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New discovery of weak-line T Tauri stars in high-Galactic latitude molecular clouds

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Abstract. Star formation efficiency in translucent molecular clouds has long been an unresolved and key issue in the field of low-mass star formation. In this paper, we report on the results of our survey for low-mass star formation in high-Galactic latitude molecular clouds, especially those of the translucent category, based on the ROSAT All-Sky Survey. Nine new weak-line T Tauri star candidates have been discovered at high-Galactic latitudes, among which, 6 are seen against – thus possibly associated with – the translucent molecular clouds, MBM 16, MBM 19 and MBM 55. Further study on the Li-rich X-ray active sources is necessary to shed more light on star formation in translucent molecular clouds.

Key words: stars: formation – stars: pre-main sequence – ISM: clouds

1. Introduction

Ever since the discovery of a dozen or so small molecular clouds at high-Galactic latitudes ($|b| > 25°$) by Magnani et al. (1985) (hereafter MBM), more than 100 such entities of the ensemble have been identified (Magnani et al. 1996b). These objects usually have diameters ranging from a few tenths to several parsecs, and masses from 10 to 10^2 $M_\odot$, which, as a whole, composed of about 10-20% of the local molecular mass inventory (Magnani et al. 1996b). The high-latitude molecular clouds are categorized as dark, translucent or diffuse molecular clouds according to van Dishoeck & Black (1988)'s classification by decreasing visual extinction, increasing importance of photochemical processes and decreasing average density. It appears that most of these clouds are translucent, gravitationally unbound (MBM), and possibly in pressure equilibrium with the interstellar medium (Keto & Myers 1986) at least in the outer regions.

Dark clouds are widely believed to be sites of star formation (Strom et al. 1975; Magnani et al. 1995). Even molecular clouds at the translucent/dark cloud boundary (e.g., MBM 12) partake in the formation of stars (Pound 1996), though star-forming clouds of this kind usually have dense molecular cores resembling those of dark clouds. While traditional diffuse molecular clouds cannot bear stars at all (Elmegreen 1985; Elmegreen 1993) for the dearth of molecular gas and consequently high-density bound cores, which are believed to be essential to low-mass star formation.

In contrast, no low-mass pre-main sequence stars (PMS) have yet been discovered to be associated with or formed in the lower extinction translucent molecular clouds (1 mag$<$ Av $<$3 mag). The issue of star formation in high-latitude translucent molecular clouds remains unresolved despite of many efforts made (Magnani et al. 1990; Caillault et al. 1995; Magnani et al. 1995; Magnani et al. 1996a), and star-formation rate in translucent molecular clouds may well be significantly lower than that in dark clouds (Hearty et al. 1999). However, the difference between a low and a null star-formation rate is crucial in understanding the origin, evolution and effects of translucent molecular clouds. Even a low star-formation rate would enhance greatly the local population of low-mass stars, and could serve as a viable explanation for the existence of isolated T Tauri stars (Rucinski & Krautter 1983) or young stars identified far away from on-going star forming regions (SFR) such as Taurus-Auriga (Neuhäuser et al. 1997; Li & Hu 1998).

A search for weak-line T Tauri stars (WTTS) in high-Galactic latitude molecular clouds, on the basis of the Einstein Imaging Proportional Counter (IPC) observations, has led to the re-discovery of one PMS (Caillault et al. 1995), yet no WTTS has been identified in the line of sight to any high-latitude translucent molecular clouds. However, the overlaps of the Einstein IPC observations and the high-latitude molecular clouds concerned are much limited ($\sim$ 6 square degrees in total), and a comparatively thorough investigation could now be carried out, on the availability of the flux limited ROSAT All-Sky Survey (RASS, Voges et al. 1996), to further elucidate the long puzzled issue on star formation in translucent molecular clouds. Previous searches for WTTS based on RASS and the ROSAT pointed observations have been conducted in and around the translucent clouds MBM 7, 40, and 55 (Magnani et al. 1996a; Hearty et al. 1999). Our sample is biased to the X-ray bright and has few sources in common with, and thus complementary to, the previous searches.

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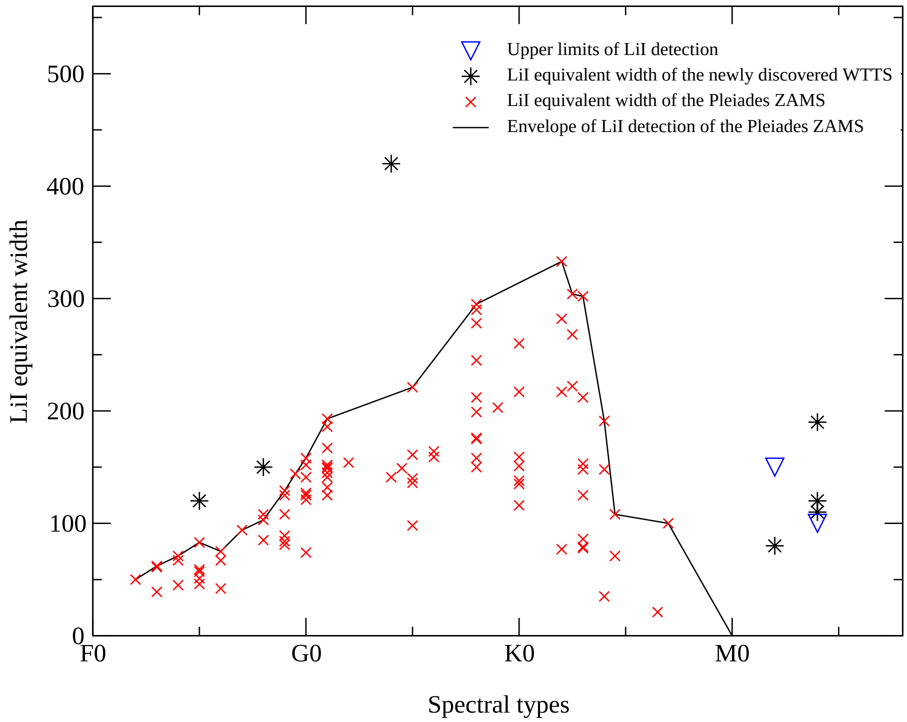

Fig. 1. Li I equivalent width of the newly discovered WTTS vs spectral type. The sloid line is for the the Pleiades ZAMS derived from Soderblom et al. (1993)

2. Observations and data reduction

Our program sources have been selected from the RASS Bright Source Catalogue (RASS-BSC) that are seen against the high-latitude molecular clouds mapped by MBM. Every optical counterpart within an error circle of 50″, which has a USNO (V1.0) R magnitude brighter than 15 has been taken as an X-ray selected WTTS candidate for follow-up optical identifications.

Intermediate resolution spectroscopic observations (with dispersion of 50Å/mm, 1.2Å/pixel and 2.5″ slit) were obtained by the 2.16m optical telescope of the Beijing Astronomical Observatory (BAO). The OMR (Optomechanics Research Inc.) spectrograph and the TEK1024 CCD detector were used during the runs of observations from Jan. 17 to 20 of 1997 and on Aug. 2 of 1999 which covered wavelength range 5700-6900Å. All spectral data were reduced with standard procedures with the NOAO Image Reduction and Analysis Facility (IRAF, version 2.10.4) software packages, and a relative flux calibration of each spectrum was performed using a mean response function. The intermediate-resolution spectra were normalized for further analysis. An IRAF command language script, called the ASCLTS (Automatic Spectral Classification of Late Type Stars, Li & Hu 1999) was applied to determine the spectral type of each late type star. Cross-correlation of each intermediate-resolution spectrum with a grid of spectral standards was carried out with the ASCLTS to obtain the best-fit spectral type. The accuracy of the spectral classification is estimated to be no more than ± one sub-class in most cases (Li & Hu 1999). The residual spectrum, derived from the target spectrum and the standard spectrum of the same spectral type, was then used to calculate the equivalent widths of the H and the Li I lines. Assuming that the young low-mass stars in our sample have their Fe abundance commensurate with the main-sequence spectral standards of the same spectral types, it is believed the Fe 6707.4Å absorption line blended with Li I 6707.8Å was able to be at least partly removed by the above mentioned procedure, and the uncertainty in the derived equivalent width W_λ(Li I) lies mainly in the estimation of the continuum. Though intermediate resolution spectroscopy has been employed, overestimation of W_λ(Li I) in our study is expected to be not serious.

3. Results and discussion

Our investigation has led to the identification of 44 possible optical counterparts to the sample of ROSAT selected X-ray active sources at high-Galactic latitudes. Nine of the optical counterparts, with W_λ(LiI) significantly larger than or comparable to the Pleiades Zero Age Main-Sequence (ZAMS) stars of the same spectral types (see Fig. 1), are considered as WTTS candidates possibly associated with the high-latitude molecular clouds. The RASS-BSC source designation, optical position, R magnitudes (USNO V1.0), estimated spectral types, equivalent widths of Hα emission and LiI absorption (positive values indicate emission and the negative represent absorption), possibly associated MBM clouds and comments on the nature of each source have been presented in Table 1. Normalized spectra of the 9 WTTS candidates with wavelength ranging from 6500Å to 6780Å are illustrated in Fig. 2.

A total of 4 (including an unresolved binary) and 2 WTTS candidates have been detected in the environs of MBM 16 and 18 respectively, lending evidence that they might be harboring stars. MBM 16 and 18 are located in a region rich of molecular gas just south of the Taurus-Auriga SFR and at least MBM 18 is probably a part of the southward extension of the Taurus-Auriga

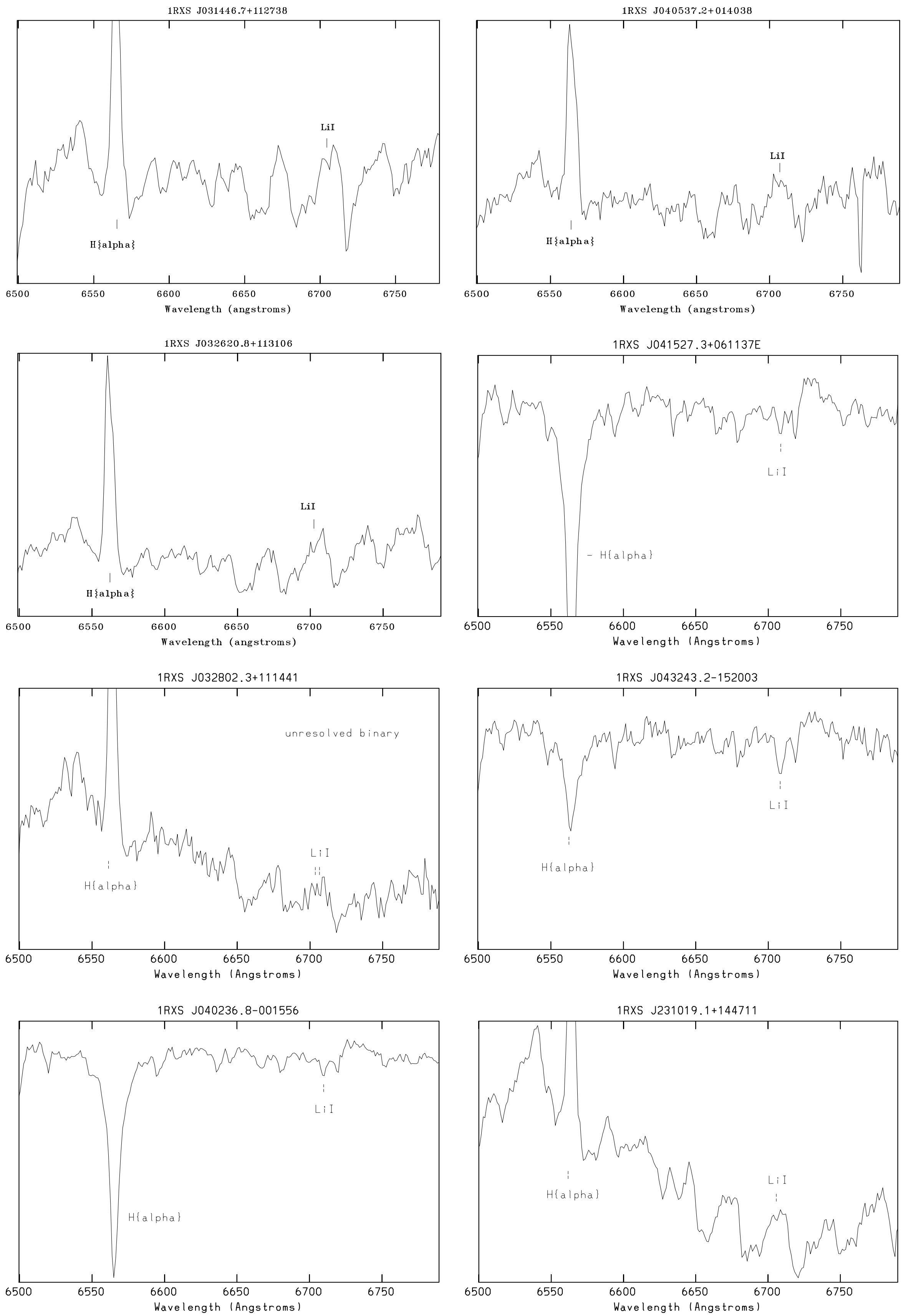

Fig. 2. Spectra of the newly discovered WTTS candidates at high-Galactic latitudes

dark cloud complex (MBM 16 is located at a distance of $\sim$ 60-95pc, as suggested by Hobbs et al. 1988). Since Taurus-Auriga is a well-known on-going low-mass SFR and a number of Li-rich X-ray active sources have been discovered further south of Taurus-Auriga (Neuhäuser et al. 1997; Magazzú et al. 1997), existence of WTTS candidates in the line of sight of these two small clouds may not be surprising and they are, to some extent, indistinguishable from those discovered around Taurus-Auriga.

A potential WTTS has been identified toward MBM 20 due to its strong LiI absorption. However, cross-identification of the WTTS, 1RXS J043243.2-152003, with the Hipparcos Catalogue has led to null results. On the scarce of any distance and proper motion information, we cannot be ascertained about the nature of this young X-ray active source or its possible association with MBM 20 — one of the most prolific sites of low-mass star formation at high-latitude (Sandell et al. 1987), though unlike its condensed regions, the envelope of MBM 20 is probably translucent and even unbound (Magnani et al. 1996b).

The left 2 WTTS candidates, 1RXS J041527.3+061137^E and 1RXS J231019.1+144711, detected in the direction of the high-latitude translucent molecular clouds MBM 19 and MBM 55 respectively as well as those found in MBM 16, are the most germane to our survey. Fig. 3 illustrates the 100 μm emission of these translucent molecular clouds and the positions of the WTTS candidates. 1RXS J041527.3+061137^E, the eastern component of a physical pair indicated by the Hipparcos data (Table 3), is a probable WTTS based on its significant Li I absorption and could be possibly associated with MBM 19, which has a total mass of $\sim 1 M_\odot$ (Magnani et al. 1996b) but unknown distance. The other source, 1RXS J231019.1+144711, with a spectral type of M3V and weak Li I absorption (since PMS models predict that early M type stars tend to deplete their lithium on the order of 10^6yrs, a comparably lower Li I absorption may still suggest its youth), is located near the condensed cores at the center of MBM 55 and could possibly be a sample young low-mass star originated from dense molecular cores in translucent clouds, which may have properties similar to those of the dark clouds.

Optical data of other identified X-ray active sources are presented in Table 2. Nearly half of the optical counterparts of the high-latitude X-ray sources have measurable Li I absorption, which indicates the X-ray selected sample of high-latitude sources are still relatively young and some of them might even be the low-mass components of the Gould Belt (Guillout et al. 1998).

Table 3 summarizes the results of our search in the Hipparcos Catalogue for optical counterparts of the X-ray sources in our sample. The source 1RXS J032409.7+123745 toward MBM 16, is located in the vicinity of the Taurus-Auriga region, and has both its distance and proper motions consistent with those of the Taurus-Auriga SFR. We believe it is likely a member of the Taurus-Auriga T association. Except for this Li-rich K0IV type source, all other sources in Table 3 are possibly nearby foreground field stars, rather than dispersed old stars ever formed in high-latitude molecular clouds situating at an average distance of about 100pc.

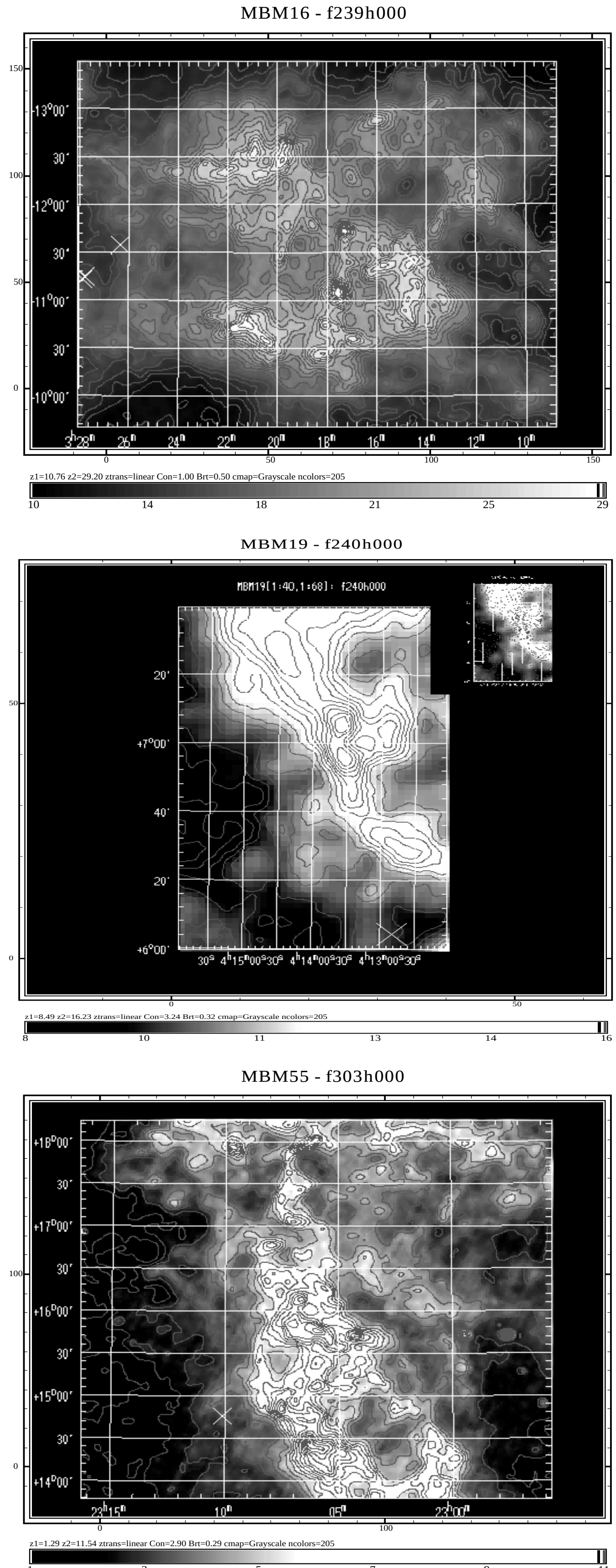

Fig. 3. 100 μm emission of the translucent molecular clouds in Table 1 and optical positions of the possibly associated WTTS candidates.

Table 1. Newly discovered WTTS candidates in high-latitude molecular clouds

RASS designation[1]	R.A.(J2000)	Dec.(J2000)	Rmag	Sp.T.	W_λ(Hα)	W_λ(Li I)	MBM[2]	comments
1RXS J031446.7+112738	03:14:46.99	11:27:29.3	12.0	M1V	4.1	-0.11	16[T]	WTTS
1RXS J032620.8+113106	03:26:21.24	11:30:55.9	13.7V	M2V	6.6	-0.18	16	WTTS
1RXS J032802.3+111441[b]	03:28:02.11	11:14:22.6	14.5	M3V	11.5	-0.19	16	WTTS
						-0.12	16	WTTS
1RXS J040236.8-001556	04:02:36.73	-00:16:08.0	05.4V	F5V	0.5	-0.12	18	WTTS
1RXS J040537.2+014038[W]	04:05:37.15	01:40:38.2	14.0	M4V	8.2	-0.11	18	WTTS candi.
1RXS J043243.2-152003	04:32:43.46	-15:20:12.6	10.0	G4V	0.9	-0.44	20	WTTS
1RXS J041527.3+061137[E]	04:15:29.17	06:11:12.0	06.5V	F8V	0.5	-0.15	19[T]	WTTS
1RXS J231019.1+144711	23:10:18.72	14:47:22.9	14.4	M3V	5.4	-0.10	55[T]	WTTS candi.

* Note: [1] 'E' & 'W' in Table 1 denote the eastern and the western optical counterparts of corresponding ROSAT X-ray sources respectively, and so forth. [2] 'b' shows the source is an unresolved binary. [3] 'T' indicates the MBM cloud is translucent.

Table 2. Optical data of other X-ray active sources in the direction of the high-latitude molecular clouds

RASS designation	R.A.(J2000)	Dec.(J2000)	Sp.T.	W_λ(Hα)	W_λ(Li I)	MBM	comments
1RXS J025804.2+204011	02:58:05.21	20:40:07.5	F0V	filled-in	-	12	dark cloud
1RXS J031924.8+124740	03:19:24.72	12:47:27.1	G0V	1.76	-0.04?	16	dark cloud
1RXS J032322.4+114122	03:23:22.71	11:41:15.9	M3V	2.67	-0.04	16	
1RXS J032409.7+123745	03:24:10.07	12:37:46.3	K0IV	filled-in	-0.14	16	
1RXS J040537.2+014038[E]	04:05:39.22	01:40:28.1	F5V	-1.09	-0.03?	18	dark cloud
1RXS J041527.3+061137[W]	04:15:26.34	06:12:00.4	G2V	0.43	-0.07?	19	
1RXS J043337.7-131528	04:33:37.79	-13:15:42.9				20	galaxy
1RXS J043520.2-145452	04:35:20.73	-14:54:45.6	K2IV	2.33	-0.02	20	dark cloud
1RXS J073101.9+460030	07:31:01.33	46:00:30.5	M2V	8.30	-	23-24	dMe
1RXS J073138.4+455718	07:31:38.51	45:57:21.5	M2V	7.00	-0.07	23-24	
1RXS J073239.5+463217	07:32:39.89	46:32:05.4	F5V	0.71	-	23-24	
1RXS J074228.1+465648	07:42:27.01	46:57:24.1	F5V	filled-in	-	23-24	
1RXS J084658.3+704452	08:46:56.94	70:44:36.1	F5V	-0.50	-	27-29	
1RXS J085527.8+704724	08:55:29.08	70:47:45.1	K3IV	0.68	-	27-29	dKe
1RXS J090415.8+725947	09:04:16.75	72:59:45.9	G3V	1.36	-	27-29	
1RXS J093428.7+694950	09:34:28.89	69:49:49.4	G0V	0.64	-	30	
1RXS J210910.1-094011	21:09:09.95	-09:40:14.6	G7IV	0.48	-0.06	46-48	
1RXS J211208.1-085004	21:12:11.17	-08:49:58.6	K0V	filled-in	-	46-48	
1RXS J212958.4+120959						49	globular cluster
1RXS J225608.4-000948	22:56:08.33	-00:09:54.3	K7V	6.5	-0.05	51	
1RXS J225852.7-001858	22:58:52.85	-00:18:57.6	G8V	0.47	-0.02	51-52	
1RXS J230529.6+260036	23:05:29.21	26:00:33.7	G9IV	0.58	-0.03?	53	
1RXS J230706.8+252807	23:07:06.70	25:28:05.8	K1IV	-0.12	-	53	
1RXS J230328.0+144341	23:03:27.92	14:43:49.0	F5V	filled-in	-	54-55	
1RXS J230617.6+183100	23:06:18.20	18:31:03.3	F2IV	filled-in	-	54-55	
1RXS J230624.3+123629[W]	23:06:23.48	12:36:27.6	M2V	2.6	0.02	54-55	
1RXS J230624.3+123629[E]	23:07:13.40	12:37:17.3	M3IV	0.5	-	54-55	dMe
1RXS J230631.9+195452	23:06:31.94	19:54:38.7	F6IV	0.43	-	54-55	
1RXS J230706.6+163153	23:07:05.25	16:32:27.1	G0IV	filled-in	-	54-55	
1RXS J230706.6+163153	23:07:02.33	16:32:12.8	F5V	0.4	-	54-55	
1RXS J230752.8+171033	23:07:52.58	17:10:15.5	F5V	0.50	-	54-55	
1RXS J230752.8+171033	23:07:52.33	17:10:17.2	K3IV	-0.12	-0.11?	54-55	
1RXS J230957.1+142540	23:09:57.12	14:25:33.3	F5V	0.5	-	54-55	
1RXS J230957.1+142540	23:09:55.12	14:25:36.9	K4V	0.6	-0.03?	54-55	
1RXS J231229.1+170935	23:12:28.99	17:09:22.0	K3V	2.0	-	54-55	dKe

Table 3. Astrometric and photometric data in the Hipparcos Catalog for the X-ray sources.

No.	Hipp.	V	π	$\mu_\alpha \cos\delta$	μ_δ	σ	$\sigma\mu_\alpha$	$\sigma\mu_\delta$	B-V	comments
1RXS J025804.2+204011	13834	5.80	31.41	234.79	-31.64	0.84	0.84	0.70	0.415	
1RXS J032409.7+123745	15850	6.03	7.06	25.97	-21.32	0.86	0.95	0.75	1.227	Tau-Aur[*]
1RXS J040236.8-001556	18859	5.38	52.00	151.20	-252.03	0.75	0.90	1.02	0.516	
1RXS J041527.3+061137^E	19859	6.32	47.20	-109.37	-108.35	1.08	1.12	1.12	0.570	
1RXS J041527.3+061137^W	19855	6.94	47.86	-101.62	-112.85	1.15	1.16	1.15	0.680	

* Note: see also Li & Hu (1998)

4. Summary

Our survey has found nine ROSAT selected WTTS candidates in the lines of sight to high-Galactic latitude molecular clouds, and 6 of which are possibly associated with translucent molecular clouds. Many of these sources (6 out of 9), as well as those presented in literature (Magnani et al. 1996a; Hearty et al. 1999), are found to have spectral types of late K to early M. Does this imply that the young low-mass stars are probably formed in small high-latitude molecular clouds? Are they likely evidence for multi-system ejection or actually low-mass counterparts of the Gould's Belt? Confirmation of their genuine association with the high-latitude molecular clouds and further studies on the nature and evolutionary status of these WTTS will no doubt shed light on star-formation activity at the high-latitudes, though star formation rate in these small molecular entities, especially in those translucent, would not necessarily be high.

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