A CO and IRAS study of Cometary Globule 12

Glenn J. White

Department of Physics, Queen Mary and Westfield College, University of London, Mile End Road, London E1 4NS, England

Received December 3, 1992; accepted April 22, 1993

Abstract. Observations of the $J = 2 - 1$ CO and $^{18}$O lines are reported towards the reflection nebula NGC 5367 in the head of Cometary Globule CG 12, which show it to be only the second example known to date of molecular outflow activity in such an object. The CO has a bipolar shape, centred close to the infrared source IRAS 13547-3944. This has a bolometric luminosity $\sim 110 L_\odot$, and lies close to a $13.5 M_\odot$ molecular core whose kinetic temperature $\sim 20 K$ and diameter $\sim 0.15 pc$. This core appears virialised, and offset from the highest temperature material along the eastern edge of the dense gas - which is probably heated by the UV radiation of a nearby B4 star. A highly collimated (axial ratio $\geq 5$) and low-luminosity molecular outflow originates close to this core, extends over a length of 0.9 pc, and contains $\sim 0.05 M_\odot$ of outflowing material. The structure of the outflow is discussed along with its relationship to the rest of the globule. This is an example of a relatively isolated low-intermediate mass star formation region, which is speculated to have formed as the result of a nearby supernova event 10 - 20 million years ago, and has to date converted about 20 percent of its gas mass into stars.

Key words: Stars: pre-main sequence - Interstellar Medium: jets and outflows

1. Introduction

The reflection nebula NGC 5367 has been proposed as a centre of low-intermediate mass star-formation (Van Till et al. 1975) triggered by the expansion of a supernova blast-wave about 10 million years ago. It surrounds the double star h636 in the head of a prominent Cometary Globule, CG 12 (Hawarden and Brand 1976) and lies at high galactic latitude ($b = 21^\circ$) in an otherwise unconfused field. NGC 5367 has an opaque optical head with a diameter $\sim 10'$, and an elongated tail - seen as wispy filaments of optical absorption and emission, extending $\sim 60'$ SE of the head. Optical and infrared photometry (Williams et al. 1977), showed the likeliest masses of the two stars in the binary system to be 4.5 and 8 $M_\odot$ (i.e. B7 and B4 stars), the latter being surrounded by a dust-shell emitting as a 1600 K blackbody. The most probable distance to NGC 5367 is 630 parsecs, and the mass of the surrounding molecular cloud $\sim 120 M_\odot$. This paper presents CO and IRAS observations of the head of CG 12 close to NGC 5367.

2. Instrumentation

Observations of the CO and $^{18}$O $J = 2 - 1$ transitions were obtained with the 15 metre James Clerk Maxwell Telescope (JCMT) in July 1992, using cryogenically cooled schottky diode receivers and a digital autocorrelation spectrometer (White 1988). The values of $\eta_{\text{ms}}$ and $\eta_{\text{mb}}$ were 0.8 and 0.6 respectively, and all values reported in this paper have been corrected to $T_{\text{mb}}$, unless otherwise stated. Correcting for sideband gains, the absolute calibration accuracy is estimated to be $\pm 15$ percent, and the pointing was measured to be good to 2" rms. The CO and $^{18}$O maps were sampled on 15" grids within the shaded areas shown in the greyscale maps of Figures 1 a), b) and within the dotted box in Figure 1 d). The far-IR maps were processed from the IRAS Sky Survey data, using the IPAC HIRES algorithm. This uses a Maximum Correlation Method (MCM) analysis technique to achieve an approximately four-fold increase in resolution relative to the normal co-add of the IRAS Sky Survey data (Aumann et al 1990). The MCM routine was run for 5, 5, 10 and 20 iterations for the 12, 25, 60 and 100 $\mu$m bands respectively, to achieve the maximum increase in resolution, while not introducing significant extra noise spikes.

3. The Data

3.1. CO and $^{18}$O Observations

Maps of the integrated CO $J = 2 - 1$ emission and the peak CO temperature are shown in Figure 1. The CO has a butterfly shape, with two lobes separated by $\sim 100''$, lying to the west of the far-infrared point-source IRAS 13546-3947. The CO $J = 2 - 1$ line intensity reaches $T_{\text{mb}} = 35 K$ at the centre of the southern lobe, and 26K in the northern one (see Figure 1 b, but is only $\sim 10 K$ at the position of the southern extension seen in the data of Van Till et al. (1975), where they find a somewhat higher temperature (exact comparison is difficult since they fail to quote their $\eta_{\text{mb}}$)). There is little velocity structure, the CO $J = 2 - 1$ lines being relatively narrow ($\Delta v \sim 2$ km s$^{-1}$ at half intensity) almost everywhere (see Section 3.2 later).

The $^{18}$O map Figure 1 d) shows a central core $\sim 35''$ west of the IRAS source, and $\sim 50''$ SW of the exciting star h636 mentioned previously, having a diameter of $\sim 0.15$ pc, slightly extended EW. The main beam brightness temperature, $T_{\text{mb}}$, is 8.8 K at the cores centre, and the velocity is constant at $-6.3$ km s$^{-1}$ everywhere (ie there is no systematic velocity gradient $\geq 3$ km s$^{-1}$ pc across the core). Assuming an abundance ratio $N(C^{18}O)/N(H_2) = 1.8 \times 10^{-7}$, the total mass is 13.5 $M_\odot$. 

Send offprint requests to: Dr Glenn White

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3.2. High velocity gas

Although most of the individual CO spectra are narrow (Δv ~2 km s⁻¹ at half intensity), and singly peaked, broader lines are seen towards two positions; a) about 2′ south of the map centre, where a broad low level wing extends ~10 km s⁻¹ to the redshifted side of the line centre, and b) close to the C¹⁸O peak, where the lines are broader and appear self-reversed at -5.2 km s⁻¹. Spectra towards two of the positions showing broad lines are shown in Figure 2.

Low intensity high velocity gas is seen between -10 and +4 km s⁻¹ as shown in Figure 1 c). This high velocity gas forms part of a highly collimated molecular flow (axial ratio ≥5) which extends ~5 arc minutes (0.9 pc) along the SE-NW direction. The molecular flow lobes originate at the edge of the C¹⁸O core. The flow structure is complex, with red and blue gas coexisting in each of the lobes. The integrated CO J = 2 → 1 emission can be used to estimate the CO column density in outflow material (Bachiller et al. 1990). The mass of the blue and red shifted gas are 0.04 and 0.01 M☉ respectively. The dynamical timescales for both lobes are similar, ~2.7 10⁴ years, and the values of the momentum, kinetic energy and mechanical luminosity of the flow are estimated to be 1.6 M☉ km s⁻¹, 1.7 10⁴ ergs s⁻¹ and 4.2 10⁻³ L☉ respectively (since there is no information on the angle of inclination, i, of the flow to the Earth, it is arbitrarily assumed to be i = 45°). Therefore, this is a relatively low luminosity outflow - comparable to those in other quiescent dark clouds (e.g.Parker et al. 1991). It is clearly

agreeing closely with the virial mass. Assuming the line of sight depth through the core is the same as its diameter, the C¹⁸O column density of 2.1 10¹⁶ cm⁻² implies a uniform volume density N_H₂ = 2.2 10¹⁴ cm⁻³. From the CO spectra towards the centre of the core, the kinetic temperature of the gas, estimated from the peak CO main beam brightness temperature, is ≤ 20K. The warmer gas lies along the eastern side of the core, suggesting that the main heating source for the eastern part of the cloud may be the binary system which includes the B4 star in h4636, instead of an embedded object in the C¹⁸O core.

Fig. 1. a) Integrated CO J = 2 → 1 map of NGC 5367. The sampling interval is 15″ and contours are at 5 K steps with the white contour at 30K km s⁻¹. The central (0,0) position of this and all following maps is α = 13h 54m 42.0s, δ = -39°47′ 42″. b) Peak CO J = 2 → 1 temperature with contours in 2.5K steps with the first white contour at 17.5K. c) high velocity gas integrated for the blue (dashed contours which are overlaid on greyscale and cover -7 to -12 km s⁻¹) and red (solid lines covering -2 to +5 km s⁻¹) wings with contours at 1K intervals starting from 3K km s⁻¹. d) Integrated CO J = 2 → 1 C¹⁸O map in 0.5 K km s⁻¹ steps, with the lowest contour at 1 K km s⁻¹. The position of IRAS 13547-3944 is indicated by a black dot on the maps at the offset position (+7, +215). This lies close to the position of h4636 at (+11, +237) indicated by + symbol. The head of the globule, as seen optically, covers the whole of the mapped region, with the tail extending off beyond the SE corner.

Fig. 2. Spectra in the J = 2 → 1 CO and C¹⁸O lines towards the offset positions (0, +140) and (-30, +230). The C¹⁸O spectra temperatures have been multiplied by a factor of 2.
impossible to be certain that the high velocity gas originated from a single central driving source, particularly because of the complex way that the blue and red-shifted gas overlap. Avery et al. (1990) reported similar co-spatiality of red and blue gas for the dark cloud L723, where the possibility of backflow along the outside of the main outflow lobe is discussed, agreeing with modelling by Cabrit et al. (1988).

3.3. IRAS observations

The infrared source IRAS 13547-3944 appears in both the IRAS Point Source, and Small Scale Structure catalogue, with total luminosities across the IRAS detector range of ~110 and 250 L⊙ for the point and extended source emission. The point source lies ~ 35′′ east of the C18O peak (as mentioned previously in Section 4.1), and is indicated on the HIRES maps shown in Figure 3 a) - d).

The 12 and 25 μm maps show a point-like core, with other compact structures present ~5′ N (at α = 13h 54m 55.2s δ = -39°41′ 31″) and 10′ SE (at α = 13h 54m 52.8s δ = -39°49′ 37″) of IRAS 13547-3944. These point sources are surrounded by lower brightness emission over an area of size ~1 pc². In the longer wavelength bands, the size of the source increases markedly, extending over ~20 x 20′′ at 100 μm. These maps show a distribution which generally resembles the large scale CO J=1-0 map of Van Tiel et al. (1975). The southern component (most prominent in the 60 and 100 μm maps) is coincident with the secondary CO J = 1-0 hotspot, close to the position of star 2 (a mid-late type B star - Brand et al. 1983), which probably heats the nearby cloud edge. Their 13CO map did not however show an enhancement towards this position. Our CO J = 2–1 emission has a peak temperature of ~7 K at this point, substantially lower than the J = 1--0 values. The infrared luminosity estimated from the IRAS data for this point is ~1.7 L⊙, indicating it not to be substantially heated by an embedded star. It is more likely that the uv radiation of star 2 is heating the edge of the cloud at this point. The dust temperature can be estimated from the ratio of the 60 and 100 μm fluxes. The maps were smoothed using a non-symmetric gaussian smoothing functions, to a 10′′ gaussian beam (like to the unsmoothed HIRES processed 100 μm map). The flux ratios (F(100μm) / F(60μm)) at the position of IRAS 13547-3944 and the southern peak of Van Tiel et al. (1975) are 4.2 and 3.2, implying dust temperatures of 32 and 36K respectively, which are similar to the peak main-beam brightness temperatures of the CO J = 2–1 data (within calibration uncertainties).

4. Discussion

Two alternative scenarios have been presented to explain the appearance of cometary globules. Reipurth (1983) suggested they were the left over cores of larger clouds, of which the ultraviolet radiation from nearby OB-stars has evaporated the outer parts, leaving behind Bok Globules. The alternative scenario by Brand et al. (1983) is for a supernova blast-wave to sweep past a cloud clump, compressing it and causing material to stream out in a tail, giving the characteristic shapes which are seen.

Several other cometary globules have been identified, particularly those related to the Gum Nebula (Pettersson 1992). Associated with this nebula is an unique system of ~ 30 opaque bright rimmed clouds with bright rims, with faint luminous

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**Fig. 3.** IRAS maps using the HIRES processing algorithm. The four maps show the a) 12 μm, b) 25 μm, c) 60 μm and d) 100 μm bands respectively, and have beam sizes 78 x 51′′, 120 x 45′′, 96 x 71′′ and 101 x 102′′ respectively, with the major axes of the distribution at position angle 145°, orthogonal to the in-scan direction. The values of the contours are shown to the upper right of the individual maps (note that the contours are not in equal steps, but are chosen to emphasise the low level emission around the intense central point source). The position of IRAS 13547-3944 is indicated by a black dot.
tails pointing away from the centre of the nebula. CO and infrared surveys have shown several to be active sites of low-mass star formation, leading to speculation that this had been induced by the passage of the blastwave of the fossil supernova shell.

Other objects similar to NGC 5367 are known, including CG 1 (Harju et al. 1990) and ESO 210-6A (also known as the HH46-47 system). CG 1 has a mass of $\sim 20-45 \ M_\odot$, with $\sim 75$ percent of this in the tail. The gas temperature is $\sim 15K$, and hydrogen densities $\sim 10^4 \ cm^{-3}$. There is no evidence for a systematic velocity gradient over the cloud, although shocked gas is seen at some velocities close to the head of the globule. Two $^{12}$CO clumps are seen in the head, having a total mass of $0.1-0.4 \ M_\odot$. Although there is evidence for recent star formation with an efficiency of $\sim 10$ percent, no molecular outflow was reported at the present epoch. In ESO 210-6A, the total gas mass is $\geq 15 \ M_\odot$, and the globule shows signs of compression behind its bright rims. A well collimated bipolar molecular outflow is aligned with an optical jet, and extends for $\sim 1$ parsec. The dynamic timescale, momentum, kinetic energy, and mechanical luminosity of this flow are very similar to the values for the NGC 5367 flow.

In the case of CG 12, Williams et al. (1977) have speculated that it has been influenced by a high galactic latitude supernova explosion between 10 and 20 Myr ago. The B7 star (star 2) sets a lower limit to the age of CG 12 of $\sim 10$ million years, and the detection of the low luminosity molecular outflow surrounding the dense core of CG 12 suggests low mass star formation to be continuing at the present epoch. The relatively high mass in recently formed stars ($\sim 20$ percent) is significantly higher than seen towards many more quiescent clouds, and supports the notion that a burst of triggered star-formation, which is still working its way through the gas, is forming stars at the present epoch. A systematic mapping programme of Cometary Globules, backed with near and far-infrared studies would be useful to search for further evidence of triggered star-formation in this class of objects. Such a study would also need to consider whether the core is in free-fall collapse, or whether external pressure has driven the collapse, and initiated any current star forming activity.

5. Conclusions

1) The NGC 5367 molecular cloud has kinetic temperatures up to 30K. The absence of strong heating from an embedded source in the cloud core, and the distribution of the warm CO suggests that UV radiation from nearby B stars are strongly heating the cloud edge. Away from the warm gas, the temperature is $\sim 10K$; typical of quiescent dark clouds.

2) A centrally condensed core with a diameter of $\sim 0.15$ parsecs, temperature $\leq 20K$, and mass $13.5 \ M_\odot$ lies $\sim 35''$ west of IRAS 13547-3944. This core appears to be close to virial equilibrium, but does not contain the dominant heating source for the region.

3) Most of the ambient gas peaks at velocities between 4 and 7 km s$^{-1}$. No large scale rotation of the cloud or cloud core is seen.

4) A highly collimated, low-luminosity molecular outflow originates close to the core, extending $\sim 0.9$ parsecs along the major axis of the cometary globule. The characteristics of this outflow are typical of those found in relatively quiescent low-mass star forming dark clouds.

References


Acknowledgements. The assistance of the staff at the Joint Astronomy Centre, Hilo is acknowledged in obtaining the JCMT observations; the IRAS data were obtained using the facilities of IPAC, of which the staff is thanked for the speedy turn-round of the HIRES data; the non-symmetric gaussian smoothing kernel was specially written by Malcolm Currie at The Rutherford Laboratorys Starlink Project Division, to whom thanks are extended. The JCMT is operated by Joint Astronomy Centre, Hilo, on behalf of the Science and Engineering Research Council, The Netherlands Foundation for Radio Astronomy, and The National Research Council of Canada. IPAC is funded by NASA as part of the IRAS extended mission programme under contract to JPL.

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