THE X-RAY SPECTRAL STUDY OF THE CHANDRA ORION ULTRA-DEEP PROJECT: CORONAL ABUNDANCES IN ORION LATE-TYPE STARS

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1. INTRODUCTION

Chemical composition is one of the key properties of many astrophysical environments. In particular, it is relevant to classify stellar populations, and to study "ambient" effects in the vicinity of individual young stars, such as selective trapping in grains, high-energy photon and particle irradiation of the circumstellar medium, mass exchange between stars and protoplanetary disks via accretion processes or outflows, fractionation effects in stellar magnetospheres or coronae.

2. AIMS AND METHODOLOGY

We performed a detailed spectral analysis of X-ray sources in the field of the Chandra Orion Ultra-deep Project (*COUP*, Getman et al., 2005) having high photon counting statistics, and identified with late-type pre-main-sequence stars. The aim of this analysis is to provide a census of individual element abundances in the coronae of these young stars, and to explore possible dependences of such abundances on the magnetic activity level, the presence of circumstellar disks, indicators of accretion, and the properties of the local environment.

The study of a large and homogeneous stellar sample allows us to overcome the statistical uncertainties associated to the analysis of individual medium-resolution *Chandra*/ACIS-I spectra. This is demonstrated by means of extensive simulations performed to validate our spectral fitting results. At the same time this approach yields reliable ensemble properties for the Orion Cluster stars.

3. THE SAMPLE

We have selected late-type stars ($T_{\rm eff} < 10^4$ K) with at least 5×10^3 total (net) extracted counts in the 0.5-8 keV energy band, and spectra not affected by strong pile-up. These criteria ensure signal-to-noise ratios of the extracted spectra, and an excellent knowledge of the instrument spectral response. The final sample includes 146 *COUP* sources.

4. SPECTRAL DIAGNOSTICS

We considered the elements O, Ne, Mg, Si, S, Ar, Ca, Fe, and Ni. At the coronal temperatures ($T \approx 10^7$ K) typical of young active stars, most of them have important H-like or He-like ion lines in the ACIS wavelength range (1.5–27.6 Å). However, the presence of clear spectral signatures depends on several factors: emissivities, plasma emission measure distribution vs. T, abundances, line blending, ISM absorption.

Here we report results based on a global spectral fitting approach with classical two-component (2-T) or three-component (3-T) thermal models, based on the APEC emissivity code V1.3.1. The solar abundances adopted for reference are those of Anders & Grevesse (1989).

5. RESULTS

First, we performed 2-T and 3-T model fitting of all the observed spectra. The results obtained with the

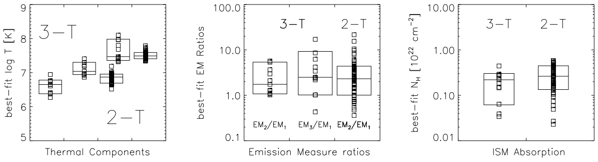

Figure 1. Box plots of temperatures, ratios of emission measures, and H column densities, derived from 2-T and 3-T fits. The upper and lower edges of each box comprise the central 68% of the data, the central value is the median.

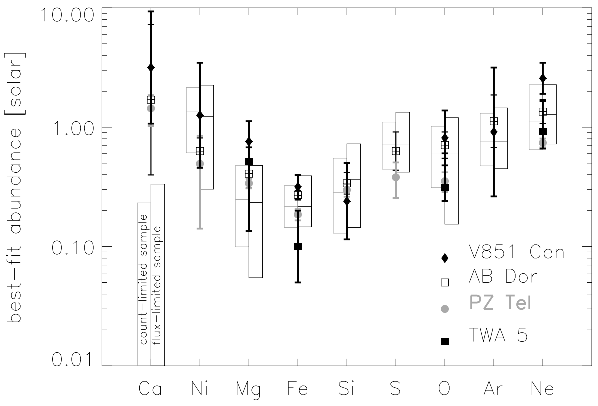

Figure 2. Abundances derived for the COUP sources. The two box plots for each element (sorted by increasing First Ionization Potential) show the fitting results for the count-limited (left) and the flux-limited (right) subsamples. The individual abundances obtained from the analysis of high-resolution grating spectra of four active stars are also shown.

3-T model were chosen only if the 2-T model yielded a poor fit (χ^2 probability $< 10\%$) and the 3-T model provided a significantly better fit (F-test probability $< 10\%$).

We verified an increasing spread of abundance values for increasing interstellar absorption, as measured by the best-fit hydrogen column density $N_{\rm H}$, together with larger and larger statistical error bars. Hence, we have empirically established a threshold $N_{\rm H} < 6 \times 10^{21}$ cm^{-2} (corresponding to $A_{\rm V} < 3$–4) to avoid biased abundance results, especially for the Ne (whose lines fall in the long-wavelength tail of the spectrum). Figure 1 shows the distributions of best-fit temperatures, corresponding volume emission measures, and $N_{\rm H}$ for this low-absorption subsample.

To check the reliability of our abundance measurements we have considered two further subsamples: a count-limited sample (35 sources with $> 10^4$ counts), and a flux-limited sample (37 sources, $f_{\rm x} > 6 \times 10^{-14}$ erg cm^{-2} s^{-1} in the 2-8 keV band). The distributions of the best-fit abundances for each element are shown in Fig. 2, for both these subsamples.

In Fig. 2 we also show a comparison of the abundances for *COUP* sources with the abundances of three young active stars, the classical T Tauri star TWA 5 in the TW Hya association (Argiroffi et al., 2005), the Weak T Tauri star PZ Tel in the β Pic association (Argiroffi et al., 2004), the ZAMS star AB Dor (Sanz-Forcada et al., 2003), and for the older active binary V851 Cen (Sanz-Forcada et al., 2004); *for these four stars the abundances were derived from analysis of high-resolution grating spectra, taken with Chandra and/or XMM-Newton*.

6. SIMULATIONS & TESTS

We have performed several simulations (1000 realizations each, taking into account the actual photon counting statistics of the observed spectra) by assuming 2-T , 3-T , or multi-T input models but different abundance distributions. In particular, we performed simulations in which all abundances were fixed to the median values of the distributions obtained for the count-limited sample. Then, we compared the simulated and observed distributions for Fe and Ne abundances: a formal K-S test shows that the distributions in each pair, for any element, are not statistically distinguishable, i.e. the observed distributions are compatible with a single abundance pattern for all stars.

7. CONCLUSIONS

The X-ray brightest *COUP* sources show a clear pattern of abundances vs. First Ionization Potential (FIP). Extensive simulations make us confident about the robustness of this result. Comparison of the observed abundance distributions for the Orion stars with simulated distributions indicate that all stars may actually have the same abundance values, i.e. the abundance spread is entirely due to statistical uncertainties. Possible outliers (e.g. stars with very high Ne abundance) are exceptions, and the size of the sample may not allow us to identify them in a reliable way. The ensemble properties of the X-ray brightest PMSs sources in Orion confirm the low metallicity of the coronal plasma (Fe abundances 0.2–0.3 solar), with respect to the solar photospheric value. There is a clear trend of increasing abundances for elements with FIP higher than Fe, and possibly also for elements with FIP lower than Fe (i.e. Fe is the least abundant in most cases), *when solar photospheric abundances are adopted for reference*. The observed abundance pattern is remarkably similar to that found from the analysis of high-resolution grating spectra of active stars, except for the case of the Ca abundance where the uncertainties are very large.

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