豺狼座第三號分子雲中的年輕恆星

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摘要

我們利用 UKST 的 Hα巡天計劃之影像資料庫，來尋找具有發射線的星球。研究的目標是豺狼座恆星形成區，爲距離地球最近的恆星形成區之一。我們以豺狼座第三號分子雲中的兩顆赫比 Ae 星爲中心，分析了視野大小爲 30 × 30 角分的影像，挑選出 46 顆具 Hα發射線之傳統金牛座 T 型星候選者，其中 22 顆爲新發現的。這 22 顆當中的其中 7 顆星位於分子雲以外，它們的 2MASS 近紅外顏色與傳統金牛座 T 型星相符，後續光譜觀測發現至少有兩顆乃傳統金牛座 T 型星，表示該地區恆星形成活動不僅限於分子雲範圍，而應該重新檢討其恆星形成歷史。我們的結果顯示 UKST 的 Hα影像資料庫，若配合 2MASS 資料以及可見光光譜觀測，對於研究恆星形成區的年輕恆星非常有價值。

Young stellar population in the Lupus 3 molecular cloud

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Abstract

We report a pilot study to identify emission-line stars by use of the image database of the hydrogen-alpha survey by the United Kingdom Schmidt Telescope. The Lupus dark clouds are among the nearest star-forming regions. We analyzed a 30' × 30' field of the UK Schmidt Hα images centered around the 2 Herbig Ae stars of the Lupus 3 cloud. A list of 46 candidate T Tauri stars have been identified, among which 22 are new identifications. Seven out of these 22 Hα stars are not associated with molecular clouds, and have 2MASS colors suggestive of being classical T Tauri stars. At least two of the candidates have been spectroscopically confirmed to be T Tauri stars, while the rest are late-type dwarfs. This suggests that star formation in Lupus 3 is not limited to association with clouds, and thus the star formation history of the region should be reassessed. The UKST H-alpha database proves to be very useful, particularly in combination with 2MASS and optical spectroscopy, in study of the young stellar population in star-forming regions.

關鍵字（Keywords)：恆星形成（star formation）、金牛座 T 型星（T Tauri stars）

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1. Introduction

Classical T Tauri stars (CTTSs) are sun-like stars in their pre-main sequence (PMS) phase, characterized by (1) emission lines in their spectra, (2) ultra-violet and near-infrared (NIR) radiation in excess of stellar photospheric emission, and (3) X-ray emission. The NIR excess is thought to originate from heated dust in the circumstellar disk, whereas the Hα emission line is supposed to come from both the chromospheric activities and the boundary layers between the star and the disk. The boundary layer is also responsible for the ultraviolet and X-ray emission. Traditionally the Hα emission line has been used to identify CTTSs. Alternatively, IR excess (e.g., Lee et al. 2005) or X-ray observations (Feigelson & Montmerle 1999) can be very efficient in search for CTTSs in star-forming regions. In addition to the CTTSs, there is another type of low-mass PMS stars, namely the weak-lined TTSs (WTTSs), which are thought to be at a more evolved stage than CTTSs in terms of clearing surplus material in the circumstellar environments. The CTTSs are characterized by strong Hα emission, with an equivalent width of Hα W(Hα) > 10 Å. In comparison, the WTTSs typically has an Hα equivalent width less than 5Å. The WTTSs also lack the IR or UV excesses in their observed spectral energy distribution.

Of the 5 nearest star-forming regions (SFRs) within 200 pc from the Sun, including Taurus, Chamaeleon, Rho Ophiuchi, R Coronae Australis and Lupus, 4 (except Taurus) are in the southern sky. The distance proximity renders these SFRs to be good targets, in terms of detection sensitivity and angular resolution, to study the star formation

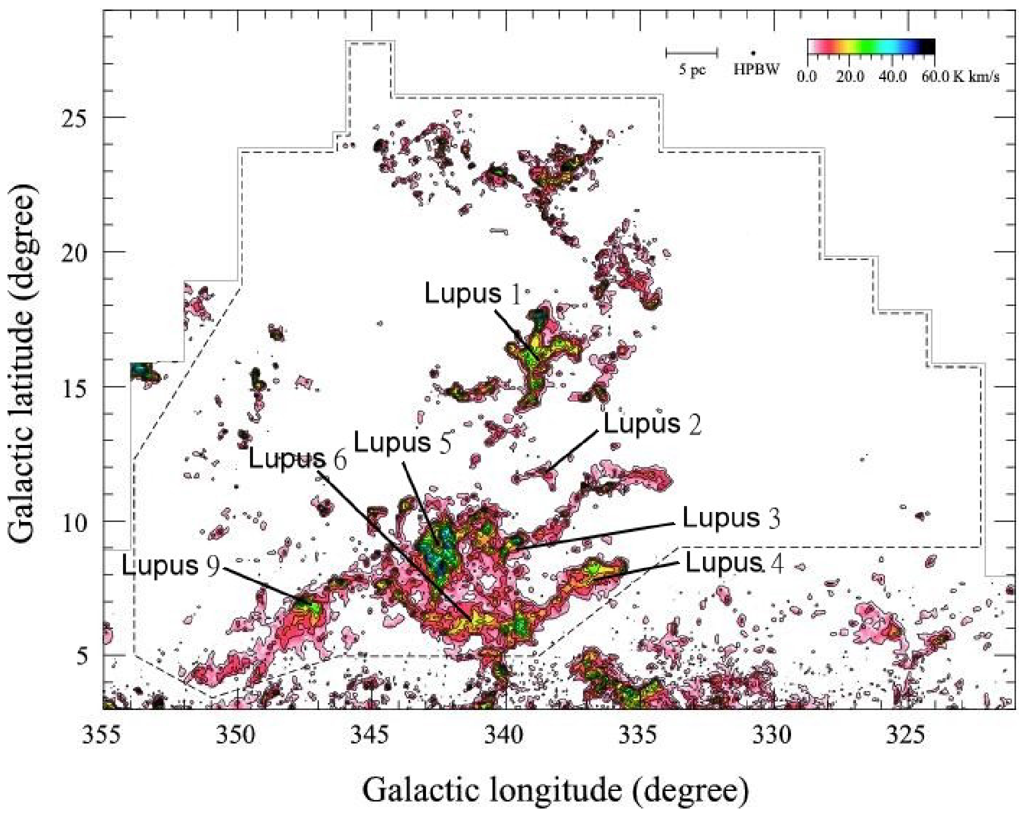

Fig. 1: The intergrated intensity map of ^{12}CO by Tachihara et al. (2001), showing the distribution of molecular clouds in the Lupus SFR.

processes and young stellar populations. The Lupus region consists of several molecular clouds (see Fig. 1), some with obvious ongoing star-forming activities (e.g., Lupus 1), while some without (e.g., Lupus 5). In this study, we focus on the Lupus 3 cloud, which has the highest column density in $C^{18}O$ J=1-0 emission (Hara et al. 1999) and the largest number of T Tauri stars in the entire Lupus SFR. Schwartz (1977) cataloged Hα stars in several southern SFRs, including Lupus, based on objective-prism observations.

The UKST Hα survey offers us a convenient set of data to study emission nebulocity and emission-line objects. The project was carried out by the UK Schmidt telescope (UKST) of the Anglo-Astralian Observatory to survey the southern Galactic plane with |b| < 10 deg and the Magellanic clouds. The survey made use of the wild-field Schmidt telescope and sensitive, high-resolution film plates (Tech-Pan), with two kinds of filters, Hα and Short-Red (SR). The original plates were scanned by the SuperCOSMOS measuring machine at the Royal Observatory, Edinburgh. Online digital atlases of the SuperCOSMOS H-alpha survey (SHS) are available. The SHS porvides a homogeneous data-set on unprecedented sky coverage and angular resolution to study the H-alpha sky. In addition to CTTS, Hα emission is a good indicator also to identify Herbig Ae/Be (HAeBe) stars, which are also PMS stars but more massive than CTTSs. Previous Hα surveys to identify CTTSs and HAeBe stars are restricted to relatively small regions with inferior sensi-tivity, resulting in incompleteness of faint young stars. To exercise the mothodology to make use of the SHS data to find PMS stars, we analyzed the Hα images of the Lupus 3 cloud to study regions away from the dense cloud, where previous observations have overlooked. We present our data analysis procedure in Sec. 2, and the list of CTTS candidates identified by our study in Sec. 3. Comments on the generalization of our method are given as Sec. 4.

2. Data reduction and analysis

To select Hα stars, we first processed the images taken by the Hα and the SR filters. As long as the emission line is not excessively strong, the SR can be taken as a continuum filter. Therefore by proper subtraction of the continuum from an image taken by the Hα filter, candidate Hα stars were identified, which were then further studied by optical spectroscopy to affirm their nature.

We analyzed the Hα and SR images, each with a field of view of 30' × 30', of the Lupus 3 cloud downloaded from the SHS website[**], with central position of RA=16h08m34.3s, Decl=-39°06'18.3" (J2000). The SHS images have been flat-fielded (Parker et al. 2005). An image taken with an Hα filter contains the radiation across the Hα line plus the continuum emission. The SR image, which has a spectral response from 590 nm to 690 nm, was used as the continuum to be subtracted from an Hα image to obtain the net Hα line emission. The scaling factor was chosen so that non-PMS star have

[**] http://www-wfau.roe.ac.uk/sss/halpha/

statistically null counts in the subtracted image. To get the proper scaling factor, we applied aperture photometry on the Hα and the SR images by *phot* task in the IRAF/NOAO package. The counts of most stars in the Hα and SR images follow a linear relation, from which the scaling factor is calculated ,

$$C(\text{H}\alpha\ \text{line}) = C(\text{H}\alpha\ \text{filer}) - s \cdot C(\text{SR filter})$$

where C is the counts of a star in the Hα, SR, or Hα-SR image, and s is the scaling factor between the Hα and the SR images. Empirally, stars away from molecular clouds are used to iterate to a proper value for the scaling factor. One sees that the choice of the scaling factor s is not unique and actually is subjective. In reality, non-PMS stars may have Hα in absorption or even in emission (active dwarfs and some giants). On the other hand, the choice of the scaling factor does not need to be highly accurate, because either an overestimate or an underestimate does not affect much the selection of ***strong*** Hα emission stars; strongest Hα stars remain so regardless of what scaling factor is used. This means the subtraction may not be quantitatively reliable but can be used qualitatively. In our study we did not use the images for quantitative analysis, but only to identify a list of candidate stars for spectroscopic observations. For the UKST data, the exposure time with Hα filter was much longer than that in SR filter, so the counts in an Hα image are generally higher than those in the corresponding SR image. For the set of images we used to process the Lupus 3 cloud, we adopted s = 1.632. Aperture photometry was performed on the continuum-subtracted Hα image. At the end, a list of 46 stars with descending Hα line counts (a rough measure of the net Hα line flux) is produced (see Table 1).

3. Results

Table 1 gives the results of the 46 Hα stars in the central 30' × 30' field of the Lupus 3 cloud. The first column is the sequence number. Column (2) and (3) list the coordinates of the star. Column (4) shows the identifications of pre-viously known sources. The empty one means a new detection by our study. Column (5) is the Hα counts we measured in the continuum-subtracted Hα image. The last column gives remarks of any followup observations. The entries are sorted by their Hα counts in decending order. Of these 46 Hα stars, 22 are new identifications. All the emission stars reported by Schwartz (1997) have been found in our analysis, except the three stars, Sz 103, Sz 104 and Sz 106, which are too close to the two luminous A-type stars, thereby defying our aperture photometry measurements. We did not find any WTTS because of their expected weak Hα strength.

Fig. 2 shows the 2MASS color-color diagram of the stars in the field of view. Emission-line stars previously known are marked by diamonds, where stars we identified in the UKST images, i.e., from Table 1, are marked by triangles. It is seen that most of the known Hα stars are located near the CTTS locus. Seven of the Hα stars in our list also fall near this region of the diagram, suggestive of being posible CTTSs. The majority of the other stars in our list should be reddened giants or active dwarfs in the Galactic

Table 1. The emission-line stars identified in the UKST Hα images

No.	R.A. (J2000) h m s	Decl. (J2000) Deg ' "	Name	Hα Counts	Remarks
1	16 08 29.70	-39 03 10.9	sz102	6112412	
2	16 08 51.59	-39 03 17.7	sz110	486947	
3	16 08 12.63	-39 08 33.4	sz96	479292	
4	16 09 01.84	-39 05 12.3	sz114	475915	
5	16 09 44.37	-39 13 30.1	sz117	317849	
6	16 08 24.05	-39 05 49.4	sz99	308262	
7	16 08 21.82	-39 04 21.2	sz97	246246	
8	16 08 25.77	-39 06 00.7	sz100	225391	
9	16 08 55.54	-39 02 33.9	sz112	220502	
10	16 07 52.31	-38 58 05.1	sz95	208090	
11	16 08 27.79	-39 00 40.3	RXJ1608.4－3900A	199076	
12	16 08 53.24	-39 14 40.1		196645	
13	16 09 42.61	-39 19 40.3	sz116	188991	
14	16 08 35.80	-39 03 47.4	Par-lup3-2	170891	
15	16 08 22.82	-39 00 59.2	RXJ1608.4－3900B	169362	
16	16 08 28.45	-39 05 32.6	sz101	169307	
17	16 08 22.51	-39 04 46.4	sz98	168945	
18	16 09 06.26	-39 08 51.3	sz115	165986	
19	16 07 31.44	-38 53 18.1		163731	
20	16 08 41.80	-39 01 36.9	sz107	158232	
21	16 07 49.60	-39 04 28.5	sz94	149063	
22	16 08 16.76	-38 55 41.9		146978	M III/V, a
23	16 07 54.07	-39 20 44.8		145512	
24	16 08 45.73	-38 53 57.6		143616	M III/V
25	16 08 47.30	-38 58 18.3		139609	M III/V, a
26	16 07 59.42	-39 14 16.5		135116	M III/V
27	16 08 37.40	-38 58 47.1		133321	M III/V
28	16 08 48.18	-39 04 19.5	sz109	125896	
29	16 08 17.43	-39 01 05.4		123775	a
30	16 08 42.78	-39 06 17.8	sz108	123574	
31	16 08 49.41	-39 05 38.9	Par-lup3-3	119580	
32	16 09 28.33	-38 55 07.2		111941	CTTS or dM, a
33	16 08 01.11	-39 02 51.6		111114	M III/V
34	16 09 49.39	-39 14 57.2		110224	M III/V
35	16 08 23.56	-39 15 41.8		109831	M III/V
36	16 09 02.21	-38 58 56.7		99449	Early M III/V
37	16 09 36.88	-39 01 45.5		99126	M III/V, a
38	16 09 48.70	-39 11 16.8	sz118	99051	
39	16 09 15.73	-38 51 39.5		97994	CTTS or dM, a
40	16 08 35.48	-39 00 35.9		97976	a
41	16 08 57.80	-39 02 22.6	sz113	90717	
42	16 09 34.13	-39 13 41.9		88608	
43	16 09 48.04	-39 18 01.3		88169	Early M III/V?
44	16 08 20.95	-39 03 15.7		86410	
45	16 09 32.77	-39 19 15.6		82338	M III/V
46	16 07 42.74	-38 53 58.3		80164	M III/V

[a]Stars with 2MASS colors consistent with being CTTSs.

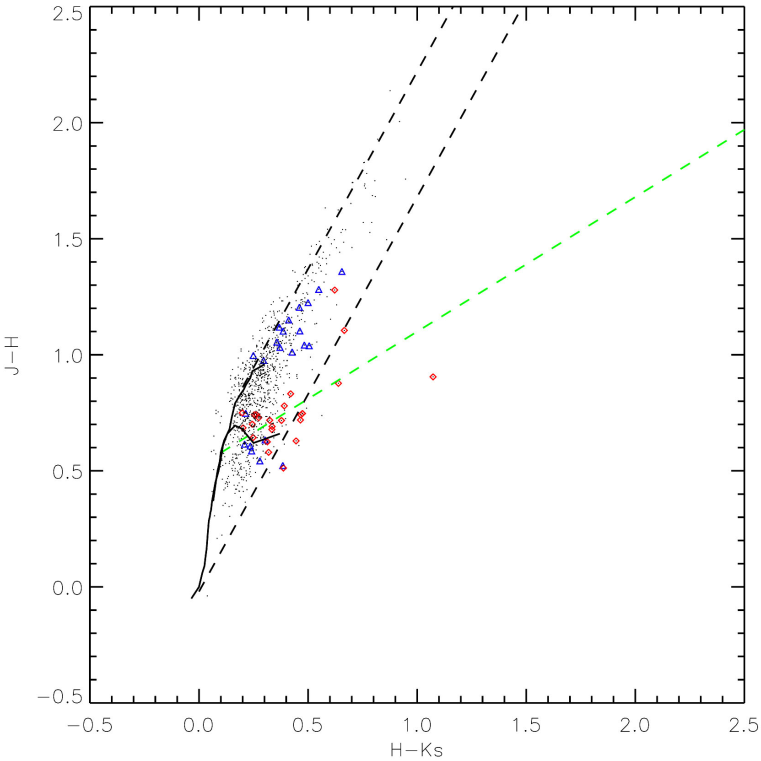

Fig. 2: NIR color-color diagram of the 2MASS sources in the Lupus 3 field. The red diamonds mark previously known emission-line stars and CTTSs. The blue triangles represent the CTTS candidates (this work). The solid curves are giant and dwarf loci, respectively (Bessell & Brett 1988). The black dash lines bracket the reddening band (Rieke & Lebofsky 1985). The green dash line is the unreddened CTTS locus (Meyer et al. 1997).

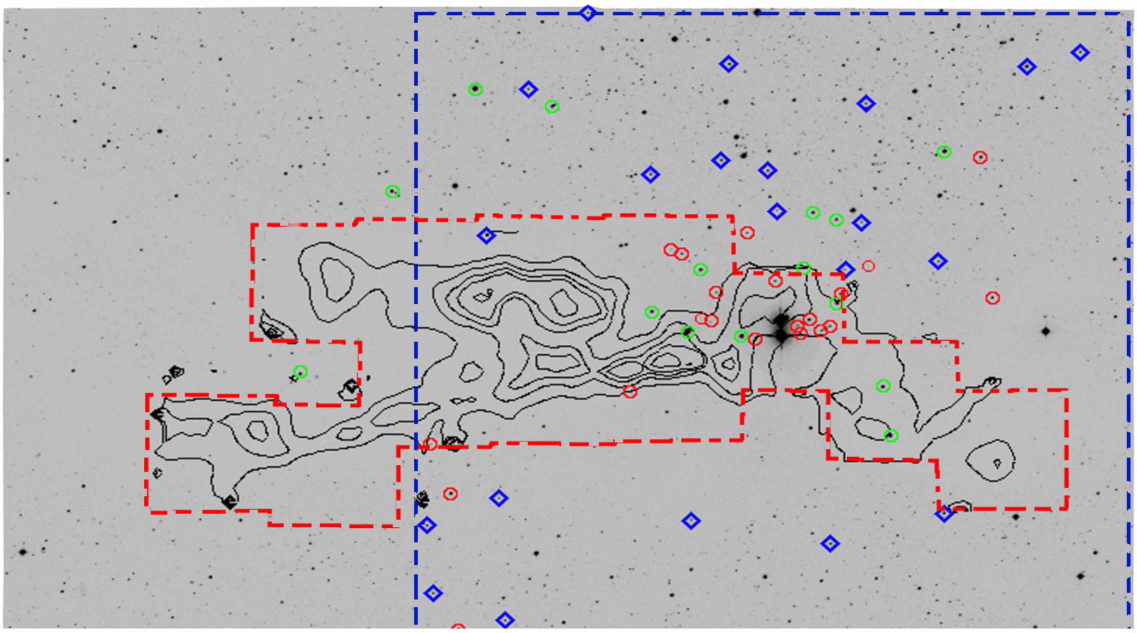

Fig. 3: Hα stars in the Lupus 3 molecular cloud. The blue frame encloses our analyzed region with an FOV of 30' × 30'. The green and red circles represent previously known T Tauri stars and emission-line stars, respectively. New identifications are marked by blue diamonds. The SHS Hα image is in the background, whereas the contours show the NICER extinction map by Teixeira et al. (2005). The red frame is the surveyed region of this extinction map. North is to the top and east to the left.

background which are not related to the Lupus cloud. Fig. 3 shows the UKST Hα image superimposed with the NICER extinction map (Teixeria et al. 2005) delineating the distribution of the dark molecular cloud. All previously known emission stars, CTTSs, WTTSs, as well as the Hα stars we have identified are separately marked. Many TTSs and emi-ssion stars surround the two central Herbig Ae stars, HR 5999 and HR 6000.

4. Comments on the Mothodology and the Results

As discussed earlier, our procedure to identify emission-line stars from the UKST images observed by the Hα and the SR filters gives only a qualitative estimate of the relative strength of the Hα line. It is assuring that star Sz 102, which has the largest known Hα equivelent width (Hughes et al. 1994), is also the strongest Hα star on our list. However, some cautions should be noted. First of all, the digital images came from scanned photographic plates (Tech-Pan films), which are nonlinear in response to incident light. In such a scanning process, it is the density of the emulsion that is directly measured, not light intensity or flux. Furthermore, bright stars are saturated in long exposures in both Hα and SR images. The counts in this case naturally are not reliable. Another issue to be considered is the different sky background in the Hα and SR images, which were taken at different nights with different moon phases. This means for each Hα-SR image pair, the scaling factor must be reevaluated.

Our Hα list includes some late-type stars, notably late-type dwarfs. They are selected either because they have genuine Hα in emission, or because their continua are underestimated. It has long been recognized that some late-type dwarfs show strong chromospheric Hα in emission, and that the fraction of such chromospherically active

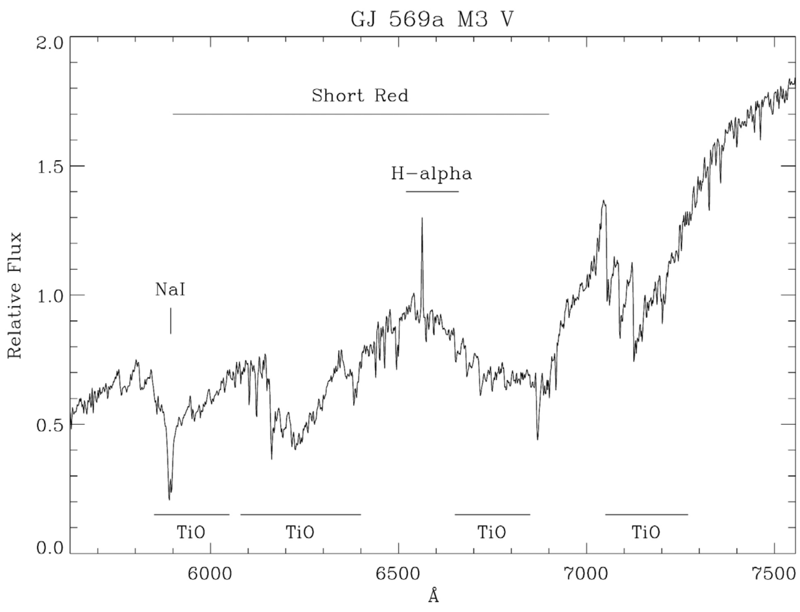

Fig. 4: The typical spectrum of a late-type dwarf contains prominent TiO absorption bands, causing an underestimate of the continuum measured by a broad-band filter. Here an M3 dwarf spectrum is shown for illustration. The spectral data were taken from the database of Departamento de Astrofisica of the University Complutense of Madrid (http://www.ucm.es/info/Astrof/fgkmsl/fgkmsl.html). Also shown are the spectral response ranges of the SHS H-alpha and Short-Red filters.

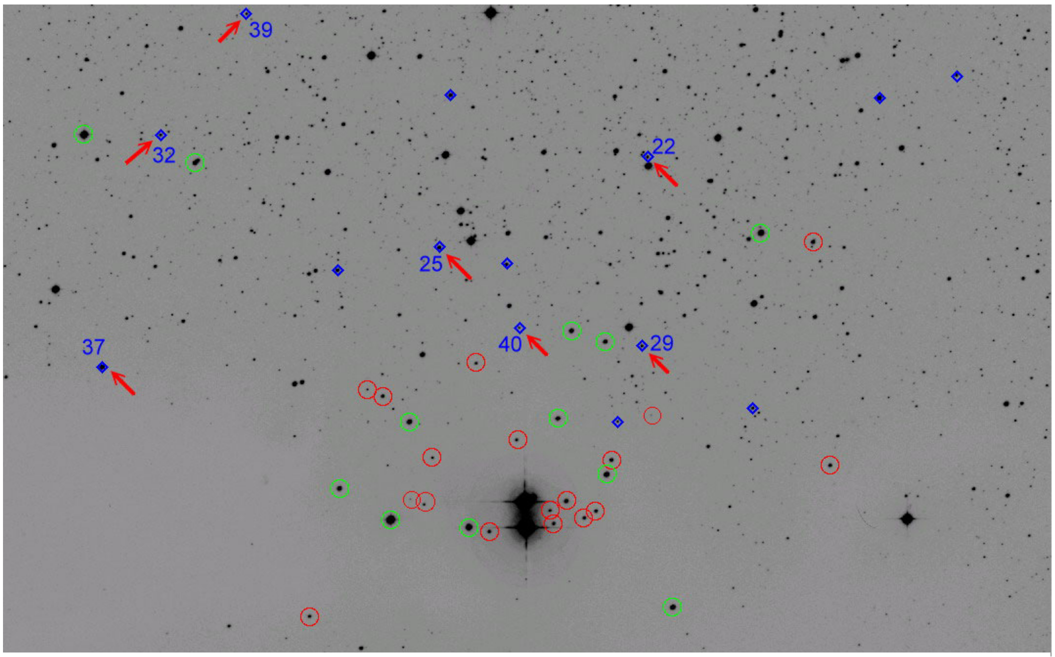

Fig. 5: The north part of Lupus 3. The symbols are the same as those in Fig. 3. The candidates which have NIR colors similar to those of CTTSs are marked by arrows.

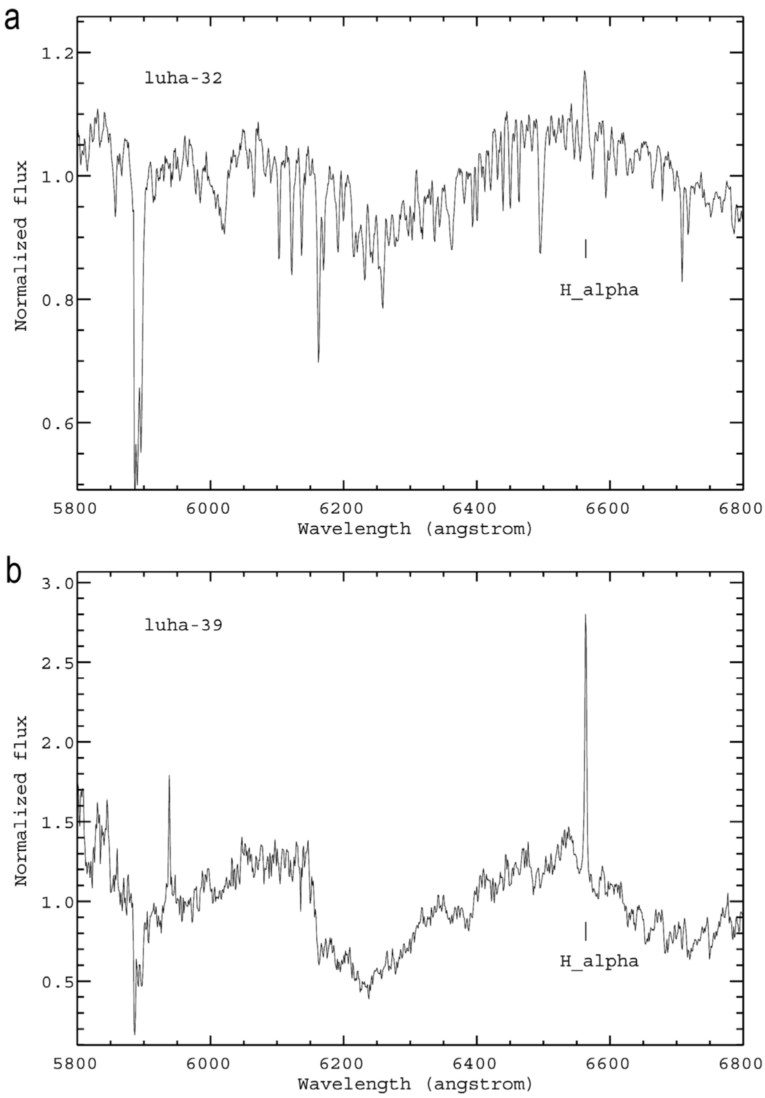

Fig. 6: Optcal spectra of stars 32 and 39. In each case, an H-alpha in emission is seen.

stars increases from spectral type K to M5.5 (Joy and Abt 1974). Even if a late-type star does not show Hα emission, such a star generally has a series of strong metal oxide absorption lines, such as the TiO, in its spectrum, as illustrated in Figure 4. This leads to an underestimation of their continuum (Pierce 2005), hence making the star be selected by our procedure.

Interestingly, the seven stars in Table 1 which are located near the CTTS locus (cf. Fig. 2) are not located around the two Herbig Ae stars, unlike the previously known PMS stars which are concentrated in this relatively small region. Instead, the CTTS candidates together young stars are all located to the north of the Lupus 3 cloud (Figure 5), where there are other molecular clouds, e.g., Lupus 1, 2 and 5 further to the north. The spectra of these candidates will be taken in 2006 by the SMARTS facilities at CTIO, and at least 2 stars have been confirmed to show Hα in emission (Figure 6), hence are either CTTSs or active M dwarfs (dM stars). The rest of the candidates we have observed are M-type dwarfs (Table 1) with no Hα feature. They were selected because of the strong TiO band contamination, as explained earlier. Higher dispersion spectra are needed to distinguish a CTTS against a dM star, for example by the presence of the Li absorption line which signifies youth. The Galactic plane is to the south. This distribution of young stars is consistent with the WTTS distribution (Krautter et al. 1997), even though the WTTS survey covered an area of 230 square deg, which is much larger than our studied region. Tachihara et al. (2001) suggested the cluster of the PMS stellar group in Lupus 3 to be formed under the influence of nearby OB stars, but there has been so far no evidence to support the assertion. Another possibility is the selection effect for which the young stars in the southern region may be simply deeply embedded in the molecular clouds and cannot be seen by optical observations. We plan to continue to search for young stars in Lupus SFRs by UKST data and 2MASS data to address these issues.

In summary, our pilot study to use archival UKST/SuperCOSMOS Hα Survey images and 2MASS data to identify candidate CTTSs in the Lupus 3 molecular cloud, found all previously known emission stars by Schwartz (1977). We found additional 22 new identifications, most of which are field stars. Seven out of these 22 Hα stars have 2MASS infrared colors consistent with those of CTTSs. We have developed the analysis pipeline to combine UKST/SHS and 2MASS, followed by optical spectroscopy, as a useful tool in study of PMS population in a SFR.

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