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X-ray emission from extremely young stellar objects

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Abstract. We summarize the recent detections of strong X-ray emission from highly obscured, optically invisible young stellar objects in several star forming regions. We discuss the X-ray properties of these objects, the origin of their strong X-ray emission, and the implications on the star formation process and the evolution of the protoplanetary disk.

1. Introduction

Young stellar objects (YSOs) can be classified by the slope of their broad-band infrared spectrum (see Adams et al. 1987). Class I sources have steeply rising near-infrared spectra and are generally optically invisible. They are interpreted as extremely young objects (age $\lesssim$ 100 000 years) which are still deeply embedded in a dense envelope of circumstellar matter. Class II sources have already dissipated most, but not all, of their circumstellar material and thus are visible in the optical, but still display a near-infrared excess. Class III sources exhibit no infrared excess and thus are thought to be essentially free of circumstellar matter. Typical examples for class II and class III sources are classical and weak line T Tauri stars.

Since the EINSTEIN era it has been known that T Tauri stars with an typical age of a few million years are strong X-ray sources. Their X-ray luminosities can exceed the solar level by factors of 100 to 1000 and can be understood as enhanced solar-type magnetic activity due to rapid stellar rotation (cf. Montmerle 1996; Neuhäuser 1997; Preibisch 1997a).

Stars which are considerably younger than T Tauri stars (i.e. significantly younger than 10^6 years) are generally optically invisible ($A_V \geq 30$ mag), either because of a dense circumstellar envelope or because they are located in a dense molecular cloud core, in which they were born. Until recently, such objects could only be detected by their strong infrared emission, and nothing was known about possible X-ray emission from deeply embedded YSOs.

In the last few years, very deep ROSAT and ASCA observations of star forming regions have provided clear evidence for X-ray emission from deeply embedded infrared YSOs in a few cases. Most of the X-ray detected objects turned out to be class I objects, while at least one object is an extremely young class II/III object. These detections demonstrate that ROSAT can be used to "X-ray" dense molecular cloud cores and reveal optically invisible YSOs.

2. X-ray detections

2.1. Corona Australis star forming region

The Corona Australis molecular cloud is one of the nearest ($D \sim 130$ pc) regions of ongoing star formation. The densest cloud core is located near the emission line star R CrA. While optical images show very few stars in this region (see Fig. 1), deep infrared surveys revealed the presence of several infrared sources, known as the Coronet cluster (cf. Wilking et al. 1997). Five of these sources are class I objects.

Koyama et al. (1996) performed a 80 ksec ASCA observation of the Coronet region and could find several peaks in their X-ray image which seem to coincide with these class I objects. However, the low spatial resolution of ASCA prevented a reliable source identification. We analyzed the archival data of two ROSAT observations and could clearly detect X-ray emission from the three class I objects TS 2.6, TS 13.1, and TS 2.4 (Neuhäuser & Preibisch 1997).

2.2. NGC 1333 star forming region

The NGC 1333 molecular cloud is a highly active star forming region in the nearby ($D \sim 300$ pc) Perseus cloud complex and contains many embedded infrared sources. Preibisch (1997b) performed a 40 ksec ROSAT HRI observation of this region and could detect 20 X-ray sources. While most of these sources are typical T Tauri stars, one ROSAT source can be identified with the highly obscured, optically invisible infrared source SVS 16 (Fig. 2).

Infrared photometry and spectroscopy of SVS 16 showed that it is a binary consisting of two M-type pre-main sequence stars (Preibisch et al. 1998). The stars are highly obscured ($A_V \sim 26$ mag) and seem to be younger

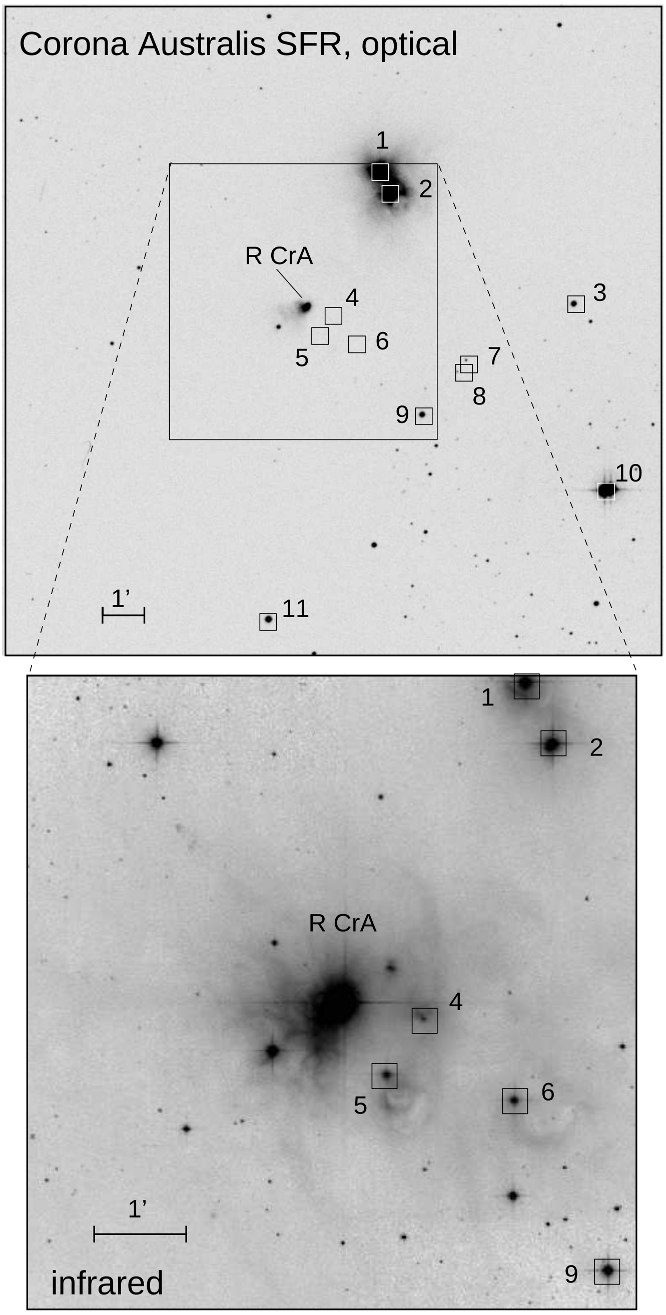

Fig. 1. Top: Optical image (produced from the Digitized Sky Survey) of the Corona Australis star forming region. The positions of the ROSAT X-ray sources are marked by the squares. Bottom: Near-infrared image of the Coronet, adapted from Wilking et al. (1997). The X-ray sources 4, 5, and 6 can be identified with class I objects.

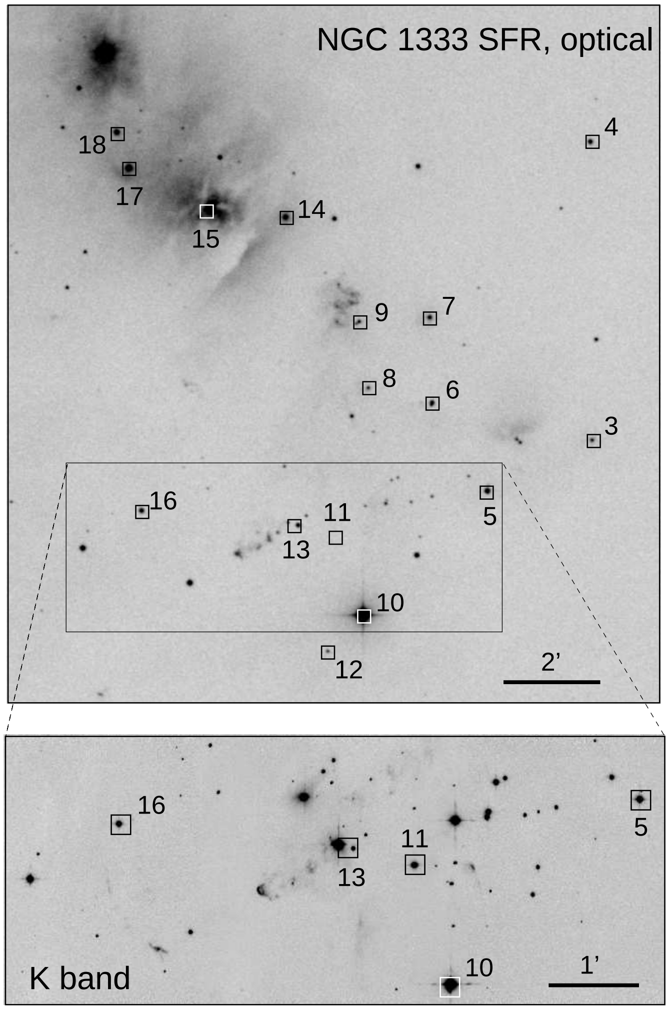

Fig. 2. Top: Optical image of the NGC 1333 star forming region. The positions of the X-ray sources are marked by the squares. Bottom: K-band image of the southern part, from Hodapp (1994). X-ray source 11 can be identified with the infrared source SVS 16.

than 10^5 yrs. Since no significant amounts of circumstellar matter around SVS 16 could be detected, the system must have accreted or dispersed nearly all of its circumstellar material very quickly. The most interesting aspect of SVS 16 is its extremely high quiescent X-ray luminosity of 2×10^{32} erg/sec. This is about 5 orders of magnitude above the solar level and at least 3 times more than any known coronal X-ray source.

2.3. Serpens star forming region

The Serpens dark cloud is another nearby ($D \sim 310$ pc) very active star forming region. Using the ROSAT HRI, Preibisch (1998) could detect strong X-ray emission from the infrared YSO EC 95 in the southern part of the cloud core (Fig. 3). This YSO is highly obscured ($A_V \approx 34$ mag) and its quiescent soft X-ray luminosity is about 1×10^{33} erg/sec, making it the most X-ray luminous YSO ever detected.

2.4. Further detections

In the ρ Oph star forming region Grosso et al. (1997) detected an extremely energetic X-ray superflare on the

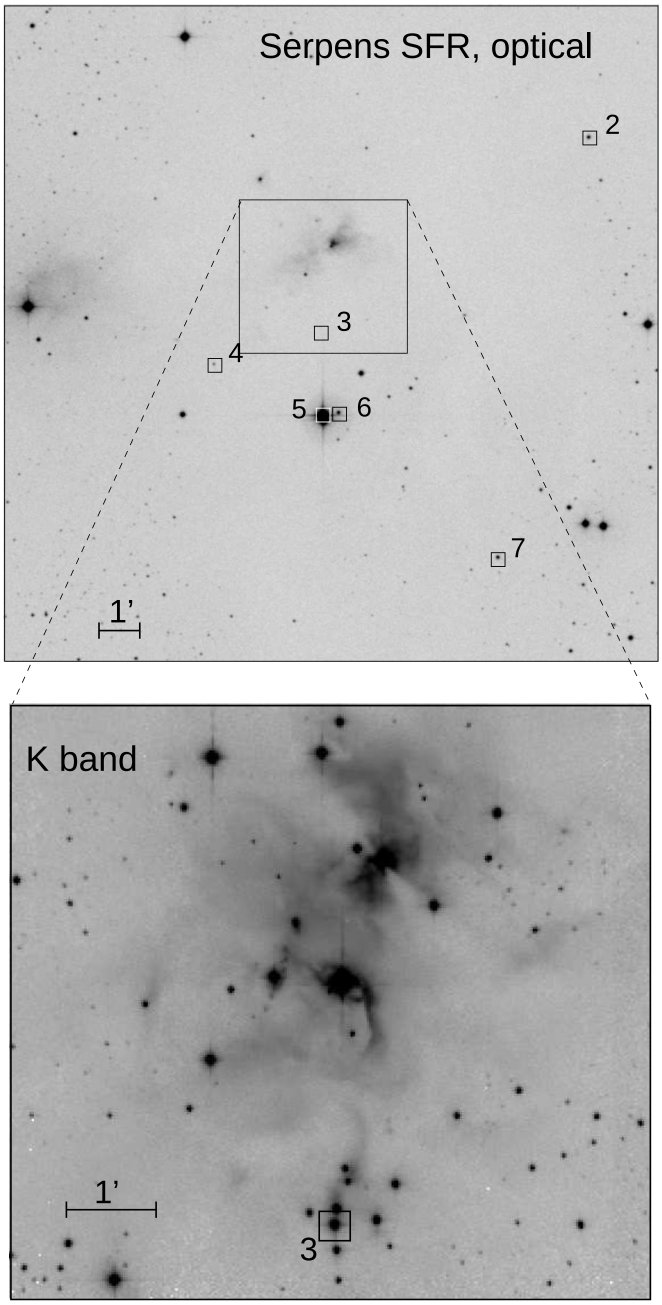

Fig. 3. Top: Optical image of the Serpens star forming region with X-ray source positions marked by squares. Bottom: K-band image of the central part, reproduced from Hodapp (1994). The X-ray source 3 can be identified with the infrared source EC 95.

class I object IRS 43 during a ROSAT HRI observation. The maximum X-ray luminosity during the flare *peak* was about 6×10^{33} erg/sec, the *quiescent* X-ray luminosity of this objects was about 6×10^{31} erg/sec.

Kamata et al. (1997) reported the ASCA detection of two further class I objects in ρ Oph, EL 29 and WL 6.

Table 1. Properties of X-ray detected infrared YSOs. We list the infrared class, extinction A_V, luminosity $L_{\rm bol}$, *quiescent* X-ray luminosity $L_{\rm X}$ in the 0.1 – 2.4 keV ROSAT band, and the fractional quiescent X-ray luminosity $\eta = L_{\rm X}/L_{\rm bol}$.

Name	class	A_V [mag]	$L_{\rm bol}$ [$L_\odot$]	$L_{\rm X}$ [$10^{30}\ \frac{\rm erg}{\rm sec}$]	$\log\eta$
EC 95	?	34	26	1000	−2.0
SVS 16	II/III	28	8	300	−2.1
IRS 43	I	33	10	60	−2.8
EL 29	I	40	48	10	−4.3
WL 6	I	25	2	8	−3.1
TS 2.6	I	41	14	2.5	−4.3
TS 13.1	I	32	12	9.3	−3.7
TS 2.4	I	39	3	4.6	−3.4
Ced 110-6	I	35	1	2	−3.3

Carkner et al. (1998) recently reported the ROSAT detection of the class I source Ced 110 IRS 6 in the Chamaeleon dark cloud.

3. Are all infrared YSOs X-ray emitters?

These detections clearly show that at least in some YSOs X-ray emission can start already in the earliest phases of stellar evolution, at ages of only about 100 000 years. It is not clear whether all infrared YSOs are X-ray sources. Carkner et al. (1998) performed a systematic survey for X-ray emission from infrared YSOs. They investigated 156 such objects, but could only detect one new X-ray emitting YSO. At present it is not clear whether this high rate of non-detections is caused by a lack of sensitivity for the very strongly extincted X-ray emission of these objects, or whether the X-ray detected YSOs are unusual in some respect (see also Sekimoto et al. 1997).

4. X-ray properties of the detected objects

The quiescent soft X-ray luminosities of the detected YSOs are summarized in Table 1. These numbers have to be compared to the X-ray luminosity of the Sun ($L_{\rm X} \approx 3 \times 10^{27}$ erg/sec, $\log\eta \approx -6$; cf. Schmitt 1997), and the most X-ray luminous T Tauri stars ($L_{\rm X} \approx 6 \times 10^{31}$ erg/sec, $\log\eta = -2.5$; cf. Gagné et al. 1995). Note that the RS CVn binaries, which are the most coronally active stars, have maximum X-ray luminosities very similar to the T Tauri stars (cf. Dempsey et al. 1993).

Most of the infrared YSOs show X-ray luminosities quite similar to those of many T Tauri stars (see Fig. 4) and thus their X-ray emission can probably be explained by the same basic mechanisms, i.e. as solar like coronal activity. The extremely strong quiescent emission from SVS 16 and EC 95 clearly exceeds the maximum X-ray luminosity of any known coronal source. However, this does not necessarily mean that a coronal origin can be excluded:

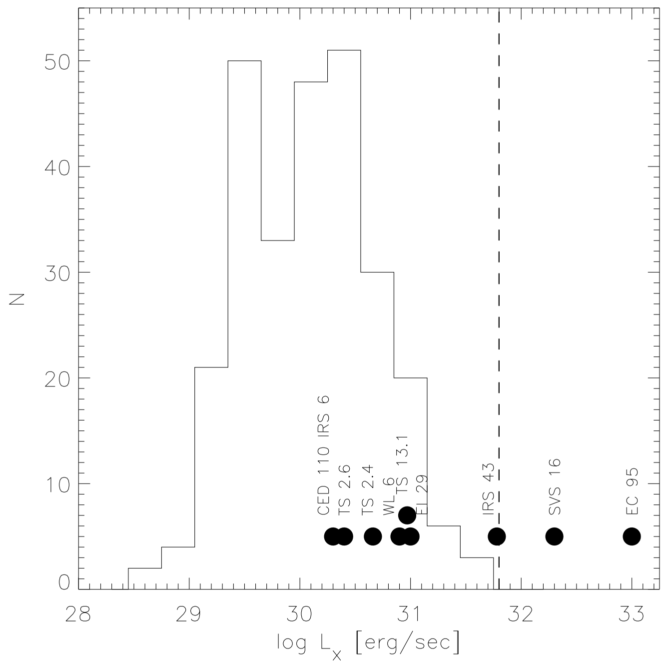

Fig. 4. Comparison of the X-ray luminosities of the infrared YSOs (big dots) with those of a large sample of T Tauri stars from nearby star forming regions (histogram). The dashed line marks the maximum X-ray luminosity of RS CVn binaries.

For SVS 16, Preibisch et al. (1998) could determine basic stellar parameters and found that the X-ray surface flux is extremely high, but still comparable to that of the most X-ray active RS CVn binary. This means, that the extreme X-ray activity of SVS 16 can probably still be explained as coronal emission; it might be the consequence of an high X-ray surface flux in combination with the very large surface area of this extremely young star.

The energetics of the superflare on IRS 43, however, is a firm piece of evidence that a non-solar-like origin has to be considered to explain this giant X-ray activity (Grosso et al. 1997). Perhaps, the extreme quiescent X-ray luminosity of EC 95 is another piece. It is unclear, how to explain these extreme levels of X-ray activity. 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, accumulated over long periods, can be stored in extended magnetic structures. This energy is then set free on very short timescales (typically a few hours) by magnetic reconnection events. Very strong, but quiescent X-ray emission, as observed on EC 95, might perhaps be explained by a large number of such reconnection events occurring very frequently, which might produce quasi-continuous X-ray activity.

Irrespective of the origin of the X-ray emission, the strong intensity of ionizing radiation (factors of 10^3 to 10^5 above the solar level) most probably has profound effects on the evolution of the circumstellar environment and the forming star itself. 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 (cf. Shu et al. 1997). The very intense X-ray emission from the forming star will effectively photoionize the circumstellar matter and undoubtedly dominate the ionization state in the environment of the YSO. Before the X-ray detections of infrared YSOs, cosmic rays were thought to be the primary source of ionization. Cosmic rays can penetrate protoplanetary disks and thus would produce a homogeneous ionization throughout the disk. In contrast to this, the *soft* X-ray emission from the YSO will be strongly absorbed and thus will produce a highly ionized thin surface layer around the disk, while the disk midplane will be a much less ionized. This effect might not only regulate the accretion process, but might also produce favorable conditions for the formation of proto-planets (cf. Glassgold et al. 1997). Perhaps, the X-ray emission from the proto-sun was a key factor for the formation of the earth and thus for our existence.

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