Extending the limits of globule detection

ISOPHOT Serendipity Survey observations of interstellar clouds

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Abstract A faint $I_{170} = 4 \text{ MJy}^{-1}$ bipolar globule was discovered with the ISOPHOT 170 µm Serendipity Survey (ISOSS). ISOSS J 20246+6541 is a cold ($T_{\text{d}} \approx 14.5$ K) FIR source without an IRAS pointsource counterpart. In the Digitized Sky Survey $B$ band it is seen as a 3' size bipolar nebulosity with an average excess surface brightness of $\approx 26 \text{ mag/arc''}$. The CO column density distribution determined by multi-isotopic, multi-level CO measurements with the IRAM-30m telescope agrees well with the optical appearance. An average hydrogen column density of $\approx 10^{22} \text{ cm}^{-2}$ was derived from both the FIR and CO data. Using a kinematic distance estimate of 400 pc the NLTE modelling of the CO, HCO$^+$, and CS measurements gives a peak density of $\approx 10^4 \text{ cm}^{-3}$. The multiwavelength data characterise ISOSS 20246+6541 as a representative of a class of globules which has not been discovered so far due to their small angular size and low 100µm brightness. A significant overabundance of $^{13}$CO is found $X(^{13}\text{CO}) \geq 150 \times X(\text{C}^{18}\text{O})$. This is likely due to isotope selective chemical processes.

Key words. ISM: clouds – dust, extinction – ISM: molecules – Infrared: ISM: continuum – Surveys

1. Introduction

Bok globules were originally detected in absorption against HII regions by Bok and Reilly (1947), and are known as small, dense interstellar clouds in the solar neighbourhood ($d \lesssim 400 \text{ pc}$). They were identified optically, and mostly the nearby ones have been catalogued so far. It is expected that they are similarly common elsewhere in the Galactic disk and in fact a few distant ones are already investigated eg. by Launhardt & Henning (1997). Their FIR properties were determined by Clemens & Barvains (1988) based on IRAS data. They emphasized the importance of finding FIR faint cold globules since these are representatives of the inactive (i.e. non-starforming) interstellar medium. Starless globules with small apparent size and low temperature (thus also very low 100 µm brightness) can be seen only by good sensitivity at wavelengths over 100 µm. An ISOPHOT study of pre-stellar cores in dark clouds with low 100 µm brightness were recently reported by Ward-Thompson et al. (2002). The ISOPHOT 170 µm Serendipity Survey (ISOSS) can be used to locate cold galactic objects even without any preliminary identification. This raises the possibility of detection of the “missing” globules via ISOSS. We present our results on ISOSS J 20246+6541 proving that it is, indeed, a small and cold isolated molecular cloud - one of the so far missed population.

2. Observation and data analysis

We searched ISOSS at medium galactic latitudes for 170 µm point sources without IRAS counterparts. The ISOSS measurements, calibration, and data analysis for interstellar clouds are described by Bogun et al. (1996), Stickel et al. (2000) and Tóth et al. (2000) respectively. ISOSS J 20246+6541 was detected as an $I_{170}$ (peak) = 4 MJy sr$^{-1}$ ($\geq 4 \sigma$) pointlike (FWHM $\leq 2.5'$) source at RA(2000)=20\textdegree 24\textmin 36\textsec Dec(2000)=+65\textdeg 40' (I=99.80, b=15.70\textordmasculine). It is without an IRAS point source counterpart.

The optical appearance of CISS1 and its neighbourhood was studied using 40' × 40' Digital Sky Survey (DSS) blue and red images. Photometry on DSS plates of all USNO sources have been done where R and B $\leq 18\text{mag}$. Integrated photographic density was derived for all these USNO sources. Photographic density values DN of the background were measured at each plate at 25 positions where neither star, nor significant background emission enhancement

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Figure 1. CO spectra at the \(^{13}\)CO(1–0) peak, (2–1) lines are overlaid as filled histograms. a, \(^{12}\)CO(1–0) and (2–1) spectra. b, \(^{13}\)CO(1–0) and (2–1) spectra. c, C\(^{18}\)O(1–0) and (2–1) spectra.

was seen. The background value is \(DN(BG)_R = 4590 \pm 190\) and \(DN(BG)_B = 4610 \pm 230\) in photographic density units for R and B bands respectively. Photometric calibration of the plates was made following Cutri’s (1993) method. The photographic density to magnitude calibration formulae were derived as \(log_{10}(DN)\) vs. magnitude relations. The scatter is large for faint stars, and the extrapolation to low photographic density (i.e. high magnitude) values results in a large error bar. In order to make surface brightness maps of ISOSS J 20246+6541, stars were removed from the optical images by substituting the "raw" (IRDS format) IRAS data. Comparison of ISOSS and ISSA data (Wheelock et al. 1994) was made as described by Tóth et al. (2000). An upper limit of the colour temperature of 14.5 K was estimated from the bisector slope of the \(I_{70}\) vs. \(I_{100}\) scatter plot. Assuming a dust temperature of 14.5 K, an average dust column density of \(1.3 \times 10^{-6}\)gcm\(^{-2}\) was derived following Hildebrand (1983). This corresponds to an average hydrogen-to-dust mass ratio of 110 (Launhardt & Henning 1997) was assumed.

3. Results

3.1. FIR results and derived parameters

ISOSS J20246+6541 is a faint FIR source with an upper limit on the \(I_{100}\) brightness of about 0.5 MJy/sr derived from the “raw” (IRDS format) IRAS data. Comparison of ISOSS and ISSA data (Wheelock et al. 1994) was made as described by Tóth et al. (2000). An upper limit of the colour temperature of 14.5 K was estimated from the bisector slope of the \(I_{70}\) vs. \(I_{100}\) scatter plot. Assuming a dust temperature of 14.5 K, an average dust column density of \(1.3 \times 10^{-5}\)gcm\(^{-2}\) was derived following Hildebrand (1983). This corresponds to an average hydrogen-to-dust mass ratio of 110 (Launhardt & Henning 1997) was assumed.

3.2. Optical images

ISOSS J20246+6541 appears as a faint, isolated reflection cloud west of the L1155/L1157 cloud complex. When smoothed to 15\(''\), the excess diffuse surface brightness distribution of ISOSS 20246+6541 shows a “bright” lobe at the NE and a fainter fragmented one at SE. The POSS B band diffuse surface brightness is shown in Fig. 2a, where the contours are drawn from 22.7 mag/\(''\) by \(-0.05\)mag/\(''\). The lowest contour corresponds to three times the standard deviation of photographical density outside the globule on the star-removed, smoothed image. The average background surface brightness is 22.8/\(''\). Linear interpolation of the \(T_{MB} = T_A^* \times (B_{eff}/F_{eff})\). The values for the main-beam efficiency, \(B_{eff}\), are 0.70 and 0.42 (July 1998), and 0.75 and 0.53 (September 2000), and the values for the forward efficiency, \(F_{eff}\), are 0.92 and 0.85 for CO(1–0) and CO(2–1), respectively.

3.3. Molecular line results, and derived parameters

All observed lines show a LSR velocity of -2.7 km/s. The FWHM widths of the \(^{12}\)CO lines are around 0.4 km/s, and around 0.3 km/s for all the other detected lines. The \(^{12}\)CO and \(^{13}\)CO integrated intensity distributions are shown in Figs. 2a and c. The bipolar shape is well seen and the CO line intensities are in accordance with the excess surface brightness distribution; the NW lobe being much brighter. The two lobes show the same radial velocity.

The physical parameters were at first approximated from the \(^{12}\)CO(1–0) and \(^{13}\)CO(1–0) spectra of the peak in-
and they are counted into the “close group” of clouds, which are

bered peak very close to ISOSS J 20246+6541 at l=100° b=15°. All the listed Yonekura clouds have N(H2) = 8.9 × 10^{14} cm^{-2}, which corresponds to N(H2) ≈ 10^{23} cm^{-2} assuming N(H2) ≈ 10^6 N(^{13}CO). This result is in agreement with the column density derived from the FIR data. The ^{12}CO and ^{13}CO lines trace the ISM well over most of the cloud. A comparison of C^{18}O to ^{13}CO lines (both 1-0 and 2-1) at the centre of the NE lobe indicates an underabundance of C^{18}O by a factor of 4. This effect is expected in cold clouds with moderate density, exposed to UV radiation (Glassgold et al. 1985). A more careful modelling may account for it as we show in the Discussion session.

4. Discussion

4.1. Distance of ISOSS J 20246+6541

The distance of ISOSS 20246+6541 can be estimated, relating it to its neighbours. Its nearest neighbours are L1122 and L1124 (Lynds 1998), and the YDM97 CO1 (Yonekura 1997). The ^{13}CO survey of Cepheus by Yonekura (1997) covers the position of ISOSS J 20246+6541 and their Fig. 6a indicates few small clouds around ISOSS J 20246+6541 (i.e. YDM97 CO1, YDM97 CO2, YDM97 CO3) and one even smaller unnumbered peak very close to ISOSS J 20246+6541 at l=100° b=15°. All the listed Yonekura clouds have N(H2) ≈ 10^{23} cm^{-2}, and they are counted into the “close group” of clouds, which on the other hand is associated with extended FIR features around ISOSS J 20246+6541. The nearest molecular clouds with negative v_{LSR} are YDM97 CO1, YDM97 CO9, CO10 at l ≈ 103° b ≈ 16°. ISOSS 20246+6541 itself has v_{LSR} = -2.7 km/s. It probably belongs to the ISM layer of the nearby Cepheus Flare GMC, and is located at about 400 pc (Kun 1998). We note that applying the size-linewidth relation of Larson (1981) the globule may be between 100 and 400 pc.

4.2. Radiative transfer models

We have modelled the NE lobe of the bipolar globule with spherically symmetric cloud models, although the NE clump shows some deviations from spherical symmetry in both ^{12}CO and ^{13}CO (see Fig. 3 b and c. With RA=20^h 24^m 44^s Dec=+65° 40’04” as the centre position, we have averaged spectra in concentric rings with radii increasing by 10' intervals up to a radii of 90'. The effective resolution of the averaged spectra is 40' for the J =1–0 lines and 20' for the J =2–1 lines.

We set the cloud parameters as follows.

1. We assume a density distribution n ∼ r^{-1.5} with a density ratio 100 between the centre and the cloud surface.
2. The kinetic temperature is assumed to rise linearly from the cloud centre. This is a crude approximation of the actual temperature structure of for a small, spherically symmetric globule without internal heating sources (e.g. Leung 1985; Nelson & Langer 1999) but will suffice for the present purposes. The temperature gradient, i.e. the difference between the outermost and innermost shells ΔT = 0 K, 6 K or 10 K. Higher contrast means too high a temperature for the outer cloud, in contradiction with the observed small linewidth.

3. Extinction-dependent relative molecular abundances X(molecule) = \frac{n(molecule)}{n(H)} were estimated according to
The cloud is cold, exposed to UV radiation and it has a peak visual extinction between 1 and 2 mag. In these conditions isotope selective processes result in a relative overabundance of $^{13}\text{CO}$ and relative underabundance of $^{12}\text{CO}$ according to Bally and Langer (1982). When applying the relative abundances, we introduced an intrinsic extinction at the cloud boundary since the $^{12}\text{CO}$ lines are not vanishing at the boundary of the NE lobe. This assumption is supported by the presence of surrounding extended cirrus-like emission seen in 100 $\mu$m on the ISSA image.

(iv) The average physical parameters are: $T_{\text{kin}} = 11$ K, $n(H_2) = 7000 \text{cm}^{-3}$.
(v) In the 5$^\circ$ environment of ISOSS 20246+6541 we found further 15 ISOSS sources with similar FIR parameters. One of those is another previously unknown globule as seen on DSS2 images.
(vi) The population of small and faint starless globules can only be explored by high sensitivity FIR measurements such as those carried out by PHT-C2 on board ISO.
(vii) We note that there are no other ISO measurements but the ISOSS within 40$^\circ$ of those carried out by PHT-C2 on board ISO.

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References

Bally J. and Langer W.D., 1982, ApJ 255, 143
Bogun S., Lemke D., Klaas U., et al., 1996, A&A 315, L71
Bohlin R.C., Savage B.D., Drake J.F., 1978, ApJ 224, 132
Bok B.J., Reilly E.F., 1947, ApJ 105, 255
Clemens D.P., Barvainis R. 1988, ApJS 68, 257
Cutri R.M., Low F.J., Guhathakurta P., 1993, PASP 105, 106
Glassgold A.E., Huggins P.J., & Langer W.D. 1985, ApJ 290, 615
Hildebrand R.H., 1983, QJRAS 24, 267
Hotzel S., Harju J., Lemke D. et al. 2001, A&A 372, 302
Juvela M., 1997, A&A 322, 943
Kun M., 1998, ApJS 115, 59
Larson R.B. 1981, MNRAS 194, 809
Launhardt R., Henning T., 1997, A&A 326, 329
Leinert Ch., Bowyer S., Haikala L.K. et al., 1998 A&AS 127, 1
Lemke D., Klaas U., Abolins J., et al., 1996, A&A 315, L64
Lynds, B.T., 1962, ApJS, 7, 1.
Leung C.M. 1985, in Protostars & Planets II, Black D.C., Matthews M.S. (eds.), The University of Arizona Press, Tucson, p. 104
Monet, D.G. et al. 1998, USNO-A2.0, Washington DC, USNO Nelson R.P., Langer W.D. 1999, ApJ 524, 923
Stickel M., Lemke D., Klaas U. et al., 2000, A&A 359, 865
Tóth L.V., Hotzel S., Krause O., et al., 2000, A&A, 364, 769
Ward-Thompson, D., André, P., Kirk, J.M., 2002, MNRAS 329, 257
Warin S., Benayoun J.J., Viala Y.P. 1996, A&A 308, 535
Wheelock S.L., Gautier T.N., Chillemi J., et al., 1994, IRAS sky survey atlas: Explanatory supplement. JPL Publication 94-11, IPAC, JPL
Yonekura Y., Dobashi K., Mizuno A., et al., 1997, ApJS 110, 21.