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Probable Association of T Tauri Stars with the L 1014 Dense Core

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Abstract

Using the Wide Field Grism Spectrograph 2 (WFGS2), we carried out slit-less spectroscopy, g’r’i’ photometry, and slit spectroscopy on the L 1014 dense core. We detected three Hα emission-line stars. We interpret one as being a weak-line T Tauri star (WTTS) and the others as classical T Tauri stars (CTTS). Since their g’–i’ colors and/or classified spectral types are consistent with those of T Tauri stars and two of them show less extinction than the cloud, these three stars are likely to be T Tauri stars associated with L 1014. Adopting an age range for T Tauri stars, 1–10 Myr, the color–magnitude diagram suggests a distance of ∼400–900 pc, rather than the previously assumed distance, 200 pc. This could strongly affect the mass estimate of L 1014-IRS, which is thought to be either a very young protostar or proto-brown dwarf.

Key words: ISM: globules — ISM: individual (L 1014) — stars: distances — stars: formation — stars: low-mass, brown dwarfs — stars: pre-main sequence

1. Introduction

In the early evolution of substellar objects, the formation of brown dwarfs in molecular clouds is of particular interest; several formation mechanisms have been proposed (e.g., Mohanty, Jayawardhana 2006; Luhman et al. 2006; Whitworth et al. 2006). One possibility is the same mechanism as low-mass stars, but with much smaller cores (e.g., Padoan, Nordlund 2004). The L 1014 dense core is a potential site for such a process.

L 1014 was previously thought to be starless because it lacks IRAS point sources (Lee, Myers 1999). Young et al. (2004) discovered a very faint infrared source (L 1014-IRS) toward the center of L 1014 with the Spitzer Space Telescope. Recent detections of a molecular outflow and a reflection nebula revealed that this central object is really embedded within the cloud core, and is not a background source associated with the Perseus arm at 2.6 kpc (Bourke et al. 2005; Huard et al. 2006).

Assuming that the distance of L 1014 is ∼200 pc, as adopted in recent literature, this embedded source becomes an ideal candidate for a very low-mass protostar, i.e., a proto-brown dwarf.

However, the mass estimate of a protostellar object depends on its adopted distance. It is, in general, not easy to determine the distance to the surrounding dark cloud, particularly that of a small, nearby dense core, since its small size implies a small number of background/foreground stars. In fact, the assumption that L 1014 is 200 pc away seems to originate from the distance estimate of B362, which is located ∼10′ north of L 1014, but this estimate is based upon the similarity of VLSR (Dieter 1973) to that of nearby clouds with a kinematic distance of ∼100–200 pc (Dickman 1976).

The L 1014 dense core is thought to be a site of very recent (< 1 Myr) star formation. We interpret the slightly extinct region extending southwest of L 1014 in the DSS-II red image as thinner molecular gas extending from the dense core. In fact, CO observations (Robert, Pagani 1993; Crapsi et al. 2005) showed the existence of molecular material in this region. We suspected that the thin molecular gas and the dense core are remnants of previous low-mass star formation over the past few Myr. If so, pre-main sequence stars, i.e., T Tauri stars, could be detected toward L 1014 and the validity of the distance estimate of L 1014 can be examined with a color–magnitude diagram by using theoretical isochrones of pre-main sequence stars.

In order to substantiate the presence of previous star formation, we surveyed Hα emission-line stars by slit-less spectroscopy around this remarkable core. Slit spectroscopy and g’r’i’ photometry were then performed on the selected stars. In this letter, we present our spectroscopic results and discuss whether the detected Hα emission-line stars are T Tauri stars associated with the L 1014 core. We also discuss the distance to L 1014.

2. Observations and Results

Slit-less grism spectroscopy and g’r’i’ photometry of L 1014 were conducted with the Wide Field Grism Spectrograph 2 (WFGS2; Uehara et al. 2004) mounted on the University of Hawaii (UH) 2.2-m telescope on 2004 November 13 UT. The detector used was a Tektronix 2048 × 2048 CCD. The field of view is 11.5′ × 11.5′ with a pixel scale of 0.′′34 pixel−1.
For slit-less spectroscopy, we took three 300 s exposures dithered by \( \sim 20'' \) with a wide H\( \alpha \) filter (FWHM = 50 nm) and a 300 line mm\(^{-1}\) grism. For the \( g' r' i' \) photometry, we took one 2 s exposure and three 10 s exposures dithered by \( \sim 20'' \) for each band. For the photometric calibration the SDSS standard star BD + 25\(^{\circ}\)4655 (Smith et al. 2002) was observed at nearly the same airmass as the target (difference \( \leq 0.16 \)). Twilight images were also taken for flat-fielding. The limiting magnitudes were \( g' \sim 20.9 \), \( r' \sim 20.6 \), and \( i' \sim 20.0 \) for 10\( \sigma \) detections.

We extracted about 2000 spectra from the slit-less spectroscopy image and examined them for the presence of H\( \alpha \) emission. As a result, we found three H\( \alpha \) emission-line stars (figure 1). From measurements of the equivalent widths (EWs), we identified one candidate (star-1) as a weak-line T Tauri star (WTTS) and two candidates (star-2 and 3) as classical T Tauri stars (CTTS). Star-1 and 2 were previously reported as H\( \alpha \) emission-line stars toward B362, but their EWs were not measured (Ogura, Hasegawa 1983). The coordinates, EWs, magnitudes and colors of these stars are given in table 1.

The observed colors of star-1, 2, and 3 correspond to types K6–K7, K2–K3, and M3–M4, respectively. For this comparison, we transformed the colors of main-sequence stars bluer than M0 from the \( UBVRI_\alpha \) system (Kenyon, Hartmann 1995) to the \( u'g'r'i'z' \) system with the equations in Smith et al. (2002). For stars whose colors are between M0 and M5, we adopted a color transformation estimated from a comparison between our \( g'r'i' \) photometry of NGC 2264 and the \( V_R I_\alpha \) photometry of Dahm and Simon (2005).

To classify the spectral types of the T Tauri star candidates, we performed slit spectroscopy using WFGS2 during 2005 November 25–28 UT. We obtained low-dispersion spectra of star-1 and 2 with a 300 line mm\(^{-1}\) grism and a 0\(''\)7 slit. The spectra covered 426–810 nm with a resolving power of \( R \sim 820 \) at 650 nm. The total integration times were 2350 s for star-1 and 1200 s for star-2. We also obtained a higher-dispersion spectrum of star-2 using a Volume-Phase Holographic (VPH) grism (Ebizuka et al. 2003) and a 0\(''\)7 slit. The VPH grism spectrum covered 586–742 nm with a resolving power of \( R \sim 4200 \) at 664 nm. The total integration time was 2940 s.

We classified the stars by comparing the spectra with the spectral atlas of Allen and Strom (1995) after normalizing each observed spectrum by fitting the continuum with a spline function. The features of the absorption lines in the low-dispersion spectra of star-1 and 2 are almost identical, closely resembling a K3V spectrum (figure 2). However, the H\( \alpha \) emission-line intensities differ. In addition, three absorption lines of CaH (6346, 6382, and 6389 \( \AA \)), which are features of mid K through M type stars, are seen in the higher dispersion spectrum of star-2 (figure 3). Furthermore, a low-dispersion spectrum over 420–700 nm of star-1 was obtained with the 65-cm telescope of the Gunma Astronomical Observatory on 2005 December 21 UT, and it is consistent with the spectrum of reddened K2V to K4V stars with a visual extinction of \( \sim 0.8–1.5 \) mag. Thus, we classified both star-1 and 2 as being K3 type. The error in the classification is one or two in the subclass.

### Table 1. Properties of T Tauri Star Candidates.

<table>
<thead>
<tr>
<th>No.</th>
<th>RA (J2000)</th>
<th>DEC (J2000)</th>
<th>EW (( \AA ))</th>
<th>( g' ) (mag)</th>
<th>( r' ) (mag)</th>
<th>( i' ) (mag)</th>
<th>( g' - i' ) (mag)</th>
<th>Candidate Type</th>
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<tbody>
<tr>
<td>1</td>
<td>21(^{h})23(^{m})58(^{s})51</td>
<td>+49(^{\circ})58'09''</td>
<td>5.4</td>
<td>15.02 ± 0.03</td>
<td>14.20 ± 0.02</td>
<td>13.46 ± 0.01</td>
<td>1.56</td>
<td>WTTS</td>
</tr>
<tr>
<td>2</td>
<td>21(^{h})23(^{m})44(^{s})72</td>
<td>+49(^{\circ})59'48''</td>
<td>21.2</td>
<td>13.74 ± 0.03</td>
<td>13.11 ± 0.02</td>
<td>12.74 ± 0.01</td>
<td>1.00</td>
<td>CTTS</td>
</tr>
<tr>
<td>3</td>
<td>21(^{h})23(^{m})29(^{s})69</td>
<td>+50(^{\circ})03'13''</td>
<td>14.9</td>
<td>18.54 ± 0.04</td>
<td>16.94 ± 0.02</td>
<td>15.99 ± 0.01</td>
<td>2.55</td>
<td>CTTS</td>
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Note: The magnitudes and colors are derived without a color correction on the assumption that the photometry system used here is well matched to the SDSS standard system (Smith et al. 2002).

### 3. Discussion

#### 3.1. Are the H\( \alpha \) Emission-Line Stars T Tauri Stars?

We detected three H\( \alpha \) emission-line stars near the small dense core. These emission-line stars are likely to be T Tauri stars because of their proximity to the molecular cloud. However, some other possibilities, including those noted by Dahm and Simon (2005), should also be considered:

1. classical Be stars,
2. Herbig Ae/Be stars,
3. dMe stars (EW < 10 \( \AA \), late K through M types),
4. chromospherically active giants, and
5) RS CVn binaries, cataclysmic variables and symbiotic variables (EW > 10 Å).

For star-1, possibilities 1)–3) are eliminated because the classified spectral type is not B or A and is earlier than late K types. Possibility 5) is unlikely because such stars usually have a Hα emission-line EW larger than 10 Å. Given star-1’s observed g′ − i′ color of 1.56 mag, and assuming an intrinsic color of ∼ 1.05 mag from the color of a K3V star in the u′g′r′i′z′ system described in section 2, we obtain a color excess of ∼ 0.51 mag. We estimate the visual extinction of star-1 to be ∼ 0.88 from this color excess and $A_V = E(g′ − i′)/0.58$ (Fiorucci, Munari 2003). On the other hand, the total extinction of the cloud toward star-1 is about 2–3 mag from the C18O and visual extinction maps of Crapsi et al. (2005). Therefore, star-1 is probably embedded in the L 1014 core envelope, eliminating possibility 4). We examined the Spitzer archival data of L 1014, obtained by the c2d legacy program (Evans et al. 2003). We identified star-1 with object SSTc2d J212358.5+495809. Its fluxes at 3.6, 4.5, 5.8, 8.0, and 24.0 μm are 11.2 ± 0.473, 9.97 ± 0.121, 6.89 ± 0.258, 4.23 ± 0.039, and 1.42 ± 0.0758 mJy, respectively. These fluxes give IRAC colors of $[3.6] – [4.5] = 0.36$ and $[5.8] – [8.0] = 0.11$, placing it outside the Class II region on the IRAC color–color diagram (see figure 4 of Allen et al. 2004). These colors and the detection at 24.0 μm support that star-1 is WTTS with a thin disk or a disk having a large inner hole. Many stars are detected in optical wavelengths, as can be seen in figure 1, but only a small number, including L 1014-IRS, are detected on the 24.0 μm image, suggesting a probable association of circumstellar material with them.

For star-2, possibilities 1)–3) are eliminated for the same reasons as star-1. Star-2’s observed color is almost the same as that expected from its spectral type, whereas the C18O map (Crapsi et al. 2005) gives an extinction of ∼ 0.5 mag at its location. We conclude that star-2 is located on the outskirts of the core, eliminating possibilities 4) and 5). Star-2 is outside the Spitzer IRAC images and is not cataloged, but it is detected at the edge of the 24.0 μm image and its 24.0 μm flux is larger than that of star-1. This also suggests that star-2 is CTTS.

Since star-3’s EW is larger than 10 Å, it is unlikely to be 3). Although the extinction of star-3 is unclear because its spectral type is unknown, the upper limit of extinction can be estimated to be ∼ 1.3 mag from the $A_V$ map of Dobashi et al. (2005)\footnote{(http://darkclouds.term.jp/).}. Even if the upper limit is adopted for the extinction, the color of star-3 is still red (late K type) relative to A or B type stars. Therefore, star-3 can not be 1) or 2). We note that the lower limit of cloud extinction toward star-3 can be estimated to be ∼ 0.1 mag from the 13CO map of Crapsi et al. (2005). Possibilities 4) and 5) remain, however these types of stars are extremely rare. For example, Neuhauser et al. (1997) classified only a few candidates for RS CVn binaries out of a ∼ 300 square degree area in the south of the Taurus molecular clouds based on their X-ray and optical studies.

The CO and $A_V$ maps have relatively low spatial resolution, and provide average extinctions toward these stars. It would be possible that the cloud is clumpy, and that these stars are located toward a part of the cloud that is slightly thinner than the average. However, the reverse would be also possible. Moreover, no major molecular clouds are identified between L 1014 and the Perseus arm (Dame et al. 2001). Thus, their association with L 1014 is very likely, since T Tauri stars are usually found near molecular clouds, and most of the CO emission probably comes from the L 1014 region, although it is difficult to definitely eliminate the possibility that they are background sources.
3.2. Color–Magnitude Diagram

We constructed a color–magnitude diagram (\(i'\) vs. \(g' - i'\)) for \(L\) 1014 to estimate the ages and masses of the T Tauri star candidates. Although it is not yet clear whether star-3 is associated with the \(L\) 1014 core or not, here we assume that all of the three stars are associated with the cloud. We adopted the isochrones and the evolutionary tracks of Palla and Stahler (1999).

First, we assumed a distance of 200 pc for \(L\) 1014 (Lee, Myers 1999; Young et al. 2004) to construct the color–magnitude diagram (figure 4). The diagram indicates ages of about 100 Myr. This is not consistent with the typical age, \(\lesssim 10\) Myr, of T Tauri stars (e.g., Stahler, Palla 2004). Thus, our observations are incompatible with a distance of 200 pc.

Second, we assumed a distance of 400 pc for \(L\) 1014, as suspected by Young et al. (2004). Figure 5 shows the color–magnitude diagram for this distance and indicates that the stars’ ages lie between \(\sim 5\) Myr and 10 Myr. This is consistent with the typical age of \(\lesssim 10\) Myr. Since these stars are not embedded in the dense core, but located toward the envelope or more outer region, they could not be so young and probably have ages of \(\gtrsim 1\) Myr. Thus, \(\sim 1–10\) Myr is plausible as their age range. Adopting this range, \(\sim 400–900\) pc seems to be more reasonable than 200 pc.

Using the color–magnitude diagram at a distance of \(\sim 400–900\) pc and applying an extinction correction for each star, we estimate masses of \(\sim 1.2–1.8\) \(M_\odot\), \(\sim 1.2–1.8\) \(M_\odot\), and \(0.3–0.5\) \(M_\odot\) for star-1, 2, and 3, respectively. Extinctions of 0.88 and 0.1–1.3 were adopted for star-1 and 3, and no extinction was assumed for star-2.

The locations of the three stars in the color–magnitude diagram suggest that these stars have almost the same age. This suggests that star-3 is at the same distance as the other two associated with the \(L\) 1014 cloud and that it might also be associated with the cloud.

4. Conclusions

We identified three T Tauri stars toward the \(L\) 1014 core by slit-less spectroscopy, \(g'r'i'\) photometry, and slit spectroscopy. One of them is a WTTS and the others are CTTS. The estimation of the extinction and the ages of T Tauri stars suggests that they are associated with \(L\) 1014. This indicates that star formation took place previously in \(L\) 1014’s progenitor cloud.

An examination of the color–magnitude diagram suggests that the distance to \(L\) 1014 is \(\sim 400–900\) pc. Since the previously assumed distance of 200 pc was based on the kinematic distance, our estimated distance is plausible if these stars are associated with \(L\) 1014.

The luminosity of the very low mass protostar formed in the \(L\) 1014 core is reported to be \(\sim 0.09\) \(L_\odot\), for a distance of 200 pc (Young et al. 2004). Assuming a distance of 400–900 pc, the mass estimate of the protostellar object (\(L\) 1014-IRS) significantly increases.

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