X-ray and Infrared Observations of the IC 5146 Dark Cloud and the FU Orionis Star Elias 1-12

Steve Skinner[1], Kimberly Sokal[1], Manuel Güdel[2], Kevin Briggs[2]

[1]CASA, Univ. of Colorado, Boulder, CO, USA (skinners@casa.colorado.edu)
[2]ETH, Institute of Astronomy, Zürich, Switzerland

Abstract

The bright B1V star BD $+46^\circ$3474 illuminates the Cocoon Nebula (IC 5146). Studies of this spectacular nebula have a long historical record dating back to Espin (1900). More recent work has uncovered at least one hundred faint T Tauri stars clustered around BD $+46^\circ$3474 with a median age of $\sim$1 Myr. Extending more than 2° westward from BD $+46^\circ$3474 is a region of high obscuration known as the IC 5146 dark cloud. *Spitzer* has revealed more than 100 YSOs with IR excesses in the cloud, and submillimeter studies have detected dense cores that may be prestellar. We present results of an XMM-Newton X-ray observation of the dark cloud centered on the young accreting FU Ori-type star Elias 1-12 (= V1735 Cyg). Its X-ray emission is much harder than expected for an accretion shock and other processes besides accretion must underlie its X-ray production. Archived *Spitzer* images show that a hard X-ray source lying $24''$ northeast of Elias 1-12 is associated with a class I protostar.

1 Overview: The IC 5146 Region

- IC 5146 originally referred to the bright nebulosity surrounding the B1V star BD $+46^\circ$3474 (Espin 1900). Common name: Cocoon nebula (Fig. 1-right). Distance estimates are 1200 pc (Herbig & Dahm 2002 = HD02) and 950 pc (Harvey et al. 2008 = Ha08).
- More than 100 faint T Tauri stars were found near BD $+46^\circ$3474 by Walker (1959) and HD02.
- Dark filamentary structure extending westward of the nebula (Fig. 1-left) is known as the IC 5146 dark cloud. Dense prestellar sub-mm cores have been detected in the filaments (Kramer et al. 2003). Ground-based near-IR studies reveal heavily-extincted ($A_v \sim$ 20 - 50 mag) young stars (Lada et al. 1999). *Spitzer* has uncovered $>$100 YSOs with IR excesses, including 29 class I sources (Ha08).
- Elias (1978) discovered that the star Elias 1-12 (= V1735 Cyg) lying $\approx 1^\circ$ west of BD $+46^\circ$3474 brightened by $\approx$5 mag between 1952 and 1965. He classified it as an FU Orionis star ("FUor"). FUors undergo powerful optical outbursts that are thought to be linked to dramatic increases in the accretion rate ($\dot{M}_{acc} \sim 10^{-5}$ $M_\odot$ yr^{-1}).

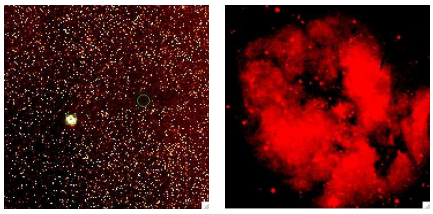

FIGURE 1: A Digitized Sky Survey (DSS) image of the IC 5146 region (filter centered at 5000 Å). N is up, E is left. *Left*: $\approx$2.9 $\times$ 2.9 deg. image of the region. The green circle in the dark cloud filament marks the position of V1735 Cyg and the green box encloses BD $+46^\circ$3474 and the Cocoon nebula (zoomed at right). *Right*: The Cocoon nebula ($\approx 8.5' \times 8.5'$).

2 X-ray Observations

- *XMM-Newton* observed IC 5146 in July 2006, with pointing centered on V1735 Cyg (= Elias 1-12). This observation was part of a broader program aimed at determining whether FU Orionis stars are X-ray sources and identifying possible emission mechanisms (e.g. magnetic coronae, accretion or outflow shocks).
- *XMM* has 3 cameras (PN, MOS1, MOS2), a $30'$ diam. field of view, $\approx 4.3''$ FWHM angular resolution, $\approx$0.3 - 10 keV energy coverage.
- The $\sim$31 ksec *XMM* exposure detected 72 sources, including V1735 Cyg (= Elias 1-12).

3 X-ray and Infrared Images

- Fig. 2 shows the *XMM* MOS image of the region near Elias 1-12 (= V1735 Cyg). Fig. 3 is a *2MASS* K-band image with X-ray source positions overlaid.
- An X-ray source is present at an offset of $0.''9$ from the *HST* GSC position of V1735 Cyg. This offset is within *XMM* position uncertainties, making V1735 Cyg the most likely counterpart.
- A second X-ray source (SM1-X) is detected $24''$ NE of V1735 Cyg. SM1-X lies $3.5''$ west of the JCMT sub-mm source SM1 discovered by Sandell & Weintraub (2001 = SW01). See Fig. 3. SM1-X is coincident with a known class I protostar (Fig. 4; Sec. 5).

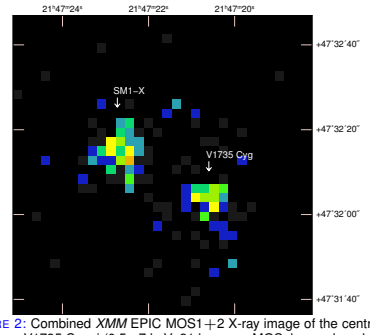

FIGURE 2: Combined *XMM* EPIC MOS1+2 X-ray image of the central region near V1735 Cygni (0.5 - 7 keV; 31 ksec per MOS; log scale; rebinned to $2.2''$ pixels; J2000 coords.).

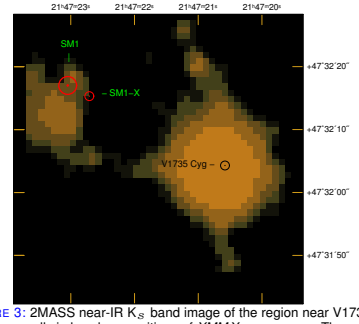

FIGURE 3: 2MASS near-IR K_s band image of the region near V1735 Cyg. The two small circles show positions of *XMM* X-ray sources. The cross enclosed by a circle shows the JCMT position of the bright sub-mm source SM1 (SW01). The radii of the circles correspond to the approximate positional accuracies ($\approx 1''$ *XMM*; $\approx 2''$ JCMT sub-mm).

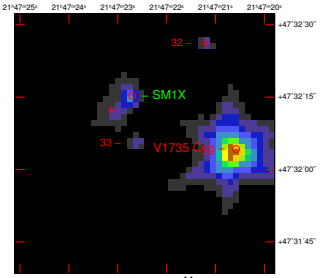

FIGURE 4: Spitzer IRAC ch1 image ($1.2''$ pixels). Circles mark the X-ray positions of V1735 Cyg and SM1-X, corresponding to *Spitzer* sources 31 and 34 (Ha08). Crosses mark 2MASS source positions. Class I *Spitzer* sources 32 and 33 (Ha08) were undetected by *XMM*.

4 Elias 1-12 (V1735 Cyg)

- Spectral fits of the X-ray spectrum of V1735 Cyg (Fig. 5) require high-temperature plasma at kT $>$ 5 keV, similar to the hot plasma detected in FU Ori (Skinner et al. 2006). Cooler plasma (kT $<$ 1 keV) is also detected in FU Ori (Fig. 5), but the detection of any cool plasma in V1735 Cyg is hindered by high absorption ($A_v \approx$ 10 mag; Elias 1978).
- The hot plasma in V1735 Cyg and FU Ori is not consistent with accretion shocks, for which cooler plasma (kT $<$ 1 keV) is expected. Magnetically-confined plasma is a more likely explanation.

5 The SM1 Region

- SM1-X is coincident with a class I protostar visible in *Spitzer* IRAC (Fig. 4) and MIPS images. It is not visible in the optical or in 2MASS (Fig. 3).
- SM1-X shows low-level X-ray variability, but no large flares. Its X-ray spectrum is hard and heavily-absorbed (Fig. 5). An Fe K emission line is detected at 6.7 keV, indicative of high-temperature plasma (T $\sim$ 40 MK). Spectral fits give kT $\sim$ 6 keV and a column density log $N_H \sim 22.9$ cm^{-2}, or $A_v \sim$ 36 mag.
- The X-ray spectrum of the class I source SM1-X is strikingly similar to that of FU Ori (Fig. 5), suggesting a possible link between class I protostars and FUors.

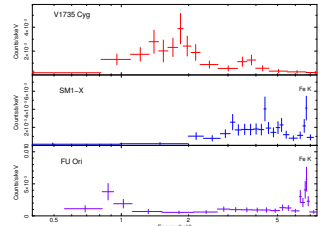

FIGURE 5: XMM PN spectra of the FUors V1735 Cyg (= Elias 1-12) and FU Ori, and the class I protostar SM1-X.

6 Summary and Open Questions

- Our survey has yielded the first X-ray detections of FU Orionis stars. The hot plasma (kT $>$ 5 keV) detected in Elias 1-12 (= V1735 Cyg) and FU Ori is indicative of magnetic processes. Cooler plasma (kT $<$ 1 keV) that *may* be shock-related is also seen in FU Ori.
- The class I protostar SM1-X near V1735 Cyg shows hard heavily-absorbed ($A_v \sim$ 36 mag) X-ray emission with low-level variability (but no flares). These properties are usually associated with magnetic activity. Magnetic processes are already at work in the early class I evolutionary stage.
- Open Questions: The X-ray spectra of FU Orionis and SM1-X show strong similarities. Is there a link between FUors and class I protostars? Class I protostars show magnetically-related X-ray behavior. How are the B-fields produced? Primordial? Two other FUors in our X-ray survey (V1057 Cyg, V1515 Cyg) were undetected with upper limits on L_x that are $\sim$10 $\times$ below FU Ori and V1735 Cyg. Why are some FUors X-ray sources, but others apparently not?

References & Acknowledgment

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This work was supported by NASA/GSFC grant NNX06AE93G.