The Astronomical Journal, 123:2590–2596, 2002 May

STRONG EMISSION-LINE STARS IDENTIFIED TOWARD THE ROSETTE NEBULA

J. Z. Li,[1,2] C. H. Wu,[1] W. P. Chen,[1] T. Rector,[3] Y. H. Chu,[1,4] and W. H. Ip[1]
Received 2001 October 29; accepted 2002 January 30

ABSTRACT

Several strong emission-line stars were found in the optical identification of the *ROSAT* PSPC sources in the Rosette Nebula. These possible X-ray emitters were classified from the low-resolution spectra obtained as Herbig Ae/Be type stars or probable weak-line T Tauri stars. A classical Be star was also identified around one of the X-ray sources studied. Our study supports the conjecture that *ROSAT* X-ray observations could trace low- and intermediate-mass star formation to a distance of ~1.5 kpc.

Key words: stars: emission-line, Be — stars: pre–main-sequence — X-rays

On-line material: color figure

1. INTRODUCTION

The Rosette Nebula, a spectacular H ii region, is excavated by the strong winds of several O stars in the central young open cluster NGC 2244, which has an age of about 3×10^6 yr (Ogura & Ishida 1981). This on-going star-forming region (Meaburn & Walsh 1986; Clayton et al. 1998; Phelps & Lada 1997) is located at a distance of ~1.5 kpc at the tip of a giant molecular complex of about 100 pc in extent (Dorland & Montmerle 1987). *ROSAT* PSPC observations of the densest rim of molecular gas southeast of the H ii region were conducted by Gregorio-Hetem et al. (1998). X-ray hardness ratios and L_X/L_{bol} ratios of the X-ray sources detected were found to be comparable to those of the low- and intermediate-mass pre–main-sequence (PMS) stars in nearby star-forming regions (SFR). The authors argued that most of the pointlike *ROSAT* sources in their sample were T Tauri and Herbig Ae/Be stars. We infer that this could probably be true for *ROSAT* PSPC sources all around this active star-forming region. To check this conjecture, all possible optical counterparts within the positional error circle of every *ROSAT* PSPC sources (Voges et al. 1994) available in a field of 1 square degree centered on the Rosette Nebula were identified, and low-resolution spectroscopic observations of those with an USNO *R* magnitude of less than 18.0 mag were performed for (1) accurate spectral classification of the optical counterparts to the *ROSAT* point sources aimed at further investigations on the origin of the X-ray emission in this region; (2) selection of a sample of late-type cluster members as low-mass PMS candidates for following up higher resolution spectroscopic study to further confirm their nature; (3) possible identification of Herbig Ae/Be, T Tauri and other strong emission-line stars such as Be stars to facilitate studies of, for example, the initial mass function in this young SFR; (4) further elucidating if X-ray explorations at the *ROSAT* detection limit can efficiently trace star formation at distances greater than 1 kpc, which might to some extent serve also as a reference to new generation X-ray investigations. In order to conduct the study outlined above, it was necessary to classify the strong emission-line stars into specific groups—in particular, as classical T Tauri stars (CTTSs), weak-line T Tauri stars (WTTSs), Herbig Ae/Be stars or otherwise emission-line stars of actually evolved status.

T Tauri stars are low-mass (up to 2 $M_\odot$), late-type (spectral types of later than mid-F) pre–main-sequence stars with ages from 10^5 yr to a few 10^7 yr. CTTSs are characterized by strong optical emission lines, ultraviolet and infrared excesses due to mainly the existence of a circumstellar disk, this subgroup of T Tauri stars are usually discovered by their conspicuous optical characteristics with especially Hα prism survey of SFRs. Unlike CTTSs, WTTSs are believed to be devoid of circumstellar matter or have dissipated their accretion disks. Because of the lack of extinction in soft X-ray, they are comparatively more X-ray luminous and therefore more easily detected by flux limited X-ray surveys like the *ROSAT* mission.

Herbig Ae/Be stars were first proposed by Herbig (1960) as a group of young, intermediate-mass objects 2 $M_\odot < M < 8$ $M_\odot$) still in their pre–main-sequence phase of evolution. As the higher mass counterparts to T Tauri stars, the criteria for identification of an object as a Herbig Ae/Be star are as follows: (1) it is usually located in an obscured region, which guarantees their youth and the exclusion of evolved stars such as Wolf-Rayet stars and planetary nebulae. (2) It has spectral types earlier than F8 and the presence of emission lines resembling those of CTTSs. (3) There is illumination of fairly bright nebulosity in their immediate vicinity. Classical Be stars which happen to project onto dark clouds are thus excluded. However, when there is clear evidence that a candidate star is associated with star-forming clouds or located in specific environments such as photodissociated regions, it should be possible to classify the objects as a Herbig Ae/Be star even without evidence of nebulosity. (4) Strong infrared excess due to the existence of circumstellar dust could also be used to eliminate classical Be stars, which have well separated loci on infrared color-color diagrams (Finkenzeller & Mundt 1984; Hillenbrand et al. 1993).

We present in this paper the study of the candidate X-ray active sources with strong emission lines [W_λ(Hα) $\gtrsim 5$ Å] in

[1] Institute of Astronomy, National Central University, Chung-Li 32054, Taiwan; ljz@astro.ncu.edu.tw.

[2] Beijing Astronomical Observatory, National Astronomical Observatories, CAS, Beijing 100012, China.

[3] National Optical Astronomy Observatories, 950 North Cherry Avenue, Tucson, AZ 85719.

[4] Department of Astronomy, University of Illinois, Urbana-Champaign, IL 61801.

the Rosette Nebula. A detailed description of the project and systematic study of the low-mass PMS candidates as optical counterparts to the *ROSAT* PSPC sources in this region will be reported in a forthcoming paper (J. Z. Li et al. 2002, in preparation).

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Spectroscopic Observations*

Low-resolution spectroscopic observations (with dispersion of 200 Å mm^{-1}, 4.8 Å $pixel^{-1}$, and 2".5 slit) of the program stars were carried out with the 2.16 m optical telescope of the Beijing Astronomical Observatory. An OMR (Optomechanics Research Inc.) spectrograph and a Tektronix 1024×1024 CCD detector were used during this run of observations from 2000 December 16 to 25.

The spectral data were reduced following standard procedures in the NOAO Image Reduction and Analysis Facility (IRAF, version 2.11) software packages. The CCD reductions included bias and flat-field correction, successful nebular background subtraction, and cosmic ray removal. Wavelength calibration was performed based on helium-argon lamps exposed at both the beginning and the end of the observations every night. Flux calibration of each spectrum was conducted based on observations of at least two of the KPNO spectral standards (Massey et al. 1988) per night. The atmospheric extinction was corrected by the mean extinction coefficients measured for Xing-Long station, where the 2.16 m telescope is located, by the Beijing-Arizona-Taiwan-Connecticut (BATC) multicolor survey (H. J. Yan 1995, private communication).

2.2. *Narrowband Imaging*

Narrowband images of the Rosette Nebula were obtained on 1999 March 3 with the Kitt Peak National Observatory 0.9 m telescope and the MOSAIC camera (Muller et al. 1998) with the Hα, [O III], and [S II] filters. For each filter, five exposures of 600 s were taken, each image slightly offset to fill in physical gaps between the MOSAIC CCDs. The pixel scale is 0".423 $pixel^{-1}$, resulting in a 59' square field of view.

3. RESULTS AND DISCUSSION

We have obtained low-resolution spectra of some 60 possible optical counterparts, with USNO *R* magnitudes of brighter than 18.0, for the sample of *ROSAT* PSPC sources in the Rosette Nebula. About one-fourth of the program stars were identified as early-type stars, though the mechanism for X-ray emission from such stars are not yet well understood. More than 40 have spectral types of later than F5, a great deal of which indicate apparent Li I λ6707 + Ca I λ6716 blended absorption in their spectra. These late-type X-ray active stars were taken as promising candidate low-mass PMS for follow-up intermediate resolution spectroscopic observations to further investigate star formation activity in the Rosette Nebula (J. Z. Li et al. 2002, in preparation), which is located at a distance of an order of magnitude farther than the most well-studied active SFR Taurus-Auriga.

Here, we report the results of our spectroscopy of three probably high-mass stars with very strong Hα emission and two other stars we believe are WTTSs. Table 1 presents the sequence number of these stars, *ROSAT* designation, X-ray luminosities assuming a distance of 1.5 kpc and negligible interstellar absorption, USNO A2.0 coordinates (J2000), visual magnitudes at the time of observations as estimated from the spectra obtained (within ± 0.2 mag), spectral types accurate to ± 1 subclass, W_λ(Hα), classification of these sources along with indicators of their possible association with corresponding X-ray emission and their member Bship to the central open cluster NGC 2244 as adopted from Ogura & Ishida (1981). Data and discussions of the other two possible optical counterparts to 1RXP J063129+0454.9—9A and 9B—are also included for completeness. We have also calculated X-ray to optical luminosity ratio corresponding to each of the possible optical counterparts discussed below, all commensurate with the presumption that they are candidates of Herbig Ae/Be stars (with L_X/L_o of 10^{-7}–10^{-5}) or TTSs (10^{-5}–10^{-3}).

The optical counterpart to 1RXP J063129+0454.9, No. 7 of the program stars, was previously classified by Verschueren (1991) as a B7 Ve. Its spectrum was found to be dominated by strong Hα and a wealth of Fe II emission lines (Fig. 1) such as (27) λ4173.5; (37) $\lambda\lambda$4515.3, 4520.2, 4549.5, 4629.3; (38) $\lambda\lambda$4522.6, 4583.8, 4582.8; (40) λ6516.1; (42) $\lambda\lambda$4923.9, 5018.4, 5169.0, 5316.8; (49) $\lambda\lambda$5276.0, 5316.6; (55) λ5534.9; (73) λ7515.3, and (74) $\lambda\lambda$6147.7, 6247.6, 6456.4, among which the multiplet (42) is the most prominent. Significant O I $\lambda\lambda$7774.1, 8446.7 and Ca II infrared triplet (IRT) $\lambda\lambda$8498.0, 8542.1, 8662.1 in emission, indicators for the existence of chromospheric activity and maybe also its X-ray active nature, were detected. Weak He I $\lambda\lambda$7065, 6678 absorption lines are present, signifying a spectral type of late B.

Though located in the central, potentially photodissociated area of the Rosette Nebula, there is a shell-like nebula around star No. 7 as indicated by our Hα imaging (Fig. 2*a*), and a similar structure was detected in the [S II] image in this region. A faint, tenuous nebula is also visible at the same position in the Palomar Observatory Sky Survey (Fig. 2*b*). This nebulosity could actually be associated with and at least partly illuminated by No. 7 rather than being coincidently projected onto its immediate vicinity, otherwise it should be easily dissipated in the strong UV radiation field and can hardly sustain for long. On the other hand, this star is independently identified as a member of NGC 2244 (Ogura & Ishida 1981), and physical association of the nebulosity with the star may not necessarily be firmly clarified to support the classification of No. 7 as a Herbig Ae/Be star, this point was made clear in the introduction. Furthermore, this B7 Ve star was found to lie right on the edge of the uncertainty ellipse of an *IRAS* point source—IRAS 06288+0456, around which there seems to have no other possible optical counterparts and No. 7 is therefore probably in association with the infrared emission. *IRAS* flux densities and directly converted magnitudes of each band (no correction of interstellar reddening) based on the *IRAS* definition of zero magnitudes are listed in Table 2. By comparing the visual magnitude (Table 1) of this star at the time of observation with the data presented in Table 2, it is obvious that No. 7 has a very large infrared color excess. According to the study of infrared properties of different groups of Be stars (Hu & Zhou 1990), classical Be stars are found to have a $V - [25]$ of less than 5, while for Herbig Ae/Be stars, this difference is usually greater than 7. With a $V - [25]$ of $\sim$8.1, we could at least exclude the possibility

TABLE 1

CLASSIFICATION OF THE STRONG EMISSION-LINE STARS

Number	*ROSAT* Designation	$\log L_X$	R.A. (J2000)	Decl. (J2000)	V_{mag}	Spectral Type	W_λ (Hα)	Classification	Optical Counterpart?	Member?
7	1RXP J063129+0454.9	30.66 ± 0.19	06 31 29.75	04 54 48.75	10.3	B7 Ve	−39.3	Herbig Be	Yes	M
9A	1RXP J063133+0450.8	30.86 ± 0.37	06 31 33.46	04 50 39.68	10.0	B2 V	3.0	B star	Probably no	M
9B			06 31 33.38	04 50 37.66	...	B4 Ve[a]	...	?	?	M
9C			06 31 31.49	04 50 59.60	12.3	B3 Ve	−20.3	classical Be	no	M
13	1RXP J063139+0505.8	30.88 ± 0.40	06 31 39.98	05 05 56.63	9.9	F3 Ve	−19.6	Herbig Ae/Be type	yes	M?
53	1RXP J063234+0433.4	30.89 ± 0.21	06 32 34.40	04 33 18.90	13.3	G0 V	−5.1	Probably WTTS	yes	?
58	1RXP J063258+0455.7	31.15 ± 0.54	06 32 57.27	04 55 56.85	13.4	G0 V	−5.0	Probably WTTS	yes	M

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Adopted from Pérez et al. 1989.

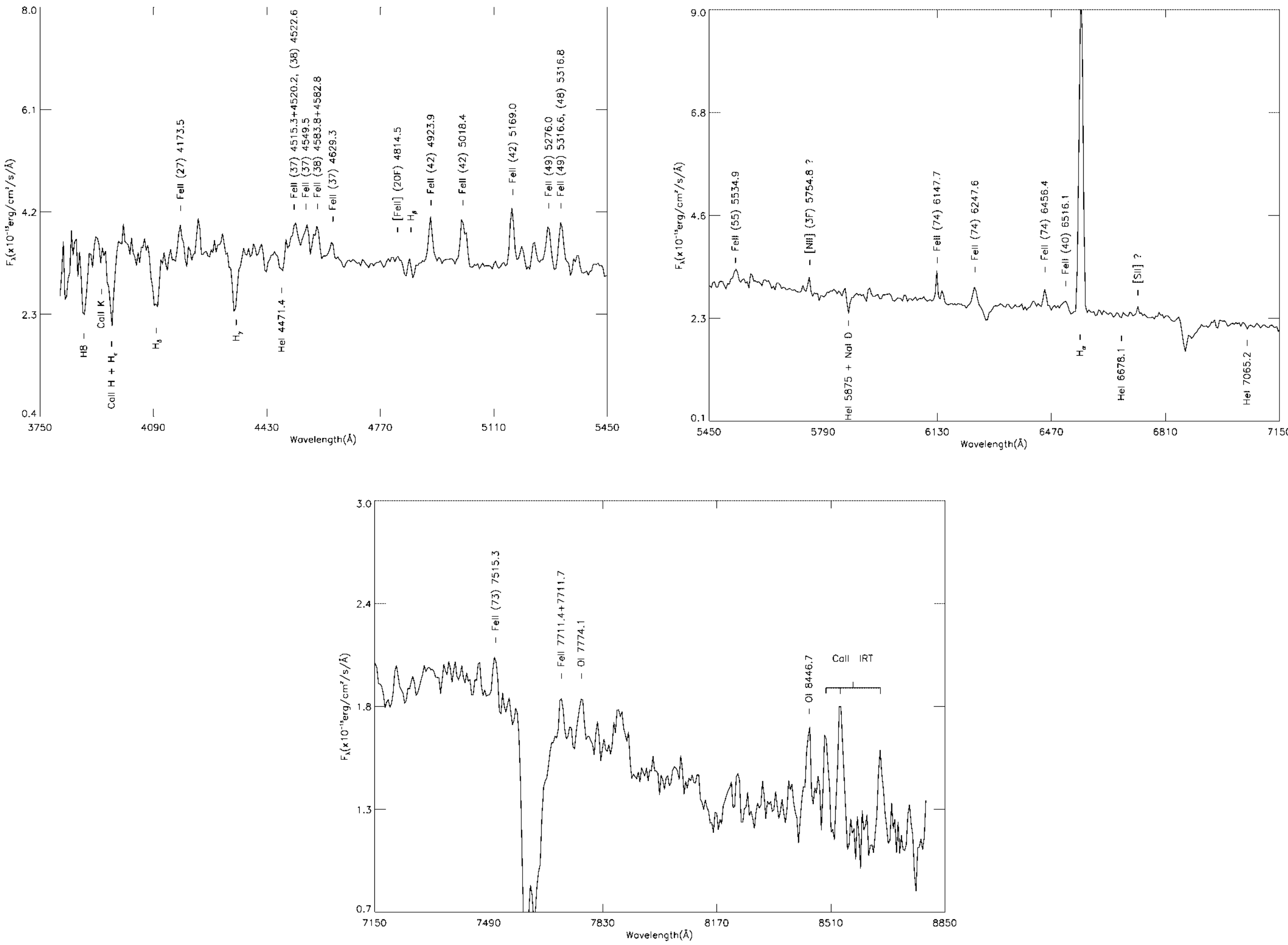

FIG. 1.—Spectral line identifications of source No. 7

that this star is a classical Be. Based on the above analysis, we feel quite sure to take No. 7 as a Herbig Ae/Be star.

Three possible optical counterparts—9A, 9B, and 9C—were investigated around 1RXP J063133+0450.8. On the basis of the spectrum taken, 9C showed strong Hα emission (Fig. 3*a*), obvious He I absorption lines $\lambda\lambda$4026.2, 4387.9, 4471.4, 4713.1, 4921.9 6678.1, 7065.2, and had a highly reddened spectrum of B3 Ve, implicating its location probably farther back into this H II region. This source has apparently no associated *IRAS* point source, no reflection nebula around and was thus classified as a classical Be star, making it unlikely to be the X-ray emitter. 9B, though documented as possibly a Hα emission source (B4 Vne as revealed by Pérez et al. 1989) failed to get resolved in this run of observations due to its proximity to 9A and its fainter brightness. The B2 V spectrum obtained for this binary system (Pérez et al. 1989) is thus dominated by 9A. However, if 9B indeed has Hα emission, it could be a good candidate Herbig Ae/Be star, since this binary system is found to be positionally associated with an *IRAS* point source—IRAS 06288+0452—and 9A, the B2 V star, cannot be responsible for the strong infrared emission. The Hα narrowband image around 9A & 9B shows a small aggregation of fainter, nearby stars, one or more of which could be cluster members (see Fig. 4). The X-ray emission could otherwise be from these low-mass components of the system.

The spectrum of source No. 13 (Fig. 3*b*) shows strong Hα emission, other members of the Balmer series and some of the Paschen series like P19 are weak but significant in emission. The *G* band happens to be contaminated by cosmic rays (left uncorrected to avoid any misleading from this), which makes it hard to conduct very accurate spectral classification. Ca II H and K are partially filled in, while the Ca II IRT and O I $\lambda\lambda$7774.1, 8446.7 are prominently in emission, all of which indicate probably an active chromosphere of this F3 Ve, which may well bear properties in between those of Herbig Ae/Be stars and CTTSs. According to the definition of Herbig Ae/Be stars introduced in § 1, we decide to include here this X-ray emitter as of the Herbig Ae/Be type.

TABLE 2

IRAS FLUX DENSITIES AND MAGNITUDES OF THE OPTICAL COUNTERPART TO 1RXP J063129+0454.9 NO. 7

	WAVELENGTH			
PARAMETER	12 μm	25 μm	60 μm	100 μm
Flux density (Jy).......	1.24	1.23	2.22L	18.95L
Magnitude	3.81	2.22	−0.35	−3.97

NOTE.—Upper limit detections of the flux densities are followed by the letter " L."

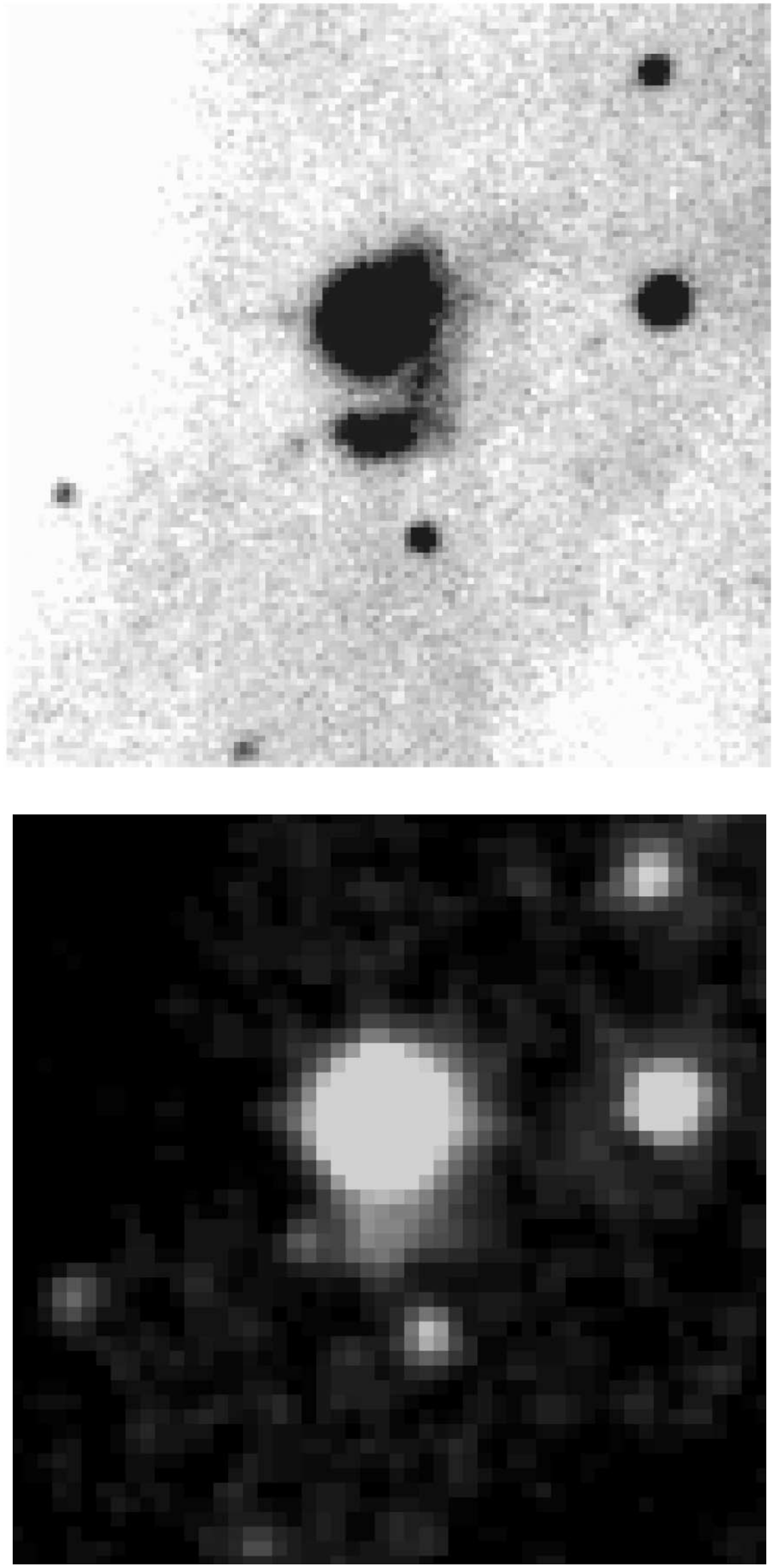

FIG. 2.—Faint nebulosity in the immediate vicinity of No. 7, as indicated by the 50″ × 50″ (*a*) Hα image around this source, and (*b*) image from the Palomar Observatory Sky Survey. North is up, and east is to the left.

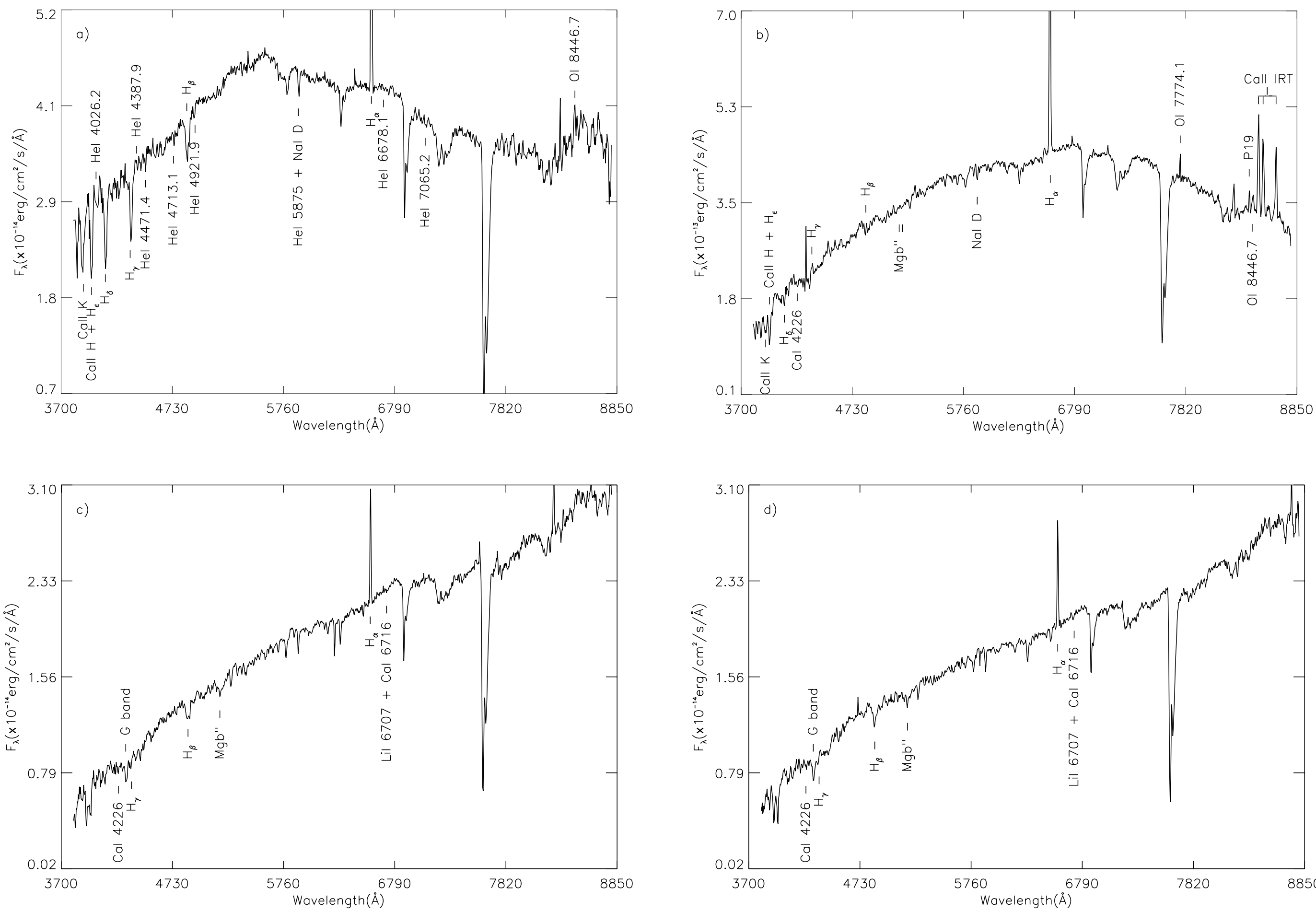

FIG. 3.—Spectra of other strong Hα emission sources: (*a*) spectrum of No. 9C; (*b*) spectrum of No. 13; (*c*) spectrum of No. 53; (*d*) spectrum of No. 58

This source was also found to be associated with an *IRAS* point source—IRAS 06290+0508, which further helps to elucidate its PMS nature. However, No. 13 was classified by Ogura & Ishida (1981) as a nonmember of NGC 2244 due probably to its PMS nature. Ogura & Ishida have constructed an extinction-free color-magnitude diagram, based on existing photoelectric and photographic observations of 400 stars with visual magnitudes of brighter than 14.1 mag. The bright main-sequence stars located in a strip centered on the ZAMS were identified as possible cluster members. This method is effective but biased to the selection of single main-sequence members. Binary systems and PMS members of the cluster might therefore be misidentified as probable field stars (for further details please refer to the context of Ogura & Ishida 1981).

Numbers 53 and 58, the optical counterparts to 1RXP J063234+0433.4 and 1RXP J063258+0455.7, respectively, both have prominent Hα emission ($\sim$5 Å) in their spectra (Figs. 3*c* and 3*d*). Hβ of No. 53 exhibited additionally a reverse emission core in the photospheric absorption. It is important to note that these two spectra clearly show prominent absorption features around λ6710, the equivalent width of which would be too large for only the Ca I λ6716 absorption of a G0 dwarf, and could be the blended lines of Li I λ6707 and Ca I λ6716, which, along with their X-ray active nature and significant Hα emission, suggest that they could be promising candidates of WTTSs. We thus classify these two X-ray emitters as possible WTTSs rather than merely chromospheric active G stars, their discovery would represent the detection of at least the high-luminosity end of the low-mass PMS in this specific region at a distance of greater than 1 kpc. Further confirmation of their nature based on following-up intermediate-resolution spectroscopic observations will also be conducted.

4. SUMMARY

Low-resolution spectroscopic observations of the sample of optical counterparts to the *ROSAT* PSPC sources in the Rosette Nebula were performed. Five strong Hα emission stars, including two Herbig Ae/Be stars, one classical Be and two probable WTTSs, were discovered in the Rosette Nebula, and detailed investigations of these were reported. Our study presents apparent evidence that X-ray detections can serve as efficient tracers of star formation to a significant distance ($\sim$1.5 kpc) across the Galaxy.

This paper, on the great rose in heaven, is dedicated by the first author to his gracious mother Fen-Hua Tian. We are grateful to an anonymous referee for the constructive comments and suggestions made on the paper. Thanks to Prof. J. Y. Hu for some valuable discussions when he is visiting at the Institute of Astronomy. This work is supported by grant NSC89-2112-M-008-021.

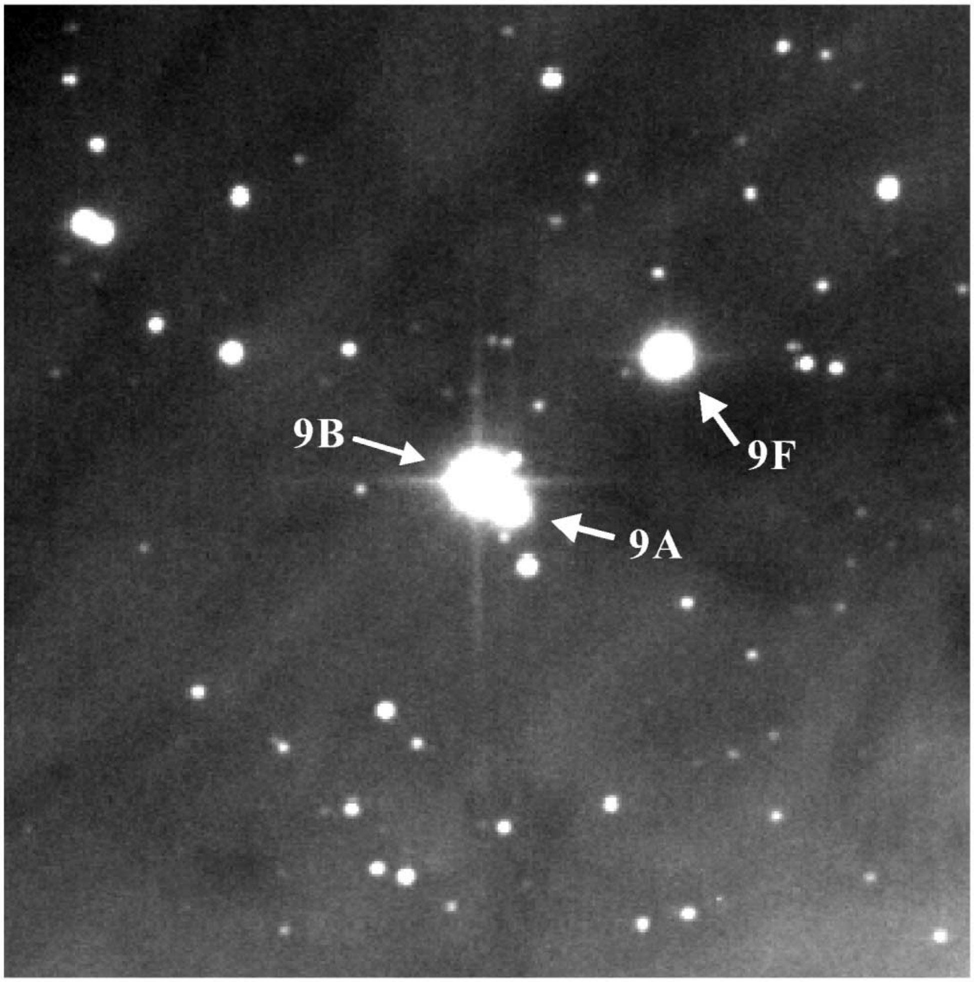

FIG. 4.—Hα image around sources 9A and 9B. North is up, and east is to the left

REFERENCES

Clayton, C. A., et al. 1998, A&A, 334, 264
Dorland, H., & Montmerle, T. 1987, A&A, 177, 243
Finkenzeller, U., & Mundt, R. 1984, A&AS, 55, 109
Gregorio-Hetem, J., et al. 1998, A&A, 331, 193
Herbig, G. H. 1960, ApJS, 4, 337
Hillenbrand, L. A., et al. 1993, in ASP Conf. Ser. 35, Massive Stars: Their Lives in the Interstellar Medium, ed. J. P. Cassinelli & E. B. Churchwell (San Francisco: ASP), 141
Hu, J. Y., & Zhou, X. 1990, Acta Astrophys. Sinica, 10, 154
Massey, P., et al. 1988, ApJ, 328, 315
Meaburn, J., & Walsh, J. R. 1986, MNRAS, 220, 745
Muller, G. P., et al. 1998, Proc. SPIE, 3355, 577
Ogura, K., & Ishida, K. 1981, PASJ, 33, 149
Pérez, M. R., et al. 1989, PASP, 101, 195
Phelps, R. L., & Lada, E. A. 1997, ApJ, 477, 176
Verschueren, W. 1991, Ph.D. thesis, Vrije Univ. Brussel
Voges, W., et al. 1994, *ROSAT* News 32