X-RAY VIEW OF V1647 ORI, THE YOUNG STAR IN OUTBURST ILLUMINATING MCNEIL'S NEBULA

N. Grosso

Laboratoire d'Astrophysique de Grenoble, Université Joseph-Fourier, 38041 Grenoble, France

ABSTRACT

McNeil's Nebula was discovered serendipitously in January 2004 in the L1630 dark cloud located in the Orion B giant molecular cloud. This reflection nebula is illuminated by V1647 Ori, a young stellar object displaying since November 2003 a dramatic optical/IR outburst, which is the origin of the rise of this fan-shaped nebula. Until recently, no X-ray satellites have had the opportunity to observe this kind of pre-main sequence eruptive object at the beginning of its accretion burst. In this respect the X-ray observations of V1647 Ori obtained in 2004 with *Chandra* (Kastner et al. 2004) and *XMM-Newton* (Grosso et al. 2005) offer new insight into pre-main sequence accretion processes. I will review these X-ray observations, which reveal a large increase of the X-ray emission compared to the pre-outburst state, and an enhanced X-ray variability. The analysis of the *XMM-Newton* spectra shows that about 75% of the intrinsic X-ray emission in the 0.5–8 keV energy band comes from a soft plasma component, reminiscent of the X-ray spectrum of the classical T Tauri star TW Hya, for which X-ray emission is believed to be generated by an accretion shock onto the photosphere of a low-mass star. The hard plasma component contributes about 25% of the total X-ray emission, and can be understood only in the framework of plasma heating sustained by magnetic reconnection events. A significant excess of Hydrogen column density is found compared to the value derived from optical/IR observations, suggesting either that there is a real excess of gas column density –which might due to an intervening outflow unveiled from ground optical spectroscopy– or that optical/IR observations do not probe the extinction down to the star itself. I will present preliminary results of the *XMM-Newton* observation of V1647 Ori obtained in March 2005.

Key words: V1647 Ori; pre-main sequence stars; X-rays.

1. INTRODUCTION

At the end of January 2004, a new bright fan-shaped nebula was discovered serendipitously (McNeil 2004) between M 78/NGC 2068 and the region of HH 24-26, two well known star-forming regions of the L1630 dark cloud located in the northern part of the Orion B giant molecular cloud, at a distance of ∼400 pc. The apex of McNeil's Nebula hosts the young low-mass star V1647 Ori (Clark 1991; Samus 2004), which is now displaying a dramatic optical/IR outburst at the origin of the rise of this reflection nebula. Briceño et al. (2004) have constrained the start of this outburst at the beginning of November 2003, and have obtained the light curve in the I-band of V1647 Ori showing a ∼5 mag brightening in about 4 months. They showed that the timescale for the nebula to develop is consistent with the light-travel time, indicating that we are observing light from the central source scattered by material in the cometary nebula.

The nature of the V1647 Ori outburst and its connection with other pre-main sequence eruptive objects, namely FUors (stellar prototype: FU Ori) and EXors (stellar prototype: EX Lupi), is still debated at the moment. Reipurth & Aspin (2004) and McGehee et al. (2004), have noted a resemblance to EXors; whereas Briceño et al. (2004), Ábrahám et al. (2004), Walter et al. (2004), and Kun et al. (2004) have proposed a FUor event. Vacca et al. (2004) have even reported that the NIR spectrum of V1647 Ori does not appear similar to any known FUor or EXor object. Continued optical/IR monitoring are necessary to determine the duration of the outburst, because outbursts last only several months in EXors compared to several decades in FUors. Both types of outburst are thought to be driven by a sudden increase of accretion through a circumstellar disk (e.g., Hartmann & Kenyon 1996, and references therein), but the distinction between FUors and EXors is still entirely empirical. The interpretation that the outburst event has its origin in accretion processes is supported by high-resolution IR spectra of V1647 Ori showing CO emission lines, likely originating from ~ 2500 K gas in an inner accretion disk region where substantial clearing of dust has occurred (Rettig et al. 2005).

The pre-outburst spectral energy distribution (SED) of V1647 Ori from IR to millimeter shows a 'flat spectrum' source (Ábrahám et al. 2004), which is usually interpreted in terms of a circumstellar envelope (Kenyon & Hartmann 1991). Andrews et al. (2004) propose that

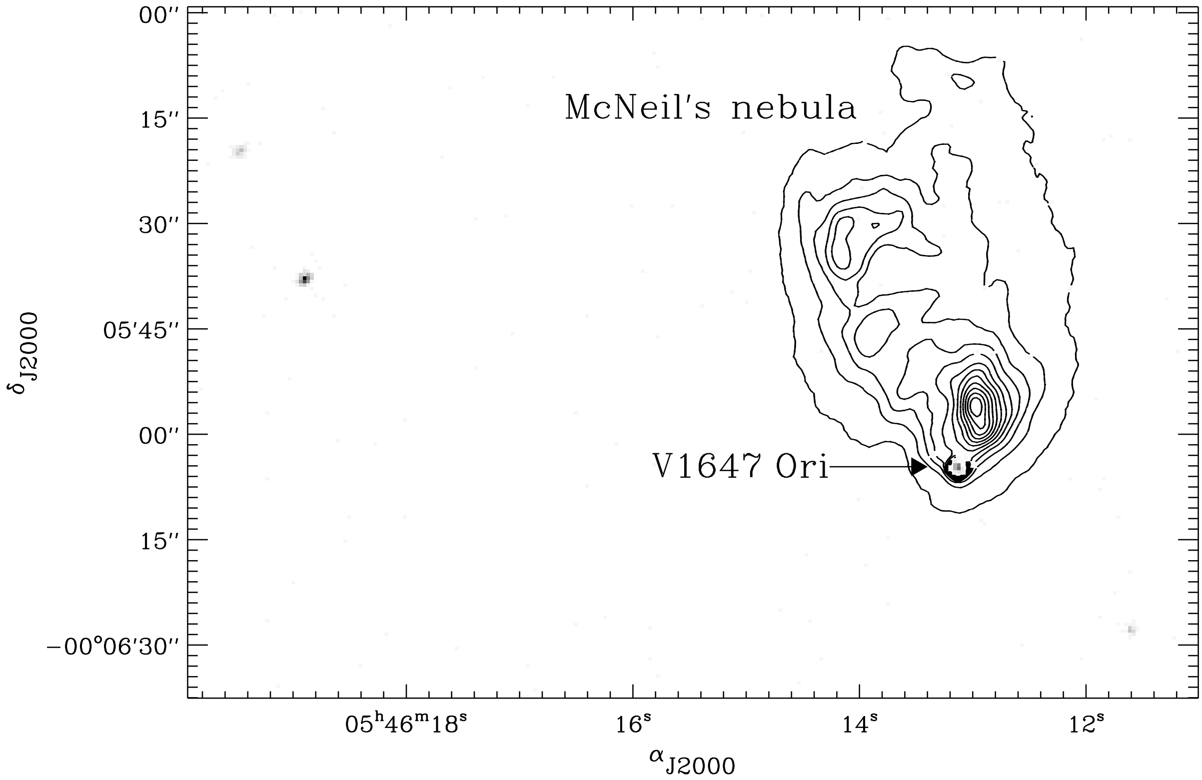

Figure 1. Chandra observation of V1647 Ori obtained on 2004 March 7 (adapted from Kastner et al. 2004). For comparison a R-band contour map of McNeil's nebula obtained with VLT/FORS2 on 2004 February 18 is overlaid. The energy range of the X-ray image is 0.5–8 keV; the pixel size is $0.5'' \times 0.5''$. The X-ray intensity is displayed with a linear scale. A hard X-ray source was detected at the position of V1647 Ori.

V1647 Ori is a transition object between a protostar with circumstellar disk plus remnant circumstellar envelope (Class I protostar), and a classical T Tauri star with circumstellar disk (Class II sources). *Spitzer* observations of V1647 Ori in early March 2004 (Muzerolle et al. 2005) show a factor of 15–20 increase in brightness across the spectrum from the optical to 70 μm, leading to a bolometric luminosity of $44\,L_\odot$, i.e. $\sim$15 times higher than the pre-outburst level, which is mainly explained by an increase of the disk accretion rate from 6×10^{-7} to $10^{-5}\,M_\odot\,yr^{-1}$.

2. X-RAY OBSERVATIONS OF V1647 ORI

Prior to this accretion outburst, V1647 Ori was serendipitously observed with *Chandra* and *XMM-Newton*. In November 2002, it was a faint X-ray source in a *Chandra/ACIS-S* $\sim$56 ks-exposure, and was not detected with a *XMM-Newton* $\sim$50 ks-exposure in September 2003, just before the beginning of the outburst. The discovery of McNeil's nebula triggered Director Discretionary Time (DDT) and Target of Opportunity (ToO) observations of V1647 Ori with *Chandra* (2×5 ks; J. Kastner, PI) and *XMM-Newton* ($\sim$38 ks; N. Grosso, PI), respectively.

2.1. *Chandra* and *XMM-Newton* observations in 2004

The first X-ray observation of V1647 Ori during this accretion outburst was obtained on 2004 March 7 with *Chandra/ACIS-S* with a 5 ks exposure. Fig. 1 shows the *Chandra* image with an embedded hard X-ray source detected at the apex of McNeil's nebula. This observation revealed a factor $\sim$50 increase in the X-ray count rate of this source, compared to the pre-outburst state (Fig. 2). On 2004 March 22, an additional 5 ks exposure with *Chandra/ACIS-S* showed that the X-ray flux remained elevated, but at a count rate only a factor $\sim$10 larger than pre-outburst (Fig. 2).

The coincidence of a surge in X-ray brightness with the optical/IR outburst demonstrates that strongly enhanced high energy emission from V1647 Ori occurs as a consequence of high accretion rates (Kastner et al. 2004). The drop of the X-ray flux on 2004 March 22 was interpreted by Kastner et al. (2004) as the possible onset of a quenching X-ray emission phase, or the triggering of a phase of strong variability in both X-ray luminosity and temperature. The burst of X-rays was most probably generated via star-disk magnetic reconnection events that occurred in conjunction with such mass infall.

This process may also launch new, collimated outflows or jets (Goodson et al. 1997). Indeed, before its recent

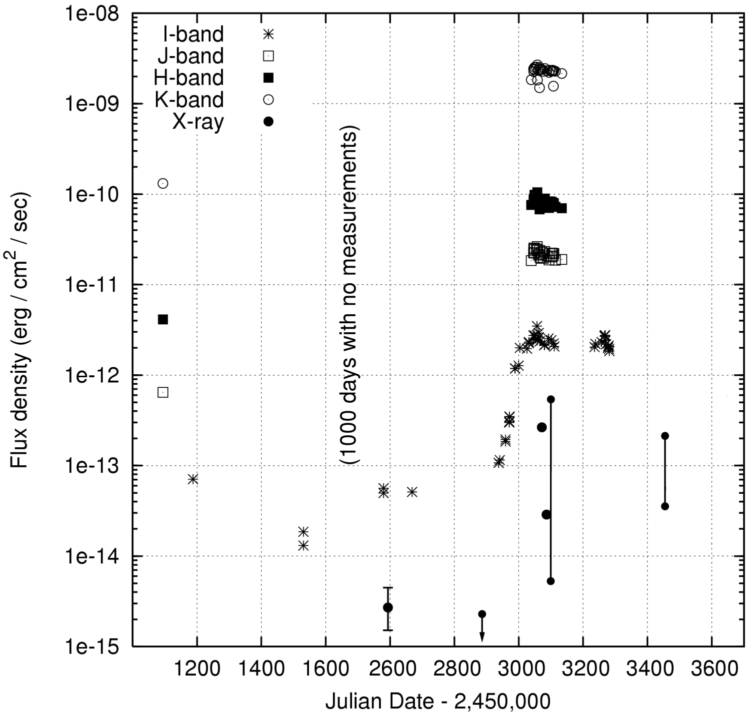

Figure 2. Near-IR and X-ray photometry of V1647 Ori from late 1998 through to April 2005 (adapted from Kastner et al. 2004; Grosso et al. 2005). The optical/IR outburst of this 'flat spectrum' source is mainly explained by an increase of the disk accretion rate from $\sim 6\times10^{-7}$ to $\sim 10^{-5}\,M_\odot\,yr^{-1}$ (Muzerolle et al. 2005). Prior to this accretion outburst, V1647 Ori was serendipitously observed with Chandra and XMM-Newton. It was a faint X-ray source in a November 2002 Chandra observation, and was not detected by XMM-Newton in September 2003, just before the beginning of the outburst. In March 2004, we were granted Chandra Director Discretionary Time (2×5 ks; J. Kastner, PI), and detected a large increase in X-ray flux post-outburst relative to pre-outburst, closely tracking the increase of the optical/IR flux (Kastner et al. 2004). A 38 ks XMM-Newton Target of Opportunity observation was then obtained in April 2004 (N. Grosso, PI; Grosso et al. 2005). In March 2005, a longer (94 ks) XMM-Newton observation was obtained (N. Grosso, PI). The ranges of X-ray flux density observed with XMM-Newton are represented by segments (see Fig. 3 and 4).

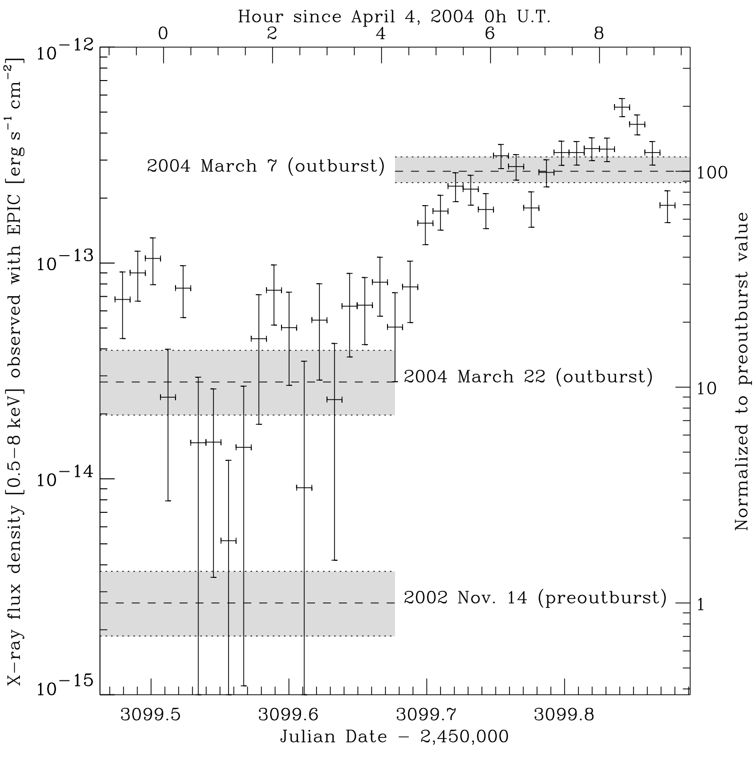

Figure 3. Enhanced X-ray variability of V1647 Ori (Grosso et al. 2005). The light curve shows the X-ray flux density observed with XMM-Newton on 2004 April 4, compared with Chandra measurements. The X-ray flux is highly volatile, varying from 10 to 200 times the pre-outburst value. Assuming a periodicity, the folding of Chandra and XMM-Newton measurements lead to a period candidate of $\sim$17 hours, which corresponds to the Keplerian rotation at a distance of 1.4 stellar radius for a one solar mass star aged of 1 Myrs. We propose that the observed X-ray flux is modulated by the Keplerian rotation of the inner part of the V1647 Ori accretion disk.

eruption, V1647 Ori had been identified as the exciting source of a chain of extended emission nebulosity that appears to terminate at HH 23, a shock-excited Herbig-Haro object, located $\sim 3'$ North from V1647 Ori (Eislöffel & Mundt 1997; Lis et al. 1999; Reipurth & Aspin 2004). The presence of these structures suggests that the present optical/IR/X-ray outburst of V1647 Ori may be merely the latest of a series of such events. Another outburst may have occurred about 37 yrs before the present event, based on a photograph obtained in Oct. 1966 which shows a similar cometary nebula (Mallas & Kreimer 1978). No clear evidence for the presence of a molecular outflow has been found in the submillimeter CO spectral line maps (Lis et al. 1999; Andrews et al. 2004). However the Hα line, which has been detected in strong emission, displays a pronounced P Cygni profile, with an absorption trough reaching velocities up to 600 km s^{-1} (Reipurth & Aspin 2004), implying significant mass loss in a powerful wind.

The *Chandra* detection of V1647 Ori in a high X-ray state triggered a ~38 ks *XMM-Newton* ToO. V1647 Ori was detected with *XMM-Newton* on 2004 April 4 (Grosso et al. 2005). The X-ray spectral fitting of the EPIC spectra shows that the bulk ($\sim 75\%$) of the intrinsic X-ray emission in the 0.5–8 keV energy band comes from a soft plasma component, with $kT_{\rm soft} = 0.9$ keV (0.7–1.1 keV, at the 90% confidence limit), reminiscent of the X-ray spectrum of Classical T Tauri star TW Hya (Kastner et al. 2002), where it is believed to be generated by an accretion shock onto the photosphere of a low-mass star. The hard plasma component, with $kT_{\rm hard} = 4.2$ keV (3.0–6.5 keV), contributes for $\sim 25\%$ of the total X-ray emission, and can be understood only in the framework of plasma heating sustained by magnetic reconnection.

The accurate measurement of the Hydrogen column density, $N_{\rm H} = 4.1 \times 10^{22}\,{\rm cm}^{-2}$ (3.5–4.7 $\times 10^{22}\,{\rm cm}^{-2}$), which is equivalent to $A_{\rm V}$=22.3–29.6 or 18.8–25.0 mag taking $R_{\rm V}$=3.1 or 5.5. By contrast optical/IR ground measurements lead to only $A_{\rm V} \sim 11$ mag (e.g., Vacca et al. 2004). This comparison suggests either that there is a real excess of gas column density –which might due to an intervening outflow unveiled from ground optical spectroscopy (Reipurth & Aspin 2004)– or that optical/IR observations do not probe the extinction down to the star itself.

The X-ray flux observed with *XMM-Newton* (see Fig. 3) ranges from roughly the flux observed by *Chandra* on 2004 March 22 (i.e., ~10 times greater than the pre-outburst X-ray flux), to a peak value that is two times greater than the one caught by *Chandra* on 2004 March 7 (i.e., ~200 times greater than the pre-outburst X-ray flux). We have investigated with X-ray color-color diagram and quantile analysis (Hong et al. 2004) time variations of the event energy distribution, but the observed count rate variations are not correlated with either temperature variations (as in X-ray flares) or column density variations, which is in favour of a variation of the observed emission measure. The combined analysis of the *Chandra* and *XMM-Newton* observed X-ray flux densities folded using trial periods indicate a good candidate at ~17 hours, which corresponds to time scale of Keplerian rotation at a distance of 1 and 1.4 stellar radius for a one solar mass star aged of 0.5 and 1 Myrs, respectively. We propose that the observed X-ray flux from V1647 Ori is indeed modulated by the Keplerian rotation of the inner part of the accretion disk.

To test this interpretation a longer *XMM-Newton* observation, needed to cover ~2 times the period candidate (130 ks), was obtained on 2005 (N. Grosso, PI).

2.2. Preliminary results of the *XMM-Newton* observation in 2005

XMM-Newton observed V1647 Ori on 2005 March 25. EPIC camera exposures had to be aborted before their scheduled end times, due to the increase of the flaring background. The duration of the EPIC PN exposure was ~107 ks. However the end of this observation was strongly affected by the elevated level of the flaring background, where the EPIC PN was nearly all the time in the counting mode, which reduced the useful exposure to only ~94 ks. Nevertheless, this continuous exposure of ~94 ks allows to cover ~1.5 times the period candidate.

Fig. 4 shows for comparison the X-ray light curves of V1647 Ori obtained with *XMM-Newton* on April 2004 (Grosso et al. 2005) and 2005 March 25 (Grosso et al., in preparation). V1647 Ori is weaker in X-rays on March 2005, which seems to coincide with a possible decay phase of V1647 Ori in the optical/IR (Aspin & Reipurth 2005). V1647 Ori is still variable in X-rays (see also Fig. 2). However, the variability is inconsistent with a periodicity of ~17 hours.

The bottom panels of Fig. 4 show the X-ray hardness ratios versus time. The X-rays emitted by V1647 Ori are harder in March 2005 than in April 2004.

The detailed analysis of the 2005 *XMM-Newton* data set using X-ray color-color diagram and quantile analysis, and spectral analysis, are in progress to constrain the nature of the observed X-ray variability of V1647 Ori and the origin of the hardening of its X-ray emission.

3. CONCLUSION

The sudden increase in the X-ray luminosity of V1647 Ori, and its large variation, appear to be best explained as due to star-disk magnetic reconnection events that are generated in association with the onset of elevated accretion rate.

The optical/IR flux of V1647 Ori is dominated by the outburst luminosity of its inner accretion disk, therefore any optical/IR modulation of the photospheric flux would be difficult if not impossible to observe. Therefore, X-rays

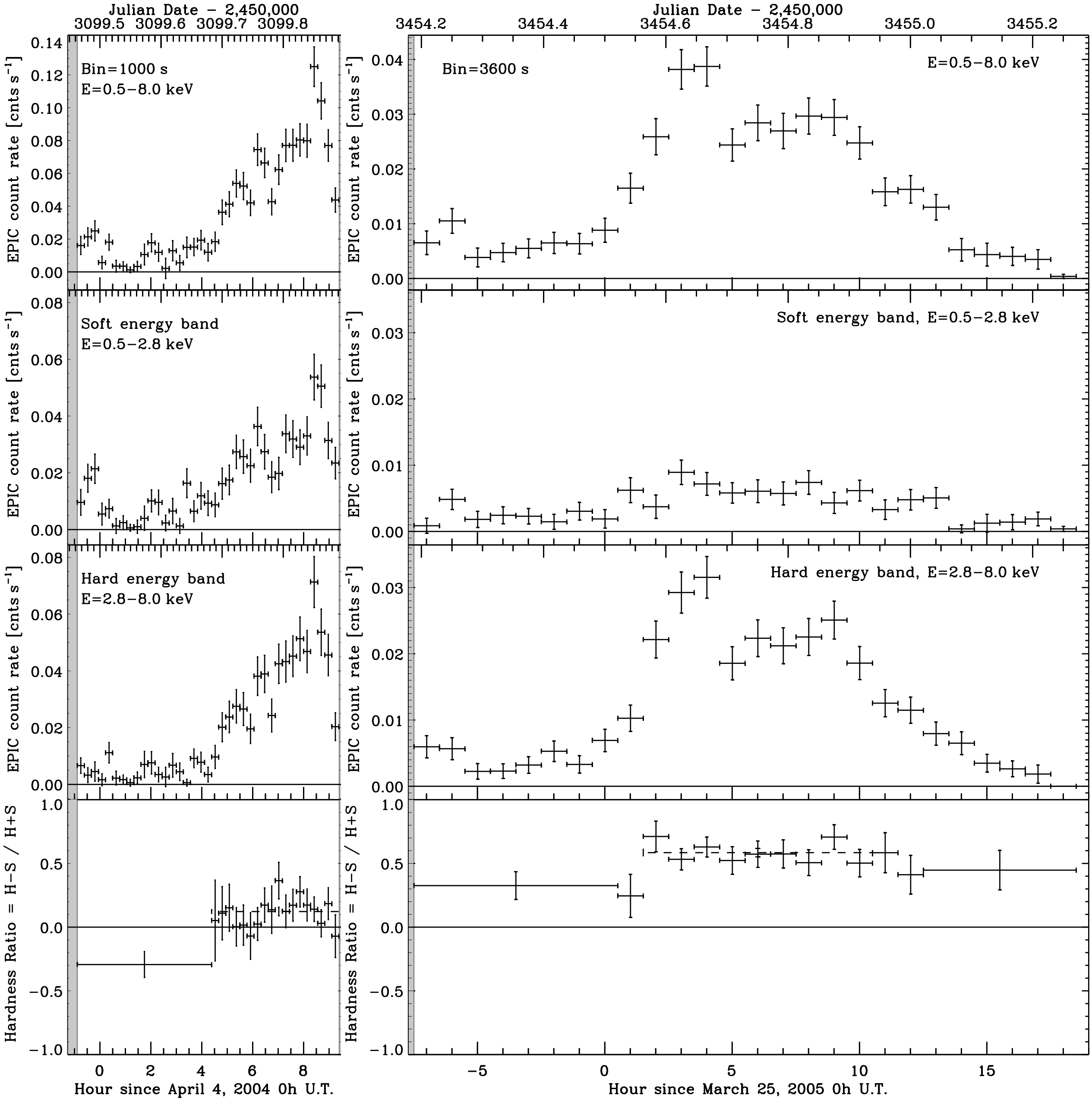

Figure 4. X-ray light curves of V1647 Ori obtained with XMM-Newton on April 2004 (Grosso et al. 2005) and March 2005 (Grosso et al., in preparation) plotted using the same scale for the time axis. The large increase of count rate during the 2004 observation was not associated with any large plasma temperature variations as for typical X-ray flares from young low-mass stars. The lack of such large temperature variations motivated the hypothesis that the potential ∼17-hour periodicity resulted from rotational modulation of the inner accretion disk. During the 2005 observation the X-ray source is weaker, but still variable. However, the variability is inconsistent with a periodicity of ∼17 hours. The nature of the variability is under investigation. The bottom panels show the X-ray hardness ratios computed with the soft energy band 0.5–2.8 keV and the hard energy band 2.8–8 keV. Dashed lines show hardness ratios averaged on larger time intervals. There is a hardening of the X-rays emitted by V1647 Ori in March 2005.

offer a unique observational window to investigate the star-disk magnetic interaction during this pre-main sequence evolutionary phase in which the accretion rate, and hence the source luminosity, are dramatically elevated above normal.

Additional *Chandra* observations of 3×20 ks exposure are also scheduled on 2005 and 2006 (J. Kastner, PI) to monitor the X-ray activity during the decay phase of V1647 Ori.

REFERENCES

Ábrahám, P., Kóspál, Á., Csizmadia, S., et al. 2004, A&A, 419, L39

Andrews, S. M., Rothberg, B., & Simon, T. 2004, ApJ, 610, L45

Aspin, C. & Reipurth, B. 2005, IAU Circ., 8600, 2

Briceño, C., Vivas, A. K., Hernández, J., et al. 2004, ApJ, 606, L123

Clark, F. O. 1991, ApJS, 75, 611

Eislöffel, J. & Mundt, R. 1997, AJ, 114, 280

Goodson, A. P., Winglee, R. M., & Boehm, K.-H. 1997, ApJ, 489, 199

Grosso, N., Kastner, J. H., Ozawa, H., et al. 2005, A&A, 438, 159

Hartmann, L. & Kenyon, S. J. 1996, ARA&A, 34, 207

Hong, J., Schlegel, E. M., & Grindlay, J. E. 2004, ApJ, 614, 508

Kastner, J. H., Huenemoerder, D. P., Schulz, N. S., Canizares, C. R., & Weintraub, D. A. 2002, ApJ, 567, 434

Kastner, J. H., Richmond, M., Grosso, N., et al. 2004, Nature, 430, 429

Kenyon, S. J. & Hartmann, L. W. 1991, ApJ, 383, 664

Kun, M., Acosta-Pulido, J. A., Moór, A., et al. 2004, arXiv:astro-ph/0408432

Lis, D. C., Menten, K. M., & Zylka, R. 1999, ApJ, 527, 856

Mallas, J. H. & Kreimer, E. 1978, The Messier album (Cambridge, Mass.: Sky Publication Co., 1978)

McGehee, P. M., Smith, J. A., Henden, A. A., et al. 2004, ApJ, 616, 1058

McNeil, J. W. 2004, IAU Circ., 8284, 1

Muzerolle, J., Megeath, S. T., Flaherty, K. M., et al. 2005, ApJ, 620, L107

Reipurth, B. & Aspin, C. 2004, ApJ, 606, L119

Rettig, T. W., Brittain, S. D., Gibb, E. L., Simon, T., & Kulesa, C. 2005, ApJ, 626, 245

Samus, N. N. 2004, IAU Circ., 8354, 1

Vacca, W. D., Cushing, M. C., & Simon, T. 2004, ApJ, 609, L29

Walter, F. M., Stringfellow, G. S., Sherry, W. H., & Field-Pollatou, A. 2004, AJ, 128, 1872