Star Formation in Massive Protoclusters in the Monoceros OB1 Dark Cloud

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ABSTRACT

We present far-infrared, submillimetre, and millimetre observations of bright IRAS sources and outflows that are associated with massive CS clumps in the Monoceros OB1 Dark Cloud. Individual star-forming cores are identified within each clump. We show that combining submillimetre maps, obtained with SCUBA on the JCMT, with HIRES-processed and modelled IRAS data is a powerful technique that can be used to place better limits on individual source contributions to the far-infrared flux in clustered regions. Three previously categorized “Class I objects” are shown to consist of multiple sources in different evolutionary stages. In each case, the IRAS point source dominates the flux at 12 & 25 µm. In two cases, the IRAS point source is not evident at submillimetre wavelengths. The submillimetre sources contribute significantly to the 60 & 100 µm fluxes, dominating the flux in the 100 µm waveband. Using fluxes derived from our technique, we present the spectral energy distribution and physical parameters for an intermediate-mass Class 0 object in one of the regions. Our new CO J=2→1 outflow maps of the three regions studied indicate complex morphology suggestive of multiple driving sources. We discuss the possible implications of our results for published correlations between outflow momentum deposition rates and “source” luminosities, and for using these derived properties to estimate the ratio of mass ejection rates to mass accretion rates onto protostars.

Key words: ISM: individual(Mon OB1) – ISM: jets and outflows – radio lines: ISM – stars: formation – techniques: image processing(HIRES).

1 INTRODUCTION

One of the outstanding questions in star formation is whether high-mass stars form in a similar manner to low-mass stars, but the answer to this question is poorly constrained observationally. Although the tendency for stars to form in clusters in regions of intermediate- and high-mass star formation has been firmly established (Testi, Palla, & Natta 1999), the main database for infrared data on these stellar nurseries remains that of IRAS, which typically probes large cloud structures identified with the formation of clusters or groups of stars (clumps), rather than the smaller condensations (~0.1 pc – cores) out of which single stars or multiple stellar systems form (McKee 1999; Myers 1999).

For many years now, the IRAS database has been used extensively to help categorize the spectral energy distributions (SEDs) of young stellar objects (YSOs) according to the proposed evolutionary scheme developed by Adams, Lada, & Shu (1987). Although this scheme was originally proposed to describe an evolutionary sequence for isolated low-mass star formation, it has since been applied to many IRAS sources that are often high-luminosity objects, begging the question of what an SED means in cases where it describes not a single star-forming core, but rather a group of objects, which may or may not be coeval. Furthermore, since the earliest surveys for bipolar outflows in molecular clouds (Bally & Lada 1983; Lada 1985), the IRAS database has been used extensively to help determine the luminosities of the driving sources of these outflows and to further establish correlations between source and outflow properties (e.g., Panagia 1991; Cabrit & Bertout 1992). A recent survey for jets in the Vela molecular clouds produced evidence that many jets are driven by low-mass objects clustered around IRAS sources which are likely to be intermediate-mass YSOs (Lorenzetti et al. 2002). This raises the interesting question...
of how the observed correlations between outflow momentum deposition rates and “source” luminosities should be interpreted.

Submillimetre continuum imaging with arrays such as SCUBA (Submillimetre Common-User Bolometer Array) on the 15-m James Clerk Maxwell Telescope on Mauna Kea can probe conditions on the scale of individual star-forming cores, and thus can be useful in separating sources in confused regions, but by themselves, these observations yield limited spectral coverage for the determination of physical properties such as temperature, bolometric luminosity, and evolutionary stage. Since protostars have SEDs that peak in the far-infrared, multiband infrared data are critical, though difficult to obtain given the current lack of operational far-infrared observatories. However, software advances in HIRES (High-RESolution) processing of IRAS data (Aumann, Fowler, & Melnyk 1990) have allowed unprecedented spatial resolutions to be achieved at FIR wavelengths (Surace et al. 1993; Terebey & Mazzarella 1994; Cao et al. 1996; Hurt & Barsony 1996; Cao et al. 1997; Barsony et al. 1998). HIRES-processing and modelling of IRAS data has even been suggested as a method for identifying Class 0 protostars (O’Linger et al. 1999).

In this paper, we apply HIRES processing and modelling techniques to massive star-forming clumps in the Monoceros OB1 dark cloud. Molecular emission from the Mon OB1 dark cloud was first mapped by Blitz (1978) at low resolution covering 11 square degrees towards the arc of dark nebulae seen on the Palomar Observatory Sky Survey print (Lynds 1962). Since the Mon OB1 dark cloud lies toward the outer Galaxy, near the galactic anticentre, confusion due to foreground and background clouds is at a minimum, affording an excellent opportunity to study the large-scale distribution of molecular material and associated star formation. Oliver, Masheder, & Thaddeus (1996, hereafter OMT96) performed an unbiased CO survey over 52 square degrees at higher sensitivity and spectral resolution than the Blitz survey in order to gain a better understanding of the large-scale structure and kinematics of the ISM towards the Mon OB1 region and study the properties of molecular clouds in the outer Galaxy. They used the IRAS Point Source Catalogue to identify sites of massive star formation in their large-scale CO survey by applying two criteria using color selection of IRAS point sources (Richards et al. 1987; Wood & Churchwell 1989).

The star-forming region that OMT96 identify as Cloud 16, associated with the young star cluster NGC 2264, has been the target of many molecular line studies, including an unbiased CO J=1−0 survey for molecular outflows (Margulis, Lada, & Snell 1988, hereafter MLS88) and search for dense gas via a multitransitional CS study (Wolf-Chase, Walker, & Lada 1995, hereafter WWL95; Wolf-Chase & Walker 1995, hereafter WW95). Prior to publication of the IRAS point source catalog, Margulis, Lada, & Young (1989; hereafter MLY89) used the IRAS database to identify 30 discrete sources within this region, and classify their SEDs in terms of the evolutionary scheme proposed by Adams, Lada, & Shu (1987). Four of these sources lie at or near the emission peaks of the CS clumps identified by WWL95: IRAS 9 (IRAS 06382+0939; also NGC 2264 IRS 1 – Allen 1972), IRAS 12 (IRAS 06382+0939), IRAS 25 (IRAS 06382+1017), & IRAS 27 (IRAS 06381+1039). Three of these sources are also identified as sites of massive star formation by OMT96 (IRAS 06382+0939, IRAS 06382+1017, & IRAS 06381+1039). All three of these IRAS sources were categorized as Class I objects by MLY89.

The primary goal of this paper is to identify individual star-forming cores located in the massive CS clumps in Mon OB1 and estimate their contributions to the IRAS fluxes that characterize the entire clumps, in order to assess the accuracy of source classes and luminosities that were previously deduced from the IRAS data. We concentrate on the three sites of massive star formation identified by OMT96, since the fourth IRAS source that coincides with a CS emission peak, NGC 2264 IRS 1, has already been studied in great detail in both molecular line and continuum emission (e.g., Schreyer et al. 1997; Ward-Thompson et al. 2000; Wang et al. 2002). In addition to the IRAS Point Source Catalogue designations, we use the nomenclature of MLS88 & MLY89 to refer to outflows and IRAS sources in this cloud. We adopt a distance to Mon OB1 of 800 pc (Walker 1956); the same distance adopted by MLS88 and MLY89. This is a compromise between more recent estimates of 700 ± 40 pc and 790 pc given by Feldbrugge & van Genderen (1991) and Sagar & Joshi (1983) based on VBLUW and UVB photometry of stars in the young cluster NGC 2264, and 950 pc, adopted by OMT96, based on photometric analysis by Pérez, Thé, & Westerlund (1987).

2 OBSERVATIONS AND DATA REDUCTION

2.1 Submillimetre Continuum Mapping: JCMT Observations

The observations presented here were obtained with the Submillimetre Common-User Bolometer Array (SCUBA) (Holland et al. 1999) at the James Clerk Maxwell Telescope (JCMT)1 located near the summit of Mauna Kea, Hawaii. The instrument contains two arrays of bolometric detectors – the Short Wave (SW) array has 91 pixels optimised for observations at 450 μm, and the Long Wave (LW) array has 37 pixels at 850 μm. Both arrays can be used simultaneously and have approximately a 2.3 arcmin diameter field-of-view on the sky. The instrument achieves sky-background limited performance by cooling the detectors to ~75 mK.

The data were obtained 9 August, 18 and 23 November 1999, and 21 October 2000, using the standard SCUBA “scan-map” observing mode (Jenness et al. 2000). Fully sampled maps at both 450 μm and 850 μm were generated with 3 arcsec sampling. The pointing was checked using a nearby blazar every ~1 hour, and was found to vary by <2 arcsec. The data were corrected for atmospheric extinction by the method recommended by Archibald et al. (2002), i.e. fitting a polynomial to the 225 GHz zenith optical depth derived by a tipping radiometer, then extrapolating to 850 μm and 450 μm. The data were reduced and maps reconstructed using the ORAC data reduction package (Jenness & Economou 2001).

1 The JCMT is operated by the Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.
Flux calibration was applied to the data using images of a planet or of the secondary calibrator source CRL618, obtained using the same observing technique as the data. Flux densities of the sources were derived using aperture photometry with a 45 arcsec diameter aperture, and then correcting for flux in the error beam using the same flux calibration images.

2.2 NRAO 12-m Continuum Photometry

We obtained 1.3 mm continuum data during December 1997, using the National Radio Astronomy Observatory (NRAO) 12-m telescope located on Kitt Peak, near Tucson, Arizona to toward the position of three compact submillimetre sources that we identified in earlier, unpublished, 850 μm SCUBA jiggle-maps, which we acquired prior to the scan-maps reported in this paper. We measured the 1.3 mm continuum flux toward these sources within a 27 arcsec beam using a dual-channel, double-sideband, SIS heterodyne receiver system. The receiver had a bandwidth of 600 MHz and was operated at a sky frequency of 231.6 GHz. The subreflector was nutated at a frequency of 4 Hz, using a 2 arcmin beam throw. Data were calibrated by chopping between sky and an ambient temperature load. Due to the inopportune positions of the planets, absolute calibration was achieved by observing NGC 2071 IR and NGC 2264 IRS, and using published 1.3 mm fluxes to scale our data (Walker, Adams, & Lada 1990; Sandell 1994). Consequently, we estimate 1.3 mm flux uncertainty to be at the 30%–40% level.

2.3 Far-Infrared Mapping: HIRES Processing of the IRAS Data

A detailed background of IRAS data and HIRES processing techniques may be found in Hurt & Barsony (1996), Barsony et al. (1998), and O’Linger et al. (1999), including an in-depth discussion of the significant merits of taking HIRES-processing beyond the standard 20 iterations, which is the default when HIRES-processing is requested remotely via electronic mail to IPAC. For the data presented here, we halted HIRES processing at 40 iterations in the 12 μm and 25 μm bands, and at 200 iterations in the 60 μm and 100 μm bands. These images do not represent “converged” data in a formal sense, as the concept of convergence in iterative solutions of nonlinear problems seldom has any absolute meaning (O’Linger et al. 1999). Our iteration limits in the various wavebands were chosen by looking at the change in the correction factor variance from one iteration to the next, and setting an acceptable threshold value (Aumann et al. 1990; Hurt & Barsony 1996; O’Linger 1997; Barsony et al. 1998).

2 The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc. The 12-m telescope (currently known as the Arizona Radio Observatory) is now operated through the University of Arizona’s Steward Observatory, with funds provided by the University of Arizona, the Research Corporation, and the National Science Foundation.

3 IPAC is funded by NASA as part of the IRAS extended mission under contract to JPL.

The irregular sampling of the sky brightness distribution by subsequent passes of the IRAS detectors results in variable spatial resolution across a HIRES-processed image. Among the diagnostic maps produced during the HIRES-processing, are “beam-sampled” maps, which may be used to compute effective resolutions achieved at various positions in the HIRES-processed image by inputting a series of user-defined, point-source “spikes” across the image. These spikes are then HIRES-processed along with the actual IRAS data, allowing effective resolutions to be calculated at the positions of the spikes. Ideally, the beam-sampled maps can be used to produce models of the actual HIRES-processed IRAS emission. For example, supplying user-defined spikes to coincide in magnitude and position with actual sources chosen from the IRAS Point Source Catalogue results in a point-source model, which can be compared to the actual HIRES-processed data (Hurt & Barsony 1996). One may subsequently add further spikes to more closely simulate the actual emission (O’Linger 1997; Barsony et al. 1998). Such spikes may represent extended emission, or, in some cases, additional embedded sources. Point-source modelling offers significant advantages over simple software aperture photometry of the HIRES-processed IRAS survey images. Whereas simple software aperture photometry suffers from uncertainties as to the proper aperture size to use, and the systematic effects that can be introduced by the processing algorithm itself, the input fluxes for the best-match image to the IRAS survey data in point-source models are known.

In some cases, higher-resolution observations may be available at a different wavelength, which can be used to estimate placement of input spikes. Our high-resolution (14 arcsec at 850 μm; 7 arcsec at 450 μm) SCUBA observations have given us prior knowledge of sources that are embedded in dense cores in the Mon OB1 dark cloud. We have used this prior knowledge to model the HIRES-processed IRAS emission from these sources. The default pixel size of 15 arcsec was used. Absolute calibration uncertainty for HIRES-derived fluxes is estimated to be 20% (Levine & Surace 1993).

2.4 NRAO 12-m OTF Mapping

We acquired CO J=2→1 maps of outflows NGC 2264 O & NGC 2264 H (associated with MLY89 sources IRAS 25, & IRAS 27) using the spectral-line On-The-Fly (OTF) mapping mode of the NRAO’s 12-m telescope in March 1996, and of NGC 2264 D (associated with MLY89 source IRAS 12) in May 1999. The OTF technique allows the acquisition of large-area, high-sensitivity, spectral line maps with unprecedented speed and pointing accuracy.

A dual-channel, single-sideband SIS receiver was used for all observations. For the March 1996 observations, the backend consisted of a 1536-channel hybrid spectrometer. The 1536 channels were divided among the two receiver polarization channels. A bandwidth of 600 MHz, yielding a spectral resolution of 781 kHz (1 km s⁻¹), was used for NGC 2264 O, and a bandwidth of 300 MHz, yielding a spectral resolution of 391 kHz (0.5 km s⁻¹), was used for NGC 2264 H. For the May 1999 observations of NGC 2264 D, the backend consisted of 500 kHz and 1 MHz resolution filter-banks, yielding velocity resolutions of 0.65 km s⁻¹ and 1.3 km s⁻¹, respectively. The filter-banks were used in parallel
mode, each of the two receiver polarization channels using 256 filterbank channels. The polarization channels were subsequently averaged together to improve signal-to-noise. Only the 500 kHz resolution data were used to produce the final map. We performed 5 map coverages for each outflow, attaining an RMS ~0.25–0.35 K for the added maps. We used the NRAO standard source Orion A (α1950 = 05h 32m 47.0s, δ1950 = +05° 24’ 18’’) to check absolute line temperatures.

The OTF data were reduced with the Astronomical Image Processing Software (AIPS), Version 15JUL95. AIPS tasks specific to OTF data are ‘OTFUV’, which converts a single 12-m OTF map (in UniPOPS SDD format) to UV (single-dish) format, and ‘SDGRD’, which selects random position single-dish data in AIPS UV format in a specified field of view about a specified position and projects the coordinates onto the specified coordinate system. The data are then convolved onto a grid. OTF data maps were first combined, then gridded into a data cube and baseline-subtracted. Channel maps as well as individual spectra were inspected to ensure good baseline removal and to check for scanning artifacts.

3 RESULTS

3.1 Background

3.1.1 IRAS 06382+0939 (IRAS 12)

IRAS 12 was classified as a Class I object by MLY89. Identified as IRAS 06382+0939 upon publication of the Point Source Catalogue, it is embedded in the northern part of a massive (1900–2500 M⊙) clump traced by CS J=2→1 emission (WWL95). J, H, K, & L’ maps of the IRAS source revealed two point sources (RNO–East & RNO–West) separated by 2.8 arcsec along a position angle of 265 degrees at the PSC position (Castelaz & Grasdalen 1988). The effective temperatures of RNO–East & RNO–West were found to be 3000 K and 10,000 K, respectively, with a combined luminosity of about 550 L⊙. The age of RNO–East was found to be less than 107 years old, and RNO–West was found to be a young high-mass star (Castelaz & Grasdalen 1988). This region was also previously observed in the far-infrared at 70 & 130 µm (Sargent et al. 1984) and from 40 to 160 µm (Cohen, Harvey, & Schwartz 1985). The latter reported a double peak, based on the higher-resolution (40–45 arcsec) capabilities of the Kuiper Airborne Observatory (KAO); their primary peak corresponds to the position of the IRAS PSC position, while their secondary peak lies more than 2 arcmin to the southeast, approximately at the peak of the CS J=2→1 and CS J=5→4 emission reported by WWL95.

M88S8 associated IRAS 12 with a large (~12 arcmin in extent), massive (16–30 M⊙), bipolar, CO outflow (NGC 2264 D), oriented with its major axis along a NE–SW direction, that has a dynamical time-scale of ~6.9 × 106 yr. High-velocity wings associated with the outflow were also observed in CS J=2→1 spectra (WW95). The outflow centroid is displaced ~2 arcmin from the IRAS PSC position. A weak (~0.6 mJy) VLA 6 cm source; a strong H2O maser; and four near-infrared sources all lie within the boundaries of the outflow, distributed in a band approximately perpendicular to the outflow axis. One of the near-infrared sources (IRS A) was identified as the probable driving source of the outflow, based on its location closest to the outflow centroid of all the near-infrared sources (Mendoza et al. 1990).

3.1.2 IRAS 06382+1017 (IRAS 25)

IRAS 25 was classified as a Class I object by MLY89. Identified as IRAS 06382+1017 upon publication of the Point Source Catalogue, it lies at the southern end of an extended, massive (500–700 M⊙) clump traced by CS J=2→1 emission (WWL95). It has been associated with a compact CO outflow, NGC 2264 O (WWL95; WW95); a giant Herbig–Haro flow, HH124, and its bow-shock pairs, HH124–E & HH124–W; an infrared reflection nebula; and a near-infrared source (Walsh, Ogura, & Reipurth 1992; Moneti & Reipurth 1995; Ogura 1995; Piché, Howard, & Pipher 1995). The near-infrared source is a barely resolved binary, with the secondary component located ~1.75 arcsec (~1400 AU) from the primary at a P.A. ≈155 degrees. The Herbig–Haro objects lie along a P.A. ≈105 degrees, while the infrared reflection nebula lies along a P.A. ≈45 degrees. Piché et al. (1995) suggested that the infrared reflection nebula might be due to the lobes of a second outflow cavity extending toward the north-east, or, alternatively, reflection off a circumstellar torus whose polar axis is roughly parallel to the axis of the Herbig–Haro flow. Rodriguez & Reipurth (1998) reported two VLA sources within the error ellipse for IRAS 06382+1017 (VLA1: α(1950) = 06h 38m 17.01s, δ(1950) = +10° 17’ 56.2’’; VLA2: α(1950) = 06h 38m 17.91s, δ(1950) = +10° 17’ 58.3’’). VLA 1 is approximately coincident with the position of the near-infrared source and reflection nebula.

3.1.3 IRAS 06381+1039 (IRAS 27)

IRAS 27 was classified as a Class I object by MLY89. Identified as IRAS 06381+1039 upon publication of the Point Source Catalogue, it lies near the northern end of a massive (500–700 M⊙) clump traced by CS J=2→1 emission (WWL95). MLS88 associated this source with an outflow that they identified as having a shorter axis along the direction of the outflow than perpendicular to the direction of the outflow (NGC 2264 H). The IRAS source is offset about 45 arcsec west of the apparent outflow centre. A striking asymmetry is seen in the velocity extents of the blue- and redshifted gas; the redshifted gas is evident from 10–30 km s−1, while the blueshifted gas was seen only from 0–3 km s−1. The mass of this outflow was computed to be Mflow = 1.6–2.3 M⊙; and its dynamical time-scale, τd = 1.2 × 105 yr, makes it the second youngest of the nine outflows mapped by MLS88. High-velocity wings associated with the outflow were also observed in CS J=2→1 spectra (WW95).

3.2 SCUBA images

In this section, we present our 450 & 850 µm SCUBA maps of the IRAS sources. Table 1 lists 450 & 850 µm fluxes for all the submillimetre sources that were identified in the three regions, the 1.3 mm fluxes that were obtained for a few sources at the former NRAO 12-m telescope on Kitt Peak, and the errors associated with the fluxes.
Table 1. Mon OB1 SCUBA & Millimetre Source Fluxes

| Source  | $\alpha$(2000) | $\delta$(2000) | 450 $\mu$m | 850 $\mu$m | 1300 $\mu$m |
|---------|---------------|---------------|------------|------------|-------------|
| RNO 06$^h$41$^m$02.8$^s$ | 09°36′10″ | <29.6 | <1.86 | ... |
| 12 S1 06$^h$41$^m$05.8$^s$ | 09°34′09″ | 47.9±0.51 | 5.38±0.019 | 1.4±0.49 |
| 12 S2 06$^h$41$^m$06.2$^s$ | 09°35′57″ | 57.0±0.51 | 5.35±0.019 | ... |
| 12 S3 06$^h$41$^m$04.1$^s$ | 09°35′01″ | 47.9±0.51 | 4.94±0.019 | ... |
| 12 S4 06$^h$41$^m$00.9$^s$ | 09°35′28″ | 42.1±0.51 | 4.15±0.019 | ... |
| 12 S5 06$^h$40$^m$49.3$^s$ | 09°34′36″ | 16.20±0.51 | 2.171±0.019 | ... |
| 12 S6 06$^h$40$^m$57.8$^s$ | 09°36′25″ | 32.34±0.51 | 2.986±0.019 | ... |
| 12 S7 06$^h$41$^m$11.6$^s$ | 09°35′34″ | 26.40±0.51 | 2.652±0.019 | ... |
| 12 S8 06$^h$41$^m$09.2$^s$ | 09°33′01″ | 9.04±0.51 | 1.447±0.019 | ... |
| 25 NIR 06$^h$40$^m$28.6$^s$ | 10°15′02″ | <2.2 | <0.056 | ... |
| 25 S1 06$^h$41$^m$03.5$^s$ | 10°15′10″ | 7.1±2.3 | 2.92±0.024 | ... |
| 25 S2 06$^h$41$^m$04.9$^s$ | 10°14′55″ | 14.8±2.3 | 3.33±0.024 | ... |
| 27 S1 06$^h$40$^m$58.5$^s$ | 10°36′54″ | 31.8±1.6 | 3.20±0.018 | 0.8±0.28 |
| 27 S2 06$^h$40$^m$59.1$^s$ | 10°36′09″ | 12.1±1.6 | 1.87±0.018 | 0.7±0.25 |
| 27 S3 06$^h$42$^m$02.0$^s$ | 10°35′30″ | 12.9±1.6 | 1.72±0.018 | ... |
| 27 S4 06$^h$40$^m$54.4$^s$ | 10°33′27″ | 7.4±1.6 | 0.65±0.018 | ... |

The 450 & 850 $\mu$m fluxes are integrated over a 45 arcsec aperture. The 1300 $\mu$m fluxes represent fluxes within a 27 arcsec beam. The 450 & 850 $\mu$m fluxes for RNO and 25 NIR are given as upper limits, since these sources have no corresponding submillimetre peaks.

3.2.1 IRAS 06382+0939 (IRAS 12)

Figure 1a shows the 850 $\mu$m emission associated with IRAS 12. Near-infrared sources (stars), the VLA source (triangle), the position of a H$_2$O maser (box) identified by Mendoza et al. (1990), and the IRAS point source error ellipse, are indicated. We detected eight compact submillimetre sources (crosses) in the mapped region, which we designate as “12 S#” in this paper. Recently, lower-resolution 870 $\mu$m observations of this region resulted in the detection of seven compact sources (Williams & Garland 2002). The map shows extended as well as compact emission, but there is clearly little emission at the position of the IRAS source, corresponding to the RNO binary. The source 12 S1 is coincident with the other far-infrared peak reported by Cohen et al. (1985). It is also approximately coincident with the peaks of the CS J=2→1 and CS J=5→4 emission reported by WWL95. The overall morphology of the extended 850 $\mu$m emission is very similar to the morphology of the CS J=5→4 emission mapped by WWL95 (see fig. 5b WWL95). Notably, WWL95 detected no CS J=5→4 emission at the position of the IRAS point source. Figure 1b shows the 450 $\mu$m emission associated with IRAS 12. Although significantly noisier than the 850 $\mu$m data, all of the submillimetre sources present in the 850 $\mu$m map are identifiable at 450 $\mu$m as well. The close association of the submillimetre and CS J=5→4 emission, which traces dense gas of ~ 10$^6$ cm$^{-3}$ (WWL95), and the fact that none of the submillimetre peaks coincides with any of the near-infrared sources identified by Mendoza et al. (1990), suggests that the submillimetre sources are very young objects, most likely Class 0 sources and/or prestellar cores. Similar anti-correlations between infrared and millimetre peaks are seen in other star-forming regions (e.g., Casali, Eiroa, & Duncan 1993; Hurt & Barsony 1996), and have been interpreted as reflecting different phases of star formation.

3.2.2 IRAS 06382+1017 (IRAS 25)

Figure 2a shows 850 $\mu$m emission associated with IRAS 25. The position of the IRAS source error ellipse, near-infrared source (star), Herbig–Haro knots HH 124 A–F (xs), and two VLA sources (triangles) are indicated. Although the emission is extended, at least two compact peaks can be identified (crosses). These peaks are also apparent in the 450 $\mu$m emission shown in Figure 2b. The brighter peak (25 S1) coincides approximately with VLA 2, which lies ≈15 arcsec to the east of VLA 1 (approximately twice the 7 arcsec resolution of our 450 $\mu$m SCUBA data). Unlike VLA 1, VLA 2 has no point-source near-infrared counterpart. It lies in a concavity seen at the north-east end of the infrared reflection nebulosity reported by Piché et al. (1995). The slightly fainter SCUBA peak to the south-east of 25 S1 (25 S2) is not associated with any known near-infrared or radio continuum source.

3.2.3 IRAS 06381+1039 (IRAS 27)

Figure 3a shows the 850 $\mu$m emission associated with IRAS 27. The position of the IRAS source error ellipse is indicated. We detected four compact submillimetre sources in the mapped region (crosses). Three of these sources lie along a filament of extended emission, similar to those seen in many other submillimetre maps of star-forming regions (e.g., Mitchell et al. 2001). Figure 3b shows the 450 $\mu$m emission associated with IRAS 27. Although the image is very noisy, we were able to obtain fluxes for all four compact sources.

3.3 HIRES maps & models

In this section, we demonstrate that IRAS fluxes tend to probe the overall properties of clumps – protostellar groups – rather than the properties of individual protostellar cores. We show that HIRES point-source models based on the source fluxes and positions given in the IRAS Point Source
Catalogue are completely inadequate to model the actual emission. Using our SCUBA data to help guide placement and fluxes of input spikes, we construct far more accurate models of the far-infrared emission. Spike positions and fluxes are adjusted until the models most closely match the data in morphology and flux. Figures 4–6 present HIRES maps for the three regions in the following manner: the first row of each figure shows the FRESCO (full-resolution CO-add) equivalent to a single iteration of HIRES) map for each waveband; the second shows HIRES results achieved after 40 iterations for the 12 & 25 \( \mu \)m wavebands, and after 200 iterations for the 60 & 100 \( \mu \)m wavebands; the third row shows point-source models of the HIRES-processed emission using single spikes corresponding to the position and fluxes given in the IRAS Point Source Catalogue; and the fourth row shows the final models of the HIRES-processed emission using multiple spikes. No 12 \( \mu \)m maps are shown for IRAS 27, which was marginally detected at the PSC position. The most striking differences between the HIRES PSC and multiple spike models are seen for IRAS 12, where objects contained within the IRAS source are spread over a larger region than objects contained within the other IRAS sources (figure 4).

Table 2 lists the final positions and magnitudes of HIRES model input spikes that were used for the relevant wavebands, and the resolutions achieved at these positions. The associated errors are computed from the \(~20\%\) error inherent in HIRES (Levine & Surace 1993) in combination with the error associated with the point-source models, which we estimate to be <8\%. This is the maximum amount that the input fluxes can vary without causing significant changes in the resulting models. We note that in all of the modelled regions it was necessary to add additional spikes in at least one of the wavebands that are not coincident with any known sources in order to closely simulate the observed emission. We interpret this as being due to the presence of extended dust emission in these regions, as is clearly seen in the SCUBA maps. We emphasize that the HIRES-derived source fluxes should therefore be interpreted as upper limits to the actual source fluxes. Additionally, many of the submillimetre sources were only weakly detected at 12 & 25 \( \mu \)m. HIRES processing is, in general, unreliable for unresolved sources significantly fainter than 1 Jy (IPAC User’s Guide, ed. 5).

The most accurate set of HIRES fluxes was derived for 12 S1 due to the brightness of this object and its relative isolation from other nearby objects. It was possible to model the HIRES-processed emission extremely closely with a single spike located at the submillimetre source position. We present the SED and derived properties for this object in §3.5. We note here that the Two Micron All Sky Survey (2MASS) Point Source Catalogue (PSC) has been released since completion of this work. Six of the submillimetre sources presented in this paper have one or more faint near-infrared counterparts. We will present SEDs and a more detailed analysis of these sources in a subsequent paper.

3.3.1 IRAS 06382+0939 (IRAS 12)

Figure 4 presents HIRES maps and models of the four IRAS wavebands for IRAS 12. Very little structure is present in all of the FRESCO maps (Figs. 4a–d); however, the HIRES-processed maps (Figs. 4e–h) clearly indicate that not all of the emission comes from IRAS 06382+0939: the 12 \( \mu \)m map shows a clear extension toward 12 S6; the 25 & 60 \( \mu \)m maps show additional extensions toward 12 S7 and separate peaks at 12 S1; and the 100 \( \mu \)m map shows a pronounced extension toward 12 S1. Comparing these maps to models based on Point Source Catalogue positions and fluxes (Figs. 4i–l) illustrates the inadequacy of these models to reproduce the actual emission. For the models shown in Figs. 4m–p, spikes were used at the submillimetre source positions; the IRAS point source position; and various other positions that either correspond to other known sources, or simply help simulate extended emission.

3.3.2 IRAS 06382+1017 (IRAS 25)

Figure 5 presents HIRES maps and models of the four IRAS wavebands for IRAS 25. Once again, very little structure is seen in the FRESCO maps (Figs. 5a–d), except for a pronounced shift to the northeast in the peak of the 100 \( \mu \)m emission. The HIRES-processed IRAS emission (Figs. 5e–h) is well-peaked on the IRAS source at 25 & 60 \( \mu \)m, but the 100 \( \mu \)m emission clearly shows the peak to be closer to the centre of 25 S1 & 25 S2. Models based on Point Source Catalogue positions and fluxes (Figs. 5i–l) fail to reproduce the actual emission, particularly at 100 \( \mu \)m. Figs. 5m–p are HIRES models using spikes at the submillimetre sources positions and the near-infrared source position (coincident with the IRAS point source). An additional spike at no known source position was required to more accurately model the 12 & 60 \( \mu \)m emission.

3.3.3 IRAS 06381+1039 (IRAS 27)

Figure 6 presents HIRES maps and models of the 25, 60, & 100 \( \mu \)m wavebands for IRAS 27. Since 27 S1 was marginally detected at 12 \( \mu \)m and the other sources are non-detections,
Figure 3. Contoured greyscale images (Jy/beam) of IRAS 27 at (a), 850 \textmu m: contours incremented in 0.32 Jy/beam intervals beginning with 0.32 Jy/beam; and (b), 450 \textmu m: contours incremented in 1.2 Jy/beam intervals beginning with 1.2 Jy/beam. Submillimetre sources are marked with crosses and the IRAS source error ellipse is indicated.

Table 2. HIRES Model Spike Positions & Fluxes

| Source       | \( \alpha (2000) \) | \( \delta (2000) \) | Spike Height (Jy) at \( \lambda \) | Effective Beam Size (MA.\(^{\prime\prime} \times \text{Min}^{\prime\prime}) \) |
|--------------|---------------------|---------------------|-----------------------------------|---------------------------------|
|              | 12 \textmu m        | 25 \textmu m        | 60 \textmu m                     | 100 \textmu m                   |
|              | 12 \textmu m        | 25 \textmu m        | 60 \textmu m                     | 100 \textmu m                   |
| RNO          | 06\(^{h}\)41\(^{m}\)02\(^{s}\)  | 09\(^{h}\)36\(^{m}\)10\(^{s}\)  | 5.5±1.2                          | 5.5±1.2                         |
|              | 06\(^{h}\)41\(^{m}\)01.7\(^{s}\)  | 09\(^{h}\)36\(^{m}\)16\(^{s}\)  | 5.5±1.2                          | 5.5±1.2                         |
| 12 S1        | <0.10               | 0.90±0.19           | 22±5                             | 134±29                         |
| 12 S2        | 0.30±0.06           | 1.10±0.02           | 27±6                             | 19+16                          |
| 12 S3        | <0.10               | <0.10               | 1.0±0.2                          | 1.0±0.2                         |
| 12 S4        | 0.50±0.11           | 0.10±0.02           | 28±6                             | 161±35                         |
| 12 S5        | <0.10               | 0.10±0.02           | 1.0±0.2                          | 0.50±0.11                       |
| 12 S6        | 0.70±0.15           | 0.60±0.13           | 16±3                             | 10±2                            |
| 12 S7        | 0.15±0.03           | 1.3±0.03            | 17±4                             | 33±7                            |
| 12 S8        | <0.10               | 0.10±0.02           | 1.5±0.3                          | 0.40±0.09                       |
| VLA          | 0.16±3              | 25±5                |                                  |                                 |
| IRS A        | 1.5±0.3             |                    |                                  | 78±64                           |
| IRS F        | 0.70±0.15           |                    |                                  | 50±43                           |
| 25 NIR       | 0.52±0.11           | 5.2±1.1             | 18±4                             | 14±3                            |
| 25 S1        | 0.17±0.04           | 1.9±0.4             | 9.5±2.0                          | 22±5                            |
| 25 S2        | 0.30±0.06           | 1.1±0.2             | 8.5±1.8                          | 28±6                            |
| 25 S3        | 0.29±0.06           | 8.0±1.7             | 50±37                            | 32±27                           |
| 25 S4        | 0.25±0.05           | 2.5±0.5             | 35±8                             | 73±16                           |
| 25 S5        | 0.18±4              |                    |                                  | 56±42                           |
| 25 S6        | <0.10               | <0.10               | 7.0±1.5                          | 13±3                            |
| 25 S7        | 0.10±0.02           | 1.2±0.3             | 10±0.2                           | 0.72±0.3                        |
| 25 S8        | 0.10±0.02           | 1.2±0.3             | 0.33±0.07                        | 60±43                           |
| 25 S9        | 0.12±0.3             |                    |                                  | 52±40                           |

Figure 4. IRAS 12 HIRES-processed emission after 1 iteration at (a) 12 \textmu m (contour levels are 5, 10, 15, & 20 M Jy/ster), (b) 25 \textmu m (contour levels are 10, 20, 30, & 40 M Jy/ster), (c) 60 \textmu m (contour levels are 50, 100, 150, 200, 250, & 300 M Jy/ster), (d) 100 \textmu m (contour levels are 100, 200, 300, & 400 M Jy/ster); after 40 iterations at (e) 12 \textmu m (contour levels are 20, 50, & 100 M Jy/ster) and (f) 25 \textmu m (contour levels are 20, 50, 100, & 200 M Jy/ster); and after 200 iterations at (g) 60 \textmu m (contour levels are 200, 600, 1.1×10\(^3\), 1.4×10\(^3\), 1.8×10\(^3\), & 2.2×10\(^3\) M Jy/ster) and (h) 100 \textmu m (contour levels are 400, 800, 1.2×10\(^3\), 1.6×10\(^3\), 2.0×10\(^3\), 2.4×10\(^3\), & 2.8×10\(^3\) M Jy/ster). HIRES-processed models using PSC positions and fluxes after 40 iterations at (i) 12 \textmu m (contour levels same as (e)); and (j) 25 \textmu m (contour levels same as (f)); and after 200 iterations at (k) 60 \textmu m (contour levels same as (g)); and (l) 100 \textmu m (contour levels same as (h)). Multi-spike HIRES-processed models after 40 iterations at (m) 12 \textmu m (contour levels same as (e)) and (n) 25 \textmu m (contour levels same as (f)); and after 200 iterations at (o) 60 \textmu m (contour levels same as (g)); and (p) 100 \textmu m (contour levels same as (h)). Source symbols are as follows: IRAS source position (ellipse); near-infrared sources (stars); submillimetre sources (large crosses); VLA source (triangle); and H\(_2\)O maser (box). Small crosses mark the position of spikes not corresponding to any known sources that were used to more accurately simulate the emission.

Figure 5. IRAS 25 HIRES-processed emission after 1 iteration at (a) 12 \textmu m (contour levels are 2, 2.5, 3, & 3.5 M Jy/ster), (b) 25 \textmu m (contour levels are 5, 10, & 15 M Jy/ster); (c) 60 \textmu m (contour levels are 10, 20, 30, 40, & 50 M Jy/ster), (d) 100 \textmu m (contour levels are 10, 15, & 20 M Jy/ster); after 40 iterations at (e) 12 \textmu m (contour levels are 5, 10, 15 & 20 M Jy/ster) and (f) 25 \textmu m (contour levels are 20, 100, & 200 M Jy/ster); and after 200 iterations at (g) 60 \textmu m (contour levels are 100, 300, 500, & 700 M Jy/ster) and (h) 100 \textmu m (contour levels are 100, 300, & 500 M Jy/ster). HIRES-processed models using PSC positions and fluxes after 40 iterations at (i) 12 \textmu m (contour levels same as (e)); and (j) 25 \textmu m (contour levels same as (f)); and after 200 iterations at (k) 60 \textmu m (contour levels same as (g)); and (l) 100 \textmu m (contour levels same as (h)). Multi-spike HIRES-processed models after 40 iterations at (m) 12 \textmu m (contour levels same as (e)) and (n) 25 \textmu m (contour levels same as (f)); and after 200 iterations at (o) 60 \textmu m (contour levels same as (g)); and (p) 100 \textmu m (contour levels same as (h)). Source symbols are as follows: IRAS source position (ellipse); near-infrared source (star); submillimetre sources (large crosses); VLA sources (triangles); and Herbig–Haro Objects (xs). The small cross in the 12 & 60 \textmu m maps marks the position of a spike not corresponding to any known source that was used to more accurately simulate the emission.
we do not include these maps. There is little structure in the FRESCO maps (Figs. 6a–c). While the HIRES-processed emission is peaked at the IRAS source position in all wavebands (Fig. 6d–f), the 60 μm map shows a clear extension along the arc formed by 27 S1, 27 S2, & 27 S3, and a separate, albeit weak, peak appears close to the position of 27 S4. The Point Source Catalogue models (Figs. 6g–i) do not adequately reproduce this emission. More accurate models (Figs. 6j–l) use spikes at the positions of the submillimetre sources, as well as multiple spikes in the immediate vicinity of 27 S1, and an additional spike along the extended ridge of 60 μm emission.

3.4 CO Outflow Maps

In this section, we present CO J=2→1 maps of outflows associated with the regions containing IRAS 12, IRAS 25, & IRAS 27. A single outflow has been previously associated with each IRAS source (NGC 2264 D, NGC 2264 O, & NGC 2264 H), based on CO J=1→0 and CS J=2→1 maps at half the resolution of the maps we present here (MLS88; WW95). Our maps indicate far more complex outflow morphology, and suggest there are multiple outflows in each region.

3.4.1 IRAS 06382+0939 (IRAS 12)

Figure 7 shows blueshifted and redshifted high-velocity CO J=2→1 emission associated with outflow NGC 2264 D (contours) superposed on the SCUBA 850 μm image (greyscale). Submillimetre sources (crosses); H2O maser (square); VLA source (triangle); near infrared sources (stars); and the IRAS error ellipse are indicated. It is clear that the IRAS point source, associated with the RNO binary, is not associated with the high-velocity CO emission. Unfortunately, we can not unambiguously discern whether the submillimetre source, 12 S1, or the near-infrared source (IRS A) identified by Mendoza et al. (1990), is the principal contributor to the outflow(s). The major portions of the blue- and redshifted lobes appear to lie at different position angles. The blue lobe does not show a well-defined position angle. The major component of the blueshifted emission extends almost due north from the near-infrared source IRS F (Mendoza et al. 1990); to the northeast of this component lies a finger of emission that points back toward 12 S1, along a P.A.=33 degrees. The major component of the redshifted emission lies roughly along P.A.=80 degrees, although a small finger of redshifted emission extends just southwest of 12 S1 along a position angle similar to the finger of blueshifted emission. Clearly, more sensitive and higher-resolution observations are needed to sort out possible contributions from the various sources in this region, but there is no apparent CO outflow associated with the IRAS point source.

3.4.2 IRAS 06382+1017 (IRAS 25)

Figure 8 shows blueshifted and redshifted CO J=2→1 emission associated with outflow NGC 2264 O (contours) superposed on the SCUBA 850 μm image (greyyscale). Submillimetre sources (crosses), VLA sources (triangles), near-infrared source (star), HH 124 A–F (xs), and the IRAS source error ellipse are indicated. Piché et al. (1995) suggested the possibility of two outflows in this region: one associated with HH 124, lying nearly E–W, and another associated with a wider-angle reflection nebula along a P.A.=45 degrees. Our observations indicate three peaks in the high-velocity CO emission: one peak in the redshifted emission and two peaks in the blueshifted emission. The western blueshifted lobe may be associated with VLA 1 (coincident with the IRAS source) and the E–W Herbig–Haro flow, or it may be associated with 25 S1 and the redshifted lobe to the north of 25 S1. The southeastern blue lobe is probably not associated with the Herbig–Haro flow, since the eastern HH knot E is redshifted, while western knots A–D are strongly blueshifted (Walsh et al. 1992). It may be associated with 25 S2. In any case, the eastern blue lobe does not appear to be related to either of the previously-reported outflows, which suggests there are at least three outflows in the region. Given the compactness of the outflows, it is not possible to unambiguously associate outflows with sources at our resolution.

3.4.3 IRAS 06381+1039 (IRAS 27)

Figure 9 shows blueshifted and redshifted CO J=2→1 emission associated with outflow NGC 2264 H (contours) superposed on the SCUBA 850 μm image (greyscale). Submillimetre sources (crosses) and the IRAS error ellipse are indicated. The high velocity gas has a very complex morphology, but our map helps to elucidate the “squat” appearance of this outflow in the MLS88 CO J=1→0 map, where the “major” axis of the outflow was reported to be shorter than the axis perpendicular to the outflow. MLS88 identified this as a single outflow oriented in a north-south direction, but our map indicates that the double-lobed redshifted emission lies east of 27 S1, along P.A.=113 degrees, and is probably as-
associated with this source (which is also coincident with the IRAS source). The small blue lobe directly to the northwest of 27 S1 is probably part of this outflow, although the morphology, as well as the velocity structure, of the blue- and redshifted gas are very different.

The origin of the blueshifted gas to the northeast of 27 S1 is unclear, but may be elucidated in Figure 10, which shows blueshifted emission integrated from 0.0 to 1.5 km s\(^{-1}\) just outside of the line core emission, and redshifted emission integrated from 8.5 to 10.0 km s\(^{-1}\) just inside the line core, and hence contaminated by ambient emission. Nevertheless, the extended redshifted gas to the southwest and the blueshifted gas to the northeast are roughly bipolar about 27 S2 at a P.A.\(\approx\)35 degrees, suggesting this source may power an outflow along this direction. The “finger” of blueshifted emission extending northeast from 27 S2 lends support to this interpretation. The blueshifted gas directly northeast of 27 S3 may be associated with this source, but the emission is fairly weak and there is no strong evidence for redshifted gas on the opposite side of 27 S3. In any case, the apparent reason for the “squat” appearance of NGC 2264 H in the lower-resolution CO J=1\rightarrow1 maps (MLS88) is the presence of at least two overlapping outflows in this region. It is interesting to note that the outflows are approximately perpendicular to the curved ridge of submillimetre emission that connects 27 S1, 27 S2, and 27 S3.

3.5 IRAS 12 S1: An Intermediate-Mass Class 0 Object

As discussed in §3.3, IRAS 12 S1 is the only source that could closely be modelled with a single spike in all IRAS wavebands, with good spatial separation from other sources. With the combined HIRES, SCUBA, and millimetre fluxes, it is possible to plot a SED with several reliable flux points on both the Wien and Rayleigh-Jeans sides of the peak to help constrain physical parameters of this object. Figure 11 displays this SED, along with a single-temperature, modified blackbody fit of the form:

\[
S_\nu = B_\nu(T_d)(1 - e^{-\nu\tau})\ d\Omega
\]  

The best fit was derived using a \(\nu^{1.4}\) wavelength dependence of the dust optical depth. The best-fit source diameter, \(d\Omega\), dust temperature, \(T_d\), and 250 \(\mu\)m optical depth are listed in Table 3. The source properties that can be derived from the model fit, such as the source bolometric luminosity, \(L_{bol}\), and the circumstellar mass, \(M_{circ}\), are also listed in Table 3, and were derived in a manner analogous to that described in Barsony et al. (1998) for other Class 0 sources. The tabulated bolometric luminosity was derived by numerical integration under the fitted curve plotted in Fig. 11.

Class 0 objects have ratios of \(L_{submm}/L_{bol}\gtrsim 5 \times 10^{-3}\), where \(L_{submm}\) is the luminosity radiated longward of 350 \(\mu\)m (Andr´e, Ward-Thompson, & Barsony 1993). The derived ratio of \(L_{submm}/L_{bol}\approx 0.03\) for IRAS 12 S1 places this object well within the Class 0 category. Additionally, if IRAS 12 S1 is the main contributor to outflow NGC 2264 D, then its outflow momentum flux (1.3\(\times\)10\(^{-3}\) M\(_{\odot}\) km s\(^{-1}\) yr\(^{-1}\)) \(<\) F\(_{CO}\) \(<\) 7.5\(\times\)10\(^{-3}\) : MLS88) is roughly an order of magnitude greater than expected for a Class 1 object of comparable bolometric luminosity, which is typical for Class 0 objects (see, for e.g., fig. 5 in Bontemps et al. 1996). The computed parameters suggest that IRAS 12 S1 comprises one or more intermediate-mass protostars.

As stated in §3.3, the recently-released 2MASS PSC indicates that six of the submillimetre sources discussed in this paper have near-infrared counterparts. IRAS 12 S1 has three faint near-infrared counterparts that lie within a 7 arcsec radius of the SCUBA position. Although lack of detection in the near-infrared has generally been used as a criterion for Class 0 status, we note that 8 of the 42 confirmed Class 0 objects listed in Table 1 of Andr´e, Ward-Thompson, & Barsony (2000) can also be associated with 2MASS point sources that lie within 7 arcsec of these objects: W3OH-TW, L1448-N(A), L1641-VLA1, HH24MMS, IRAS 08076, L483-MM, G34.24+0.13MM, & S106-SMM. W3OH-TW & G34.24+0.13MM are candidate massive Class 0 objects, and L1641-VLA1, IRAS 08076, & L483-MM are listed as borderline Class 0 objects (Andr´e et al. 2000). L1448-N(A) has
Figure 11. SED of IRAS 12 S1: Plotted fluxes are presented in Tables 1 & 2. Parameters of the plotted fit are presented in Table 3.

Table 3. IRAS 12 S1 Source Properties

| Parameter | Symbol & Units | Value |
|-----------|----------------|-------|
| IRAS 12 S1 α(2000) | D(pc) | 06°41′m05.8s |
| IRAS 12 S1 δ(2000) | D(pc) | 09°34′99″ |
| Adopted Distance | D(pc) | 800 |
| Fit temperature | T_d (K) | 23 |
| Fit optical depth | τ_250μm | 0.04 |
| Fit source diameter | d(′)(arcsec) | 28 |
| Bolometric luminosity | L_{bol} (L_⊙) | 107.5 |
| | L_{submm}/L_{bol} | 0.03 |
| Circumstellar envelope mass | M_{env} (M_⊙) | 17.6 |

The adopted distance, originally estimated by Walker (1956), is the same distance adopted for the surveys of Margulis, Lada, & Snell (1988) and Margulis, Lada, & Young (1989), which are discussed in the text.

recently been suggested to be a borderline Class 0 object by O’Linger et al. (2003), who argue that lack of detection shortward of 10 \( \mu m \) should be discarded as a criterion for Class 0 status, since this characteristic reflects current technology rather than intrinsic source properties.

4 DISCUSSION

It is important to ascertain which sources within clumps drive molecular outflows and/or jets in order to investigate similarities and differences between low- and high-mass YSOs that are associated with these phenomena, and to accurately correlate sources and outflow parameters. Our new observations and modelling indicate that previously categorized “Class I objects” in the Mon OB1 dark cloud are, in fact, associated with protoclusters containing multiple sources at different evolutionary stages. In two cases, the object identified as the “IRAS point source” is undetected at submillimetre wavelengths, but lies near multiple submillimetre sources. In both cases, the submillimetre sources contribute significantly to the IRAS fluxes at 60 & 100 \( \mu m \), but the IRAS source dominates at shorter wavelengths.

Correlations between outflow force or momentum deposition rate, \( F_{CO} \), and source luminosity, \( L_{bol} \), have been noted over many decades of luminosity since the earliest surveys for outflows (e.g., Bally & Lada 1983; Panagia 1991; Cabrit & Bertout 1992). Many of these correlations were established by making extensive use of the IRAS database to help establish source luminosities. Furthermore, the \( F_{CO}/L_{bol} \) ratio has been used to estimate the fraction of the accretion flow that is ejected in the wind, in order to help distinguish between different models of the wind ejection mechanism (e.g., Richer et al. 2000). Our results suggest that many of the noted source-outflow correlations may reflect the sum total of source and outflow properties from a protocluster or protogroup rather than the properties of individual sources within the cluster. Hence, the relationship between outflow momentum and source bolometric luminosity at high source luminosities is particularly called into question.

To investigate the effect of our results on the previously-calculated IRAS luminosities for the sources in this study, we note that MLY89 calculated IRAS’ luminosities for the Mon OB1 sources IRAS 12, IRAS 25, & IRAS 27 to be 330 \( L_⊙ \), 110 \( L_⊙ \), & 87 \( L_⊙ \), respectively. Applying MLY89’s equation (1) to the IRAS upper limits we derived for the “point sources”, we find the luminosities for IRAS 12 (RNO), IRAS 25 (NIR), and IRAS 27 (27 S1) to be 150 \( L_⊙ \), 28 \( L_⊙ \), & 74 \( L_⊙ \), respectively. For the first two cases the recalculated luminosities are significantly lower than the original calculations. Calculated in this manner, the IRAS luminosity of the source that we identify as a likely contributor to NGC 2264 D, 12 S1, is only \~48 \( L_⊙ \); however, the bulk of the luminosity from this source is emitted at longer wavelengths and our calculated bolometric luminosity is 107.5 \( L_⊙ \).

Our results indicate that extreme care must be taken when using outflow momentum deposition rates and source luminosities in order to infer the relationship between accretion rates and outflow. Outflow momentum deposition rates cannot be unequivocally correlated with source luminosities in many of the clustered regions for which these luminosities were derived from IRAS fluxes. The similar resolving ability of the Stratospheric Observatory for Infrared Astronomy (SOFIA) at infrared wavelengths to the JCMT’s SCUBA at submillimetre wavelengths, combined with higher-resolution outflow observations, should enable a critical assessment of the properties of outflows and driving sources in many clustered regions.

5 SUMMARY

(i) We have used HIRES-processing and modelling of IRAS data, along with SCUBA imaging, to identify individual cores embedded in massive CS clumps in the Mon OB1 dark cloud, and estimate their contributions to the IRAS fluxes.

(ii) Each CS clump had been previously associated with a single IRAS point source. The associated YSO was, in each case, linked with a single molecular outflow and had been assigned a Class I type SED.

(iii) In two of the three clumps studied, none of the bright submillimetre sources is coincident with the identified IRAS “point source”.

(iv) In all three CS clumps, an associated IRAS point source dominates the 12 & 25 \( \mu m \) emission; however, new objects identified through their submillimetre continuum emission and distinct from the 12 & 25 \( \mu m \) IRAS point sources, are major contributors to the observed, extended 60 & 100 \( \mu m \) IRAS emission. These results suggest that the previously-classified “Class I” objects actually consist of multiple sources at different evolutionary stages.

(v) We were able to closely model the object IRAS 12 S1 using a single spike in all IRAS wavebands, with good spatial separation from other sources. Using the combined HIRES, SCUBA, and millimetre fluxes to plot an SED with several reliable flux points on both the Wien and Rayleigh-Jeans sides of the peak, we have calculated the dust temperature, bolometric luminosity, and circumstellar mass of this source. The SED and physical parameters of this source, to-
together with its likely status as the principal driving source of outflow NGC 2264 D, suggest that IRAS 12 S1 is a Class 0 Object harboring one or more intermediate-mass protostars.

(vi) While it is not possible to derive individual SEDs for all of the embedded objects due to the presence of extended emission and source confusion, we can at least place good upper limits on the individual flux contributions and thus compare the new IRAS “point source” luminosities to luminosities that were previously derived using IRAS Point Source Catalogue fluxes. In the two cases where the IRAS point source is not coincident with a submillimetre source, such a comparison indicates that the IRAS sources to be of significantly lower bolometric luminosity than previously estimated.

(vii) Our new CO J=2→1 outflow maps of the three regions we studied indicate complex outflow morphology suggestive of multiple driving sources. We find that the submillimetre source, 12 S1, contributes to driving the NGC 2264 D outflow; however, the previously assumed driving source for this flow, the source at the IRAS PSC position (RNO), cannot be associated with any high-velocity CO emission. There are hints of three separate outflows in the vicinity of IRAS 25: a giant Herbig–Haro flow, probably powered by the near-infrared source which lies at the IRAS PSC position, and two very compact CO outflows that may be associated with the submillimetre sources 25 S1 & 25 S2. In the IRAS 27 region, the strongest submillimetre source (27 S1), which is also coincident with the IRAS PSC position, apparently drives the redshifted gas associated with the outflow NGC 2264 H. The multi-lobed appearance of the blueshifted gas, and the morphology of the low-velocity redshifted gas, suggest the presence of two other outflows in this region: a bipolar outflow associated 27 S2, and blueshifted gas that may be associated with 27 S3.

(viii) Our results have implications for the method of using outflow momentum deposition rates and source bolometric luminosities in order to infer the fraction of the accretion flow that is ejected into the wind of protostars, and thus for using this method to distinguish between different proposed launching mechanisms. It is clear that in many cases outflow momentum deposition rates cannot be unequivocally correlated with source luminosities in many of the clustered regions for which luminosities were derived using IRAS fluxes.

(ix) Six of the submillimetre objects identified in this paper can be associated with faint objects identified from the recently-released Two Micron All Sky Survey Point Source Catalogue. A detailed analysis of the physical properties and evolutionary status of these sources will be presented in a subsequent paper.

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REFERENCES

Adams F.C., Lada C.J., Shu F.H., 1987, ApJ, 312, 788
Allen D.A., 1972, ApJ, 172, L55
André Ph., Ward-Thompson D., Barsony M., 1993, ApJ, 406, 122
André Ph., Ward-Thompson D., Barsony M., 2000, in “Protostars & Planets IV”, ed. V. Mannings, A.P. Boss, & S.S. Russell, 59
Archibald E.N. et al., 2002, MNRAS, 336, 1
Aumann H.H., Fowler J.W., Melnyk M., 1990, AJ, 99, 1674
Bally J., Lada C. J., 1983, ApJ, 265, 824
Barsony M., Ward-Thompson D., André P., O’Linger J., 1998, ApJ, 509, 733
Blitz L., 1978, PhD thesis, Columbia Univ.
Bontemps S., André P., Terebey S., Cabrit S., 1996, A&A, 311, 858
Cao Y., Prince T.A., Terebey S., Beichman C.A., 1996, PASP, 108, 535
Cao Y., Prince T.A., Terebey S., Beichman C.A., 1997, ApJS, 111, 387
Cabrit S., Bertout C., 1992, A&A, 261, 274
Casali M. M., Eiroa C., Duncan W. D., 1993, A&A, 275, 195
Castelaz M. W., Grasdalen G., 1988, ApJ, 335, 150
Cohen M., Harvey P. M., Schwartz R. D., 1985, ApJ, 296, 633
Feldbrugge P.T.M., van Genderen A.M., 1991, A&AS, 91, 209
Holland et al., 1999, MNRAS, 303, 659
Hurt R. L., Barsony M., 1996, ApJ, 460, L45
Jenness T., Economou F., 2001, www.jach.hawaii.edu/JACpublic/stardocs/sun231.htx/sun231.html
Jenness T., Holland W.S., Chapin E., Lightfoot J.F., Duncan W.D., 2000, in Manset N., Veillet C., Crabtree D., eds, ASP Conf. Ser. Vol. 216, ADASS IX. Astron. Soc. Pac., San Francisco, p. 559
Lada C.J. 1985, ARA&A, 23, 267
Levine D.M., Surace J., 1993, in IPAC User’s Guide, 5th ed., IPAC, Pasadena
Lorenzetti D., Giannini T., Vitali F., Massi F., Nisini B., 2002, ApJ, 564, 839
Lynds B.T., 1962, ApJS, 7, 1
Margulis M., Lada C.J., Snell R.L. (MLS88), 1988, ApJ, 333, 316
Margulis M., Lada C.J., Young E.T. (MLY89), 1989, ApJ, 345, 906
McKee C., 1999, in Kylafis N.D., Lada C.J., eds, The Origin of Stars & Planetary Systems. Kluwer, Dordrecht, p. 20
Mendoza E.E., Rodriguez L.F., Chavarria-K C., Neri L., 1990, MNRAS, 246, 518
Mitchell G.F., Johnstone D., Moriarty-Schieven G., Fich M., Tothill N.F.H., 2001, ApJ, 556, 215
Moneti A., Reipurth B., 1995, A&A, 301, 721
Myers P., 1999, in Kylafis N.D., Lada C.J., eds, The Origin of Stars & Planetary Systems. Kluwer, Dordrecht, p. 67
Ogura K., 1995, ApJ, 450, L23
O’Linger J., 1997, MSc thesis, Univ. of California, Riverside
O’Linger, J., Cole, D. M., Ressler, M. E., & Wolf-Chase, G., 2003, accepted by AJ pending minor revisions
O’Linger, J., Wolf-Chase G., Barsony M., Ward-Thompson D., 1999, ApJ, 515, 696
Oliver R. J., Masheder M.R.W., Thaddeus P. (OMT96), 1996, A&A, 315, 578
Panagia N., 1991, in Kylafis N., Lada C.J., eds, The Physics of Star Formation and Early Stellar Evolution. Kluwer, Dordrecht, p. 565
Pérez M.R., Thé P.S., Westerlund B.E., 1987, PASP, 99, 1050
Piché F., Howard E.M., Pipher J.L., 1995, MNRAS, 275, 711
Richards P.J., Little L.T., Toriseva M., Heaton B.D., 1987, MNRAS, 228, 43
Richer J.S., Shepherd D.S., Cabrit S., Bachiller R., Churchwell E., 2000, in “Protopstars & Planets IV”, ed. V. Mannings, A.P. Boss, & S.S. Russell, 867
Rodríguez L.F., Reipurth B., 1998, Revista Mexicana de Astronomía y Astrofísica, 34, 13
Sagar R., Joshi U.C., 1983, MNRAS, 205, 747
Sandell G., 1994, MNRAS, 271,75
Sargent A.I., Van Duinen R.J., Nordh H.L., Fridlund C.V.M., Aalders J.W.G., Beintema D., 1984, A&A, 135, 377
Schreyer K., Helmich F.P., van Dishoeck E.F., Henning Th., 1997, A&A, 326, 347
Surace J.A., Mazzarella J., Soifer B.T., Wehrle A.E., 1993, AJ, 105, 864
Terebey S., Mazzarella J., eds, 1994, Science with High Spatial Resolution Far-Infrared Data. JPL 94-11, Pasadena, CA
Testi L., Palla F., Natta A., 1999, A&A, 342, 515
Walker C.K., Adams F.C., Lada C.J., 1990, ApJ, 349, 515
Walker M.F., 1956, ApJS, 2, 365
Walsh J.R., Ogura K., Reipurth B., 1992, MNRAS, 257, 110
Wang H., Yang J., Wang M., Yan J., 2002, A&A, 389, 1015
Ward-Thompson D., Zylka R., Mezger P.G., Sievers A.W., 2000, A&A, 355, 1122
Williams J.P., Garland C.A., 2002, ApJ, 568, 259
Wolf-Chase G.A., Walker C.K. (WW95), 1995, ApJ, 447, 244
Wolf-Chase G.A., Walker C.K., Lada C.J. (WWL95), 1995, ApJ, 442, 197
Wood D.O.S., Churchwell E., 1989, ApJ, 340, 265
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