An X-Ray Superflare from an Embedded Protostar

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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. The behaviour and intensity of the flare can be modelled as arising from a magnetically confined, low-density plasma bubble $\sim$ 0.05–0.3 AU in diameter (much larger than the star itself), and the X-ray luminosity 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.

2. Observation

Using the ROSAT HRI (David *et al.*, 1996) we obtained a deep exposure of the ρ Oph F Core (see Fig. 1). This exposure was performed in two observations totalling 40,013 sec in the middle of a group of Class I sources.After astrometric correction one variable source (see Fig. 2, and Fig. 3) is found to be located only 1.2$''$ away from the Class I source YLW15, or IRS43 (Leous *et al.*,1991; Wilking *et al.*, 1989; Greene *et al.*, 1992; Strom *et al.*, 1995), and 6.7$''$ away from another IR source (for a further discussion on astrometry see Grosso *et al.*, 1997). The identification with YLW15 is thus very reliable, especially since this source lies almost at the center of the HRI field, where the best angular resolution and sensitivity are obtained.

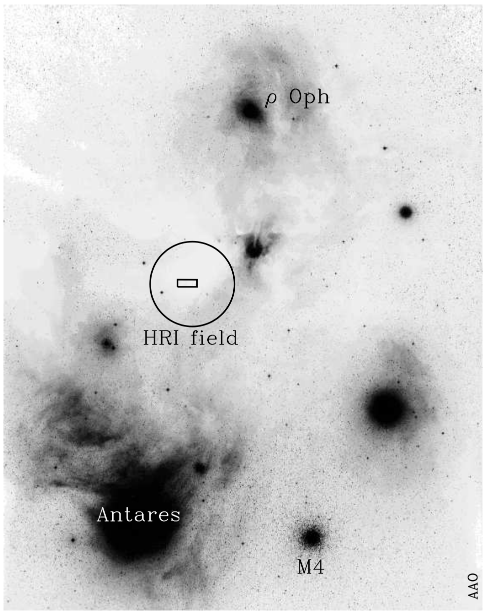

Fig. 1. Optical negative image of the ρ Ophiuchi molecular cloud. The ROSAT HRI observed area is shown (HRI field, 40 arc minute diameter). The rectangular box is the ROSAT HRI image zone enlarged in figure 2.

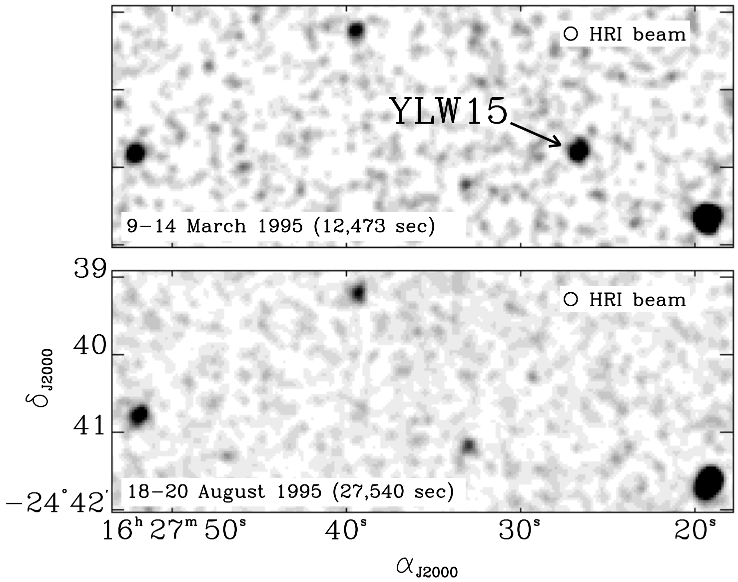

Fig. 2. Detail of the HRI X-ray images of the ρ Oph F Core. *Upper image* : first observing period between 9 and 14 March 1995 (12,473 sec). *Lower image* : second observing period between 18 and 20 August 1995 (27,540 sec). The two images are normalized to identical exposures (12,473 s). The variability of one source, YLW15, is clearly visible.

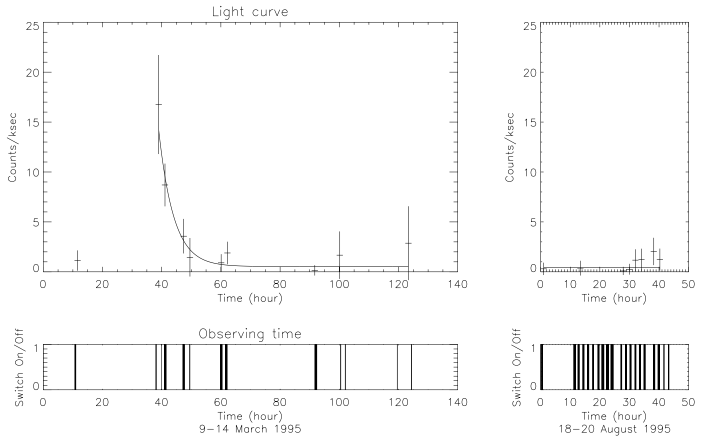

Fig. 3. Light curve of YLW15 using 2-hour bins and one σ error bars. The 2-hour bin count rate was estimated from photon counts during the observing sessions (vertical bars in the lower panel). The continuous line in the first exposure is a least-square fit to an exponential decay, and weights equal to $1/\sigma^2$: $N(t) = 0.5 \pm 0.4 + (13.7 \pm 3.4) \times \exp(-t/5.1 \pm 1.9 \text{ hr})$ counts ksec^{-1}. The quiescent level is 0.41 ± 0.47 counts ksec^{-1}, consistent in both observations with the end of the exponential decay.

We interpret such a time behaviour as post-flare cooling of a hot plasma : estimating the physical conditions of this plasma will help determine the origin of the flare. The upper panels of the Table 1 give the model plasma parameters at the observed flare peak, assuming a magnetically confined plasma sphere. Because the HRI has no spectral resolution, we have to explore a wide range of temperatures $\mathbf{T}_X$. $\mathbf{n}_e$ is the electronic density, assumed to be uniform, calculated assuming a radiative cooling of the plasma bubble (Van den Oord & Mewe, 1989), **B** is the minimum value of the confining magnetic field, and l is the sphere diameter deduced from the emission measure. The lower panels of the table give the peak flare luminosities, calculated assuming a Raymond-Smith spectrum and with a best visual extinction estimate $A_V = 30$ (for a further discussion on the visual extinction see Grosso *et al.*, 1997). $\mathbf{L}_{X,HRI}^{app}$: apparent luminosities in the HRI bandwidth (0.1–2.4 keV); $\mathbf{L}_{X,HRI}^{corr}$: same, corrected for extinction; $\mathbf{L}_{X,tot}$: total intrinsic luminosities, 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 $L_{X,tot}/L_{bol,*}$ ($L_{bol,*} = 10 L_{\odot}$) and the minimum size of the X-ray emitting region l 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 (Cameron, 1995; Feigelson, 1982; Woolum & Hohenberg, 1993; Lee *et al.*, 1997).

Tab. 1 - Model plasma parameters and X-ray luminosities of YLW15 at flare peak for $\mathbf{A}_V$ = 30

$\mathbf{T}_X$ (10^7 K)	1	3	6	12
$\mathbf{n}_e$ (10^{10} cm^{-3})	1.6	5.4	8.0	13
B (Gauss)	36	110	180	330
log $\mathbf{L}_{X,HRI}^{app}$	31.6	31.7	31.7	31.8
log $\mathbf{L}_{X,HRI}^{corr}$	33.8	33.6	33.5	33.5
log $\mathbf{L}_{X,tot}$	34.6	35.1	35.2	35.5
$l/\mathbf{R}_\odot$	35	27	25	23

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