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ROSAT detection of Class I protostars in the CrA Coronet

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Abstract. We analyze archival ROSAT data of the CrA star forming region. X-ray emission from five infrared Class I protostars in the Coronet cluster was recently found in ASCA data, however, with low spatial resolution and partly ambiguous source identification. ROSAT high spatial resolution data confirm the X-ray detection of three Class I protostars. The other two infrared protostars might be extincted to strongly for being detected in the softer ROSAT bandpass. Alternatively, the X-ray emission might be strongly variable and they might have been too faint in X-rays at the time of the ROSAT observations.

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

1. Introduction

The Corona Australis (CrA) molecular cloud complex is one of the nearest regions ($\sim 130\ pc$, Marraco & Rydgren 1981) of ongoing star formation. The densest cloud core is located near the emission line star R CrA. The extinction in this region ranges up to $A_V \approx 35$ mag (Wilking et al. 1992). In optical images, only the star T CrA is visible within $\sim 3'$ from R CrA. Taylor & Storey (1984) performed an infrared (IR) survey of the core and could detect 15 IR sources, known as the Coronet cluster. Further IR observations by Wilking et al. (1986, 1992) revealed more IR sources and showed that five of the sources detected by Taylor & Storey (1984) have an IR spectral index of $a > 0.2$. These five sources are therefore classified as Class I objects (see Wilking et al. 1984). Such objects are thought to be extremely young stars, which are still deeply embedded in their dense circumstellar envelope and are often called protostars (Shu et al. 1987). Recently, Wilking et al. (1997, henceforth W97) performed a deep near-IR (NIR) imaging survey of the R CrA core. Their sample of 692 K-band sources can be expected to reveal the complete population of Class I and II sources in the core, the latter being classical T Tauri stars.

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While many of the optically visible pre-main sequence stars are know to be rather strong and variable X-ray emitters (e.g., Montmerle et al. 1983, Neuhäuser et al. 1995, Preibisch et al. 1996), ROSAT detections of Class I protostars were reported only very recently (Casanova et al. 1995, Preibisch 1997, Grosso et al. 1997); see Neuhäuser (1997) for a review.

Koyama et al. (1996, henceforth K96) presented the results of a deep (80 ksec) ASCA observation of the Coronet region. In their X-ray image they find five peaks which seem to coincide with the positions of five Class I protostars. However, the positional uncertainties of the ASCA sources is quite large ($\sim 20''$) and the individual sources are only partially resolved. ROSAT observations provide a much better spatial resolution (FWHM $\approx 5''$ for the High Resolution Imager, HRI) and thus are better suited for proper source identifications. The softer energy range of the ROSAT band (0.1 – 2.4 keV) as compared to ASCA (0.5 – 10 keV), however, is much more affected by X-ray extinction. This means that ASCA is more sensitive to strongly extincted X-ray sources. The combination of deep ROSAT *and* ASCA observations provides a very good basis for the study of deeply embedded objects.

2. ROSAT observations

We analyzed two data sets from the ROSAT data archive: The 15.0 ksec Positional Sensitive Proportional Counter (PSPC) observation 200493 and the 19.6 ksec HRI observation 201395. Both observations were performed in several parts, separated by some months. For details on ROSAT and its instruments, see Trümper (1983).

Source detection was performed separately for the HRI and the PSPC data with EXSAS (Zimmermann et al. 1994): Local source detection by sliding-window techniques followed by a maximum likelihood test to discern between sources and statistical background fluctuations. The 'likelihood of existence' $\mathcal{L}$ provides a measure for the presence of a source above the local background. Since we search for faint sources, we accept all sources with $\mathcal{L} \geq 6$ (corresponding to a 3σ detection).

In order to check the accuracy of the X-ray source positions we compared them with the positions of stars in the Guide Star Catalog (GSC) and of the NIR sources listed by W97. About 15 X-ray sources could be uniquely identified with optical or NIR counterparts and we could find no systematic deviation between the optical/NIR positions and the X-ray source positions.

In Fig. 1 we show the ROSAT X-ray image of the Coronet cluster region, Fig. 2 shows a chart of the same region. At the position of three of the five Class I sources we can detect X-ray emission. There are no other young stars like classical or weak-line T Tauri stars known close to the relevant X-ray positions. The background subtracted source count rates are summarized in Table 1. For the two Class I sources not detected in X-rays we determined 90% confidence count rate upper limits by comparing the counts in a detection cell at the target position with the nearby background.

Since the PSPC has some spectral resolution, we can compute hardness ratios, defined as follows: If S, M, and H are the count rates in the soft (0.1 – 0.4 keV), medium (0.5 – 0.9 keV), and hard (0.9 – 2.1 keV) bands, respectively, then $HR\,1 = (M + H - S)/(M + H + S)$ and $HR\,2 = (H - M)/(H + M)$.

In order to compute X-ray luminosities from the count rates one has to specify the two spectral parameters: the plasma temperature T and the absorbing hydrogen column density $N_{\rm H}$. In principle, these parameters can be found by fitting the X-ray spectra of the sources. However, from the ROSAT data no spectra can be extracted due to the very low number of detected counts. The same is true for the ASCA data. However, K96 were able to extract and analyze an integrated spectrum for the whole Coronet cluster. Their spectral fit with a thermal bremsstrahlung model gave a plasma temperature of $kT \approx 7$ keV and a hydrogen column density of $N_{\rm H} \approx 4 \times 10^{22}\,{\rm cm}^{-2}$.

For the extinction of the Class I protostars Wilking et al. (1986) give values between $A_V = 32$ mag and $A_V = 45$ mag. Since it is quite difficult to determine the extinction for Class I protostars, these numbers are estimates rather than accurate values. Since we want to compare our ROSAT X-ray luminosities with those reported by K96, we also assume Raymond-Smith X-ray spectra (Raymond & Smith 1977) with $kT = 7$ keV and $N_{\rm H} = 4 \times 10^{22}\,{\rm cm}^{-2}$, corresponding to $A_V \approx 20 - 30$ mag.

The ASCA X-ray luminosities (K96) were computed for the same spectral parameters, but for the energy band 0.5 – 10 keV. We transformed the ASCA X-ray luminosities to the 0.1 – 2.4 keV ROSAT band using the PIMMS simulator provided by the HEASARC Online Service.

The Coronet cluster was also observed during the ROSAT All-Sky Survey, but none of the Class I sources were detected (at typical exposure times of 500 seconds only), and the upper limits count rates are consistent with the pointed data listed below. Additionally, the area was

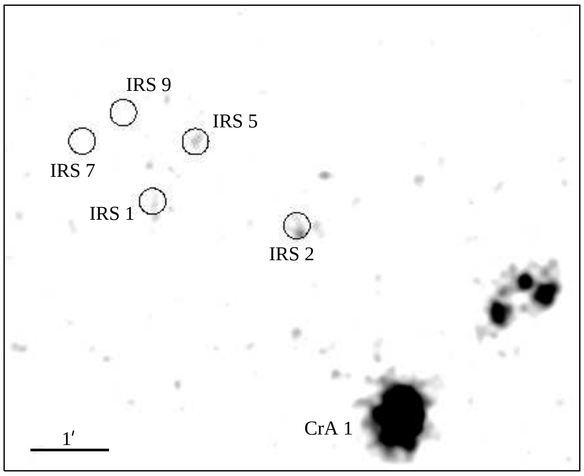

Fig. 1. ROSAT X-ray image of the Coronet region. This image was produced by merging the data of the PSPC and the HRI and smoothing it with a Gaussian filter. (Note that this image is only meant to be an illustration and was not used for the source detection.) The circles with radii of 10″ mark the positions of the Coronet Class I protostars.

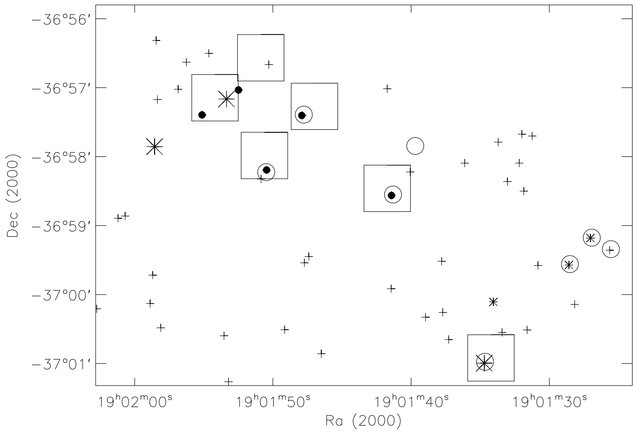

Fig. 2. This chart shows about the same field as the X-ray image. Here, the positions of the ROSAT X-ray sources are marked by the open circles, the open squares show the ASCA source positions as given by K96. The size of these symbols indicates the uncertainties of the X-ray positions. Optically visible stars are shown as asterisks, the NIR sources found by W97 as crosses and the Class I protostars as solid dots.

observed by the *Einstein Observatory*, but again, no Class I protostar was detected (Walter et al. 1997).

3. Notes on individual sources

CrA IRS 1. The PSPC source has an X-ray luminosity roughly consistent with the ASCA findings, our HRI upper limit is much larger. There is a very faint X-ray source $\sim 16''$ south of IRS 1 (Fig. 1). The position of this source, $\alpha_{2000} = 19^h01^m50.5^s$ and $\delta_{2000} = -36°58'21''$, is within

Table 1. X-ray detected Class I protostars in the Coronet cluster. We list source names from Taylor & Storey (1984); $J = 2000.0$ IR positions and the spectral indices a; $J = 2000.0$ ROSAT X-ray positions (HRI for IRS 2 and 5, PSPC for IRS 1) and positional offset between IR and X-ray position; a questionmark behind the detector indicates a doubtful identification; likelihood of existence $\mathcal{L}$ of the ROSAT sources; the ROSAT PSPC and ASCA hardness ratios; ROSAT X-ray count rates; and X-ray luminosities computed for the ROSAT 0.1 – 2.4 keV energy band.

Source names	IR position	ROSAT position	detector	$\mathcal{L}$	$HR\,1,2$ (PSPC) HR (SIS)	count rate [cts ksec^{-1}]	L_X [10^{30} erg sec^{-1}]
IRS 1	19 01 50.5	19 01 50.6	PSPC	40.1	$HR\,1 = 0.1 \pm 0.3$, $HR\,2 = 0.8 \pm 0.1$	1.12 ± 0.24	2.5 ± 0.5
TS 2.6	-36 58 12	-36 58 05	HRI			< 1.15	< 9.6
	$a = 1.5$	$5''$ off	SIS		$HR = 0.8$		~ 1.7
IRS 2	19 01 41.4	19 01 41.3	PSPC	201.9	$HR\,1 = 0.7 \pm 0.1$, $HR\,2 = 0.9 \pm 0.1$	4.26 ± 0.54	9.3 ± 1.2
TS 13.1	-36 58 34	-36 58 34	HRI	6.4		0.44 ± 0.19	3.7 ± 1.6
	$a = 0.67$	$5''$ off	SIS		$HR = 0.4$		~ 0.9
IRS 5	19 01 47.9	19 01 47.7	PSPC	15.8	$HR\,1 = 0.4 \pm 0.3$, $HR\,2 = 0.9 \pm 0.1$	2.07 ± 0.58	4.6 ± 1.2
TS 2.4	-36 57 24	-36 57 22	HRI	8.5		0.49 ± 0.19	4.1 ± 1.7
	$a = 1.3$	$4''$ off	SIS		$HR = 0.7$		~ 1.4
IRS 7	19 01 55.1		PSPC			< 0.46	< 1.0
R 1	-36 57 24		HRI			< 0.35	< 2.9
	$a = 2.3$		SIS ?		$HR = 0.9$		~ 6.3
IRS 9	19 01 52.5		PSPC			< 0.55	< 1.2
R 2	-36 57 02		HRI			< 1.00	< 8.3
	$a = 1.8$		SIS ?		$HR = 0.8$		~ 1.0

$4''$ of that of a very faint ($K = 14.52$) IR source found by W97. Virtually nothing is know about this source, and since W97 did not detect this source in the J band, we only know that its color of $H - K = 2.0$ is comparable to the Class I sources.

CrA IRS 2. This is the softest ASCA source (K96), but the hardest PSPC source. The three X-ray luminosities (PSPC, HRI, and ASCA) are significantly different indicating variability on a time scale of years.

CrA IRS 5. The PSPC and HRI X-ray luminosities agree well, but are larger than the ASCA luminosity.

CrA IRS 7. No X-ray sources could be detected in the ROSAT images at the position of this star. Our luminosity upper limits are significantly below the X-ray luminosity found with ASCA. The identification of the ASCA source with IRS 7 is doubtful, since the optically visible star R CrA is closer to the source position than IRS 7. However, R CrA is not detected in the ROSAT images (we derive an upper limit of 1 counts ksec^{-1} from the HRI observation and 0.5 counts ksec^{-1} from the PSPC data). The ASCA source is very hard ($HR = 0.9$), i.e. strongly absorbed, and is most probably not associated with R CrA, for which an extinction of only $A_V = 2.4$ mag was determined.

CrA IRS 9. The upper limits we derive from the ROSAT data are higher than the ASCA X-ray luminosity reported by K96. This is consistent with the assumption that this source is too strongly extincted for being detected in the ROSAT band. The identification of the ASCA X-ray source with IRS 9 is doubtful, since the ASCA source position is closer to the Class II source IRS 6 than to IRS 9. The NIR colors of IRS 6 as given by Taylor & Storey (1984) are consistent with an extinction of $A_V \approx 25$ mag. This might be enough to produce a X-ray hardness ration of $HR = 0.8$ as found for the ASCA source. Since the ROSAT images show no source at the position of IRS 6, the question of whether IRS 6 or IRS 9 is the counterpart of the ASCA source remains open.

4. X-ray Variability

It is very interesting to investigate the X-ray variability of the Class I protostars, especially since K96 detected a large X-ray flare on their source 8 (IRS 7). Unfortunately, due to the very low count rates and the rather moderate exposure times of the ROSAT observations, no meaningful lightcurves can be extracted from the ROSAT data.

The only source for which we can get at least some information is IRS 2, which has the largest count rate in the ROSAT observations. The PSPC pointing was carried out in three major parts separated by a few month, and the source is detected in all three observations with count rates being 2.45 ± 0.91, 4.04 ± 0.75, and 4.65 ± 1.06 cts ksec^{-1}, indicating variability also on a time scale of months. We performed a Kolmogorov-Smirnov test to analyze the arrival times of the X-ray photons. The probability that the source is variable is 0.72 for the PSPC data and 0.88 for the HRI data. This means that we cannot prove that the count rates are variable and all variations might be only statistical fluctuations. However, it should be noted that due to the small number of detected photons, the sensitivity of the test is low, and count rate variations by factors up to 5 might easily hide within the Poisson noise. All we can say is that the source did not show a strong flare during the ROSAT observations.

CrA IRS 1 was detected only in the shortest of the three PSPC slots, lasting only 3.1 ksec, again indicating variability on a time scale of months.

5. Discussion

It is now clear that at least some Class I protostars exhibit very luminous and variable X-ray emission. Casanova et al. (1995) reported the possible detection of up to ten Class I protostars in a deep ROSAT PSPC observation of the ρ Oph dark cloud, the identifications being ambiguous due to low spatial resolution and source confusion. The detection of one source, IRS 43 (YLW 15), could recently be confirmed by a deep HRI observation (Grosso et al. 1997). Preibisch (1997) reports the X-ray detection of the Class I protostar SVS 16 in a deep HRI pointed observation of the NGC1333 star forming region.

Older low-mass pre-main sequence stars like classical (Class II) and weak-line (Class III) T Tauri stars also show strong solar-like coronal X-ray emission; they are fully convective stars and have deep convection zones. Since Class I protostars are extremely young ($\lesssim 10^5$ yrs) and still in the main accretion phase, it is questionable, whether they have developed coronae already. Hence, the X-ray emission mechanism may be different. Preibisch (1997), however, estimated the X-ray surface flux of the HRI detected Class I source SVS 16 in NGC1333, and – by comparison with coronal sources like T Tauri stars – concluded that solar-like coronal X-ray emission cannot be excluded.

Strong X-ray flares might yield insight into the emission mechanism since they indicate magnetic energy release. One of the ASCA sources (probably IRS 7) showed a strong flare in addition to quiescent emission during the rest of the observation (K96). Also, ρ Oph IRS 43 (YLW 15) has shown a very powerful flare during the recent HRI observation (Grosso et al. 1997). During the flare, its X-ray flux increased by at least a factor of 20, and it was not really detected before and after the flare. Accounting for the extinction, Grosso et al. (1997) estimate its X-ray luminosity during the flare to be at least 10^{34} erg sec^{-1}, comparable to the bolometric luminosity of this object.

Recently, Hayashi et al. (1996) proposed a model for Class I X-ray emission: Closed magnetic loops connecting the stellar and disk magnetic fields get twisted due to rotation of the disk. Magnetic loops expand and open field configurations develop with current sheets inside the expanding loops. Plasma is ejected and becomes sufficiently hot to emit X-rays as hard as observed with ASCA. As soon as the plasma has cooled down, after about one day, one should observe an optical jet.

Grosso et al. (1997) discuss several alternatives: magnetic field reconnections in the infalling envelope, at the Alfvén surface between the stellar magnetosphere and the accretion disk, at the X-point above the corotation radius, or at the interface between disk and stellar wind. Also, X-ray detected Class I protostars may in fact be close binaries with magnetic field configurations like in RS CVn-type binaries; c.f. Grosso et al. (1997).

The surprising detection of deeply embedded IR Class I protostars in X-rays is due to the fact that the extinction cross section of interstellar material is very similar near 1 keV as near $\sim 2\,\mu$m (Ryter 1996), so that X-ray observations really allow us to "X-ray" the densest and optically invisible parts of molecular clouds and provide an alternative tool for investigating the earliest phases of low-mass star formation.

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