The initial conditions of isolated star formation - VI.
SCUBA mapping of prestellar cores.

J. M. Kirk\textsuperscript{1,2}, D. Ward-Thompson\textsuperscript{1} and P. Andr\textsuperscript{e}\textsuperscript{3}

\textsuperscript{1} Department of Physics and Astronomy, Cardiff University, 5 The Parade, Cardiff, CF24 3YB
\textsuperscript{2} Department of Astronomy, 207 Astronomy Building, 1002 West Green St, Urbana, IL 61801, USA
\textsuperscript{3} CEA, DSM, DAPNIA, Service d’Astrophysique, C.E. Saclay, F-91191 Gif-sur-Yvette Cedex, France

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ABSTRACT
Observations have been carried out with the submillimetre common-user bolometer array (SCUBA) at the James Clerk Maxwell Telescope (JCMT) of regions of comparatively isolated star formation in molecular cloud cores. 52 starless cores were observed, which are molecular cloud cores that do not contain any sign of protostellar activity such as infrared sources or bipolar outflows. These are all therefore candidate prestellar cores, which are believed to represent the stage of star formation that precedes the formation of a protostar. 29 of the 52 cores were detected at 850 \( \mu \)m at varying levels of signal-to-noise ratio greater than 3\( \sigma \) at peak, while 23 of the cores were observed but not detected. The mean detection lower limit of the data corresponds roughly to an \( A_V \sim 15 \) under typical assumptions. The detected cores were split into ‘bright’ cores and ‘intermediate’ cores, depending on their peak flux density at 850 \( \mu \)m. Those with peak 850-\( \mu \)m flux densities greater than 170 mJy/beam were designated ‘bright’ cores. Those with peak 850-\( \mu \)m flux densities less than this value were designated ‘intermediate’ cores. This dividing line corresponds to a mean detection limit of 10\( \sigma \) at peak, and an approximate \( A_V \sim 50 \) under typical assumptions. 13 of the 29 detected cores are found to be bright and 16 are intermediate. The data are combined with our previously published ISO data, and the physical parameters of the cores, such as density and temperature, are calculated. The bright cores are detected with sufficiently high signal-to-noise ratio to allow their structure to be mapped. Radial flux density profiles of these show flattened inner regions and sharp boundaries, consistent with previous observations of prestellar cores. Detailed fitting of the bright core radial profiles shows that they are not critical Bonnor-Ebert spheres, in agreement with previous findings. However, we find that intermediate cores, such as B68 (which has previously been claimed to be a Bonnor-Ebert sphere), may in fact be consistent with the Bonnor-Ebert criterion, suggesting perhaps that cores pass through such a phase during their evolution. We also find that the masses of the bright cores have a mean value of approximately the same order as their virial masses. We make rough estimates of core lifetimes based on the statistics of detections and find that the lifetime of a prestellar core is roughly \( \sim 3 \times 10^5 \) years, while that of a bright core is \( \sim 1.5 \times 10^5 \) years. Comparisons with some models that regulate collapse using either magnetic fields or turbulence show that no model can match all of the data. Models that are tuned to fit the total prestellar core lifetime, do not predict the relative numbers of cores seen at each stage.

Key words: stars: formation – ISM: dust – infrared: ISM – submillimetre: ISM

1 INTRODUCTION

Star formation occurs in dense cores within molecular clouds (e.g. Williams, Blitz & McKee 2000). Study of such regions was hampered for many years by their very large optical depths at near-infrared and optical wavelengths. It is only since the opening up of the far-infrared to submillimetre regime that astronomers have been able to study molecular clouds in detail. In this series of papers we report on a programme of molecular cloud core studies at infrared and submillimetre wavelengths.

Theories of star formation have until now lacked a
detailed observational determination of the initial conditions of the protostellar collapse phase (e.g. see: André, Ward-Thompson & Barsony 2000 for a review). The pre-protostellar (or prestellar for short) core phase (Ward-Thompson et al. 1994 – hereafter Paper I) is believed to be the stage of star formation that precedes the formation of a protostar and hence should represent observationally the initial conditions of protostellar collapse.

Some recent observations have even indicated that the Initial Mass Function (IMF) of stars may be determined at the prestellar core stage (Motte, André & Neri 1998; Motte et al. 2001). Furthermore, theory predicts that the core geometry prior to this stage is critical in determining the manner of collapse (e.g. Whitworth & Summers 1985; Foster & Chevalier 1993; Whitworth et al. 1996). For example, a decreasing accretion rate is obtained when the initial radial density profile is relatively flat in the centre, and steepens towards the edge (Foster & Chevalier 1993; Henriksen, André & Bontemps 1997; Whitworth & Ward-Thompson 2001). Therefore it is of vital importance to star formation theories to determine observationally the physical parameters of prestellar cores.

Molecular line surveys of dense cores by Myers and co-workers identified a significant number of isolated cores (Myers & Benson 1983; Myers et al. 1988; Benson & Myers 1989). Comparisons of these surveys with the IRAS point source catalogue detected a class of core that had no associated infrared source. The lack of an embedded source led to the classification of these as ‘starless’ cores (Beichman et al. 1986). In this series of papers we have been studying starless cores in some detail.

In Paper I (Ward-Thompson et al. 1994) we found that the cores all appeared to follow a form of density profile that was relatively flat in the centre and steeper towards the edge. This is similar to the profiles predicted by theory to produce a decreasing accretion rate with time (Whitworth & Summers 1985; Foster & Chevalier 1993). In Papers II & III (André, Ward-Thompson & Motte 1996; Ward-Thompson, Motte & André 1999) we found that the radial density profiles of the cores appear similar to those predicted by magnetically-regulated models of star formation (e.g. Mouschovias 1991), the details of the time-scales required by the models at different stages did not appear to match exactly the life-times calculated from the numbers detected at each evolutionary stage. The flat inner radial density profiles were also seen in absorption at 7 & 15 μm using ISO/CAM (Bacmann et al., 2000).

In Paper IV (Jessop & Ward-Thompson 2001) we showed that a temperature gradient from the outside-in was probably required to explain the data. This is significant because a decrease in temperature could potentially produce a decrease in submillimetre flux, and hence possibly explain the apparent flattening observed towards the centre of prestellar cores.

However, in Paper V (Ward-Thompson, André & Kirk 2002) we showed that although the edges of prestellar cores appear warmer than their centres. This is consistent with external heating of the cores. The central regions of cores are nevertheless consistent with being isothermal (at the resolution of ISOPHOT). Hence the flattening previously observed in the centres of prestellar cores’ submillimetre radial flux density profiles translates directly into a flattening of their volume density profiles. A recent claim that this is not the case (Zucconi, Walmsley & Galli 2001) does not take account of the fact mentioned above that we also see the same form of radial density profile in absorption (Bacmann et al 2000) towards prestellar cores as we see in emission. This cannot be explained by a temperature gradient. A larger ISOPHOT survey of one of our sample, L183, was carried out by Lehtinen et al., (2003), who found results consistent with our survey.

The significance of the form of the radial profile is that it determines the subsequent nature of the protostellar collapse. The form of profile that produces a decreasing accretion rate with time appears consistent with the observed relative numbers of Class 0 and Class I protostars (André, Ward-Thompson & Barsony 1993; André 1994; Ward-Thompson 1996) and is also consistent with a decreasing accretion rate extending throughout the pre-main-sequence phase (e.g. Kenyon & Hartmann 1995; Safier, McKee & Stahler 1997).

Recent radiative transfer modelling (Stamatellos & Whitworth 2003; Stamatellos et al., 2004) indicates that submillimetre wavelengths are the best to use for studying density variations in cold molecular cloud cores. In this paper we present the results of a SCUBA survey of prestellar cores at wavelengths of 450 and 850 μm to study further the detailed morphologies of prestellar cores.

2 THE SAMPLE

Our sample of cores is mainly derived from the molecular line surveys of dense cores by Myers and co-workers (Myers & Benson 1983; Myers et al. 1988; Benson & Myers 1989), by choosing only those cores that have no associated infrared sources. These cores are known generally as ‘starless’ cores (Beichman et al. 1986). As such, our sample is an approximate subset of the roughly 200 cores catalogued by Jijina et al. (1999). We have also added a couple of cores that we ourselves found to be strong submillimetre sources (L1689SMM and L1521SMM). In addition, there are two cores with nearby star formation that may have affected their ‘starless’ status – L43 and L1524.

The sample contains a total of 52 cores, which are listed in Tables 1–3. The majority of the cores lie in or near the constellations of Taurus-Auriga (22 cores) and Ophiuchus (21 cores). Of the remaining cores, five lie in Aquila and four lie in Cepheus. Some cores form part of more extended molecular cloud structures, while others are more isolated Bok globules (e.g. Bok & Reilly 1947).

Figures 1 & 2 show the distribution of the cores in the Taurus-Auriga and Ophiuchus regions respectively. It can be seen that the cores do not cluster in the centres of dense molecular clouds. For example, in Figure 1 the cores can be seen to be scattered apparently randomly across the Taurus molecular cloud. Likewise, in Figure 2 it can be seen that some of the cores lie near to the cluster-forming ρ Oph main cloud, but none of them lie directly within it. All lie either on the fringes of the cloud or along the filamentary streamers to the north. We note that not all of our sample of cores were detected in NH₃, and so not all may in fact be dense cores – some may be simply sight-lines with high column density.
Figure 1. Image of the IRAS 100µm emission from the region of Taurus-Auriga (Wheelock et al. 1994). Superposed are contours of CO (J=1→0) intensity (Dame, Hartman & Thaddeus 2001). The positions of the cores in our sample are marked.
Figure 2. Image of the IRAS 100µm emission from the region of Ophiuchus (Wheelock et al. 1994). Superposed are contours of CO (J=1→0) intensity (Dame et al., 2001). The positions of the cores in our sample are marked.
found value of 168
mean value. There are two exceptions to this: The L1551
of Figure 1, is actually part of the
and the L1582A core, which is visible at the southern edge
the L134/L183 cloud and L1778. These can be seen in the
ance as the rest of the Ophiuchus cores (Bok & McCarthy
we follow previous workers in assigning B68 the same dis-
this was based upon assumptions about the stability of this
may be slightly closer, at a distance of 125 pc (Snell 1981).
(de Geuss, Bronfman & Thaddeus 1990). Additionally, L63
poses of this paper, as the difference lies within 1
1999), but we will not distinguish between them for the pur-
this mean value at 125 pc (Bertout, Robichon & Arenou

Tables 1–3 indicate whether or not a core was detected in
NH3 (Benson & Myers 1989).
For the Taurus-Auriga cores, we adopt a distance of
140±20 pc (e.g. Elias 1978; Ungerechts & Thaddeus 1987;
Kenyon, Dobrzycka & Hartmann 1994). There is some evi-
dence that the southern cores may be slightly closer than
this mean value at 125 pc (Bertout, Robichon & Arenou
1999), but we will not distinguish between them for the pur-
purposes of this paper, as the difference lies within 1 σ of
the mean value. There are two exceptions to this: The L1551
cloud is somewhat further away, and we use the recently
found value of 168±20 pc for this cloud (Bertout et al. 1999);
and the L1582A core, which is visible at the southern edge
of Figure 1, is actually part of the λ Orionis Bubble at a
distance of 400±40 pc (Murdin & Penston 1977).
For the Ophiuchus cores we adopt a distance of
130±20 pc, in the light of Hipparcos measurements of the
star ρ Ophiuchi, which was found to be at a distance of
128±10 pc (Bertout et al. 1999). There is some evidence
that L1719 and L1721 (see Figure 2) may be slightly more
distant at 150 pc and associated with the star χ Ophiuchi
(de Geuss, Bronfman & Thaddeus 1990). Additionally, L63
may be slightly closer, at a distance of 125 pc (Snell 1981).
However, all of these lie within 1σ of our adopted distance
of 130 pc, so we treat the whole Ophiuchus sample to be at
the same distance.
B68 lies between the main Ophiuchus complex and the
Galactic Plane, and was recently claimed to be at a distance
of only 80 pc (Hotzel et al. 2002). However, the evidence
for this was based upon assumptions about the stability of this
core and the case for this revision is as yet unproven, so
we follow previous workers in assigning B68 the same dis-
ance as the rest of the Ophiuchus cores (Bok & McCarthy
1974). The only exceptions to this distance assignment are
the L134/L183 cloud and L1778. These can be seen in the
upper right of Figure 2. They have been found to be at
distance of 110±10 pc (Mattila 1979; Franco 1989), and
therefore this is the distance we adopt for these cores.
For the clouds in the Aquila region there is some pos-
sible confusion as there are two complexes on the same line
of sight. L530 and L549 have distances of 530 pc (Beichman
et al. 1986), and we here assign L547 the same distance by
virtue of its proximity to L530. L581 has been associated
with the Aquila Rift at a distance of 200 pc (Lee & Myers
1999), as has B133 (Paper III), and we use the same value
here. We adopt a distance for the Cepheus clouds (L1148
and L1155) of 325±25 pc (Straizys et al. 1992).

The selection effects associated with our sample are
somewhat complex. The original sample (Myers, Linke &
Benson 1983) was selected based upon criteria stating that
the core must be less than 5 arcmin in diameter, must be
visible as a patch of obscuration on the Palomar Observa-
tory Sky Survey (POSS), must be within 10° of the Galac-
tic Plane, and must be ‘elongated and with a condensation’
(Myers et al. 1983). The further selection effect for starless
cores requires that the cores must not have an IRAS source
within 6 arcmin, or one core diameter, as defined by the CO
(J=1→0) emission, that is detected at either 25μm or both
60 & 100μm (Beichman et al. 1986).

A further bias in our sample is that most of the cores lie
in previously known and famous star-forming regions, with
by far the majority lying in either Ophiuchus or Taurus-
Auriga. This is because the original CO observations were
primarily directed towards known areas of nearby star for-
mentation (Myers et al. 1983). However, since these two regions
are at very similar distances, they at least provide us with
a largely homogeneous sample of cores. The more distant
cores that appear to have similar brightness must of course
have higher luminosities.
3 OBSERVATIONS

The observations were carried out using the Submillimetre Common User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT). Observations in the Right Ascension (RA) range 15–21 hours were carried out in the evenings of 1997 August 7–13 between 17:30 and 01:30 H.S.T. (03:30–11:30 UT). Observations in the RA range 04–06 hours were carried out in the mornings of 1997 October 4–7 from 01:30 to 09:30 H.S.T. (11:30–19:30 UT).

The observations were conducted simultaneously at 850 and 450 µm using a 64-point jiggle pattern to create fully sampled maps of 2.3 arcmin diameter fields around the coordinate centres (Holland et al. 1999). Time-dependent variations in the sky emission were removed by chopping the secondary mirror at 7 Hz with a chop throw of 120 arcsec in azimuth. The submillimetre zenith opacity at 850 and 450 µm was determined using the 'sky dip' method and by comparison with the 1.3-mm sky opacity. The average 850-µm zenith optical depth was 0.33 ± 0.09 for the August run and 0.25 ± 0.09 for the October run, corresponding to a mean zenith transmission of 72% and 78% respectively. The average 450-µm optical depth was 1.81 ± 0.66 for the August run and 1.55 ± 0.74 for the October run, corresponding to a zenith transmission in the range of ~10–30% and ~10–45% respectively.

The data were reduced in the normal way using the SCUBA User Reduction Facility (Jenness & Lightfoot 1998). Calibration was performed using observations of the planets Mars and Uranus taken during each shift. We estimate that the absolute calibration uncertainty is ±10% at 850 µm and ±25% at 450µm, based on the consistency and reproducibility of the calibration. The average beam size full-width at half maximum (FWHM) was found to be 14.8 arcsec at 850 µm and 8.2 arcsec at 450 µm. There was found to be a negligible error beam at 850 µm, but at 450 µm a significant error beam was detected that was found to contribute up to 50% of the flux density. This was taken into account when calibrating the data. In the final maps it was found that the average 1σ noise (off-source) was 17 mJy/beam at 850 µm and 91 mJy/beam at 450 µm. To see the morphology of the cores at 450 µm it was found necessary to smooth the data to the same resolution as the 850-µm data.

4 RESULTS

We observed 52 starless cores from the catalogue of Myers and co-workers (Myers & Benson 1983; Myers et al. 1988; Benson & Myers 1989). We list the core names, positions and measured flux densities in Tables 1–3. We detected 29 cores with 850-µm peak signal-to-noise levels greater than 3σ. Some were detected with significantly higher signal-to-noise ratio than others because some cores are significantly brighter than others. Consequently, we divided the detected cores into two groups: 'bright' and 'intermediate'. We basel this division on the 850-µm peak flux density of the cores, but we note that the 450-µm flux densities scale roughly accordingly.

We defined a core as 'bright' if its peak 850-µm flux density was found to be greater than, or equal to, 170 mJy/beam. This level was chosen for a number of reasons. Firstly, this value is 10 times the mean 1σ level of ~17 mJy/beam of our observations. In addition, in terms of the physical parameters of the cores themselves, this lower limit brightness cutoff represents a lower limit H2 co-
Table 3. Source names, positions searched and 850- & 450-µm upper limits to the flux densities of the 23 cores which were undetected – i.e. their peak flux densities are less than three times the 1-σ level. The limits are measured using a FWHM beam size of 14.8 arcsec and are quoted to 2 sig. figs. The quoted upper limits are based on the statistical measurement errors. Absolute calibration errors are ±10% at 850 µm and ±25% at 450 µm. Sources marked with a * show some evidence for low level emission at one edge of the field, so their peaks may have been missed. The final column indicates whether or not a NH$_3$ detection is associated with the source (Benson & Myers 1989).

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<td>L1495D</td>
<td>04°14′27.5″</td>
<td>+28°14′49″</td>
<td>≤ 48</td>
<td>≤ 3300</td>
<td>N</td>
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<td>≤ 36</td>
<td>≤ 370</td>
<td>N</td>
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<td>04°18′32.5″</td>
<td>+25°29′37″</td>
<td>≤ 48</td>
<td>≤ 1600</td>
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<td>L1521C</td>
<td>04°19′19.2″</td>
<td>+27°16′29″</td>
<td>≤ 42</td>
<td>≤ 270</td>
<td>Y</td>
</tr>
<tr>
<td>L1521B*</td>
<td>04°24′18.3″</td>
<td>+26°36′47″</td>
<td>≤ 84</td>
<td>≤ 250</td>
<td>N</td>
</tr>
<tr>
<td>L1521A</td>
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<td>+26°16′00″</td>
<td>≤ 27</td>
<td>≤ 280</td>
<td>Y</td>
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<tr>
<td>L1551C*</td>
<td>04°31′25.9″</td>
<td>+18°09′11″</td>
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<td>≤ 750</td>
<td>N</td>
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<tr>
<td>L1507A</td>
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<td>+29°44′19″</td>
<td>≤ 54</td>
<td>≤ 570</td>
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<td>L1517C</td>
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<td>+30°35′10″</td>
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<td>≤ 300</td>
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<td>+30°38′46″</td>
<td>≤ 36</td>
<td>≤ 770</td>
<td>N</td>
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<td>+31°41′58″</td>
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<td>−07°07′21″</td>
<td>≤ 30</td>
<td>≤ 270</td>
<td>N</td>
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<td>−04°37′03″</td>
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<td>≤ 140</td>
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<td>−04°35′00″</td>
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<td>≤ 350</td>
<td>Y</td>
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<td>L1721</td>
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<td>+18°54′44″</td>
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<td>≤ 140</td>
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<td>≤ 160</td>
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<td>−23°41′32″</td>
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<td>≤ 280</td>
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</tr>
<tr>
<td>L121</td>
<td>16°39′28.4″</td>
<td>−14°05′21″</td>
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<td>≤ 530</td>
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<td>≤ 30</td>
<td>≤ 490</td>
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<td>−04°18′50″</td>
<td>≤ 48</td>
<td>≤ 1200</td>
<td>N</td>
</tr>
<tr>
<td>L581</td>
<td>19°07′26.2″</td>
<td>−03°54′49″</td>
<td>≤ 42</td>
<td>≤ 1300</td>
<td>N</td>
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</table>

Source density of n(H$_2$)~5×10$^{22}$ cm$^{-2}$, or a value of A$_V$ ~50, using typical assumptions T=10K, K$_{500}=0.01$cm$^2$g$^{-1}$, N(H$_2$)/A$_V=9.4 \times 10^{20}$ cm$^{-2}$mag$^{-1}$ (see section 5.3 below for discussion; see also e.g. Bohlin, Savage & Drake 1978; Ferking et al. 1982). Also, by using reasonable assumptions about core geometries (see section 5.3 below) we find that this corresponds to an approximate minimum volume number density of n(H$_2$)~3×10$^7$cm$^{-3}$ at the distance of the majority of our sample. This is discussed in more detail below.

This value also corresponds roughly to cores for which we could detect the 450-µm emission sufficiently to produce a map of this emission in most cases. Finally, the 10-σ peak level typically meant that we could map the detailed structure of most of these cores at 850 µm out to reasonable radii (see below). Table 1 lists the peak and integrated flux densities of the bright cores. Throughout this paper we list all sources in order of increasing Right Ascension (RA). The integrated flux densities were measured in a 150-arcsec diameter circular aperture. 13 of the 52 cores satisfy the criterion for bright cores.

A core was defined as undetected if its peak 850-µm flux density was less than 3 times the 1σ level of the particular observation. Table 2 lists the peak and integrated flux densities of the intermediate cores. The integrated flux densities were once again measured in a 150-arcsec diameter circular aperture. 16 of the 52 cores have intermediate brightness under this definition.

Table 3 lists the positions searched and 3σ upper limits of the peak flux densities of the cores we designate as undetected, having peak 850-µm values less than 3 times the 1σ value of the observation. 23 of the 52 cores were undetected. Note that some of the upper limits are higher than some of the peak flux densities detected for a small number of the intermediate cores. This is due to the varying atmospheric conditions during the observations. It is also possible for the undetected cores that we missed the core peak if it did not lie within the 2.3-arcmin field of view of SCUBA.

The position centres for L134 and L134A do not coincide exactly with some listed positions for molecular line observations of these sources so we list the three sigma upper limits observed in the locations observed. L1551C was observed in the normal manner, but it was found afterwards that a bright source (possibly L1551B) was present in the ‘off’ beam position, making it impossible to map in the beam-switching mode we were using. Hence we list the three sigma upper limit at the location observed but note that it may be an underestimate. There are a small number of cores for which we believe we may have missed their brightest peaks. These are indicated by asterisks in the three Tables. In terms of our statistics of numbers of cores in each category, we estimate that this introduces an error of roughly ±3.

We found that for the bright cores we could map their 850-µm structure with reasonable signal-to-noise ratio but for intermediate cores we could not make their structure without smoothing to slightly lower resolution. However, for the 16 intermediate cores we were still able to make integrated flux density measurements to obtain their total 850-µm flux densities. Roughly half of the intermediate cores were not detected significantly at 450 µm. We also note that all of our ‘bright’ detections with SCUBA coincide with NH$_3$ detections (for the sources in common), whereas four out of sixteen cores found with SCUBA to be ‘intermediate’ were not detected in NH$_3$. In addition, 18 out of 23 of our ‘faint’ cores were not detected in NH$_3$. This seems to indicate that our SCUBA maps are tracing roughly similar material to NH$_3$ maps. Since the latter is a volume density tracer, we believe that our SCUBA mapping (with a finite chop throw) also appears to be tracing volume density.

Figures 3 & 4 show the 850- & 450-µm maps of the 13 cores designated as bright. The 450-µm maps have been smoothed to the same resolution as the 850-µm data (14.8 arcsec). The first thing that is apparent from the maps is that none of the cores are circular, but rather they show a variety of morphologies. Most of the cores appear elongated – some to the extent that one would call them filamentary. The cores that we would class as filamentary are L1521D, L183, L1696A & L1689SMM. This is based on the fact that these cores show evidence for a low level ridge or filament in which the core is embedded.

Most cores have only one peak, although some have two or more. L43 is somewhat of an exception, in that it is the only source in our sample where there is another source in the field of view as well as a prestellar core. The more westerly of the two peaks that can be seen in the map is the classical T Tauri star RNO 91 (Cohen 1980). L1696A...
appears to contain two prestellar sources. We here call them L1696A-N and L1696A-S. L1689B, L63 and B133 all show low level emission apparently extending beyond at least one edge of the map (e.g. for L1689B there is extended emission in the east-west direction).

In nine of the cores (L1521D & F, L1517B, L1582A, L1544, L1689SMM, L43, L1689B & L63) the 850- and 450-µm maps show a very similar morphology, clearly indicating that they are tracing the same dust, albeit with lower signal-to-noise ratio at 450 µm. Any slight differences can be attributed to anomalous refraction effects (e.g. Zyka et al. 1995). In two cases (L1524 & B133) the core does not appear to have been detected significantly at 450 µm despite having relatively high signal-to-noise ratio at 850 µm. This may be due either to varying atmospheric conditions during the observations, or to anomalous refraction effects (e.g. Zyka et al. 1995). Alternatively, in the case of L1524, the core peak may have been missed. In general, if the differences between 850 and 450 µm are real, then they must be due to changes in dust temperature or emissivity across a core.

In the remaining 2 cores (L183 & L1696A) the 450-µm map appears somewhat different to the 850-µm map. In both of these latter cases the approximate overall size appears the same at both wavelengths and the outer contours appear to trace roughly the same material, but they appear to disagree somewhat over the peak of the core. L183 has only one peak at 850 µm at the southern end of the core, but has apparently two peaks at 450 µm – one coincident with the 850-µm peak, and the other at the northern end of the core. For L1696A two peaks are seen at 850 µm, but only one at 450 µm. Furthermore, the 450-µm peak coincides with the slightly weaker of the two 850-µm peaks.

Figures 5 & 6 show the 850-µm maps of the 16 cores we designated as ‘intermediate’, due to their somewhat lower levels of peak emission (although for a few of the cores the peak may have been missed). The data in Figures 5 & 6 have been smoothed to an effective FWHM resolution of 25 arcsec. Consequently, some of the structure has been smoothed out of the maps. Nonetheless, in some maps there is some remaining structure that can be discerned. For example, L1521SMM can still be seen to have two peaks, and 10 of the cores (L1498, L1521E, L1517A, L1512, L1719D, L1709A, L1689A, L530D, L1148 & L1155H) can still be seen to have some elongation. In all of the designated intermediate sources there was no structure discernible in the 450-µm maps after smoothing, even for the sources detected above the 5σ level on peak at 450 µm.

The majority of the cores shown in Figures 3 & 4 can be seen to be non-circular. Consequently, we fitted an elliptical two-dimensional Gaussian to each of the cores. This allowed us to measure the full-width at half-maximum (FWHM) of the major and minor axis of each core, and to ascertain the position angle (PA) of the major axis in each case. The values of FWHM and PA for each core are listed in Table 4, as well as the ratio of the two FWHM values, which we shall refer to as the aspect ratio. From our sample of bright cores, those with double peaks or with a potentially missed peak (L1524, L1696A and L43) were excluded from this treatment. Furthermore, L1689SMM was seen to be too ‘ridge-like’ to determine a one-dimensional radial profile. For the remaining nine cores listed in Table 4 the weighted mean aspect ratio is 0.62±0.15 (c.f. Goodwin et al 2002).

5 CORE PROPERTIES

5.1 Core morphologies and comparison with ISO data

In Paper V we presented data from the Infrared Space Observatory ISO (Kessler et al. 1996), using the long-wavelength photo-polarimeter ISOPHOT (Lemke et al. 1996), of 18 prestellar cores that were a subset of the 52 cores discussed in this paper. We can therefore compare the far-infrared observations in Paper V with the submillimetre observations presented here. All of the 18 cores observed with ISOPHOT were detected at both 170 & 200 µm, but most were undetected at 90 µm, indicating that they are cold (Paper V).

We note that of the 18 cores observed with ISOPHOT, 8 have been classified in this paper as bright cores in terms of their SCUBA 850-µm flux densities – L1517B, L1544, L1582A, L183, L1696A, L1689B, L63 & B133. 7 of the 18 cores appear in the intermediate brightness category – L1498, L1517A, L1512, L1709A, L1689A, B68 & L1155C. The remaining three cores were undetected by SCUBA – L1517C, L1709C & L204B. Consequently, the ISOPHOT subsample represents a cross-section of the cores. Note that the typical flux densities of the cores at 200 µm are significantly greater than their flux densities at 850 µm simply due to the spectral shape of cores at the typical temperatures observed (see below).

Of the three non-detections, L1517C was seen to be the weakest core at 200 µm, implying that the SCUBA sensitivity limit may not have been sufficient to detect it. However, L1709C and L204B were not among the faintest cores at 200 µm, possibly indicating that we may have missed their peaks with SCUBA. ISOPHOT had a much lower resolution at 200 µm (∼90 arcsec) than SCUBA at 850 µm (∼14 arcsec), allowing us to make much larger maps of typically 10–20 arcmin with ISOPHOT (see Paper V).

For the sources that we have here classified as bright or intermediate cores we can compare the morphologies of the SCUBA 850-µm maps with the ISOPHOT 200-µm maps. Figures 7 & 8 show the SCUBA and ISOPHOT contour maps for these sources superposed on POSS optical grey-scale images of the same regions. We exclude L1709A from further consideration in this paper as its peak may have been missed. We also exclude L63 from this analysis as its 200-µm map shows that its far-IR peak may have been missed (see Paper V).

Study of Figures 7 & 8 shows that in each case we see a strong coincidence of peak 200-µm emission with peak 850-µm emission and peak optical obscuration. In most cases the morphology of the far-infrared emission also closely traces the optical obscuration. For example, for 10 of the cores in Figures 7 & 8, the peak 200-µm emission and 850-µm emission overlie one another precisely. Furthermore, the elongation direction seen in the 200-µm emission in L1582A exactly matches the elongation in optical obscuration in the same region. Similarly, the 850-µm emission in L1696A lines up with the edge of the optical obscuration. However, in this
Figure 3. Greyscale images with contours superposed of 850- and 450-µm continuum maps of six of the thirteen cores designated as bright – L1521D & F, L1524, L1517B, L1544 & L1582A. The lowest (dashed) contour in each case is at a level of 3σ. The solid contours start at a level of 5σ, and the contour interval is 2σ. The 1σ noise levels for each source at each wavelength are listed in Table 1. The 450-µm data have been smoothed to the same resolution as the 850-µm data (14.8 arcsec). Note that the peak of the emission may have been missed in the case of L1524.
Figure 4. Greyscale images with contours superposed of 850- and 450-μm continuum maps of seven of the thirteen bright cores – L183, L1696A, L1689SMM, B133, L43, L1689B & L63. Details as in Figure 3.
Figure 5. Greyscale images with contours superposed of 850-μm continuum maps of 12 of the 16 cores designated intermediate in brightness at 850 μm – L1498, L1521SMM & E, L1517A, L1512, L1713D, L1709A, L1689A, L234E, B68 & L530D. The lowest (dashed) contour in each case is at a level of 3σ. The solid contours start at a level of 5σ, and the contour interval is 2σ. The 1σ noise level for each source is listed in Table 2. The data have been smoothed to a FWHM resolution of 25 arcsec.
of the grey-body fits found in this way are listed in Table 4

5.2 Core Temperatures

The similarity in morphology between the ISOPHOT and SCUBA data for each core seen in Figures 7 & 8 lead us to ascertain that for most of the cores it is the same dust that we are seeing in emission at both 200 & 850 \( \mu \)m. The coincidence of emission at both of these wavelengths with optical obscuration show that this dust is also absorbing at shorter wavelengths. Therefore, for these sources we can combine the integrated flux measurements presented in Tables 1 & 2 with the far-infrared data to produce spectral energy distributions (SEDs) of the sources. We have previously used the measurements integrated in a 150-arcsec diameter aperture in Tables 1 & 2 of this paper and table 5 of Paper V and plotted the resultant spectral energy distributions in Paper V. We also incorporated 1.3-mm data from Paper III.

The solid curves on each of the plots in Paper V are modified black-body curves, often known as grey-body curves. The monochromatic flux density, \( F_\nu \), of a grey-body, at frequency \( \nu \), radiated into solid angle \( \Omega \) is given by:

\[
F_\nu = \Omega fB_\nu(T)(1-e^{-(\nu/\nu_c)\beta}),
\]

where \( B_\nu(T) \) is the Planck function, \( \nu_c \) is the frequency at which the optical depth is unity, \( \Omega \) is the solid angle of the aperture, \( f \) is the filling factor of the source within the aperture and \( \beta \) is the dust emissivity index. The temperatures of the grey-body fits found in this way are listed in Table 4 for reference. The error-bars on the temperatures are typically \( \pm 2 \)K. This could introduce uncertainties in the mass estimates (see below).

5.3 Core Masses

Submillimetre continuum emission is optically thin, and hence it is a direct tracer of the mass content of molecular cloud cores. For a spherical isothermal dust source at distance \( d \), the total (dust + gas) mass, \( M(r < R) \), contained within a radius \( R \) from the centre, is related to the submillimetre flux density \( S_{850 \mu m}(\theta) \) integrated over a circle of projected angular radius \( \theta = R/d \) by the equation:

\[
M(r < R) = \frac{[S_{850 \mu m}(\theta) d^2] / [\kappa_{850} B_{850}(T)]}. 
\]

where \( \kappa_{850} \) is the dust opacity per unit mass column density at \( \lambda = 850 \mu m \) and \( B_{850}(T) \) is the Planck function at the same wavelength, for a dust temperature \( T \). The dust temperatures are taken from Paper V and Table 4, except for L1521D & F, which are rotational line temperatures taken from Codella et al (1997), and which therefore assume thermal equilibrium between the gas and dust for these sources. For the dust opacity, we follow the method we adopted in Paper II, and use \( \kappa_{850} = 0.01 \text{ cm}^2\text{g}^{-1} \) (see Papers II & III and AWB93 for detailed justifications both of this value of \( \kappa_{850} \) in particular and this method of obtaining masses in general). The uncertainties in the masses due to a combination of uncertainties in \( \kappa \) and in measuring the temperature could be as high as a factor of a few.

Table 4 lists the masses, column densities and volume densities for all of the cores within various radii. The column density follows directly from the mass. The peak volume density is calculated from the peak column density, assuming that the extent of the column is the geometric mean of the other two core axis FWHMs. The FWHM volume density is calculated from the FWHM mass and the volume enclosed by a tri-axial ellipsoid, again assuming that the line of sight FWHM is the geometric mean of the other two FWHMs. Table 4 also lists the total mass of each core within a 150-arcsec diameter aperture (\( M_{150} \)). In addition we calculate the virial mass (\( M_{\text{vir}} \)) for each core, using the \( \text{NH}_3 \) linewidth.
Figure 7. Composite images of SCUBA 850-µm maps (bold white contours) and ISOPHOT 200-µm maps (narrower grey contours) superposed on POSS optical (grey-scale) images for 6 regions – L1498, L1517, L1512, L1544, L1582A & L183. The dashed contours designate the edge of the ISO mapped regions. Each field is 16 arcmin square except for L1517.
Figure 8. Composite images of SCUBA 850-µm maps (white bold contours) and ISOPHOT 200-µm maps (grey narrower contours) superposed on POSS optical (grey-scale) images for 6 cores – L1696A, L1155C, L1689A & B, B68 & B133. The dashed contours indicate the edge of the SCUBA mapped regions. Each field is 16 arcmin square.
Table 4. Fitted source properties for the sub-set of bright cores (above the line), together with a subset of the intermediate cores (below the line), for which we have ISOPHOT data, and hence can determine the SED and dust temperature (also including L1521D & F, whose temperatures are taken from Codella et al. 1997). Columns 1, 2 & 3 list the source name, its distance and its temperature found from fitting its SED. Typical error-bars on the temperatures are ±2 K. Columns 4, 5 and 6 list the full-width at half-maximum (FWHM) of the major and minor axes, the position angle of the major axis (measured north through east) and the ratio of the two axes, as determined by a two-dimensional Gaussian fit to the 850-μm data. The beamwidth has been deconvolved from the FWHM quoted, and we estimate the error on the core FWHMs to be equivalent to half a beamwidth (~7 arcsec) for the bright cores and roughly double this (~14 arcsec) for the intermediate cores. The error on the position angle is ~±5° and ~±10° for bright and intermediate cores respectively. Columns 7 and 8 list the values found for the central column density \(N(H_2)_C\) and maximum extinction \(A_V\) from the 850-μm flux densities. Typical errors on these values are ±20–30%. Columns 9 and 11 give the mean central (\(\pi_c\)) and FWHM (\(\pi_F\)) volume number densities. Error-bars on these values may be as high as 50%. The FWHM mass (\(M_F\)) and the total mass in a 150-arcsec aperture (\(M_{150}\)), calculated from the FWHM submillimetre flux density and the total flux density in a 150-arcsec aperture respectively, are listed in columns 10 & 12 using the method explained in the text. Error-bars are in the region of ±30%. Column 13 lists the virial mass (\(M_{vir}\)) calculated from the NH\(_3\) linewidth (Benson & Myers 1989) in a region of radius equal to the FWHM. Error-bars here are also ~±30%.

<table>
<thead>
<tr>
<th>Source</th>
<th>D (pc)</th>
<th>T (K)</th>
<th>FWHM (arcsec)</th>
<th>Aspect Ratio</th>
<th>P.A. (°)</th>
<th>(N(H_2)_C) (cm(^{-2}))</th>
<th>(\pi_c) (cm(^{-3}))</th>
<th>(M_F) (M(_\odot))</th>
<th>(\pi_F) (cm(^{-3}))</th>
<th>(M_{150}) (M(_\odot))</th>
<th>(M_{vir}) (M(_\odot))</th>
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</thead>
<tbody>
<tr>
<td>L1521D</td>
<td>140</td>
<td>10</td>
<td>0.048×0.021</td>
<td>0.44</td>
<td>42</td>
<td>5×10(^{22})</td>
<td>5×10(^{5})</td>
<td>0.5</td>
<td>3×10(^{5})</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
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<td>140</td>
<td>9</td>
<td>0.019×0.012</td>
<td>0.66</td>
<td>153</td>
<td>1×10(^{23})</td>
<td>3×10(^{6})</td>
<td>0.4</td>
<td>2×10(^{6})</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>L1517B</td>
<td>140</td>
<td>10</td>
<td>0.028×0.019</td>
<td>0.68</td>
<td>21</td>
<td>4×10(^{22})</td>
<td>5×10(^{5})</td>
<td>0.3</td>
<td>4×10(^{5})</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>L1544</td>
<td>140</td>
<td>9</td>
<td>0.057×0.029</td>
<td>0.50</td>
<td>148</td>
<td>1×10(^{23})</td>
<td>7×10(^{6})</td>
<td>1.6</td>
<td>6×10(^{6})</td>
<td>3.1</td>
<td>2.4</td>
</tr>
<tr>
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<td>400</td>
<td>15</td>
<td>0.054×0.026</td>
<td>0.47</td>
<td>18</td>
<td>2×10(^{22})</td>
<td>1×10(^{5})</td>
<td>0.4</td>
<td>1×10(^{5})</td>
<td>4.8</td>
<td>2.3</td>
</tr>
<tr>
<td>L183</td>
<td>110</td>
<td>10</td>
<td>0.020×0.012</td>
<td>0.59</td>
<td>179</td>
<td>8×10(^{22})</td>
<td>1×10(^{6})</td>
<td>0.3</td>
<td>1×10(^{6})</td>
<td>1.8</td>
<td>0.9</td>
</tr>
<tr>
<td>L1689B</td>
<td>130</td>
<td>11</td>
<td>0.027×0.022</td>
<td>0.82</td>
<td>68</td>
<td>5×10(^{22})</td>
<td>6×10(^{5})</td>
<td>0.4</td>
<td>5×10(^{5})</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>L63</td>
<td>130</td>
<td>11</td>
<td>0.024×0.011</td>
<td>0.48</td>
<td>111</td>
<td>5×10(^{22})</td>
<td>9×10(^{5})</td>
<td>0.2</td>
<td>8×10(^{5})</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>B133</td>
<td>200</td>
<td>13</td>
<td>0.048×0.037</td>
<td>0.78</td>
<td>175</td>
<td>2×10(^{22})</td>
<td>2×10(^{5})</td>
<td>0.4</td>
<td>2×10(^{5})</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>L1498</td>
<td>140</td>
<td>10</td>
<td>0.103×0.052</td>
<td>0.50</td>
<td>100</td>
<td>3×10(^{22})</td>
<td>1×10(^{5})</td>
<td>0.5</td>
<td>3×10(^{5})</td>
<td>1.5</td>
<td>2.6</td>
</tr>
<tr>
<td>L1512</td>
<td>140</td>
<td>12</td>
<td>0.080×0.034</td>
<td>0.43</td>
<td>135</td>
<td>2×10(^{22})</td>
<td>1×10(^{5})</td>
<td>0.3</td>
<td>3×10(^{5})</td>
<td>0.6</td>
<td>2.5</td>
</tr>
<tr>
<td>B68</td>
<td>130</td>
<td>13</td>
<td>0.074×0.047</td>
<td>0.63</td>
<td>23</td>
<td>1×10(^{22})</td>
<td>4×10(^{5})</td>
<td>0.2</td>
<td>2×10(^{5})</td>
<td>0.4</td>
<td>2.1</td>
</tr>
</tbody>
</table>

(Benson & Myers 1989). The measured masses of the bright cores all appear to be of a similar order to their virial masses.

There are two cores in common (L1544 and L1689B) between Table 4 and the sample of Bacmann et al. (2000). They calculated the central volume densities of cores based on their mid-IR absorption seen in ISOCAM data. In both of these cases they found a central volume density of \(6×10^3\) cm\(^{-3}\). We find values of 5 and \(7×10^5\) cm\(^{-3}\) respectively, in very good agreement. In fact all of the volume densities of the bright cores lie in the range of \(10^5–10^6\) cm\(^{-3}\). The intermediate cores all have significantly larger FWHM, and generally lower column densities, which together entail significantly lower volume densities, all around a few \(10^3\) cm\(^{-3}\). Therefore we deduce that bright cores are significantly more centrally condensed than intermediate cores.

5.4 Core radial profiles

The radial density profiles of the cores can be measured in the case of our ‘bright’ cores and used for comparison with theoretical predictions to attempt to assess the stability and potential evolution of the cores. This is most easily assessed for spherically symmetric cores. Despite the fact that the majority of the cores are non-circular we still make radial profiles for the bright cores, with the exception of those with double peaks or with a potentially missed peak (L1524, L1696A and L43). Furthermore, L1689SMM and L183 are seen to be too ‘ridge-like’ to determine a one-dimensional radial profile.

We generate azimuthally averaged radial profiles for the remaining 8 cores by assuming that our observed cores are ellipsoids (as defined by the parameters in Table 4) which are aligned with the plane of the sky. We then remove instrumental effects that might cause us to miscalculate the profiles. Chief amongst these effects is that caused by ‘chopping’.

The JCMT uses a chopping secondary mirror to remove the bright, slow, varying component of the submillimetre sky (see above). This introduces a characteristic differential pattern in the data. Every point in the output map is equal to the true flux density at that point minus the mean of the true flux density at two points offset by ±120 arcsec in a direction given by the position angle of the chop throw. The two positions arise due to the effect of ‘nodding’ the telescope between ‘left’ and ‘right’ beams. The two ‘off-beam’ positions serve to improve the sky removal.

If the true sky flux density distribution is \(S_{sky}(x,y)\), and the off-beams are at offsets (+\(a\), +\(b\)) and (−\(a\), −\(b\)), then the flux density distribution of the output map, \(S_{map}(x,y)\), will be given by:

\[
S_{map}(x,y) = S_{sky}(x,y) - 0.5 \times [S_{sky}(x+a,y+b) + S_{sky}(x-a,y-b)].
\]

For a source that is significantly smaller than the chop throw:

\[
S_{sky}(x+a,y+b) = S_{sky}(x-a,y-b) = 0,
\]

so:

\[
S_{map}(x,y) = S_{sky}(x,y)
\]

and:

\[
S_{map}(x+a,y+b) = S_{map}(x-a,y-b)
\]
However, for more extended sources, chopping causes one to underestimate the true extent of the flux density distribution parallel to the chop throw, while having relatively little effect on the extent of the flux density distribution orthogonal to the chop throw. This has important implications for fitting flux density profiles to extended sources, and must be taken into account.

To replicate the effect of chopping on a given core, we generate a synthetic core map by taking a known, circularly symmetric column density distribution and compressing it along a minor axis to obtain the core’s observed axis ratio. The direction of the minor axis is chosen so as to match the observed position angle of the elliptical core. The synthetic map is then convolved with a Gaussian beam with the same FWHM as the average FWHM of the measured telescope beam during our observations. A simulated chop that has the same position angle and chop throw as the actual chop is applied to the synthetic map by using the standard SURF software routine ‘add-dbm’ (Jenness & Lightfoot 1998).

A number of synthetic maps are produced with different input parameters. The synthetic maps and the real maps are then analysed in exactly the same fashion and the profiles are compared (see section 5.5 below). When a real core profile matches one of its synthetic core profiles then the parameters of the real core can be deduced from the synthetic profile. If a real core cannot be taken into account.

Table 5. Fitted source properties for the bright cores in Table 4 (apart from L1521D and L183, which appear too elongated or filamentary to be approximated as circularly symmetric). Column 1 lists the source name. Columns 2, 3 & 4 list the values found for $R_{\text{flat}}$, $\xi_{\text{max}}$ and $R_{\text{edge}}$ from Bonnor-Ebert fits to the radial density profiles (see text for details). See text for discussion of the fitting methodology and associated errors. The critical value of $\xi_{\text{max}}$ for a stable Bonnor-Ebert sphere (6.5) is significantly exceeded in 6 out of 7 cores. The effective temperature required by the Bonnor-Ebert fit, $T_{\text{eff}}$, is listed in column 5. The values of $T_{\text{eff}}$ are in all cases significantly higher than our measured values from the SED fitting. The need for such high effective temperature values implies that the cores are not Bonnor-Ebert spheres.

<table>
<thead>
<tr>
<th>Source</th>
<th>$R_{\text{flat}}$ (AU)</th>
<th>$\xi_{\text{max}}$</th>
<th>$R_{\text{edge}}$ (AU)</th>
<th>$T_{\text{eff}}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1521F</td>
<td>3400</td>
<td>$\geq 7.5$</td>
<td>$\geq 13000$</td>
<td>52</td>
</tr>
<tr>
<td>L1517B</td>
<td>5800</td>
<td>$\geq 10$</td>
<td>$\geq 29000$</td>
<td>35</td>
</tr>
<tr>
<td>L1544</td>
<td>4800</td>
<td>10</td>
<td>24000</td>
<td>71</td>
</tr>
<tr>
<td>L1582A</td>
<td>11000</td>
<td>9</td>
<td>50000</td>
<td>33</td>
</tr>
<tr>
<td>L1689B</td>
<td>3800</td>
<td>$\geq 14$</td>
<td>$\geq 27000$</td>
<td>28</td>
</tr>
<tr>
<td>L63</td>
<td>3600</td>
<td>$\geq 15$</td>
<td>$\geq 27000$</td>
<td>26</td>
</tr>
<tr>
<td>B133</td>
<td>6800</td>
<td>4</td>
<td>13000</td>
<td>24</td>
</tr>
</tbody>
</table>

5.5 Comparison with Bonnor-Ebert spheres

If we assume that the cores are supported against gravity by hydrostatic pressure and we neglect magnetic and turbulent contributions, then for a spherically symmetric sphere of gas, Poisson’s equation can be written as:

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left( \frac{r^2}{\rho} \frac{\partial P}{\partial r} \right) + 4\pi G \rho = 0,$$

where $r$ is the radius, $\rho(r)$ is the density and $P(r)$ is the pressure at radius $r$. Given that we find the cores to be roughly isothermal, we can use an equation of state of the form:

$$P = \frac{\rho k T}{m} + \frac{a}{3} T^4.$$

Then equation 7 reduces to:

$$\frac{1}{\xi^2} \frac{d}{d\xi} \left( \xi^2 \frac{d\psi}{d\xi} \right) - \psi = 0,$$

where we have introduced the usual dimensionless parameters $\xi = (2r/R_{\text{flat}})$, and $\psi = -\ln(\rho/\rho_c)$. In these expressions $\rho_c$ is the central volume density at $r = 0$, and $R_{\text{flat}} = (kT/\pi mG\rho_c)^{1/2}$, where $T$ is the temperature, $m$ is the mean particle mass, $k$ is Boltzmann’s constant and $G$ is the gravitational constant (Chandrasekhar 1939). We note parenthetically that the parameter $R_{\text{flat}}$ is two thirds of the King Length (e.g. Binney & Tremaine 1987), which is analogous to the Jeans length, but is defined using the central density of a sphere rather than its mean density.
Figure 9. 850-µm azimuthal elliptically-averaged, normalised radial flux density profiles (reading left-to-right from top) of: L1521D, L1521F, L1517B, L1544, L1582A, L1689B, L63 and B133. Data points are shown on a logarithmic scale at half beam spacings with 1σ error bars. The solid curves are the best fit Bonnor-Ebert profiles (no unique fit could be obtained for L1521D), while the dashed curves are the 850-µm beam profiles.
To compare this theoretical result with the data in Figure 9 we can transform the function $\psi(\xi)$ into $\rho(\tau)$ and project this into column density $\Sigma(b)$ by integrating along the line of site ($b$ is the radial impact parameter). The form of the solution is governed by two parameters, $R_{\text{flat}}$ and $R_{\text{edge}}$. $R_{\text{flat}}$ can be thought of as being roughly the point on the radial profile where the central ‘flat’ region ends and the profile becomes steeper (c.f. Paper II).

The model definition of $R_{\text{edge}}$ is the radius at which $\Sigma(b) = 0$. It is also known as the truncation radius. In practice, it was taken to be the radius at which the core emission either becomes indistinguishable from the background cloud emission, or becomes steeper in volume density profile than $r^{-3}$ (c.f. Bacmann et al. 2000). The family of solutions for $\xi_{\text{max}} = (2R_{\text{edge}}/R_{\text{flat}})$ are known as Bonnor-Ebert spheres (Ebert 1955; Bonnor 1956). The critical value of $\xi_{\text{max}}$ is 6.5. Any core with a value greater than this is unstable against collapse. Others have used a similar form of profile to infer the stability of dense cores (e.g. Alves, Lada & Lada 2001).

The two radii $R_{\text{flat}}$ and $R_{\text{edge}}$ can be fitted to a data set, such as those shown in Figure 9, using a $\chi^2$ minimisation routine. This was achieved by minimising the variance between an observed data set and a grid of synthetic profiles (see section 5.4 above) parameterised by $R_{\text{flat}}$ and $\xi_{\text{max}}$. Table 5 lists the values of $R_{\text{flat}}$, $R_{\text{edge}}$ and $\xi_{\text{max}}$ found for seven of the eight cores illustrated in Figure 9. We could not obtain a constrained fit for L1521D, so we exclude it from further analysis. The seven cores that we fit typically have $R_{\text{flat}} \sim 3000–6000$ AU.

The errors on the resultant fit can be estimated from a contour map of the $\chi^2$ variation in the $R_{\text{flat}}-\xi_{\text{max}}$ plane. $R_{\text{flat}}$ for our data is found to be generally well-defined with a relative 1-$\sigma$ error-bar of around 10–15%. However, $\xi_{\text{max}}$ is in general somewhat less well constrained for our data, because chopping creates a degeneracy between Bonnor-Ebert solutions that have large values of $R_{\text{edge}}$. Hence the error bars on the values in Table 5 are quite large - typically up to 50%. This is because the drop in signal-to-noise towards the edge of our maps and the finite size of the maps combines with the low signal-to-noise required for the data, because chopping creates a degeneracy between Bonnor-Ebert solutions that have large values of $R_{\text{edge}}$. Hence the error bars on the values in Table 5 are quite large - typically up to 50%.

All of the above profile fitting is based on the normalised flux density profiles in Figure 9. However, the absolute values of the central column densities quoted in Table 5 can be used to calculate the effective temperature, $T_{\text{eff}}$, of the Bonnor-Ebert fit. Table 5 lists the effective temperature, $T_{\text{eff}}$, required by the Bonnor-Ebert fitting for each core. These Bonnor-Ebert effective temperatures can be compared with the temperatures calculated from the observed spectral energy distribution of each core listed in Table 4. In all cases the Bonnor-Ebert effective temperature is a factor of 2 or more greater than the observed core temperature. This tells us that, at least for these bright cores in our sample, a critical Bonnor-Ebert sphere is not consistent with the radial density profiles of the cores.

The parameter $\xi_{\text{max}}$ describes the degree of central condensation, with cores with larger flat central regions being more stable against gravitational collapse. Remembering that the critical value of $\xi_{\text{max}}$ for a stable solution is 6.5, we see that six out of seven of our cores significantly exceed this value.

Our conclusion is in agreement with the findings of Evans et al. (2001), who studied a smaller number of pre-stellar cores and found that they also could not be fitted as critical Bonnor-Ebert spheres. This is interesting, because their fitting analysis was somewhat different from ours, and yet they reach ultimately the same conclusion. Of the cores in common between their small sample and ours there are some differences in fitting parameters. For example, they allow the temperature to decrease towards the centre and consequently find smaller values of $R_{\text{flat}}$ than those reported here assuming isothermal cores. As already mentioned in section 1 above, our findings from ISO (Paper V) suggest that the central core regions are nearly isothermal.

Evans et al. (2001) also do not treat the chopping in two dimensions, as we do. Furthermore, for one of the cores, L1689B, they use a value for the inter-stellar radiation field (ISRF) that is too small for the environs of Ophiuchus in which L1689B is situated (c.f. Andrè et al. 2003). Nevertheless they arrive at the same conclusion as we do that the cores are not critical Bonnor-Ebert spheres. Hence this conclusion is probably reasonably robust and independent of fitting model.

Other work has also shown that a purely thermal Bonnor-Ebert equilibrium model can be ruled out in some cases because the central temperature predicted by the model is much higher than the observed temperature (e.g. Andrè et al. 2003; Harvey et al., 2003b). We can also compare our result to the previous work of Alves et al. (2001) mentioned above. They studied one of our sample, B68, and found that it was consistent with a critical Bonnor-Ebert sphere. We have classified B68 as an intermediate core, and it can be seen from Table 2 and Figure 5 that it is one of the fainter members of that group.

Figure 10 shows the radial flux density profile for our 850-µm data. We calculated the normalised Bonnor-Ebert profile for B68 based on the parameters quoted by Alves et al. (2001). This is shown as the solid line in Figure 10. It can be seen that the shape of the flux density profile that we ob-

![Figure 10](image-url)
served for B68 is consistent with a Bonnor-Ebert profile with the value of $\xi_{\text{max}} = 6.9$ found by Alves et al. We may conjecture, therefore, that cores might pass through a phase (during part of the intermediate core phase) in which they resemble the structure of a critical Bonnor-Ebert sphere while their mean central densities are still relatively low – only a few $10^4$ cm$^{-3}$ (see discussion in section 6.1 below). Then by the time they reach mean central densities of a few $10^5$ cm$^{-3}$, typical of the bright cores, they have passed through a critically stable equilibrium, and are either collapsing or else have some other means of support, even though the shape of their radial density profiles still resembles that of a super-critical Bonnor-Ebert sphere.

The interpretation of density structure in terms of Bonnor-Ebert profiles is interesting, although there are other caveats to studies of this nature. Some recent work has shown that even highly non-equilibrium cores can demonstrate a Bonnor-Ebert form of profile (e.g. Ballesteros-Paredes et al. 2003). Furthermore, it can be difficult to differentiate between forms of profile based on a two-dimensional representation such as an astronomical image.

Recent work by Harvey et al. (2003a) has shown that for some data-sets the profiles can often be fitted by many different forms of profile. This would tend to suggest that interpreting a particular profile in terms of a pressure-balanced equilibrium may be over-interpreting a limited amount of data. Nonetheless, even if there may be ambiguity over exactly how to model the density profiles, some forms of profile can be ruled out. For instance both the singular isothermal sphere and the logotropic non-isothermal sphere models can be ruled out (c.f. Bacmann et al., 2000).

Taken at face value, our result says that the majority of our bright cores are not critical, Bonnor-Ebert, pressure-supported spheres. This could either be indicating that the cores are already collapsing, or that there is some additional form of support that is operating, such as the support of a magnetic field or turbulence. These possibilities are discussed in the next section.

6 DISCUSSION

6.1 Categorising cores

We have observed 52 starless cores, including 50 positions from the catalogues of Myers and co-workers (e.g., Myers et al. 1983; Benson & Myers 1989). For the remainder of this paper we will ignore the two additional positions that we discovered (L1689SMM & L1521SMM) and merely discuss the remaining 50 cores. Of these 50, we detected 27 (54%) and failed to detect 23. Of the 27 detections, we classified 12 as bright and 15 as intermediate.

There is a clear difference between the bright and intermediate cores. Bright cores are more massive and sub-millimetre bright than intermediate cores. They also have higher central densities. It is a necessity of star formation that to form a star a cloud must evolve from an extended, low-density state to a much higher-density, more centrally-condensed core with eventually an embedded protostar. Therefore it is reasonable to conjecture that bright cores may be more evolved than intermediate cores, and hence closer to forming a protostar. We can use this hypothesis to infer evolutionary timescales for each category of core.

We saw in Tables 1–3 that there is a clear correlation between our SCUBA detections and the NH$_3$ detections of Benson & Myers (1989). All of our bright cores have NH$_3$ detections, and all except 3 of our intermediate cores have NH$_3$ detections (ignoring the two additional sources that we added to the Benson & Myers list). Similarly, only 4 of our non-detections were detected in NH$_3$. Therefore, we can say that a detection in NH$_3$ is roughly equivalent to a SCUBA detection. However, we note that almost all of the positions we surveyed (both detections and non-detections) have CO detections (Myers et al. 1983).

The amplitude of flux density fluctuations to which we are sensitive, given our detection sensitivity limit, corresponds to fluctuations in column density of $\sim 10^{22}$ cm$^{-2}$. Furthermore, our observing method is only sensitive to structures on scales smaller than roughly twice our chop throw, because the method of chopping that we use effectively subtracts away the larger-scale emission from extended clouds, on scales of $\sim 240$ arcsec or greater. Thus our observing method is most sensitive to structures on smaller scales than this. Consequently, our data are sensitive to fluctuations on scales that correspond to roughly $\leq 0.1$ pc at the typical distances of our sources. Hence our data are picking up the emission from dense molecular cloud cores on these sizescales.

The typical central volume densities of our bright cores are in the range of $\sim 2 \times 10^4 - 2 \times 10^6$ cm$^{-3}$ (Table 4). The intermediate cores (Table 2) have flux densities that translate into typical volume densities of $\sim 5 \times 10^4 - 2 \times 10^5$ cm$^{-3}$. For our third group of non-detected cores we can only place an upper limit on their column densities. This limit is roughly $10^{22}$ cm$^{-2}$. However, if they were of similar size to the detected cores, this would translate into an upper limit volume density of approximately $\leq 5 \times 10^4$ cm$^{-3}$ (c.f. Kirk 2003). We do not see any statistically significant differences between the cores in Taurus and those in Ophiuchus. However, this is perhaps not surprising, as none of our Ophiuchus cores lie in the cluster-forming region of $\rho$ Oph (see section 2). Hence all of our cores are relatively isolated, whatever region they lie in.

6.2 Core lifetimes

The numbers of cores detected can be used to determine typical statistical time-scales for particular evolutionary stages. This method was first employed for these cores by Beichman et al. (1986), who found that there were roughly equal numbers of their sources with and without embedded protostars. Those without embedded sources were labelled starless cores. Extrapolating from the typical T Tauri star lifetime to the lifetime of cores with embedded sources, they estimated the starless core lifetime to be roughly a few times $10^6$ years (c.f. Paper I).

This was subsequently refined by Lee & Myers (1999), who used a larger sample, to be $\sim 0.3-1.6 \times 10^6$ years. This value is based upon an estimated range in lifetimes for Class I sources of $\sim 1-5 \times 10^5$ years. Within this range the best estimate for the Class I lifetime is $\sim 2 \pm 1 \times 10^5$ years (e.g. Greene et al., 1994; Kenyon & Hartmann 1995). Con-
sequently, this corresponds to a starless core lifetime of \(\sim 6 \pm 3 \times 10^5\) years.

We have detected 27 out of 50 starless cores, so we arrive at a timescale for cores detected in the submillimetre of \(\sim 3 \times 10^5\) years. We note that this is only an approximate value, as is the following. We have previously called the submillimetre detected cores prestellar cores (c.f. Papers I–V). We also note that this lifetime we derive is consistent with that which we have found in previous studies (e.g. Paper I). We shall refer to this time-scale as \(t_{\text{submm}}\).

The minimum central volume density of a submillimetre detected core is \(\sim 5 \times 10^4\) cm\(^{-3}\). At this density the free-fall time \(t_{ff}\) is \(\sim 10^5\) years. Hence the statistical timescale we find for prestellar cores is roughly three times the free-fall time at the typical minimum density of a submillimetre detected prestellar core \(\sim t_{\text{submm}} \sim 3t_{ff}\).

We can make a similar calculation for the cores we classified as ‘bright’. These constitute 12 out of the total of 27 prestellar cores, or 44%. Hence we derive a statistical timescale for the bright cores, \(t_{\text{bright}}\), of \(\sim 1.5 \times 10^5\) years. The minimum central volume density of a bright core is \(\sim 2 \times 10^4\) cm\(^{-3}\). At this density the free-fall timescale is \(\sim 7 \times 10^4\) years. Once again the observed timescale is longer than the free-fall time at the typical minimum density of a bright core, this time twice as long \(- t_{\text{bright}} \sim 2t_{ff}\).

One additional caveat to our lifetime calculations is that if some of the cores do not go on to form stars (perhaps because they are dispersed before they can collapse) then our lifetimes will be over-estimated. We believe this is unlikely because the cores are so centrally condensed (and mainly exceed their virial mass – see Table 4) that they cannot easily self-disperse, and the probability of a significant number being over-run by externally-induced shocks on a timescale before they collapse is very low, given their relatively isolated locations.

Thus it appears that prestellar cores may live a few times longer than their free-fall collapse times. Hence we see quite clearly that prestellar cores cannot generally all be in free-fall collapse, and there must be some mechanism responsible for retarding the collapse. We now consider what that mechanism might be. Most star formation models appear to fall into one (or both) of two ‘camps’ when it comes to the mechanism they use for retarding collapse – turbulence, and magnetic fields. We will treat each in turn.

6.3 Comparison with turbulent models

One possibility is that the cores could be supported by turbulence. A recent model has produced simulated cores that mimic many of the observed properties of actual cores, such as their densities, temperatures and radial profiles (Ballesteros-Peredes et al. 2003). In this model the cores live for approximately a free-fall time.

Taken at face value, this is a factor of \(\sim 2-3\) times shorter than our estimated timescale for submillimetre cores above (see also André et al., 2004). Hence, this model that appears to be able to mimic some of the observed properties of prestellar cores, may not be able to reproduce the lifetimes of cores. We also note that this model does not reproduce the narrow linewidths observed in these cores. The observed linewidths have a mean value of \(0.27\) kms\(^{-1}\) (Ballesteros-Peredes et al. 2003), whereas the model predicts linewidths of \(\sim 1.5\) kms\(^{-1}\) (Ballesteros-Peredes et al. 2003).

We have noted elsewhere (c.f. Ward-Thompson et al. 2000) that turbulent models which include magnetic fields can only reproduce polarisation maps of prestellar cores if they are in the regime where the turbulent and magnetic energies are roughly equal (e.g. Ostriker, Gammie & Stone 1999; Ostriker, Stone & Gammie 2001; Crutcher et al. 2004).

However, these same models can only produce the observed core radial density profiles described above (see also Bacmann et al., 2000) if they are in the regime where the magnetic field dominates over the turbulence, in apparent contradiction with the polarisation results (Ward-Thompson et al., 2000). Consequently, turbulent models may be able to reproduce some of the observations, but they cannot match all of the data simultaneously.

6.4 Comparison with magnetic models

Another possibility is that magnetic fields alone are responsible for retarding collapse, and the cores are undergoing ambipolar diffusion. This is the process by which the neutrals drift past the ions, which are supported by the magnetic field, and precipitate the collapse process (e.g. Mouschovias 1991).

We have previously compared our observations to ambipolar diffusion models in Papers II and III. However, they were based on either individual cores or small number statistics. Now we are able to make a detailed comparison based on our large-scale survey. As a specific illustration, we begin with a comparison of the models of Ciolek & Mouschovias (1994 – hereafter CM94).

We have derived an approximate timescale, \(t_{\text{submm}}\), for our complete sample of detected cores of \(\sim 3 \times 10^5\) years. This corresponds to the timescale for a core to evolve from our minimum detection limit of \(\sim 5 \times 10^4\) cm\(^{-3}\) to the point at which it contains a protostar. The timescale predicted by CM94 ‘model A’, for a core to evolve from this density to forming a protostar is \(\sim 3 \times 10^6\) years, or a factor of \(\sim 10\) too long.

Taking the bright cores only, we have derived a timescale of \(\sim 1.5 \times 10^5\) years. This corresponds to the timescale for a core to evolve from a lower density limit of \(\sim 2 \times 10^5\) cm\(^{-3}\) to the point at which it contains a protostar. The timescale predicted by CM94 ‘model A’, for a core to evolve from this density to forming a protostar is \(\sim 3 \times 10^5\) years. This is in better agreement, although it still disagrees by a factor of \(\sim 2\). We see similar results for other models of CM94. We have previously reported similar findings (c.f. Paper III).

However, we have other constraints on the magnetic models. Observations of magnetic fields in molecular clouds have shown that most clouds have a ratio of mass to magnetic flux that is within a factor of \(\sim 2\) of the critical ratio whereby the two are in balance (e.g. Crutcher 1999; Crutcher et al., 2004).

The ratio of mass to magnetic flux in the centre of a core is given by CM94 in terms of the parameter \(\mu\). This is normalised such that \(\mu=1\) corresponds to the critical case where the magnetic field can just support the mass of the core against collapse (see also Ciolek & Basu 2000 – hereafter CB00). ‘Model A’ quoted above has \(\mu<0.25\).
A somewhat contrasting constraint on the models is provided by the radial density profiles of the cores observed in mid-infrared absorption, which show the cores to have very sharp edges (Bacmann et al., 2000). The only ambipolar diffusion models which can produce such sharp edges require a strong magnetic field in the low density ambient molecular cloud. This requires $\mu<1$. Thus no model can reproduce all of the observations.

Nonetheless, we can compare the timescales estimated from our data with those predicted by models that are closer to critical initial conditions. For example, CB00 modelled the evolution of L1544, one of our bright cores, with an initial value of $\mu=0.8$. They predict that the timescale for a core to evolve from $\sim 5 \times 10^3$ cm$^{-3}$ to forming a protostar is $\sim 1 \times 10^7$ years. This is in very good agreement with our estimated $\sim 3 \times 10^7$ years for the lifetime of a submillimetre core.

CB00 further predict that the timescale for a core to evolve from $\sim 5 \times 10^5$ cm$^{-3}$ to forming a protostar is $\sim 9 \times 10^7$ years. This is consistent to within a factor of 2 of our estimated $\sim 1.5 \times 10^7$ years for the lifetime of a bright core. However, we note that the ratio of the two timescales, $t_{\text{submm}}$ and $t_{\text{bright}}$, is $\sim 4$ for the model and only $\sim 2$ estimated from our observations. Hence we appear to be observing roughly a factor of 2 too many bright cores relative to the numbers of intermediate cores.

It seems that, for one of these models to match the overall timescales of prestellar cores, as well as many of the other observations, the initial conditions must be close to critical (e.g. Crutcher 1999; Crutcher et al., 2004). However, initially critical models appear to under-predict the numbers of bright cores seen. It is possible that some selection effects in our sample may account for this, but it is not obvious how such an effect might be operating. It is also possible that a more elaborate ambipolar diffusion model that incorporates the effects of a non-uniform (turbulent) component to the magnetic field may fare better in comparison with the observations.

### 6.5 Comparison with other data-sets

We can compare our data with data from the literature, and place overall constraints on all of the models. A similar comparison was carried out for a number of different data-sets in the literature by Jessop & Ward-Thompson (2000). They calculated statistical lifetimes for a number of data-sets, using the same method as we have used in this paper. They then plotted the calculated statistical lifetime against the mean volume density, adapted from Jessop & Ward-Thompson (2000), as shown in Figure 11. We here reproduce the data from that figure in our Figure 11. Remember that each data-point in Figure 11 represents a whole sample of cores, rather than just a single measurement. Jessop & Ward-Thompson (2000) found a best fit to the data of:

$$\tau_{AD} \propto n(H_2)^{-0.85},$$  \hspace{1cm} (10)

with a reduced chi-squared of 1.15. We show this as a solid line on Figure 11.

We then add to the previous data on Figure 11 the two samples we have studied here, labelling the intermediate cores as ‘Int’ and the bright cores as ‘Br’. We use the mean (FWHM) volume density of each core sample for consistency with previous surveys, and the lifetimes we calculated above.

We can also plot on Figure 11 the various model predictions. The turbulent models discussed above all predict evolution on timescales roughly equal to the free-fall time. This is shown on Figure 11 as the lower dashed line labelled ‘n$^{-0.5}$ (ff)’. A line corresponding to ten times the free-fall time is shown as the upper dashed line labelled ‘10ff’.

This is roughly equivalent to the model of cosmic ray ionisation-regulated star formation (e.g. Mouschovias 1991). Other symbols refer to literature data as follows: J – Jessop & Ward-Thompson (2000); W – Wood et al. (1994); C – Clemens & Barvainis (1988); B1 – Bourke, Hyland & Robinson 1995; B2 – Bourke et al. (1995); M – Myers et al. (1983). See text for further details.

**Figure 11.** Plot of inferred starless core lifetime against mean volume density, adapted from Jessop & Ward-Thompson (2000), using their original data with two additional data-points from this paper for the intermediate and bright core samples, marked as ‘Int’ and ‘Br’ respectively. The best fit power-law to the original data of $\tau \propto n(H_2)^{-0.85}$ is shown as a solid line and labelled ‘n$^{-0.85}$’. Note that the intermediate core data are consistent with this fit, but the bright core data lie somewhat above the extrapolation of this line. The free-fall timescale ($\tau \propto n(H_2)^{-0.5}$), as predicted by the ‘turbulent’ models discussed in the text (e.g. Ballesteros-Paredes et al., 2003), is shown as the lower dashed line and labelled ‘n$^{-0.5}$ (ff)’. A line corresponding to ten times the free-fall time is shown as the upper dashed line labelled ‘10ff’.

Hence the manner in which the ionisation of a core is regulated will strongly affect the timescale on which a core is predicted to evolve under ambipolar diffusion. Ionisation of the gas can be caused by both ultra-violet radiation and by cosmic rays. The relation between ionisation and volume density is usually taken to be a power-law. For example, Mouschovias (1991) uses cosmic ray-induced ionisation and finds:

$$\chi_i \propto n(H_2)^{-0.5},$$  \hspace{1cm} (11)

which leads to:

$$\tau_{AD} \propto n(H_2)^{-0.5}.$$  \hspace{1cm} (12)
This is shown as the upper dashed line on Figure 11, and labelled ‘10ff’ (c.f. Ciolek & Basu 2001).

When ionisation is dominated by UV radiation, and additional factors are included, such as chemical effects and the role of multiple charge carriers, the volume density has a slightly different influence on the recombination rate, and hence the ionisation fraction. For example, McKee (1989) finds:

\[ \chi_1 \propto n(H_2)^{-0.75}, \]  

(13)

leading to:

\[ \tau_{AD} \propto n(H_2)^{-0.75}, \]  

(14)

which is close to the best-fit power-law in Figure 11. However, UV ionisation is only prevalent at low column densities, which is close to the best-fit power-law in Figure 11. How-

core in every case. Hence we see that the cores are not critical Bonnor-Ebert spheres. The masses of the bright cores were seen to have a mean value of approximately 1.5 times their virial masses, possibly also indicating that the cores are not supported by internal thermal pressure.

Approximate estimates of core lifetimes were made, based on statistics of detections and relative numbers of cores with embedded young stellar objects. The lifetime of a submillimetre detected core, or prestellar core, was estimated at \( \sim 3 \times 10^5 \) years, while that of a bright core was estimated to be \( \sim 1.5 \times 10^5 \) years. None of the current theoretical models were seen to be able to exactly match all of the observed physical parameters. Models that regulate collapse magnetically via the ionised component of the gas were seen to be able to match the timescales at lower densities, but did not reproduce the relative numbers of bright and intermediate cores.

7 CONCLUSIONS

In this paper we have presented submillimetre continuum data of a large sample of starless cores. We have detected 29 out of 52 cores at a wavelength of 850 \( \mu \)m. Our detection limit corresponds to an \( A_V \) of roughly 15. Of the 29 detected cores, 13 were detected at a peak flux density level of greater than 170 mJy/beam, which corresponds to an \( A_V \) of roughly 50. These 13 cores were designated ‘bright’ cores. The 16 detected cores with peak flux density levels less than this value were designated ‘intermediate’ cores.

The data were combined with previous ISO data and the physical parameters of the cores were derived. The temperatures of the cores are all around 10 K. The central volume densities of the bright cores were found to lie in the range of \( 2 \times 10^5 - 2 \times 10^6 \) cm\(^{-3}\). The central volume densities of the intermediate cores were seen to lie in the range of \( 5 \times 10^4 - 2 \times 10^5 \) cm\(^{-3}\).

The radial density profiles of the bright cores were measured, and seen to follow the now familiar form of having a flat central profile that steepens towards the edge. Detailed comparison of the profiles with that of a Bonnor-Ebert sphere showed that 6 out of 7 cores had a value of \( \xi_{max} \) significantly greater than the critical value of 6.5. The effective temperature required by the Bonnor-Ebert fitting also exceeded (by factors of \( \sim 2-8 \)) the measured temperature of the

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REFERENCES


Paper II


