LOW-MASS STAR FORMATION IN THE GUM NEBULA: THE CG 30/31/38 COMPLEX

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ABSTRACT

We present photometric and spectroscopic results for the low-mass pre–main-sequence (PMS) stars with spectral types K–M in the cometary globule (CG) 30/31/38 complex. We obtained multiobject high-resolution spectra for the targets selected as possible PMS stars from multiwavelength photometry. We identified 11 PMS stars brighter than $V = 16.5$ with ages $\lesssim 5$ Myr at a distance of approximately 200 pc. The spatial distribution of the PMS stars, CG clouds, and ionizing sources (O stars and supernova remnants) suggests a possible triggered origin of the star formation in this region. We confirm the youth of the photometrically selected PMS stars using the lithium abundances. The radial velocities of the low-mass PMS stars are consistent with those of the cometary globules. Most of the PMS stars show weak H$\alpha$ emission with $W_{\lambda}(\text{H}\alpha) < 10$ Å. Only one out of the 11 PMS stars shows a moderate near-IR excess, which suggests a short survival time ($t < 5$ Myr) of circumstellar disks in this star-forming environment. In addition, we find five young late-type stars and one Ae star that have no obvious relation to the CG 30/31/38 complex. We also discuss a possible scenario of the star formation history in the CG 30/31/38 region.

Key words: circumstellar matter — H $\alpha$ regions — ISM: globules — stars: formation — stars: low-mass, brown dwarfs — stars: pre–main-sequence

1. INTRODUCTION

Most massive stars are found in their natal clusters and associations. Low-mass pre–main-sequence (PMS) stars are also found in close proximity to massive stars, such as those seen in the Orion Nebula Cluster (ONC; O’Dell et al. 1993; Bally et al. 1998) and in the vicinity of the Wolf-Rayet + O star binary system $\gamma^2$ Vel (Pozzo et al. 2000). As soon as the massive stars begin to burn hydrogen, the protostellar clouds and T Tauri stars in the vicinity of the massive stars could be affected by the winds and strong radiation of massive stars. In contrast to stars formed in such a strong radiation field, low-mass stars formed in a quiet environment unaffected by massive stars, such as in the Taurus star-forming region, may be able to retain larger reservoirs of circumstellar materials, which could prolong the lifetime of accretion disks.

Globules are isolated dense clouds of molecular gas (Bok & Reilly 1947) with masses of the order of $10–100 \, M_\odot$, and typical sizes of $0.1–1$ pc. Bok & Reilly (1947) and Bok (1977) initiated studies of star formation in globules, and these have been followed by many others (Schwartz 1977; Reipurth 1983; Sugitani et al. 1986, 1995; Lefloch & Lazaref 1994; Megeath et al. 1996; Hester et al. 1996; Alves et al. 1997; Wolk & Walter 1998; Bally et al. 2001; Kim 2002; Kim et al. 2003 and references therein). These globules may form one to a few low-mass stars in a very short timescale compared to the mean lifetime of globules, 1 to a few $10^6$ yr (see Elmegreen 1998 for review and references therein). These globules are possible birth places for isolated low-mass stars, such as the Sun.

In this paper, we present a study of the star-forming region CG 30/31/38, which lies about 50–100 pc from an early O star and OB associations. This distance range is still close enough to be influenced by the radiation but too far to be affected by the winds of the hot stars.

The CG 30/31/38 star-forming region is a complex of small molecular cloud cores in the Gum Nebula evaporating as a result of ionizing radiation from an O star, $\zeta$ Pup, and perhaps also from a progenitor of the Vela supernova remnant (SNR). The total ionizing radiation of two OB associations, Vela OB2 and Trumpler 10, may also be responsible for some ionizing fluxes in the Gum Nebula and might have affected this CG 30/31/38 region.

1.1. The Gum Nebula

The Gum Nebula, one of the largest H $\alpha$ regions in our Galaxy, was discovered about half a century ago (Gum 1952, 1955). It covers a large part of southern sky in Vela, Puppis, Pyxis, Canis Major, and Carina. It is located in the Galactic plane, with a 36$'$ diameter, centered at $l = 258^\circ$ and $b = -5^\circ$. The nebula is the largest apparent H $\alpha$ region, with a 36$'$ diameter. The linear diameter is 250 pc at a distance of 450 pc (Brandt et al. 1971; Reynolds 1976a, 1976b). The nature of the Gum Nebula remains unclear; this may be an old SNR, a fossil Strömgren sphere (Brandt et al. 1971), expanding H $\alpha$ regions (Reynolds 1976a, 1976b; Chanot & Sivan 1983), and/or a stellar wind bubble (Sahu & Sahu 1993, and references therein). The hot stars $\zeta$ Pup (O4 If) and $\gamma^2$ Vel (WC8 + O7.5 I) and two OB associations (Trumpler 10 and Vela OB2) near its geometric center can account for most of the photoionization in the nebula, and their UV radiation is probably the cause of the evaporation of the CGs (Bertoldi & McKee 1990; Lefloch & Lazaref 1994).

The distances toward these associations, $\zeta$ Pup, $\gamma^2$ Vel, and the Vela SNR, and their relation with the Gum Nebula are poorly understood and remain controversial. The canonical values for the distances to these objects are about 400–500 pc (Brandt et al. 1971; Hawarden & Brand 1976; Zealey et al. 1983; Henning & Launhardt 1998 and references therein). However, more recent studies, especially using the Hipparcos data, suggest distances of 200–400 pc (de Zeeuw et al. 1999; Knude & Nielsen 2000; Hoogerwerf et al. 2001 and references therein).
The Gum Nebula contains at least 32 cometary globules (CGs; Hawarden & Brand 1976; Sandqvist 1976; Reipurth 1983; Zealey et al. 1983). Cometary globules are small, bright-rimmed, isolated clouds with head and tail cometary morphology. These are evaporating clouds, which are normally associated with H II regions and OB stars. High-resolution imaging with the Hubble Space Telescope (HST) has revealed smaller, solar-system–sized globules in Orion (O’Dell et al. 1993; Bally et al. 1998), in which dusty protostellar disks are seen in silhouette. Herbig-Haro (HH) objects and outflow sources are often found in Bok globules, cometary globules (CGs), and bright-rimmed clouds. Examples include B335 (FerriÈÈe & Langer 1982; Keene et al. 1983), HH 120 in CG 30, HH 46/47 in the Gum Dark Cloud (GDC) 1–7 (Bok 1977; Reipurth 1983), and CB 34 (Keene et al. 1983; Clemens & Barvainis 1988; Khanzadyan et al. 2002). Some PMS stars have been identified in the vicinity of Bok globules and CGs (Reipurth 1983; Pettersson & Reipurth 1994; Alves et al. 1997; Kim 2002).

The tails of the CGs in the Gum Nebula are directed away from the central ionizing sources ζ Pup, γ² Vel, and the Vela pulsar, suggesting that CGs are evaporating away from a common center. The locations of CGs and the direction of the tails show that CGs probably lie at the periphery of the wind-blown shell. If CGs were located on the line of sight between us and their ionizing sources, their tails would not be noticeable. However, the CGs located along the periphery of a sphere can be seen easily, because the tails evaporate in the transverse direction as projected in the sky. Therefore, even though CGs are located about 50–70 pc away from the ionizing sources, the dispersion in distances among the CGs cannot be too large, because we are most likely to sample those near or along the periphery that show prominent tails.

From his kinematic studies of the CGs in the Gum Nebula, Sridharan (1992) showed that CGs are expanding away from the common center with a velocity of ~12 km s⁻¹. The velocity gradients along the CG tails imply that these tails have expanded for about 3–6 Myr. An extended shell around the Vela OB2 association, the IRAS-Vela shell, has a size and location that seem to be consistent with the ringlike spatial distribution of the CGs (Sahu 1992). Note that the radius of this ring of CGs is smaller than that of the Gum Nebula. The expansion of this shell might have been caused by radiation-driven stellar winds and multiple supernova explosions. The expansion velocities of CGs and this shell, on the order of 10 km s⁻¹, are consistent with this, implying that the cause of CG expansion may be the same as the one for the IRAS-Vela shell.

1.2. The CG 30/31/38 Complex

Cometary globules, such as the CG 30/31/38 complex in the Gum Nebula, provide a unique and convenient setting for studying star formation in an intermediate radiation field at a moderate distance from hot stars. Figure 1 is the Digital Sky Survey (DSS) image of the CG 30/31/38 complex. CG 38 is the smallest CG in this complex, seen just below CG 30. The head of CG 30 (~2° in diameter) contains a Herbig-Haro system, HH 120, and the IR source CG 30-IRS 4 (Reipurth 1983; Pettersson 1984). Its ~10'' long tail points away from the central ionizing sources (i.e., Vela SNR, Vela OB2). CG 31 has five distinct clouds. The tail of CG 31 A is ~25°–30° long (1–1.5 pc at 200 pc). The change in the orientation of the tails of CG 31 coincides with the proper motion direction of ζ Pup. Pettersson (1987) identified three early M stars with Wₗ(Hα) > 10 Å in this region as Hα-emitting T Tauri stars.

Recent studies of the reddening in this direction (Nielsen et al. 2000; Knude & Nielsen 2000) suggest a distance as close as 200 pc, about half the canonical value. We use 200 pc as a conservative value for the distance of this cometary globule complex throughout this paper.

2. OBSERVATIONS

To identify PMS stars in the CG 30/31/38 region, we obtained X-ray, optical, and near-IR photometry. We then obtained high-resolution multiobject spectra of photometrically selected samples to confirm the youth and membership of the samples. In this section, we describe these observations, the data reduction processes, and the calibration of the multiwavelength photometry and high-resolution multiobject spectroscopy.

2.1. ROSAT HRI Photometry

X-rays are an efficient means of selecting candidate low-mass PMS stars (Montmerle et al. 1983; Walter et al. 1988 and references therein), because these stars are rapidly rotating and highly convective, the two ingredients that generate strong solar-like coronal and chromospheric activity. Magnetically active PMS stars (G, K, and M dwarfs) have X-ray luminosities of >10²⁹ ergs s⁻¹ and X-ray to bolometric flux ratios (fX/fbol) of about 10⁻³ to 10⁻⁴ (Walter et al. 1988; Feigelson et al. 2002; Flaccomio et al. 2003a and references therein). In contrast, the Sun’s X-ray luminosity varies from 10²⁶ to 10²⁷ ergs s⁻¹, and its flux ratio varies from 10⁻⁶ to 10⁻⁷. We use the spatial coincidence of bright stars with an X-ray to bolometric flux ratio of fX/fbol > 10⁻⁴ as the initial selection criterion of the potential PMS stars. Since this criterion also selects magnetically active foreground stars and fast rotators, we also obtained optical and near-IR imaging data to select an unbiased photometric sample of candidate PMS stars.

The CG 30/31/38 region was targeted in the ROSAT observation RH 210400, an 18,364 s exposure obtained between 1994 May 12 and 15. The image was centered at α = 8°0m2, δ = −36°6'. Thirteen X-ray sources were detected in the 23' radius field of the CG 30/31/38 region by the standard Standard Analysis Software System (SASS) source detection algorithm in 12' x 12' or 24' x 24' detection cells (Table 1). Eight of the nine sources detected in the 12' x 12' cell were recovered in the larger detection cell. These X-ray sources show a non-uniform spatial distribution, generally outlining the heads of CG 30 and CG 31 (Fig. 1).

The High Resolution Imager (HRI) has little intrinsic energy resolution; we converted the HRI count rates (0.4–2 keV) to fluxes using the standard energy-to-counts conversion factor (ECF) for the Raymond-Smith spectral model. We assumed a 1kT thermal spectrum and converted AF to NHI (NHI = 2.0 x 10¹¹ cm⁻² mag⁻¹ AF). We estimated AF values from the spectral types (see § 3.3) and observed B – V colors, adopting intrinsic colors from dwarf stars (Kenyon & Hartmann 1995; Luhman 1999; Leggett et al. 2001). We assumed the standard galactic extinction law with R = 3.1.

2.2. Optical Follow-up Photometry

We obtained optical photometry of selected CG complexes in the Gum Nebula on the nights of 1996 January 29–30. We

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5 See Table 5c and Fig. 30 from The ROSAT High Resolution Imager (HRI) Calibration Report, http://hea-www.harvard.edu/rosat/rsdc/.../HRI_CAL_REPO.../hri.html.
used the Cerro Tololo Inter-American Observatory (CTIO) 0.9 m telescope with the 2048 × 2048 Tektronix CCD (pixel scale of 0′.4 pixel−1 in a 13′6 field of view) and UBVRI filters. During 2001 March 6–12, we obtained more BVR photometry in these fields with the same setup. All data were obtained on photometric nights, with a mean seeing of 1′.2.

Bias, dome flat fields, and sky flat fields were taken at the beginning and end of each night. Long (60 and 300 s) and short (10 and 20 s) exposures were taken for all the object fields to avoid saturation of bright stars in the fields. Landolt (1992) standard fields were observed several times per night to establish photometric calibration.

Since the Gum Nebula lies in the Galactic plane, there are typically more than 2000 stars in each field, many of which are heavily blended. We reduced the images with the IRAF Daophot package. Since the point-spread function (PSF) depends on the location within the CCD, we selected between 40 and 80 PSF stars in each field and determined the spatial dependence of the PSF using quadratic fits in both directions of the CCD.

The FWHM values used for the IRAF Daophot photometry were between 1′.2 and 1′.8 pixels, while the radius for standard star photometry was 18 pixels. Therefore, an aperture correction was made to the 18 pixel (7″2) aperture. The photometric errors are about 1% at V ≤ 18 and 5%–10% at V ∼ 21. The aperture correction is accurate to 1%–2%, in general.

We used imwcs in WCSTools (Mink 1999), version 2.7.2, for the astrometric solutions. The positions of stars were determined using the Gaussian centroid algorithm in the IRAF phot routine, and then the astrometric solution was derived by fitting the pixel coordinates of stars to the known positions of USNO-A2.0 astrometric standards (Monet et al. 1998) located in each image. The imwcs package projects the image onto the tangent plane of the sky, rotates the image, and fits a polynomial to the x and y coordinates. In each image, about 120–150 stars were matched with USNO-A2.0 astrometric standards, with an average error of ∼0′.1. We then averaged the positions measured in the V, R-, and I-band images for each star to give the final position.

2.3. Near-IR Photometry

We obtained JHK images covering all the X-ray sources using the CIRIM detector on the CTIO 1.5 m telescope during 1996 February 5–6 and 1997 February 17–20. CIRIM uses a 256 × 256 HgCdTe NICMOS 3 array, and at f/13.5 gives a pixel scale of 0′.44 pixel−1. Images were dithered by ±15″ in right ascension and declination and median filtered to determine
the level of the sky. For the targets we used a six-point dither pattern. We used a four-point dither pattern for the standard stars.

We reduced and analyzed the data using the IDL DoCIRIM software (Walter 2000) and custom-written IDL codes. We first generated median sky-filtered and sky-subtracted images. Standard stars were chosen from the Elias (Elias et al. 1982) and UKIRT faint star (FS) standard star lists.6 For astrometry we match stars in an image with USNO-A2.0 catalog stars and determine the image center and plate scale. We performed standard star photometry using a radius of 20 pixels (8 arcsec) and generated the photometric solution on the CIT system. For object stars we derived the aperture corrections from the standard stars and determined the image center and plate scale. We performed standard

### Table 1

**ROSAT HRI Sources in the CG 30/31/38 Complex**

| XRS        | \( \alpha \) (J2000.0) | \( \delta \) (J2000.0) | \( \Delta \alpha^a \) (s) | \( \Delta \delta^b \) (arcsec) | Detect Cell\( ^c \) (arcsec) | Count Rate\( ^d \) (counts s\(^{-1} \)) | Net Counts\( ^e \) | S/N\(^f \) |
|------------|-------------------------|------------------------|-------------------------|-------------------------------|-------------------------------|--------------------------------|----------------|---------|
| 1........... | 08 07 59.8 ± 0.5         | −35 57 50.5 ± 4.2      | 0.87                    | 16.82                         | 24                            | 0.00756 ± 0.00106             | 107            | 3.4     |
| 2........... | 08 08 21.5 ± 0.5         | −36 03 37.5 ± 4.2      | 0.65                    | 9.58                          | 24                            | 0.00108 ± 0.00051             | 18             | 3.2     |
| 3........... | 08 08 37.4 ± 0.2         | −36 09 46.9 ± 1.9      | 0.19                    | 3.58                          | 12                            | 0.00102 ± 0.00041             | 17             | 3.6     |
| 4........... | 08 08 37.8 ± 0.1         | −36 03 56.8 ± 0.6      | 0.02                    | 1.55                          | 12                            | 0.02042 ± 0.00112             | 360            | 15.9    |
| 5........... | 08 08 38.8 ± 0.6         | −36 19 25.1 ± 4.6      | 0.17                    | 4.33                          | 24                            | 0.00138 ± 0.00073             | 21             | 3.2     |
| 6........... | 08 08 39.0 ± 0.1         | −36 04 58.5 ± 0.6      | 0.29                    | 3.40                          | 12                            | 0.01937 ± 0.00109             | 340            | 15.3    |
| 7........... | 08 08 45.2 ± 0.2         | −36 08 38.1 ± 1.3      | 0.20                    | 2.14                          | 12                            | 0.00232 ± 0.00046             | 41             | 5.8     |
| 8........... | 08 08 46.6 ± 0.6         | −36 07 41.2 ± 4.5      | 0.22                    | 11.56                         | 24                            | 0.00111 ± 0.00038             | 14             | 3.0     |
| 9........... | 08 09 02.9 ± 0.2         | −35 51 28.6 ± 1.2      | 0.02                    | 3.12                          | 12                            | 0.02126 ± 0.00149             | 300            | 7.7     |
| 10.......... | 08 09 13.1 ± 0.3         | −36 10 29.0 ± 2.5      | 0.39                    | 0.71                          | 12                            | 0.00085 ± 0.00035             | 16             | 3.2     |
| 11.......... | 08 09 22.2 ± 0.2         | −36 06 47.2 ± 1.9      | 0.05                    | 3.67                          | 12                            | 0.00120 ± 0.00038             | 22             | 3.6     |
| 12.......... | 08 09 24.6 ± 0.3         | −36 13 24.0 ± 2.4      | 0.09                    | 0.90                          | 12\(^g\)                      | 0.00064 ± 0.00036             | 11             | 3.0     |
| 13.......... | 08 09 35.1 ± 0.2         | −36 13 08.8 ± 1.8      | 0.05                    | 2.30                          | 12                            | 0.00343 ± 0.00055             | 60             | 4.7     |

Notes.—Values are taken from the SASS output. Note that the uncertainty on the count rate does not directly translate to a S/N: the former corresponds to a large radius containing 90% of the encircled energy. The significance of the count rate of the weak sources is decreased, because background noise dominates. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

\(^a\) X-ray–optical position offset in right ascension.
\(^b\) X-ray–optical position offset in declination.
\(^c\) Detect cell size in arcsec.
\(^d\) Net count rate within the 90% encircled energy radius.
\(^e\) Net source counts (above background) within the 90% encircled energy radius.
\(^f\) S/N within the detect cell.
\(^g\) Not detected in the 24" detection cell.

\(*\) See http://www.jach.hawaii.edu/JACpublic/UKIRT/astronomy/calib/ukirt_stds.html.

2.4. Matching Optical and Near-IR Counterparts to X-Ray Sources

We matched the coordinates of X-ray sources with those of optical and near-IR stars to identify potential counterparts. The **ROSAT** HRI X-ray source positions have much larger positional errors (see Table 1) than those of the optical and near-IR catalogs. The matching algorithm therefore identified optical and near-IR sources within the X-ray error circles (Table 1). The HRI flux limit was such that a star matching the \( f_X > 10^{-4} \) criterion has \( V \leq 16 \). Since X-ray, optical, and near-IR data were not obtained simultaneously, and PMS stars are variable, we also considered stars up to 1 mag fainter. Twelve of the HRI sources have bright \( V \leq 17, K \leq 13 \) optical and near-IR counterparts within the 3 \( \sigma \) X-ray error circles. For the X-ray sources that were matched with more than one optical and IR source, we chose the brightest sources among all the sources within the error circle. The faintest optical counterpart, XRS 3, has a \( V \) magnitude of 17.27; XRS 1 does not have an optical counterpart with \( V \lesssim 17 \) within its 3 \( \sigma \) X-ray error circle.

2.5. Optical Spectroscopy

During 2002 March 6–8, we obtained multispectroscopic high-resolution spectra of the candidate PMS stars (see § 3) using the HYDRA multifiber spectrograph on the CTIO Blanco 4 m telescope in echelle mode. The goals of these spectroscopic observations were to confirm the youth of these stars using Li i \( \lambda 6708 \) absorption lines and to measure their radial velocities. The spectra also reveal the spectral types, and we can estimate extinction to the PMS stars by comparing the measured colors with the intrinsic colors expected for the observed spectral types. The radial velocities let us determine membership probabilities by comparing the distribution of velocities with that of the CGs. Using CTIO HYDRA, one can obtain spectra of up to 135 objects (stars and sky) in a 40° field of view simultaneously. Since the overall efficiency of the HYDRA in echelle mode is about 3%, we chose targets that were brighter than \( V \sim 17 \) mag. The signal-to-noise ratio (S/N) was sufficient to detect Li i lines with strengths expected of PMS stars.

2.5.1. Spectroscopic Sample Selection

We selected as targets those stars that are coincident with the HRI X-ray sources and other stars whose colors lie in the appropriate region in the color-magnitude diagram (CMD) for PMS stars at a distance of \( \sim 200 \) pc. The \( V \) magnitudes of the targets range between 10 and 17. In each field there are between 50 and 200 objects near the PMS locus in the CMD (Fig. 2). At the bluer end \( (V - I \sim 1.0) \) of the CMD, the non–X-ray–emitting stars in the PMS locus are heavily contaminated by background stars in the galaxy, but the fainter and redder candidates are less likely to be contaminated. Since the Gum Nebula is located in the Galactic plane, some of the fields suffer severe contamination.
et al. 1990). The AV counterparts of X-ray sources are indicated with crosses and asterisks. Diamonds use the evolutionary models with almost parallel to the isochrones. Isochrones are from Baraffe et al. (1998), x is discussed in more detail in background nebula emission-line profiles. The sky subtraction was done the same way as on night 2. IRAF dispcor was then used to dispersion-correct the sky spectra and object spectra using the Th-Ar solution as reference spectrum. The starting wavelength and dispersion (Å pixel⁻¹) were derived for each of the 135 fibers; then the zero point was shifted using the cross-correlation results from Th-Ar and etalon spectra.

2.5.2. Spectroscopic Observations, Data Reduction, and Wavelength Calibration

We observed 144 objects in two 40' diameter fields on 2002 March 6 and 7. Three exposures were taken of each target field. These were combined using IRAF combine with the median sigma clipping algorithm. Three offset sky spectra were also taken at a position offset 10'' from the targets after each target exposure. These sky spectra have 10% of the integration time of the target spectra. These sky offset images were used to identify background nebula emission-line profiles. The sky subtraction is discussed in more detail in § 2.5.3.

We used the IRAF HYDRA package for basic data reduction and also some custom-written IDL codes for various calibration purposes. We first fitted the CCD overscan of each image interactively and trimmed all images. We then created a combined bias (zero) for each night and subtracted it from all images. We created a “milky flat” image from daylight sky exposures, which we used to flatten all other images.

Scattered light was subtracted from images using the abscat task. The scattered light is a global two-dimensional feature and is subtracted before each aperture is traced and extracted. Then the IRAF apall task was used to extract spectra. The FWHM of a fiber is about 6–7 pixels, so we selected 3 pixels for the upper and lower widths and extracted a total of 6 pixels centered at the center of each trace.

We took about five dusk and five dawn twilight sky spectra each night to make combined dusk and dawn sky spectra. Th-Ar comparison lamp exposures were taken at the beginning and end of each night for wavelength calibration. The mean residual of the wavelength solutions is ≤0.08 Å (0.5 pixels). Etalon comparison lamp exposures were taken before and after taking the Th-Ar lamps and between every configuration of object fields to correct for the zero-point shift throughout the night. We selected as the reference the etalon spectrum that was taken immediately before or after the Th-Ar comparison exposure each night; all other etalon spectra were cross-correlated in pixel space. We calculated the zero-point shifts in pixels and then applied the shift to derive wavelength vectors for all object spectra.

Since the Th-Ar signal was weak during the first night of observation, because of a faulty lamp, we used the second night’s Th-Ar solution. Some apertures that contained a high enough S/N in the first night’s Th-Ar spectra were cross-correlated with the second night’s Th-Ar spectra. The median pixel shift of 0.023 pixels is very small. We applied this shift to first night’s Th-Ar solution; the rest of the wavelength calibration using the etalon was done the same way as on night 2.

2.5.3. Sky Background Subtraction

The nebulosity in these regions complicates the sky subtraction. In addition to the offset sky spectra, we also devoted between 10 and 20 fibers in each configuration field to the sky. Here we use the term “sky background” to refer to the emission lines due to nebulosity, which is particularly important for measuring the strength of the stellar Hα lines. The sky emission-line strengths of Hα and [N II] vary across the 40' field of view. The background sky line profiles vary spatially because of the kinematics of the expanding gas shell in the Gum Nebula.

We group the sky spectra into three general categories, based on the Hα and [N II] line profiles and strength. Group 1 has narrow and strong Hα and [N II], group 2 has asymmetric and broader line widths than group 1, and group 3 has broader line widths than group 2, possibly with double-peaked lines.

To check the strength and profile of night-sky emission lines, we compared the night-sky spectra obtained during the long exposure with the combined three offset sky spectra that were taken 10'' offset from the target field immediately following each of the three subexposures. Although the strength of the Hα lines in the offset sky spectra was 10% of that of the long exposure skylines, the offset sky spectra helped determine which subgroup of sky profile should be used for each star.

We subtracted the appropriate sky spectrum from the object spectra. Because of the spatially variable background skyline profiles, the sky background cannot be perfectly subtracted. However, after careful checking, we are confident that we can derive the equivalent width of Hα to an accuracy of ∼0.8 Å. Line emission is not a problem at the 6708 Å wavelength of Li i.

3. RESULTS

From X-ray, optical, and near-IR spectroscopy, we have identified 16 young stars (Table 2). Eight of the 13 X-ray sources (XRS) listed in Table 1 are spectroscopically confirmed young stars, two X-ray sources were not observed, and three do not appear to be young stars. We identified eight more young stars, not detected in the ROSAT HRI observations, on the basis of the Li i λ6708 absorption line. Of the 16 stars, the radial velocities of 11 are consistent with that of the CGs (Sridharan 1992; Nielsen et al. 1998). In this section we discuss our results from X-ray photometry, optical and near-IR photometry, and optical spectroscopy.

3.1. X-Ray Photometry

In Table 1 we present X-ray count rates of the 13 X-ray sources. We also present the offsets in the X-ray coordinates.
| KWW  | XRS  | Spectral Type | \( \alpha \) (J2000.0) | \( \delta \) (J2000.0) | \( W(H\alpha) \) (Å) | \( W(Li i)^a \) (Å) | \( \log N(Li)^b \) (NLTE/LTE) | \( A_V \pm \sigma(A_V)^c \) (mag) | \( \log (f_X/f_B)^d \) | \( V_{LSR} \) (km s\(^{-1}\)) | Note |
|------|------|--------------|----------------|----------------|----------------|----------------|-----------------|----------------|---------------|----------------|------|
| 464  | 1    | M3 V         | 08 08 00.667    | −35 57 33.68   | −2.8           | 0.67 ± 0.02   | 2.70/3.31       | 0.2 ± 0.2      | 0.0186        | 6.69           | Night 1, HBC 553\(d\) |
| 1892 | 2    | M1 V         | 08 08 22.153    | −36 03 47.08   | −26.6          | 0.54 ± 0.04   | 2.54/3.08       | 0.3 ± 0.3      | 0.0028        | 4.87           | ...            |
| 598  | 3    | M2 V         | 08 08 37.586    | −36 09 50.48   | −11.5          | 0.70 ± 0.04   | 2.83/3.35       | 0.3 ± 0.3      | 0.0147        | 4.21           | ...            |
| 1863 | 4    | M1 V         | 08 08 37.824    | −36 03 55.25   | −2.8           | 0.74 ± 0.03   | 3.08/3.41       | 0.4 ± 0.2      | 0.0335        | 8.92           | ...            |
| 1637 | 6    | K6 V         | 08 08 39.286    | −36 05 01.90   | −2.4           | 0.63 ± 0.01   | 3.65/3.41       | 0.1 ± 0.1      | 0.0061        | 5.51           | SB2            |
| 873  | 7    | K7 V         | 08 08 45.403    | −36 08 40.24   | −7.9           | 0.68 ± 0.02   | 3.57/3.37       | 0.6 ± 0.2      | 0.0028        | 4.95           | P Cyg profile in H\(\alpha\) |
| 1043 | 8    | M3 V         | 08 08 46.821    | −36 07 52.76   | ...            | ...            | ...             | ...            | ...           | 9.01           | ...            |
| 975  | 9    | M2 V         | 08 08 33.870    | −36 08 09.82   | −8.43          | 0.50 ± 0.06   | 2.19/3.00       | 1.3 ± 0.2      | ...           | 6.30           | ...            |
| 1302 | 10   | M4 V         | 08 09 51.778    | −36 23 02.87   | −8.23          | ...           | ...             | ...            | ...           | ...            | ...            |
| 1953 | 11   | M3 V         | 08 08 26.929    | −36 03 35.45   | −4.24          | 0.56 ± 0.03   | 2.39/3.12       | 0.5 ± 0.3      | ...           | 7.20           | ...            |
| 2205 | 12   | M4 V         | 08 08 14.872    | −36 02 09.46   | −4.34          | 0.62 ± 0.04   | 2.58/3.23       | 0.3 ± 0.3      | ...           | 8.03           | ...            |
| 1055 | 13   | G5 V         | 08 09 02.9      | −35 51 28.6    | 3.23           | 0.14 ± 0.02   | 2.89/2.86       | ...            | ...           | −91.35         | ...            |
| 314  | 14   | A3e          | 08 09 52.001    | −36 00 36.92   | 6.2            | ...           | ...             | 3             | ...           | −15.11         | ...            |
| 1125 | 15   | <F8 V        | 08 09 15.140    | −36 09 14.22   | 5.75           | 0.32 ± 0.02   | 3.87/4.00       | 0.12 ± (<0.12) | ...           | 152.60         | SB2\(e\)       |
| 1333 | 16   | <F8 V        | 08 09 34.749    | −36 06 40.90   | 5.23           | 0.12 ± 0.02   | 3.05/3.00       | 0.16 ± (<0.16) | ...           | 19.08          | ...            |
| 1806 | 17   | <F8 V        | 08 09 33.255    | −36 13 09.14   | 0.81           | 0.13 ± 0.02   | 3.09/3.00       | 0.08 ± (<0.08) | ...           | −10.70         | ...            |

**Notes.**—The spectral types and equivalent widths of H\(\alpha\) and Li\(i\) for PMS stars are presented. Note that XRS 9, KWW 1055, KWW 1125, KWW 1333, and KWW 1806 are more likely to be 50–100 Myr old field stars with strong magnetic activity. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

\(a\) The errors were determined by measuring \(W(Li i)^{\alpha}(\lambda)\) multiple (>10) times.

\(b\) Lithium abundance for both LTE and NLTE models (NLTE from Pavlenko & Magazzu 1996; LTE from Duncan 1991).

\(c\) The uncertainty in \(A_V\) value is mainly introduced by the uncertainty of spectral type determination (~0.5–1 subtype for K and M stars, >1 for G type and earlier).

\(d\) Pettersson (1987); Herbig & Bell (1988).

\(e\) Both components show the same lithium strength. The equivalent width here is for the blueshifted component.
and the optical counterparts. Table 2 lists spectroscopically confirmed young stars along with their spectral types, Hα and Li equivalent widths, Li abundances, and AV range of fK and M type stars are known to have log (fX/fbol) = −3.0. This suggested that the HRI sources represent ≤15% of the X-ray–bright PMS population, if we assume that LX/fbol of the 0.1–2 M⊙ PMS stars follows that of typical young star clusters. If the log (fX/fbol) of this star-forming region follows the distribution of ONC (Flaccomio et al. 2003a, 2003b) for the mass range of 0.2–1.0 M⊙, there could be roughly 6 times more PMS stars with log (fX/fbol) < −3.0.

3.1.2. Variability

We examined the X-ray light curves for variability. Since the number of source counts is small, we could look only for evidence of gross changes in the count rate. Of the brighter sources, only KWW 1637 (XRS 6), a double-lined spectroscopic binary PMS system, shows any evidence of variability, at about the 2 σ confidence level in 30 ks bins. The variation on timescales between 30 and 250 ks is no more than about 30% from the mean. Among the weaker sources, KWW 1055 (XRS 10) appears to be variable. All the counts arrived in the first half of the observation. The probability that the source is constant is 0.007 on the basis of χ² statistics.

3.2. Color-Magnitude Diagram

Figure 2 is the V, V − I CMD for objects in the CG 30/31/38 region. Stars that are likely counterparts of X-ray sources are indicated with crosses and asterisks. The limiting magnitude of the X-ray flux, assuming log (fX/fbol) = −4, corresponds to a V magnitude of ∼16. The reddening vector, plotted on upper part of the CMD, is a line running almost parallel to the isochrones. Evolutionary tracks and isochrones are from Baraffe et al. (1998), modified using a temperature scale and colors from Kenyon & Hartmann (1995), Luhman (1999), and Leggett et al. (2001) for low-mass stars. Isochrones for ages of 2 Myr, 5 Myr, and 2 Gyr are plotted for a distance of 200 pc.

The positions of X-ray sources plotted in the CMD (Fig. 2) seem to delineate two distinct loci parallel to either the zero-age main sequence or a PMS isochrone. The upper locus is defined by the X-ray sources plotted in the CMD (Fig. 2) and the lower locus is defined by the X-ray sources plotted in the CMD (Fig. 2). The positions of X-ray sources plotted in the CMD (Fig. 2) seem to delineate two distinct loci parallel to either the zero-age main sequence or a PMS isochrone. The upper locus is defined by the X-ray sources plotted in the CMD (Fig. 2) and the lower locus is defined by the X-ray sources plotted in the CMD (Fig. 2). The positions of X-ray sources plotted in the CMD (Fig. 2) seem to delineate two distinct loci parallel to either the zero-age main sequence or a PMS isochrone. The upper locus is defined by the X-ray sources plotted in the CMD (Fig. 2) and the lower locus is defined by the X-ray sources plotted in the CMD (Fig. 2).
by six X-ray sources (crosses) and three previously cataloged PMS stars (diamonds; Herbig & Bell 1988). A 5 Myr isochrone (Baraffe et al. 1998) at the 200 pc distance of the cloud complex is a good match to this locus (see Fig. 2). Four X-ray sources (asterisks) and one Hα source (diamond; Schwartz et al. 1990) trace a distinctly different locus about 2–3 mag fainter than the upper locus. At a 200 pc distance these objects lie below the main sequence; they must represent a distinct and more distant population.

By using the minimum likely distance of 200 pc to the CG 30/31/38 complex (Knodl et al. 1999), we can place an upper limit on the age of the stars if they are indeed PMS stars at a common distance. The uncertainty in the age does correlate with the uncertainty in the distance. However, for young low-mass stars one can use the lithium abundance to further constrain the age (see §3.4). For example, M stars with log N(Li) \sim 3 are likely to be younger than \sim 5 Myr old (Walter et al. 1994; Martin et al. 1994 and references therein). Conversely, by assuming (or measuring) an age we can constrain the distance to the cloud complex, if it is spatially related to the stars.

3.3. Spectra

Multiwavelength photometry enables us to produce a large and unbiased sample of candidate PMS stars but is subject to contamination. Because photometry alone can be ambiguous, spectroscopy is necessary to confirm the youth and membership of stars using Li i \lambda 6708 lines and radial velocities. In the previous sections, we described the selection of candidate PMS stars using X-ray, optical, and near-IR photometry. To confirm the youth of our photometrically selected PMS stars, we obtained high-resolution multiobject spectra of our candidates. In §2.5 we described the multifiber spectroscopic observations using CTIO 4 m HYDRA, data reduction, and calibration. Here we present the spectra and results from our spectroscopic observations and analysis.

3.3.1. Spectral Type Determination

Spectra of PMS stars are shown in Figures 5a–5e. We flattened the continua of the spectra using a polynomial fit and normalized to unity. We estimated the spectral types by comparing spectra of 26 standard stars obtained at comparable dispersions.

The \lambda 6400–6720 wavelength range is not ideal for spectral type determination, because of the paucity of strong lines that can be used for spectral type determination. We estimated the spectral types mainly using Fe i and Ca i lines. The strength and structure of the \lambda 6495 blend was used to distinguish spectral types for the spectral range of F–K. TiO bands were used for the determination of late K and M spectral types.

The results are summarized in Table 2 and also discussed in the Appendix. The uncertainties on the spectral type are about 0.5 subtypes for K and M stars and are larger for stars with earlier spectral types.

3.3.2. Spectroscopically Confirmed PMS Stars

In Figures 5a–5e we show the spectra of the confirmed and possible PMS stars. Two of the confirmed PMS stars (KWW 1892 and KWW 1953) were observed twice. Three of the X-ray sources (XRS 5, 11, and 12) in the photometrically selected sample do not appear to be PMS stars. Spectra of KWW 1043 (XRS 8) and XRS 13 were not obtained, because these were too faint. We identified the Li i \lambda 6708 absorption line in 15 stars. Ten of these also have Hα in emission. Only KWW 873 shows a near-IR excess. One star on the lower locus, KWW 314, is an early-type star with an Hα profile reminiscent of an Ae star. The spectral type is A3 (see the Appendix). Not surprisingly, no Li absorption is evident.

Primarily on the basis of the presence of the Li i \lambda 6708 line (§3.4), we confirm that eight X-ray sources, KWW 464, 1892, 598, 1863, 1637, 873, and 1055 and XRS 9, are PMS stars. Hα line profiles of these PMS stars are described in more detail in the Appendix. We also find eight other young or active stars that were not detected (or not observed) in X-rays, KWW 314, 975, 1125, 1302, 1333, 1806, 1953, and 2205 (see Table 2).

Three PMS stars from the Herbig-Bell catalog (Herbig & Bell 1988), HBC 553, 554, and 555, also lie along the upper locus in the V, V − I CMD (Fig. 6, diamonds). We observed two of these stars, KWW 1892 (HBC 553) and KWW 975 (HBC 554). We did not observe KWW 1043 (XRS 9), the likely counterpart of HBC 555. Table 2 includes the derived properties of these HBC sources.

Short descriptions of each of these stars can be found in the Appendix. Table 2 summarizes our results. In Figure 6 the stars marked with crosses and asterisks are the X-ray sources, as in Figure 2. We mark the confirmed PMS stars with filled circles (upper locus) and open triangles (lower locus). Note that the PMS stars in the upper locus are clustered spatially below the CG 31 complex (Fig. 1, boxes with circles).

Inclusion of the optically identified young stars strengthens the case for the existence of two parallel loci in this CMD (Fig. 6). The upper locus is defined by the X-ray sources (crosses), HBC sources (diamonds), and spectroscopically young stars (filled circles). The Li abundance, \fx f_{\text{ref}} ratio, and Hα emission are all consistent with the interpretation of the upper locus as an isochrone defining a PMS stellar population.

The lower locus is defined by X-ray sources (asterisks) and spectroscopically confirmed young stars (open triangles). Note that only one X-ray source (KWW 1055) is confirmed to be a PMS star, while XRS 11 and 12 are not PMS stars. As mentioned earlier, the spectrum of XRS 13 was not obtained. If the stars on the lower locus are at 400 pc, the age inferred from isochrone fitting is \sim 100 Myr. If young, these stars are likely to be at a distance greater than 400 pc. They may be unrelated to the CG complex and the stars on the upper locus.

3.4. Lithium Abundance

The lithium abundance is of interest because it both probes stellar structure and age and also constrains primordial nucleosynthesis models (Duncan 1991 and references therein). The universal primordial Li abundance, log N(Li), is 3.1 (on the scale of log N(H) = 12); however, the Li abundance of halo stars is 2.1, while the mean distribution of log N(Li) values for PMS stars in young clusters peaks at 3.1 (Duncan 1991; Martin et al. 1994).

High Li abundances can be indicative of the youth of solar mass or less massive stars, because the temperature at the base of the convection zone is still too low to burn lithium for 1–10 Myr. These cool stars (M \leq 1 M_\odot) have deeper convective envelopes, and processes such as convective overshooting mix the surface and deeper (hotter) layers, causing faster Li depletion than in higher mass stars. For higher mass stars (M > 1 M_\odot), Li depletion is not significant, because they spend less time in the PMS stage, and the convection zone is thinner than in low-mass stars (King 1993; Ventura & Zappieri 1998). Because of this fast lithium depletion, lithium can be a good indicator of ages in low-mass stars.

We derive lithium abundances, log N(Li), using both non-LTE (NLTE; Pavlenko & Magazzu 1996) and LTE (Duncan...
Fig. 5a

HYDRA/echelle spectra of confirmed PMS stars associated with cometary globules. Continua are flattened and normalized to unity. (d, e) HYDRA/echelle spectra of young stars that are unlikely to be associated with the CG 30/31/38 complex.
1991) analyses. The results are presented in Table 2. Since these curves of growth are valid for $T_{\text{eff}} > 3500$ K, the curves of growth for lower temperature were extrapolated for the stars with $3200 \, K < T_{\text{eff}} < 3500 \, K$. The derived Li abundances for K6 and K7 stars (XRS 6 and XRS 7) are higher than the universal value (3.82 and 3.56, respectively, for NLTE). The high values for these K stars are consistent with observations of other PMS stars (e.g., Basri et al. 1991; Martín et al. 1994; Walter et al. 1997a).

The individual values of log $N$(Li) among the M stars, all on the upper locus, range from 2.19 to 3.08 (in NLTE), with a mean of $2.68 \pm 0.28$ ($3.26 \pm 0.15$ in LTE), where the uncertainties are the standard deviation of the means. The uncertainty on any single log $N$(Li) value is about 0.2 dex. The mean Li abundance is consistent with the expected age of the cloud complex ($\leq 3 \, \text{Myr}$). The wide range in log $N$(Li) among the individual stars could be due to the difficulty of determining the continuum level. The uncertainty in the adopted $T_{\text{eff}}$ of up to 200 K compounds the uncertainty. For KWW 1892 and KWW 975, the $W_\lambda$(Li) for two different nights vary by 0.14 and 0.16 Å, which caused 0.38 and 0.52 dex differences in the Li abundances, respectively.

The F--G stars on the lower locus also show high Li abundances. Since F--G stars do not burn lithium as fast as late K or M stars do, such stars need not be pre–main-sequence, but could be 50–100 Myr old main-sequence stars.

### 3.5. Kinematics of PMS Stars and CGs

Radial velocities were derived using Li i $\lambda$6707.8 and Ca i $\lambda$6671/6685 lines. The FWHM of a fiber of the HYDRA echelle spectrograph is about 6 pixels (0.96 Å, $\sim 43.9 \, \text{km s}^{-1}$); however, we can derive a radial velocity good to about 3 km s$^{-1}$ by centroiding. To estimate radial velocities, we derived $\delta V = \lambda_{\text{obs}} - \lambda_0$, where $\lambda_{\text{obs}}$ is observed wavelength and $\lambda_0$ for Li i and Ca i are from Kameswara Rao & Lambert (1993). The heliocentric correction of approximately $-8.2 \, \text{km s}^{-1}$ was then applied. To compare the velocity with $V_{\text{LSR}}$ (velocities with respect to the local standard of rest) for the CGs, we then derived $V_{\text{LSR}}$ for all the stars. The correction to $V_{\text{LSR}}$ is about $-17.3 \, \text{km s}^{-1}$ (Lang 1980). We present the radial velocities in Table 2.

The $V_{\text{LSR}}$ of the K--M type PMS stars range from 4.2 to 8.9 km s$^{-1}$, with a mean measurement error of 2.9 km s$^{-1}$. This is similar to that of the CG clouds (Nielsen et al. 1998) of 5.1–7.4 km s$^{-1}$. This strongly supports the association of the PMS stars with the CG 30/31/38 clouds. The 2.7 km s$^{-1}$ $V_{\text{LSR}}$ of XRS 10 is not significantly lower than the rest of the PMS stars. The radial velocities of the stars along the lower locus are inconsistent with the $V_{\text{LSR}}$ of the CGs, unless some of these are single-lined spectroscopic binaries.

### 3.6. Spectroscopic Binaries

Binary stars yield fundamental astrophysical parameters: stellar masses and, occasionally, radii. It is very difficult to estimate masses and ages of PMS stars by only fitting models, as is the case in our study. Dynamical determination of the masses of binary PMS stars would enable us to better estimate the ages.

Spectroscopic binaries have short (few days) periods. This means that the separation of the two stars is very small. Mayor & Mermilliod (1984) suggested that the dynamical evolution of the short-period low-mass binary systems depends on their PMS history. These spectroscopic binaries are therefore a very
important resource to help us better understand the star formation history of multiple systems.

We identified two double-lined spectroscopic binary systems (SB2): KWW 1637 and KWW 1125 (in Figs. 5b and 5d). The separation between the Li i \lambda 6708 lines is \(0.7-0.8\) \(\text{\AA}\) (\(\sim 33\) \(\text{km} \text{s}^{-1}\)) for XRS 6 and \(4.5\) \(\text{\AA}\) (\(\sim 200\) \(\text{km} \text{s}^{-1}\)) for KWW 1125. XRS 6 is a strong X-ray source that also shows significant X-ray variability. KWW 1125 has broad H\alpha and Li absorption lines with a large separation between the lines of the two components, which means that this system may have a very short, approximately a few days, orbital period.

HBC 554, also known as PH\alpha 14 (Pettersson 1987), is a visual binary star (Reipurth & Zinnecker 1993). Therefore, of the 17 stars listed in the Table 2, there are at least three binary systems. Unfortunately, we have only single-epoch observations on these systems; we cannot determine any orbital parameters with only the current data.

3.7. Color-Color Diagrams and the Circumstellar Disk Fraction

In the color-color diagrams (Figs. 7 and 8) we plot the young stars using filled circles (K-M stars from the upper locus) and triangles (lower locus). In Figure 7 the X-ray sources are plotted as crosses and asterisks for comparison.

Among the stars in the upper locus, only KWW 873 shows a convincing near-IR excess in both Figures 7 and 8, with \(H - K \sim 0.2\) mag. KWW 1892 and KWW 1637 may have marginal excesses. KWW 1892 is clearly a classical T Tauri star (CTTS), on the basis of its H\alpha equivalent width. However, a small excess (\(H - K \leq 0.1\)) of KWW 1892 is within the uncertainties of spectral type and \(A_V\) measurements. KWW 1637, an SB2 binary system, shows variability in X-rays and also between the near-IR photometry from this study and Two Micron All Sky Survey (2MASS) photometry; therefore, it is unclear whether this system has near-IR excess (\(H - K \approx 0.1\)) due to a circumstellar disk. Four upper-locus stars lie along the CTTS locus.

(Meyer et al. 1997) in Figure 8, but they have reddened photospheres with \(A_V\) values between 0.5 and 1.3 and do not have near-IR excess. The stars in the lower locus (triangles) have normal photospheric colors within the scatter.

A near-IR excess may indicate the presence of an inner circumstellar disk around a young star (e.g., Hillenbrand 2005, and references therein). In our color-color diagrams, one PMS star among the 11 on the upper locus shows a convincing near-IR excess. The circumstellar disk fraction for this group of stars is \(\sim 9\%\). The disk fraction derived using only \(JHK\) colors will underestimate the true disk fraction, especially among the cooler stars. Therefore, we consider \(\sim 9\%\) as a lower limit. This low circumstellar disk fraction is consistent with those seen in star-forming regions in which O stars are present, such as Upper Sco (Walter et al. 1994; Hillenbrand 2005) or NGC 2362, which shows about a 10\% disk fraction at the age of \(\sim 5 \pm 1\) Myr. However, it is lower than some other known star-forming regions, such as NGC 2264 (\(
\sim 55\%\) at \(\sim 3\) Myr; Haisch et al. 2001) and the TW Hydrae association (\(
\sim 20\%\) at \(\sim 10\) Myr).

The survival time of inner circumstellar disks in T Tauri associations is suggested to be about 3–10 Myr; however, exceptions exist in some cases that show very low circumstellar disk fractions in young (<3 Myr) associations (e.g., Walter et al. 1988; Haisch et al. 2001; Hillenbrand 2005 and references therein). When exposed to strong UV radiation from nearby O stars, surrounding reservoir gas that supplies gas to the circumstellar disks evaporates quickly. By losing reservoir gas as a result of the photoevaporation, those circumstellar disks exposed to UV radiation would likely have shorter lifetimes than the systems without a source of UV radiation nearby.

4. DISCUSSION

We have identified 16 young low-mass stars along the line of sight to the CG 30/31/38 complex. These stars trace out two distinct loci in the CMD.

The 11 stars that lie along the upper locus have K-M spectral types. Their Li abundances are consistent with an age \(\leq 5\) Myr. Their location in the CMD is consistent with a 5 Myr isochrone at the \(\sim 200\) pc distance of the CG complex. The
4.2–8.9 km s$^{-1}$ ($\pm$2.9 km s$^{-1}$) stellar radial velocities agree well with the 5–7.5 km s$^{-1}$ radial velocities of the CG 30/31/38 complex (Sridharan 1992; Nielsen et al. 1998). This supports the interpretation that these 11 PMS stars are physically associated with the CG complex.

The stars on the lower locus must be in the background, whether or not they form a coherent group. However, they show neither coherent radial velocities (see Table 2) nor a spatial concentration. We suggest that these stars are unlikely to be associated with CGs or with the 11 PMS stars along the upper locus. These stars all have spectral types earlier than K and all lack H$\alpha$ emission. Five of the F–G stars exhibit strong Li i absorption lines. Of the three X-ray sources on the lower locus (KWW 1055, XRS 11, and XRS 12), only KWW 1055 shows the Li i $\lambda$6708 line.

KWW 314, which lies on the lower locus, is an early-type star. We obtained a low-dispersion (4.3–8.9 km s$^{-1}$) spectrum using the SMARTS 1.5 m Ritchey-Chrétien spectrograph in 2004 February. The spectral type is A3, and the extinction $E_{B-V}$ is 0.9 ± 0.2 mag. There is no emission above the continuum between 3500 and 5100 Å. The $B-V = 1.11$ is consistent with an early A star reddened by $A_V \sim 3$ mag. This suggests an intrinsic $V \sim 12$. The distance modulus then places this star at $\sim$1.2 kpc. The extinctions to the other stars on the lower locus are much smaller and inconsistent with that of KWW 314. We conclude that the lower locus is not a physical association but a spurious alignment of six young, possibly PMS background stars and a perhaps unrelated A3e star.

The log ($f_x/f_{bol}$) values of the PMS stars imply that all the K and M stars detected in X-rays are active PMS stars. Since the X-ray detections are only slightly above the sensitivity limit, we are likely seeing only the peak of the luminosity distribution if the log ($f_x/f_{bol}$) relation of this region is similar to that of other star-forming regions (e.g., Flaccomio et al. 2003a, 2003b). If we assume that the log ($f_x/f_{bol}$) of this star-forming region follows the distribution of the ONC (Flaccomio et al. 2003a, 2003b) in the mass range of 0.2–1.0 $M_{\odot}$, there should be roughly 6 times as many PMS stars, all with log ($f_x/f_{bol}$) < −3.0, as we have detected here. This suggests that deeper X-ray exposures may find about 35 more PMS stars with log ($f_x/f_{bol}$) < −3.0 in this region.

The $V, V-I$ CMD (Fig. 6) shows a cutoff of the upper locus at $V \sim 18$, below which no stars are found. The optical photometry is complete to $V \sim 20$; therefore, the lack of stars below $V \sim 18$ ($M \sim 0.2 M_{\odot}$) is significant. This may be due to selective reddening of lower mass stars, or it may be interpreted as evidence of a truncated mass function below a certain mass. Deeper and more complete X-ray and IR observations will help us to obtain a more complete census of PMS stars to answer whether the mass function of this star-forming region is indeed truncated and differs from those of other star-forming regions.

In the color-color diagrams (Figs. 7 and 8), about 9% of the PMS stars show the near-IR excesses indicative of an inner circumstellar disk. This low circumstellar disk fraction, also seen in other OB associations, may be due to the influence of ionizing sources, such as ζ Pup, the progenitor of the Vela SNR, and other O stars. The parent gas cloud, which feeds the accretion disks, may be destroyed by the photoevaporation process from nearby O stars at the early stages of PMS evolution. This photoevaporation could result in a short disk survival time as well as low final masses of those stars. The lifetime of truncated disks with a mass of 1 $M_{\odot}$ is about 1 Myr if the mass accretion rate onto the star is about $10^{-6} M_{\odot}$ yr$^{-1}$. Therefore, about 1 Myr after the disk ceases to accrete from the surrounding cloud, the circumstellar disks should dissipate, which may explain the low circumstellar disk fraction seen here compared to that of quiet star-forming regions such as Taurus.

Three PMS stars show evidence of accretion in their H$\alpha$ emission-line profiles. Even though their near-IR excesses are not significant, they may still possess circumstellar disks. We suggest that the circumstellar disk fraction and disk lifetime depends not only on age but also on the environment. Mid-IR photometry will help us to derive a more reliable estimate of the circumstellar disk fraction of these systems.

We identified two double-lined spectroscopic PMS binary systems (KWW 1637 and KWW 1125). KWW 1953 was observed twice on different nights; the Li i $\lambda$6708 line profiles are very wide (about 2 Å) and are also varying. This may be due to the fast rotation of the star, or it could also be a potential double-lined binary that was not completely resolved.

4.1. Star Formation in Photoevaporating Globules and Star Formation History of the CG 30/31/38 Complex

For globule-sized triggered star formation, the triggering mechanism can be shock compression by a supernova explosion (Vanhala et al. 1996), an expanding H II region (Fukuda & Hanawa 2000), radiation-driven implosion (Lefloch & Lazaref 1994, 1995; Lefloch et al. 1997), or the stellar wind from massive stars (Boss 1995 and references therein). Ionizing photons from OB stars photoevaporate the molecular clouds, destroying giant molecular clouds. However, before the total destruction of whole cloud occurs, preexisting dense parts or cores of the parent molecular cloud can survive and form one star or a group of stars.

The CG formation scenario was discussed by Bertoldi & McKee (1990). Lefloch & Lazaref (1994) imply that these small globules in H II regions are evaporating and being compressed because of the external ionizing sources. Theoretical studies involving “rocket effects” and the “radiation-driven implosion” models (Oort & Spitzer 1955; Reipurth 1983; Lefloch & Lazaref 1994) explain how a shock can drive into a spherical clump, compress it, and produce the cometary shape of clouds in pressure equilibrium with surrounding photoevaporating gas. The globule then can be accelerated away from the UV source as it photodecays.

Whether small-scale triggered star formation can happen in globules depends on a number of physical conditions, such as the timescale needed to form a star, the rate of photoevaporation, the shock velocity, and magnetic field strength and orientation. The theoretical studies mentioned above show that star formation can be triggered in globules on a timescale short compared to the time needed to destroy or evaporate globules via UV radiation and/or shocks.

Here we suggest a simple star formation history of the CG 30/31/38 complex in the broader context of the star formation history of the Gum Nebula.

About 6–15 Myr ago, young clusters (now Vela OB2 and Trumpler 10) formed in a giant molecular cloud; OB stars in these clusters ionized their neighboring clouds, and the H II region expanded (the Gum Nebula). Their wind-blown shells may have been comparable in size to those commonly seen in the giant H II regions of other galaxies, such as those seen in the HST image of NGC 4214.

Approximately 5 Myr ago, the clouds photoevaporated in the UV radiation field of the luminous O stars, while low-mass stars formed in dense cores of the pre–CG 30/31/38 complex. Under the strong UV radiation from the O stars, the surrounding gas...
reservoir of these young stellar objects began to dissipate. This resulted in an accretion disk lifetime shorter than those of stars forming far from sources of ionizing radiation.

Some 1 million years ago, the runaway early O star $\zeta$ Pup moved closer to this CG complex, dissipating the clouds surrounding these young stars. The kink in the direction of the CG 31 tails is consistent with the direction of motion of $\zeta$ Pup. By now, the UV radiation has evaporated most of the clouds, although a few dense cores remain. The most recent episode of triggered star formation has occurred in the dense core of CG 30, as evidenced by the Herbig-Haro object HH 120. Note that the average age of this kind of HH objects is suggested to be $\leq 10^4$ yr (e.g., Reipurth et al. 2000).

5. SUMMARY

1. Using multiwavelength photometry and spectroscopy, we identify 14 new PMS stars, adding to the three previously known H$_\alpha$-emitting stars in the CG 30/31/38 region. The spectroscopic sample is complete to $V \sim 16.5$; the optical limiting magnitude is about 20.

2. The stars in the CG 30/31/38 complex lie along two distinct loci in the CMD.

3. The upper locus has an age of $\leq 5$ Myr at $d = 200$ pc. The spectral types of the stars on the upper locus are K6–M4. The mean Li abundance for M stars $[\log N$(Li) $= 2.68 \pm 0.28$ for NLTE and 3.26 $\pm 0.15$ for LTE] implies an age of 2–5 Myr and supports the youth of the PMS stars. The radial velocities of these stars are consistent with the published velocities of the CG 30/31/38 cloud complex.

4. The lower locus has an age of $< 100$ Myr at $d \sim 2$ kpc. The stars along the lower locus have spectral types F–G, with one Ae star. With the exception of KWW 1055, these stars have radial velocities that are not consistent with those of the CG 30/31/38 complex.

5. The $\sim 9\%$ circumstellar disk fraction derived using optical and near-IR excesses is consistent with those seen in other star-forming regions with O stars, such as the Upper-Scorpius, and is lower than those typical of quiet regions, such as Taurus. This suggests that the loss of the gas reservoir for accretion disks at this early stage of star formation is due to the radiation from the OB stars.

6. We find two double-lined spectroscopic binaries in the sample. Including the known visual binary HBC 554, the observed multiplicity fraction among the 17 PMS stars is 18%, which sets the lower limit to the true multiplicity fraction in this region.

7. We conclude that there have been at least two episodes of star formation in the CG 30/31/38 region: (1) ongoing star formation triggered by UV radiation from OB stars in the head of the CG 30 cloud, as exemplified by HH 120; and (2) $< 5$ Myr old low-mass ($0.2$–$1\,M_\odot$) PMS stars that outline the CG 31 complex, whose formation may have been triggered by pre-existing O stars such as the progenitor of the Vela SNR and $\zeta$ Pup, as well as other OB stars in Vela OB2 and Trumpler 10.

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APPENDIX

NOTES ON INDIVIDUAL PMS STARS

In this appendix we discuss some of the spectroscopically confirmed PMS stars. Coordinates and optical and near-IR photometry are in Tables 3 and 4.

KWW 464: This star is 17" away from XRS 1, a 4 $\sigma$ deviation. The M3 spectral type is based on the TiO band strengths. The $W_\lambda$(H$_\alpha$) $\sim 0.66$ Å indicates that this is a young star that is unlikely to be older than 5–10 Myr. The equivalent width of H$_\alpha$ is approximately $-4$ Å; therefore it is a naked/weak-line T Tauri star (see Table 2).

KWW 1892 = XRS 2 = HBC 553: Figure 5a shows two spectra of KWW 1892 (XRS 2; M1–M2), obtained on consecutive nights. This object, also known as HBC 553 (Pettersson 1987; Herbig & Bell 1988), has the strongest H$_\alpha$ emission line $[W_\lambda$(H$_\alpha$) $\sim 30$ Å] in our sample. The H$_\alpha$ emission-line profile shows changes on the second night, while the absorption-line profiles do not. The FWHM of the H$_\alpha$ line varied from 4–5 Å (night 1) to 3 Å (night 2). On the basis of $W_\lambda$(H$_\alpha$), this is the only CTTS in our sample.

| Identification | $U - B$ | $B - V$ | $V$ | $V - R$ | $R - I$
|----------------|---------|---------|-----|---------|---------|
| KWW 464......... | ...     | 1.52 $\pm$ 0.04 | 15.82 $\pm$ 0.03 | 1.14 $\pm$ 0.04 | 1.22 $\pm$ 0.05 |
| KWW 1892......... | 1.04 $\pm$ 0.03 | 1.42 $\pm$ 0.03 | 15.17 $\pm$ 0.02 | 1.12 $\pm$ 0.03 | 1.23 $\pm$ 0.02 |
| KWW 598......... | 0.81 $\pm$ 0.08 | 1.35 $\pm$ 0.04 | 17.27 $\pm$ 0.02 | 1.45 $\pm$ 0.03 | 1.77 $\pm$ 0.02 |
| KWW 1863......... | $-0.29$ $\pm$ 0.47 | 3.01 $\pm$ 0.34 | 14.65 $\pm$ 0.01 | 1.10 $\pm$ 0.02 | 1.22 $\pm$ 0.03 |
| KWW 1637......... | 1.05 $\pm$ 0.02 | 1.20 $\pm$ 0.02 | 12.15 $\pm$ 0.01 | 0.92 $\pm$ 0.02 | 0.66 $\pm$ 0.03 |
| KWW 873......... | 0.99 $\pm$ 0.02 | 1.35 $\pm$ 0.02 | 13.81 $\pm$ 0.01 | 0.92 $\pm$ 0.02 | 0.90 $\pm$ 0.02 |
| KWW 1043......... | 0.36 $\pm$ 0.04 | 1.31 $\pm$ 0.03 | 16.61 $\pm$ 0.02 | 1.25 $\pm$ 0.03 | 1.55 $\pm$ 0.06 |
| KWW 1055......... | 0.41 $\pm$ 0.02 | 0.96 $\pm$ 0.01 | 14.40 $\pm$ 0.01 | 0.58 $\pm$ 0.02 | 0.63 $\pm$ 0.03 |
| KWW 975......... | $-0.10$ $\pm$ 0.03 | 1.15 $\pm$ 0.02 | 15.56 $\pm$ 0.01 | 1.12 $\pm$ 0.02 | 1.35 $\pm$ 0.03 |
| KWW 314......... | ...     | 1.11 $\pm$ 0.01 | 15.14 $\pm$ 0.00 | 0.73 $\pm$ 0.00 | 0.77 $\pm$ 0.00 |
| KWW 1806......... | 0.71 $\pm$ 0.02 | 0.94 $\pm$ 0.01 | 13.99 $\pm$ 0.01 | 0.68 $\pm$ 0.22 | 0.43 $\pm$ 0.06 |
| KWW 1125......... | $-0.01$ $\pm$ 0.02 | 0.47 $\pm$ 0.02 | 12.35 $\pm$ 0.01 | 0.30 $\pm$ 0.02 | 0.37 $\pm$ 0.02 |
| KWW 1302......... | 1.39 $\pm$ 0.01 | 15.76 $\pm$ 0.00 | 1.20 $\pm$ 0.00 | 1.42 $\pm$ 0.00 |
| KWW 1333......... | 0.24 $\pm$ 0.02 | 0.65 $\pm$ 0.01 | 13.64 $\pm$ 0.01 | 0.47 $\pm$ 0.02 | 0.44 $\pm$ 0.02 |
| KWW 1953......... | 1.05 $\pm$ 0.03 | 1.37 $\pm$ 0.03 | 15.58 $\pm$ 0.02 | 1.21 $\pm$ 0.02 | 1.42 $\pm$ 0.02 |
| KWW 2205......... | 0.49 $\pm$ 0.49 | 2.38 $\pm$ 0.35 | 16.20 $\pm$ 0.02 | 1.25 $\pm$ 0.02 | 1.40 $\pm$ 0.17 |
**KWW 1637 = XRS 6**: Li i λ6708, Ca i λ6717, and other Fe i lines all are doubled, strongly indicating that this is a double-lined spectroscopic PMS binary system that has 0.8–1 Å separation (40–45 km s\(^{-1}\)) at this epoch. The X-ray emission was strong and variable.

**KWW 873 = XRS 7**: Although \(W_v(\text{H}\alpha)\) is less than 10 Å, the line profile, with a blueshifted absorption reversal, implies a strong wind in this system.

**KWW 975 = HBC 554**: The spectrum of KWW 975 (HBC 554) in Figure 5b shows asymmetric H\(\alpha\) and Li i line profiles. The H\(\alpha\) line profile has dips (stronger on the redshifted side), which could indicate accretion or infalling gas in the system. Background sky emission subtraction affects only the narrower component and not the broader line profile. Herbig & Bell (1988) identified HBC 554 as a visual binary system and classified the spectral type of this star as M1.5, which is consistent with our spectral type estimate (M2).

**KWW 1953**: The Li i λ6708 line and Fe i lines show asymmetric and broad line profiles. KWW 1953 may be a rapidly rotating star or an unresolved double-line binary system.

**KWW 1055 = XRS 10**: The H\(\alpha\) line is in absorption (Fig. 5d). The Li line equivalent width is consistent with no Li depletion. Although it appears on the lower locus, and hence at a greater distance, the radial velocity is marginally consistent with that of the CG 30/31/38 complex.

**XRS 9**: XRS 9 is a fast rotator. It is not an H\(\alpha\) emission source, but it shows a marginal Li i line (Fig. 5d). All the absorption lines are broadened, most likely because of rotation. All the lines, including the metal lines Fe i and Ca i, show flat bottoms, which may suggest a spot on its surface. The radial velocity is inconsistent with those of the of CGs and associated PMS stars. It is likely to be a young star in the background.

**KWW 314**: The double-peaked H\(\alpha\) emission arising from a broad H\(\alpha\) absorption line is typical of an Ae/Be star (and not necessarily of a young object). A low dispersion spectrum confirms that this is an A3 (±2) star with \(E_{B-V} = 0.9 \pm 0.2\) mag. Its \(V_r\) is \(\sim 3\) mag (see Tables 3 and 4), and thus \(V \sim 12\) mag. The distance modulus is then \(\sim 10.5\) mag (\(\sim 1.2\) kpc). The radial velocity (\(V_{\text{LSR}} = -15.11\) km s\(^{-1}\)) is inconsistent with that of the CGs and PMS stars. This is therefore likely to be a background star unrelated to the CG 30/31/38 complex.

**KWW 1125**: This is a young double-lined spectroscopic binary system with undepleted Li abundances. The spectrum (Fig. 5d) shows broad and double-peaked H\(\alpha\) and Li i absorption lines. Fe i and Ca i lines also seem to have double lines. The two components are \(\sim 4\) Å (180 km s\(^{-1}\)) apart at the epoch of observation; this is likely to be a short-period system with a period of a few days. The redshifted component has \(\sim 50\%\) of the line strength of the blueshifted component in H\(\alpha\), but the Li i strengths of both components are similar. At this epoch the radial velocities are \(-65.6\) km s\(^{-1}\) for the blueshifted component and \(152.6\) km s\(^{-1}\) for the redshifted component. Since only one epoch was observed, we have no information on the systemic velocity or the mass ratio.

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