# X-ray emission from PTT stars

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**Abstract**

We present preliminary results on an XMM-Newton observation dedicated to Post-T-Tauri (PTT) stars. We observed the visual binary 2RE J0241-53 of the Horologium association of nearby PTT stars. The XMM observations have been complemented with ground-based optical spectroscopy and photometry. Several flares have been observed. The X-ray spectrum of the brightest star during quiescence indicates a rather cool corona (with no emission at temperatures $\geq$ 10 MK) more similar to that of the Classical T-Tauri star TW Hya (observed with Chandra and XMM-Newton) and at variance with that of another PTT Star (PZ Tel) observed with Chandra. Approximate analysis shows large Ne/Fe, N/Fe, C/Fe abundances (compared to solar photospheric values).

*Key words:*
Post-T-Tauri stars, X-ray emission, Spectroscopy

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## Introduction

In recent years, XMM-Newton and Chandra observations have shown that a great number of stars produce strong X-ray emission. In particular this occurs in young pre-main-sequence (PMS) stars. It is important to understand how the X-ray emission is formed, and relate it to stellar characteristics such as age and rotation.

According to the current understanding of low-mass star formation (cf. Feigelson and Montmerle 1999), PMS stars go through several phases, from infalling protostar (Class 0), to evolved protostar (Class I), to Classical T-Tauri (CTT) star (class II or CTT), to Weak-lined T-Tauri (WTT) star (class III or WTT). The distinction between CTT and WTT stars is normally based on the strength of chromospheric emission lines (stronger in WTT) and on the infrared excess (strong in CTT). However, many CTT and WTT stars are found to have the same age. It is usually assumed that the observed characteristics indicate that CTT stars have accretion disks, which might have a role in the X-ray emission, while WTT stars are disk-free. Post-T-Tauri (PTT) stars were postulated by Herbig (1978) to be slightly older T Tauri stars that might be more dispersed from their birth sites, hence far from star forming regions. From the point of view of the physical processes that might produce the X-rays (i.e. the absence of a disk and the presence of solar-type magnetic activity as opposed to accretion as is believed to occur in CTT stars) PTT stars are similar to WTT stars. However, PTT stars have physical characteristics very different from zero-age main-sequence stars (ZAMS).

Only a few high-resolution X-ray grating spectra of PMS stars have been obtained. Some studies have recently been published, and many are in progress. These X-ray observations show a complex picture, in which the X-ray spectra of stars of the same classes present different characteristcs.

CTT stars have been observed a few times with high-resolution X-ray grating spectra. TW Hya was observed with Chandra (Kastner et al., 2002) and XMM-Newton (Stelzer and Schmitt, 2004). The main findings were the lack of hot ($T > 10$MK) emission, and anomalous chemical abundances. Recently, XMM/RGS observations of another CTT star, SU Aur, have been obtained (cf Pallavicini et al., this volume), which show instead very hot emission, and suggest that the X-ray spectrum of TW Hya may not be representative for this class of stars.

A few observations of WTT stars are now available. HD 98800 observations are reported by Kastner et al. (2004), while observations of other WTT stars are reported in Pallavicini et al. (this volume). These stars have very hot coronae, with emission from plasma formed at $T > 10$MK.

In terms of WTT stars classified as PTTS, high-resolution Chandra X-ray spectra of PZ Tel (a member of the Tucana association) have been reported by Argiroffi et al. (2004). PZ Tel presented a very hot corona. Here, we present preliminary results from an XMM-Newton observation (with RGS as a primary instrument) of two PTT stars, 2RE J0241-53. We compare the main characteristics of the spectrum of the brighter star in terms of temperature and chemical abundance with those of PZ Tel and TW Hya. Further in-depth analysis and details will be published in a forthcoming paper.

One of the most striking results from XMM-Newton and Chandra observations of active stars are their (apparent) peculiar chemical abundances. In the solar case, coronal abundances appear to be correlated with the first ionization potential (FIP) of the various elements. The abundances of elements with low FIP ($< 10$ eV, e.g. Fe) appear enhanced (with respect to the photospheric values) compared to those of the high FIP ($> 10$ eV, e.g. Ne) elements. There are, however, variations depending on the solar feature observed, and possibly on its evolution.

Active young stars present a complex variation of chemical abundances (cf. the reviews of Güdel 2004, Audard et al. 2003). Chemical abundance variations are important to study because they must be associated with the physical processes that occur in the chromosphere. Ultimately, they could reflect on the origin of the heating mechanisms of the coronal plasma. Laming (2004) suggested that the FIP and anti-FIP effects are associated with the upward-propagating chromospheric waves impinging on the coronal structures.

## 1 The target

2RE J0241-53 (EUVE J0241-530) is a bright XUV visual binary, discovered by the ROSAT and EUVE all-sky surveys. The stars were studied by Jeffries et al. (1996), who used high-resolution ROSAT observations to show that both stars are soft X-ray emitters, with the weaker component contributing about 1/4 the total emission. The system is composed of two dK7e and dM3e young and fast rotating ($v$ sin $i$=12, 70 km/s) stars, with an angular separation of 22". Since the two stars are almost aligned along the N-S direction, we will refer to them as the northern and southern component. Both stars have strong chromospheric emission (large H$\alpha$ and Ca H+K equivalent width EW), and are very active. Recurrent flares in both components have been reported (including large flares, cf. Ball and Bromage 1995). The southern star is Li-rich. ROSAT observations indicated that the southern star was 3 times brighter than the northern one in the XUV. Jeffries et al. suggested that the system could represent a pair of PTT stars. The PTT classification was later confirmed by Torres et al. (2000) on kinematic grounds. Torres et al. identified the binary as belonging to the nearby Horologium association of young stars, with an age of $\sim 30$ Myr.

## 2 Observations

XMM successfully observed the stars for 38ks between 21:30 and 8:20 UT on 9-10 Feb 2004. XMM-Newton is equipped with a suite of EPIC (PN and MOS) X-ray CCD cameras and two reflection grating spectrometers (RGS 1,2). XMM-Newton also has an optical telescope (OM) which allows broad-band photometry in the UV. We designed the observation to operate EPIC in the small window mode and the OM in fast mode (1s time resolution) with two small windows centred on the two stars. We used different OM filters in succession: U (21:30-00:40 UT), UVW1 (00:45-04:34 UT), UVM2 (05:43-08:09 UT). The instruments performed extremely well, in particular the OM. To separate the spectra of the two sources, the observation needed to be performed at specific roll angles.

In theory the OM should provide continuous support of the X-ray observations, so ground-based photometry should not be necessary. In reality this is not the case, because filter selection on the OM has some limitations, and because during ground station handovers the OM is switched off, causing data gaps.

The scientific importance of having spectral information on the lower atmospheric layers such as the chromosphere, in particular for flare stars, is self-evident. However, organising simultaneous ground-based observations is particularly difficult, given the fact that normally XMM observations are scheduled only a few weeks in advance. We were fortunate to obtain one week of photometric and spectral observations at the South African Astronomical Observatory (SAAO) around the the time of the XMM observation. Spectra were obtained using the SAAO 1.9m grating spectrograph with 1 Å resolution in the wavelength range 3700 – 4360 Å on 6 consecutive nights. UBV aperture photometry was carried out for 3 consecutive nights with the 0.5m telescope. On the night of the XMM observation, SAAO covered the period 18:32 UT - 00:04 UT.

We were also able to obtain CCD B- and U-band photometry with the 0.9m and low-resolution (17.2 Å FWHM) spectroscopy on the 1.5m telescope at Cerro Tololo Interamerican Observatory (CTIO, Chile) covering part of the XMM observation, during 01:17–04:40 UT. Other photometric observations were obtained at the Pico dos Dias Observatory (Brasil) during 23:00-00:30 UT, courtesy of Carlos Alberto and Germano Quast. CASLEO (Argentina) also planned photometry (courtesy of Federico Gonzalez), but the weather was cloudy.

## 3 Results

Fig. 1 (top) shows a sample SAAO spectrum of the northern star. Strong chromospheric emission is present. The southern star presents a similar spectrum. The striking feature was the high variability of these lines even at the 90s time resolution of the observations, and during quiescence in the X-ray emission/ U-band. Equivalent widths were measured for the H$\delta$ and Ca II K lines. The values for the Northern star on the XMM night are shown in Fig. 1.

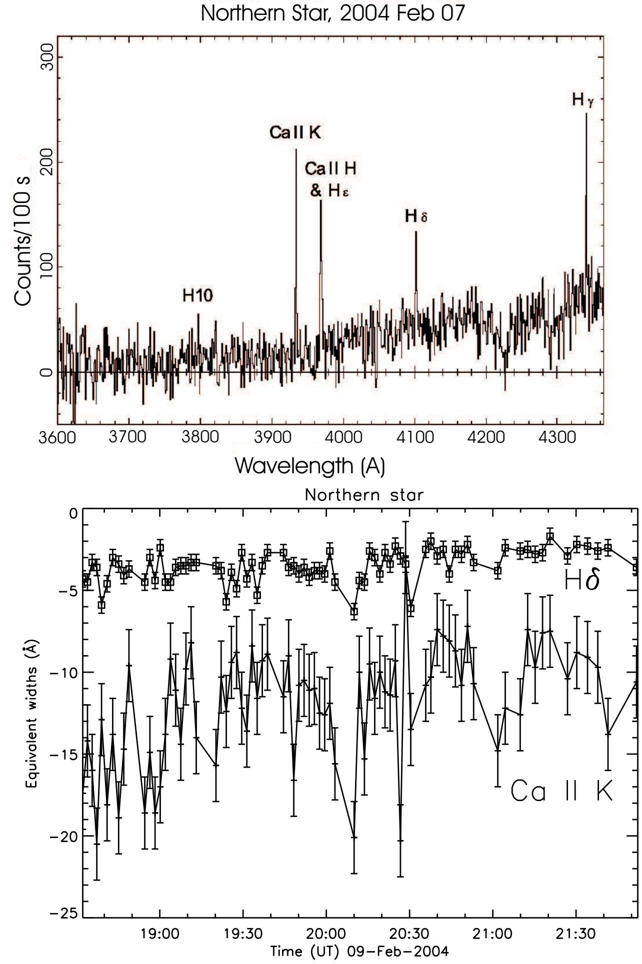


Fig. 1. SAAO spectrum of the northern star (above) and equivalent widths during the night of the XMM observation (below).

We performed relative aperture photometry on the XMM/OM fast-mode windows and on the CTIO B- and U-band images. The background regions were stationary and with low count rates, compared to the source regions. We performed the standard pipeline processing of the XMM X-ray data and constructed energy-resolved light-curves of both sources. Fig. 2 gives an overview of the X-ray and U-band light curves of the two stars. Both stars are confirmed to be active, with strong variability and flares. The northern star had two large X-ray flares toward the end of the observations. The first flare was not observed by the OM, and only partly by CTIO. The second flare was observed by the OM but with low signal-to-noise, due to the low-counts filter used at that time. The southern star was in an unusually quiescent state for most of the observation, with X-ray count rates only 2.6 times higher than those of the northern component. A flare occurred at 01:10 UT, and the X-ray count rates had a sudden increase toward the end of the observation. This increase occurred over a period of 5-10 minutes, and the star reached a steady

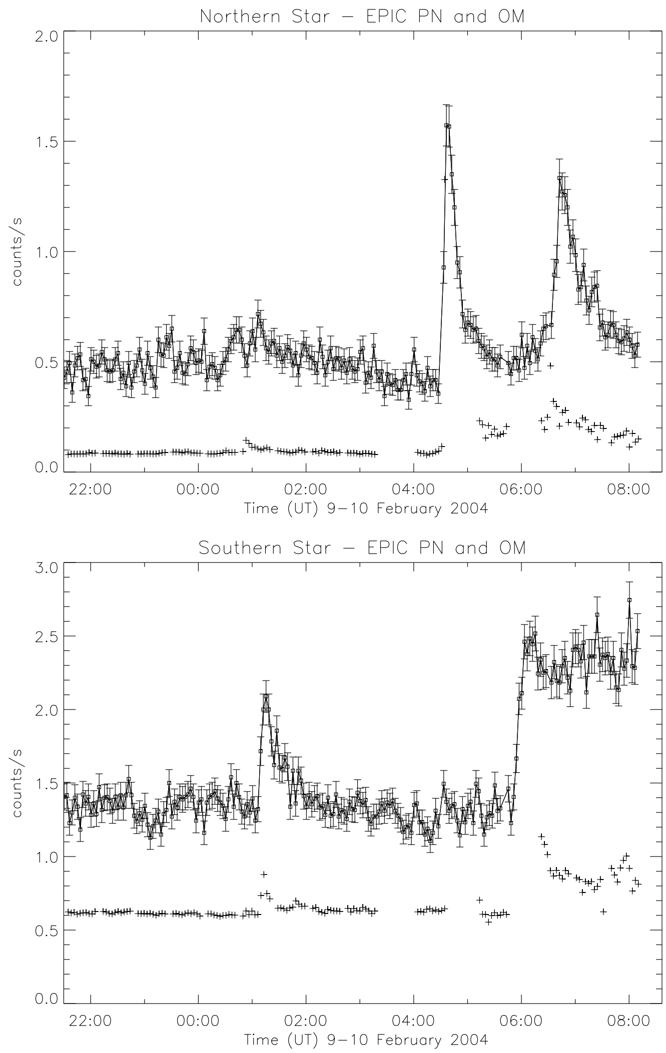


Fig. 2. X-ray (EPIC PN) and UV (OM) light curves of the XMM observation. The upper points show the EPIC count rates for the two stars in the entire 0.2–12 keV energy band. The lower points show the normalised OM count rates in the successive filters.

state that lasted at least until the end of the observation, i.e. at least 2 hours. This increase in the X-ray emission in the southern component is still under investigation. The increase was observed by all the XMM instruments. The spectral characteristics do not suggest this being a flat-top flare. The presence of a minor secondary component is not completely ruled out, since radial velocities for this star show a larger than normal scatter (Carlos Alberto, priv. comm.).

The observed flares showed the usual characteristics, i.e. a short-duration increase in the optical U-band, followed by a slower but longer-lasting increase in the X-rays (Neupert effect, cf. Neupert 1968). The U-band emission is mainly dominated by bremsstrahlung of non-thermal electrons, probably directly re-

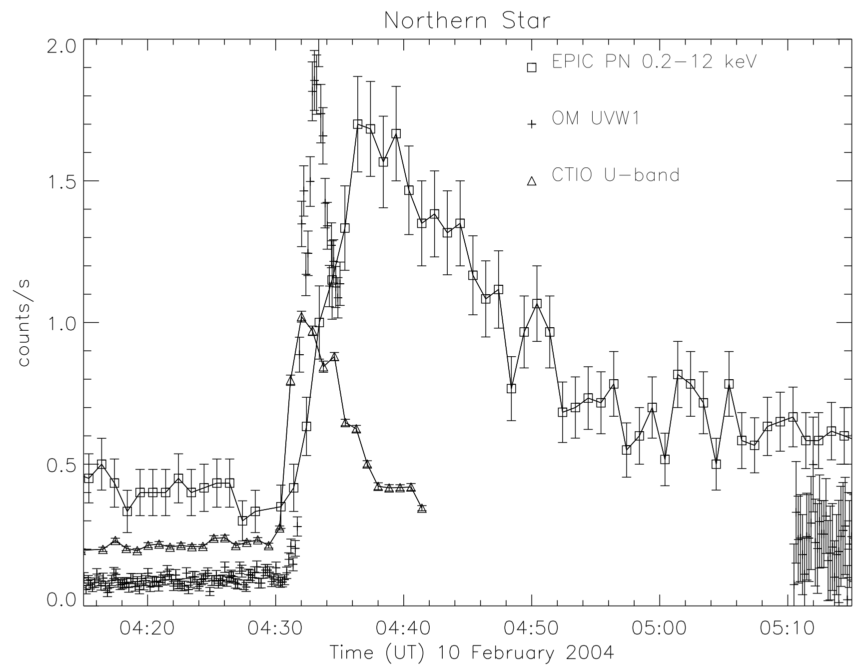


Fig. 3. Light curves for the first large flare on the Northern star. See text for details.

lated to the creation of a large number of energetic particles at the beginning of the energy release. Beams of fast particles would impinge on the chromosphere and induce chromospheric evaporation of plasma, filling the atmosphere in the form of flaring X-ray loops or arcades of loops. Fig. 3 shows the EPIC count rates in two energy bands, both of which peak approximately where the vertical line is located. Superimposed on the graph, we have the corresponding CTIO U-band and XMM/OM UVW1 count rates (normalised). The light curves in the U and UVW1 bands clearly peak a few minutes before the X-rays.

The XMM observation contains many interesting aspects. A detailed analysis of the various features requires a discussion of atomic physics, line identifications and blending issues, and is left to a forthcoming paper. Here, we present in Fig. 4 the averaged first-order RGS spectrum of the southern component, extracted during 21:30–04:00 UT. During this period, the star was mainly in quiescence, with the exception of a small flare.

The strongest lines are the oxygen and neon H- and He-like lines, with very little Fe XVII emission. In contrast with the spectra of other WTT stars, Fe XVIII emission is weak, and hotter emission (Fe XIX, Fe XX, Fe XXI and higher ionization stages) absent.

For comparison, the first-order Chandra MEG spectra of PZ Tel (with twice the exposure time – 74 ks) and of TW Hya (48 ks) are also shown in Fig. 4 (the data were processed with the CIAO 3.2.2 version and the latest calibrations).

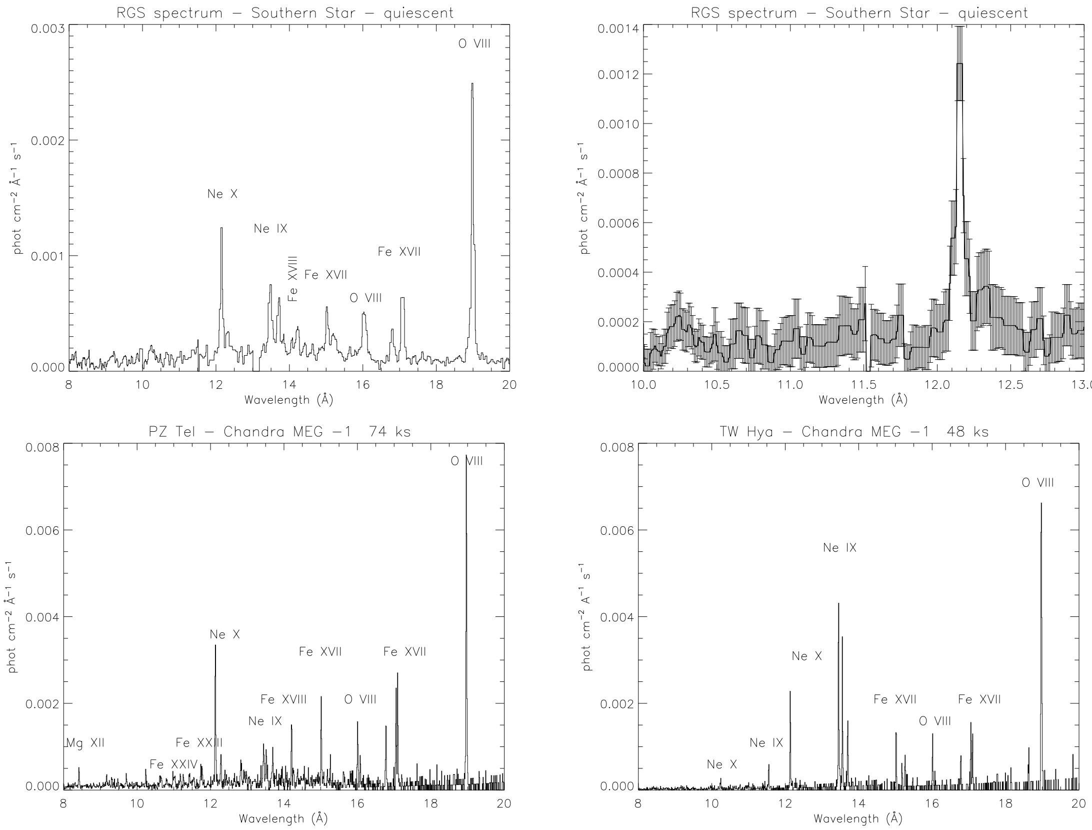


Fig. 4. Top: XMM-Newton RGS spectrum of 2RE J0241-53S during quiescence, with an enlarged part of the spectrum showing the uncertainties related to the noise and background subtraction. Bottom: spectra of PZ Tel (Chandra, 74 ks) and TW Hya (Chandra, 48 ks).

PZ Tel presents strong 'hot' emission. Compared to Fe XVII, its spectrum shows strong Fe XVIII, Fe XIX and Fe XX emission. Also, PZ Tel shows strong emission from temperatures $T > 10$MK (Fe XXIII and Fe XXIV $n = 3 \rightarrow n = 2$ transitions). In contrast, the spectrum of the CTT star TW Hya does not have any significant emission at temperatures higher than those where Fe XVII is formed.

Coronal abundances can be obtained with emission measure techniques. To obtain accurate values, a thorough analysis which takes into account the many uncertainties associated with the various methods and assumptions (e.g. ionization equilibrium) used is needed (see, e.g., Del Zanna et al. 2002, Del Zanna et al. 2001). This goes beyond the scope of this paper. We have obtained approximate values assuming the ionization fractions of Arnaud and Rothenflug (1985) and the CHIANTI atomic data (Young et al., 2003). Compared to solar photospheric values, the southern star has enhanced Ne/Fe, O/Fe, N/Fe, C/Fe abundance ratios, approximately 3, 1.5, 4, 4, respectively. For example, Fig. 5 shows the emission measure loci curves (cf. Del Zanna et al. 2002 and references therein for definitions) for a few of the prominent lines in the spectrum of the southern star. For comparison, we note that for TW Hya Kastner et al. (2002) estimated enhanced Ne/Fe, O/Fe, N/Fe, by factors of 10, 1.5, 5, while for PZ Tel Argiroffi et al. (2004) found Ne/Fe, O/Fe enhanced by factors of 2, 1.6.

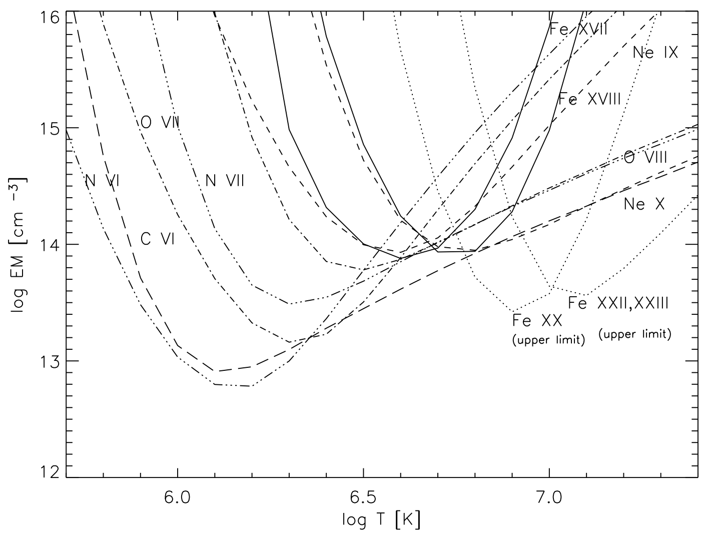


Fig. 5. Emission measure loci curves for a few of the prominent lines in the spectrum of the southern star, calculated assuming ionization equilibrium. The emissivities were calculated with Ne, O, N, C/Fe abundance ratios enhanced (compared to their solar photospheric values) by factors of 3, 1.5, 4, 4, respectively.

## 4 Discussion and conclusions

X-ray spectral observations of PTT stars are difficult to obtain because the stars are faint and require long exposure times. However, a single spectrum is worth thousands of images or broad-band observations. The X-ray spectrum of 2RE J0241-53S is largely different from what we could predict on the basis of the broad-band ROSAT and EUVE measurements, which were in a different spectral region.

The X-ray spectrum shows a distinctive difference compared to the few other spectra of WTT stars (in particular the PTT star PZ Tel), due to the absence of any 'hot' ($T \geq 10$ MK) emission. In this respect, the X-ray spectrum of 2RE J0241-53S is more similar to that of the CTT star TW Hya. It is interesting to note (cf. Pallaviciini et al, this issue) the large differences in the X-ray spectra of stars of the same class (TW Hya, SU Aur; PZ Tel, 2RE J0241-53S).

In terms of coronal abundances, 2RE J0241-53S appears to be closer to other PTT/WTT stars (such as PZ Tel), which show similar large Ne/Fe enhancements. We note, however, that coronal abundances should be compared to photospheric abundances of the same star. In turn, measurements of photospheric abundances of active stars are scarce, show large scatter, and are difficult to obtain within a reasonable accuracy, in particular for the fast rotators, which are common among young stars.

PZ Tel is a member of the Tucana association, a local ($\simeq$45 pc) group of young ($\simeq$20-30 Myr) stars, while 2RE J0241-53 is a member of the Horologium association. The Tucana and Horologium associations have similar characteristics. Recently, Rojas and Gregorio-Hetem (2005) provided measurements of photospheric abundances for 9 members of the former and 3 members of the latter association. A large scatter of values can be found, with variations up to factors of 3. However, on average the photospheric abundances are not too different from the solar ones, hence the chemical anomalies that are found in these PTT stars are presumably real, despite all the cautionary remarks that can be made.

Much of our understanding of PTT stars could be improved with simultaneous multi-wavelength observations, but unfortunatley these are difficult to obtain. Also, accurate knowledge of stellar characteristics such as age, rotation and photospheric abundances of the stars would be required. Further X-ray observations of active stars with different ages are crucial for a better understanding of any correlation between age and X-ray emission, and to identify the mechanisms that produce the X-ray emission in the first place.

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