Intense X-Ray emission from an Embedded Infrared Protostar in the ρ Ophiuchi Cloud

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Abstract. We report X-ray observations with the ROSAT High Resolution Imager (HRI) of one of the nearest star-forming regions – the ρ Ophiuchi cloud – that clearly show an intense X-ray flare associated with a deeply embedded protostar. The peak X-ray luminosity, after correcting for extinction, is $\geq$ 10–100 times the Sun's bolometric luminosity, and equals or exceeds the bolometric luminosity of the forming star. Taken together, the evidence suggests that the X-rays are not created by the type of magnetic activity seen on the Sun or on other young low-mass stars, but rather are associated with processes in the circumstellar accretion disk, or within the envelope.

1. Introduction

Class I protostars (Lada, 1987) are very young, low-mass stellar objects that are, according to current models, composite : they include a central star (still in the process of formation) surrounded by an accretion disk $\sim$ 10–100 AU in radius and embedded in an extended, infalling envelope of gas and dust up to $\sim 10^4$AU in size (Shu *et al.*, 1987). X-ray emission from such protostars has recently been reported (Casanova *et al.*, 1995; Koyama *et al.*, 1996), suggesting that X-ray ionization of gas and heating of dust could profoundly influence the physical and chemical properties of young stellar systems. But these observations did not have the resolution necessary to rule out a non-protostar origin for the emissions (see Fig. 1).

2. Observation

The positions of ρ Ophiuchi X-ray sources are shown in Fig. 1. Our observation of X-ray emission from the class I source YLW15 (Leous *et al.*,1991), also called IRS43, is shown in Fig. 2 and Fig. 3 (see the captions for details).

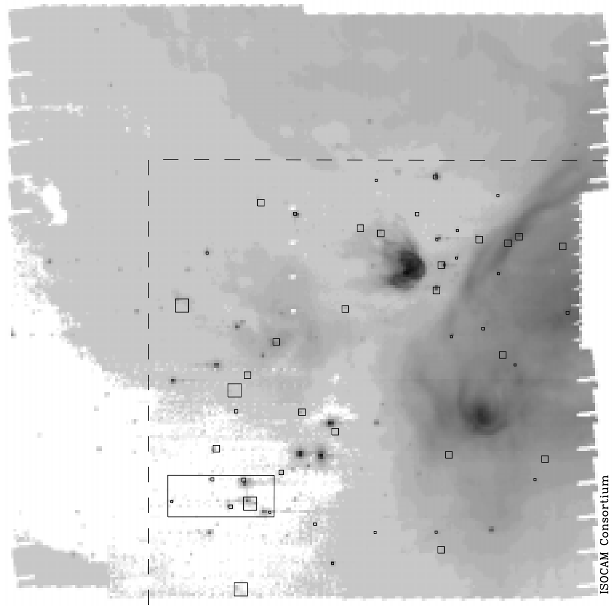

Figure 1. The ρ Ophiuchi molecular cloud seen with ISOCAM (Abergel *et al.*, 1996; Survey Nordh *et al.*, 1997). The dashed box shows the area of the ROSAT Position Sensitive Proportional Counter field studied by Casanova *et al.* (1995). The squared boxes show the error boxes of the X-ray sources detected in this area. The most of these X-ray sources are T Tauri (class II and III), few X-ray sources coincide with class I protostars, but possible faint non-protostellar counterparts are also found in the same error boxes. The rectangular box is the ROSAT HRI image zone enlarged in figure 2.

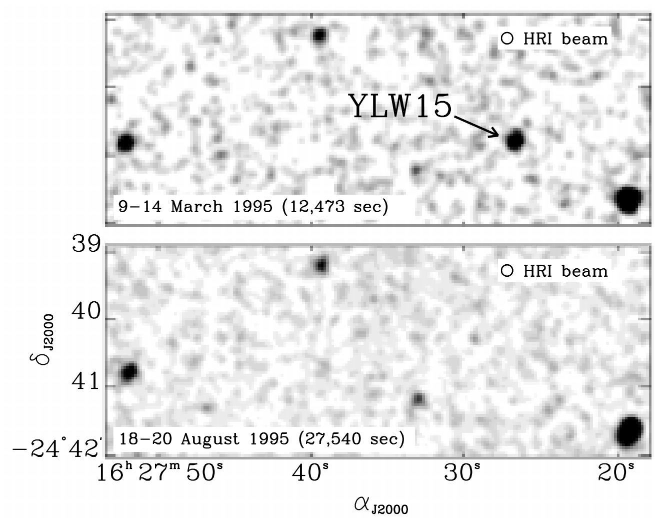

Figure 2. Detail of the ROSAT HRI X-ray images of the ρ Oph F Core. *Upper image* : first observing period between 9 and 14 March 1995 (12,473 sec). *Lower image* : second observing period between 18 and 20 August 1995 (27,540 sec). The two images are normalized to identical exposures (12,473 s). The variability of one source is clearly visible.This source is the class I YLW15 (for a further discussion on astrometry see Grosso *et al.*, 1997).

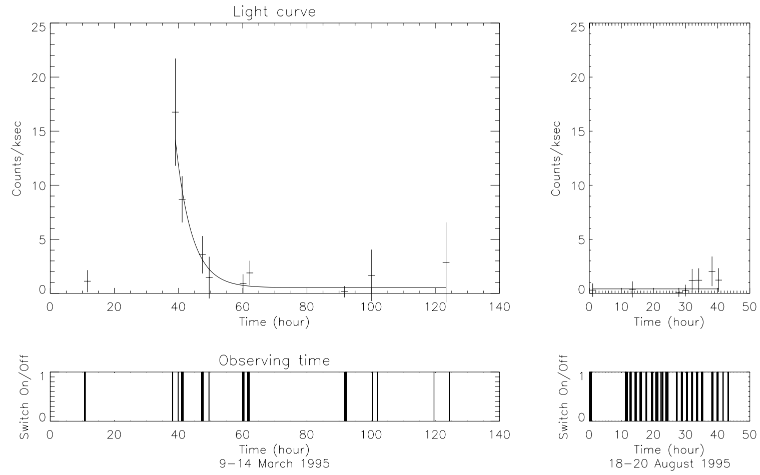

Figure 3. Light curve of YLW15 using 2-hour bins and one σ error bars. The 2-hour bin count rate was estimated from photon counts during the observing sessions (vertical bars in the lower panel).

We interpret such a time behaviour of the light curve as post-flare cooling of a hot plasma. The determination of the X-ray luminosity of the flare critically depends on the extinction suffered by the X-rays due to the circumstellar envelope and to the interstellar medium along the line-of-sight. Millimeter continuum observations indicate that YLW15 is surrounded by a relatively dense, compact dusty envelope, deeply embedded within, and smoothly blends into, the ρ Oph F dense core (Motte *et al.*, 1997). These measurements yield, for the envelope alone, a column density $N_{H,env} = 2 - 9 \times 10^{22}\mathrm{cm}^{-2}$ (depending on the details of the merging between the envelope and the dense core), and a visual absorption $A_{V,env} = 10 - 40$ (Ryter, 1996). They also suggest that YLW15 is embedded in a cloud core, so that the total extinction $A_{V,tot} = A_{V,env} + A_{V,cloud}$ must be higher by several magnitudes at least. An estimate of $A_{V,tot}$ may be derived from $A_{V,tot} \sim 12[(H-K) - (H-K)_0]$ (Wilking *et al.*, 1989), where $(H-K)_0$ is the uncertain intrinsic near-IR color index of the central protostar and circumstellar disk. We obtain $A_{V,tot} \simeq 44$ if $(H-K)_0 \simeq 0$ (no disk) and $A_{V,tot} \simeq 33$ if $(H-K)_0 \simeq 0.9$ (disk with flat spectrum). Another estimate of $A_{V,tot}$ can be obtained by modeling the near-IR portion of the SED as in Myers *et al.* (1987). Taking published values of $L_{bol,\star}$ $(10 L_\odot)$ and of J, H, K, L photometry (Wilking *et al.*, 1989), we find $A_{V,tot} > 31 \pm 2$. We conclude that $A_{V,tot}$ is very likely in the 20–40 magnitude range, with a best estimate $A_{V,tot} \sim 30$.

The Table 1 give the X-ray luminosities at the observed flare peak, assuming a magnetically confined plasma sphere and a Raymond-Smith spectrum, as a function of the estimated range of visual extinction. Because the HRI has no spectral resolution, we have to explore a wide range of temperatures $\mathbf{T}_X$. $\mathbf{L}_{X,HRI}^{app}$ is the apparent luminosity in the HRI bandwidth (0.1–2.4 keV), and $\mathbf{L}_{X,tot}$ is the total intrinsic luminosity, integrated over all X-ray energies after correction for bandwidth and extinction. These values are actually lower limits, since the flare maximum may have occurred before our observation (see Fig. 3). The remarkably high value of $L_{X,tot}/L_{bol,*}$ require a flare much more powerful and larger than seen in any stellar analogue of solar-type magnetic activity.

3. Conclusion

We are thus compelled to consider non-solar-type origins for the flare where the magnetic structure is connected to circumstellar components (the circumstellar accretion disk or within the envelope), or another protostar (protostellar binary system), with a mechanism of explosive release of energy stored in magnetic fields through reconnection. Our result show that large numbers of hard photons are likely to be present in the protostellar system, X-rays will efficiently photoionize the circumstellar envelopes and the protostellar accretion disk, and also affect their chemistry (Casanova *et al.*, 1995; Maloney *et al.*, 1996). Protostellar X-rays may regulate the rate of accretion from the disk onto the star (Glassgold *et al.*, 1997). The disk would also be bombarded by shocks and energetic protons associated with the X-ray flares. As the early Sun should have passed through the flaring Class I protostellar phase, the existence of such shocks, as well as X-ray and particle irradiation phenomena, may resolve several long-standing mysteries (isotopic anomalies, chondrule melting, excess particle irradiation) in ancient meteorites (e.g. Cameron, 1995; Lee *et al.*, 1997).

Table 1. X-ray luminosities of YLW15 at flare peak, as a function of the extinction

	$\mathbf{T}_X$ (10^7 K)	1	3	6	12
A_V=20	log $L^{app}_{X,HRI}$	31.3	31.5	31.5	31.5
	log $L_{X,tot}$	33.7	34.0	34.3	34.5
A_V=30	**log $L^{app}_{X,HRI}$**	**31.6**	**31.7**	**31.7**	**31.8**
	log $L_{X,tot}$	**34.6**	**35.1**	**35.2**	**35.5**
A_V=40	log $L^{app}_{X,HRI}$	31.8	32.0	32.0	32.0
	log $L_{X,tot}$	35.0	35.9	36.1	36.4

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