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X-RAY SPECTRAL VARIABILITY DURING AN OUTBURST IN V1118 ORI

M. Audard,[1] M. Güdel,[2] S. L. Skinner,[3] K. R. Briggs,[2] F. M. Walter,[4]
G. Stringfellow,[3] R. T. Hamilton,[5] and E. F. Guinan[5]

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ABSTRACT

We present results from a multiwavelength campaign to monitor the 2005 outburst of the low-mass young star V1118 Ori. Although our campaign covers the X-ray, optical, infrared, and radio regimes, we focus in this Letter on the properties of the X-ray emission in V1118 Ori during the first few months after the optical outburst. *Chandra* and *XMM-Newton* detected V1118 Ori at three epochs in early 2005. The X-ray flux and luminosity stayed similar within a factor of 2 and at the same level as in a preoutburst observation in 2002. The hydrogen column density showed no evidence for variation from its modest preoutburst value of $N_{\rm H} \sim 3 \times 10^{21}$ cm^{-2}. However, a spectral change occurred from a dominant hot plasma (∼25 MK) in 2002 and in 2005 January to a cooler plasma (∼8 MK) in 2005 February and in 2005 March. We hypothesize that the hot magnetic loops high in the corona were disrupted by the closing in of the accretion disk due to the increased accretion rate during the outburst, whereas the lower cooler loops were probably less affected and became the dominant coronal component.

Subject headings: accretion, accretion disks — circumstellar matter — stars: coronae — stars: individual (V1118 Orionis) — stars: pre–main-sequence — X-rays: stars

1. INTRODUCTION

The origin of X-rays remains an important topic for young accreting stars. Although scaled-up, solar-like magnetic activity is the dominant mechanism in most moderately accreting young stars (Gahm 1980; Walter & Kuhi 1984; Damiani et al. 1995; Damiani & Micela 1995, etc.; see Bertout 1989; Feigelson & Montmerle 1999; Güdel 2004 for reviews), there is also evidence that accretion may play an important role in others (Kastner et al. 2002; Stelzer & Schmitt 2004; Schmitt et al. 2005). Shocks in jets may also contribute to the soft X-ray component observed in some young stars (Güdel et al. 2005a; Kastner et al. 2005). Highly accreting stars can help us to understand how the accretion disk interacts with the stellar magnetosphere and photosphere and to understand the importance of accretion in the X-ray emission in young stars. A handful of such young stars display powerful eruptive events with flux increases in the optical regime of a few magnitudes. Such outbursts are thought to originate during a rapid increase of the disk accretion rate over a short period of time, from values of 10^{-7} to 10^{-4} $M_\odot$ yr^{-1} (see Hartmann & Kenyon 1996). The origin of the change in accretion rate is subject to debate and could be triggered by close companions or thermal disk instabilities. Two classes of erupting young stars have emerged: FU Orionis stars (FUors), which display outbursts of 4 mag and more that last several decades, and EXors (named after the prototype EX Lup), which display smaller outbursts ($\Delta V = 2$–3 mag) that last from a few months to a few years and that may occur repeatedly (e.g., Herbig 1977).

On 2005 January 10, Williams et al. (2005) reported the outburst of V1118 Ori, a low-mass M1e young EXor star ($d = 470$ pc; $M_\star = 0.41$ $M_\odot$; $R_\star = 1.29$ $R_\odot$; $P_{\rm rot} = 2.23 \pm 0.04$ days; $L_{\rm bol} \geq 0.25$ $L_\odot$; $\log T_{\rm eff}({\rm K}) = 3.562$; $\log t({\rm yr}) = 6.28$; Hillenbrand 1997; Stassun et al. 1999). V1118 Ori has been known for its outbursts in the past (e.g., 1983–1984, 1988–1990, 1992–1994, 1997–1998; see Garcia Garcia & Parsamian 2000 for details). For this 2005 outburst, we have started a multiwavelength monitoring campaign. In this Letter, we report first results from our campaign and focus on the observations in the X-ray regime obtained with *Chandra* and *XMM-Newton*.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *X-Ray*

About 2 weeks after the IAU Circular by Williams et al. (2005), *Chandra* observed V1118 Ori, and *XMM-Newton* subsequently observed in 2005 February and March. We also retrieved archival data of serendipitous, preoutburst observations of V1118 Ori by *XMM-Newton* in 2001 October and by *Chandra* in 2002 September. The latter was published by Ramírez et al. (2004), who reported the detection of V1118 Ori (source S029). Table 1 provides a log of the observations.

The *Chandra* data were reduced with the CIAO 3.2.1 software with CALDB 3.01. For the 2005 observation, we extracted 12 events in the 0.1–10 keV range from a circle with a radius of 2″ centered at the position of V1118 Ori on the ACIS-S detector. For the background, we used a nearby 10″ radius circle. The scaled background contribution was 0.52 events. For the 2002 observation, in contrast, we used extraction radii of 15″ and 45″ for V1118 Ori and the nearby background, respectively, because of the large off-axis angle ($\theta = 8\farcm85$) of V1118 Ori on the ACIS-I detector.

The *XMM-Newton* data were reduced with the SAS 6.1.0 software. For the 2005 observations, events were extracted using circles with radii of 20″ for V1118 Ori and 60″ for the background located in a nearby source-free region. For the 2001 observation, when only MOS2 data were available,[6] we used circles of similar sizes as above at the expected position of V1118 Ori and for

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[1] Columbia Astrophysics Laboratory, Mail Code 5247, 550 West 120th Street, New York, NY 10027; audard@astro.columbia.edu.

[2] Paul Scherrer Institut, 5232 Villigen PSI, Switzerland; guedel@astro.phys.ethz.ch, briggs@astro.phys.ethz.ch.

[3] Center for Astrophysics and Space Astronomy, University of Colorado, 389 UCB, Boulder, CO 80309-0389; skinners@casa.colorado.edu, guy.stringfellow@colorado.edu.

[4] Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, NY 11794-3800; fwalter@astro.sunysb.edu.

[5] Department of Astronomy and Astrophysics, Villanova University, Villanova, PA 19085; ryan.hamilton@villanova.edu, edward.guinan@villanova.edu.

[6] The EPIC pn was off and the orientation of the MOS1 detector was such that V1118 Ori fell outside the field of view.

TABLE 1

Observation Log and X-Ray Properties of V1118 Ori

Parameter	2001 October	2002 September	2005 January	2005 February	2005 March
Satellite	*XMM-Newton*	*Chandra*	*Chandra*	*XMM-Newton*	*XMM-Newton*
Data set	X/0112590301	obs/2548	obs/6204	X/0212480301	X/0212480401
Duration (ks)	40	48	5	20	20
Observation date	2001 Oct 3	2002 Sep 6–7	2005 Jan 26	2005 Feb 18–19	2005 Mar 21
Observation time (UT)	01:02–12:03	12:57–02:54	03:07–05:04	22:36–04:50	16:20–22:08
Average Julian date − 2,450,000	2,185.8	2,524.3	3,396.7	3,420.6	3,451.3
Net counts	<26.3	169.7	11.5	494.1[a]	252.5[a]
$N_{\rm H}$ (10^{21} cm^{-2})	…	$2.7^{+1.2}_{-0.9}$	$1.4^{+3.6}_{-1.4}$	$4.3^{+1.3}_{-1.1}$	$1.4^{+0.8}_{-0.5}$
T (MK)	…	$25.1^{+6.3}_{-4.8}$	$46^{+\infty}_{-28}$	$7.7^{+1.3}_{-0.8}$	$15.9^{+3.9}_{-2.0}$
EM (10^{53} cm^{-3})	…	$1.5^{+0.4}_{-0.3}$	$0.5^{+0.6}_{-0.2}$	$4.0^{+1.4}_{-1.4}$	$2.9^{+0.6}_{-0.5}$
$Z/Z_{\odot}$	…	$:=0.17$	$:=0.17$	$0.17^{+0.20}_{-0.06}$	$:=0.17$
$F_{\rm X}$ (10^{-14} ergs cm^{-2} s^{-1})[b]	<2.3	3.1–3.7	0.9–3.5	2.6–3.1	5.2–6.6
$L_{\rm X}$ (10^{30} ergs s^{-1})[b]	<1.1	1.5–1.8	0.3–1.3	3.2–3.8	2.5–3.2

Note.—The uncertainties are based on 68% Bayesian confidence ranges, whereas the upper limits for 2001 are 95% Bayesian upper limits.

[a] Net counts for the sum of pn, MOS1, and MOS2 in 2005 February and for the sum of MOS1 and MOS2 in 2005 March.

[b] X-ray luminosity and absorbed X-ray flux in the 0.1–10 keV range, assuming $d = 470$ pc.

the background. Although ellipses would better represent the shape of the point-spread function at large off-axis angles where V1118 Ori fell on the MOS2 detector, SAS does not accurately calculate effective areas for such shapes.

2.2. *Optical and Near-Infrared*

We obtained optical (*V*, *R*, and *I*) and near-infrared (*J*, *H*, and *K*) photometry using the SMARTS[7] 1.0 and 1.3 m telescopes. Magnitudes are measured differentially with respect to field stars. We have used Two Micron All Sky Survey magnitudes to convert the *JHK* differential magnitudes to true observed magnitudes. For the optical bands, we have used arbitrary reference magnitudes of $V_{\rm ref} = 10.25$, $R_{\rm ref} = 9.5$, and $I_{\rm ref} = 8.75$ to match the magnitudes obtained by the Villanova group. Details about the SMARTS data will be provided elsewhere together with accompanying spectra (G. Stringfellow et al. 2005, in preparation).

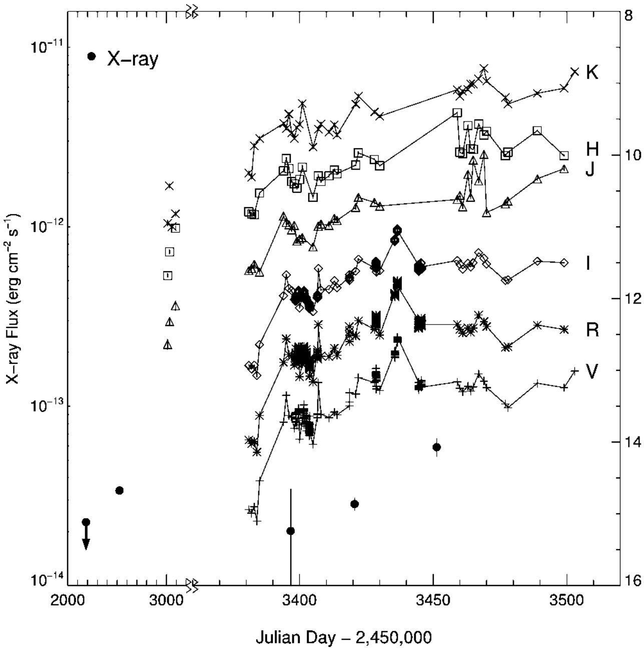

Fig. 1.—Long-term light curves of V1118 Ori. Notice the broken time axis with different scales for the preoutburst epoch (1200 days) and the outburst epoch (160 days). Constant zero-point magnitudes were added to the optical SMARTS data to eye-match the Villanova data (see text). The uncertainties are plotted but are small compared to the day-to-day variability observed in the optical and near-infrared. The left *y*-axis refers to X-ray data, whereas the right *y*-axis refers to the photometric optical and near-infrared data.

Photometric coverage of V1118 Ori from the Villanova University Observatory was obtained from 2005 January 28 to March 16. Observations were carried out in standard Bessel *V*, *R*, and *I* filters. Dark and flat-field frames were collected at the end of each night's observations. We assigned a standard error of 0.05 mag for these observations, estimated from the signal-to-noise ratio and seeing conditions.

2.3. *Radio*

The Very Large Array (VLA)[8] observed V1118 Ori on 2005 January 24 from 04:56 to 05:56 UT in hybrid BnA configuration, using the continuum mode at 8.435 GHz (3.56 cm) with a total bandwidth of 100 MHz. The primary and secondary calibrators were 3C 48 and J0541−056, respectively. The total on-source time was 38 minutes for V1118 Ori.

Data were edited and calibrated using AIPS.[9] We obtain a 3 σ upper limit to the flux density of V1118 Ori of $S_{3.6} \leq 0.075$ mJy, corresponding to $L_{3.6} \leq 2 \times 10^{16}$ ergs Hz^{-1} s^{-1}.

3. RESULTS

Figure 1 shows light curves of V1118 Ori in the optical and near-infrared bands and in X-rays. During each of the X-ray observations, the X-ray flux stayed relatively constant and showed no strong variability due to, e.g., flares. We have thus used the full duration of the observations for our spectral analysis. We fitted the background-subtracted spectra with 1-*T* collisional ionization equilibrium models (additional components were not needed) based on the Astrophysical Plasma Emission Code (APEC 1.3.1; Smith et al. 2001) as implemented in XSPEC (Arnaud 1996) with a photoelectric absorption component,

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[7] SMARTS (the Small and Medium Aperture Research Telescope System) is a consortium of universities and research institutions that operate the small telescopes at Cerro Tololo under contract with the Association of Universities for Research in Astronomy, Inc.

[8] The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

[9] Astronomical Image Processing System (AIPS) is a software package developed by NRAO.

N_H, generally free to vary and that uses cross sections from Balucinska-Church & McCammon (1992). Abundances are relative to the solar photospheric values (Grevesse & Sauval 1998). Table 1 summarizes the best-fit models, X-ray fluxes, and luminosities with 68% confidence ranges.

The observations in 2001 and 2002 are useful to determine the preoutburst X-ray properties of V1118 Ori and compare them with those in the early phases of outburst in 2005. Unfortunately, V1118 Ori was not detected in 2001 down to $F_X < 2.3 \times 10^{-14}$ ergs cm^{-2} s^{-1} (95% Bayesian upper limit; Kraft et al. 1991). However, it was detected in 2002 (see Ramírez et al. 2004), and its X-ray spectrum was dominated by a hot plasma (25 MK) and low N_H (3×10^{21} cm^{-2}) after we fixed the metallicity at the outburst value, $Z = 0.17$ (see Table 1).

The *Chandra* 2005 January observation collected too few counts to fit a conventional binned spectrum. We have instead used a maximum likelihood fit method for unbinned data as described in Güdel et al. (2005b). Briefly, the method compares the distribution of the event energies with the spectral energy distribution of template spectra characterized by the plasma T, N_H, and L_X, for a fixed metallicity (we adopted $Z = 0.17$). We determined that the plasma in V1118 Ori was hot (>18 MK), similar to the preoutburst 2002 data.

We fitted the *XMM-Newton* European Photon Imaging Camera (EPIC) pn and MOS spectra of 2005 February simultaneously. Whereas the X-ray flux and N_H did not vary much compared to 2005 January and 2002 September, the X-ray spectrum of V1118 Ori was instead dominated by a cooler 8 MK plasma with $Z = 0.17$. To establish whether a real change in plasma temperature and N_H occurred between 2002 and 2005 February, we performed simultaneous fits of these spectra, with each parameter (i.e., T and N_H) in turn (1) tied to be the same value in both observations but free to vary and (2) allowed to vary independently. We kept Z fixed to 0.17 but left the normalizations free to vary in each observation. F-test results confirmed that the joint fit was significantly improved by allowing the temperature to be different ($F = 27.59$, for a probability of <0.001 that the improvement is by chance). On the other hand, allowing different N_H for a model with two temperature components was not significantly better ($F = 0.42$, for a probability of 0.52). Figure 2 shows the observed (absorbed) X-ray fluxed spectra in the hard 2002 preoutburst state and in the 2005 February soft outburst state.

The 2005 March *XMM-Newton* data were of lower quality than those of 2005 February, due to a much higher background level resulting from solar activity. The pn data were more affected than the MOS data, so we fitted only the MOS1 and MOS2 spectra simultaneously. We obtained cool temperatures of 6–16 MK for plasma abundances between $Z = 0$ (best-fit abundance) and $Z = 0.17$ (fixed value of 2005 February). As above, we performed simultaneous fits of the 2005 March and February spectra. F-test results confirmed that the fit quality did not improve when the temperature ($F = 0.56$ for a probability of 0.46) or N_H ($F = 0.85$ for a probability of 0.36) were allowed to be different in the two observations. However, the same comparison of the 2005 March data with that of 2002 September found a significant improvement in fit quality when we allowed the temperatures to be different ($F = 6.64$ with a probability of 0.01) although not the N_H ($F = 1.47$ with a probability of 0.23). Thus, the 2005 March plasma temperature is significantly cooler than in 2002, while in line with the temperature observed in 2005 February. In conclusion, at some point after the initial outburst, a marked change in plasma temperature occurred, which has remained unchanged on a timescale of at least 1 month.

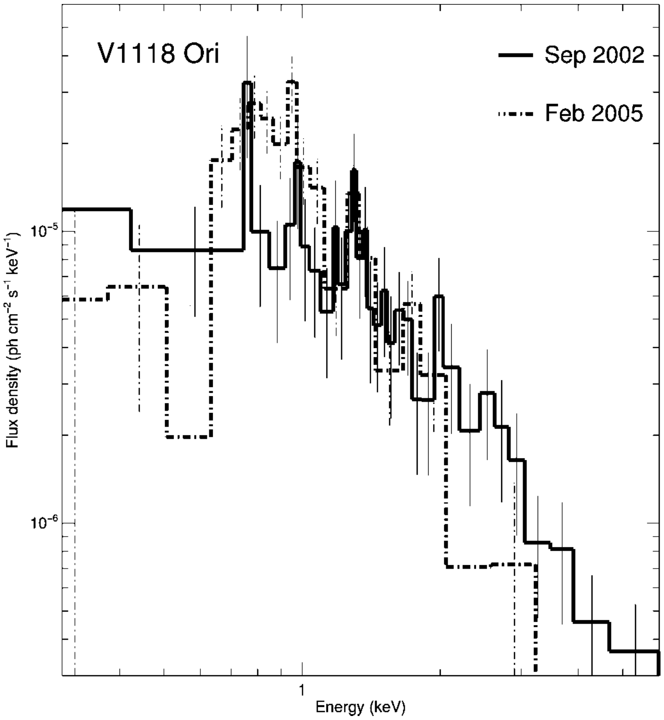

FIG. 2.—Fluxed spectra (uncorrected for photoelectric absorption) of the 2002 September (*solid line*) and 2005 February (*dash-dotted line*) observations of V1118 Ori. The soft excess (0.6–1 keV) is visible in the *XMM-Newton* observation during the outburst. In contrast, the hard (>2 keV) in the preoutburst *Chandra* data is evident.

4. DISCUSSION

The X-ray properties of the 2005 outburst of the EXor-type star V1118 Ori are remarkable in view of its temperature change, which was not immediate but occurred a few months after the onset of the outburst in the optical and near-infrared regimes. Furthermore, the X-ray flux and luminosity of V1118 Ori varied by only a factor of 2 during the outburst and compared to the serendipitous observation in 2002. The fluxes in the optical and near-infrared varied more significantly, within factors of 2–10 (see Fig. 1). The hydrogen column density stayed relatively low, $N_H \sim (1–5) \times 10^{21}$ cm^{-2}, throughout the observations, giving no indication for additional absorption during the outburst.

The disappearance of the hot plasma component, replaced by a dominant cool plasma in 2005 February and March, is intriguing. There was no evidence that the high temperatures observed in 2002 and 2005 January were due to flares. First, the X-ray light curves showed no evidence for flares. Second, flares in magnetically active stars are accompanied by increases in both flux and luminosity. However, the X-ray fluxes, e.g., in 2002 [$F_X \sim (3.4 \pm 0.3) \times 10^{-14}$ ergs cm^{-2} s^{-1}] and in February 2005 ($F_X \sim 2.9^{+0.2}_{-0.3} \times 10^{-14}$ ergs cm^{-2} s^{-1}), are similar. In addition, the X-ray luminosity in 2005 February is about twice as large as the X-ray luminosity in 2002. Thus, it is plausible that the dramatically increased accretion rate onto the star is responsible, directly or indirectly, for the change in the plasma temperature.

When the accretion disk closed in near the star due to the increase in mass accretion rate, as suggested by models for accreting binaries (Elsner & Lamb 1977; Ghosh & Lamb 1979), it plausibly disrupted the magnetosphere. Using the scaling laws of Rosner et al. (1978), the height of a magnetic loop, h, is related to the temperature at its apex (most of the emission measure [EM] in a loop has a similar temperature) and the average electron density, n_e in units of cm^{-3}, as $h = 8.41 \times 10^5 T^2/n_e$ in units of cm. If the loops have a density n_e of 10^{10} cm^{-3}, as is consistent with the densities observed in magnetically active stars (Ness et al. 2004), we get loop heights of 5×10^{10} cm for $T = 25$ MK, i.e., of the order of the stellar radius (8.6×10^{10} cm). In contrast, cooler loops (e.g., 8 MK) have 10 times smaller heights, i.e., they are smaller than the stellar radius and thus compact compared to the dimensions of the accretion disk; thus, when the accretion disk grows inward due to an increased mass accretion rate, the hotter loops interact first with the accreting matter and are likely to be disrupted. A new magnetic configuration then may have led preferentially to compact cool loops, thus enhancing the EM of the previously undetected cool coronal component.

The above properties contrast with those of another erupting young star, V1647 Ori, which displayed a strong X-ray flux increase coincident with the optical/near-infrared outburst (Kastner et al. 2004). In addition, V1647 Ori displayed a high N_{H} ($\sim 4 \times 10^{22}$ cm^{-2}), which was interpreted as an indication for a dense disk wind (Grosso et al. 2005). A cool component was detected together with the hot component in V1647 Ori, but Grosso et al. (2005) interpreted the former component as accretion shocks onto the stellar photosphere. It is unlikely that the cool component in V1118 Ori originates from shocks because free-fall velocities of matter falling from the truncation radius are too slow. Even if X-rays would be generated in shocks, they would likely be too absorbed to be detected (Drake 2005).

The V1118 Ori observations suggest that the enhanced mass accretion rate during its outburst likely had an indirect impact on the star's X-ray emission. Long-term multiwavelength monitoring will provide important clues to understanding the importance of accretion in the X-ray emission in highly accreting young stars.

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