

The DEMs and the abundances from both methods are compared in Figs. 2 and 3. *We find excellent agreement between the two methods.* The abundances show a relatively flat distribution, tending toward increased high-FIP abundances for the most active stars (inverse FIP effect, Brinkman et al. 2001) but decreased high-FIP elements for the less active stars (solar-like FIP effect).

4. Conclusions

We have studied high-resolution X-ray spectra of a sample of solar analogs at different ages and activity levels. Relatively high electron densities seem to be common in these coronae, with \(n_e\) up to a few times \(10^{10}\) cm\(^{-3}\) for the youngest solar analogs. We find a systematic trend in the EM distribution and in the elemental abundances, independent of the methodology used (single-line fits or combined analysis of selected parts of the spectrum). While the two most active stars (47 Cas, EK Dra) show a significant extension of the DEM toward 20–30 MK, this hot bump is missing in the more evolved stars. We speculate that this emission measure component is related to flaring. As the activity decays toward older stars, fewer strong flares contribute to the high-\(T\) EM. Further, as the EM distribution changes, so does the elemental abundance distribution. While the most active stars reveal an inverse FIP effect or a flat distribution, the more evolved stars show a pronounced solar-like FIP effect.

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Figure 2. Emission measure distributions. Left: From SPEX, using polynomials of order 6 (black) and order 8 (green). Right: From individual-line-based inversion; black gives average, and red histograms illustrate the 1σ ranges.
Figure 3. A/Fe abundances as a function of FIP, relative to solar photospheric (Anders & Grevesse 1989; Grevesse & Sauval 1999; Allende Prieto et al. 2001, 2002). Filled: Single-line analysis; open: SPEX.

References

Perryman, M. A. C./ESA. 1997, The Hipparcos & Tycho Catalogues, SP-1200