ASTROE2 XRS **SPECTROSCOPY OF THE PRE-MAIN-SEQUENCE STAR DOAR 21**

1 Introduction and Context

Pre-main-sequence (PMS) stars are strong sources of X-ray emission, showing generally hard and time variable emission line spectra, indicative of several keV plasma. The origin of the X-ray emitting plasma on PMS stars is thought to be magnetic activity, perhaps similar to that seen on main sequence cool stars, but scaled up due to stronger magnetic fields, faster rotation, and/or larger surface area. However, statistics on large samples of PMS stars show some intriguing differences between this class of X-ray source and the more evolved cool coronal sources (Feigelson et al. 2003 ApJ 584:911). It is therefore not clear whether the magnetic dynamo purported to be the source of the hot, X-ray emitting plasma has similar physics to the solar dynamo or whether it is a different type of dynamo entirely. It is also possible that, at least in some PMS stars, the X-ray emission is related to the circumstellar disk or even to accretion (Kastner et al. 2002 ApJ 567:434).

High-resolution X-ray spectroscopy of strong PMS X-ray sources plays an important role in answering these fundamental questions about stellar magnetic activity, dynamo mechanisms, and accretion. Most PMS stars are too far away or obscured to produce high signal-to-noise X-ray spectra. In fact, *Chandra* grating spectra for only two PMS stars have been published thus far: the classical T Tauri star (CTTS) TW Hya (Kastner et al. 2002) and the diskless "naked" T Tauri star HD 98800 A (Kastner et al. 2004 ApJ 605:L49), both of which are part of the $\sim$ 10-Myr-old TW Hya association. We are about to submit a paper on *Chandra* spectroscopy of DoAr 21, which is a member of the ρ Oph star forming region and with an age of $\sim$ 1 Myr is ten times younger than the stars in the TW Hya association. We find very hot plasma, doubling in temperature during a large flare, and marginally broadened emission lines, as well as density-sensitive line ratios with values intermediate between those of TW Hya and HD 98800 A.

DoAr 21 appears to be in an evolutionary state that is intermediate between the rapidly-accreting classical T Tauri stars (CTTS) and the diskless"naked" T Tauri stars. DoAr 21 has been cited as having no disk since it has no near-infrared excess (e.g. Luhman & Rieke 1999, ApJ 525:440). However, we have re-analyzed the available photometric data, and we find a clear *mid*-infrared excess from 10–14 μm. Similarly, in contrast to low-resolution observations showing the Hα line of DoAr 21 in absorption, our new echelle spectra of DoAr 21 show that the central absorption is flanked by weak but broad (> 100 km s^{-1}) emission wings, indicating the presence of low-level accretion onto the star. These findings are consistent with those of Bary et al. (2002 ApJ 576:73), who detected H_2 in emission around DoAr 21, and the detection of PAH emission by Hanner et al. (1995 ApJ 438:250). Taken together, these data suggest that DoAr 21 is in the process of losing its circumstellar disk. The observations proposed here offer a chance to see whether this influences the system's x-ray emission; in particular we can test whether our tentative detection of an X-ray-emitting-plasma density intermediate between that for the CTTS TW Hya and the diskless HD 98800 A is real.

The properties of DoAr 21 are intriguing, as they indicate an intermediate evolutionary stage between CTTS and naked T Tauri stars, and its very high levels of X-ray emission and flaring suggest that an *XRS* spectrum would be quite high-quality. The new questions raised by the *Chandra* spectroscopy of DoAr 21, including suggestions of broadened emission lines and density sensitive line ratio values intermediate between those of TW Hya and HD 98800 A, can be addressed using the capabilities of the *Astro E-2 XRS*. We are therefore proposing a 100 ks observation of DoAr 21 using *Astro E-2*. This observation will provide important information about (1) the densities of the hot plasma components, (2) the kinematics of the hot plasma, and (3) the properties of the very hottest ($\sim$ 30 to 50 MK) plasma component. A 100 ks observation also will likely provide a comparison of quiescent

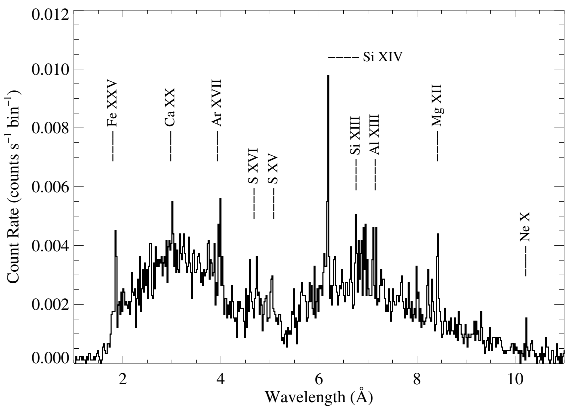

Figure 1: *Chandra* HEG spectrum (92 ks exposure), with several strong lines labeled. Note particularly the S XV and Fe XXV complexes, which will provide important diagnostic information in the proposed XRS observation.

and flare properties of the hot plasma on DoAr 21. Finally, the simultaneous *XIS* data will provide modest resolution time-variable spectral information about several dozen other PMS stars in the DoAr 21 region of the ρ Oph cloud.

The proposed probes of density, temperature, and kinematics of the X-ray-emitting gas are only possible with the spectral resolution and sensitivity of *Astro E-2*. These observations present a unique opportunity to precisely determine the physical conditions of the hot plasma around one of the few very young stars that is bright enough to yield a high-quality X-ray spectrum.

2 XRS Spectral Diagnostics

Our *Chandra* grating observations of DoAr 21 revealed a hard X-ray source, dominated by a bremsstrahlung continuum, but with several moderately strong emission lines, from Ne X up to Fe XXV. The HETGS/HEG spectrum, which we fit with a two temperature (1.5 keV and 5.5 keV) thermal model, are shown in Figure 1.

The diagnostics and physical properties our proposed *XRS* observation will elucidate include:

1) **Density**: He-like forbidden-to-intercombination line ratios are sensitive to electron density, via collisional excitation out of the metastable ^3S level. Features from Si, S, Ar and Ca can be used to probe densities of $\sim 10^{13}$ cm^{-3} (they are also sensitive to strong UV radiation, which may be present in PMS stars due to accretion streams and boundary layers, as suggested by Kastner et al. (2002)). Most intriguing is the result that the CTTS TW Hya shows the Mg XI f/i ratio in the "high density limit" of $f/i \approx 0$ (Kastner et al. 2002) while HD 98800 A shows the f/i ratios in the "low density limit" (Kastner et al. 2004), which is what is usually seen in main sequence coronal sources. Unlike the CTTS TW Hya, HD 98800 A has no circumstellar material at all (Koerner et al. 2000 ApJ 533:L37; Prato et al. 2001 ApJ 549:590). Our *Chandra* observations of DoAr 21 show the Si XIII and S XV f/i ratios with an intermediate value, though with large error bars, which might be understood in terms of the modest amount of circumstellar material that is inferred in this source. *Astro E-2 XRS* spectroscopy can provide a much better determination of the S XV f/i ratio (especially, but probably also Si XIII and Ar XVII) than the *Chandra HETGS* spectroscopy could. Our proposed 100 ks observation will determine whether the f/i ratio in DoAr 21 is more like that seen in the CTTS TW Hya or the naked T Tauri star HD 98800 A (Figure 2). The higher densities in PMS stars with active accretion might be understood in terms of coronal mechanism or in terms of the accretion itself. The proposed observation will also have high enough signal to noise to look for changes in the f/i ratio during flaring.

2) **Kinematics**: The emission line widths in the *Chandra* observations hint at some broadening, perhaps due to co-rotation or disk kinematics but the signal-to-noise and spectral resolution of those data are slightly too low to determine the significance of the broadening. The strongest line in the *Chandra* spectra, Si Ly-α, has a FWHM of 450 $\pm$ 100 km s^{-1}, and the other relatively strong lines have widths consistent with several hundred km s^{-1}, but not inconsistent with zero broadening. With the superior

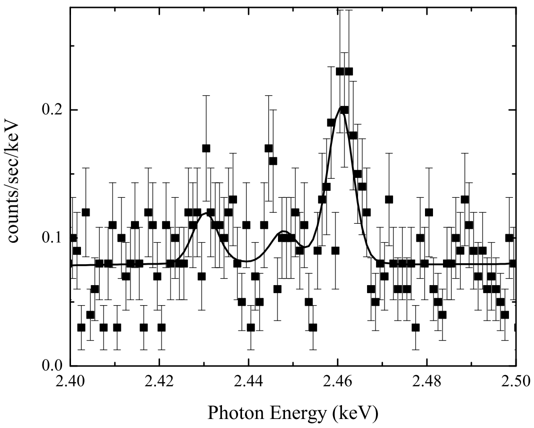

Figure 2: Simulated S XV "f-i-r" feature for DoAr 21 in a 100 ks *XRS* observation. The flux levels are based on the best-fit two-temperature model as determined from the overall *Chandra* spectra. This simulation was done with the APEC thermal model within XSPEC, with a low electron density.

throughput and resolution of the *XRS*, especially at the photon energies of the Fe K emission features, we will be able to determine emission line widths, even if the broadening is less than 100 km s^{-1}. This will enable us to assess whether the hot plasma on DoAr 21 is associated with a quasi-Keplerian disk or is stationary and confined in smaller loops anchored to the photosphere. We would also be able to detect expanding plasma during a flare event.

3) **Temperature**: During the flare observed in the *Chandra* pointing, the hot component of the plasma doubled in temperature from 2.5 keV to nearly 6 keV. The *Chandra* spectra were not very sensitive to higher temperatures, however, due to the low sensitivity around the Fe K lines shortward of 2 Å. With the *XRS*, we will be able to make much more precise temperature determinations from the Fe K complex, with the ratio of Fe XXVI to Fe XXV being sensitive to the highest temperatures, and the strength of the iron satellite lines being sensitive to the temperature distribution below about 30 MK (Oelgoetz & Pradhan 2001 MNRAS 327:L42). With the sensitivity

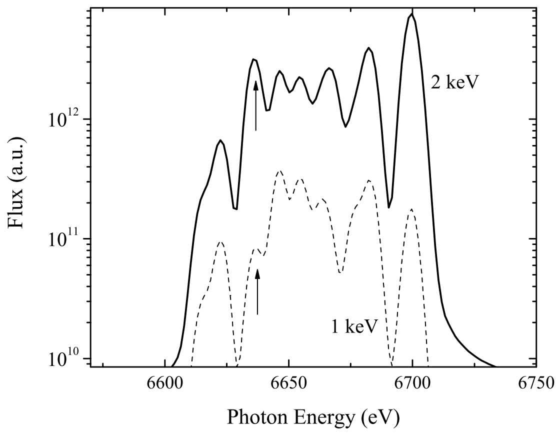

Figure 3: PrismSpect simulation of the Fe XXV complex for two different temperatures, 1 keV and 2 keV. The arrow indicates the forbidden, or z line, which gets stronger with increasing temperature. The line at 6.7 keV is the w, or resonance, line. The features in between are dominated by Fe XXIV satellite lines, which are also temperature sensitive.

and resolution of the *XRS*, we should be able to do much better than the coarse, two-temperature description of the plasma temperature that came out of the *Chandra* data. This proposed observation will provide some of the most precise information to date about the plasma temperature distribution in very high temperature stellar coronal plasmas. In Figure 3 we show two models of the Fe K complex for two different temperatures, made with our non-LTE statistical equilibrium code, PrismSpect. The simulations clearly show the temperature sensitivity of the forbidden and satellite features, described by Oelgoetz & Pradhan (2001). With PrismSpect's ability to model time-dependent atomic kinetics and spectral properties of plasmas, we will be able to look for signatures of non-equilibrium plasma, perhaps related to flaring, using Fe K diagnostics described by Oelgoetz & Pradhan (2004 astro-ph/0408065).

In addition to the *XRS* spectrum of DoAr 21, the proposed 100 ks observation will provide excellent imaging spectroscopy of the ≈ 70 known

X-ray sources in the *XIS* field of view. Gagné et al. (2004 ApJ 613:in press) detect 34 sources in ρ Oph cloud core A near DoAr 21 whose *ACIS-I* count rates exceed 10^{-3} counts s^{-1}. These sources would produce $\sim 3 \times 10^{-3}$ counts s^{-1} in the four *XIS*s or $\sim$ 300 counts in 100 ks. The *XIS* field contains at least three Class 0/I protostars, a dozen proto-brown dwarf candidates, $\sim$ 30 T Tauri stars, and the unusual magnetic B-star binary Oph S1. The cluster is sparse so the sources will be well resolved despite the 1 arcmin-radius XIS blur circle. All these classes of X-ray sources are hard and highly variable on timescales of hours. The *XIS* data will allow us to perform time-resolved, CCD spectroscopy of large flares on approximately a dozen sources.

3 Feasibility and Analysis

DoAr 21 is significantly brighter than the other sources within a one arcminute radius, so contamination of our spectrum should not be significant. We have performed an *XRS* simulation using XSPEC and the publicly available response matrix and ARF. Using the best-fit two-temperature model that we fit to the *Chandra* spectrum, we determine a *XRS* count rate of 0.39 counts s^{-1}. The Fe K and S XV complexes are predicted to have roughly 500 and 200 counts, respectively.

As described above, we will be using, in addition to the standard modeling and analysis tools, the PrismSpect (MacFarlane, et al. 2003, *Proc. 3rd Intl. Conf. on Inertial Fusion Sciences*, Am. Nucl. Soc., Lagrange Park, IL) code, which has been used to model He-like fir complexes in hot stars (e.g. Cassinelli et al. 2001 ApJ 554:L55; Cohen et al. 2003 ApJ 586:495) as well as being used extensively to model X-ray spectra of laboratory plasmas.

4 Conclusions

DoAr 21 is an X-ray bright PMS star, one of the very few 1-Myr-old stars bright enough to yield a high-quality spectrum to place constraints on the PMS X-ray emission mechanism. Simply on the merits of the quality of the expected spectrum, this source is well matched to the capabilities of the *Astro E-2 XRS*. The caracteristics of this star are particularly interesting because both its X-ray properties (primarily the He-like f/i ratios) and its circumstellar properties lie in between those observed on the two other well-studied PMS stars, TW Hya and HD 98800 A. Furthermore, several specific diagnostics are available with the *XRS* - including line widths and temperature- and density-sensitive line ratios - that can address open questions about PMS X-ray production mechanisms. Finally, The XIS data will provide coarse spectral information on the time-dependent properties of several dozen T Tauri stars and brown dwarfs in the region of the ρ Oph cloud near DoAr 21.

Our group has significant expertise in the study of PMS stars, at many wavelengths, and also in X-ray spectral analysis and modeling of both astrophysical and laboratory plasmas, as well as sophisticated modeling tools that can be used in this analysis. As such, we are capable of analyzing and interpreting the high-quality *XRS* spectrum of DoAr 21.