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The X-ray emission from Z Canis Majoris during an FUor-like outburst and the detection of its X-ray jet

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ABSTRACT

Accretion shocks have been recognized as an important X-ray emission mechanism for pre-main sequence stars, and yet the X-ray properties of FUor outbursts, events that are caused by violent accretion, have been given little attention. We observed the FUor object Z CMa during optical outburst and quiescence with *Chandra*. No significant changes in X-ray brightness and spectral shape were found, suggesting that the X-ray emission is coronal. The binary nature of Z CMa makes the origin of the X-ray source ambiguous. However, the moderate hydrogen column density derived from our data makes it unlikely that the embedded primary star is the X-ray source. The secondary star, which is the FUor object, is thus responsible for both the X-ray emission and the ongoing accretion outburst, which seem, however, to be unrelated phenomena. The secondary is also known to drive a large outflow and jet, which we detect here for the first time in X-rays. The distance of the X-ray emitting outflow source to the central star is greater than in jets of low-mass stars.

Key words. X-rays: stars – accretion, accretion disks – stars: pre-main sequence – stars: variables: general – stars: activity – stars: winds, outflows

1. Introduction

Variability is a dominant observational signature in pre-main sequence (pre-MS) stellar evolution. Besides the ubiquitous short-duration flares related to magnetic reconnection events, various types of long-term outbursts are reported: FUor events are characterized by optical intensity changes of up to 4 mag and a fading phase of decades, EXor events are less extreme and shorter (months to few years). Both types of outburst are associated with a sudden increase in the accretion rate, such that the disk outshines the central star leading to characteristic spectral signatures (e.g. Hartmann & Kenyon 1996). The spectra of FUor objects resemble that of F-G supergiants, while EXor objects have a later spectral type. The FUor and EXor phenomena are probably recurrent, about once every 10^4 yrs for the FUors and every few years in the case of EXors. Only a minor fraction of pre-MS stars are classified as FUor or EXor (Ábrahám et al. 2004; Herbig 2008). Different mechanisms have been proposed as triggers for the outbursts: dynamical interaction with a close binary companion (Bonnell & Bastien 1992; Reipurth & Aspin 2004), thermal instability in a disk with high accretion from a surrounding envelope (Bell & Lin 1994), and changes in the magnetic field configuration (van den Ancker et al. 2004).

In recent years it has been recognized that accretion makes a significant contribution to the X-ray emission of some pre-MS stars (Kastner et al. 2002; Stelzer & Schmitt 2004), making FUor and EXor objects interesting targets for X-ray studies. Plasma temperatures of up to a few 10^6 K can be produced in the accretion shocks that form when matter is funneled along the magnetic field lines onto the stellar surface. In the first dedicated X-ray survey of FUor objects, Skinner et al. (2009) have detected two of four stars with *XMM-Newton*. None of their targets were in a state of recent optical outburst during the X-ray observation. Only two EXors have been observed in X-rays during an optical outburst, with contradictory results (Kastner et al. 2006; Audard et al. 2005).

The X-ray spectrum of the prototype FU Ori shows a surprisingly complex absorption pattern: while the harder emission is strongly absorbed and can be ascribed to an embedded stellar corona, the origin of the weakly absorbed soft emission is unclear (Skinner et al. 2006). Possible scenarios include the overlaid effect of a binary companion, accretion shocks, and shocked jets. Indeed, Günther et al. (2009) have recently shown that the unresolved soft component in the X-ray spectrum of the pre-MS star DG Tau can be explained as emission from a post-shock cooling zone in the innermost part of its optical outflow. Soft emission (few MK) is only an indirect means of inferring outflows in X-rays and a signature that is easily confused with contributions from accretion. Direct detection of X-ray emission from pre-MS jets by means of a displacement with respect to the central coronal source has only been achieved in a handful of cases (see summary in Bonito et al. 2007).

In this article we examine the X-ray properties of Z CMa during its recent optical outburst, we compare them to its quiescent state, and we present the X-ray detection of its jet. Z CMa is a 0.1″ pre-MS binary. While the southeast (SE) FUor object dominates the light at optical wavelengths, the north-west (NW) component is a powerful infrared (IR) source (Koresko et al. 1991).

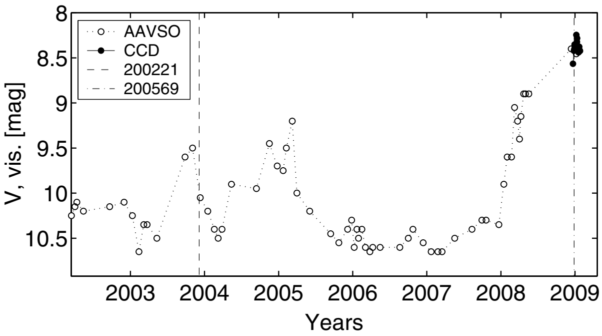

Fig. 1. Lightcurve of Z CMa; vertical lines indicate the date of *Chandra* observations.

Table 1. Observing log for *Chandra* exposures of Z CMa.

ObsID	SeqNo	Instrument	Date [UT]	Expo [ks]
3751	200221	ACIS-S2	2003-12-07 22:00	38
10845	200569	ACIS-S3	2008-12-28 22:48	40

The FUor star has ~3 $M_\odot$ and is located just below the birthline in the HR diagram (Hartmann et al. 1989). Assuming that the IR source is coeval, it can be modeled as a B0 III star with 16 $M_\odot$ (van den Ancker et al. 2004). The optically dominating component is, therefore, the secondary in the binary system. This star is likely responsible both for the FUor phenomena and for the jet and molecular outflow observed at radio and optical wavelengths (Poetzel et al. 1989; Evans et al. 1994; Velázquez & Rodríguez 2001). The long-term lightcurve of Z CMa exhibits features of both FUor and EXor-like events. Optical outbursts of ~1 mag are superposed on a two-decade long decay (van den Ancker et al. 2004). An alternative explanation for the irregular light variations of Z CMa is scattered light from the embedded primary that penetrates an envelope of variable thickness (Hartmann & Kenyon 1996).

In Jan 2008 Z CMa started a large optical outburst (see Fig. 1). Visual brightness estimates[1] are available for the initial gradual increase by ~1.5 mag. Further visual observations and additional BVR_CI_C CCD photometric observations[2] have resumed after a ~6 month-long gap. Z CMa reached its (temporary) maximum of ~8.3 mag at the beginning of Jan. 2009.

2. Data analysis and results

A *Chandra* observation of Z CMa carried out in Dec. 2003 was presented by Stelzer et al. (2006) in the framework of a survey for X-ray emission from Herbig stars. The source was not in optical outburst during that observation. We obtained another 40 ks of *Chandra* Director's Discretionary Time to search for changes in the X-ray characteristics during the recent optical outburst. Table 1 gives the observing log. For consistency we re-analyze here the 2003 observation analogous to the new data set.

We used the CIAO package[3], version 4.0, and we started with the level 1 events file provided by the *Chandra* X-ray Center.

[1] We obtained the visual photometry from the American Association of Variable Star Observers (AAVSO) at http://www.aavso.org

[2] The CCD photometry was obtained by Czech observers L. Brát and L. Šmelcer; see http://var2.astro.cz/meduza/light-curves-ccd.php?star=Z%20CMa&shv=CMa of VSES CAS.

[3] CIAO is made available by the *Chandra* X-ray Center and can be downloaded from http://cxc.harvard.edu/ciao/download/

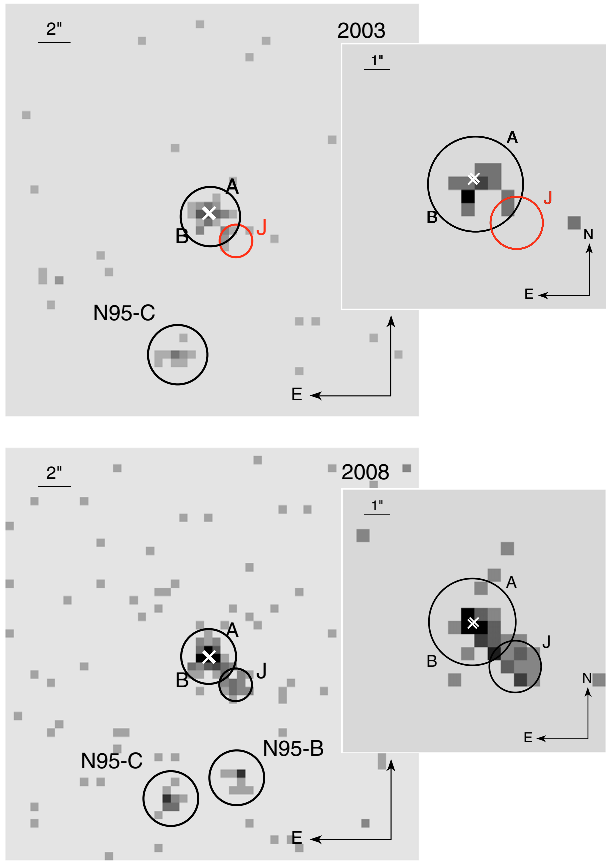

Fig. 2. *Chandra*/ACIS images for the 0.2–8 keV band in a 25″ × 25″ region around Z CMa (0.5″ pixels) for the 2003 (*top*) and the 2008 (*bottom*) observation; zoom on Z CMa in the 0.2–1 keV band for both epochs. All detected X-ray sources are marked with black circles, and the binary components are shown as white x-shaped symbols. The position of the X-ray source detected in the 2008 image to the SW of the central source labeled "J" is overlaid in the 2003 image as a red circle. In 2008, the soft band image shows continuous emission along the jet axis rather than distinct X-ray sources.

In the process of converting the level 1 events file to a level 2 events file for each of the observations, we performed the following steps. We removed the pixel randomization to optimize the spatial resolution. We filtered the events file for event grades (retaining the standard grades 0, 2, 3, 4, and 6), and applied the standard good time interval file.

For our science goal of detecting the X-ray source(s) associated with Z CMa, source detection was restricted to a 100 × 100 pixel wide image (1 pixel = 0.5″) and a congruent, monochromatic exposure map for 1.5 keV centered on the optical position of Z CMa. Source detection was carried out with the WAVDETECT algorithm (Freeman et al. 2002). We used wavelet scales between 1 and 8 in steps of $\sqrt{2}$. We tested a range of detection significance thresholds and found that $\sigma_{\rm th} = 10^{-5}$ avoided spurious detections and at the same time separated close emission components.

The two X-ray images are shown in Fig. 2 with optical positions of the binary and detected X-ray sources overlaid. The brightest X-ray source coincides in both observations with the unresolved binary star. Two new X-ray sources, not seen in the 2003 data, are detected in the 2008 image. Especially remarkable is the faint source in the SW elongation of Z CMa (named "J" henceforth). The position angle of this source is

Table 2. X-ray parameters of the Z CMa binary and its jet.

Date	Opt/IR	Offax [′]	Counts in 0.3−8 keV	Expo* [s]	P_{KS}
Dec. 2003	Z CMa	1.95	47.6 ± 6.9	17857.	0.54
Dec. 2003	jet	1.91	<9.4	17857.	–
Dec. 2008	Z CMa	0.30	107.2 ± 10.4	39594.	0.50
Dec. 2008	jet	0.34	20.7 ± 4.6	39610.	0.32

* The effective exposure time in the 2003 Dec. observation is substantially reduced with respect to the duration of the observation because the star is near a chip border.

(225 ± 5)° and agrees roughly with the orientation of the blue-shifted part of the optical jet detected by Poetzel et al. (1989). In the broad band image (0.2−8 keV), this source is separated by 2.4″ from Z CMa. If only photons below 1 keV are considered, the 2008 image shows elongated emission along the same axis suggesting a chain of weak X-ray sources extending to the SW of Z CMa. There is no significant soft excess in the SW direction during 2003 (see zoom in Fig. 2). The remaining X-ray sources (labels "N95-B" and "N95-C" in Fig. 2) are tentatively identified with pre-MS candidates mentioned by Nakajima & Golimowski (1995). In the following we concentrate on the analysis of the X-ray emission associated with Z CMa and its jet.

We calculated the source count rates in the following way. First, the point-spread-function (PSF) was computed for each X-ray position. A circular source photon extraction region was defined as the area that contains 95% of the PSF. Only for source "J" was the extraction region restricted to 90% of the PSF to avoid contamination from the wings of the central source. The background was extracted individually from a squared region centered on the source extraction area and several times larger than the latter one. Circular areas centered on the positions of the X-ray sources were excluded from the background area. The S/N was computed from the counts summed in the source and background areas, respectively, after applying the appropriate area scaling factor to the background counts. In practice, the background is very low (a fraction of a count in the source extraction area). Finally, count rates were obtained using the exposure time at the source position extracted from the exposure map. We estimated a 95% confidence upper limit for the count rate at the position of "J" in the 2003 Dec. observation using the algorithm of Kraft et al. (1991). In Table 2 we summarize the relevant X-ray parameters of the Z CMa binary and the source "J" identified with the jet.

An individual response matrix and auxiliary response were extracted for the position of each source using standard CIAO tools. The spectrum of the brighter source (Z CMa) was binned to a minimum of 10 counts per bin and that of the fainter one ("J") to 5 counts per bin. As mentioned above, the background of ACIS is negligibly low. We fitted the spectra in the XSPEC 12.4.0 environment with a one- or two-temperature thermal model subject to photo-absorption (WABS · APEC and WABS · [APEC + APEC], respectively).

For the brighter source (Z CMa), the 1-T fit of the 2008 Dec. observation displays substantial residuals slightly below 1 keV, and we resort to the 2-T model. The best fit N_H is $7^{+5}_{-6} \times 10^{21}$ cm^{-2}, compatible with the range of values published for the optical extinction A_V = 2.4...4.6 mag (Elia et al. 2004; Acke & van den Ancker 2004). Assuming a particle density of 0.3 cm^{-3}, the galactic absorption at 1 kpc amounts to $\sim 10^{21}$ cm^{-2}. Therefore, Z CMa may have some additional absorption related to the star-forming environment. On the other

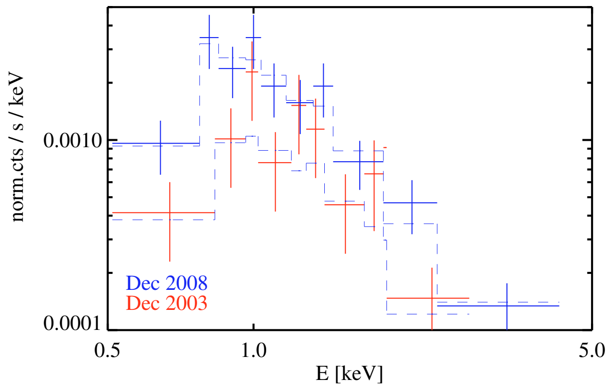

Fig. 3. Folded *Chandra*/ACIS spectra of Z CMa. Overplotted on both spectra is the best-fit model obtained for the 2008 observation (dashed lines).

hand, our measurement does not rule out negligible circumstellar absorption. In our best-fit model, the soft component (kT_1 = $0.4^{+0.7}_{-0.2}$ keV) dominates the hard component (kT_2 ∼ 7.5 keV; unconstrained) with an emission measure $\log EM_1$ [cm^{-3}] = $53.9^{+1.2}_{-0.6}$ vs. $\log EM_2$ [cm^{-3}] = $53.1^{+0.4}_{-0.3}$. Due to the large confidence intervals of the spectral parameters, we only determine a lower limit on the X-ray flux, adopting a minimum N_H of $\sim 10^{21}$ cm^{-2} coming up for the interstellar absorption but neglecting any possible contribution from the environment of the star. We find $f_x > 1.6 \times 10^{-14}$ erg/cm^2/s for the 0.5−8.0 keV band, corresponding to $\log L_x$ [erg/s] > 30.3 at a distance of 1050 pc.

For the 2003 Dec. observation due to low photon statistics, we cannot formally exclude the 1-T model. Iso-thermal models are known to be an oversimplification, and the number of thermal components needed to fit stellar X-ray spectra generally increases with photon statistics. We do not present a detailed spectral analysis of this data set because the quality is poor; however, we can test the compatibility of the 2003 spectrum with the 2-T model parameters derived from the 2008 observation. Indeed, we find from a direct comparison of the 2008 best-fit model to the spectrum observed in 2003, without fitting it to the data, a χ^2_{red} = 1.0 (5 d.o.f.). The good agreement is also evident from Fig. 3 where we plot both observed spectra, together with the best-fit model of the 2008 data. Differences in the appearance of the two spectra in Fig. 3 stem from the data and the model being shown folded with the instrument response matrix. We recall here that Z CMa is located on two different CCD chips and at different off-axis angle, in the 2003 and 2008 data sets (see Table 1), and this implies different spectral response and effective area.

The fainter source ("J") has only 20 counts in Dec. 2008. The 1-T model gives the same absorption as found for Z CMa albeit with even larger uncertainties (N_H = $7^{+8}_{-7} \times 10^{21}$ cm^{-2}). The large error bar of the column density makes it impossible to determine the emission measure and flux of this source to even an order of magnitude precision. The temperature of source "J" is also not well-constrained ($0.2^{+0.8}_{-0.1}$ keV), but probably relatively soft. We find a median photon energy of 0.9 keV for "J" versus 1.2 keV for Z CMa. Analogously to the case of Z CMa, we estimate a lower limit for the X-ray flux of "J" by adopting N_H of $\sim 10^{21}$ cm^{-2}, corresponding to the expected interstellar absorption. The derived value of 2×10^{-15} erg/cm^2/s translates to $\log L_x$ [erg/s] > 29.4 if we assume that the distance of this source is the same as for the one associated with Z CMa.

Lightcurves were extracted and searched for variability with a maximum likelihood method that divides the sequence of photons in intervals of constant signal (see Stelzer et al. 2007) and, independently, with the Kolmogorov-Smirnov (KS) test. According to this analysis, both sources are not variable within the individual exposures. The significance level of the KS statistic for each source is given in the last column of Table 2, where the high values of $P_{\rm KS}$ indicate that the data is not significantly different from the assumption of a constant source.

3. Discussion

3.1. The central X-ray source

Prior to our observations, only two pre-MS stars had been monitored in X-rays during an optical EXor outburst. V1647 Ori has shown a factor 100 increase in the X-ray luminosity and a steady decay in the subsequent two years correlated with the near-IR lightcurve. With respect to the pre-outburst state, the spectrum was hard throughout the decaying phase (3.6 keV) and incompatible with X-ray emission from accretion shocks (Kastner et al. 2006). The other EXor object observed in X-rays during an outburst is V1118 Ori. Audard et al. (2005) show that its X-ray luminosity varied only by a factor of two with respect to the pre-outburst value, but the spectrum softened during the EXor event. A possible explanation given by Audard et al. (2005) is a changing structure of the magnetosphere that moved inward as a result of strong accretion and disrupted the higher, hotter coronal loops. After the outburst, V1118 Ori was seen to have faded by a factor of four in X-ray luminosity but had not significantly changed its X-ray temperature (Lorenzetti et al. 2006).

For Z CMa, the X-ray brightness and temperature are remarkably constant when the 2003 quiesence and the 2008 outburst data are compared. Overall, the temperature structure of the X-ray spectrum of Z CMa is typical of coronal sources observed with similar statistics (e.g. Schmitt et al. 1990). Clearly, the spectrum is much softer than that of V1647 Ori during its EXor event. The low statistics make it impossible to single out eventual contributions from accretion and/or jet shocks. Similarly, low statistics impeded Skinner et al. (2009) to constrain the temperature of the soft component in the X-ray spectrum of the FUor star V1735 Cyg that they observed outside outburst with *XMM-Newton*. Their confidence level on the temperature of the soft component of V1735 Cyg is similar to ours (0.1−1 keV), leaving open the question of whether this emission is accretion-related. We have estimated a lower limit to the X-ray luminosity of Z CMa that is compatible with the X-ray luminosities reported by Skinner et al. (2009) for V1735 Cyg and FU Ori. As those authors point out, these luminosities are at the high end of the $L_{\rm x}$ distribution of T Tauri stars possibly implying that FUor objects have higher than average T Tauri mass. For Z CMa this observation is consistent with the high mass of 3 $M_{\odot}$ from the literature.

The binary nature of Z CMa leaves room for further speculations on the origin of the X-ray emission. (i) The X-rays could be from the less massive star, which is in this case non-variable both in the optical and X-rays, and the optical variations due to changes in scattered light from the primary. However, the recent optical photometry has a clear outburst signature and we discard the scattered-light scenario. (ii) The optical variations may come from the FUor star and the X-rays from the embedded primary. This hypothesis is also unlikely as much higher X-ray absorption would be expected than is observed. We conclude that probably the same star (the less massive optical component) is responsible for both the optical outburst and the X-ray emission but that both phenomena are unrelated. Although the existence of a corona cannot be taken for granted for an intermediate-mass star, our recent detection of the magnetic field of Z CMa supports this interpretation (Hubrig et al. 2009, A&A, submitted).

3.2. The displaced X-ray source

A new X-ray source is detected in the 2008 image in the SW elongation of the source associated with the Z CMa binary. Its position angle agrees with that of the optical jet (Poetzel et al. 1989) and the radio jet (Velázquez & Rodríguez 2001), suggesting an interpretation as emission from an internal jet shock. According to the strong shock condition (Zel'dovich & Raizer 1966), our confidence interval of measured X-ray temperatures, 0.1...1 keV, is compatible with shock velocities between ∼300...900 km s^{-1}. At a distance of ∼2″, corresponding approximately to the location of the new X-ray source, the jet was seen to move at ≤600 km s^{-1} in optical forbidden lines (Poetzel et al. 1989). Considering the unknown inclination, this is a lower limit for the true velocity of the jet propagation. Our estimate for the shock speed is, therefore, compatible with the expectation that $\upsilon_{\rm shock} < \upsilon_{\rm jet}$. Z CMa has a higher mass than most other pre-MS stars with X-ray detected jets (see summary by Bonito et al. 2007). The far distance of the displaced X-ray emission from the central star is remarkably similar to that of the only other high-mass pre-MS object with known X-ray jet, HH 80/81 (Pravdo et al. 2004). For the X-ray luminosity, we estimated a conservative lower limit of 2.6×10^{29} erg/s, which could easily be underestimating the intrinsic luminosity by one order of magnitude or more if the extinction was much higher than the assumed interstellar value. Our result is compatible with X-ray luminosities derived for other pre-MS jets (see Bonito et al. 2007). However, all X-ray observations of this object class are hampered by similarly low statistics and, consequently, poorly constrained parameters.

Because of the relatively low X-ray temperature that can be achieved in pre-MS jets, an image limited to soft photons should better trace the outflow. Indeed, we find continuous soft emission between Z CMa and source "J" in the 2008 image. Possibly several knots along the jet axis produce X-rays at any time. A similar finding was reported for DG Tau where the X-ray jet was detected both at close (50 AU) and greater (1140 AU) separation from the central star (Güdel et al. 2008; Schneider & Schmitt 2008).

In 2003 there was no X-ray source at the position of "J". The upper limit to the count rate at this epoch does not exclude X-ray emission at similar levels as observed in the 2008 image. However, examination of the photon centroids reveals that all counts are in the upper left of the photon extraction area (see Fig. 2) indicating weak emission in the same SW direction as "J" but at a distance of only ∼1.2″ from the central source. If this emission is interpreted as the head of a moving shock front that has expanded (and brightened) within the past 5 years to the position of "J", its projected velocity would be ∼900 km s^{-1}. This value roughly agrees with our measurement from the X-ray temperature. However, the analysis of the soft-band image from 2008, where continuously extended soft emission from Z CMa out to ∼2.4″ is detected, suggests that "J" represents the temporary radiative loss of a localized blob of material impacted by an intermittent jet. The weak emission closer to the star may represent similar but independent events.

We add that alternative explanations are perceivable for the X-ray emission displaced from Z CMa. Scattered stellar light reflected from the outflow cavities was discussed by Bally et al. (2003) for the case of HH 154, but seems unlikely to hold for Z CMa because of the large displacement of >2000 AU with respect to the central star. Again for HH 154, Murphy et al. (2008) suggest magnetic reconnection in the space between two interacting jets from the two binary components. There is no observed evidence of a second jet in Z CMa. High-quality, high-resolution imaging of the Z CMa outflow should help to clarify this question. Monitoring of the X-ray morphology during the next decade should also help to constrain the nature of the emission. For an assumed jet diameter of 100 AU, we can estimate the electron density from the observed X-ray emission measure and derive a radiative cooling time of ~20 yrs.

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