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LETTER

Letter to the Editor

Super-strong X-ray emission from a deeply embedded young stellar object in the Serpens cloud core

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Abstract. We report the ROSAT detection of strong X-ray emission from an optically invisible infrared source in the Serpens star forming region. The X-ray source can be identified with the infrared star EC 95, a deeply embedded ($A_V \approx 34$ mag) young stellar object. The quiescent soft X-ray luminosity of this object is about $(6–18) \times 10^{32}$ erg/sec, making it the most X-ray luminous young stellar object ever detected. Since this exceeds the quiescent, i.e. non-flaring, X-ray luminosity of any known coronal X-ray source by at least about one order of magnitude, our result suggests that a non-solar-like origin for the X-ray emission of EC 95 has to be considered.

Key words: Stars: formation, pre-main sequence, coronae – X-rays: stars

1. Introduction

The Serpens dark cloud is a nearby ($d = 310$ pc), very active star forming region (for a review see Eiroa 1991). A large number of young stellar objects (YSOs) can be found in this region, many of which are highly obscured and therefore optically invisible. After the early detection of 20 infrared sources by Strom et al. (1976), modern infrared imaging surveys by Eiroa & Casali (1992) and Giovannetti et al. (1998) have now revealed the presence of more than 150 near-infrared (NIR) sources. Some 50 of these objects most probably are associated to the cloud, and a large fraction of them has no optical counterpart. The Serpens cloud contains many further signposts of star forming activity, e.g. Herbig Haro objects (Reipurth & Eiroa 1992), molecular outflows (Eiroa et al. 1992), and several class 0 protostars (Hurt & Barsony 1996).

The optically invisible source 4 of Strom et al. (1976), SVS 4 hereafter, could be resolved into a small cluster of at least 11 individual NIR sources by Eiroa & Casali (1989). These sources are surrounded by nebulosity, display very red colors, and exhibit a moderate NIR excess. Thus, they are believed to be YSOs deeply embedded in the molecular could core. With a stellar mass density of $\approx 10^5\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$, SVS 4 constitutes one of the densest clusterings of YSOs know (Eiroa & Casali 1989).

2. ROSAT X-ray observations

We have obtained deep ROSAT pointed X-ray observations of the Serpens star forming region with the HRI detector. For details on ROSAT and the HRI we refer to Trümper (1983) and David et al. (1996). The first observation was performed between 27 September and 2 October 1995 with a total exposure time of 7637 sec. A second pointing with 9728 sec exposure time was performed between 15 March and 14 April 1998. We merged the two individual data sets and performed a detailed data analysis with the EXSAS software system (cf. Zimmermann et al. 1993). Source detection was performed with a maximum likelihood method and revealed seven individual X-ray sources with $S/N > 5$ in the $40' \times 40'$ field of view.

Six of these sources can be identified with optically visible stars (see Fig. 1). Unfortunately, for none of these stars high quality celestial coordinates are available. We thus extrapolated their coordinates from those of nearby stars listed in the Guide Star Catalogue (Lasker et al. 1990) or the Hipparcos catalogue. A comparison of the X-ray and optical coordinates of the X-ray detected stars shows good agreement within a few arcseconds and no indication for any systematic shifts. We conclude that the astrometric accuracy of our X-ray coordinates is about $\pm 4''$.

The most interesting result of the ROSAT observation is the detection of source number 3, X3 hereafter, for which no possible counterpart can be seen in the optical image. X3 is detected at the position $\alpha = 18^{\mathrm{h}}29^{\mathrm{m}}57.9^{\mathrm{s}}$, $\delta = +1^\circ 12' 47''$ (J2000) with a positional uncertainty of $\pm 2''$. The distribution of photons is consistent with a point source. The background subtracted source count rate is 1.2 ± 0.3 cnts/ksec. We could find no significant variations of the count rate in the two individual observations, i.e. at timescales of hours to days. The count rate in the first observation (1.5 ± 0.5 cnts/ksec) seems to be higher than in the second observation (0.9 ± 0.4 cnts/ksec), the difference, however, being not significant. We thus conclude that we are observing quiescent, non-flaring X-ray emission.

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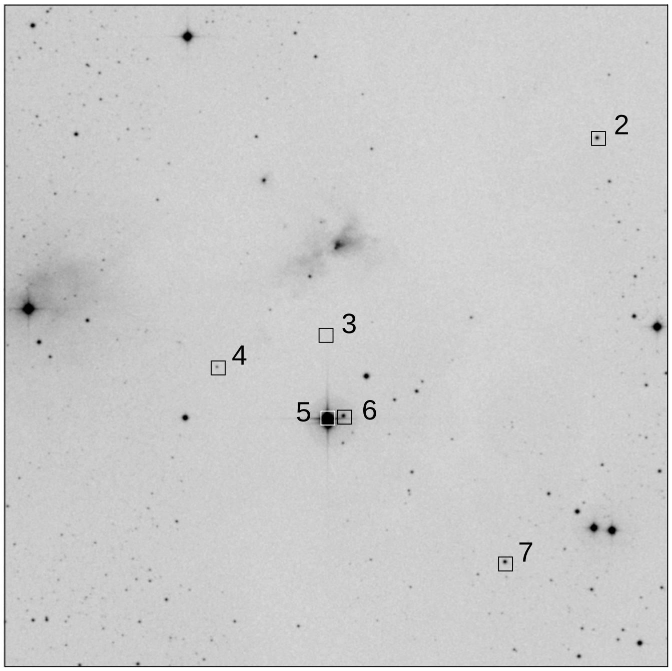

Fig. 1. Optical image (produced from the Digitized Sky Survey), showing a $15' \times 15'$ field centered on the Serpens cloud core. North is up and east is to the left. The positions of the X-ray sources are marked by squares and labeled by source numbers.

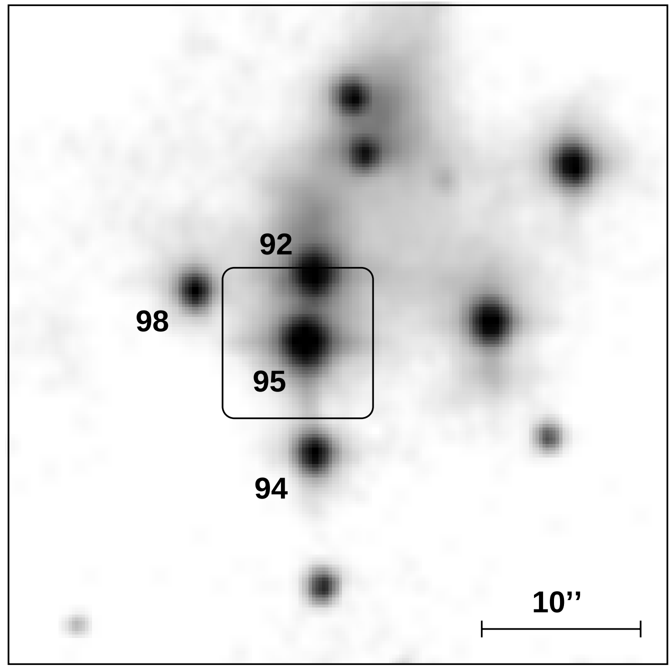

Fig. 2. K'-band image of the SVS 4 group, reproduced from Hodapp (1994). North is up and east is to the left. The X-ray error box for source X3 is shown. For some of the infrared sources their numbers according to Eiroa & Casali (1992) are indicated next to each source.

3. The infrared counterpart of X3

A comparison with infrared images of the star forming region shows that X3 is located in the SVS 4 group of YSOs. For the identification we used the NIR source tables from Eiroa & Casali (1992) and Giovannetti et al. (1998). Down to the detection limit of these surveys at $K \lesssim 16.3$, four individual NIR sources have been found within $10''$ of the X-ray position, namely EC 95, EC 92, EC 94, and EC 98 (see Fig. 2). The position of X3 is only $2''$ east of EC 95, but at least $6''$ away from any other NIR source. Thus, EC 95 is the most likely counterpart of X3. However, we note that the total positional uncertainty is significant in comparison with the separation of the NIR sources in this very dense group. The total positional uncertainty is composed of three components: The intrinsic uncertainty of the X-ray source position ($2''$), the astrometric uncertainty of the X-ray coordinates ($4''$), and finally the uncertainty in the coordinates of the NIR sources ($2''$; cf. Eiroa & Casali 1992). This yields a total uncertainty of $\sqrt{(2'')^2 + (4'')^2 + (2'')^2} \sim 5''$.

Thus, we cannot fully exclude the possibility that one of the other NIR sources, especially EC 92, might be the counterpart of X3. However, even in that case, none of our conclusions below would be seriously affected, since all four NIR objects are similarly deep embedded.

Since no further data seem to be available on the individual stars in SVS 4, we have to estimate their extinctions and luminosities from the NIR data. We assume these stars to have intrinsic colors as found to be typical for YSOs, i.e. $(J-H)_0 \approx 0.8 \pm 0.2$ and $(H-K)_0 \approx 0.5 \pm 0.3$ (cf. Strom et al. 1993, Meyer et al. 1997), and use the reddening relations $A_V = 3.55\ A_J = 9.37\ E(J-H)$ and $A_V = 8.93\ A_K = 16.25\ E(H-K)$ (cf. Rieke & Lebofsky 1985). Stellar luminosities can then be estimated from the dereddened J-band magnitudes using the bolometric relation from Greene et al. (1994; their Eq. 2). The resulting extinctions and stellar luminosities are given in Table 1.

Table 1. Data on the NIR sources within $10''$ of X3. Δ gives the positional offset from X3, the NIR magnitudes and colors are from Eiroa & Casali (1992), extinctions and stellar luminosities have been estimated as described in the text.

star EC	Δ	K [mag]	$J-H$ [mag]	$H-K$ [mag]	A_V [mag]	$L_\star$ $[L_\odot]$
95	$2''$	9.8	4.4	2.5	34 ± 2	26 ± 10
92	$6''$	10.2	3.6	2.2	26 ± 2	7 ± 3
98	$8''$	12.1		2.6	34 ± 5	3 ± 1
94	$8''$	11.6		2.7	36 ± 5	5 ± 2

It is not easy to derive further information about the evolutionary state of these stars[1]. Mid-infrared photometric data, which would allow us to determine the infrared spectral index according to the classification scheme of Adams et al. (1987),

[1] From the data presented here we cannot fully exclude the possibility that the counterpart of X3 might be an extragalactic object behind the star forming region. However, we note that very recently we could obtain NIR spectra for EC 95 and EC 92. The data analysis is not yet finished, but both objects seem to display photospheric features in their spectra and thus are late type stars and no extragalactic objects.

are not available. SVS 4 contains a rather strong IRAS source, but even in the high-resolution-processed IRAS images presented by Hurt & Barsony (1996) the spatial resolution is far too low to identify the contributions of the individual NIR sources. Using the $12\,\mu$m IRAS flux as an upper limit to the flux of each NIR source, we find that all four NIR sources might be possibly classified as class I objects. Such objects are thought to be very young (only a few 100 000 yrs old) stars which are still deeply embedded in a circumstellar envelope (cf. André & Montmerle 1994). This suggests the four NIR sources to be very young objects. On the other hand, their quite small NIR excesses (Giovannetti et al. 1998) might suggest that they could be somewhat more evolved, older objects. Another estimate can be based on the location of SVS 4 at the edge of the southern cloud core in the center of the dark cloud (cf. Casali & Eiroa 1993). This core contains the two class 0 protostars SMM 2 and SMM 4, which are YSOs in their earliest observable phase of evolution with an estimated age of only a few 10 000 yrs (Hurt & Barsony 1996). This shows clearly that the star forming activity of this core is ongoing. Since no optically visible T Tauri stars can be found in the vicinity of the core and SVS 4, it seems that the star formation process in this cloud core has started only recently. This suggests that the YSOs in SVS 4 are very young objects, probably not older than a few $100\,000$ yrs.

4. X-ray luminosity

In order to transform the observed ROSAT count rate into an X-ray luminosity, we interpret the X-ray emission as optically thin thermal plasma emission (see Raymond & Smith 1977). The transformation factor depends on the plasma temperature and the column density of X-ray absorbing material along the line of sight. The optical extinction can be transformed into the hydrogen column density using the relation $N_{\rm H} = A_V \times 2.23 \times 10^{21}\,{\rm cm}^{-2}$ (Ryter 1996). Since the HRI has not enough spectral resolution to measure the plasma temperature, we explore a range of temperatures, $kT =$ (1–3) keV, which is typical for active stellar X-ray sources and YSOs (e.g. Montmerle 1996; Preibisch et al. 1996).

Using these parameters, we computed model X-ray spectra and determined the transformation factor between the count rate and the *de*reddened X-ray flux by folding these spectra through the detector response function with the corresponding EXSAS commands. From this we find that for an extinction of $A_V \sim 34 \pm 2$ mag the count rate of 1.2 cnts/ksec corresponds to an X-ray luminosity of $L_{\rm X} = (1.8 \pm 0.5) \times 10^{33}$ erg/sec for $kT = 1$ keV and $L_{\rm X} = (6.3 \pm 1.6) \times 10^{32}$ erg/sec for $kT = 3$ keV. This yields a fractional X-ray luminosity of $L_{\rm X}/L_\star \approx$ (4–22) $\times 10^{-3}$ for EC 95. It should be noted that these values include only the flux in the 0.1–2.4 keV ROSAT band. If we extrapolate this to the total X-ray band (0.1–100 keV), we find that EC 95 radiates as much as $\approx$(7–25)% of its total luminosity in X-rays.

If EC 92 instead of EC 95 were the correct identification for X3, then the X-ray luminosity would be $L_{\rm X} \approx$ (2–7) $\times 10^{32}$ erg/sec, the fractional X-ray luminosity would be $L_{\rm X}/L_\star \approx$ (5–32) $\times 10^{-3}$ in the ROSAT band, and $\approx$ (5–30)% in the total X-ray band.

5. Discussion

YSOs in the T Tauri phase (at ages of a few 10^6 yrs) are known to be strong X-ray sources. Their X-ray emission is generally believed to be enhanced solar like coronal activity. The high X-ray luminosities of T Tauri stars, which typically exceed the solar level by factors of 100 to 1000, can be explained by the fast rotation and the large surface areas of these young objects (e.g. Montmerle 1996).

The X-ray properties of EC 95, however, are extreme: EC 95 is $500\,000$ times more X-ray luminous and has a 7500 times higher fractional X-ray luminosity than the Sun. These properties remain outstanding even when compared to the most X-ray active T Tauri stars: EC 95 is at least 10 times more X-ray luminous than the X-ray brightest T Tauri stars in the Orion nebula (Gagné et al. 1995) and its fractional X-ray luminosity is at least twice as high as that of any T Tauri star. It seems questionable whether such an exceptionally high X-ray luminosity can be still explained by a solar-like coronal emission mechanism.

It is interesting to compare EC 95 to other X-ray detected infrared YSOs. Up to now, there are 7 reliable X-ray detections of optically invisible infrared YSOs: TS 2.6, TS 13.1, and TS 2.4 in the R CrA molecular cloud core (Koyama et al. 1996; Neuhäuser & Preibisch 1997), IRS 43 = YLW 15 (Grosso et al. 1997), EL 29 and WL 6 (Kamata et al. 1997) in the ρ Oph star forming region, and SVS 16 in the NGC 1333 star forming region (Preibisch 1997; Preibisch et al. 1998). Most of these objects show X-ray luminosities quite similar to many T Tauri stars, and at least 60 times lower than EC 95.

Two of these objects, IRS 43 and SVS 16, however, are much brighter in X-rays. IRS 43 showed an extremely energetic X-ray superflare with a *peak* X-ray luminosity of about 6×10^{33} erg/sec and seems to have a *quiescent* X-ray luminosity of about 6×10^{31} erg/sec (assuming $A_V = 30$ mag and $kT = 1$ keV; Grosso et al. 1997 and priv. comm.). For SVS 16 in NGC 1333, $L_{\rm X} = (2.0 \pm 0.5) \times 10^{32}$ erg/sec and $L_{\rm X}/L_\star = 8 \times 10^{-3}$ was found by Preibisch et al. (1998). While IRS 43 is a typical class I source deeply embedded in its dense circumstellar envelope, SVS 16 displays no evidence for significant amounts of circumstellar material and thus appears to be a very young (probably less than a few 10^5 yrs old) YSO which has lost its circumstellar material very quickly (cf. Preibisch et al. 1998).

The energetics of the superflare on IRS 43 were the first firm piece of evidence that a non-solar-like origin has to be considered to explain the giant X-ray activity of this YSO (Grosso et al. 1997). The extremely high quiescent X-ray luminosity we find for EC 95 is the second piece, because it exceeds that of all known coronal X-ray sources (including all RS CVn binaries, which are the most coronally active stars; cf. Dempsey et al. 1993) by at least about one order of magnitude. It is unclear, how to explain our result. Powerful X-ray flares on YSOs might be explained by recent models of magnetic interaction between the forming star and its circumstellar environment (cf. Hayashi et al. 1996; Shu et al. 1997). In these models, large amounts of energy can be accumulated and stored in extended magnetic structures. This energy is then set free on very short timescales (typically a few hours) by magnetic reconnection events. The super-strong, but quiescent X-ray emission we observe from EC 95, however, requires a steady supply of energy. If EC 95 has a circumstellar disk, a possible explanation for its strong X-ray emission might be a large number of reconnection events occurring very frequently, which would produce quasi-continuous X-ray activity.

Irrespective of the origin of the X-ray emission, the strong intensity of ionizing radiation most probably has profound effects on the circumstellar environment of the YSO. Accretion and outflow processes as well as the magnetospheric coupling between the star and its circumstellar disk are regulated by the interaction of ionized material with magnetic fields (Shu et al. 1997). The very intense soft X-ray emission from the forming star will effectively photoionize the circumstellar matter. If the YSO is surrounded by a protoplanetary disk, this will produce a thin, highly ionized surface layer in the disk and might not only regulate the accretion process, but also affect the formation of proto-planets (cf. Glassgold et al. 1997).

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