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Enhanced star formation in the cometary globules of the Gum nebula

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ABSTRACT

Evidence for an enhanced rate of star formation in the cometary globules of the Gum nebula is presented. The *IRAS* Point Source Catalog has been searched for sources with spectral energy distributions characteristic of young stellar or protostellar objects associated with the compact heads of the cometary globules. The surface density of such sources associated with the cometary globule heads is found to be ~ 3–12 times the density in dark clouds in a neighbouring comparison area and in the northern sky. The *IRAS* sources associated with the cometary globule heads have luminosities in the range from ~ 0.5 to ~ 20 $L_\odot$, characteristic of low-mass young stellar or protostellar objects. It is suggested that the enhanced star formation in the cometary globule heads in the Gum nebula is a result of shock-induced star formation triggered by the same event that created the Gum nebula complex.

Key words: shock waves – stars: formation – ISM: individual: Gum nebula – infrared: stars.

1 INTRODUCTION

The Gum nebula was discovered by Colin Gum (1952) as a large region of Hα emission nebulosity in Vela–Puppis in the southern sky. With an angular diameter of ~ 36°, it is one of the largest structures of interstellar matter in our neighbourhood in the Galaxy. At an estimated distance of 400 pc (see e.g. Reynolds 1976), its linear diameter is ~ 250 pc. The luminous stars ζ Puppis (O4f) and γ^2 Velorum (WC8 + O9I), and the young Vela pulsar and supernova remnant are within the central 10° of the nebula. In addition to the ionized gas, the Gum nebula region contains a number of dark clouds and clouds with bright rims and cometary tails – the so-called cometary globules (CGs). The CGs were first noted by Hawarden & Brand (1976), and a total of ~ 30 CGs have now been found in the Gum nebula (Sandqvist 1976; Reipurth 1983; Zealey et al. 1983).

The CGs in the Gum nebula region are characterized by compact and dense heads that are completely opaque so that no background stars are seen through them, and by faintly luminous tails generally pointing away from the centre of the Gum nebula, suggestive of a physical association between the CGs and the Gum nebula. Projected on to the plane of the sky, the CGs lie in an annulus extending from ~ 50 to ~ 80 pc from the centre of the Gum nebula (Zealey et al. 1983). Models for the origin of the Gum nebula have been reviewed by Bruhweiler, Kafatos & Brand (1983), and scenarios for the formation of the CGs have been suggested by Zealey et al. (1983) and Reipurth (1983). A study of the kinematics of the CGs in the Gum nebula has been made recently by Sridharan (1992).

Evidence for continuing star formation in the Gum nebula region has been growing. Bok (1978) noted that the Herbig–Haro objects HH 46 and HH 47 are associated with Sandqvist 111, a dark cloud in the Gum nebula. Bernes 135, a pre-main-sequence star, is associated with the cometary globule CG1 (Reipurth 1983; Brand et al. 1983). CG 30 contains the Herbig–Haro object HH 120 and the infrared source CG 30-IRS 4 (Pettersson 1984). The small nebulae Re 4, having spectral characteristics similar to Herbig–Haro objects, and Re 5, associated with the infrared source IRAS 08196 – 4931, are found in the dark cloud Sandqvist 109 in this region (Graham 1986; Graham & Heyer 1989; Scarrott et al. 1992). The nebulosity associated with the infrared source IRAS 08211 – 4158 (Campbell & Persson 1988) in the Gum nebula has been found to have characteristics similar to Herbig–Haro objects (Graham 1991). In the region near CG 30 the dark clouds DC 259.2 – 1.6 and DC 253 – 1.7 were found to have nine T Tauri stars by Pettersson (1987). The Hα emission object Wra 220 associated with CG 22 has been found to be an infrared source with the *Infrared Astronomical Satellite* (*IRAS*), and Sahu et al. (1988) have suggested that it is a pre-main-sequence star formed in the globule. Star formation in the molecular clouds in the Gum nebula complex could have been triggered by the same event and physical processes that created the Gum nebula, and a search for young stellar objects in this region is likely to reveal more of them. While some of the dark clouds seen in this area could be either behind the Gum nebula or foreground to it, the pattern of the orientations of the cometary tails of the CGs suggests that all CGs are physically associated with the Gum nebula. The CGs are therefore good candidates for a search for young stellar objects (YSOs) forming within the clouds belonging to the Gum nebula complex.

In this paper we present the results of a search for infrared sources (with spectral energy distributions characteristic of YSOs) in the *IRAS* Point Source Catalog (*IRAS* 1985) associated with the cometary globules in the Gum nebula. The statistics of *IRAS* associations with the CGs is compared with that found for dark clouds in a nearby comparison area and with other dark clouds in the northern sky. Evidence for enhanced star formation in the CGs is found.

2 *IRAS* SOURCES ASSOCIATED WITH COMETARY GLOBULES

The CGs have compact heads with angular sizes ~2 arcmin (Hartley et al. 1986). Their tail lengths vary from ~2 arcmin to more than a degree (Zealey et al. 1983). While the heads are completely opaque, background stars can be seen through the tails, which are therefore less dense. The heads are also characterized by sharp boundaries. The three cometary globules in the Gum nebula, CG 1, CG 22 and CG 30, which are already known to have some signs of star formation associated with them, have all their YSOs within the globule heads. Star formation in the CGs is thus likely to be concentrated in the dense globule heads. For this reason, and because the CG tails have ill-defined boundaries and much lower densities, we carry out a search for *IRAS* associations only in the CG heads. The CG heads are approximately elliptical in shape, with typical dimensions $\sim 2 \times 1$ arcmin^2. We first search for *IRAS* sources within a circular area of angular radius 2 arcmin centred around the cloud centroid coordinates. The centroid positions given in the Hartley et al. (1986) catalogue of southern dark clouds are used, since these are more accurate than those in Zealey et al. (1983), whose numbering system for the CGs is adopted. 29 of these objects have been identified in Hartley et al. (1986). We have chosen a search radius of 2 arcmin because the uncertainties in the cloud centroid coordinates are ~15 arcsec and those in the *IRAS* Point Source Catalog source positions are up to ~45 arcsec, and because the typical value for the semimajor axis representing the elliptical CG head is ~1 arcmin. We search for *IRAS* sources that have flux densities increasing with wavelength, a characteristic of young stellar or protostellar objects embedded within dark clouds. In the following, such spectral energy distributions will be referred to as 'YSO-type'.

Table 1 lists the CGs in the Gum nebula and the 'YSO-type' *IRAS* sources associated with the globule heads. The globule centroid positions and the dimensions of the head (major and minor axes representing the elliptical shape) are taken from Hartley et al. (1986). The *IRAS* source positions and their angular separations Δr from the globule centroid coordinates are also given.

It can be seen from Table 1 that, out of the 29 CGs in the Gum nebula, 16 have 'YSO-type' *IRAS* sources within 2 arcmin of the globule head centroid positions. The area searched is 364 arcmin^2 (=0.101 deg^2). The source density is therefore 158 deg^{-2}. However, the actual total CG head cloud area is much smaller because most of the CG heads have dimensions smaller than the search diameter of 4 arcmin. The total CG head area is 0.023 deg^2. If the 'YSO-type' *IRAS* sources are indeed within the CG heads, then their actual density is 696 deg^2. All the 16 'YSO-type' *IRAS* sources are likely to be young stellar or protostellar objects embedded within the CG heads, and not chance associations between background *IRAS* sources and the CG heads. For comparison, in a circular area of 2 deg^2 centred at RA(1950) = $8^h 18^m$, Dec.(1950) = 44° 00′ in the central region of the Gum nebula complex where there are no clouds, we find 39 infrared sources in the *IRAS* Point Source Catalog; only 12 of them have flux densities increasing with wavelength, characteristic of YSOs. Thus the surface density of background sources of 'YSO type' is 6 deg^{-2}, while that of the 'non-YSO-type' sources is 14 deg^{-2}. The physical association between the 'YSO-type' *IRAS* sources and the CG heads is further strengthened when we note that relaxation of the constraint on the spectral characteristics of the *IRAS* sources (that the flux densities increase with wavelength) and inclusion of all *IRAS* sources in the *IRAS* Point Source Catalog, located with 2 arcmin of the CG head centroids, adds only one source to the list of *IRAS* associations. This additional source (IRAS 07311 − 5038) is found at an angular distance of 80 arcsec from the centroid of CG 15, which also has a 'YSO-type' source (IRAS 07309 − 5039) at a distance of 57 arcsec from the centroid. IRAS 07311 − 5038 has flux densities decreasing with wavelength, characteristic of a hotter field star. The ratios of the number of 'YSO-type'/'non-YSO-type' *IRAS* sources found in search areas around the CG heads and in the comparison field are 16 (=16/1) and 0.44 (12/27) respectively.

In the above discussion, for uniformity, we have considered only those CGs in the Gum nebula complex that have been identified in Hartley et al. (1986). CG 23, listed in Zealey et al. (1983), does not appear in the Hartley et al. (1986) catalogue, and was also not detected by Sridharan (1992). We do not find any *IRAS* point source within 5 arcmin of the position for CG 23 given in Zealey et al. (1983). There are two more CGs (CG 37, 38) and four small dark clouds (GDC 1, 2, 3, 4) with bright rims at the edges pointing to the centre of the Gum nebula, for which accurate positions are available (Reipurth 1983). We have carried out a search for *IRAS* sources within 2 arcmin of the centroid positions for these clouds. We find two sources, IRAS 08242 − 5050 and IRAS 08250 − 5030, at angular separations of 1.37 and 0.70 arcmin from the centroids of GDC 1 and 4 respectively; both have spectral energy distributions of the 'YSO type'. It is to be noted that Herbig–Haro objects HH 46–47 are associated with GDC 1 (Reipurth 1983). No *IRAS* associations are found for CG 37, 38 and GDC 2, 3. Combining the statistics of *IRAS* associations for these clouds with those for the CGs in the Hartley et al. (1986) catalogue, the surface density of 'YSO-type' *IRAS* sources in the total area searched becomes 148 deg^{-2}; if the actual cloud area is considered, then the surface density of 'YSO-type' *IRAS* sources physically associated with the CGs in the Gum nebula is 583 deg^{-2}.

An increase of the search radius from 2 to 5 arcmin adds only 10 *IRAS* sources (irrespective of their spectral energy distributions). The increase in the number of *IRAS* sources is only ~50 per cent for an increase in the search area by a factor of ~6. This indicates that the sources found within 2 arcmin of the CG head centroids are indeed physically associated with them and are not members of a field population.

Table 1. Cometary globules in the Gum nebula and the associated 'YSO-type' *IRAS* sources.

CG No.	Centroid Position RA (1950)	DEC	Head size	IRAS Association	RA (1950)	DEC	Angular Separation
	(h m s)	(° ′)	(′)	Source	(s)	(″)	Δr(′)
1	07 17 56	−44 29.6	2×2	07178−4429	54.0	24	0.41
2	07 14 28	−43 52.3	2×2	07144−4352	28.3	41	0.39
3	07 37 42	−47 46.2	3×1.5	07378−4745	50.5	17	1.72
4	07 32 41	−41 47.7	4×1	none			
5	07 39 16	−43 42.1	1×0.5	07391−4342	06.8	07	1.66
6	07 29 05	−46 37.3	3×1	none			
7	09 12 14	−42 17.6	2×1.5	none			
8	07 40 59	−41 08.8	2×1	07408−4108	53.5	41	1.04
9	07 39 07	−41 19.9	2×1	07389−4119	58.8	15	1.67
10	07 40 51	−41 58.0	0.5×0.5	none			
13	07 12 50	−48 23.9	5×3	none			
14	07 37 18	−49 43.8	3×1	07372−4945	13.0	20	1.73
15	07 31 03	−50 39.1	3×1	07309−5039	58.1	38	0.94
16	07 26 20	−50 58.3	2×1	none			
17	08 51 04	−51 40.5	1×1	none			
18	08 51 04	−50 28.7	0.5×0.5	none			
22	08 26 48	−33 35.8	3×5	08267−3336	44.1	31	1.08
24	08 17 33	−42 45.3	1×1	none			
25	07 35 56	−47 49.7	< 0.5 × 0.5	07358−4750	49.6	30	1.34
26	08 14 03	−33 41.5	2×1	08140−3340	04.0	43	0.81
27	08 10 29	−33 36.6	2×1	08105−3335	32.5	52	1.03
28	08 10 25	−33 47.2	1×1	08103−3346	22.8	06	1.19
29	08 10 27	−33 52.0	1×1	none			
30	08 07 39	−35 55.9	3×2	08076−3556	40.2	07	0.33
31	08 07 04	−35 50.5	7×3	none			
32	08 12 26	−34 21.7	3×1.5	08124−3422	29.6	02	0.81
33	08 13 32	−33 55.5	0.6×0.8	none			
34	07 27 53	−41 04.2	3×1	none			
36	08 35 23	−36 27.4	1×1	08354−3626	24.3	09	1.28

3 *IRAS* SOURCES ASSOCIATED WITH DARK CLOUDS IN A COMPARISON AREA

Star formation in dark clouds is now known to be a common phenomenon (e.g. Beichman et al. 1986). Thus *IRAS* sources are found to be associated with even apparently quiescent, isolated dark clouds. The CGs in the Gum nebula seem to be in an active environment. Their morphology suggests that external pressures have been at work on these clouds. It may therefore be interesting to see whether the frequency of *IRAS* associations for the CGs in the Gum nebula is different from that for clouds in other areas.

The CG heads are dense dark clouds of opacity class A, defined as the clouds through which no background stars are visible (Hartley et al. 1986). This opacity class is equivalent to the opacity class 6 of Lynds (1962). In a neighbouring area between Galactic longitudes $l = 275°$ and $295°$ there are 27 opacity class A clouds in the Hartley et al. (1986) catalogue. We have searched for 'YSO-type' *IRAS* sources in the *IRAS* Point Source Catalog associated with these clouds. In only five out of the 27 clouds are 'YSO-type' *IRAS* sources found within 2 arcmin of the cloud centroids. The area searched is 339 arcmin^2 ($= 0.094$ deg^2) and the source density of 'YSO-type' *IRAS* sources is 53 deg^{-2}. The source density for the CGs in the Gum nebula can also be compared with that found for the northern opacity class 6 clouds in the Lynds (1962) catalogue, studied by Parker (1988). For this sample of dark clouds, Parker (1988) found the 'YSO-type' *IRAS* source density to be 45 deg^{-2}.

The density of 'YSO-type' *IRAS* sources associated with the CGs in the Gum nebula is thus ~ 3 times the density of such sources for dark clouds in a comparison area and the northern clouds. If the actual cloud area for the small CG heads is considered, then the ratio of source densities for the CG heads (~ 600 deg^{-2}) and the comparison clouds (~ 50 deg^{-2}) could be as large as a factor of ~ 12. It can therefore be concluded that star formation in the CGs in the Gum nebula is taking place at an enhanced rate compared with other compact clouds in the field.

4 DISCUSSION

We will now assume that all the 18 'YSO-type' *IRAS* sources found within 2 arcmin of the centroids of the CG heads are physically associated with them, and discuss their properties. Table 2 lists these *IRAS* associations and gives the flux densities measured by *IRAS* in the 12-, 25-, 60- and 100-μm bands. The ratio of flux densities at 100 and 60 μm, $S_{100\,\mu\mathrm{m}}/S_{60\,\mu\mathrm{m}}$, can be used to calculate the colour temperature T_c of the dust emitting the infrared radiation. The values of T_c are listed in Table 2. Also listed in Table 2 are the luminosities L_IRAS of the sources, emitted in the *IRAS* bands. Following Margulis, Lada & Young (1989), the luminosity is given by

$$L_\mathrm{IRAS} = 4\pi d^2 \int S_\nu \,\mathrm{d}\nu = 1.72\,(0.6777\,S_{12\,\mu\mathrm{m}} + 0.384\,S_{25\,\mu\mathrm{m}} + 0.104\,S_{60\,\mu\mathrm{m}} + 0.400\,S_{100\,\mu\mathrm{m}})\,\mathrm{L}_\odot,$$

assuming a distance $d = 400$ pc for the clouds. Since the flux densities are rising with wavelength, a substantial fraction of the bolometric luminosity may be emitted at wavelengths longer than 100 μm. We estimate this bolometric correction ΔL to the luminosity by assuming that the maximum

Table 2. Properties of the 'YSO-type' *IRAS* sources associated with the CG heads.

CG No.	IRAS source	IRAS flux densities in Jy at 12μm	25μm	60μm	100μm	L_{IRAS} ($L_{\odot}$)	L_{bol} ($L_{\odot}$)	T_c (K)
1	07178−4429	6.71	7.65	12.90	32.80	17.42	18.81	39
2	07144−4352	0.25L	0.38L	0.54:	8.59	0.68	1.61	23
3	07378−4745	0.25L	0.25L	1.78	12.79	1.19	2.57	28
5	07391−4342	0.25L	0.25L	0.93	4.64	0.48	0.98	31
8	07408−4108	0.25L	0.25L	1.64	8.21	0.85	1.74	31
9	07389−4119	0.25L	0.25L	1.54	5.80	0.67	1.30	34
14	07372−4945	0.25L	0.25L	0.73:	8.65	0.72	1.65	24
15	07309−5039	0.29L	0.25L	0.62L	6.33	0.43	1.11	<25
22	08267−3336	0.40	1.10	3.17	13.88	2.71	4.21	33
25	07358−4750	0.25L	0.25L	0.43L	3.75	0.26	0.66	<26
26	08140−3340	0.25L	0.25L	0.40L	3.19	0.22	0.56	<26
27	08105−3335	0.25L	0.25L	0.40L	3.94	0.27	0.70	<30
28	08103−3346	0.25L	0.25L	0.64L	5.27	0.36	0.93	<26
30	08076−3556	0.63	3.75	18.00	46.69:	9.62	14.66	39
32	08124−3422	0.25L	0.31	11.65	39.75	5.01	9.30	35
36	08354−3626	0.25L	0.25L	0.70	5.26	0.48	1.05	27
GDC 1	08242−5050	0.87	6.35	25.83	57.32:	13.77	18.66	42
GDC 4	08250−5030	0.25L	0.25L	1.18	16.72	1.36	2.79	23

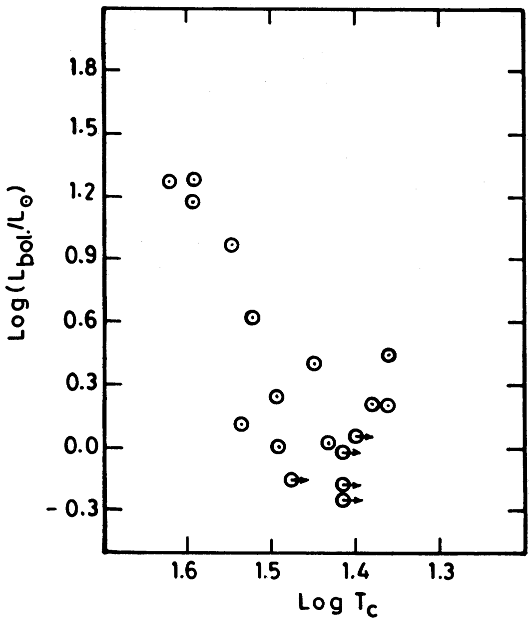

Figure 1. Plot of bolometric luminosity $L_{\rm bol}$ versus the colour temperature $T_{\rm c}$ for the 'YSO-type' *IRAS* sources associated with cometary globules in the Gum nebula.

observed flux density $S_{\nu,\max}$ is also the maximum over the entire spectrum, and that the spectrum is like that of a blackbody for wavelengths longer than $\lambda_{\max}(=100\ \mu\rm m$ here), the wavelength at which the flux density is maximum. ΔL can be written as

$$\Delta L = 5.33\times10^{-5}(d/{\rm pc})^2(S_{\nu,\max}/{\rm Jy})(\lambda_{\max}/\mu{\rm m})^{-1}\ {\rm L}_{\odot},$$

where d is the distance to the source (Myers et al. 1987). For the Gum nebula $d=400$ pc. The bolometric luminosity $L_{\rm bol}=L_{IRAS}+\Delta L$. The bolometric luminosities thus estimated are listed in Table 2, and range from ~ 0.5 to $\sim 20\ {\rm L}_{\odot}$, characteristic of young stellar or protostellar objects of low mass ($\lesssim 1\ {\rm M}_{\odot}$). Fig. 1 shows a plot of the bolometric luminosity L against the colour temperature $T_{\rm c}$. Higher luminosity sources have higher values of the colour temperature $T_{\rm c}$. This behaviour is also characteristic of young stellar or protostellar objects embedded in dense clouds (Beichman et al. 1986). It may therefore be concluded that low-mass star formation is currently taking place in the CG heads in the Gum nebula complex.

The 'YSO-type' infrared sources found here are within very small, dense clouds. The small mass of the CG heads implies a high efficiency of star formation in the cloud. At the distance of 400 pc the CG head linear sizes range from ~ 0.05 to ~ 0.3 pc, the median being ~ 0.1 pc. For a molecular hydrogen density $n_{\rm H_2}\sim 3\times10^4\ {\rm cm}^{-3}$ (see e.g. Harju et al. 1990), the mass of a CG head with linear size ~ 0.1 pc is ~ 1 ${\rm M}_{\odot}$. If stars with masses in the range from ~ 0.3 to $\sim 1\ {\rm M}_{\odot}$ are forming in the CG heads, then the efficiency of star formation (defined as the fraction of the cloud mass that collapses to form the star) is ~ a few times 10 per cent.

Zealey et al. (1983) had noted that the distribution of CGs is not uniform around the geometric centre of the complex of the CGs in the Gum nebula. Most of the CGs are concentrated in the north to south-west sector. It is interesting to see that *IRAS* associations for the CGs are found only in this sector, and none of the CGs in the opposite sector (CGs 7, 17 and 18 in the east to south-east sector) has any associated *IRAS* source. Also CG 24, the CG closest to the centre of the complex, has no associated *IRAS* source. The orientation of the tail of CG 24 is also peculiar. It points more in the direction of the centre than away from it.

The relatively enhanced rate of star formation in the CGs in the Gum nebula suggests that the physical process which gave rise to the formation of the Gum nebula complex of CGs also triggered star formation in the CG heads. A number of models (see review in Bruhweiler et al. 1983) have been proposed for the origin of the Gum nebula and that of the CGs (Reipurth 1983; Zealey et al. 1983). No single generally accepted model has yet emerged. Intense stellar winds or ultraviolet radiation from massive stars, or supernova explosions have been suggested to be the cause in different models. The same processes that created the Gum nebula complex would shock the gas/dust globules and eventually trigger a star-forming collapse in the globule heads.

5 CONCLUSION

We have searched for infrared sources in the *IRAS* Point Source Catalog associated with the compact heads of the cometary globules in the Gum nebula. About 50 per cent of the cometary globule heads are found to have *IRAS* sources with flux densities increasing with wavelength ('YSO-type' sources), characteristic of young stellar objects embedded in dense dust clouds. The surface density of 'YSO-type' sources in the cometary globule heads is $\sim 3-12$ times the density of such sources in dark clouds in a neighbouring comparison area and in the northern sky. It can be concluded that star formation in the cometary globule heads in the Gum nebula is taking place at an enhanced rate as compared to other isolated clouds in the Galaxy. The sources in the cometary globule heads have luminosities in the range from ~ 0.5 to ~ 20 $L_\odot$, characteristic of low-mass, young stellar or protostellar objects. The efficiency of star formation in the cometary globule heads could be as large as a few tens per cent. It is suggested that the physical process that was responsible for the formation of the Gum nebula complex also triggered shock-induced star formation in the cometary globule heads.

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