X-rays and Protostars in the Trifid Nebula

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ABSTRACT

The Trifid Nebula is a young HII region recently rediscovered as a “pre-Orion” star forming region, containing protostars undergoing violent mass ejections visible in optical jets as seen in images from the Infrared Space Observatory and the Hubble Space Telescope. We report the first X-ray observations of the Trifid nebula using ROSAT and ASCA. The ROSAT image shows a dozen X-ray sources, with the brightest X-ray source being the O7 star, HD 164492, which provides most of the ionization in the nebula. We also identify 85 T Tauri star and young, massive star candidates from near-infrared colors using the JHK_s color-color diagram from the Two Micron All Sky Survey (2MASS). Ten X-ray sources have counterpart near-infrared sources. The 2MASS stars and X-ray sources suggest there are potentially numerous protostars in the young HII region of the Trifid. ASCA moderate resolution spectroscopy of the brightest source shows hard emission up to 10 keV with a clearly detected Fe K line. The best model fit is a two-temperature \( T = 1.2 \times 10^6 \) K and \( 39 \times 10^6 \) K) thermal model with additional warm absorbing media. The hotter component has an unusually high temperature for either an O star or an HII region; a typical Galactic HII region could not be the primary source for such hot temperature plasma and the Fe XXV line emission. We suggest that the hotter component originates in either the interaction of the wind with another object (a companion star or a dense region of the nebula) or from flares from deeply embedded young stars. 

Subject headings: HII regions - Stars: formation - X-rays: individual (Trifid Nebula) - infrared:Stars
1. Introduction

H II regions contain various types of X-ray emitting sources such as high- and low-mass stars, binaries, and protostars. Single massive O and B stars emit soft X-rays from shocks in their radiatively unstable, outwardly moving outer atmospheres. X-ray emission from late-type stars is attributed to magnetically heated stellar coronae and magnetically-driven stellar flares. Protostars produce X-rays via magnetic heating, and perhaps from accretion or excretion disks and/or interaction of stellar jets with the circum-nebular gas. Massive binaries can produce X-ray emission from colliding stellar winds; close low-mass binaries can produce X-rays via mass exchange and enhanced dynamo action. X-ray emission provides a sensitive tracer of these different stellar populations, and along with infrared colors, is one of the main probes to identify protostars and pre-main-sequence (PMS) stars.

Studies of X-ray emission from H II regions/star forming regions have recently made significant advances due to ROSAT (Casanova et al. 1995), ASCA (e.g., Koyama et al. 1996), and most recently Chandra observations (Garmire et al. 2000). For example, in the ρ Oph core region, 70% of the near-infrared sources associated with protostars and molecular cores have X-ray counterparts (Casanova et al. 1995), and a large number of X-ray sources are found to be low-mass PMS stars in other star forming regions such as Orion (Alcalá et al., 1997), Chamaeleon (Alcalá et al., 1996; Feigelson et al. 1993), Lupus (Krautter et al. 1997), and Taurus-Auriga (Neuhüser et al. 1995; Wichmann et al. 1997). Flare-like X-ray events have been detected from T Tauri stars (Kamata et al. 1997; Koyama et al. 1994). The X-ray emitting sources in the Monoceros and Rosette molecular clouds are also mostly T Tauri and Herbig Ae/Be stars and they typically show luminosities of $L_x \sim 10^{30} - 10^{32}$ ergs s$^{-1}$ (Gregorio-Hetem et al. 1998). Recent Chandra observation of the Orion Nebula resolved a thousand X-ray emitting PMS stars with a mass range of 0.05 $M_\odot$ to 50 $M_\odot$, and a combined infrared and X-ray study suggested that the X-ray luminosity depends on stellar mass, rotational history, and magnetic field (Garmire et al. 2000).

At a distance of 1.67 kpc (Lynds et al. 1985), the Trifid Nebula, M 20, is one of the best-known astrophysical objects and one of the prettiest: it glows brightly in red light and is trisected by obscuring dust lanes. At an age of $\sim 3 \times 10^5$ years, the Trifid is one of the youngest known H II regions. Observations with the Infrared Space Observatory (ISO) and the Hubble Space Telescope (HST) show the Trifid as a dynamic, “pre-Orion” star forming region containing young stars undergoing episodes of violent mass ejections, and protostars (like HH399) losing mass and energy to the nebula in optically bright jets (Cernicharo et al. 1998, hereafter CLC98; Lefloch & Cernicharo 2000; Hester et al. 1999). The ionization of the nebular gas is
dominated by the O7.5 star HD 164492. HD 164492 is a luminosity class V (Levato 1975) or III (Conti & Alschuler 1971) star with a bolometric luminosity of $L_{bol} \sim 0.5-1.6 \times 10^{39}$ ergs s$^{-1}$ and an X-ray luminosity of $6 \times 10^{32}$ ergs s$^{-1}$ (Chlebowski et al. 1989). The mass loss rate of this O star is $\dot{M} = 2 \times 10^{-6}$ M$_{\odot}$ yr$^{-1}$ (Howarth & Prinja 1989) and the wind terminal velocity is $V_\infty = 1580$ km s$^{-1}$ (Prinja, Barlow, & Howarth 1990).

X-ray observations of the Trifid offer a unique opportunity to study the influence of a massive star on star formation in an exceptionally young star forming region. Initially X-ray emission from the Trifid was reported only from the O star in the Einstein IPC catalog (Chlebowski et al. 1989). We serendipitously discovered a complex of X-ray emission from the Trifid Nebula in a PSPC observation of the nearby supernova remnant W28 (Rho et al. 1995). Subsequently, we started an extensive investigation of the X-ray emission from the Trifid Nebula. In this paper, we present the first detection of a dozen X-ray sources in the Trifid Nebula, and we correlate these with protostar candidates identified using the Two Micron All Sky Survey (2MASS) data. The ROSAT images show multiple point sources including HD 164492 and several T Tauri stars, and the ASCA spectra show hard X-ray emission including detection of an Fe K line. We discuss identifications of the X-ray emitting sources and the origin of the unusually hard X-ray emission from the Trifid.

2. X-ray Sources in the Trifid

2.1. X-ray Observations

The Trifid Nebula was observed using the X-ray telescope on ROSAT (Trümper 1993) with the Position Sensitive Proportional Counter (PSPC) as the imaging detector. The PSPC on-axis angular resolution is 25$''$ (FWHM, at 1 keV), and the PSPC covers a 2$^\circ$ field of view in the 0.1–2.4 keV energy band. Two PSPC observations were analyzed for this paper: rp900375 centered on HD 164492 and observed on 1993 September 8 for an exposure of 9,365 s (PI: S. Snowden), and rp500236 centered on the supernova remnant W28 and observed on 1993 April 1 for an exposure of 10,476 s (PI: R. Pisarski; Rho et al. 1995).

We also performed an ASCA observation (PI: J. Rho; sequence number 26051000) toward the center of the Trifid Nebula. The observation took place on 1998 September 30 to October 2. ASCA (Tanaka 1992) has two detector pairs: Gas Imaging Spectrometers (GIS2 and GIS3) and Solid-state Imaging Spectrometers (SIS0 and SIS1). The SIS covers an energy band of 0.5–10 keV and the GIS 0.6–10 keV. The on-axis
angular resolution of the GIS and SIS is about 1–2 arcminutes. Each GIS counter has a circular field of view of 35′ diameter while the field of view of each SIS CCD is an 11′ square, and thus both GIS and SIS detectors sufficiently cover the entire Trifid Nebula. We filtered the data using a few criteria such as Cut off Rigidity (COR) and earth elevation (based on Revision 2 processing). After filtering, the exposure time was 57 ks for the GIS and 53.5 ks for the SIS. The entire Trifid Nebula region after background subtraction has count rates of 0.050±0.001 cts s$^{-1}$ for SIS0, 0.040±0.001 cts s$^{-1}$ for SIS1, 0.030±0.008 cts s$^{-1}$ for GIS2, 0.039±0.009 cts s$^{-1}$ for GIS3, and 0.086±0.004 cts s$^{-1}$ for the ROSAT PSPC, in their respective energy bands (integrated over all channels).

### 2.2. X-ray Source Identification

The ROSAT PSPC image of the Trifid Nebula is shown in Figure 1. This image for the first time reveals that the Trifid Nebula contains numerous X-ray sources. We have identified X-ray sources in the PSPC image using the FTOOLS task SRCDETECT and estimated the count rates and uncertainties. The detected point sources are presented, in order of increasing right ascension, in Table 1 and marked in Figure 1. Table 1 lists the position, count rate, and σ of detection for ten sources detected at > 3σ and two possible sources (sources 11 and 12) detected with somewhat lower confidence. We here define new X-ray sources detected in ROSAT PSPC image, as ROSAT X-ray source in the Trifid (RXT). Since the count rate is very small except for the O star HD 164492, we estimated the luminosity by assuming an absorption column density $N_H = 3 \times 10^{21} \text{cm}^{-2}$ ($A_V \sim 1.5^m$, see Section 4 for details), and a thermal spectrum with $kT=1 \text{ keV}$. The X-ray emission of PMS stars is understood to be thermal emission from gas rapidly heated to a temperature of $\sim 1 \text{ keV}$ by violent magnetohydrodynamical reconnection events (Feigelson & Montmerle 1999). The correspondence between the PSPC count rate and the X-ray unabsorbed flux is $1 \times 10^{-3} \text{ PSPC cts s}^{-1} \sim 2.95 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2}$. Using this conversion, the luminosities of the X-ray sources are computed and given in Table 1.

We have examined the source list database using SIMBAD, identified counterparts to the X-ray sources at other wavelengths, and marked them in Figure 1. To visualize the correspondence of X-ray sources with either optical or radio sources, we have plotted the X-ray contours over an Hα image (F. Winkler, private communication) in Figure 1. Twenty-four sources from the Guide Star Catalog (GSC) are visible in the Hα image in Figure 2. The brightest X-ray point source, RXT8 in Table 1, corresponds to the O star HD 164492. The possible X-ray source RXT11 coincides with the B8 star HD 313596 (R.A. 18$^h$02$^m$35$^s$
and Dec. $-22^\circ 59'54''$), and the possible X-ray source RXT12 with the optical star GSC.J06842.00001 (R.A. $18^h02^m34.8^s$ and Dec. $-23^\circ 03'06.3''$). None of the other GSC stars coincide with X-ray peaks. A radio source, GPSR5 6.980–0.286 (R.A. $18^h02^m28.1^s$ and Dec. $-23^\circ 03'46.3''$; Becker et al. 1994), is close to the X-ray emitting area, but does not have a corresponding X-ray peak. Four protostars (TC0, TC1, TC3 and TC4 sources in CLC98) have been reported in the Trifid Nebula (CLC98), which are marked in Figure 1, but only one is close to the X-ray peak at HD 164492. In the next section we correlate the PSPC X-ray sources with sources showing near-infrared color excesses, and present candidate protostars.

3. Near-Infrared Sources from 2MASS: Young Stellar Objects

We have identified Young Stellar Objects (YSOs) using the Two Micron All Sky Survey (2MASS) data (Skrutskie et al. 1997). Using identical telescopes in the northern and southern hemispheres, 2MASS is mapping the entire sky in the J (1.11-1.36 $\mu$m), H (1.5-1.8 $\mu$m) and K$_s$ (2-2.32 $\mu$m) bands to a limiting point source sensitivity of approximately 16.5 mag, 16.0 mag, and 15.5 mag, respectively (Cutri et al. 2000). The data towards the Trifid Nebula were taken on 1998 June 14 using the southern telescope, and most of these data were included in the 2MASS Second Incremental Release, but a small portion of area was in the 2MASS Working Database due to large photometric uncertainties at the time of the Incremental Release. The photometry is typically better than 5% (Cutri et al. 2000).

We used the 2MASS point source catalog to extract sources within an 8-arcmin radius centered on R.A. $18^h02^m30^s$ and Dec. $-23^\circ 02'00''$. We have selected sources with the following criteria. First, we selected the sources which were detected in all three J, H, and K$_s$ bands. We then selected sources with the signal to noise ratio greater than 10 (i.e., the J, H and K$_s$ magnitudes are brighter than 15.8 mag, 15.1 mag, and 14.3 mag, respectively). These selections produced $\sim$1,100 such sources. We then accepted sources with photometric uncertainties $\sigma < 0.25$ mag whose fit to the point spread function produced reduced $\chi^2$ $\nu < 2$. This last criterion excluded blended sources that caused higher uncertainties in the photometry. This is important in the Galactic plane where near-infrared sources are crowded and the 2MASS has a limited spatial resolution ($3'5$). This criterion removed inaccurate blue points that appeared in the JHK$_s$ color-color diagram (as described below). The criteria we have used are conservative for the magnitude

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1The source designation TC0, TC1, etc. was assigned by CLC98. Since this designation was already in use, for indexing purposes these sources should be referred to as [CLC98] 0, etc.
limit and photometric uncertainties of the 2MASS survey.

We plotted the sources in the JHK$_s$ color-color diagram, as shown in Figure 3a, in order to identify YSOs with infrared color excess. Figure 3b shows H-K$_s$ vs K$_s$ magnitude for the selected sample. The interstellar reddening vector from Rieke & Lebofsky (1985) is also plotted. Adopting the intrinsic colors of giant and dwarf stars from Bessell and Brett (1988), we find the visual extinction towards this direction is as high as A$_V$=30 mag for stars on the back side of the Trifid Nebula. The observed JHK$_s$ colors of YSOs can be explained by circumstellar disk models (Lada & Adams 1992). We identified the T Tauri stars with (J-H)$_{CTTS}$ = 0.58±0.11×(H-K$_s$)$_{CTTS}$ +0.52±0.06 (Meyer et al. 1997) and H-K$_s$ >0.6 mag, where CTTS is classical T Tauri stars. These T Tauri stars fall between the two solid lines in Figure 3a. The stars below the extinction curve (dashed line in Figure 3a) and above the T Tauri star lines (solid line in Figure 3a) are massive YSOs (Lada & Adams 1992); these stars are plotted as diamonds in Figure 3a. In total, we found 41 T Tauri star candidates and 44 massive YSO candidates from the 2MASS sources which are listed in Table 2. The T Tauri stars and YSOs are generally located along the ionization front. Figure 3c shows optical images, and T Tauri stars, massive YSOs, and X-ray sources are marked. Figure 3d shows a color composite of the J, H and K$_s$ images, with the J image in blue, H image in green, and K$_s$ image in red. T Tauri stars, massive YSOs, and X-ray sources are marked. The image also shows a number of protostars at the ionization front along the dust lane.

These protostar candidates were cross-correlated with the X-ray sources. Taking into account the resolution of the PSPC, we identify a possible coincidence if the separation between a 2MASS source and an X-ray source is less than 15$''$. Three X-ray sources (RXT 1, 6, and 7) are coincident with either T Tauri stars or YSOs; they are noted in Table 3. Figure 3d shows that many red 2MASS stars within the X-ray source error boxes could be considered coincidences, but they are not included in the list of sources selected according to the aforementioned conservative criteria, as they are not detected in one or both of the J and H bands. Therefore, we have relaxed the selection criteria and extracted 2MASS sources from the same area excluding only sources with an artifact flag. We made a list of the 2MASS sources that are within 15$''$ from X-ray sources. Each X-ray source has ~10 2MASS counterpart candidates; only the red stars are identified as possible counterparts to the X-ray sources. Seven red 2MASS star counterparts of X-ray sources are identified and listed in Table 3, with J, H, and K$_s$ magnitudes and reasons that they were not selected in the earlier list of T Tauri star or massive YSO candidates (either J='fil' or high reduced $\chi^2$ indicating multiple or extended sources with large photometric uncertainties). These 7 sources are likely protostars because their infrared colors are red and they also emit X-rays. By itself, an infrared color excess indicates
either the presence of a YSO or a heavily extincted main-sequence star. The 2MASS counterparts of the X-ray sources are marked in the JHK\textsubscript{s} color-color diagram (Figure 3a) and on the 2MASS composite image (Figure 3d). A few X-ray sources do not have obvious optical or 2MASS counterparts.

There are five known massive YSOs in the Trifid with mid-infrared emission detected using ISO (CLC98). These protostars were not identified as proto-stellar candidates from the 2MASS data, probably because they are too deeply embedded to be detected in the near-infrared. A 2MASS red star is the counterpart of the protostar TC2 in CLC98; we expect there are large numbers of such embedded protostars in the Trifid Nebula not detected in the near-infrared observations. This population is likely correlated with highly extincted dust lanes (see Figure 3d) and molecular clouds.

4. X-ray Spectral analysis

The ASCA SIS image is shown in Fig. 4 with the PSPC contours superposed. The X-ray emission is dominated by the emission from the O star. We extracted ASCA and ROSAT spectra from the entire region of the Trifid Nebula. The spectrum (Fig. 5a) shows clear Fe K line emission along with weak Si and S lines, and a hard continuum tail up to 10 keV, the highest energy observable by ASCA. We extracted a background-corrected spectrum from a smaller region centered on HD 164492. HD 164492 is the brightest X-ray source in the Trifid, and the shape of the spectrum of the entire region in the ASCA data is not significantly different from the spectrum of this star alone due to the broad ASCA point spread function. We made hard (> 3keV) and soft (< 3keV) maps using the ASCA data, but no obvious difference was noticeable at the spatial resolution (1′) of ASCA. We also extracted an off-source ASCA spectrum in this direction, suspecting a contribution from the Galactic ridge emission. However, the off-source spectrum showed that the observed off-source emission is dominated by scattered emission from sources within the Trifid Nebula. The detection of hard emission from the Trifid is unusual, because most single O stars have very little emission at energies above 2 keV and rarely show Fe K emission (Corcoran et al. 1993). The only massive stars to show such hard X-ray spectra are binaries, either high mass X-ray binaries (HMXBs) with collapsed companions, or colliding wind binaries with non-collapsed (O or WR star) companions which have strong stellar winds and significant colliding wind X-ray emission.

We simultaneously fit the set of five spectra– the ROSAT/PSPC, ASCA/SIS0, SIS1, GIS2 and GIS3 spectra– using single- or two-temperature thermal models (Mewe-Kaastra plasma model; Kaastra 1992) with a single absorbing column density $N_H$. The fits were unacceptable (reduced $\chi^2$ of 3). We next
attempted a two-temperature model. Following Corcoran et al.’s (1994) models of δ Ori and λ Ori, we also included an additional ionized (“warm”) absorbing medium, as representative of the photoionized stellar wind material (Waldron 1984; Corcoran et al. 1994), and allowed different amounts of absorption for the hot and cold components. The line-of-sight extinction value is known toward this direction; $A_V = 1.3$-1.5 mag, i.e., $E(B-V) \sim 0.3$-0.4 mag (Kohoutek et al. 1999; Lynds & O’Neil 1985). Using $E(B-V)$ of 0.4 mag, we expect an ISM $N_H \sim 3 \times 10^{21}$ cm$^{-2}$, with which we have fixed the $N_H$ value in our fit (also note that when we allow $N_H$ to vary, $3 \times 10^{21}$ cm$^{-2}$ falls within the errors). The model yielded an acceptable fit with $kT_1 \sim 0.14$ keV ($1.2 \times 10^6$ K) and $N_{H,1} = 5.9 \times 10^{21}$ cm$^{-2}$, and a hotter component with $kT_2 \sim 3.3$ keV ($3.9 \times 10^7$ K) and $N_{H,2} = 2.7 \times 10^{21}$ cm$^{-2}$, with a line of sight ISM $N_H = 3 \times 10^{21}$ cm$^{-2}$. The abundances are fixed at solar abundances. The fit results are summarized in Table 4, along with the Fe K line characteristics. The cold component arises from the O star atmosphere but the hot component might arise from a number of different sources such as unresolved interacting binaries, active low mass stars, or PMS stars.

5. The Nature of The Hard X-ray Component

Our simultaneous ASCA/PSPC fits yield a total X-ray luminosity of $1.9$-$2.5 \times 10^{34}$ erg s$^{-1}$ (0.3-10 keV) using the two-temperature model shown in Table 4. If attributed to HD 164492, then the ratio of X-ray and bolometric luminosities ($=\log L_x/L_{bol}$) is between $-5.0$ and $-4.5$, which is much higher than the typical ratios of log $L_x/L_{bol} \sim -7$ for a single O-type star (Chlebowski 1989; Berghöfer et al. 1996). The 3 keV X-ray component is somewhat of a mystery, since winds from single O-type stars are not known to produce such high temperature emission. Typically the highest temperature emission observed in O star X-ray spectra has $kT < 1$ keV (e.g., Corcoran et al. 1994).

We discuss a few possibilities to explain the hot component in the Trifid Nebula. It may be that the hot component arises in the interaction of the wind from the O7.5 star with another object (either a companion star or a dense region of the nebula) outside the O star atmosphere. Colliding winds between an early-type star and an early-type companion (another O star or a Wolf-Rayet star) can produce shock-heated material in the wind interaction regions (Stevens et al. 1992) reaching temperatures of $10^7$ – $10^8$ K, and emit X-rays. However, recent photometric and spectroscopic studies of this region found no evidence of a companion for HD 164492 (Kohoutek, Mayer & Lorenz 1999). Unless the collision occurs far from the star ($d > 25''$) it will be unresolved to the ROSAT PSPC. However, recent radio and near-infrared observations toward the
central region of the Trifid detected 3 sources close to the O star (Yusef-Zadeh et al. 2000) which may be either stars or nebular knots photoionized by the UV field of HD 164492.

Hard emission could also arise in single O stars from non-thermal emission produced by Fermi acceleration by shocks in the O star wind (Chen & White 1991). The hard component is suggested as a non-thermal tail produced by inverse Comptonization of the photospheric UV field by a population of fast particles accelerated by a distribution of shocks. Although it is not possible to determine if the hard emission is from a non-thermal tail or the two thermal temperature component from goodness of the fit to the spectra, the presence of the Fe K line suggests that the second component is thermal. The sources of the two spectral components need to be resolved spatially in order to determine their origins. Enhanced hard X-ray emission might also be produced by an oblique magnetic rotator as suspected in another O7 star, θ1 Orionis C, the central star of the Orion nebula (Gagné et al. 1997).

The X-ray properties of the core of the HII region W3 share a number of similarities to the Trifid emission: for W3, the luminosity is a few $10^{33}$ erg s$^{-1}$ with a similarly high temperature (Hofner & Churchwell 1997). In W3 (and possibly in the Trifid), the high temperature component may be produced by a hot, wind-shocked cavity that results when strong stellar winds interact with a surrounding dense molecular cloud (e.g. Churchwell 1990). The presence of a known young stellar object (TC1 in CLC98) is consistent with the presence of a molecular cloud in the Trifid. In addition, IRAS observations of HD 164492 (van Buren et al. 1995) show a bow-shock structure around the star, perhaps indicative of a wind-cloud collision which might produce the high temperature X-ray emission. The stellar wind outflow at a speed of 1600 km s$^{-1}$ should produce a post-shock temperature of $\sim$30 million degrees, though the observed temperature may be lower since radiative cooling is rapid. CLC98 suggested that the HCO$^+$ molecular clouds (likely the dust lanes) are fragmented shell around the nebula. In other words, the clouds and dust lanes we see in the optical image are located at the surface of the ionized sphere. If this is the case, the 1600 km s$^{-1}$ wind will be interacting with the lower-density, ionized medium and the shocked stellar wind can emit at high temperatures, while the photoionized materials of the edge of clouds could supply sufficient density to emit strong X-rays.

The other possibility is that the hot component arises from deeply embedded young stars especially since at least one embedded T Tauri star (TC1 in CLC98, which is marked in Figure 1) exists near the O star. The TC1 source in CLC98 shows a large shift in the spectral energy distribution and violent ejections of high-velocity material (CLC98). Other ASCA observations showed bright X-ray sources with
temperatures of 2-5 keV due to flares of protostars in the ρ Ophiuchi dark cloud (Koyama et al. 1994), the Orion Nebula (Yamauchi & Koyama 1993), and the R Coronae Australis molecular cloud (Koyama et al. 1996). The hard emission was attributed to flares from individual PMS stars with typical X-ray luminosities in the range $10^{30-32}$ erg s$^{-1}$, and the peak luminosity of flares is shown to be as large as $10^{33-35}$ erg s$^{-1}$ and a temperature as high as $10^8$ K (Feigelson & Montmerle 1999; Grosso et al. 1997). The hard emission from W3 may be of a similar origin. Signs of active star formation in the Trifid have recently been reported (Lefloch et al. 2001): there is a dust cocoon or circumstellar disk around several members in the center of the Trifid, and one young stellar source shows a silicate feature in the circumstellar disk. Neither the ρ Ophiuchi dark cloud or the R Coronae Australis molecular cloud is as bright in hard X-rays as the Trifid Nebula, which may imply there are higher number of protostars present in the Trifid. Large numbers of protostars unresolved to ASCA would dilute any flux variability produced by flares.

In summary, one of two scenarios is likely responsible for the hard emission: the emission may arise from HD 169942 by the interaction of the wind from the O star with another object (a companion star or a dense region of the nebula), or from unresolved emission from active PMS stars. With our current data, we can not determine if one is more favored. To conclusively identify the hot component, a high resolution image is needed to locate the emitting object in order to determine whether the observed emission is produced near the O star, or whether a distributed group of active PMS stars dominates the observed emission. Along with the images, time resolved spectra could allow us to distinguish whether the hard emission is flare-like (time variable).

6. Identification of X-ray and Infrared Sources within the Trifid

The detected X-ray sources and their counterparts are listed in Table A. Most of X-ray sources are likely protostars or PMS stars; one source is a T Tauri star, two are massive protostars, and the others are unclassified protostars. The JHK$_s$ color-color diagram using the 2MASS data suggests that there are $\sim$80 protostars present in this nebula. It has been already shown (CLC98; Lefloch & Cernicharo 2000) that massive protostars (17-60 M$_\odot$) are forming in the Trifid and they are associated with molecular gas condensations at the edges of clouds, and their dynamical ages are $3\times10^4$ yr. Whether low-mass protostars and T Tauri stars can be formed in a young ($3\times10^5$ yr) region such as the Trifid is still an open question. Low-mass PMS stars of similarly young age were found in the Orion Nebula using new Chandra observations (Hillenbrand et al. 1998; Garmire et al. 2000). The Chandra observation also showed the presence of young,
low mass (0.1-3$M_\odot$) PMS stars as X-ray sources (Garmire et al. 2000). The populations of low mass and massive protostars are similar in the Trifid, while we expect higher populations of low mass protostars based on the initial mass function. This is consistent with the fact that the Trifid is a very young HII region; T Tauri stars have yet to form there. The distribution of T Tauri stars and massive YSOs is not obviously correlated with the molecular cloud distribution. It is possible that they are highly embedded in the molecular clouds, and their near-infrared colors cannot be fully obtained to identify protostars because either J and/or H flux is unavailable. This is consistent with the fact that 2MASS images show a higher population of red stars in the southern part of the Trifid. The HST images covering the southern part suggested presence of embedded stars at the head of the evaporating globules (Hester et al. 1999). Deep near-infrared images and spectroscopy will likely reveal hundreds of young protostars in the Trifid as suggested by 2MASS and HST data.

Whether diffuse X-ray emission exists within the Trifid Nebula is currently unknown, because of the limited spatial resolution of the PSPC images. For the unidentified X-ray sources 5 and 10, we cannot determine whether they are a part of diffuse emission or whether they are real point sources. They are very likely normal stars, but the possibility that they are knots of diffuse emission can not be ruled out. Diffuse X-ray emission from HII regions has been detected, although it is rare. A few examples are found such as in the Carina Nebula (Seward & Chlebowski 1982), RCW 49 (Goldwurm et al. 1987; Belloni & Mereghetti 1994), and the Cygnus Superbubble (Bochkarev & Sitnik 1985), and recently Wang (1999) reported diffuse X-ray emission from the giant HII region 30 Dor in the Large Magellanic Cloud. ROSAT and BBXRT observations of the Carina Nebula show large-scale diffuse emission over at least 40′, as well as discrete X-ray sources and hot gas surrounding $\eta$ Car (Corcoran et al. 1999). The nature of diffuse emission is unclear in HII regions. Seward & Chlebowski (1982) suggested that stellar winds from the OB association adequately heat the plasma. Wang (1999) suggested that the X-ray thermal diffuse emission arises in blister-shaped region by loops of ionized gas and the structure is explained by the mass loading of the hot gas, produced by the central OB association.

We compare the Trifid Nebula with 30 Dor to determine whether stellar winds in the Trifid may produce observable diffuse X-rays. The stellar wind luminosity in 30 Dor is a few $\times 10^{39}$ ergs s$^{-1}$, and the X-ray luminosity of 30 Dor is $\sim 10^{38}$ ergs s$^{-1}$ (Wang 1999). The stellar wind luminosity of HD 146692 is $L_w = 1.7 \times 10^{36}(\dot{M}/2 \times 10^{-6} M_\odot yr^{-1})(V/1580$ km s$^{-1})^2$ erg s$^{-1}$. If the Trifid emits diffuse X-rays similarly to 30 Dor, we would expect $\sim 10^{35}$ ergs s$^{-1}$ diffuse X-ray emission from the Trifid. This is higher than the total X-ray luminosity of the Trifid. It is likely that supernova heating contributes significantly to the
bright X-ray emission from 30 Dor. The Trifid Nebula is too young to have hosted supernova explosions, so its diffuse X-ray emission should be much fainter than that of 30 Dor.

Future high resolution X-ray observations by new telescopes such as Chandra and XMM should be able to resolve the O star from its immediate environment and discrete X-ray sources such as T Tauri stars, numerous protostars, young and old normal stars, and to resolve the source of the high temperature emission. A deep near-infrared image with other wavelength observations can identify the PMS stars and protostars, and their mass populations. The Trifid Nebula is an exciting laboratory to understand early stage of star forming activities in HII region.

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Table 1: X-ray sources detected in the PSPC image of the Trifid Nebula

| Name  | RA (2000) | DEC (2000) | Count Rate    | Detection (σ) | Log (L_x) |
|-------|-----------|------------|---------------|---------------|-----------|
| RXT1  | 18:02:52.8| -23:02:18.1| 0.0014±0.0005 | 5             | 31.12     |
| RXT2  | 18:02:39.3| -22:58:34.3| 0.0011±0.0004 | 3.5           | 31.02     |
| RXT3  | 18:02:41.18| -23:03:51.8| 0.0014±0.0006 | 3.5           | 31.12     |
| RXT4  | 18:02:36.0| -23:01:36.3| 0.0019±0.0006 | 4             | 31.05     |
| RXT5  | 18:02:35.0| -23:01:29.4| 0.0021±0.0006 | 4.5           | 31.29     |
| RXT6  | 18:02:27.9| -22:59:47.9| 0.0016±0.0006 | 4             | 31.17     |
| RXT7  | 18:02:25.4| -22:59:51.4| 0.0010±0.0005 | 3             | 30.97     |
| RXT8  | 18:02:23.35| -23:01:47.0| 0.0131±0.0013 | 8             | (see Table 4) |
| RXT9  | 18:02:21.1| -23:03:21.5| 0.0010±0.0004 | 4             | 30.97     |
| RXT10 | 18:02:12.38| -22:55:37.0| 0.0012±0.0004 | 4.5           | 31.05     |
| RXT11 | 18:02:34.92| -22:59:55.6| 0.0006±0.0003 | 2.5           | 30.75     |
| RXT12 | 18:02:31.67| -23:02:25.6| 0.0007±0.0003 | 2.5           | 30.82     |
Table 2: 2MASS Young Stellar Object and T Tauri Star candidates in the Trifid Nebula

| #  | Designation          | Designation          | #  | Designation          | Designation          |
|----|----------------------|----------------------|----|----------------------|----------------------|
| 1  | 2MASSI J1802121-230439 | 2MASSW J1802379-230211 | 1  | 2MASSI J1802158-230555 | 2MASSW J1802331-230135 |
| 2  | 2MASSI J1802211-230437 | 2MASSW J1802211-230234 | 2  | 2MASSI J1802102-230403 | 2MASSW J1802197-230136 |
| 3  | 2MASSI J1801592-230406 | 2MASSW J1802441-230245 | 3  | 2MASSI J1802129-230348 | 2MASSW J1802281-230142 |
| 4  | 2MASSW J1802139-230213 | 2MASSW J1802367-230302 | 4  | 2MASSW J1802197-230136 | 2MASSW J1802336-230154 |
| 5  | 2MASSW J1802142-230144 | 2MASSW J1802500-230332 | 5  | 2MASSI J1801575-230121 | 2MASSI J1802109-230305 |
| 6  | 2MASSI J1802168-230110 | 2MASSW J1802361-230428 | 6  | 2MASSI J1801214-225856 | 2MASSI J1802395-230343 |
| 7  | 2MASSI J1801561-230009 | 2MASSW J1802361-230412 | 7  | 2MASSI J1802173-225614 | 2MASSI J1802211-230437 |
| 8  | 2MASSI J1802044-225829 | 2MASSW J1802319-230440 | 8  | 2MASSI J1802108-225532 | 2MASSI J1802409-230459 |
| 9  | 2MASSI J1802122-225825 | 2MASSI J1802372-230503 | 9  | 2MASSI J1802205-225458 | 2MASSI J1802349-230505 |
| 10 | 2MASSW J1802202-225807 | 2MASSI J1802369-230656 | 10 | 2MASSI J1802205-225458 | 2MASSI J1802263-230730 |
| 11 | 2MASSI J1802401-225721 | 2MASSI J1802470-230702 | 11 | 2MASSI J1802162-225530 | 2MASSI J1802242-230910 |
| 12 | 2MASSI J1802377-225850 | 2MASSI J1802290-230704 | 12 | 2MASSI J1802464-225546 | 2MASSI J1802403-230913 |
| 13 | 2MASSI J1802463-225912 | 2MASSI J1802247-230729 | 13 | 2MASSI J1802473-225729 | 2MASSI J1802384-230934 |
| 14 | 2MASSI J1802433-225931 | 2MASSI J1802344-230806 | 14 | 2MASSI J1802367-225804 | 2MASSI J1803003-230134 |
| 15 | 2MASSI J1802491-225945 | 2MASSI J1802339-230924 | 15 | 2MASSI J1802312-225911 | 2MASSI J1802467-230130 |
| 16 | 2MASSI J1802503-225949 | 2MASSI J1802518-230810 | 16 | 2MASSI J1802365-225929 | 2MASSI J1802538-230033 |
| 17 | 2MASSI J1802438-225550 | 2MASSI J1802499-230740 | 17 | 2MASSI J1802228-225935 | 2MASSI J1802566-230026 |
| 18 | 2MASSI J1802441-230020 | 2MASSI J1802541-230736 | 18 | 2MASSI J1802175-225938 | 2MASSI J1803023-230022 |
| 19 | 2MASSI J1802266-230036 | 2MASSI J1802473-230428 | 19 | 2MASSI J1802409-225941 | 2MASSI J1802490-225656 |
| 20 | 2MASSW J1802226-230101 | 2MASSI J1802482-230309 | 20 | 2MASSI J1802344-230102 |
| 21 | 2MASSI J1802467-230130 | 2MASSI J1802524-230227 | 21 | 2MASSI J1802284-230115 |
| 22 | 2MASSW J1802271-230201 | 2MASSI J1802548-225901 | 22 | 2MASSW J1802408-230131 |

\(^a\)2MASSI and 2MASSW indicate the Incremental Release and Working Database catalogs, respectively.
Table 3: Infrared Counterparts of the X-ray Sources Detected in PSPC Images

| RXT   | 2MASS<sup>a</sup> | d<sup>b</sup> | R.A. (2000)<sup>c</sup> | Dec (2000)<sup>c</sup> | J<sup>d</sup> | H<sup>d</sup> | K<sub>s</sub><sup>d</sup> | Comments<sup>e</sup> |
|-------|------------------|-------------|---------------------|-------------------|----------|----------|----------|------------------|
| RXT1  | YSO              | 10          | 18:02:52.4          | −23:02:27.2       | 15.17    | 13.93    | 13.18    | -                |
| RXT2  | red              | 8           | 18:02:39.7          | −22:58:29.0       | 17.72    | 15.06    | 13.50    | J='fill'         |
| RXT3  | red              | 5           | 18:02:41.4          | −23:03:48.2       | 17.83    | 14.24    | 12.42    | J='fill'         |
| RXT4  | red              | 12.8        | 18:02:36.8          | −23:01:43.9       | 15.85    | 12.78    | 11.34    | high psf Δχ²     |
| RXT5  | NONE             |             |                     |                   |          |          |          |                  |
| RXT6  | TTS              | 13          | 18:02:30.5          | −22:59:28.7       | 12.71    | 11.65    | 10.91    | -                |
| RXT7  | YSO              | 12          | 18:02:30.6          | −23:00:36.0       | 15.21    | 12.90    | 11.34    | -                |
| RXT8<sup>f</sup> | Multiple        |             |                     |                   |          |          |          |                  |
| RXT9  | red              | 6           | 18:02:21.5          | −23:03:19.0       | 15.04    | 13.58    | 11.87    | J='fill'         |
| RXT10 | NONE             |             |                     |                   |          |          |          |                  |
| RXT11<sup>f</sup> | red           | 4           | 18:02:34.7          | −22:59:52.1       | 16.52    | 12.42    | 10.58    | J='fill'         |
| RXT12 | red              | 9           | 18:02:31.3          | −23:02:18.2       | 15.12    | 13.17    | 11.36    | J='fill'         |

<sup>a</sup>Notes for the 2MASS sources: TTS = T Tauri star; YSO = massive young stellar objects; red = red 2MASS star

<sup>b</sup>Projected distance between the X-ray and 2MASS sources.

<sup>c</sup>Coordinates of the 2MASS counterparts.

<sup>d</sup>J, H and K<sub>s</sub> magnitudes of the 2MASS sources.

<sup>e</sup>J='fill' means the J band photometry is measured in band-filled within the aperture, indicating their photometric uncertainties are large. ‘high psf Δχ²’ means the goodness of the fit of a point spread function is high, indicating the sources are either extended or unresolved double sources.

<sup>f</sup>RXT8 is HD 164492 (O7 star) and/or YSO (TC1 in CLC98), and RXT11 also coincides with HD 313596 (B8 star).
Table 4: Spectral fit results from simultaneous fit using ASCA/PSPC

| Parameters                                      | Trifid               |
|------------------------------------------------|----------------------|
| ISM $N_H$ ($10^{21}$ cm$^{-2}$)                 | $\equiv 3$           |
| $T_2$                                           | $3.3\pm0.6$ keV ($=3.9\times10^7$ K) |
| $\log EM_2$ (cm$^{-3}$)                         | 55.8                 |
| Wind $N_H$, hot component ($10^{21}$ cm$^{-2}$) | $2.7^{+2.3}_{-2.0}$ |
| $T_1$                                           | $0.14^{+0.06}_{-0.04}$ keV ($=1.2\times10^6$ K) |
| $\log EM_1$ (cm$^{-3}$)                         | 57.4                 |
| Wind $N_H$, 1 component ($10^{21}$ cm$^{-2}$)   | $5.9^{+1.1}_{-0.9}$  |
| flux                                           | $2\pm0.5 \times10^{-12}$ |
| unabsorbed flux                                 | $8\pm2\times10^{-11}$ |
| Luminosity (erg s$^{-1}$)                       | $2.5\times10^{34}$ [d(kpc)/(1.67 kpc)]$^2$ |
| Fe K Line Central energy (keV)                  | $6.65^{+0.1}_{-0.2}$ |
| Fe K Equivalent Width (keV)                     | $1.7\pm0.3$          |
| Fe K Flux (photons s$^{-1}$ cm$^{-2}$)          | $6(\pm0.4)\times10^{-4}$ |
REFERENCES

Alcalá, et al., 1996, A&ASS, 119, 7

Alcalá, et al., 1997, A&ASS, 114, 109

Becker, R.H., White, R.L., Helfand, D. J., Zoonematkermani, S., 1994, ApJS, 91, 347

Belloni, R., & Mereghetti, S., 1994, A&A, 286, 935

Bessell, M.S., & Brett, J.M., 1988, PASP, 100, 1134

Berghöfer, T. W., Schmitt, J. H. M. M., & Cassinelli, J. P., 1996, A&AS, 118, 481

Bochkarev, N. G.& Sitnik, T. G., 1985, Ap&SS, 108, 237

Casanova, S., Montmerle, T., Feigelson, E. D., Andre, P., 1995, ApJ, 439, 752

Cernicharo et al. 1998, Science, 282, 462 (CLC98)

Chen, W., & White, R.L., 1991, ApJ, 366, 512

Chlebowski, T. & Harnden, F. R. Jr., 1989, ApJ, 341, 427

Churchwell, E., 1990, A&A Rev., 2, 79

Conti, P.S., & Alschuler, W.R., 1971, ApJ, 170, 325

Corcoran, M. F., Swank, J., Rawley, G., Petre, R., Schmitt, J., & Day, C., 1995, (Serie de Conferencias) RevMexAA, 2, 97

Corcoran, M. et al, 1993, ApJ, 412, 792

Corcoran, M. et al. 1994, ApJ, 436, L95

Cutri, R. M. et al., http://www.ipac.caltech.edu/2mass/releases/first/doc/explsup.html

Feigelson, E. D, Casanova, S., Montmerle, T., Guibert, J., 1993, ApJ, 416, 623

Feigelson, E. D, & T. Montmerle, 1999, ARA&A, 363

Gagné, M., Caillault, J.-P., Stauffer, J.R., & Linsky, J.L., 1997, ApJ, 478, L87
Garmire G., Feigelson, E. D., Broos, P., Hillenbrand, L. A., Pravdo, S. H., Townsley, L., Tsuboi, Y., 2000, AJ, 120, 1426

Grosso N. et al., 1997, Nature, 387, 56

Goldwurm, A., Caraveo, P. A., & Bignami, G. F., 1987, ApJ, 322, 349

Gregorio-Hetem, J., Montmerle, T., Casanova, S., & Feigelson, E.D. 1998, A&A, 331, 193

Hester, J.J. et al., 1999, BAAS, 194.681

Hillenbrand, L.A., et al. 1998, ApJ, 116, 1816

Hofner, P., & Churchwell, E., 1997, ApJ, 486, L39

Howarth, I. D., & Prinja, R. K., 1989, ApJS, 69, 527

Kamata, Y., Koyama, K., Tsuboi, Y., Yamauchi, S., 1997, PASJ, 49, 461

Kaastra, J.S., 1992, An X-ray Spectral Code for Optically Thin Plasmas (SRON-Leiden Report)

Kohoutek, L, Mayer, P., Lorenz, R., 1999, A&AS, 134, 129

Koyama, K., Asaoka, I., Kuriyama, T., & Tawara, Y., 1994, PASJ, 44, L255

Koyama, K. Ueno, S., Kobayashi, N., & Feigelson, E. D., 1996, PASJ, 48, L87

Krautter, J., et al. 1997, A&ASS, 123, 329

Lada, C. J., & Adams F.C., 1992, ApJ, 393, 278

Lefloch, B. & Cernicharo, J., 2000, ApJ, 545, 340

Lefloch, B., et al., 2001, A&A (astroph-0101435)

Levato, A., 1975, A&AS, 19, 91

Lynds, B. T., & O’Neil, E. J., Jr., 1985, ApJ, 294, 578

Meyer, M.R., Calvet, N., Hillenbrand, L., 1997, AJ, 114, 288

Neuhäuser, R., Sterzik, M. F., Schmitt, J.H.M.M, Wichmann, R., & Krautter, 1995, A&A, 297, 391
Prinja, R. K., Barlow, M. J., & Howarth, I. D., 1990, ApJ, 361, 607

Rho, J.-H., Petre, R., Pisarski, R., and & Jones, L. R., 1995, in “Röntgenstrahlung from the Universe”, eds. H.-U. Zimmermann et al. (Garching: MPE), p273

Rieke, G. H., & Lebofsky, M.J., 1985, ApJ, 288, 618

Seward, F. D. & Chlebowski, T., 1982, ApJ, 256, 530

Skrutskie, et al., 1997, “The impact of large scale near-IR sky surveys”, ed.by F. Garzon et al., p25

Stevens, I.R., Blondin, J.M., Pollock, A.M., 1992, ApJ, 386, 265

Tanaka, Y., Inoue, H., & Holt, S.S., 1994, PASJ, 46, L37

Trümper, J., 1993, Science, 260, 1769

van Buren, D., Noriega-Crespo, Al, & Dgani, R., 1995, AJ, 110, 2914

Wang, Q. D., 1999, ApJL, 510, 139L

Waldron, W.L., 1984, ApJ, 282, 256

Wichmann, R., Sterzik, M., Krautter, J., Metanomski, A. & Voges, W., 1997, A&A, 326, 211

Yamauchi, S. & Koyama, K., 1993, ApJ, 405, 268

Yusef-Zadeh, F., Shure, M., Wardle, M., & Kassim, N., 2000, ApJ, 540, 842

This manuscript was prepared with the AAS LaTeX macros v4.0.
Fig. 1.— The PSPC X-ray image and detected sources (RXT) are marked with numbers. The count rates for each source are listed in Table 1. Known sources are also marked with the labels.

Fig. 2.— PSPC X-ray contours superimposed on an H $\alpha$ image of the Trifid Nebula (courtesy of Dr. Winkler). The optical image was obtained on 4 July, 1994 (UT) from the Burrell Schmidt telescope of Case Western Reserve University, through a 25 Å bandpass H $\alpha$ filter. The total exposure time is 1800 s, and the scale is 2.0$^\prime\prime$/pixel$^{-1}$. The strongest X-ray peak is at the O star, HD 164492.

Fig. 3.— (a) Near-infrared JHK$_s$ color-color diagram: location in color-color diagram is used to determine T Tauri-stars and massive young stellar objects. Normal stars (dots), T Tauri-stars (filled circles), and massive young stellar objects (diamonds) are shown with different symbols. The 2MASS counterparts of X-ray sources are marked with crosses; the sources above the extinction curve have high photometric uncertainties. They are 2MASS-red stars in Table 3 (see the text for details). Extinction vector is shown for 5 magnitude as the thick line labeled A$_v$. The thick curves are intrinsic colors of giant and dwarf stars. (b) Diagram of H-K$_s$ vs. K$_s$. T Tauri stars and young massive protostars fall below (younger age) the PMS stars in this diagram. The symbols are the same as those in (a). (c) T Tauri stars (circles) and massive young stellar objects (diamonds), X-ray sources (crosses), and known embedded young stellar objects (triangles: from Cernicharo et al. 1998) are marked on Optical image. (d) 2MASS three color image (blue, green and red for J, H, and K$_s$, respectively). The symbols are the same as those in (c). The diffuse, blue emission is probably P $\beta$ (in the J band) from the HII region.

Fig. 4.— ASCA SIS image (gray scale ranges 0.7-4.5 counts (6.4$^\prime\prime$/pixel$^{-1}$) superposed on ROSAT contours.

Fig. 5.— (a) GIS1 and GIS2 spectra of the Trifid Nebula with its best-fit of a two-temperature thermal model with additional warm absorbing media. Hard emission and Fe XXV line appear in the spectra. (b) SIS0 and SIS1 and PSPC spectra with the best-fits. (c) Each of two temperature components ($\sim$1.2$\times$10$^6$ K and 3.9$\times$10$^7$ K) is marked on the SIS0 spectrum.
Fig. 1
Fig. 3b
Fig. 3c
Fig. 3d is a color figure (see separate page)
Fig. 5c
This figure "f3dcolor.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0107111v1