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# A NEW STELLAR NURSERY IN THE SOUTHERN CROSS

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## ABSTRACT

The $\beta$ cephei variable $\beta$ Cru was the focus of a pointed observation using the PSPC aboard *ROSAT* during the AO4 observation cycle. The field contains the target star $\beta$ Cru, an x-ray binary 4U 1246−58, and several previously unidentified x-ray sources and diffuse emission with a complicated morphology. The data for the brightest 6 previously unidentified sources suggest an identification as T Tauri stars. We present the x-ray timing and spectral data for these candidate T Tauri stars along with data on their possible optical counterparts. From the anticorrelation of the observed x-ray flux with observations in the infrared utilizing archival *IRAS* data, the complicated diffuse emission structure appears to be the result of shadowing of the Galactic x-ray background by foreground molecular gas. © *1996 American Astronomical Society.*

## 1. INTRODUCTION

Imaging x-ray observations provide an excellent tool for discovering and studying young stellar objects such as pre-main sequence stars which, due to their very active nature, tend to be x-ray bright. With the emergence of x-ray observatories star formation regions have been studied in great detail in the x-ray band and many serendipitous x-ray sources have been detected [Walter (1986) and references therein].

We present a *ROSAT* pointed observation with the Position Sensitive Proportional Counter (PSPC) of the field of the $\beta$ cephei variable $\beta$ Cru acquired during the summer of 1993. The 2° circular field of view of the PSPC is observed to contain, in addition to the program object $\beta$ Cru, a low mass x-ray binary (LMXRB), 4U 1246−58, some 20 previously unknown point like x-ray sources, and a diffuse emission structure. The observation was taken as a part of a larger program to study the x-ray characteristics of the $\beta$ cephei variables. In this work we will focus our attention on other serendipitously discovered x-ray emitting objects and the general x-ray morphology observed within the 2° diameter circular field of view.

The detection of these additional x-ray sources may resolve the mystery of the anomalously high x-ray flux of $\beta$ Cru as measured with the Low Energy Detector (LED 1) by Agrawal *et al.* (1984). Agrawal *et al.* (1984) carried out an x-ray survey of $\beta$ cephei variable stars with both the Imaging Proportional Counter (IPC) aboard *Einstein* and the LED 1 of *HEAO 1-A2* . During this program the B0.5 III $\beta$ cephei variable $\beta$ Cru was detected at a very high x-ray flux of 1.15 $\times 10^{-10}$ erg cm$^{-2}$ sec$^{-1}$ in the LED 1 of the *HEAO 1-A2* experiment. They speculated that a part of the detected flux could be due to x-ray like events produced in the LED 1 due to the ultraviolet flux from $\beta$ Cru. However, the contamination due to UV flux could be no more than 15% based on observations of Sirius B as they pointed out. Stern *et al.* (1981) also showed that the x-ray flux detected with the LED 1 on *HEAO 1-A2*is generally higher when compared with the fluxes detected with the IPC on *Einstein*. The anomalously large x-ray flux from $\beta$ Cru as measured by the LED 1 has never been adequately explained and the discrepancy between the IPC and LED 1 measurements has never been reconciled. With the detection of the bright x-ray sources in this field of view, the anomalous flux attributed to $\beta$ Cru by the LED 1 observation likely arose due to the presence of these additional x-ray sources. We will suggest that the 6 point like x-ray sources are T Tauri stars embedded in a star formation region which also includes $\beta$ Cru.

A description of the field and the temporal and spectral analyses for the detected sources are given in Sec. 2. The implications of the observation is discussed in Sec. 3. Finally, the summary and conclusion can be found in Sec. 4.

## 2. OBSERVATIONS AND ANALYSIS

During an observation of the B0.5 III $\beta$ cephei variable $\beta$ Cru with the Position Sensitive Proportional Counter (PSPC) aboard *ROSAT*, several x-ray point sources and diffuse emission were observed within the field of view. Detailed descriptions of the satellite, x-ray mirrors, and detectors can be found in Trümper (1983) and Pfeffermann *et al.* (1986). In short, *ROSAT* contains an x-ray mirror assembly with a 2° field of view. The PSPC is a gas-filled proportional counter sensitive over the energy range of 0.1−2.4 keV with an energy resolution of $\Delta E/E \sim 0.43$ at 0.93 keV, and a spatial resolution of $\sim 25''$ in the center of the focal plane. The observations reported in this paper were obtained between 1993 July 12 and 1993 August 27 with a total effective exposure time of 12,401 sec. Including the program object, $\beta$ Cru, some 26 x-ray point sources were detected by the source detection algorithm above a threshold of Log Likelihood $>10$ (Fig. 1). One of the additional objects is identified with the LMXRB 4U 1246−58 owing to its positional coincidence with the Uhuru coordinates and the observed spectrum. Of the additional x-ray sources 6 are relatively bright

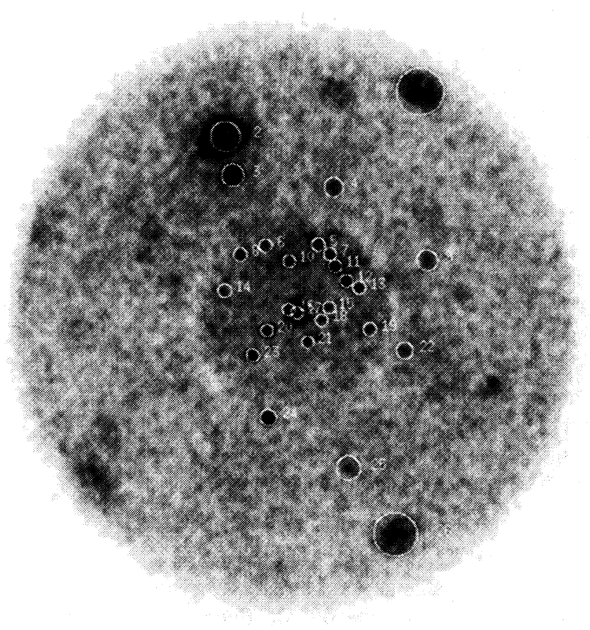

FIG. 1. Greyscale *ROSAT* PSPC image of the field of $\beta$ Cru. Each circle represents the error in the detected x-ray point source position by the source detection algorithm above a threshold of log likelihood > 10. The source number 17 and 2 correspond to $\beta$ Cru and 4U 1246−58, respectively. The additional bright x-ray point sources 11, 12, 20, 23, 24, and 3 are the candidate T Tauri stars numerically listed (1–6, respectively) in Table1.

and within $\sim 30'$ of $\beta$ Cru (i.e., contained within or very close to the central region of the PSPC detector). The positions of these 6 sources are given in Table 1 and hereafter we will refer to them by their numerical listing as given in Table 1. The data handling, preparation and analysis was carried out with the MIDAS/EXSAS and the XSPEC version 8.33 software. The source + background counts for each object were extracted from a circle with a radius commensurate with the point response function of the telescope at that particular position within the detector. Background counts were extracted from a source free annulus centered on the program object where applicable otherwise a source free circle adjacent to the program object was utilized. The background subtracted, vignetting, and dead time corrected counting rates in the 0.1−2.4 keV energy band are $(6.7\pm0.3)\times10^{-2}$, $(4.7\pm0.2)\times10^{-2}$, $(1.43\pm0.04)\times10^{-1}$, $(4.1\pm0.2)\times10^{-2}$, $(2.1\pm0.2)\times10^{-2}$, and $(5.2\pm0.3)\times10^{-2}$ counts cm$^{-2}$ sec$^{-1}$ for source 1–6, respectively. We searched the available on-line catalogs and examined the fields of these 6 sources on the ESO Southern Survey Plates. Candidate optical counterparts for the 6 point sources are found in the *Digitized Sky Survey* (DSS) of the Space Telescope Science Institute (STSI) [Figs. 2(a)–(f)]. We chose the brightest objects within the x-ray error circle as the prospective optical counterparts of the x-ray point sources in which all but one case (source 5) are also the objects closest to the center of the error circle. Four of the objects, sources 2, 3, 5, and 6 are also found in the *Guide Star Catalog* (GSC) within the x-ray error circle. The DSS optical counterparts for the other 2 (sources 1 and 4) are not listed in the GSC and it may be due to the known incomplete sampling in the GSC near very bright stars. The $V$ band optical magnitudes, $m_V$, for these 2 sources are estimated by comparing the luminosity of the sources with that of nearby GSC sources. In the case of source 5, where the selected candidate optical counterpart is not the closest to the center of the x-ray error circle, the $V$ band magnitude for the optical counterpart would decrease by $\sim 0.5$ if the object located closest to the center of the x-ray error circle was selected as the candidate optical counterpart. This difference would not impact the results we are presenting here. The GSC and DSS counterpart positions and the magnitudes are given in Table 1.

The vignetting, dead time corrected and background subtracted light curves for the 6 x-ray point sources are displayed in Fig. 3. The variability is tested by comparing the distribution of countrates in the light curve with normal statistical distributions. The probability that the source intensity is constant at the mean countrates is $\leqslant 1\%$ for the source 1 and 3 while for sources 2, 4, 5, and 6 the probability that the flux is constant is only 6%, 1%, 4%, and 7%, respectively. The time scales of the intensity variations are $\sim 30$ minutes – a few hours and are apparent for sources 1 and 3 while the time scales for the other 4 point sources are more ambiguous but not inconsistent with the behavior observed in sources 1 and 3. This variability time scale is consistent with that of T Tauri stars (Walter & Kuhi 1984) (see Sec. 4 for the detail).

The observed counting rates from the sources provided sufficient photons (on the order of $\sim 10^2-10^3$) during the observation that statistically meaningful spectral fits were possible. A two temperature Raymond-Smith model (Raymond & Smith 1977) was necessary to adequately describe the spectral distribution of counts for all of the 6 point sources (Fig. 4). A single temperature Raymond-Smith yielded large reduced $\chi^2$ and was found to be statistically improbable as an adequate description of the underlying source distribution. The best fitting parameters for

TABLE 1. The x-ray determined and optical counterparts positions from the GSC (*Guide Star Catalog*) and the DSS (*Digitized Sky Surveys*) for sources 1–6. The optical magnitudes $m_V$ for the GSC sources are as given in the catalog and $m_V$ for the DSS sources are estimated by comparing the apparent luminosity with nearby GSC sources.

| Source | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $\alpha_X$(J2000) | $12^h46^m40.85^s$ | $12^h46^m22.59^s$ | $12^h48^m30.87^s$ | $12^h48^m54.40^s$ | $12^h48^m29.89^s$ | $12^h49^m24.26^s$ |
| $\delta_X$(J2000) | −59°31′ 43.4″ | −59°34′ 38.8″ | −59°44′48.3″ | −59°49′ 48.1″ | −60°02′ 28.3″ | −59°13′ 18.9″ |
| Optical Counterparts | √ | √ | √ | √ | √ | √ |
| $\alpha_O$(J2000) | $12^h46^m41.0^s$ | $12^h46^m23.0^s$ | $12^h48^m31.6^s$ | $12^h48^m54.6^s$ | $12^h48^m32.3^s$ | $12^h49^m24.4^s$ |
| $\delta_O$(J2000) | −59°31′ 41″ | −59°34′ 38″ | −59°44′ 49″ | −59° 49′ 45″ | −60°02′ 43″ | −59°13′ 11″ |
| $m_V$ | 12.3 | 9.54 | 10.76 | 13.3 | 13.0 | 12.86 |
| Catalog | DSS | GSC8659−702 | GSC8659−1804 | DSS | GSC8988−106 | GSC8659−2351 |

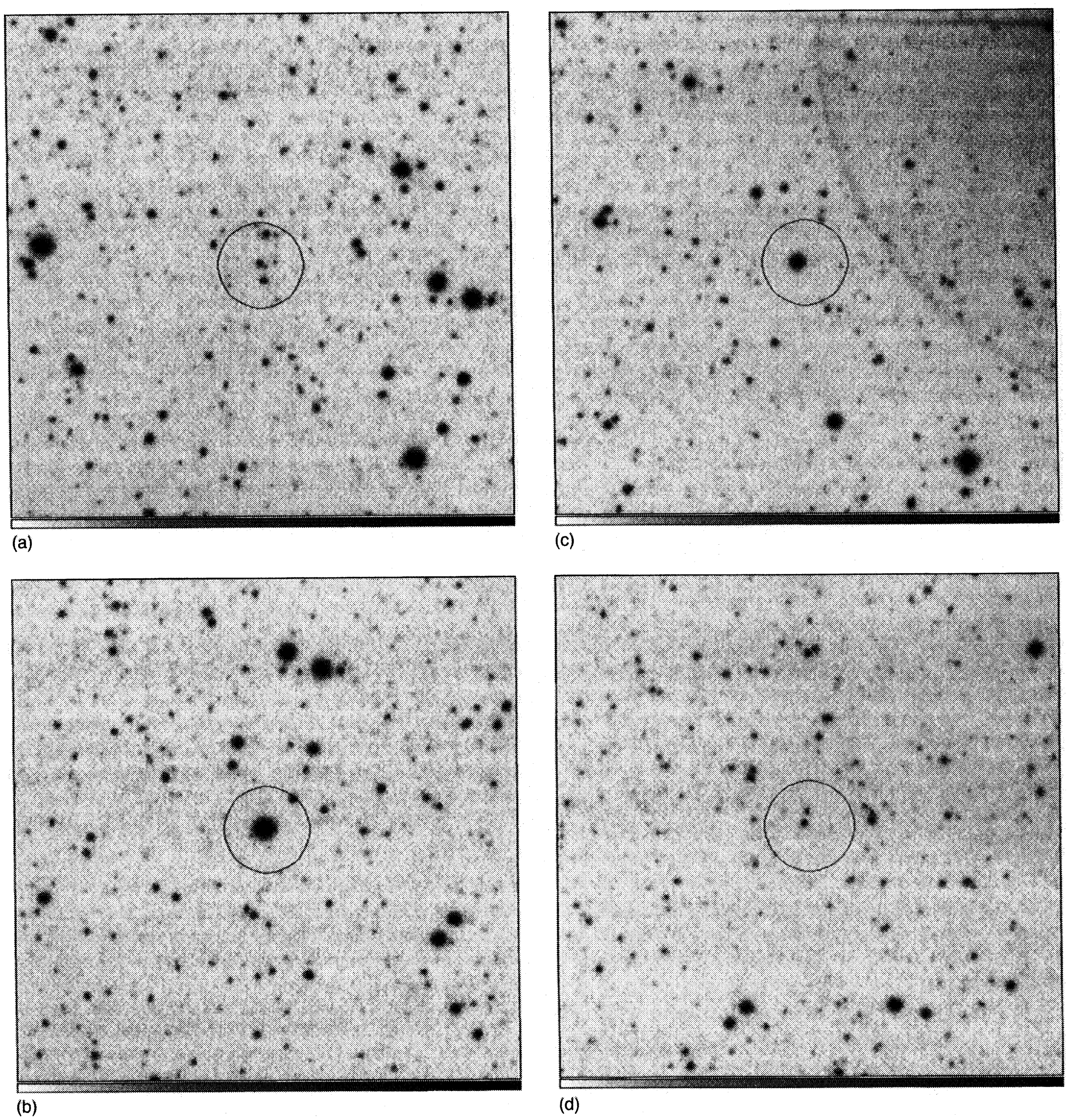

FIG. 2. Greyscale DSS images of the optical counterparts for the 6 x-ray point sources 1–6 (a–f). Each image has a 7.5′×7.5′ field of view centered at the position of the x-ray source. The circle indicates the error in the position of the x-ray point source and the cadidate optical counterpart is the brightest object within the x-ray error circle. With the exception of source 5, these brightest objects are also located closest to the center of the x-ray error circle.

each of the 6 point sources are given in Table 2. The spectral distribution of the diffuse x-ray emission as primarily observed in the M band (0.5–1.0 keV) (Fig. 6) is also studied. Because of its relatively large scale structure ($\geqslant$0.5 degree$^2$) and the embedded point sources we selected 3 different subsections over the whole emission region and tried several nearby circular regions for the background subtraction. A Raymond-Smith model can describe this diffuse emission with best fitting parameters of $N_H \sim 8\times10^{21}$cm$^{-2}$ and $T \sim 1.6$ million K with a reduced $\chi^2 \sim 1.4$.

## 3. DISCUSSION

T Tauri stars are bright x-ray sources and well known as x-ray variables (Gahm 1980; Montmerle *et al.* 1983; Feigelson & DeCampli 1981; Walter & Kuhi 1984; Strom *et al.* 1990). Variability on various time scales has been studied by Walter & Kuhi (1984). On short time scales (30 minutes–hours), any strong variability is likely due to flaring events and emergence and rearrangement of loop structures in corona. On time scales of days variations may be due to rota-

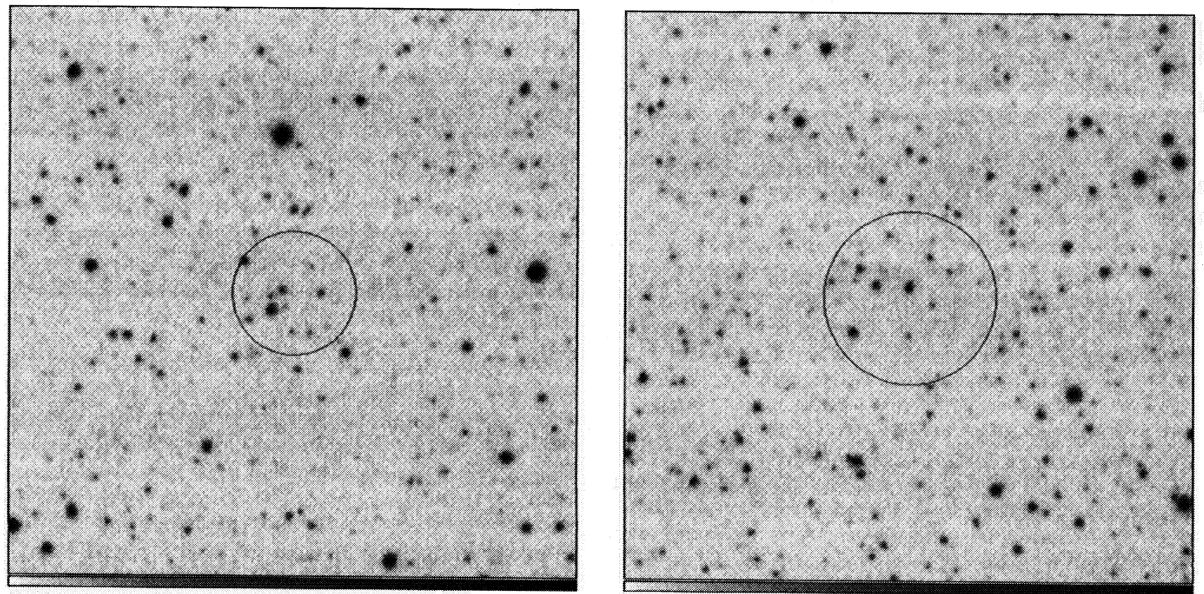


FIG. 2. (continued)

tional modulation of the x-ray flux. On longer time scales of years, variability may be associated with the changes in the magnetic flux or flux distribution at the stellar surface. The x-ray variability of the 6 bright x-ray point sources on time scales of ~30 minutes–a few hours are consistent with that of T Tauri stars due to flaring events.

The spectra for all of the 6 point sources have the same structure and a two component Raymond-Smith model is found to adequately describe the spectral distribution of their counting rates. The best fit values for the high temperature component is evidence of the existence of an $\sim 10^7$ K corona, which is observed in other T Tauri stars (Walter & Kuhi 1984). The need of the low temperature component is, however, more like that of young low mass star clusters such as the Pleiades [cf. Caillault (1994) and references therein] (see below for more discussion).

The observed optical counterparts of the 6 x-ray point sources allow a determination of $f_X/f_V$, the ratio of x-ray to

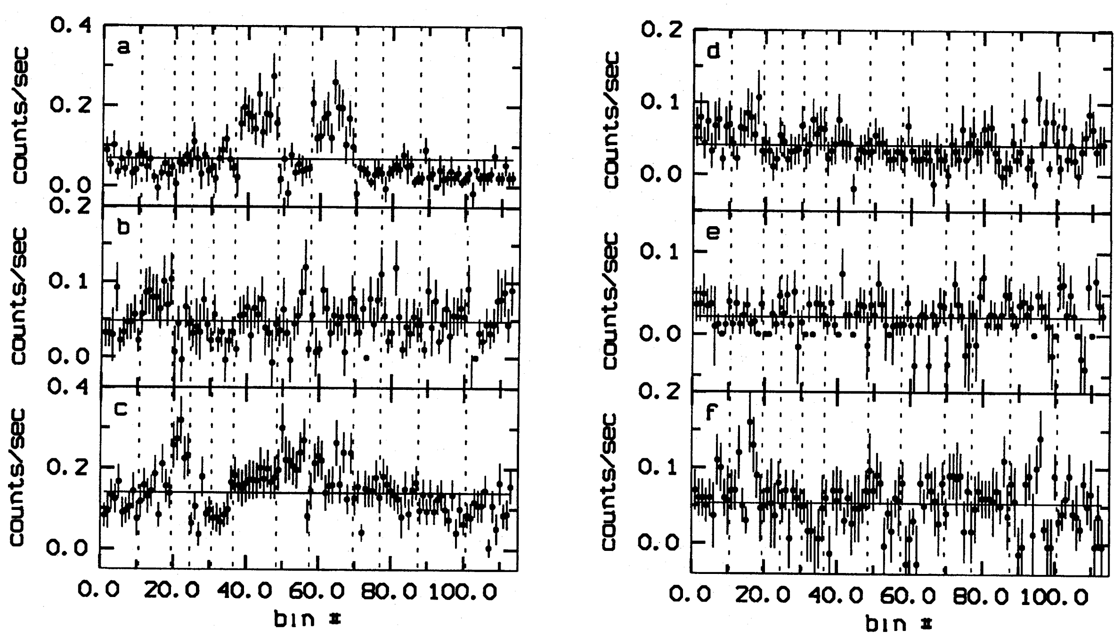


FIG. 3. The vignetting corrected, deadtime corrected and background subtracted light curves for the x-ray point sources 1–6 (a–f). Each bin is a 100 sec integration and the gaps in the data have been suppressed for purposes of display. The vertical dashed lines correspond to the gaps in the observation. The horizontal solid lines are the mean counting rates. The effective exposure time is 12,401 sec.

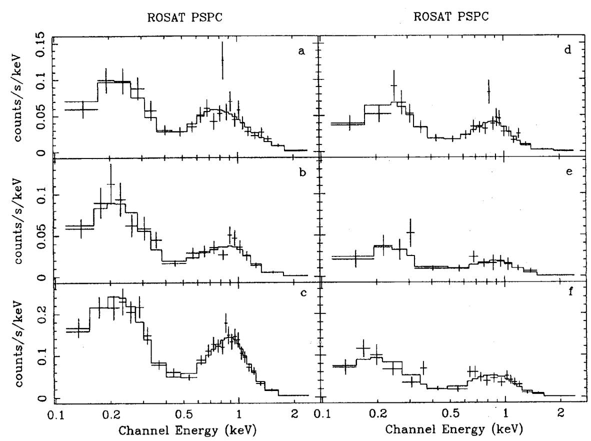


FIG. 4. The vignetting corrected, deadtime corrected and background subtracted spectra for the x-ray point sources 1–6 (a–f). The histogram is the best fitting model from Table 2.

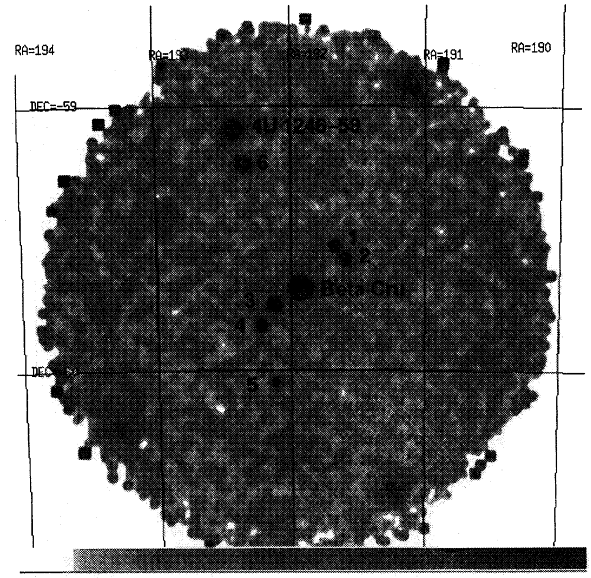


FIG. 5. The vignetting, dead time corrected and flat-fielded C band (0.1 – 0.3 keV) count rate map of the *ROSAT* PSPC field under investigation. The grid marks the J2000 equatorial coordinates with *N* up and *E* to the left. $\beta$ Cru, the LMXRB 4U 1246−58, and the 6 x-ray point sources are labeled on the figure. The greyscale corresponds to the range 0 to 1.6 × $10^{-3}$ counts $\sec^{-1}$ $\mathrm{arcmin}^{-2}$.

*V* band optical flux. Provided the optical flux for a zero magnitude star in the *V* band, $f_0=3.6\times10^{-6}$ ergs $\mathrm{cm}^{-2}$ $\sec^{-1}$ the fluxes of the optical counterparts with known apparent magnitudes are calculated to be $f_{V1}=4.33\times10^{-11}$, $f_{V2}=5.50\times10^{-10}$, $f_{V3}=1.79\times10^{-10}$, $f_{V4}=1.72\times10^{-11}$, $f_{V5}=2.27\times10^{-11}$, and $f_{V6}=2.58\times10^{-11}$ ergs $\mathrm{cm}^{-2}$ $\sec^{-1}$ for sources 1–6 respectively. With the estimated x-ray fluxes of the 6 point sources in the 0.1–2.4 keV energy band (Table 2), the x-ray to *V* band optical flux ratios are determined and displayed in Table 2. The observed x-ray to *V* band optical flux ratios for T Tauri stars are in the range of $\sim10^{-2}$–$10^{-3}$ based on the x-ray data of Walter (1986), Feigelson & DeCampli (1981), and Feigelson *et al.* (1993) (We assume a bolometric correction of $f_{\mathrm{bol}}\sim5$ $-10\times f_V$ hereafter.) These values are in good agreement with the estimated x-ray to V band optical flux ratios of the 6 x-ray point sources.

The existence of hot coronae, the observed variability, and the x-ray to *V* band optical flux ratios lead us to conjecture that the 6 point like sources are candidate T Tauri stars. In addition, and in support of this conjecture, archival *IRAS* 100 $\mu$m maps of this region display large scale structure indicative of the presence of molecular gas. We have overlaid the *IRAS* 100 $\mu$m contours on our x-ray map for comparison (see Fig. 7) and the observed morphology is not inconsistent with expectation if we are observing a star forming region.

Assuming these point sources are T Tauri stars, we can estimate their distance. Observed x-ray luminosities of T Tauri stars are mostly in the range of $\sim10^{29}$– a few $10^{31}$ ergs $\sec^{-1}$ (Walter & Kuhi 1984; Feigelson & DeCampli 1981; Feigelson *et al.* 1993). Taking a typical x-ray flux for a T Tauri star as $L_X\sim10^{30}$ ergs $\sec^{-1}$, we derive a distance to these sources of $\sim$100–250 pc. The estimated $N_H$ value ($\sim8\times10^{21}$ $\mathrm{cm}^{-2}$) for the M band diffuse emission is greater by at least an order of magnitude compared with the best fitting $N_H$ values for the point sources (Table 2), which implies the diffuse emission is unrelated to the point sources. This $N_H$ difference and the observed anticorrelation between the M band x-ray image and the *IRAS* 100 $\mu$m contours (Fig. 7) suggest that the morphology of the M band x-ray data is a result of shadowing of a local enhancement of the Galactic soft x-ray background due to the foreground molecular gas. Combining the derived distance scale to the point sources with the M band x-ray shadowing and the lack of any shadow in the C band (0.1–0.3 keV) x-ray map (Fig. 5) due to the molecular gas, the hypothesis that the point sources and the molecular gas are co-spatial is supported.

The weak T Tauri stars (WTTS) or naked T Tauri stars

TABLE 2. The best fitting two component Raymond-Smith thermal plasma model for each of the sources 1–6. The values in parentheses are the 90% confidence level limits on the parameter and a uc entry corresponds to an unconstrained value. The $f_X/f_V$ value utilizes the optical magnitude as given in Table 1.

| Source | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| reduced $\chi^2$ | 1.10 | 0.82 | 0.79 | 0.87 | 0.71 | 1.55 |
| $N_H(10^{20}\ \mathrm{cm}^{-2})$ | 1.1(0.4−5.8) | 1.0(0.1−7.1) | 1.0(0.3−5.1) | 6.0(0.5−8.8) | 2.0(uc−10.9) | 0.4(uc−2.2) |
| $T_l$ ($10^6$ K) | 3.4(1.2−6.7) | 2.1(0.6−5.1) | 2.0(0.9−4.4) | 1.0(0.9−3.6) | 1.7(uc) | 3.5(1.1−9.6) |
| $T_h$ ($10^6$ K) | 22.3(1.2−uc) | 11.5(8.7−63.1) | 10.3(8.8−14.0) | 8.8(6.1−12.2) | 10.9(uc) | 11.8(1.1−uc) |
| $EM_l/EM_h$ | 0.3(0.2−uc) | 0.6(0.1−31.7) | 0.4(0.2−7.4) | 9.8(0.2−60.4) | 0.7(uc) | 0.5(0.1−2.7) |
| $f_X$ (ergs $\mathrm{cm}^{-2}$ $\mathrm{s}^{-1}$) | $6.41\times10^{-13}$ | $3.96\times10^{-13}$ | $11.95\times10^{-13}$ | $3.94\times10^{-13}$ | $1.83\times10^{-13}$ | $4.42\times10^{-13}$ |
| $f_X/f_V$ | $10^{-1.83}$ | $10^{-3.15}$ | $10^{-2.17}$ | $10^{-1.64}$ | $10^{-2.09}$ | $10^{-1.77}$ |

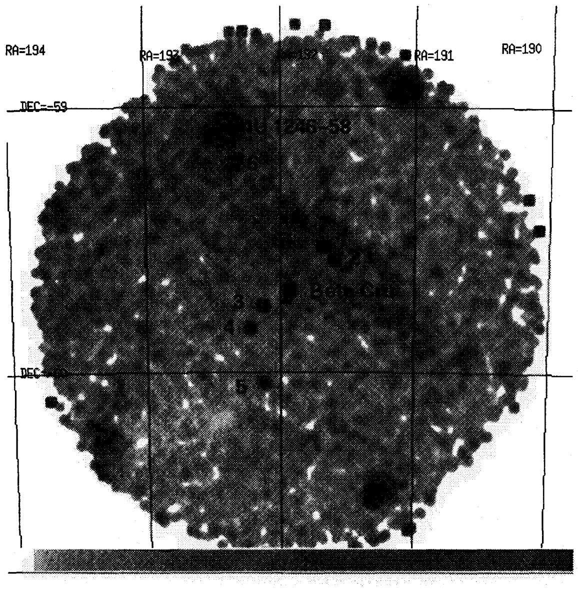


FIG. 6. The vignetting, dead time corrected and flat-fielded M band (0.5 – 1.0 keV) count rate map of the *ROSAT* PSPC field. The greyscale corresponds to the range 0 to 1.1 × $10^{-3}$ counts $sec^{-1}$ $arcmin^{-2}$.

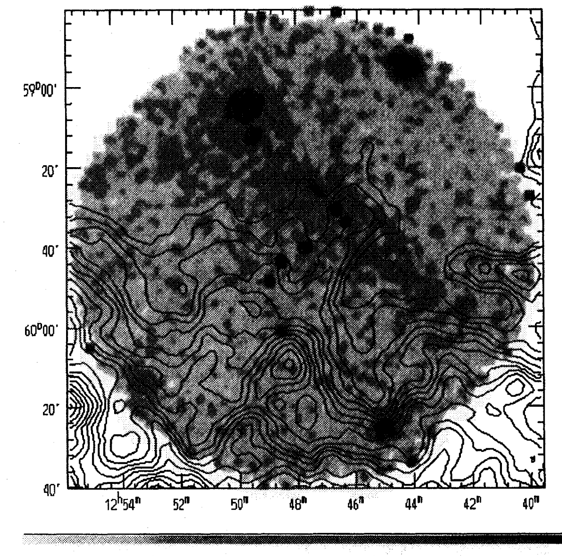


FIG. 7. The *IRAS* 100 $\mu$m contours superposed on the M band x-ray image. The *IRAS* contours are from 80 to 132.5 MJy/sr in intervals of 2.5 MJy/sr. The greyscale for the x-ray image displays the same range of counting rates as Fig. 6.

(NTTS) tend to be found at the edge of a star formation region (Walter 1986) and have relatively high mean $f_X/f_V(\sim 10^{-2.36}-10^{-2.66})$ compared with the classical T Tauri stars (CTTS) $(\sim 10^{-3.05}-10^{-3.35})$ (Neuhäuser *et al.* 1994; cf. Caillault 1994). We conjecture that the 6 point sources are WTTS rather than CTTS owing to their presence at the edge of a molecular cloud (Fig. 7) and the high mean $f_X/f_V$ $(\sim 10^{-2})$ of the 6 point sources. However, $f_X/f_V$ for source 2 $(\sim 10^{-3.15})$ is more like one for a CTTS. This indicates that we may be observing a mixed population of WTTS and CTTS. However, the WTTS (or NTTS) are distinguished from CTTS more strictly in their lack of circumstellar envelopes which manifests itself in the absence of H$\alpha$ line emission and infrared excesses in the stellar spectrum. Considering the presence of a $\beta$ cephei variable star ($\beta$ Cru) in this star forming region we speculate, assuming these candidate T Tauri stars and $\beta$ Cru are coeval, that the age of the 6 candidate T Tauri stars are $\sim$ a few $\times 10^7$ years. This likely age scale and the need of a two temperature model for the proper spectral description of the observed counting rates of the point sources might imply that these point sources are a relatively older population of T Tauri stars (approaching close to the main sequence). Follow up *R* and *I* band and H$\alpha$ emission line observations will be necessary to sort out the relative populations of these active young stars in this region.

## 4. SUMMARY AND CONCLUSION

During an observation of the B0.5 III $\beta$ cephei variable $\beta$ Cru with the *ROSAT* PSPC, some 20 previously unidentified x-ray point sources and diffuse emission were observed. The identification of 6 of these point sources as T Tauri stars is suggested on the basis of the temporal variation (on time scale of $\sim$ 30 minutes–a few hours) of the x-ray intensity, the spectral description implying the existence of hot coronae, the estimated x-ray to *V* band optical flux ratio, and the presence of surrounding molecular gas (as observed by *IRAS* 100 $\mu$m data). The diffuse emission structure observed in the M band is likely not related to the 6 point sources due to the high $N_H$ value derived from the spectral analysis and we conclude, according to the observed anticorrelation between the M band x-ray and the *IRAS* 100 $\mu$m data, that the M band diffuse structure is a result of the x-ray shadowing by foreground molecular gas. The x-ray shadowing in the M band, the absence of any shadow in the C band data, and the estimated distance scale ($\sim$100–250 pc) of the point sources (provided they are T Tauri stars) support the co-spatial location of the 6 point sources and $\beta$ Cru (distance $\sim$ 150 pc) in the molecular gas. We thus speculate that we are observing a previously unknown active star formation region centered on $\beta$ Cru. We finally conjecture that these candidate T Tauri stars are WTTS rather than CTTS based upon their location at the edge of a star forming molecular cloud and their relatively high x-ray flux to *V* band optical flux ratio.

Follow-up optical observations such as H$\alpha$ emission line and *R* and *I* band observations will be necessary for a detailed identification of these point sources and to ascertain if these sources are members of a young stellar cluster in this region. In addition, although we argued the M band diffuse emission likely shows an x-ray shadowing by the foreground molecular gas, the anticorrelation between x-ray and infrared observations in Fig. 7 is straightforward only in the southeast of $\beta$ Cru and is less convincing in the northwest. The determination of the detailed nature of this diffuse emission will require further study.

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