COMPLETION OF A SCUBA SURVEY OF LYND'S DARK CLOUDS AND IMPLICATIONS
FOR LOW-MASS STAR FORMATION

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ABSTRACT

We have carried out a survey of optically selected dark clouds using the bolometer array SCUBA on the James Clerk Maxwell Telescope at $\lambda = 850$ $\mu$m. The survey covers a total of 0.5 deg$^2$ and is unbiased with reference to cloud size, star formation activity, and the presence of infrared emission. Several new protostars and starless cores have been discovered; the protostars are confirmed through the detection of their accompanying outflows in CO (2–1) emission. The survey is believed to be complete for Class 0 and Class I protostars, and yields two important results regarding the lifetimes of these phases. First, the ratio of Class 0 to Class I protostars in the sample is roughly unity, very different from the 1:10 ratio that has previously been observed for the $\rho$ Ophiuchi star-forming region. Assuming star formation to be a homogeneous process in the dark clouds, this implies that the Class 0 lifetime is similar to the Class I phase, which from infrared surveys has been established to be $\sim 2 \times 10^5$ yr. It also suggests there is no rapid initial accretion phase in Class 0 objects. A burst of triggered star formation some $\sim 10^5$ yr ago can explain the earlier results for $\rho$ Ophiuchus. Second, the number of starless cores is approximately twice that of the total number of protostars, indicating a starless core lifetime of $\sim 8 \times 10^5$ yr. These starless cores are therefore very short lived, surviving only two or three free-fall times. This result suggests that, on size scales of $\sim 10^4$ AU at least, the dynamical evolution of starless cores is probably not controlled by magnetic processes.

Key words: ISM: clouds — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

Systematic surveys of the earliest stages of low-mass star formation provide vital information on the physics of cloud collapse. In particular, if complete samples of protostars and prestellar cores can be identified, their relative lifetimes can be estimated, if it is assumed that the clouds are not being observed at a special time in their evolution. Such studies are vital for differentiating between models of star formation, which can predict very different protostellar accretion histories. In some models, the evolution of molecular cloud cores is controlled entirely by strong magnetic fields, leading to lifetimes determined by the ambipolar diffusion timescale, which is typically $10^7$ yr (Ciolek & Mouschovias 1994). However, recent three-dimensional numerical simulations of turbulent, gravitationally unstable clouds show that cores can form and evolve over only a few dynamical timescales, even if significant magnetic fields are present (Li et al. 2000; Heitsch, Mac Low, & Klessen 2001). For typical cloud conditions, this implies evolution on timescales of about $10^6$ yr.

Once a gravitationally unstable core has formed and started to collapse, the accretion rate of the protostar is governed by the initial conditions at the onset of collapse. The idealized collapse of a singular isothermal sphere (Shu 1977) proceeds with a uniform accretion rate. Other accretion models starting from different initial conditions predict a short phase of rapid accretion, succeeded by a more or less constant accretion rate (e.g., Foster & Chevalier 1993; McLaughlin & Pudritz 1997). If evolutionary phases of different accretion rates can be identified observationally, then their relative lifetimes can then be estimated, possibly enabling the discrimination between these different models.

Complete surveys of infrared protostars have been used to obtain good estimates for the lifetime of infrared protostars, in particular the Class I, II, and III phases of protostellar evolution. From such surveys, Wilking, Lada, & Young (1989) and Kenyon et al. (1990) conclude that the Class I phase lasts $\sim 2 \times 10^5$ yr in the low-mass, star-forming regions of $\rho$ Ophiuchus and Taurus, and this lifetime is consistent with typical cloud collapse models (e.g., Adams, Lada, & Shu 1987). However, the timescales associated with the earlier phases of star formation, specifically the Class 0 phase (Andrè, Ward-Thompson, & Barsony 1993) and the precollapse phase (Ward-Thompson et al. 1994), are much more uncertain. Most samples of dense cores derive originally from catalogs of optically selected dark clouds, which were subsequently searched for associated IRAS emission (e.g., Beichman et al. 1986; Clemens & Barvainis 1988; Benson & Myers 1989; Lee & Myers 1999; Jijina, Myers, & Adams 1999). Since Class 0 protostars are typically too cold and faint to have been detected by IRAS, complete samples of both Class 0 protostars and truly “starless” cores (as opposed to cores lacking an associated IRAS source or 2 $\mu$m emission) have been difficult to obtain. In one of the few regions where complete samples of Class 0 and Class I objects exist—the $\rho$ Ophiuchi cloud—the results imply that the Class 0 phase lasts only one-tenth of the Class I phase in this region, i.e., $2 \times 10^4$ yr (Andrè & Montmerle 1994). However, there are few, if any, good statistical constraints in other regions of star formation.
The advent of large bolometer arrays on millimeter and submillimeter telescopes has made the first systematic surveys for the earliest phases of star formation possible. Typical observing wavelengths, $\lambda \sim 0.5$–$1$ mm, lie toward the Rayleigh-Jeans side of the Planck function for all reasonable dust temperatures $T \gtrsim 7$ K. Millimeter and submillimeter dust emission is therefore an excellent tracer of the youngest embedded protostars and starless dense cores, which are regions of high dust column density that can be too cold for detection by far-infrared instruments. In this paper, we present the second and concluding part of a survey, using the submillimeter camera SCUBA on the James Clerk Maxwell Telescope (JCMT), of dust continuum emission from typical, nearby, molecular clouds forming low-mass stars. The observations are sufficiently sensitive to detect all the embedded protostars and starless cores above a certain mass limit, and so they allow us to estimate the lifetimes of these earliest phases of star formation. In an earlier paper (Visser, Richer, & Chandler 2001, hereafter Paper I), we presented initial results derived from images of the smaller clouds in the sample. Here we include the images of the larger clouds and, using the full survey, present a detailed analysis of the structure of the cores, their star-forming properties, and the properties of their molecular outflows. We also estimate the relative and absolute lifetimes of the various prestellar and protostellar phases based on their detection rates.

2. SOURCE SAMPLE

The clouds observed were selected from those listed as opacity class 6 in the Lynds catalog of dark nebulae, which contains 1802 optically dark clouds selected from the POSS plates (Lynds 1962). Lynds cataloged the clouds by eye based on their apparent opacity, using an arbitrary scale of 1 to 6, with the class 6 clouds being the most opaque ($A_V \gtrsim 10$ mag). These estimates were based on a comparison of the cloud with a neighboring field on the POSS plate, and the classification is therefore somewhat subjective. The Lynds catalog contains a total of 147 opacity class 6 clouds covering a total area of $\sim 2$ deg$^2$, with individual clouds having a mean minor axis of 4' and major axis of 11'. Some of these clouds are small and round, like globules, but others are extended and filamentary. The optical appearance of most clouds is quiescent, with only a small fraction of the clouds looking shocked.

Star formation in Lynds class 6 clouds has been studied by Parker (1991) following a reanalysis of their positions (Parker 1988) and an investigation of their association with IRAS sources. However, the selection criteria he used based on IRAS detections failed to find the well-known Class 0 source B335 (L663) (Parker 1989), demonstrating the importance of understanding the selection effects introduced by such wavelength-dependent criteria. Our optical selection criterion corresponds to a limiting column density and is biased toward finding nearby clouds.

Forty-two opacity class 6 clouds were selected from the Lynds catalog with sizes and positions determined by the observing time allocated and observing mode available at the JCMT (see § 3 below). This resulted in an essentially random selection of clouds. The first to be observed were the small or filamentary clouds that could be mapped using the single SCUBA field of view, before the commissioning of large-area (scan) mapping. These results are presented in Paper I. The larger clouds were mapped when scan mapping became available. Because of the local sidereal time ranges allocated to the observations, we were able to map several areas in $\rho$ Ophiuchus, and more than one-third of all the clouds are part of the $\rho$ Ophiuchi cloud complex. The full sample contains no biases relating to size, star formation activity, or the presence of infrared emission, and so is statistically representative of nearby, dark clouds. The names and positions of all the clouds surveyed are given in Table 1, along with identifications from the Barnard (1927) catalog (B) and the Clemens & Barvains (1988) catalog (CB).

2.1. Distances

The distances to nearby clouds can be difficult to determine because neither star counts nor kinematic determinations are very reliable. The use of foreground star counts requires a precise knowledge of the distribution of the stars in the direction of the cloud, and the cloud needs to be large to make the count statistically relevant. The LSR velocity of the cloud is usually influenced by local motions and cannot, on its own, be used to determine the distance toward the cloud. Nevertheless, to be able to obtain physical parameters from the data, the correct distances need to be known. Here we use the method of associating the dark clouds with larger molecular cloud complexes (see, e.g., Launhardt & Henning 1997). Fifteen of our clouds have distances previously reported in the literature (Hilton & Lahulla 1995) with which our distance estimates agree very well. A discussion of the distances for the clouds presented in Paper I is given in an appendix to that paper. For the larger clouds that were scan mapped details are given by Visser (2000). The assumed distances and associated cloud complexes are summarized in Table 1.

2.2. IRAS Sources

Table 2 lists the IRAS sources in the Point Source Catalogue (PSC) associated with the Lynds clouds in our sample. Association is defined to be all IRAS/PSC sources within the SCUBA maps, and the IRAS sources that were associated with the clouds by Parker (1988). Most of the IRAS sources in Table 2 had already been associated with the Lynds clouds by Parker. Five IRAS sources covered by the SCUBA maps were not associated by Parker (even though they sometimes satisfy Parker's selection criteria, e.g., IRAS 19186+2325 in L771), and these are marked with a "d." Sources associated with the cloud by Parker, but not covered by the maps, are marked with a "b." The eight candidate protostars in common with those selected and studied by Parker (1991) are indicated with a "c."

Information about the nature of some of these IRAS sources is available in the literature and is included in Table 2. IRAS 16445–1352 is probably cirrus of the type very common in $\rho$ Ophiuchus, since it is only detected at 60 and 100 $\mu$m and is extended at both wavelengths (Beichman et al. 1986). IRAS 16455–1405$^1$ is listed as a Class I source by Bontemps et al. (1996). An outflow was not detected, however, and the source was identified by Parker (1991) as a T Tauri star with an optical counterpart. This source is not covered by the SCUBA map and is not discussed further. T Tauri stars covered by this survey are IRAS 16459–1411

1 Mistyped as 16445–1405 by Bontemps et al. (1996).
IRAS 22051+5848 is a protostar with an outflow presented by Parker, Padman, & Scott (1991). Launhardt, Ward-Thompson, & Henning (1997) suggest that IRAS 23228+6320 is a protostar, but an outflow is not detected (Parker et al. 1991). Massive outflows are detected from IRAS 21017+6742 (Myers et al. 1988) and from the vicinity of 19180+1116 and 19180+1114 (Armstrong & Winnewisser 1989). Anglada, Sepulveda, & Gomez (1997) argue that of these latter two it is more likely that 19180+1116 drives the outflow, taking into account ammonia emission, their spectral energy distributions (SEDs), and the location of the sources with respect to the CO flow. Identifications from the literature are listed in column (7) of Table 2.

In general, field stars and T Tauri stars are detected in the 12 and 25 μm IRAS bands with their SEDs rising toward shorter wavelengths, while embedded protostars (and cirrus

TABLE 1
SAMPLE OF LYNDS OPAcity CLASS 6 CLOUDS

| Source   | α (B1950.0)a | δ (B1950.0)a | Other Namesb | V_LSR (km s^{-1}) | D (pc) | References | Associated Complex |
|----------|--------------|--------------|--------------|-------------------|------|------------|-------------------|
| L31 ...... | 16 47 31     | −19 02 15    | CB 67        | 4.8               | 160  | 1, 2       | Ophiucus          |
| L53 ...... | 17 20 26     | −23 59 45    |              |                   | 160  | Ophiucus   |
| L55 ...... | 17 19 55     | −23 54 30    | B69          | 4.6               | 160  | Ophiucus   |
| L57 ...... | 17 19 36     | −23 47 15    | B68, CB 82   | 3.5               | 160  | 2, 3       | Ophiucus          |
| L63 ...... | 16 47 14     | −17 59 00    |              | 5.8               | 160  | 1, 3       | Ophiucus          |
| L129 ..... | 16 52 15     | −16 17 15    |              |                   | 160  | 1          | Ophiucus          |
| L158 ..... | 16 44 30     | −13 52 45    |              | 4.3               | 160  | 1, 3       | Ophiucus          |
| L162 ..... | 16 46 13     | −14 05 30    |              |                   | 160  | 1, 3       | Ophiucus          |
| L222 ..... | 17 38 24     | −19 46 00    | CB 94        | 10.6              | 160  | Ophiucus   |
| L232     | 17 37 53     | −19 42 00    | CB 93        | 10.3              | 160  | Ophiucus   |
| L226 ..... | 17 37 45     | −19 38 00    | CB 92        | 10.5              | 160  | 2          | Ophiucus          |
| L229 ..... | 17 37 26     | −19 31 15    |              |                   | 160  | Ophiucus   |
| L231 ..... | 17 37 31     | −19 32 45    |              |                   | 160  | Ophiucus   |
| L233 ..... | 17 42 18     | −20 00 00    | B83A, CB 95  | 11.1              | 160  | 2          | Ophiucus          |
| L255 ..... | 16 45 02     | −09 49 30    |              |                   | 160  | 1, 3       | Ophiucus          |
| L260 ..... | 16 44 33     | −09 31 45    |              | 3.5               | 160  | 1, 3       | Ophiucus          |
| L328 ..... | 18 14 05     | −18 03 00    | B93, CB 131  | 6.6               | 190  | 2, 4       |                  |
| L448 ..... | 18 14 35     | −04 41 00    |              | 5.0               | 200  | 3, 5       | Aquila Rift       |
| L543 ..... | 19 04 11     | −06 18 15    | B134, CB 181 | 11.3              | 400  | 3, 6       |                  |
| L663 ..... | 19 34 32     | +07 27 30    | B335, CB 199 | 8.3               | 250  | 3, 7       |                  |
| L673 ..... | 19 18 25     | +11 07 45    |              | 5.0               | 300  | 3, 5       | Cloud B           |
| L675 ..... | 19 21 31     | +11 01 45    | CB 193       | 7.5               | 300  | 5          | Cloud B           |
| L694 ..... | 19 38 45     | +10 47 45    | B143, CB 200 | 9.6               | 250  | 7          |                  |
| L709 ..... | 19 11 39     | +16 21 45    | CB 184       | 6.3               | 300  | 2, 5       | Cloud B           |
| L771 ..... | 19 18 43     | +23 24 15    | CB 190       | 11.0              | 400  | 5          | Vulpecula Rift    |
| L860 ..... | 20 01 26     | +35 53 15    | B146         | ?                 | 700  | 8          | Cygnus Rift       |
| L917 ..... | 20 38 11     | +43 58 00    |              | ?                 | 700  | 8, 9       | Cygnus Rift       |
| L944 ..... | 21 15 48     | +43 05 30    |              | 5.5               | 700  | 8          | Cygnus Rift       |
| L951 ..... | 21 18 20     | +43 18 45    |              | 5.2               | 700  | 8          | Cygnus Rift       |
| L953 ..... | 21 19 32     | +43 08 15    |              | 6.3               | 700  | 8          | Cygnus Rift       |
| L1014 ..... | 21 22 18     | +04 46 30    |              | 4.7               | 200  | 3, 10      |                  |
| L1021 ..... | 21 19 58     | +05 44 30    |              | ?                 | 200  | 4          |                  |
| L1103 ..... | 21 40 34     | +56 30 00    |              | ?                 | 150  | 3, 6       |                  |
| L1111 ..... | 21 38 54     | +57 34 30    | B161, CB 233 | −0.9              | 150  | 6          |                  |
| L1165 ..... | 22 05 17     | +58 52 15    |              | −1.1              | 300  | 9          | Cloud 157         |
| L1166 ..... | 22 03 47     | +59 19 00    | B173, CB 236 | −2.9              | 300  | 9          |                  |
| L1172 ..... | 21 01 19     | +67 33 15    |              | 4.5               | 440  | 3, 11      | Cepheus           |
| L1185 ..... | 22 27 34     | +58 54 00    |              | ?                 | 300  | 11         |                  |
| L1246 ..... | 23 23 00     | +63 20 00    | CB 243       | −11.1             | 730  | 2, 11      | Cepheus OB3       |
| L1262 ..... | 23 24 19     | +74 01 45    | CB 244       | 3.9               | 200  | 2, 3, 11   |                  |
| L1704 ..... | 16 27 50     | −23 35 30    | CB 65        | 2.4               | 160  | Ophiucus   |
| L1709 ..... | 16 29 36     | −23 47 15    |              | 2.5               | 160  | 3          | Ophiucus          |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

References:—(1) Nozawa et al. 1991; (2) Launhardt & Henning 1997; (3) Hilton & Lahulla 1995; (4) Lee & Myers 1999; (5) Dame et al. 1987; (6) Leung, Kutner, & Mead 1982; (7) Tomita, Saito, & Ohtani 1979; (8) Dame & Thaddeus 1985; (9) Dobashi et al. 1994; (10) Robert & Pagani 1993; (11) Yonekura et al. 1997.
clouds) are detected at 60 and 100 μm with SEDs rising toward longer wavelengths. This trend is seen in the sample presented in Table 2, although many of the IRAS fluxes are high upper limits owing to confusion.

3. SUBMILLIMETER CONTINUUM OBSERVATIONS AND DATA REDUCTION

Observations were made using the submillimeter camera, SCUBA, on the 15 m JCMT on Mauna Kea, Hawaii (Holland et al. 1999). SCUBA comprises two arrays of bolometer detectors, which can be used simultaneously by means of a dichroic beam splitter. The arrays are cooled to a temperature of 0.1 K to achieve high sensitivity. The 37 bolometers of the long-wavelength array are optimized for observations at 850 μm, and the 91 bolometers of the short-wavelength array are optimized for operation at 450 μm. The diffraction-limited FWHM beam sizes at these two wavelengths are 14′′ and 8′′, respectively. At 850 μm, the beam is well approximated by a single Gaussian, but at 450 μm there is an extended error beam containing a roughly equal amount of power to the main diffraction beam, spread over a diameter of approximately 40′′. Most of the conclusions in this paper are therefore based on the 850 μm data.

The bolometers form a hexagonal pattern and are spaced approximately two beamwidths apart. To produce fully sampled images, either the secondary mirror is moved in a so-called jiggle pattern, or the arrays are scanned across the

### Table 2

**IRAS PSC Associations with the Lynds Dark Clouds**

| Source (1) | IRAS Name(s) (2) | \( F_{\lambda}(12\,\mu\text{m})^a \) (Jy) | \( F_{\lambda}(25\,\mu\text{m})^a \) (Jy) | \( F_{\lambda}(60\,\mu\text{m})^a \) (Jy) | \( F_{\lambda}(100\,\mu\text{m})^a \) (Jy) | Identification (7) |
|------------|------------------|--------------------------|--------------------------|--------------------------|--------------------------|------------------|
| L53        | 17205–2359       | 0.26L                    | 0.48L                    | 0.70L                    | 12.23L                   | ...               |
| L158       | 16442–1351       | 0.31L                    | 0.52L                    | 1.70                     | 33.80L                   | ...               |
| L162       | 16465–1405\(^bc\) | 0.63                     | 0.90                     | 1.23                     | 13.29L                   | T Tauri           |
| L226       | 17375–1936       | 0.64                     | 0.40L                    | 0.63                     | 6.48                     | ...               |
| L255       | 16451–0953       | 0.25L                    | 0.32L                    | 0.60                     | 12.88L                   | ...               |
| L260       | 16466–0924       | 0.32L                    | 0.92L                    | 0.40L                    | 5.30                     | ...               |
| L694       | 19389+1048       | 0.25L                    | 0.25L                    | 0.40L                    | 7.91                     | ...               |
| L709       | 19116+1623       | 0.97                     | 0.57                     | 0.98L                    | 12.50L                   | OH/IR star        |
| L711       | 19186+2325\(^d\) | 0.25L                    | 0.25L                    | 1.03                     | 6.61                     | ...               |
| L951       | 21186+4320       | 0.25L                    | 0.25L                    | 1.84L                    | 6.84                     | ...               |
| L1165      | 22051+5849       | 2.16                     | 0.48                     | 0.53L                    | 105.90L                  | ...               |
| L1172      | 21017+6742\(^d\) | 0.28L                    | 0.26                     | 1.33                     | 5.83                     | ...               |
| L1246      | 23228+6320\(^d\) | 0.26                     | 0.74                     | 2.06                     | 7.98                     | ...               |
| L1262      | 23238+7401\(^d\) | 0.25L                    | 0.78                     | 9.60                     | 15.20L                   | ...               |
| L1704      | 16277–2332\(^d\) | 0.74L                    | 0.54L                    | 0.92                     | 20.02L                   | ...               |
| L1709      | 16291–2351       | 0.25L                    | 0.39L                    | 0.86L                    | 3.59                     | ...               |
| L1262      | 16285–2353\(^b\) | 0.19                     | 3.73                     | 9.44                     | 60.86L                   | Protostar         |
| L1260      | 16285–2356       | 0.31L                    | 0.42L                    | 1.01L                    | 60.86L                   | ...               |
| L1262      | 16285–2358       | 0.35L                    | 0.81                     | 0.97L                    | 60.86L                   | Star              |

\(^a\) Flux density in the IRAS bands. “ L ” indicates an upper limit.

\(^b\) IRAS source not covered by our SCUBA map.

\(^c\) Source studied by Parker 1991.

\(^d\) IRAS source not associated with the cloud by Parker 1988.
sky in “scan map” mode. For both of these methods, the secondary mirror also chops at a rate of 7.8 Hz to remove most of the sky emission. The jiggle mode is ideal for sources smaller than the field of view of the arrays (2/3), while scan mapping is used for more extended sources. Further technical details of observing with SCUBA on the JCMT are described by Holland et al. (1999).

A sample of 24 compact Lynds clouds was observed in 1997 September using jiggle mode, before scan mapping was fully commissioned (Paper I). Three larger clouds were also scan-mapped at this time as part of the commissioning of this mode (L663, L1165, and L1262). Weather conditions were average and stable (zenith atmospheric opacity at 850 μm, τ850 = 0.2–0.7) but not good enough to obtain 450 μm data. A further 15 clouds were scan mapped under extremely good weather conditions (τ850 = 0.12) in 1998 July, providing good data at both 850 and 450 μm. Measurements at 450 μm were also made of some of the clouds observed in 1997 during this second observing run. The total survey of 42 clouds covered an area of ~0.5 deg2, or ~7 pc2 for the distances listed in Table 1. Table 3 indicates whether a cloud was observed in jiggle mode or scan mode.

The sky transmission was monitored by performing sky dips throughout each night, and the telescope pointing was checked regularly using nearby bright sources (usually a blazar or a planet). The pointing accuracy was 2′′–3′′. The focus and alignment of the secondary mirror were also checked two or three times every night. The absolute calibration is obtained from observations of Mars and Uranus, observed using the same mode and chop throw as the observations of the dark clouds.

### Table 3
Flux Densities and Cloud Properties of the Sample

| Source | 450 μm | 850 μm | 450 μm | 850 μm |
|--------|--------|--------|--------|--------|
| L31    | 0.11 ± 0.02 | 4.6    | Jiggle 0.06 | 1.5 |
| L33    | <0.12    | ...    | Jiggle <0.05 | <1.5 |
| L55    | 0.10 ± 0.02 | 1.1    | Jiggle 0.05 | 1.3 |
| L57    | 1.1 ± 0.19 | 0.14 ± 0.02 | 45 2.8 | Scan 0.07 | 1.8 |
| L63    | 2.6 ± 0.23 | 0.31 ± 0.03 | 945 52.3 | Scan 0.15 | 4.1 |
| L129   | <0.09    | ...    | Scan <0.05 | <1.3 |
| L158   | 1.9 ± 0.42 | 0.22 ± 0.03 | 415 19.6 | Scan 0.11 | 3.0 |
| L162   | 0.38 ± 0.05 | 51.9    | Scan 0.18 | 5.1 |
| L222   | 0.12 ± 0.02 | 0.3    | Jiggle 0.06 | 1.5 |
| L223   | 0.12 ± 0.02 | 0.4    | Jiggle 0.06 | 1.5 |
| L226   | <0.09    | ...    | Jiggle <0.05 | <1.3 |
| L229   | <0.09    | ...    | Jiggle <0.04 | <1.1 |
| L231   | <0.09    | ...    | Jiggle <0.04 | <1.0 |
| L233   | <0.06    | ...    | Jiggle <0.03 | <0.9 |
| L255   | <0.09    | ...    | Scan <0.04 | <1.0 |
| L260   | 1.4 ± 0.24 | 0.21 ± 0.02 | 16 1.1   | Scan 0.10 | 2.8 |
| L262   | 0.7 ± 0.12 | 0.21 ± 0.02 | 8 1.7    | Jiggle 0.14 | 2.8 |
| L483   | 6.5 ± 0.23 | 1.3 ± 0.03 | 400 13.1 | Scan 0.99 | 17.3 |
| L543   | <0.12    | ...    | Scan <0.33 | <1.4 |
| L663   | 1.1 ± 0.10 | 7.3    | Scan 1.38 | 15.4 |
| L673   | 1.5 ± 0.21 | 0.42 ± 0.03 | 55 51.1 | Scan 0.71 | 5.5 |
| L675   | 0.07 ± 0.02 | 0.1    | Jiggle 0.11 | 0.9 |
| L694   | 1.0 ± 0.18 | 0.27 ± 0.03 | 430 21.9 | Scan 0.32 | 3.6 |
| L709   | 0.06 ± 0.01 | 0.6    | Jiggle 0.10 | 0.8 |
| L771   | 1.5 ± 0.25 | 0.14 ± 0.02 | 105 9.4 | Scan 0.43 | 1.9 |
| L860   | 0.09 ± 0.01 | 1.0    | Jiggle 0.87 | 1.2 |
| L917   | 0.09 ± 0.02 | 1.1    | Jiggle 0.85 | 1.2 |
| L944   | 0.8 ± 0.12 | 0.21 ± 0.02 | 5 1.4    | Jiggle 1.99 | 2.9 |
| L951   | 0.07 ± 0.02 | 0.5    | Jiggle 0.66 | 0.9 |
| L953   | 0.06 ± 0.02 | 0.2    | Jiggle 0.59 | 0.8 |
| L1014  | 0.8 ± 0.12 | 0.15 ± 0.02 | 5 0.9    | Jiggle 0.11 | 1.9 |
| L1021  | 0.09 ± 0.03 | 0.7    | Jiggle 0.07 | 1.2 |
| L1103  | 0.11 ± 0.03 | 1.4    | Jiggle 0.05 | 1.4 |
| L1111  | 0.10 ± 0.03 | 0.7    | Jiggle 0.04 | 1.3 |
| L1165  | 0.99 ± 0.12 | 17.2   | Scan 1.69 | 13.1 |
| L1166  | 0.10 ± 0.02 | 0.7    | Jiggle 0.17 | 1.4 |
| L1172  | 2.6 ± 0.30 | 0.20 ± 0.03 | 770 12.3 | Scan 0.75 | 2.7 |
| L1185  | 0.09 ± 0.02 | 0.9    | Jiggle 0.15 | 1.2 |
| L1246  | 1.8 ± 0.15 | 0.40 ± 0.02 | 13 4.0   | Jiggle 4.07 | 5.4 |
| L1262  | 0.69 ± 0.06 | 10.5   | Scan 0.53 | 9.2 |
| L1704  | 0.8 ± 0.19 | 0.10 ± 0.02 | 0.5    | Scan 0.05 | 1.3 |
| L1709  | 4.9 ± 0.37 | 1.03 ± 0.03 | 690 64.5 | Scan 0.50 | 13.7 |

*Uncertainties are statistical only; upper limits are 3σ.*
The chop throw for the jiggle maps was 150°, with the chop direction dependent on the structure of the cloud. To remove slowly varying background emission, instrumental offsets in SCUBA, and telescope asymmetries, the telescope is also nodded every 16 s to place the source in the opposite beam.

When mapping extended sources in scan-map mode, smaller chop throws must be used to avoid significant degradation of the beam efficiency at the edges of the arrays. In addition, the telescope is not nodded, so that instrumental and other offsets have to be established during the data reduction using baselining algorithms. The resulting maps are images of the sky convolved with a dual beam function, which is the single telescope beam convolved with positive and negative delta functions separated by the chop throw (the chop function). The chop function must be deconvolved from the image to obtain a representation of the sky. Conceptually, this deconvolution is equivalent to a division of the Fourier transform (FT) of the image by the FT of the chop function. The FT of the chop function, however, is a sine function, and clearly problems will arise at spatial frequencies close to nulls in the sine function, where the noise will be greatly amplified by the division.

There are two ways of solving the problem of noise amplification near nulls in the sine function, and both have been used here. The conventional observing method is to scan the telescope in the same direction as the chop throw (usually azimuth). The resulting dual-beam map can be restored with the Emerson-Klein-Haslam (EKH) algorithm (Emerson, Klein, & Haslam 1979). The deconvolution of the chop function is essentially carried out by dividing the FT of the map with a weighted FT of the chop function, where the weighting excludes spatial frequencies that have been attenuated to less than 0.5 of their original amplitude. The scan maps obtained during commissioning of this mode were observed in this way.

The other method is the "Emerson2" technique (Emerson 1995; Jenness, Lightfoot, & Holland 1998), used during the 1998 July observations. Here six maps are made, three of which are chopped in right ascension, and three of which are chopped in declination. Chop throws of 20°, 30°, and 65° were used for each map, and the resulting spatial frequency coverage at 850 and 450 μm is shown in Figure 1. With the exception of the zero spatial frequency, these chop throws ensure that the nulls of the FT of each do not coincide, up to the spatial frequency limit of the telescope beam. The disadvantages of not chopping in the azimuth direction (which gives the best subtraction of sky emission and ground spillover) is outweighed by the improved signal-to-noise ratio because of the more efficient deconvolution of the chop function (Jenness et al. 1998).

The data were reduced using the SCUBA User Reduction Facility (SURF; Jenness & Lightfoot 1998). Data from noisy or bad bolometers have been removed. Details of the reduction of the jiggle maps are given by Visser (2000) and Paper I. For the scan maps, a baseline must be removed for each scan and for each bolometer. Various methods for baseline removal are provided in SURF. Some work better than others for a given map, but none is entirely satisfactory, and baseline removal is still an unsolved problem. The chop function is then deconvolved from the data, adjoining maps are mosaicked together and are interpolated from the coordinates of the SCUBA arrays to equatorial coordinates. This interpolation can result in a slight degradation of the resolution, compared with the diffraction beams given above, for both jiggle maps and scan maps. The effective resolution at 850 μm is ~15°.

The incomplete spatial frequency coverage for scan maps (Fig. 1) results in the low spatial frequencies (corresponding to large-scale structure in the image) being measured with low sensitivity, and the zero spatial frequency (i.e., the total power in the map) not being measured at all. The deconvolution of the chop function is therefore similar in many respects to the deconvolution of the dirty beam from an image made by an interferometer, where an attempt is made to extrapolate the measured visibility function to zero spatial frequency while maintaining consistency with the measured data. In the Emerson2 algorithm as implemented in SURF, the effect is to amplify the noise on low spatial frequencies, so that the final images have the equivalent of "1/f" noise in the image plane: spatial scales corresponding to a few chop throws or more are measured with low sensitivity and thus have high noise values, whereas structures on scales between the maximum chop throw and the beam size are measured with dynamic ranges limited only by the thermal noise.

4. RESULTS OF THE SUBMILLIMETER CONTINUUM IMAGING

4.1. Cloud Structure

The 24 compact Lynds clouds observed using SCUBA in jiggle mode have been presented in Paper I and will not be reproduced here. The 15 clouds detected in scan map mode are shown in Figures 2–16. Contour plots of the 850 μm or 450 μm continuum emission are overlaid on optical images from the STScI Digitized Sky Survey, with contour levels indicated in the figure captions. All the images have been...
smoothed with a 20'' Gaussian (FWHM), apart from those of L158 and L1172 (Figs. 4 and 13), for which a 25'' Gaussian was used. This smoothing improves the signal-to-noise ratio in the maps and brings out the faint, extended structure. The smoothing also suppresses high spatial frequency noise introduced by the data reduction process. The area of each cloud surveyed is outlined by a dashed line. Eight clouds from the total of 42 were not detected, five in jiggle mode and three in scan map mode. Further details of these nondetections, including the areas covered by the SCUBA maps of these clouds, are given by Visser (2000). The positions of sources from the \textit{IRAS} PSC are indicated by triangles in each image.

The optical shapes of the clouds in this sample are varied. The clouds L57, L543, L663, and L675 are round and globule-like. The clouds L860, L951, and L1103 appear to have been swept up by a shock or wind and are cometary-like. The structure of L673, on the other hand, is very filamentary. The submillimeter continuum emission also encompasses a wide range of structures. Of the clouds that were detected, some exhibit purely diffuse, extended emission, some contain compact submillimeter sources, and others, such as L63, L694, and L944, have a combination of both. The extended submillimeter emission from L31 and L953 correlates very well with extinction in the optical images.

Fig. 2.—Deep SCUBA images of L57 (B68) at 450 \(\mu\)m (top) and 850 \(\mu\)m (bottom). The \textit{IRAS} source associated with this cloud by Launhardt \\& Henning (1997) is 2'' south of the cloud and is not covered by the SCUBA map. The 450 \(\mu\)m contour levels are at \(3\sigma, 4.5\sigma, 6\sigma, 7.5\sigma,\) and \(9\sigma (\sigma = 67\) mJy beam\(^{-1}\)). The 850 \(\mu\)m contour levels are at \(1\sigma, 2\sigma, 3\sigma, 4\sigma,\) and \(5\sigma,\) with \(\sigma = 14\) mJy beam\(^{-1}\).

Fig. 3.—L63 contains a well-known starless core (Ward-Thompson et al. 1994; Ward-Thompson, Motte, \\& André 1999) in the southeast part of the cloud, detected here at 850 \(\mu\)m (bottom) but not at 450 \(\mu\)m (top). Extended emission is detected at both wavelengths. No \textit{IRAS} sources are associated with this cloud. Both the 450 \(\mu\)m and 850 \(\mu\)m contour levels are at \(1\sigma, 2\sigma, 3\sigma, 4\sigma,\) and \(5\sigma,\) with \(\sigma_{450} = 335 \) mJy beam\(^{-1}\) and \(\sigma_{850} = 38\) mJy beam\(^{-1}\).
The extended submillimeter emission from a few clouds does not correlate well with the dust extinction: see, for instance, L162, and the southern part of L673. In the case of L673, this might be caused by poor atmospheric conditions during observation of the southern part. This would increase the noise level toward the south and may also explain why 450 µm emission is only detected toward the northern parts of the cloud. The lowest contour levels in the south may therefore trace correlated noise and is not very reliable. L162 was also observed under less than optimum weather conditions. In general, scan maps can sometimes exhibit not only suspicious extended positive features, but also negative features—artifacts introduced by the deconvolution process and the lack of accuracy at low spatial frequencies. Several techniques have been used in the literature to solve this problem, such as fitting two-dimensional polynomials or surfaces to background emission in the image plane (e.g., Johnstone & Bally 1999; Bianchi et al. 2000). Such methods are, however, ad hoc, and no such subtraction has been performed on the images presented in Figures 2–16. Unsatisfactory as this may be, uncertainty in the structure of extended features in these images will not affect the identification of compact objects such as protostars and starless cores.

4.2. General Properties of the Clouds

The peak flux densities in the unsmoothed maps are listed in Table 3 for both observed wavelengths. The peak position in the 850 µm map of a cloud does not necessarily coincide with the peak position in the 450 µm image (see, e.g., L63 in Fig. 3). For those scan maps exhibiting negative features, the peak fluxes have been measured from a local zero level, determined from cuts through the peak of the emission. This increased the peak flux densities of 10 sources by ~10%. The total systematic error in the 450 and 850 µm peak flux densities is about 50% and 20%, respectively, and is due to negative features and fluctuations in the optical depth of the atmosphere. Also presented in Table 3 are the statistical uncertainties and integrated flux densities for extended emission. The typical noise level in a 850 µm map is 25 mJy beam$^{-1}$. The noise levels on the 850 µm EKH maps of L663, L1165, and L1262 are considerably higher, however, because of the poor weather conditions. The integrated flux densities were obtained by summing the flux density within a box around the extended emission of the cloud. The box sizes varied depending on the size of the clouds, but the boxes always covered the extended emission down to the 1σ detection limit, staying clear of the noisy edges of the maps. No correction has been made for the (potentially spurious) negative or positive features in the scan maps when measuring the integrated flux densities.

The 850 µm peak flux densities have been used to calculate masses, column densities, space densities, and extinction, $A_V$, and are presented in Table 3. Assuming low optical depth at 850 µm the total mass (gas plus dust) traced by the submillimeter dust emission is found from $M = D^2 F_{\nu}/B_{\nu}(T)\kappa_{\nu}$, where $D$ is the distance to the source, $F_{\nu}$ is the flux density at frequency $\nu$, $B_{\nu}(T)$ is the Planck function for dust temperature $T$, and $\kappa_{\nu}$ is the dust opacity per unit mass of gas plus dust. For $\kappa_{850\mu m} = 0.0012$ m$^2$ kg$^{-1}$ and a temperature $T = 12$ K, this gives $(M/M_\odot) = 1.9 \times 10^{-8}(D/pc)^2[F_{850\mu m}(mJy\ beam^{-1})]$. The peak masses obtained in this way range from 0.04 to 4.07 $M_\odot$. The column density has been calculated using $N(H_2) = F_{\nu}/B_{\nu}(T)\kappa_{\nu}\mu m_{H_2}\mu M_\odot$, where $m_{H_2}$ is the mass of an H$_2$ molecule, $\mu$ is the mean molecular weight of the particles, assumed to be 1.36, and $\Omega_b$ is the solid angle of the beam. For the same values of $\kappa_{850\mu m}$ and $T$ used above and $\Omega_b = 15''$, this reduces to $[N(H_2)/m^{-2}] = 1.33 \times 10^{24}[F_{850\mu m}(mJy\ beam^{-1})]$. An estimate of the mean space density is obtained by assuming the depth of the cloud is similar to the beam size at the distance of the cloud. The mean peak column density is $3.9 \times 10^{26}$ m$^{-2}$, and the mean peak density is $7.6 \times 10^{11}$ m$^{-3}$, but the values for individual clouds cover a broad range. The peak extinction is calcu-

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**Fig. 4.**—Extended emission is detected from L158 at both 450 µm (top) and 850 µm (bottom). Three IRAS sources are covered by the SCUBA map (triangles), but none of these can be associated with submillimeter emission. IRAS 16445–1352 is not a Class I object as sometimes quoted but is cirrus (Beichman et al. 1986; Bontemps et al. 1996). The other two IRAS sources are both only detected at 60 µm and could also be cirrus. The 450 µm contour levels are at 1, 2, and 3 $\sigma$ ($\sigma = 268$ mJy beam$^{-1}$). The 850 µm contour levels are at 1, 2, 3, and 4 $\sigma$ ($\sigma = 24$ mJy beam$^{-1}$).
lated using \( A_V/\text{mag} = N(\text{H}_2)/(0.95 \times 10^{25} \text{ m}^{-2}) \) (Bohlin, Savage, & Drake 1978), and for the detected clouds all have \( A_V \geq 8 \text{ mag} \), agreeing well with that measured for dark clouds using isotopomers of CO (Myers, Linke, & Benson 1983). The total gas mass and mean column densities are also presented in Table 3, calculated using the integrated flux densities. The total mass observed in the survey is \( \sim 400 M_\odot \), with the most mass (\( \sim 90 M_\odot \)) associated with L673. The mean cloud column density varies between \( \sim 1 \) and \( 10 \times 10^{25} \text{ m}^{-2} \) with three exceptions: L663, L1165, and L1262. These three clouds were those observed with the EKH technique, and the dynamic range on these maps is too small to be able to detect the lower column densities.

It is clear that the above calculations of mass, column, and space densities depend on the assumptions made about the dust opacity, dust temperature, and distance of the cloud. The dust opacity used is that of Hildebrand (1983) and is probably uncertain by a factor of 3 or so (Henning, Michel, & Stognienko 1995). The assumed dust temperature of 12 K is typical for quiescent, dark, molecular clouds (Myers et al. 1983) but is likely to be an underestimate for those clouds containing young stellar objects. Radiation from protostars heat the surrounding material out to \( \sim 10^4 \text{ AU} \) (Chandler & Richer 2000), and protostellar outflows can also heat the cloud through shocks. However, temperatures in the range 8–20 K will not change the derived cloud masses by more than a factor of 2. Uncertainties in the cloud distances potentially have a stronger influence on the cloud mass. The numbers presented in Table 3 should therefore be regarded just as indicative of general cloud conditions.

5. A CATALOG OF COMPACT DUST CORES

The submillimeter images of the 42 Lynds clouds presented in § 4.1 and Paper I show many compact objects, possibly pre-protostellar or protostellar in nature. A compact object not containing a protostar is not necessarily pre-protostellar, however. A dense core must be gravitationally bound before it can collapse and form a star, and it is not possible to determine whether a clump is gravitationally bound from dust emission alone. The term “starless core” is therefore used here to denote a compact source not associated with an outflow.

Various definitions of a “core” can also be found in the literature. Myers et al. (1983) were the first to study cores in dark molecular clouds systematically and defined a core as a small (0.1 pc), dense (\( 3 \times 10^{10} \text{ m}^{-3} \)), and cold (10 K) condensation that is close to stable equilibrium and may evolve into a low-mass star. Williams, Blitz, & McKee (2000) define a core as a region in which a single star (or multiple

![Figure 5](image-url)
system such as a binary) forms and which is gravitationally bound. Here we use the term core to refer to the compact submillimeter objects in the SCUBA survey, which are not necessarily gravitationally bound.

5.1. Identification of the Cores

Compact submillimeter (SMM) objects in the Lynds clouds have been identified by spatially filtering the SCUBA images. Each map was smoothed with a 20 Gaussian, and the smoothed map was then subtracted from the original map. This removed all large cloud structures, as well as the unreliable positive and negative features resulting from the beam deconvolution of the scan maps. The remaining image contains only compact structures, and all structures at a level $\geq 3$ $\sigma$ were identified as cores. Although this method is somewhat subjective, it does select in a quantitative way all the features seen by eye, and all known protostars and preprotostellar cores. Ideally, one would like to use a fixed physical scale (such as a limiting $A_V$) to select the dense cores. However, this fixed value would be dominated by the noisiest map.

Forty SMM cores were identified in the manner described above, and are listed in Table 4. The positions of the cores have been obtained from Gaussian fits to the emission and so do not necessarily coincide exactly with the emission peak. Four cores were rejected from the list (in L31, L55,
and two in L917), since they appear near the edge of the map where spiky negative and positive features can occur, a known artifact resulting from the regridding algorithm. L158-SMM2 is suspiciously spiky too, but since it is not near the edge of the map, it is included in the list.

There are 10 cores that lie within 12" of sources in the IRAS PSC and so can be directly associated with those sources. These associations are listed in Table 4. All 10 cores are known protostars. Both L673-SMM1 and L1709-SMM5 lie within 40" of an IRAS source (19180+1116 and 16285–2356, respectively) and are possible associations. In order to verify these possible associations, HIRES images of the IRAS data for L673 and L1709 were obtained from IPAC. Figures 17 and 18 demonstrate that IRAS 19180+1116 can confidently be associated with L673-SMM1, and IRAS 16285-2356 with L1709-SMM5.

Figure 19 shows 850 μm emission from all the cores in the sample on the same angular scale, with the central positions from Table 4 marked as stars. All associated IRAS sources are very near the core positions, apart from IRAS 19180+1116 and 16285–2356. Some of the cores are very compact and round (see, e.g., L260-SMM1, L673-SMM1, and L1262-SMM1), while others are more extended (e.g., L63-SMM1, L158-SMM1, and L673-SMM8). It has been suggested that emission from T Tauri stars and Class I sources is more centrally condensed than emission from Class 0 sources (André & Montmerle 1994). Certainly, the only T Tauri star detected, L162-SMM1, is very compact, as expected. L63-SMM1, a starless core, appears extended, and the known protostars vary from compact (L483-SMM1) to very compact (L1709-SMM1). Figures 20 and 21 illustrate the locations of the submillimeter cores in L673 and L1709, the two clouds containing multiple sources.

5.2. Completeness

The detection limit in terms of mass is different for each cloud, owing to varying noise levels and distances. In order to establish that we have complete (or at least representative) samples of starless cores, Class 0, and Class I sources down to a certain mass limit, we must consider each of these effects. Starless cores and Class 0 sources are easier to detect than Class I sources at submillimeter wavelengths. Class 0 sources (for which the envelope mass, $M_{\text{env}}$, is greater than the mass of the forming protostar, $M_*$) have more material
in their envelopes than Class I sources (for which $M_{\text{env}} < M_\star$), and starless, pre-protostellar objects still have all their material in an "envelope," since they have not yet formed a hydrostatic protostellar core. Our main problem is, therefore, potentially missing Class I sources associated with the observed Lynds clouds.

In §9, we compare the detection rates of Class 0 and Class I sources in our sample with those previously observed for $\rho$ Ophiuchus by André & Montmerle (1994), for which the detected ratio of Class 0 sources to Class I was 1:10. In order for such a comparison to be meaningful, it is important to establish whether our samples of Class I protostars meet the same completeness criteria. André & Montmerle found that, for Class I sources in $\rho$ Ophiuchus, $M_{\text{env}}$ ranges from $\sim$0.015 to $\sim$0.15 $M_\odot$ with a median value of $\sim$0.06 $M_\odot$, assuming a dust temperature of 30 K, and $\kappa_{1.3 \text{ mm}} = 0.001$ m$^2$ kg$^{-1}$. The detection mass limit for the Lynds clouds mapped using SCUBA can be calculated using these same parameters, adopting a 3 $\sigma$ flux detection limit, the distances given in Table 1, and scaling $\kappa_{1.3 \text{ mm}}$ to a wavelength of 850 $\mu$m assuming a frequency dependent dust opacity, $\kappa_\nu \propto \nu^{\beta}$, with $\beta = 1.5$. The detection limit for most clouds is then less than 0.015 $M_\odot$ in our survey. Only the furthest clouds (L543, L771, L860, L917, L944, L951, L953, L1172,
and L1246) and the clouds for which the maps are noisy (L663, L1165, and L1262) have higher mass detection limits, ranging from $\sim 0.02$ to $\sim 0.09 \, M_\odot$. We could, therefore, have missed some Class I sources in these clouds. However, we would still have expected these sources to have been detected by IRAS; even for the most distant cloud, its 60 $\mu$m detection limit of 0.25 Jy is equivalent to $M_{\text{env}} \sim 0.003 \, M_\odot$.

In total, there are nine IRAS sources associated with the clouds mentioned above (Table 2), and five of these sources are known protostars, which we have detected. We do, therefore, need to investigate the nature of the remaining four IRAS sources in order to exclude the possibility that these are low-mass Class I protostars, undetected in the SCUBA maps. The IRAS colors of 22051+5849 in L1165 do not correspond to those of a protostar, and this is certainly not a Class I source. Two IRAS sources not detected as submillimeter cores, 19343+0727 in L663 and 19186+2325 in L771, do have the colors consistent with being protostellar, but these sources can be identified with bright, optically visible stars. The remaining undetected IRAS source is 21186+4320, a source with an entry in the PSC at only 100 $\mu$m. A HIRES 60 $\mu$m image of this cloud showed far-infrared emission displaced from the PSC position, and the 60 $\mu$m peak in the HIRES map was not

![Fig. 10.](image1)

L694 contains a bright embedded submillimeter continuum source, clearly detected at 850 $\mu$m (bottom) but not at 450 $\mu$m (top). Extended emission is detected at both wavelengths and correlates well with the optical dust extinction. The maps cover two IRAS sources, but neither has been detected. IRAS 19389+1048 is probably cirrus, and IRAS 19380+1045 is very likely a (young) field star. The 450 $\mu$m contour levels are at $1\sigma$, $2\sigma$, $3\sigma$, $4\sigma$, $5\sigma$, $6\sigma$, and $8\sigma$ ($\sigma = 201$ mJy beam$^{-1}$). The 850 $\mu$m contour levels are at $1\sigma$, $2\sigma$, $3\sigma$, $4\sigma$, $5\sigma$, $6\sigma$, $7\sigma$, and $8\sigma$ ($\sigma = 25$ mJy beam$^{-1}$).

![Fig. 11.](image2)

Extended emission has been detected from L771 at both 450 $\mu$m (top) and 850 $\mu$m (bottom) and appears different at the two wavelengths. The IRAS source in this field can probably be associated with the bright star (triangle). The 450 $\mu$m contours are at $3\sigma$ and $6\sigma$ ($\sigma = 100$ mJy beam$^{-1}$). The 850 $\mu$m contours are at $3\sigma$ and $4\sigma$ ($\sigma = 20$ mJy beam$^{-1}$).
covered by the SCUBA image. None of the undetected IRAS sources is therefore a Class I source, and our sample of submillimeter cores should be complete for Class I sources down to \( M_{\text{env}} = 0.015 M_\odot \).

6. A \( ^{12}\text{CO} \ J = 2–1 \) SURVEY FOR OUTFLOWS FROM THE COMPACT CORES

6.1. Observations

To determine the nature of the newly identified compact cores a search for outflows was carried out in the \( J = 2–1 \) transition of \( ^{12}\text{CO} \) (230.538 GHz) using receiver A2 on the JCMT. Observations were made in 1998 July and by JCMT staff in service mode throughout 1999. Spectra were obtained in a five- or nine-point pattern, with the central spectrum on the dust peak from the SCUBA 850 \( \mu \)m map. The system temperature was typically 440 K and the integration time of each spectrum was 2 minutes, to give an rms level of 0.2 K in a bandwidth of 0.16 MHz (0.2 km s\(^{-1}\)).

Table 4 shows which submillimeter cores have been searched for outflows and whether or not high-velocity gas was detected. Ten cores were not observed in \( ^{12}\text{CO} \) (2–1): L483-SMM1 is a well-known protostar, whose outflow has already been extensively studied; L162-SMM1 is a T Tauri star; and L158-SMM2 is the unreliable “spiky” source. The other seven cores were not searched owing to limited observing time but seem to be extended and are unlikely to contain embedded protostars (Fig. 19). They have therefore been classified as “probably starless” cores since, strictly speaking, their nature is still unidentified. Of the 40 cores identified in § 5, 10 are known protostars, eight of which were already known to drive outflows. The two protostars for which this was not known are L162-SMM1 (a Class II object) and L1246-SMM1 (which does show high-velocity line wings in these new data). Of the 30 remaining cores, 22 were searched for high-velocity gas, and the \( ^{12}\text{CO} \) (2–1) line emission from three of these cores (L673-SMM1, L944-SMM1, and L1709-SMM5) shows high-velocity emission, indicative of an outflow.

Larger maps of the three new outflows and seven of the known eight flows (all but L483-SMM1) were subsequently observed in \( ^{12}\text{CO} \) (2–1) in 1998 July and throughout 1999 in service mode with receiver A2 on the JCMT. Many of the old maps of the known outflows are incomplete, of poor resolution, or not in \( ^{12}\text{CO} \) (2–1), and our new observations provide a homogeneous sample. All these maps were made using the on-the-fly mapping mode with a cell size of 5\(^{\prime}\) and an integration time of 5 s per point. The spectra were taken by position-switching to eliminate instrumental and atmospheric effects. Pointing was checked regularly, and the system was calibrated using standard chopper wheel
techniques to obtain spectra on the $T_A^*$ scale. The main beam efficiency at this wavelength is 0.66.

6.2. Outflow Maps

The large-scale maps of the outflows have been slightly smoothed and are shown in Figures 22–29. Previous observations and results from these new maps are described below.

6.2.1. L260

L260-SMM1 drives a very compact bipolar outflow, which was classed only as an uncertain detection by Bontemps et al. (1996). The outflow has been detected again here. This source has been classified as Class I (Bontemps et al. 1996) and also has been identified optically (Ichikawa & Nishida 1989). Optical identifications are rare for Class I sources, and this fact, together with the detection of only a very compact and weak outflow, suggest that this protostar is either fairly evolved and accreting the last of its material or is being observed close to pole-on (Fig. 22).

6.2.2. L483

The outflow from L483-SMM1 has been extensively studied, so no new map was obtained for this flow. The high-velocity gas exhibits a distinct east-west bipolar structure, with a high degree of symmetry about the IRAS source (Parker 1989; Fuller et al. 1995). The low-level, extended emission in the SCUBA images of this source (Fig. 7) reflects the shape of the outflow cavities, as has been observed for the Class 0 protostar L1527 (Chandler & Richer 2000). Indeed, the detection of the outflow from L483-SMM1 in $^{12}$CO $J = 4 \rightarrow 3$ by Hatchell, Fuller, & Ladd (1999) confirms the presence of heated gas, and the dust emission probably traces this same material.

6.2.3. L663

L663-SMM1 (B335) drives an outflow very similar in structure to that of L483-SMM1 and has also been studied extensively (e.g., Cabrit, Goldsmith, & Snell 1988; Moriarty-Schieven & Snell 1989). The map presented here (Fig. 23) is of limited extent and does not cover the entire outflow but is included for completeness.

6.2.4. L673

The full extent of high-velocity gas in L673 mapped by Armstrong & Winnewisser (1989) in $^{12}$CO (1–0) emission is 12$''$. The resolution of their map was poor (half-power beamwidth of 3$''$/9), however, and it is not clear from their data whether IRAS 19180+1114 or 19180+1116 drives the outflow. Anglada et al. (1997) argue that it is more likely for IRAS 19180+1114 to be the origin of the flow, but our new map (Fig. 24) suggests that both L673-SMM1 (associated with IRAS 19180+1116) and L673-SMM2 (IRAS 19180+1114) have outflows. At least, it is clear that both sources have blueshifted outflow, but the structure of the redshifted gas is more complicated. The situation near the southern cores in L673 is even more confused. A small map (120$''$ $\times$ 80$''$) was made to cover L673-SMM3 and L673-SMM5, and some high-velocity gas was detected (the $^{12}$CO line is 6.5 km s$^{-1}$ wide), so it is possible that one of these two cores is a protostar. The emission from L673-SMM3 is more centrally condensed than L673-SMM5 (Fig. 20) and L673-SMM3 has therefore been classified as a protostar candidate, and L673-SMM5 as a starless core, but more observations are needed to confirm this. Both L673-SMM6 and L673-SMM8 also show some redshifted high-velocity gas, but this is difficult to interpret from the limited $^{12}$CO data available. Both cores have therefore been classified as starless.

6.2.5. L944

This protostar is newly detected by this survey, with both the continuum emission and outflow previously unknown. Its outflow is presented in Paper I.
6.2.6. L1165

The bipolar outflow of L1165-SMM1 was partly observed by Parker (1989) but is now fully covered by the new $^{12}$CO map (Fig. 25).

6.2.7. L1172

The outflow emanating from L1172 is very extended and was detected in $^{12}$CO (1–0) by Myers et al. (1988). Unfortunately, the $^{12}$CO (2–1) map presented here covers only a part of the outflow owing to limited observing time and includes L1172-SMM2 but not L1172-SMM1 (see Fig. 26). It is, however, more likely that L1172-SMM1 drives the outflow, since this submillimeter source is closer to the IRAS source. L1172-SMM1 has, therefore, been classified as a protostar, and L1172-SMM2 as starless. The properties of this outflow have not been studied further, owing to the limited map.

6.2.8. L1246

L1246-SMM1 is a previously known protostar (Launhardt et al. 1997), but an outflow had not been detected, despite sensitive searches (Parker et al. 1991). The CO outflow has now been detected and mapped, confirming the protostellar nature of this source, and is presented in Paper I.

6.2.9. L1262

The bipolar outflow from L1262-SMM1 has been observed by Bontemps et al. (1996). The new map made with the JCMT is larger in extent and is shown in Figure 27.

6.2.10. L1709

A blueshifted outflow driven by L1709-SMM1 has been presented by Bontemps et al. (1996). Parker (1989) noted, however, that a redshifted outflow is very likely also present, and this redshifted outflow has now been detected (Fig. 28). A new outflow emanating from L1709-SMM5 has also been mapped (Fig. 29). Spectra obtained in a five-point pattern centered on L1709-SMM3 showed some redshifted, high-velocity gas, but this is probably due to the outflow emanating from L1709-SMM1, and L1709-SMM3 has been classified as starless.

6.3. Outflow Dynamics

The dynamical properties of the observed outflows are given in Table 5. The mass of high-velocity molecular gas in the outflows has been calculated assuming low optical depth and local thermodynamic equilibrium with an excitation temperature of $T_{\text{ex}} = 20$ K. The abundance of $^{12}$CO relative to $\text{H}_2$ is assumed to be $5 \times 10^{-5}$, and the distances used in the calculations are those in Table 1. The kinetic energy in
bound of the redshifted wing) corresponds to the velocity at which emission is no longer positively detected above the noise. The extent of the outflow is the distance from the core to the edge of the redshifted outflow plus the core to the edge of the blueshifted outflow. The outflow in L663 has not been completely mapped, and the extent measured is therefore a lower limit. The velocity width is the total width of the outflow at the 1σ noise level. The dynamical age, $\tau_\nu$, is the outflow extent divided by the velocity width and is an indication of the lifetime of the outflow. No correction has been made for flow inclination in calculating the above quantities.

The momentum flux (or force) of an outflow is the ratio of the flow momentum to the dynamical age. We have applied a correction factor of 10 in calculating the values of the momentum flux displayed in Table 5 to account for a combination of the optical depth of the CO emission and a mean inclination angle of the flow, thereby enabling a direct comparison with the momentum fluxes presented by Bontemps et al. (1996). Bontemps et al. argue that, if outflows are momentum-driven and momentum is conserved along the flow direction, full maps of an outflow are not needed in order to obtain an estimate of the momentum flux. In the case of L663-SMM1 (B335), we have investigated this by comparison with values from the literature. Based on a map even more limited than that shown in Figure 23, Bontemps et al. derive a momentum flux (corrected using the above factor of 10 for line opacity and flow inclination) for the L663 outflow of $1.2 \times 10^{-5} \, M_\odot \, km \, s^{-1} \, yr^{-1}$. These authors do not specify the assumed $^{12}$CO-to-H$_2$ abundance used in their calculations, although much of their analysis is compared directly with the work of Cabrit & Bertout (1992), who use a value of $1 \times 10^{-4}$, a factor of 2 higher than that assumed here. Converting the Bontemps et al. value for the momentum flux to an abundance of $5 \times 10^{-5}$ therefore gives $2.4 \times 10^{-5} \, M_\odot \, km \, s^{-1} \, yr^{-1}$. Cabrit et al. (1988) mapped the entire flow, and using a $^{12}$CO-to-H$_2$ abundance of $1.8 \times 10^{-4}$ obtain a momentum flux of $2.4 \times 10^{-5} \, M_\odot \, km \, s^{-1} \, yr^{-1}$, including measured corrections for optical depth and flow inclination. Converting this to the same abundance used here gives $8.6 \times 10^{-5} \, M_\odot \, km \, s^{-1} \, yr^{-1}$. Our value for the momentum flux of $4.7 \times 10^{-5} \, M_\odot \, km \, s^{-1} \, yr^{-1}$ lies in the same range as those previously reported, when the different abundances assumed are taken into account. Thus, to within a factor of a few, the estimates of the outflow momentum flux using the Bontemps et al. assumptions seem reasonable and can be used for qualitative comparisons within the sample, since they are calculated for all sources in a consistent manner.

Most of the outflows are clearly bipolar. The outflows emanating from L260-SMM1 and L1709-SMM5 have their red- and blueshifted lobes overlapping to a large degree, and we may be observing these flows close to pole-on. The outflows in L673 are the most complex. The two submillimeter cores clearly drive blueshifted outflows, but it is less obvious which source drives the redshifted gas. The outflow properties of both L673-SMM1 and L673-SMM2 in Table 5 are therefore based only on the blueshifted gas. The redshifted outflow is very massive ($0.07 \, M_\odot$) and energetic ($2.2 \times 10^{36} \, J$) compared with the other outflows in the sample and may be a combination of flows associated with both cores.
7. CLASSIFICATION OF THE PROTOSTARS

A statistical analysis of source properties and relative lifetimes requires that all the protostars in our sample be classified according to some scheme approximating age or evolutionary status. Several such classifications have been used in the past, from the rather coarse division according to the near- to mid-infrared SED to the more continuous bolometric temperature ($T_{\text{bol}}$). Other source properties have also been found to correlate with either the SED classification or $T_{\text{bol}}$, the subsequent interpretation of which can be somewhat model-dependent. Here, we place the protostars observed in our sample into these classification schemes and compare the results with those reported in the literature.

Fig. 16.—Extended continuum emission and compact sources are detected from L1709 at both 450 \( \mu \text{m} \) (top) and 850 \( \mu \text{m} \) (bottom). There are four IRAS sources in this cloud (triangles). The protostar IRAS 16285–2355 can be clearly associated with a submillimeter continuum source. South of this protostar, IRAS 16285–2356 is very close to another compact continuum source. The other two IRAS sources are not associated with submillimeter emission. The 450 \( \mu \text{m} \) contour levels are at 4 \( \sigma \), 6 \( \sigma \), 8 \( \sigma \), 10 \( \sigma \), and 12 \( \sigma \) (\( \sigma = 134 \text{ mJy beam}^{-1} \)), and the 850 \( \mu \text{m} \) contours are at 2 \( \sigma \), 4 \( \sigma \), 6 \( \sigma \), 8 \( \sigma \), 10 \( \sigma \), 14 \( \sigma \), 18 \( \sigma \), and 22 \( \sigma \), with \( \sigma = 20 \text{ mJy beam}^{-1} \).
The flux densities of the protostars at 450 and 850 μm were obtained from HIRES data, as described in Paper I. Far-infrared flux densities for the protostars in L673 and L1709, where inspection of Table 2 indicates considerable confusion in the PSC, were also obtained from HIRES images (Figs. 17 and 18) for all IRAS bands except 100 μm, for which the resolution is insufficient to separate emission from the multiple sources. Upper limits only are therefore given for 100 μm flux densities. At 60, 25, and 12 μm, the emission was integrated in a box around the protostar after subtraction of a background level (a circular aperture does not work here because of the elliptical IRAS beam). The HIRES flux densities are listed in Table 7; the absolute uncertainty in these values is ~30%.

The SEDs have been fitted with a single-temperature gray-body spectrum, $F_\nu \propto \nu^\beta B_\nu(T_{\text{dust}})$. The dust emission is assumed to be optically thin, and $\beta$ is fixed at 1.5. The fitted values of the dust temperature, $T_{\text{dust}}$, are given in Table 6, and spectra are plotted in Figure 30. Where available, the gray-body spectrum is fitted to 850, 450, and 100 μm data. For the protostars with no 450 μm flux density measure-

### TABLE 4

| Core          | R.A. (B1950.0) | Decl. (B1950.0) | IRAS Association | Searched for Outflow? | Outflow Detected? | Identification       |
|---------------|----------------|-----------------|------------------|-----------------------|-------------------|----------------------|
| L55-SMM1 ......| 17 19 55.3     | −23 55 30       |                   | Yes                   | No                | Starless core        |
| L57-SMM1 ......| 17 19 35.7     | −23 47 08       |                   | No                    |                  | Probably starless    |
| L63-SMM1 ......| 16 47 20.1     | −18 01 12       |                   | Yes                   | No                | Starless core        |
| L158-SMM1 ......| 16 44 33.9     | −13 53 50       |                   | Yes                   | No                | Starless core        |
| L158-SMM2 ......| 16 44 23.4     | −13 53 01       |                   | No                    |                  | Probably starless    |
| L162-SMM1 ......| 16 45 56.1     | −14 11 25       | 16459–1411        | No                    |                  | Known T Tauri star   |
| L260-SMM1 ......| 16 44 13.7     | −09 29 58       | 16442–0930        | Yes                   | Yes               | Known protostar      |
| L260-SMM2 ......| 16 44 24.6     | −09 24 62       |                   | No                    |                  | Probably starless    |
| L328-SMM1 ......| 18 14 05.0     | −18 03 12       |                   | Yes                   | No                | Starless core        |
| L483-SMM1 ......| 18 14 50.2     | −04 40 48       | 18148–0440        | No                    | Yes               | Known protostar      |
| L663-SMM1 ......| 19 34 35.1     | +07 27 20       | 19345+0727        | Yes                   | Yes               | Known protostar      |
| L673-SMM1 ......| 19 18 04.0     | +11 16 37       | 19180+1116?       | Yes                   | Yes               | New protostar        |
| L673-SMM2 ......| 19 18 04.6     | +11 14 23       | 19180+1114        | Yes                   | Yes               | Known protostar      |
| L673-SMM3 ......| 19 18 26.6     | +11 08 31       |                   | Yes                   | No                | Candidate protostar  |
| L673-SMM4 ......| 19 18 03.5     | +11 18 54       |                   | Yes                   | No                | Starless core        |
| L673-SMM5 ......| 19 18 30.3     | +11 08 03       |                   | Yes                   | No                | Probably starless    |
| L673-SMM6 ......| 19 18 26.8     | +11 10 19       |                   | Yes                   | No                | Starless core        |
| L673-SMM7 ......| 19 18 01.9     | +11 17 10       |                   | Yes                   | No                | Starless core        |
| L673-SMM8 ......| 19 18 41.2     | +11 06 04       |                   | Yes                   | No                | Starless core        |
| L694-SMM1 ......| 19 38 42.2     | +10 50 03       |                   | Yes                   | No                | Starless core        |
| L860-SMM1 ......| 20 01 25.9     | +35 53 30       |                   | No                    |                  | Probably starless    |
| L860-SMM2 ......| 20 01 29.0     | +35 52 57       |                   | No                    |                  | Probably starless    |
| L944-SMM1 ......| 21 15 51.2     | +43 06 08       |                   | Yes                   | Yes               | New protostar        |
| L951-SMM1 ......| 21 18 20.0     | +43 19 17       |                   | Yes                   | No                | Starless core        |
| L951-SMM2 ......| 21 18 22.9     | +43 19 51       |                   | Yes                   | No                | Starless core        |
| L1014-SMM1 ......| 21 22 33.9     | +49 46 05       |                   | Yes                   | Yes               | Known protostar      |
| L1165-SMM1 ......| 22 05 09.7     | +58 48 05       | 22051+5848        | Yes                   | Yes               | Known protostar      |
| L1172-SMM1 ......| 21 01 42.5     | +67 42 19       | 21017+6742        | Yes                   | Yes               | Known protostar      |
| L1172-SMM2 ......| 21 01 47.1     | +67 42 13       |                   | Yes                   | No                | Starless core        |
| L1172-SMM3 ......| 21 01 35.6     | +67 39 14       |                   | No                    |                  | Probably starless    |
| L1246-SMM1 ......| 23 22 51.9     | +63 20 10       | 23228+6320        | Yes                   | Yes               | Known protostar      |
| L1246-SMM2 ......| 23 23 03.5     | +63 20 16       |                   | Yes                   | No                | Starless core        |
| L1262-SMM1 ......| 23 23 48.8     | +74 01 07       | 23238+7401        | Yes                   | Yes               | Known protostar      |
| L1262-SMM2 ......| 23 23 28.7     | +74 01 58       |                   | Yes                   | No                | Starless core        |
| L1704-SMM1 ......| 16 27 49.8     | −23 35 42       |                   | No                    |                  | Probably starless    |
| L1709-SMM1 ......| 16 28 34.6     | −23 55 06       | 16285–2355        | Yes                   | Yes               | Known protostar      |
| L1709-SMM2 ......| 16 28 28.4     | −23 49 34       |                   | Yes                   | No                | Starless core        |
| L1709-SMM3 ......| 16 28 42.3     | −23 54 04       |                   | Yes                   | No                | Starless core        |
| L1709-SMM4 ......| 16 29 46.3     | −23 46 19       |                   | No                    |                  | Ridge, probably starless |
| L1709-SMM5 ......| 16 28 31.3     | −23 56 55       | 16285–2356?       | Yes                   | Yes               | New protostar        |

a The two IRAS sources indicated with a question mark (?) lie within 40" of the submillimeter cores.

b L483-SMM1 was not searched for high-velocity gas, but its outflow has been extensively studied by other authors (see § 6.2.2).
ment, only the 850 and 100 \(\mu m\) flux densities are used (i.e., for L162-SMM1, L633-SMM1, L1165-SMM1, and L1262-SMM1). For the four protostars with 100 \(\mu m\) upper limits, the 850, 450, and 60 \(\mu m\) flux densities are used (i.e., L673-SMM1, L673-SMM2, L1709-SMM1, and L1709-SMM5). All fits have \(\chi_2^2 < 1\) apart from L1709-SMM5, for which \(\chi_2^2 = 1.3\).

In order to classify the protostars according to the scheme proposed by Lada & Wilking (1984) based on the near- to mid-infrared spectral index and extended to sources not detected in the infrared by André et al. (1993), infrared measurements are needed. L162-SMM1 is an optically identified T Tauri star (Ichikawa & Nishida 1989) and is classified as Class II by André & Montmerle (1994). The protostars detected in the near-infrared are L260-SMM1 (Myers et al. 1987), L1165-SMM1 (Tapia et al. 1997), and L1709-SMM1 (Myers et al. 1987), and so are Class I protostars. The Class 0 protostars not detected in the near-infrared are L483-SMM1 (Fuller et al. 1995) and L663-SMM1 (Hodapp 1998). L1246-SMM1 and L1262-SMM1 have been classified as Class 0 sources by Launhardt et al. (1997) based on unpublished near-infrared photometry. The remaining five protostars have to be classified without near-infrared measurements.

7.1.1. Ratio of \(L_{bol}/L_{submm}\)

A method proposed for classifying protostars by André et al. (1993) that does not depend on near- and mid-infrared detections is to evaluate the ratio \(L_{bol}/L_{submm}\), which for a constant mass accretion rate should be approximately proportional to \(M_*/M_{env}\). The ratio \(L_{bol}/L_{submm}\) will increase with age, as material from the envelope is accreted onto the protostar. André et al. classify protostars as Class 0 when \(L_{bol}/L_{submm} < 200\), where \(L_{bol}\) is measured from 1 to 1300 \(\mu m\), and \(L_{submm}\) is the submillimeter luminosity from 350 to 1300 \(\mu m\). Unfortunately, \(L_{bol}\) cannot be determined without near-infrared measurements, and the best we can do here is to calculate the luminosity from 12 to 1300 \(\mu m\). This will underestimate \(L_{bol}\) particularly for the older sources. Lower limits to \(L_{bol}\) have therefore been calculated by integrating under the gray-body fit from 1300 to 150 \(\mu m\) and by regarding the \textit{IRAS} PSC or HIRES upper limits as real detections. This latter assumption may tend to overestimate \(L_{bol}\), and Figure 30 shows it will affect mainly those protostars not detected by \textit{IRAS} at 12 \(\mu m\). For both L663-SMM1 and L944-SMM1, which are not detected at either 12 or 25 \(\mu m\), the bolometric luminosity has been calculated by integrating under the gray-body fit only. Estimates of \(L_{bol}\), \(L_{submm}\), and \(L_{bol}/L_{submm}\) are listed in Table 6. Applying the
criterion that a protostar is a Class 0 source when $L_{\text{bol}}/L_{\text{submm}} < 200$ results in only one Class I source in this sample, suggesting that a different limit should be used for a sample that does not include near-infrared emission in determining $L_{\text{bol}}$. Indeed, a limit of $\sim 50$ is needed to reproduce most of the classifications of those protostars with previous measurements or good upper limits in the near- and mid-infrared. The only source that then does not match its previous classification is L483-SMM1, which has recently been described as a transition Class 0/Class I object by Tafalla et al. (2000) based on a study of the emission from various molecular species.

7.1.2. Bolometric Temperature

A more continuous indicator of age, the bolometric temperature ($T_{\text{bol}}$), was introduced by Myers & Ladd (1993). $T_{\text{bol}}$ is the temperature of a blackbody having the same mean frequency as the observed continuum spectrum and is a measure of circumstellar obscuration. Chen et al. (1995) quantify the Class 0/Class I boundary as $T_{\text{bol}} = 70$ K and Class I/Class II as $T_{\text{bol}} = 650$ K. Table 6 lists values of $T_{\text{bol}}$ derived from the SEDs in Figure 30 in a manner similar to the measurement of $L_{\text{bol}}$ described above. Again, the lack of near- and mid-infrared data for these sources will tend to lower the derived $T_{\text{bol}}$. Nevertheless, the values in Table 6 should be a good indicator of evolutionary state, albeit with different class boundaries from those obtained by Chen et al. L162-SMM1 has a $T_{\text{bol}}$ considerably lower than the 650 K limit assigned by Chen et al., but this source is also likely to be the most seriously affected by the lack of near-infrared data included in its SED. A Class 0/Class I boundary at $T_{\text{bol}} = 65$ K gives reasonably good agreement with previous classifications for the other protostars. The class implied for L1709-SMM5 obtained from its $T_{\text{bol}}$ is not consistent with that implied by its $L_{\text{bol}}/L_{\text{submm}}$, and this source may be a transition object similar to L483-SMM1.

7.2.Envelope Masses

The mass of circumstellar material associated with each protostar has been estimated from its 850 $\mu$m flux density and the dust temperature derived from fitting its SED and is also given in Table 6. A dust opacity of $\kappa_{850\mu m} = 0.002$ m$^2$ kg$^{-1}$ has been assumed, consistent with the 1.3 mm dust opacity recommended by Ossenkopf & Henning (1994) for very dense regions for $\beta = 1.5$. The envelope masses of the protostars obtained in this way range from 0.01 to 2.15 $M_\odot$ and agree well with masses derived by other authors for pre-
Fig. 19.—Images of all 40 submillimeter cores identified in the sample of Lynds dark clouds. Contours show the 850 μm emission, the positions in Table 4 are represented by stars, and triangles represent IRAS sources from the PSC.
Fig. 19.—Continued
viously known sources (Bontemps et al. 1996; Launhardt et al. 1997; André, Ward-Thompson, & Barsony 2000).

7.2.1. Ratio of $M_{\text{env}}/L_{\text{bol}}$

Under the assumption that Class 0 and Class I protostars derive their luminosity primarily from accretion such that $L_{\text{bol}} = \frac{G \dot{M} M_*}{R_*}$, and that the accretion rate, $\dot{M}$, and stellar radius, $R_*$, are constant, the ratio $M_{\text{env}}/L_{\text{bol}}$ is proportional to $M_{\text{env}}/M_*$. If the Class 0/Class I division is set at $M_{\text{env}}/M_* = 1$ (such that Class 0 sources have $M_{\text{env}}/M_* > 1$), then $\dot{M} = \frac{10^{-6} \, M_\odot \, \text{yr}^{-1}}{R_* = 3 \, R_\odot}$ results in $M_{\text{env}}/L_{\text{bol}} > 0.1 \, M_\odot/L_\odot$ for Class 0 sources (André & Montmerle 1994). This criterion for classification identifies those same objects as Class 0 sources as does the $L_{\text{bol}}/L_{\text{submm}} > 50$ criterion above (§ 7.1.1; see also Table 6).

7.3. Outflow Properties

A correlation between outflow momentum flux, $F_{\text{CO}}$, with envelope mass was found by Bontemps et al. (1996) and has been confirmed for other source samples (e.g., Henning & Launhardt 1998). Class 0 sources drive more powerful and better collimated outflows than Class I protostars. Figure 31 plots $F_{\text{CO}}$ versus $M_{\text{env}}$ for the 10 protostars for which we have outflow data (Figs. 22–29). The outflow momentum flux for both L673-SMM1 and L673-SMM2 are lower limits owing to the confusion concerning the red outflow. The dashed line plotted is the best linear fit between $\log F_{\text{CO}}$ and $\log M_{\text{env}}$ found by Bontemps et al. (1996). It is clear that the momentum fluxes of outflows in our sample agree very well with those observed by Bontemps et al., with only two
sources lying at some distance from the relationship found by those authors. These are L1246-SMM1 (the Class 0 source, to the right of the dashed line in Fig. 31) and L1709-SMM5 (the Class I source to the left of the dashed line). The displacement of L1246-SMM1 might be explained by a wrongly assigned distance. It is listed in Table 1 as having $D = 730$ pc, and as such is the most distant in this sample. If this source were actually closer, its position in Figure 31 would shift to the left and down, since $M_{\text{env}} \propto D^2$ and $F_{\text{CO}} \propto D$. The overlapping red- and blueshifted lobes of the L1709-SMM5 outflow was suggested above (§ 6.3) to indicate we may be observing this source pole-on. Were this the case, the correction factor applied to $F_{\text{CO}}$ that accounts for a mean inclination angle and CO line optical depth may be severely overestimated and could explain the location of this source in Figure 31.

Bontemps et al. (1996) also find that outflows from Class 0 protostars are more efficient than those from Class I protostars, when $F_{\text{CO}}$ is compared with the maximum...
momentum flux available in stellar photons, $L_{\text{bol}}/c$. The outflow efficiency, given by the ratio $F_{\text{CO}}c/L_{\text{bol}}$, is listed in Table 6 for the 10 outflow sources mapped, and this trend is clearly evident: the Class 0 sources typically have $F_{\text{CO}}c/L_{\text{bol}} \approx 300$. Table 6 also illustrates the nature of L1709-SMM5 as an object in transition between Class 0 and Class I. L1246-SMM1 again stands out as having an outflow considerably weaker than other Class 0 sources. The outflow efficiency scales as $1/D$, so an overestimated distance might again help bring this source into line with the others in this sample. The distance of L1246 has been estimated by associating it with Cep OB3 (Paper I). If it were

Fig. 24.—Blueshifted outflows are clearly detected from both submillimeter cores in L673, the outflow from L673-SMM1 in the northeast, and the outflow from L673-SMM2 directed toward the southeast. It is less clear which source is responsible for the redshifted flow. The blueshifted gas is integrated between $V_{\text{LSR}} = -2.0$ and 3.0 km s$^{-1}$. Contours of the blueshifted flow from L673-SMM1 (top) are at 0.7 + 0.4$n$ K km s$^{-1}$, and for L673-SMM2 (bottom), they are at 2.0 + 1.0$n$ K km s$^{-1}$. The redshifted gas is integrated from 9.0 to 15.0 km s$^{-1}$ with contours at 7.0 + 2.0$n$ K km s$^{-1}$. The contours are overlaid on the SCUBA 850 $\mu$m image.

Fig. 25.—Outflow in L1165. Redshifted gas is integrated over the LSR velocity range $-1.0$ to 2.7 km s$^{-1}$ with contours at $2.6 + 0.7n$ K km s$^{-1}$, and the blueshifted gas is integrated from $-6.0$ to $-3.2$ km s$^{-1}$ with contours at $1.5 + 0.3n$ K km s$^{-1}$, where $n = 1, 2, 3, \ldots$. The contours are overlaid on the SCUBA 850 $\mu$m image.

Fig. 26.—Partly mapped outflow in L1172. Redshifted gas is integrated over the range 4.0 to 10 km s$^{-1}$ with contours at $8.0 + 2.0n$ K km s$^{-1}$, and blueshifted gas is integrated between $-5.0$ and 1.0 km s$^{-1}$ with contours at $4.0 + 1.0n$ K km s$^{-1}$. The contours are overlaid on the SCUBA 850 $\mu$m image.

Fig. 27.—Outflow in L1262. Redshifted gas is integrated over the range 6.0 to 10.5 km s$^{-1}$ with contours at $1.0 + 1.0n$ K km s$^{-1}$, and the blueshifted gas is integrated from $-3.0$ to 2.0 km s$^{-1}$ with contours at $0.5 + 0.5n$ K km s$^{-1}$. The contours are overlaid on the SCUBA 850 $\mu$m image.
close enough to raise its outflow efficiency by the factor of 4 or 5 needed to bring it in line with the Bontemps et al. correlation, it would have to be rather isolated.

7.4. Sizes

The emission from the Class 0 sources is extended, and some objects, such as L483-SMM1, clearly exhibit structure related to the outflow. All the sources identified as Class I protostars in Table 6 are unresolved apart from L1709-SMM5. L1709-SMM5 stands out among all the cores identified as protostellar in nature as being the most extended, and in many respects resembles the starless cores. This raises the possibility that L1709-SMM5 in fact comprises several sources in superposition along the line of sight. Higher resolution observations are needed to confirm this idea.

8. PHYSICAL PROPERTIES OF THE STARLESS CORES

The masses, column densities, and inferred space densities of those cores not containing embedded protostars are listed in Table 8, along with the protostar candidate L673-SMM3. The integrated flux densities at 850 μm have been measured within an aperture after the subtraction of background emission, as described in § 5.1. For some of the more extended cores, such as L260-SMM2, the subtraction of background emission may subtract extended emission from the core itself. However, in most cases, the background subtraction is clearly desirable in order to obtain integrated flux densities representing only the compact submillimeter core. The size of the aperture used was determined from radially averaged intensity profiles, after background subtraction, to include all the observed emission. Table 8 gives the diameter of the aperture used for each core. The masses were

| Protostar   | Mass ($M_\odot$) | Energy (J) | Extent (AU) | $\Delta V$ (km s$^{-1}$) | $\tau_d$ (yr) | Momentum Flux ($M_\odot$ km s$^{-1}$ yr$^{-1}$) |
|-------------|-----------------|------------|-------------|-------------------------|---------------|------------------------------------------|
| L260-SMM1   | 0.0002          | $4.8 \times 10^{32}$ | 7200        | 5.5                     | $0.6 \times 10^4$ | $0.4 \times 10^{-6}$                  |
| L663-SMM1   | 0.0062          | $>1.2 \times 10^{35}$ | $>23750$    | 23.0                    | $>0.5 \times 10^4$ | $>4.7 \times 10^{-5}$                 |
| L673-SMM1a  | 0.0052          | $7.4 \times 10^{34}$ | 48000       | 7.0                     | $3.3 \times 10^4$ | $5.7 \times 10^{-6}$                  |
| L673-SMM2a  | 0.0260          | $4.0 \times 10^{35}$ | 54000       | 7.0                     | $3.7 \times 10^4$ | $2.6 \times 10^{-5}$                  |
| L944-SMM1   | 0.0590          | $6.4 \times 10^{35}$ | 76400       | 11.0                    | $3.3 \times 10^4$ | $5.7 \times 10^{-5}$                  |
| L1165-SMM1  | 0.0134          | $8.2 \times 10^{34}$ | 48000       | 8.5                     | $2.7 \times 10^4$ | $1.1 \times 10^{-5}$                  |
| L1246-SMM1  | 0.0190          | $5.9 \times 10^{34}$ | 58400       | 6.0                     | $4.6 \times 10^4$ | $7.2 \times 10^{-6}$                  |
| L1262-SMM1  | 0.0039          | $2.9 \times 10^{34}$ | 26000       | 10.0                    | $1.2 \times 10^4$ | $8.3 \times 10^{-6}$                  |
| L1709-SMM1  | 0.0032          | $5.0 \times 10^{35}$ | 40000       | 11.0                    | $1.7 \times 10^4$ | $4.7 \times 10^{-6}$                  |
| L1709-SMM5  | 0.0171          | $1.5 \times 10^{35}$ | 21600       | 11.0                    | $0.9 \times 10^4$ | $5.2 \times 10^{-5}$                  |

* The outflow properties of both L673-SMM1 and L673-SMM2 are based only on the blueshifted gas.
The mean mass of the cores is $1.1 M_\odot$, which is systematically higher than those of the protostellar envelopes by approximately $0.6 M_\odot$. If the starless cores are indeed progenitors of the protostars in this sample, we might therefore expect that the starless cores will, in time, produce stars of $\sim 0.5--1 M_\odot$. This result must be taken with some caution, since different dust opacities and dust temperatures have been used for calculating the masses for each population, in such a way that these two factors both serve to increase the apparent mass of the starless cores. However, the assumption that the temperatures in the protostellar envelopes are higher than those in the starless cores is probably a good one, and even if the same dust opacity were used for all sources, the starless cores would still be more massive than the protostellar envelopes.

The 26 starless cores in Table 8 represent the largest sample of these objects for which submillimeter continuum images have been made to date and therefore provide a unique data set with which to study the properties of these objects. In particular, if the cores are isothermal, the radial intensity profile of the submillimeter emission can be directly inverted to determine the radial density profile in the cores. Analytical and numerical studies show that the mass infall rate during the protostellar phase depends on the radial density profile at the onset of collapse and on the equation of state of the material. Singular models have an $n \propto r^{-2}$ density profile resulting in a constant accretion rate (Shu 1977). Density profiles with a flatter inner region, however, will result in a high mass infall rate initially, possibly corresponding to the Class 0 phase, followed by a phase with a low accretion rate, possibly corresponding to the Class I phase (Foster & Chevalier 1993; Henriksen, Andrè, & Bontemps 1997). The evolution of a protostar will also depend on whether the core from which it is forming has an "edge." The Shu picture has star formation taking place in an essentially infinite reservoir of material, in which case the final mass of the star being formed will be determined by a local process, such as the interaction between its outflow and accretion. If, however, the core has a well-defined edge, the final stellar mass may be determined by the shape of the core in the precollapse phase.

The starless cores that have been studied to date in millimeter/submillimeter continuum emission do not appear to show the $r^{-2}$ density profile predicted by the singular isothermal model of Shu (1977). Instead, they have shallow density profiles in their inner regions, in qualitative agreement with models of magnetically supported cloud cores (Ward-Thompson et al. 1994; Andrè, Ward-Thompson, & Motte 1996; Motte, Andrè, & Neri 1998; Ward-Thompson et al. 1999; Shirley et al. 2000). The density profiles of a number of starless cores have also been studied in absorption in the mid-infrared (Bacmann et al. 2000). These also exhibit density profiles that flatten toward the center, and several also have sharp edges. Such profiles need very strong background magnetic fields to be supported, but they are also well fitted by Bonnor-Ebert–type hydrostatic equili-

### Table 6

**Properties of the Protostars in the Sample of Lynds Dark Clouds**

| Protostar       | $F_{\nu}$ (Jy) | $T_{\text{dust}}$ (K) | $L_{\text{bol}}$ ($L_\odot$) | $L_{\text{submm}}$ ($L_\odot$) | $T_{\text{bol}}$ (K) | $M_{\text{env/protostar}}$ ($M_\odot$) | $M_{\text{protostar}}/L_{\text{bol}}$ ($M_\odot/L_\odot$) | Outflow Efficiency | Class |
|-----------------|----------------|-----------------------|-------------------------------|-------------------------------|-----------------------|----------------------------------------|------------------------------------------------|-------------------|-------|
| L162-SMM1 ...... | ...            | 0.28                  | 22.0                          | 0.5                           | $6 \times 10^{-2}$     | 82                      | 120 0.03 0.07 260 0.02 30 1                         | 00                | II    |
| L260-SMM1 ...... | 0.67           | 0.11                  | 28.0                          | 0.6                           | $3 \times 10^{-2}$     | 250                     | 104 0.01 0.02 230 0.02 30 1                         | 00                | I     |
| L483-SMM1 ...... | 23.62          | 2.67                  | 27.0                          | 9.0                           | 0.10                  | 91                      | 55 0.33 0.04 90 0.02 30 1                         | 00                | 0     |
| L663-SMM1 ...... | ...            | 1.93                  | 21.0                          | 2.8                           | 0.10                  | 29                      | 31 0.51 0.18 82 0.02 30 1                         | 00                | I     |
| L673-SMM1 ...... | 5.28           | 0.60                  | 24.0                          | 2.8                           | 0.05                  | 59                      | 70 0.20 0.07 100 0.02 30 1                         | 00                | I     |
| L673-SMM2 ...... | 6.88           | 0.97                  | 22.0                          | 2.8                           | 0.07                  | 38                      | 49 0.35 0.12 45 0.02 30 1                         | 00                | I     |
| L944-SMM1 ...... | 2.54           | 0.42                  | 21.0                          | 4.4                           | 0.17                  | 27                      | 30 0.88 0.20 63 0.02 30 1                         | 00                | I     |
| L1165-SMM1 ...... | ...            | 1.23                  | 28.0                          | 11.7                          | 0.10                  | 115                     | 59 0.32 0.03 50 0.02 30 1                         | 00                | I     |
| L1172-SMM1 ...... | 3.08           | 0.35                  | 20.0                          | 1.8                           | 0.06                  | 32                      | 62 0.31 0.17 280 0.02 30 1                         | 00                | I     |
| L1246-SMM1 ...... | 4.00           | 0.78                  | 19.0                          | 8.0                           | 0.31                  | 26                      | 62 2.15 0.27 40 0.02 30 1                         | 00                | I     |
| L1062-SMM1 ...... | ...            | 0.89                  | 20.0                          | 1.1                           | 0.03                  | 40                      | 57 0.16 0.14 370 0.02 30 1                         | 00                | I     |
| L1709-SMM1 ...... | 7.55           | 1.01                  | 26.0                          | 1.8                           | 0.02                  | 66                      | 67 0.09 0.06 130 0.02 30 1                         | 00                | I     |
| L1709-SMM5 ...... | 8.36           | 0.54                  | 25.0                          | 0.9                           | 0.01                  | 75                      | 44 0.05 0.06 270 0.02 30 1                         | 00                | I     |

* Classifications ascribed by this work, not based on near/mid-infrared data.

### Table 7

**IRAS Flux Densities Derived from HIRES Images for Several Protostars**

| Protostar       | IRAS Association | $F_{\nu}(12 \mu m)$ (Jy) | $F_{\nu}(25 \mu m)$ (Jy) | $F_{\nu}(60 \mu m)$ (Jy) | $F_{\nu}(100 \mu m)$ (Jy) |
|-----------------|------------------|--------------------------|--------------------------|--------------------------|---------------------------|
| L673-SMM1 ...... | 19180+1116       | 1.0                      | 3.9                      | 11.9                     | 57.8L                     |
| L673-SMM2 ...... | 19180+1114       | 0.2                      | 0.3                      | 6.0                      | 57.8L                     |
| L944-SMM1 ...... | ...              | 0.2L                     | 0.2L                     | 1.3                      | 10.0                      |
| L1709-SMM1 ...... | 16285--2355      | 0.7                      | 1.8                      | 3.8                      | 26.1L                     |
| L1709-SMM5 ...... | 16285--2356      | 0.1                      | 1.4                      | 3.5                      | 26.1L                     |
brium models for isothermal, self-gravitating cores confined by external pressure.

Radial intensity profiles for all the starless cores in our sample were obtained from the SCUBA 850 µm images by averaging data points in a 3") wide ring at radius $r$ from the core center (Table 4) from $r = 0''$ to $450''$ or the edge of the map. The mean ellipticity of the starless cores is 1.5, and the assumption of circular symmetry should therefore result in a representative intensity profile (see also André et al. 1996), although there is clearly scope for more detailed modeling. Eighteen of the cores have had DC offsets subtracted to obtain sensible zero levels for the background. Emission from nearby cores or protostars were not removed before the profile fitting. A single power-law model for the density distribution did not fit most of the starless cores, so the intensity profiles have been modeled with a density dis-

Fig. 30.—SEDs of all the protostars in the survey. The lines are gray-body fits to the submillimeter and far-infrared data, as described in the text.
distribution consisting of two power laws. The density is assumed to have the form $n \propto r^{-\gamma}$ from $r = 100$ AU to a radius $r_0$, beyond which $n \propto r^{-\delta}$. The density at $r < 100$ AU was assumed to be zero to avoid any singularity. An outer cutoff radius $r_1$ has also been implemented to model the observed edge of the profile. A temperature $T_{\text{dust}} = 12$ K has been assumed, and dust opacity is $\kappa_{850 \mu m} = 0.0012$ m$^2$ kg$^{-1}$. The resulting intensity profile was calculated from the model by integrating the density distribution along the line of sight and convolving it with a 15" Gaussian to simulate the JCMT beam at 850 $\mu$m. The four parameters $r_0$, $r_1$, $\gamma$, and $\delta$ were then adjusted to produce the best fit. The density at $r_0$, $n_0$, was normalized to reproduce the observed flux density.

Profiles of all the starless cores were fitted, except for L158-SMM2, which is a suspected artifact of the regridding algorithm (§ 5.1), and L1709-SMM4, which is an extended ridge and clearly should not be modeled by a spherically symmetric core (Fig. 19). All the fitted cores apart from L673-SMM6 and L951-SMM2 show a flat inner part in the intensity profile, with a steepening in the radial power-law exponent beyond $r_0$, out to $r_1$, where the intensity profile merges into the background. Excluding these two cores, we find mean values of $\gamma = 0.9 \pm 0.3$ and $\delta = 1.9 \pm 0.3$. Figure 32 shows one of the best fits, L694-SMM1, an average fit, L1262-SMM2, and a very poor fit, L673-SMM7. The parameters of these fits are also given in Table 8. For none of our cores is the radial density profile steeper than $r^{-3}$, as was found for three starless cores by Bacmann et al. (2000). However, the best-fit values of $\delta$ are positively correlated with values of $r_1$ in our fitting, so that a larger value of $\delta$ can, to some extent, be compensated for by a larger value of $r_1$.

Both the results presented here and previous work seem to rule out the singular isothermal spheres developed by Shu and coworkers (but see also the recent, more detailed, Fig. 31.—Outflow momentum flux (Table 5) vs. envelope mass. Open circles are the Class 0 sources, filled circles are Class I sources. The dashed line is the best fit found by Bontemps et al. (1996).

### Table 8

| Core          | $F_{\nu}$(850 $\mu$m) (Jy) | Aperture (arcsec) | Mass ($M_\odot$) | $N(H_2)$ ($\times 10^{22}$ m$^{-2}$) | $m(H_2)$ ($\times 10^{13}$ m$^{-3}$) | $n_0$ ($\times 10^{11}$ m$^{-3}$) | $r_0$ (AU) | $r_1$ (AU) | $\gamma$ | $\delta$ |
|--------------|----------------------------|------------------|-----------------|--------------------------------------|-------------------------------------|----------------------------------|------------|------------|----------|----------|
| L55-SMM1.....| 0.34                       | 80               | 0.16            | 2.5                                  | 1.3                                 | 0.20                             | 8000       | 13000      | 1.3      | 2.0      |
| L57-SMM1.....| 1.43                       | 200              | 0.67            | 1.7                                  | 0.3                                 | 0.47                             | 6000       | 20000      | 0.7      | 1.6      |
| L63-SMM1.....| 1.31                       | 140              | 0.61            | 3.1                                  | 0.9                                 | 1.55                             | 4000       | 50000      | 0.7      | 1.8      |
| L158-SMM1....| 1.02                       | 180              | 0.48            | 1.5                                  | 0.3                                 | 0.20                             | 25000      | 45000      | 0.9      | 2.0      |
| L158-SMM2....| 0.19                       | 60               | 0.09            | 2.4                                  | 1.7                                 | ...                              | ...        | ...        | ...      | ...      |
| L260-SMM2....| 2.10                       | 200              | 0.99            | 2.4                                  | 0.5                                 | 0.22                             | 13000      | 25000      | 1.0      | 2.0      |
| L328-SMM1....| 0.84                       | 90               | 0.56            | 4.8                                  | 1.9                                 | 1.72                             | 3500       | 10000      | 0.6      | 2.1      |
| L673-SMM3a...| 0.34                       | 60               | 0.56            | 4.3                                  | 1.6                                 | 6.88                             | 1500       | 47500      | 1.5      | 2.0      |
| L673-SMM4....| 0.69                       | 100              | 1.14            | 3.2                                  | 0.7                                 | 2.17                             | 3500       | 67000      | 0.6      | 2.0      |
| L673-SMM5....| 0.55                       | 80               | 0.91            | 4.0                                  | 1.1                                 | 1.60                             | 3900       | 29000      | 0.6      | 2.2      |
| L673-SMM6....| 0.53                       | 100              | 0.88            | 2.5                                  | 0.6                                 | 5.15                             | 1000       | 60000      | 2.6      | 1.8      |
| L673-SMM7....| 0.24                       | 50               | 0.39            | 4.4                                  | 2.0                                 | 1.65                             | 3000       | 75000      | 0.9      | 1.5      |
| L673-SMM8....| 1.00                       | 110              | 1.65            | 3.8                                  | 0.8                                 | 1.25                             | 3500       | 33000      | 0.6      | 1.6      |
| L694-SMM1....| 1.38                       | 120              | 1.58            | 4.4                                  | 1.0                                 | 0.84                             | 8000       | 45000      | 0.8      | 2.7      |
| L860-SMM1....| 0.27                       | 80               | 2.41            | 1.9                                  | 0.2                                 | 0.10                             | 15000      | 40000      | 1.5      | 1.8      |
| L860-SMM2....| 0.15                       | 50               | 1.33            | 2.7                                  | 0.5                                 | 0.07                             | 15000      | 37000      | 1.7      | 1.8      |
| L951-SMM1....| 0.14                       | 60               | 1.22            | 1.7                                  | 0.3                                 | 0.23                             | 8000       | 20000      | 1.2      | 1.6      |
| L951-SMM2....| 0.15                       | 60               | 1.33            | 1.9                                  | 0.3                                 | 0.57                             | 2000       | 80000      | 2.4      | 1.2      |
| L1014-SMM1...| 0.55                       | 90               | 0.40            | 3.1                                  | 1.2                                 | 0.71                             | 4000       | 18000      | 1.4      | 1.8      |
| L1172-SMM2...| 0.32                       | 50               | 1.34            | 5.9                                  | 1.8                                 | 1.74                             | 3500       | 40000      | 0.6      | 1.7      |
| L1172-SMM3...| 1.30                       | 180              | 4.61            | 1.8                                  | 0.2                                 | 0.07                             | 50000      | 110000     | 0.9      | 1.7      |
| L1246-SMM2...| 0.33                       | 50               | 3.19            | 6.0                                  | 1.1                                 | 1.02                             | 6000       | 33000      | 0.8      | 2.3      |
| L1262-SMM2...| 1.31                       | 100              | 0.96            | 6.0                                  | 2.0                                 | 12.40                            | 1000       | 48000      | 0.9      | 1.5      |
| L1704-SMM1...| 0.57                       | 110              | 0.27            | 2.2                                  | 0.8                                 | 0.46                             | 5000       | 16000      | 0.9      | 2.1      |
| L1709-SMM2...| 1.42                       | 120              | 0.67            | 4.5                                  | 1.6                                 | 2.47                             | 3500       | 40000      | 0.7      | 1.8      |
| L1709-SMM3...| 1.55                       | 120              | 0.73            | 5.0                                  | 1.7                                 | 3.76                             | 2000       | 45000      | 0.7      | 1.4      |
| L1709-SMM4...| 2.51                       | 180              | 1.18            | 3.6                                  | 0.8                                 | ...                              | ...        | ...        | ...      | ...      |

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*L673-SMM3 is a candidate protostar (see § 6.2.4).*
modeling of starless cores by Evans et al. 2001) and the logotropic model having \( n \propto r^{-1} \) at large radii proposed by McLaughlin & Pudritz (1997), as the precollapse density profile of starless cores. Instead, the radial density profiles resemble more closely those expected for pressure-bounded Ebert spheres (e.g., Foster & Chevalier 1993) or for which magnetic pressure is important (e.g., Ciolek & Mouschovias 1994; Basu & Mouschovias 1995).

9. STATISTICS, TIMESCALES, AND IMPLICATIONS FOR LOW-MASS STAR FORMATION

Assuming star formation is a homogeneous process in our sample of dark clouds, and that the starless cores–Class 0 sources–Class I protostars represent an evolutionary sequence, statistical lifetimes of these different stages can be derived from the relative numbers of objects in these different phases. We find a total of seven Class 0 sources, five Class I sources, one candidate protostar, and 26 starless cores. All these cores and protostars are observed in 21 clouds, i.e., in half of the sample of optically dark molecular clouds. Fifty percent of the clouds are therefore quiescent.

9.1. Ratio of Class 0 to Class I Sources

One of the most remarkable results of this survey is that the ratio of Class 0 sources to Class I sources is not 1 to 10, as has been observed in previous surveys of the \( \rho \) Ophiuchi main cloud (André & Montmerle 1994; Motte et al. 1998), which are also believed to be complete. Furthermore, this result comes in spite of the fact that a significant fraction of the cores in our sample are associated with the \( \rho \) Ophiuchi complex. Separating our sample into those clouds that are associated with \( \rho \) Ophiuchus and those that are not results in rather small numbers, but the comparison is nevertheless worth investigating. For the Lynds clouds associated with \( \rho \) Ophiuchus (see Table 1), we find three Class I protostars, one Class II source, and 10 starless cores, giving a Class 0–to–Class I ratio consistent with earlier results. For the non–\( \rho \) Ophiuchi clouds, we find seven Class 0 sources, two Class I sources, and 17 starless cores. Excluding the clouds in \( \rho \) Ophiuchus therefore makes the potential ratio of Class 0 to Class I sources even higher.

We have considered whether the discrepancy between the ratio of Class 0 to Class I sources observed in Lynds dark clouds compared with that observed for \( \rho \) Ophiuchus is the result of the completeness limit of our sample. For the full sample, and the statistics are more consistent with a 1 : 1 ratio. This suggests that the lifetime of a Class 0 source in a Lynds dark cloud is as long as the lifetime of a Class I source, a result that is supported by the dynamical lifetimes of the outflows. The mean dynamical age of the Class 0 outflows presented here is \( 2.7 \times 10^4 \) yr, compared with the Class I outflows of \( 1.8 \times 10^4 \) yr. Even if the dynamical lifetime of the outflow in L1246 is overestimated because of the uncertainty in its distance, the mean age of the remaining Class 0 outflows is \( 2.2 \times 10^4 \) yr, similar to that measured for the Class I sources.

The lifetime of the Class I phase is believed to be reasonably well established owing to complete infrared surveys of the \( \rho \) Ophiuchus and Taurus star-forming regions (Wilking et al. 1989; Kenyon et al. 1990). If a lifetime of \( \sim 2 \times 10^5 \) yr is adopted for Class I protostars, the statistical lifetime of Class 0 sources in this sample will be similar. Of course, this assumes that stars form in molecular clouds continuously and in a homogeneous fashion. However, the different ratio of the numbers of Class 0 to Class I sources found here, compared with other surveys, might indicate that stars do not form in such a homogeneous way, demonstrating that the star formation process
is highly dependent on the local environment. There are three ways this might work:

1. Class 0 sources may represent a different branch of star formation and may not be precursors of Class I sources. Indeed, Jayawardhana, Hartmann, & Calvet (2001) have suggested that some Class 0 sources may be protostars forming in very high density regions and are, in fact, at the same evolutionary stage as the Class I sources forming in lower density environments. If this were true, however, it would imply that the Lynds dark clouds are of higher density than the cores in $\rho$ Ophiuchus. A comparison of our results with those of Motte et al. (1998) shows the opposite to be the case.

2. If Class 0 sources are precursors to Class I sources, it may be that the environment, with its local initial conditions, determines how long the Class 0 phase lasts. For example, if the Lynds clouds represent a more quiescent environment than the clouds in $\rho$ Ophiuchus, there may be more time for the starless cores in the Lynds clouds to evolve toward a singular isothermal sphere before the onset of collapse. In this case, the collapse might progress with a constant accretion rate, and the Class 0 phase could then last longer in these clouds. In $\rho$ Ophiuchus, the star formation may be triggered before the starless cores reach a singular state, in which case a more dramatic Class 0 phase (higher accretion rates) would precede the Class I phase. However, none of the starless cores detected here has the characteristics of a singular isothermal sphere on small scales.

3. Perhaps a more likely possibility is that star formation is not a steady process. If star formation relies heavily on triggering, the sample of embedded protostars in $\rho$ Ophiuchus may be dominated by an older, more evolved population due to a burst of star formation some $\sim 10^{5}$ yr ago. Indeed, on large scales, it is thought that star formation in $\rho$ Ophiuchus may have been triggered by a supernova in the Scorpio-Centaurus OB association (de Geus 1992). Motte et al. (1998) conclude that the small-scale structure of the $\rho$ Ophiuchi main cloud is also consistent with the passage of a shock, and that the youth of the protostars over a large region indicate star formation must have been synchronized by an external mechanism.

The previous, short, lifetimes derived for Class 0 protostars in $\rho$ Ophiuchus also had another important implication for accretion during early protostellar evolution. A distinguishing feature of Class 0 protostars is that they are surrounded by a considerably larger reservoir of circumstellar material than Class I protostars (see, e.g., Table 6), and a short time spent in this phase implied a considerably higher accretion rate for Class 0 protostars compared with the Class I phase. If, instead, protostars spend a similar amount of time in the Class 0 and Class I phases, there may be no such initial period of rapid accretion.

9.2. Ratio of Starless Cores to Protostars

There are 26 starless cores compared with a total of 12 or 13 embedded protostars in our sample of Lynds clouds, so the ratio is approximately 2:1. This suggests that the lifetime of a starless core as detected in the SCUBA survey is only twice as long as the lifetime of an embedded protostar. The lifetime of the Class 0 and Class I phase combined is $\sim 4 \times 10^{5}$ yr, and from this the estimated lifetime of starless cores is $\sim 8 \times 10^{5}$ yr. This is only 2–3 times the free-fall time for an average core in the sample, $\sim 3 \times 10^{5}$ yr. Using the power-law density profiles given in Table 8, we have examined whether the thermal pressure of gas at a temperature of 10–12 K is sufficient to provide support against gravitational collapse for the starless cores on scales $r \sim 10^{4}$ AU. In all cases, a velocity dispersion of $\sim 0.1$–0.2 km s$^{-1}$ is required, comparable with the isothermal sound speed for gas at 10 K. It therefore seems entirely feasible that the starless cores are in hydrostatic equilibrium and do not need the support of magnetic fields on these size scales. The cores are, therefore, on the verge of collapse, and it is unlikely that strong magnetic fields are important for the collapse dynamics of starless cores once they reach densities of $\sim 10^{10}$ m$^{-3}$. Of course, this does not rule out the possibility that magnetic fields may be important for providing support in molecular clouds on larger size scales, nor does it suggest that magnetic fields may not be important dynamically for the formation of the starless cores.

9.3. Ratio of Quiescent Clouds to Star-forming Clouds

Since all the compact cores are observed in half of the sample of dark clouds the other half of the sample are quiescent clouds. The combined duration of the starless core phase and embedded phase is $\sim 1 \times 10^{6}$ yr and the statistical lifetime of a quiescent Lynds class 6 cloud is thus also $\sim 1 \times 10^{6}$ yr. The comparison made here is, however, difficult since all the clouds have different sizes, and some of the clouds are complexes of smaller clouds (e.g., L673). Nevertheless, these clouds are known to have reasonably long lifetimes and should at least be stable for long enough to form stars. Some T Tauri stars are also still found in this type of cloud, suggesting that the clouds have lifetimes $\gtrsim 10^{6}$ yr.

10. SUMMARY AND CONCLUSIONS

We have surveyed a sample of optically selected dark clouds for the submillimeter dust emission associated with embedded protostars and starless dense cores. The optical selection criterion is equivalent to a limiting column density ($A_v \gtrsim 10$ mag) and avoids biases relating to the infrared properties of older protostars and other indicators of star formation potential or activity. Furthermore, the clouds are predominantly nearby, giving a sample for which good spatial resolution can be obtained. All clouds were imaged at $\lambda = 850$ $\mu$m, with a spatial resolution of $\sim 2,000$–$10,000$ AU, depending on the distance. A total of 42 dark clouds, covering an area of 0.5 deg$^2$, are included in the survey.

Compact submillimeter cores have been identified in the clouds, and we have established whether the cores contain embedded protostars through a combination of association with $IRAS$ emission and/or the presence of high-velocity CO (2–1) emission from protostellar outflows. The survey is complete for starless cores, and for Class 0 and Class I protostars, to a mass limit of 0.015 $M_\odot$. Half of the clouds, 21 in total, do not contain any compact submillimeter cores and are therefore quiescent as far as star formation activity is concerned. The other half contain a total of seven Class 0 protostars, five Class I protostars, one Class II source, a candidate protostar (L673-SMM3), and 26 starless cores. The ratio of Class 0 to Class I protostars found in this survey is therefore close to unity and is not consistent with the previous result found for the $\rho$ Ophiuchi cloud, where a
ratio of 1 to 10 has been observed (André & Montmerle 1994; Motte et al. 1998). The ratio of starless cores to cores containing embedded protostars is approximately 2 to 1. The implied lifetimes of the Class 0 and starless core phases are therefore \(\sim 10^3\) and \(\sim 8 \times 10^3\) yr, respectively.

The different ratio of Class 0 to Class I protostars detected in our survey compared with previous work suggests star formation is highly dependent on the local environment. Our new results provide several possibilities for the nature of low-mass star formation: (1) Class 0 sources are at the same evolutionary stage as Class I sources, but represent a different branch of star formation, e.g., star formation in high density environments. However, a comparison between our study and that of Motte et al. (1998) suggests the Lynds clouds are actually less dense than those in \(\rho\) Ophiuchus. (2) If Class 0 sources are precursors to Class I sources, the local environment may determine the lifetime of the Class 0 phase. For example, if the Lynds clouds are more quiescent than those in \(\rho\) Ophiuchus, they may have more time to evolve toward the singular \(\propto r^{-2}\), which predicts a more uniform accretion rate. However, none of the starless cores detected here has the characteristics of a singular isothermal sphere. (3) Star formation is not steady, and relies heavily on triggering. The ratio of Class 0 to Class I protostars in \(\rho\) Ophiuchus can then be explained by being dominated by an older, more evolved population caused by a burst of star formation some \(\sim 10^5\) yr ago. We regard this as the most likely possibility. Furthermore, if the lifetime of the Class 0 phase is actually similar to that of the Class I phase, Class 0 protostars may not have such dramatically high accretion rates compared with Class I protostars, as has previously been assumed.

The lifetime of the starless cores found in this survey is similar to the \(\sim 10^3\) yr derived from surveys using the lack of an \(\textit{IRAS}\) association to define “starless” (e.g., Lee & Myers 1999). The cores therefore last only 2–3 free-fall times before collapsing. Temperatures of only \(\sim 10–12\) K are needed for the dominant support mechanism of the cores to be thermal pressure. The starless cores are therefore on the verge of collapse, and it is unlikely that strong magnetic fields are important for the collapse dynamics of the cores on scales \(r \sim 10^4\) AU. Further work is needed to determine the velocity structure of these cores through molecular line spectroscopy.

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McLaughlin, D. E., & Pudritz, R. E. 1997, ApJ, 476, 750
Moriarty-Schieven, G. H., & Snell, R. L. 1989, ApJ, 338, 952
Motte, F., & André, P. 2001, A&A, 365, 440
Motte, F., André, P., & Neri, R. 1998, A&A, 336, 150
Myers, P. C., Fuller, G. A., Mathieu, R. D., Beichman, C. A., Benson, P. J., Schild, R. E., & Emerson, J. P. 1987, ApJ, 319, 340
Myers, P. C., Heyer, M., Snell, R., & Goldsmith, P. 1988, ApJ, 324, 907
Myers, P. C., & Ladd, E. F. 1993, ApJ, 413, L47
Myers, P. C., Linke, R. A., & Benson, P. J. 1983, ApJ, 264, 517
Nozawa, S., Mizuno, A., Teshima, Y., Ogawa, H., & Fukui, Y. 1991, ApJS, 77, 647
Ossenkopf, V., & Henning, Th. 1994, A&A, 291, 943
Parker, N. D. 1988, MNRAS, 235, 139
———. 1989, Ph.D. thesis, Univ. Cambridge
———. 1991, MNRAS, 251, 63
Parker, N. D., Padman, R., & Scott, P. F. 1991, MNRAS, 252, 442
Robert, C., & Pagani, L. 1993, A&A, 271, 282
Shirley, Y. L., Evans, N. J., Rawlings, J. M. C., & Gregersen, E. M. 2000, ApJS, 131, 249
Shu, F. H. 1977, ApJ, 214, 488
Tafalla, M., Myers, P. C., Mardones, D., & Bachiller, R. 2000, A&A, 359, 967
Tapia, M., Persi, P., Bohigas, J., & Ferrari-Toniolo, M. 1997, AJ, 113, 1769
Tomita, Y., Saito, T., & Ohtani, H. 1979, PASJ, 31, 407
Visser, A. E. 2000, Ph.D. thesis, Univ. Cambridge
Visser, A. E., Richer, J. S., & Chandler, C. J. 2001, MNRAS, 323, 257 (Paper I)
Ward-Thompson, D., Motte, F., & André, P. 1999, MNRAS, 305, 143
Ward-Thompson, D., Scott, P. F., Hills, R. E., & André, P. 1994, MNRAS, 268, 276
Wilking, B. A., Lada, C. J., & Young, E. T. 1989, ApJ, 340, 823
Williams, J. P., Blitz, L., & McKee, C. F. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 97
Yonekura, Y., Dobashi, K., Mizuno, A., Ogawa, H., & Fukui, Y. 1997, ApJS, 110, 21