THE JCMT GOLDBELT SURVEY: A FIRST LOOK AT DENSE CORES IN ORION B


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ABSTRACT

We present a first look at the SCUBA-2 observations of three sub-regions of the Orion B molecular cloud: LDN 1622, NGC 2023/2024, and NGC 2068/2071, from the JCMT Gould Belt Legacy Survey. We identify 29, 564, and 322 dense cores in L1622, NGC 2023/2024, and NGC 2068/2071 respectively, using the SCUBA-2 850 μm map, and present their basic properties, including their peak fluxes, total fluxes, and sizes, and an estimate of the corresponding 450 μm peak fluxes and total fluxes, using the FellWalker source extraction algorithm. Assuming a constant temperature of 20 K, the starless dense cores have a mass function similar to that found in previous dense core analyses, with a Salpeter-like slope at the high-mass end. The majority of cores appear stable to gravitational collapse when considering only thermal pressure; indeed, most of the cores which have masses above the thermal Jeans mass are already associated with at least one protostar. At higher cloud column densities, above 1–2 × 10^{23} cm^{-2}, most of the mass is found within dense cores, while at lower cloud column densities, below 1 × 10^{23} cm^{-2}, this fraction drops to 10% or lower. Overall, the fraction of dense cores associated with a protostar is quite small (<8%), but becomes larger for the densest and most centrally concentrated cores. NGC 2023/2024 and NGC 2068/2071 appear to be on the path to forming a significant number of stars in the future, while L1622 has little additional mass in dense cores to form many new stars.

Key words: dust, extinction — stars: formation — submillimeter: ISM

Supporting material: machine-readable table

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1. INTRODUCTION

The James Clerk Maxwell Telescope (JCMT) Gould Belt Survey has mapped nearly all of the nearby (∼500 pc) significant star-forming regions visible from Hawaii with the SCUBA-2 instrument (Holland et al. 2013), tracing thermal emission from dust grains at 850 and 450 μm (Ward-Thompson et al. 2007). A subset of these star-forming regions has also been mapped in 3–2 line emission of CO isotopologues using HARP (Buckle et al. 2009). With a variety of nearby star-forming regions mapped in a uniform manner, one of the goals of the GBS is to characterize the properties of dense cores and their surroundings, and determine the influence of the larger environment on their formation and evolution. In this paper, we present a first look at the SCUBA-2 observations of the Orion B molecular cloud, identifying dense cores and analyzing their basic properties. Buckle et al. (2010) earlier presented a first look analysis of the 12CO, 13CO, and C18O line observations in Orion B.

The Orion B molecular cloud is part of the larger Orion complex, a large (∼100 pc long; Maddalena et al. 1986), nearby (∼415 pc, e.g., Anthony-Twarog 1982; Menten et al. 2007) set of associated molecular clouds forming both low- and high-mass stars (e.g., Bally 2008). The best-studied part of the Orion complex is the Orion A cloud, which includes the Integral Shaped Filament (e.g., Bally et al. 1987) and the Orion Nebula Cluster (e.g., Muench et al. 2008). The Orion B cloud lies northeast of the Orion A cloud and has a similar total mass of about 10^5 M_☉ (e.g., Maddalena et al. 1986; Meyer et al. 2008) but a smaller fraction of dense gas. This lower fraction of dense gas also translates into a lower overall star formation rate (two to seven times lower; Meyer et al. 2008). Lombardi et al. (2014) found that the surface density of young protostars varies roughly with the square of the extinction (or total column density) in Orion. The bulk of star formation in Orion B is concentrated within three clusters, NGC 2024, NGC 2068, and NGC 2071, which are estimated to contain 60%–90% of the current young stellar objects (YSOs) in Orion B, while a fourth cluster, NGC 2023, is forming a smaller number of stars (e.g., Lada et al. 1991; Meyer et al. 2008). The most active parts of these four regions have been analyzed using prior submillimeter observations, including dust continuum maps from SCUBA (e.g., Johnstone et al. 2001, 2006; Mitchell et al. 2001; Motte et al. 2001; Nutter & Ward-Thompson 2007) and the polarimeter attached to SCUBA (Matthews et al. 2002; Matthews & Wilson 2002). Our SCUBA-2 observations cover a larger area around these four regions than the original SCUBA data—2.1 and 1.7 square degrees were mapped by SCUBA-2 in NGC 2023/2024 and NGC 2068/2071 respectively, compared to 0.5 and 0.3 square degrees with SCUBA. Our SCUBA-2 observations also cover a fifth region, LDN 1622 (0.6 square degrees mapped), which contains roughly 30 YSOs (Reipurth et al. 2008). 1622 is formally part of “Orion East” and has a typical CO centroid velocity different from the neighboring Orion B (e.g., ∼1 km s⁻¹ versus ∼10 km s⁻¹; Maddalena et al. 1986). Reipurth et al. (2008), however, cite other evidence that suggests 1622 is still part of the same Orion complex at a similar distance as Orion A and B, though a few observations suggest a distance of less than 200 pc (see discussion in Reipurth et al. 2008).

Star-forming regions tend to display hierarchical structure, as recent Herschel Gould Belt Survey results (e.g., André et al. 2010, 2014) have beautifully illustrated. The larger-scale (column) density distribution of material is often traced with CO observations (e.g., Maddalena et al. 1986), estimates of the dust column density based on stellar reddening (e.g., Lombardi et al. 2011), or more recently, combining Herschel and Planck measurements of dust emission (e.g., Lombardi et al. 2014). SCUBA-2 is insensitive to the largest scale of (lower) column density, like any ground-based submillimeter instrument, but provides a higher-resolution view of smaller-scale dense objects than the former measurements can usually provide. For example, D. Ward-Thompson et al. (2015, in preparation) show that in the Taurus molecular cloud, SCUBA-2 is particularly sensitive to the denser, more compact objects that will likely become (or already are) the birthing sites of protostars, even when the effects of ground-based filtering are accounted for.

In our first-look analysis, we examine the dense cores detected by SCUBA-2 in the context of the larger-scale column density (using data from Lombardi et al. 2014), as well as already-formed young protostars (using data from Megeath et al. 2012 and Stutz et al. 2013). In this paper, we describe the SCUBA-2 observations (Section 2), identify the dense cores therein (Section 3), analyze the basic properties of the cores including their masses, gravitational stability, and relationship with the material in the larger cloud (Section 4), discuss our results (Section 5), and summarize our conclusions (Section 6).

2. OBSERVATIONS

Orion B was observed with SCUBA-2 (Holland et al. 2013) at 850 and 450 μm as part of the JCMT Gould Belt Survey (Ward-Thompson et al. 2007). Three separate regions were observed: the areas around L1622, NGC 2023/2024, and NGC 2068/2071, as illustrated in Figure 1. Our SCUBA-2 observations cover most of the high flux areas in the Herschel 500 μm map from Schneider et al. (2013). The SCUBA-2 observations were obtained between 2012 February and 2014 November with some initial science verification data taken in 2011 October and November. Most data were observed as fully sampled 30’’ diameter circular regions using the PONG 1800 mode (Kackley et al. 2010). Several science verification observations taken in the NGC 2023/2024 and NGC 2068/2071 regions were instead taken in PONG 900 mode, which fully samples a 15’’ diameter circular region (Kackley et al. 2010). Each area of sky was observed between four to six times in PONG 1800 mode, with the number of repeats depending on weather conditions. Neighboring fields were set up to overlap slightly to create a more uniform noise in the final mosaic. The PONG 900 observations are not included in the final mosaic that we analyze here, to maintain an approximately uniform noise level and sensitivity to larger-scale structures across the areas observed.

The data reduction used for the maps presented here follow the GBS Legacy Release 1 methodology, which is discussed in Mairs et al. (2015). The data presented here were reduced using an iterative map-making technique (makemap in SMURF35; Chapin et al. 2013b), and gridded to 3” pixels at 850 μm and 2”.

35 We downloaded the Herschel 500 μm map from http://www.herschel.fr/cea/gouldbelt/en/Phocea/Vie_des_labos/Ast/ast_visu.php?td=ast--66

35 SMURF is a software package used for reducing JCMT observations, and is described in more detail in Chapin et al. (2013a).
pixels at 450 μm. The iterations were halted when the map pixels, on average, changed by <0.1% of the estimated map rms. The initial reductions of each individual scan were coadded to form a mosaic from which a signal-to-noise mask was produced for each region. The final mosaic was produced from a second reduction using this mask to define areas of emission. In Orion B, the mask included all pixels with signal-to-noise ratio of 2 or higher at 850 μm. Testing by our data reduction team showed similar final maps using either an 850 μm based or a 450 μm based mask for the 450 μm reduction, when using the signal-to-noise ratio-based masking scheme described here. Using identical masks at both wavelengths for the reduction ensures that the same large-scale filtering is applied to the observations at both wavelengths (e.g., maps of the ratio of fluxes at both wavelengths are less susceptible to differing large-scale flux recovery). Detection of emission structure and calibration accuracy are robust within the masked regions, but are less certain outside of the masked region (Mairs et al. 2015).

Larger-scale structures are the most poorly recovered outside of the masked areas, while point sources are better recovered. A spatial filter of 600″ is used during both the autormask and external mask reductions, and an additional filter of 200″ is applied during the final iteration of both reductions to the areas outside of the mask. Further testing by our data reduction team found that for 600″ filtering, flux recovery is robust for sources with a Gaussian FWHM less than 2/5, provided the mask is sufficiently large. Sources between 2/5 and 7/5 in diameter were detected, but both the flux and the size were underestimated because Fourier components representing scales greater than 5′ were removed by the filtering process. Detection of sources larger than 7/5 is dependent on the mask used for reduction. At a distance of 415 pc, 7/5 corresponds to 0.9 pc.

The data are calibrated in mJy per square arcsec using aperture flux conversion factors (FCFs) of 2.34 Jy/pW/arcsec² and 4.71 Jy/pW/arcsec² at 850 μm and 450 μm, respectively, as derived from average values of JCMT calibrators (Dempsey et al. 2013). The PONG scan pattern leads to lower noise in the map center and mosaic overlap regions, while data reduction and emission artifacts can lead to small variations in the noise over the whole map. The pointing accuracy of the JCMT is smaller than the pixel sizes we adopt, with current rms pointing errors of 1/2″ in azimuth and 1/6″ in elevation (see http://www.eaobservatory.org/JCMT/telescope/poivning/poivning.html); JCMT pointing accuracy in the era of SCUBA is discussed in Di Francesco et al. (2008).

The observations for Orion B were taken in both grade one (τ_{225 GHz} < 0.05) and grade two (0.05 < τ_{225 GHz} < 0.08) weather, corresponding to τ_{850 μm} < 0.21 and 0.21 < τ_{850 μm} < 0.34 respectively (Dempsey et al. 2013), with a mean value of τ_{225 GHz} of 0.06 ± 0.01. At 850 μm, the final noise level in the mosaic is typically 0.05 mJy arcsec⁻² per 3″ pixel, corresponding to 3.7 mJy per 14′′ beam. At 450 μm, the final noise level is 1.2 mJy arcsec⁻² per 2″ pixel, corresponding to 59 mJy per 98′′ beam. (Note the beam sizes quoted here are the effective beams determined by Dempsey et al. 2013 and account for fact that the beam shape is well-represented by the sum of a Gaussian primary beam shape and a fainter, larger Gaussian secondary beam.) The noise levels for each PONG observing area in the final mosaic is given in Table 1 in terms of the typical rms in a pixel.

Figures 2 through 4 show the final reduced images, along with their associated noise maps. The external masks applied are indicated by the blue contours on the 850 μm noise map. Note that the isolated pixels in the mask at the map edges will have no effect on the scale of a dense core, since the contiguous area within those parts of the mask is too small. Several of the brightest sources of emission in the maps are surrounded by negative (“bowl”) features. These features may slightly diminish the sizes and total fluxes we derive for sources in Section 3, but based on artificial source-recovery tests discussed in Mairs et al. (2015) and our mask-making strategy, we expect our results to be accurate to 20% or better.

Portions of the NGC 2023/2024 and NGC 2068/2071 regions were also observed by the GBS in ¹²CO (3-2) with HARP (Buckle et al. 2010) and reduced using ORAC-DR (Jenness et al. 2015). These areas are indicated as contours in Figures 1, 3, and 4. The ¹²CO (3-2) emission line lies within the 850 μm continuum band, and therefore some fraction of the 850 μm flux may in fact not be thermal dust emission (e.g., Johnstone et al. 2003). Observations of other star-forming regions (e.g., Johnstone et al. 2003; Drabek et al. 2012; Hatchell et al. 2013; Sadavoy et al. 2013; Buckle et al. 2015; Pattle et al. 2015; Salji et al. 2015) have shown that this “contamination” is generally not a large effect (<20%), the main exception being regions with faint dust emission and bright CO outflows, where the ¹²CO emission can dominate (up to 90%). Over the regions where we have HARP CO observations, we estimate the level of CO contamination on the observed 850 μm flux. Following the procedure outlined in Drabek et al. (2012), we run an extra round of data reduction with the CO integrated intensity map included as a negative
Table 1

<table>
<thead>
<tr>
<th>Region</th>
<th>Name</th>
<th>RA(^b)</th>
<th>Decl(^b)</th>
<th>(\sigma)(^c)</th>
<th>(\sigma)(^d)</th>
<th>N(_{\text{obs}})(^e)</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>(J2000.0)</td>
<td>(J2000.0)</td>
<td></td>
<td>(mJy arcsec(^{-2}))</td>
<td>(mJy beam(^{-1}))</td>
<td></td>
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<td>LDN 1622</td>
<td>ORIONBN_850_solo</td>
<td>5:54:33</td>
<td>1:49:34</td>
<td>0.053</td>
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<td>3.9</td>
</tr>
<tr>
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<td>ORIONBN_450_E</td>
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<td>0:13:60</td>
<td>0.050</td>
<td>1.0</td>
<td>3.7</td>
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<td>ORIONBN_450_S</td>
<td>5:46:17</td>
<td>0:06:30</td>
<td>0.050</td>
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<td>3.7</td>
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<td>0:24:42</td>
<td>0.055</td>
<td>1.7</td>
<td>4.0</td>
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<td>ORIONBN_850_N</td>
<td>5:47:33</td>
<td>0:45:26</td>
<td>0.047</td>
<td>0.9</td>
<td>3.4</td>
</tr>
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<td>-1:09:11</td>
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<td>1.0</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Notes.


\(^b\) Central position of each observation.

\(^c\) Pixel-to-pixel (rms) noise for the final mosaic of all of the observed PONG 1800s for the given area at 850 \(\mu\)m and 450 \(\mu\)m respectively.

\(^d\) Effective noise per beam (i.e., point source sensitivity) for the final mosaic of all of the observed PONG 1800s for the given area at 850 \(\mu\)m and 450 \(\mu\)m respectively.

\(^e\) Total number of PONG 1800 observations taken at each wavelength. Note that this count may include partially completed scans.

Figure 2. The SCUBA-2 850 \(\mu\)m (top) and 450 \(\mu\)m (bottom) observations of L1622 in Orion B. The left panel on each row shows the entire map, while the middle panel shows the noise, and the right panel shows a zoom on a zone of stronger emission. In the left and right panels, the scaling is approximately logarithmic, while the middle panel is shown with a linear scale. The black circle in the upper right corner shows the effective beamsize at each wavelength, while the scale bar at the bottom indicates the angular distance corresponding to 1 pc at the assumed cloud distance of 415 pc. The external mask used in the reduction is indicated by the blue contour on the 850 \(\mu\)m noise map (signal-to-noise ratio \(\geq 2\) at 850 \(\mu\)m in the initial reduction). An identical mask was used at 450 \(\mu\)m.
source of emission in each raw data file, scaled to the atmospheric transmission of that evening. These CO-subtracted maps are then mosaicked together, and compared with the original 850 \( \mu \)m mosaic. This procedure ensures that the CO data are filtered and processed identically to our 850 \( \mu \)m data.

We calculate the fractional CO contamination level as

\[
\frac{f_{\text{CO}}}{S_{\text{850,orig}} - S_{\text{850,noco}}} = \frac{S_{\text{850,noco}}}{S_{\text{850,orig}}} (1)
\]

where \( S_{\text{850,orig}} \) is the flux in the original 850 \( \mu \)m map and \( S_{\text{850,noco}} \) is the flux in the CO-subtracted 850 \( \mu \)m map. Most of the area mapped has \( f_{\text{CO}} \) below the (fractional) noise level at the same location, implying an overall very small contamination level. In NGC 2068/2071, several small zones at the outskirts of the NGC 2071 cluster show \( f_{\text{CO}} \) above the 20% level, but these are generally in areas of lower 850 \( \mu \)m flux. In NGC 2023/2024, slightly off of the main NGC 2024 cluster, there are several dense cores which show contamination levels above 50% over part of their extent (less than half of their full extent, and usually substantially less). In general, however, the level of CO contamination is small. Since most of the cores fall outside of the region with CO observations, we do not include the CO flux corrections in any of our subsequent analysis.

3. SOURCE IDENTIFICATION

We identify cores in the three 850 \( \mu \)m Orion B maps using FellWalker (Berry 2015), a source identification algorithm available as part of the CUPID\(^5\) package (Berry et al. 2007) in Starlink. The basic premise of FellWalker is to define the peaks and sizes of objects in images based on local gradients, and the extent of pathways which lead to a given peak. Like the more traditionally used ClumpFind algorithm (Williams et al. 1994), FellWalker does not assume a geometry when identifying cores. ClumpFind, however, splits zones of complex emission into multiple cores based on user-selected contour levels, whereas FellWalker relies on local gradients instead; Watson (2010) found FellWalker generally produces superior results to ClumpFind, including a generally better recovery of accurate peak and total fluxes of artificial cores inserted into maps.

\(^5\) http://www.starlink.ac.uk/cupid
FellWalker provides both a listing of the peak flux position for each dense core and also a dense core footprint (i.e., a set of pixels all belonging to the core). Appendix A discusses the details of our source identification process.

We ran FellWalker with very relaxed settings, identifying 260, 1383, and 1020 potential sources, from which we then culled unreliable sources from. After this subsequent elimination, we identified 29 reliable cores in L1622, 564 in NGC 2023/2024, and 322 in NGC 2068/2071. See Appendix A for more details on our core identification strategy. Our final core list includes cores with peaks potentially as low as twice the local noise level. While this is fainter than most core searches would be extended to, a careful comparison of the 850 μm data with the Herschel 500 μm data revealed that faint structures below the formal 3σ typical cutoff were, in fact, real, and appear to have similar extents at both wavelengths. The dense cores we identify are shown in Figures 5–7, with the dense core footprints, and the Spitzer-identified protostars from Megeath et al. (2012) and Herschel-identified protostars from Stutz et al. (2013) also shown (see next section for more discussion on identifying protostellar cores). We note that in Figure 5, more closed contours are apparent than the total number of cores identified. FellWalker does not require that cores have contiguous boundaries, and therefore sometimes near a core edge, some pixels will be excluded, e.g., due to low flux, while other neighboring pixels do satisfy all of the core criterion and are included. These isolated pixels represent a small fraction of individual cores and by definition are located in low-flux areas of the map. Therefore, these isolated pixels have minimal influence on the properties we measure (recall that the core size is based on the total area of the core footprint, not the maximal core extent).

Table 2 provides a full list of the dense cores we identify within each of the three regions. In the table, core locations correspond to the position of peak flux within the core. The peak flux and total flux are calculated without any background emission subtracted, but see Section 4 for further treatment of this issue. The peak flux is given in Jy bm⁻¹, with the conversion from mJy arcsec⁻² made assuming an effective beam size of 14''6 (Dempsey et al. 2013). The core size is the effective radius, R eff, calculated as the radius of a circle which spans the same area as the dense core (calculated using the full flux).
Table 2
Dense Cores Identified with FellWalker

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Region</th>
<th>Index</th>
<th>RA(^a) (J2000.0)</th>
<th>Decl.(^a) (J2000.0)</th>
<th>850 (\mu)m</th>
<th>450 (\mu)m</th>
<th>CO Contam.</th>
<th>Bggrd</th>
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<td></td>
<td></td>
<td></td>
<td>Peak(^b) (Jy bm(^{-1}))</td>
<td>Total(^b) (Jy)</td>
<td>(R_{\text{eff}}) (^b) (pc)</td>
<td>Peak(^c) (Jy bm(^{-1}))</td>
</tr>
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<td>L1622</td>
<td>1</td>
<td>5:54:24.60</td>
<td>+01:44:19.7</td>
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<td>4.889</td>
<td>0.121</td>
<td>4.656</td>
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<td>8</td>
<td>5:54:40.00</td>
<td>+01:43:40.7</td>
<td>0.088</td>
<td>0.241</td>
<td>0.060</td>
<td>0.604</td>
</tr>
<tr>
<td>J055421.7+014210</td>
<td>L1622</td>
<td>9</td>
<td>5:54:21.79</td>
<td>+01:42:10.7</td>
<td>0.080</td>
<td>0.370</td>
<td>0.063</td>
<td>0.875</td>
</tr>
</tbody>
</table>

Notes:
\(^a\) Position of peak emission in the dense core.
\(^b\) Peak flux, total flux, and effective radius of the dense cores, as measured at 850 \(\mu\)m. The effective beamsize at 850 \(\mu\)m is 14\(^{\prime}\)6.
\(^c\) Peak flux and total flux at 450 \(\mu\)m within the dense core boundaries defined on the 850 \(\mu\)m image (note that the total flux may be negative in regions without a detected 450 \(\mu\)m signal). The effective beamsize at 450 \(\mu\)m is 9\(^{\prime}\)8.
\(^d\) Is the dense core associated with a protostar in Spitzer (Megeath et al. 2012) or Herschel (Stutz et al. 2013)?
\(^e\) CO contamination: fraction of dense core footprint where CO observations exist, peak and total flux at 850 \(\mu\)m in CO subtracted mosaic (–1 indicates null values).
\(^f\) Background subtracted total flux at 850 \(\mu\)m.

(This table is available in its entirety in machine-readable form.)
The original SCUBA instrument at JCMT observed parts of NGC 2023/2024 and NGC 2068/2071 (e.g., Johnstone et al. 2001, 2006; Mitchell et al. 2001; Motte et al. 2001; Nutter & Ward-Thompson 2007). Motte et al. (2001) used a wavelet-based scheme to identify dense cores, which generally identifies more compact regions of emission. Other SCUBA analyses (Johnstone et al. 2001, 2006; Mitchell et al. 2001; Nutter & Ward-Thompson 2007) used ClumpFind, which tends to act more similarly to FellWalker, in identifying larger zones of emission around each core. We provide a detailed comparison of the dense cores identified in Nutter & Ward-Thompson (2007) as well as those published in the SCUBA Legacy Catalog (Di Francesco et al. 2008) with our SCUBA-2 results in Appendix B. We find generally good agreement between the cores identified in SCUBA and their corresponding match in the SCUBA-2 data. Different core identification schemes, however, can subdivide regions of complex emission differently, which generally leads to larger differences in the total fluxes and sizes of the cores between the two measurements than peak fluxes. The SCUBA-2 observations are factors of four to six times more sensitive than the SCUBA observations, with a median noise level of 3.7 mJy bm$^{-1}$ compared to 16–23 mJy bm$^{-1}$ in SCUBA (Nutter & Ward-Thompson 2007).

4. DENSE CORE PROPERTIES

We first classify all of the dense cores as starless or protostellar. Our aim is to make a conservative list of starless cores. We start by using the Spitzer catalog from Megeath et al. (2012) to identify protostars. Specifically, any dense core which contained one or more protostars listed in the “all protostars” list from Megeath et al. (2012) within the dense core’s boundary was classified as a protostellar. We supplement our list of protostars by running a similar procedure on the full list of candidate protostars from Stutz et al. (2013) using Herschel data. In other words, if any pixel of a core has a protostar lying within it from either catalog, we classify the core as protostellar. We note that the Herschel catalog covers a smaller area within Orion B, and focuses exclusively on the most embedded YSOs. This procedure allows us to identify five protostellar cores in L1622, 25 in NGC 2023/2024 (of which 3 were Herschel-based) and 34 in NGC 2068/2071 (of which 6 were Herschel-based). The number of starless cores in each region is therefore 24, 539, and 288 in L1622,

Figure 5. Dense cores identified in L1622. The background grayscale image shows the SCUBA-2 850 μm emission. The red contours show the dense core boundaries, as identified with FellWalker, while the blue triangles show locations of protostars from the Spitzer YSO catalog of Megeath et al. (2012) and blue asterisks show the Herschel YSO catalog of Stutz et al. (2013). Dark symbols indicate protostars associated with a dense core, while light symbols indicate unassociated protostars. The light yellow contour denotes the Herschel coverage for the Stutz et al. (2013) catalog (A. Stutz 2015, private communication).

Figure 6. Dense cores identified in NGC 2023/2024. See Figure 5 for the plotting conventions used.
NGC 2023/2024, and NGC 2068/2071 respectively. Table 2 denotes which dense cores we defined as protostellar.

4.1. Masses

In addition to the dense core properties returned directly from FellWalker (size, peak flux, and total flux), the core mass is an important property. Using only the total 850 \( \mu \)m flux measured for each core, we estimate the mass using the equation

\[
M = \frac{S_\nu D^2}{\kappa_\nu B_\nu(T)}
\]  

(2)

from Hildebrand (1983), where \( S_\nu \) is the total flux at frequency \( \nu \), \( \kappa \) is the dust opacity, and \( B \) is the blackbody function at temperature \( T \). This simplifies to

\[
M = 1.06 \times S_{850 \mu m} \times (e^{\frac{128}{T}} - 1) 
\times (\kappa_{850 \mu m}/0.0125 \text{ cm}^2 \text{ g}^{-1})^{-1} \times (D/415 \text{ pc})^2
\]  

(3)

with \( M \) in solar masses and \( S_{850 \mu m} \) in Jy km s\(^{-1}\). We adopt a dust opacity of \( \kappa_\nu = 0.1 \times (\nu/10^{12} \text{Hz})^\beta \text{ cm}^2 \text{ g}^{-1} \) with \( \beta = 2 \), i.e., \( \kappa_{850 \mu m} = 0.0125 \text{ cm}^2 \text{ g}^{-1} \), following Pattle et al. (2015) and Salji et al. (2015) among others, and a distance of 415 pc following Buckle et al. (2010). These two assumptions are similar to those used in previous SCUBA analyses. Note, however, that Motte et al. (2001), Johnstone et al. (2006), and Nutter & Ward-Thompson (2007) assume a distance of 400 pc, while Johnstone et al. (2001) assumes 450 pc. Also, Johnstone et al. (2001) and Nutter & Ward-Thompson (2007) assume \( n_{\text{H}_2} = 0.01 \text{ cm}^{-3} \) while Motte et al. (2001) and Johnstone et al. (2006) assume \( n_{\text{H}_2} = 0.02 \text{ cm}^{-3} \).

The dense cores are likely to have a range of temperatures (both within each core, and core-to-core), although the largest variation would be expected for the protostellar cores. Schneider et al. (2013) find dust temperatures of \( \sim 20 \text{K} \) or higher around the NGC 2023/2024 and NGC 2068/2071 clusters, where most of the SCUBA-2 emission is observed.\(^{37}\) We therefore assume a constant temperature of 20 K, consistent with Johnstone et al. (2006) and Nutter & Ward-Thompson (2007), as well as Sadavoy et al. (2010); Motte et al. (2001), however, assumed a temperature of 15 K for starless cores and 20–40 K for protostellar cores, while Johnstone et al. (2001) assumed a constant value of 30 K. Johnstone et al. (2006) note the four most massive cores they identified in Orion B are known to harbor bright far-infrared sources which have heated them to above 50 K, which would lower their estimated masses considerably from the value measured assuming 20 K. At 50 K, the masses would be a factor of 3.3 lower than assuming a temperature of 20 K. We expect high temperatures to be most likely in some of the brightest protostellar cores, where the masses we estimate are largest. Uncertainties in the dust opacity and cloud distance also increase the uncertainty in the dense core mass estimates. The dust opacity at 850 \( \mu \)m likely has some variation across the cloud, with some inter-core and core-to-core variations, as seen in the \( \beta \) variations measured across the Perseus molecular cloud by Chen et al. (2015) and Sadavoy et al. (2013). We expect that the distance will generally be relatively constant across the cloud, and is more likely to affect global population values (i.e., changes would increase/decrease all masses by the same factor), and should have a smaller effect on the relative masses estimated.

In addition to the uncertainties in the conversion factor between flux and mass, there is one other important consideration. Structures within molecular clouds are hierarchical in nature, although our SCUBA-2 observations are insensitive to the largest of these structures. Source identification algorithms such as FellWalker associate zones of emission with a single source, whereas other types of algorithms such as those based on dendrograms (e.g., Rosolowsky et al. 2008) treat emission as nested levels in a hierarchy of emission. Under the latter scheme, only a fraction of the total emission at a given position would be associated with the top level of the hierarchical structure (i.e., the dense core), while some fraction of the emission would be associated with underlying larger structures. We therefore make a second estimate of the total flux associated with each core which accounts for some of this larger-scale structure. Conservatively, we take the median flux value of pixels along the boundary of a core as representing the constant background level of underlying layers of structure, and subtract that value from every pixel lying within the core. We refer to this as the background-subtracted total flux (and mass), and include the background-subtracted flux in Table 2. This background subtraction method will overestimate the

\(^{37}\) While the maps at each Herschel wavelength analyzed by Schneider et al. (2013) are publicly released, the derived temperature and column density maps are not similarly available at present. A full re-derivation of the dust temperature across Orion B based on the Herschel data is beyond the scope of our present analysis.
contribution of larger-scale emission, particularly in the more clustered parts of the cloud, and therefore provides a strict lower limit to the dense core masses.

Figure 8 shows the cumulative mass functions measured from the total and background subtracted fluxes for the starless core population in each of the three regions observed (top row and bottom left panel), and also as a combined sample (bottom right panel). We omit the protostellar cores on the basis that their masses are more likely to be overestimated by assuming a constant temperature of 20 K. We estimate the completeness level from a flux level of $3\sigma$ across an area equal to the median starless core size. At the higher-mass end of the distribution, the slope is roughly consistent with the canonical Salpeter IMF (Salpeter 1955) for either estimate of the dense core masses.

This similarity of the slope with the Salpeter IMF agrees with the original SCUBA analysis of Motte et al. (2001), and the combined SCUBA Orion A and B results of Nutter & Ward-Thompson (2007), among others. Although the Herschel core mass distribution for Orion B is not yet available for a direct comparison (see, however, Schneider et al. 2013 for the Orion B column density PDF), other star-forming regions tend to follow a similar profile (see, e.g., André et al. 2014).

At the very highest masses, we appear to have a slight deficit of starless cores relative to a pure Salpeter distribution. For example, extrapolating the mass function shown in black from around 1 Jy (around $1$ M$_\odot$) up to 10 Jy using a Salpeter slope implies that there should be roughly three cores with total fluxes above 10 Jy, whereas our sample contains only one. The
discrepancy between the Salpeter slope and the observed distribution of cores becomes even larger when the background subtracted masses are used instead. Both, however, are consistent within 3σ Poisson uncertainties. An even larger sample of dense cores, ideally at least 10 times more cores with high masses, would be needed to confirm whether or not this result is statistically significant. An absence of massive dense starless cores might also be partially attributable to the tendency of object-identification algorithms to split large sources into multiple components. A real dearth of the most massive starless cores might also be partially attributable to a slightly higher detection rate of protostars in the infrared; since massive cores tend to have higher densities, it is possible that their natal protostars would tend to have higher accretion rates, and therefore higher luminosities. A larger sample size, combined with a detailed consideration of the typical accretion rates derived for detected protostars, would be necessary to test this scenario.

4.2. Core Stability

Using the sizes and estimated masses of all the dense cores, we can determine which cores are stable to gravitational collapse. Figure 9 shows the core masses and radii for all three regions, as indicated by the different colors. The JCMT effective beam width and the approximate flux sensitivity, i.e., three times the median noise level integrated across a given area are also shown. Our core selection criterion is slightly more complex than can be captured by a single completeness level. In particular, we removed sources that failed several local signal-to-noise ratio criteria, which are more stringent than the global level indicated. In Figure 9, we show masses derived from the total fluxes of all cores (left panel), as well as masses derived from background-subtracted total fluxes (right panel). The background-subtracted mass estimates tend to be smaller (as expected), and can be significantly smaller than our nominal total mass completeness level. We emphasize that our simple method for estimating the background level overestimates the true core background, likely by a significant amount for cores in crowded regions, and therefore those results should be treated with caution.

Assuming a spherical geometry for the dense cores allows us to estimate their mean densities. Lines of constant density of $10^4$, $10^5$, and $10^6$ cm$^{-3}$ are plotted in Figure 9. Most of the cores in the left panel lie between $10^4$ cm$^{-3}$ and several $10^5$ cm$^{-3}$. Although not explicitly calculated there, the range spanned by our more massive dense cores is similar to that inferred from Figure 5 of Johnstone et al. (2001) and Figure 7 of Johnstone et al. (2006). Motte et al. (2001) use a wavelet-based source-finder and include deconvolution of the telescope beam in their final size measurement, which tends to lead to smaller sizes (and therefore higher mean densities) than we report. We also compared our results to those we would obtain using core sizes deconvolved by the telescope beam. Deconvolution had little effect most cores, since the majority of cores that we identify are significantly larger than the beam.

In Figure 9, we also plot the locus of Jeans mass for each radius for an assumed temperature of 20 K. Dense cores above the Jeans mass are expected to be unstable to collapse if thermal pressure provides the only avenue of support against gravitational collapse, and indeed, the majority of cores in this regime are associated with a protostar (of 33 cores in the unstable regime, 24 are protostellar), although we caution that the protostellar masses may be overestimated. Using instead the background-subtracted mass decreases the already small number of cores which lie above the Jeans instability line (17 unstable cores, of which 15 are protostellar). Johnstone et al. (2001, 2006) similarly found that most dense cores lie within the range of stable Bonnor–Ebert sphere models (an equilibrium isothermal sphere model; Ebert 1955; Bonnor 1956). In addition, cores above this range tended to have high central concentrations, which are correlated with the presence of
protostars (see discussion in the following section). Motte et al. (2001), however, argued that most of their identified dense cores were gravitationally unstable, with this difference being directly attributable to their smaller core size measurements obtained using a wavelet-based technique.

The inclusion of velocity information from a dense gas tracer is important to determine the role of turbulent motions in offsetting gravitational instability. While primarily sensitive to more diffuse gas than our SCUBA-2 observations, HARP 13CO and C18O observations of NGC 2023/2024 and NGC 2068/2071 show typical line widths of 1–3 km s$^{-1}$ (Buckle et al. 2010), suggesting that some level of non-thermal support is likely present in the Orion B dense cores. With observations of a dense gas tracer such as N$_2$H$^+$, a more detailed consideration can be made of the level of non-thermal support present for each dense core (e.g., Kirk et al. 2007; Pattle et al. 2015).

While non-thermal support mechanisms can explain the presence of starless cores lying above the Jeans stability line, it is harder to understand the presence of protostellar cores which appear to be Jeans stable. The most likely possibility is that the core boundaries we use in our analysis encompass both a smaller-scale unstable region where the protostar has formed and a larger-scale zone around it which is still stable, therefore making the core as a whole to appear to be stable.

4.3. Concentration

We measure the central concentration of each dense core as:

$$ C = 1 - \frac{1.13B^2S_{850}}{\pi R_{\text{eff}}^2 F_{850}} $$

following Johnstone et al. (2001), where $B$ is the effective beam width (in arcsec), $S_{850}$ is the total flux (in Jy), $R_{\text{eff}}$ is the effective radius (in arcsec; see Section 3 for the definition of $R_{\text{eff}}$), and $F_{850}$ is the peak flux (in Jy bm$^{-1}$). For dense cores that are well-approximated by the Bonnor–Ebert sphere model, those having concentrations above 0.72 would be unstable to gravitational collapse (Johnstone et al. 2001). Previous work (Jørgensen et al. 2007, 2008; van Kempen et al. 2009) has also shown that highly concentrated dense cores tend to be associated with protostars.

In Figure 10, we show the concentration of the dense cores compared with their masses and effective radii. The top panel shows that the majority of protostellar cores have high concentrations that are normally taken to indicate gravitational instability (42 protostellar cores, versus 23 at lower concentrations). The starless cores have a much tighter distribution of concentrations around a value of ~0.72, which a two-sided KS test shows is statistically distinct, with a probability of $3 \times 10^{-10}$ that the protostellar and starless core concentrations were drawn from the same parent sample. We note that some of the cores are elongated, complicating both the application of the Bonnor–Ebert sphere model and the interpretation of the concentration measurement. FellWalker does not calculate core elongations, since it does not fit any pre-determined shape to the cores. We use the ratio of the “size” of the core along the horizontal and vertical axes, each defined as the flux-weighted standard deviation of core pixel values from the flux-weighted center position, as a rough proxy for core elongation. With this measure, only 12% of the cores are elongated (ratios of 2 or higher), and they have a similar distribution of concentrations and effective radii to the other cores, so they do not bias the global distribution.

Lower concentrations for protostellar cores could indicate more evolved sources (c.f. van Kempen et al. 2009). SCUBA-2 is insensitive to the mass contained within the central protostar itself, so a protostar which has accreted much of the mass in its envelope would tend to have a lower concentration (see Mairs et al. 2014 for a discussion of protostellar mass versus “envelope” mass in the context of comparisons with numerical simulations). The protostellar cores which lie the furthest below the thermal Jeans line and those with smaller total masses both tend to have lower concentrations as well, which supports this hypothesis.

In contrast to prior work, we find that a significant number of starless dense cores have high concentrations that would nominally indicate instability (299 starless cores have concentrations above 0.72 while 551 have lower concentrations). At least some of these higher values of concentrations are likely attributable to the increased sensitivity of SCUBA-2 compared with SCUBA. Johnstone et al. (2003, 2006) find a range of concentrations from about 0.3 to 0.9 for dense cores in Orion B using SCUBA data, whereas our concentration measurements range between roughly 0.5 and 0.95. Since the resolutions of SCUBA and SCUBA-2 are identical, these differences must be attributable to the improved sensitivity of SCUBA-2 data and possibly also the core identification algorithm used (ClumpFind versus FellWalker). FellWalker, like ClumpFind, tends to include lower flux material around peaks within the boundary of a core. Thus, cores identified in higher sensitivity observations will tend to have larger sizes and total fluxes, with the core area increasing faster than the total flux (since only faint pixels are being added). We therefore expect that the
increased sensitivity of the SCUBA-2 observations, coupled with the improved recovery of larger-scale emission, will increase the concentrations of our cores relative to similar analyses of SCUBA observations. At the same time, cores with larger areas relative to their fluxes (or masses) will appear more stable in the mass versus radius analysis shown in Figure 9.

4.4. Dense Cores and Ambient Cloud Pressure

Lombardi et al. (2014) used a combination of Planck and Herschel data across Orion (A and B clouds) to estimate the total column density of material down to a resolution of 36″ in areas with Herschel coverage. We use this map, including Lombardi et al.’s recommended scalings between optical depth at 850 μm and total column density, to compare with the SCUBA-2 dense cores. L1622 falls outside of the Lombardi et al. (2014) column density map, and so is not included in this analysis. Previous analyses (e.g., Onishi et al. 1998; Johnstone et al. 2004; Hatchell et al. 2005; Enoch et al. 2006, 2007; Kirk et al. 2006; Könyves et al. 2013) have shown that dense cores tend to be found in regions of higher overall column density, although historically these analyses have relied on much lower resolution measurements of the overall cloud column density.

Under the assumption that a molecular cloud is a sphere, the column density at a given location within the cloud can be used as a proxy for the external pressure due to the overlying weight of the cloud. In this simple model, a higher local column density implies a three-dimensional position closer to the cloud center, and hence a larger weight of overlying cloud material. While the Lombardi et al. (2014) column density map clearly shows that the Orion B cloud is more complex than a sphere, the spherical assumption provides a practical method to estimate the bounding pressure on dense cores due to the ambient cloud material. Furthermore, the model’s implication that sources in higher column density zones are likely surrounded by more material than those in lower column density zones seems generally reasonable. Following McKee (1989), and the implementation in Kirk et al. (2006), the pressure at depth $r$ in a cloud is given by

$$ P(r) \approx \pi G \bar{S} \Sigma(r) $$

where $\bar{S}$ is the mean column density and $\Sigma(r)$ is the column density measured at cloud depth $r$. For cores near the cloud center, the column density along the line of sight to the core is roughly twice this value, i.e., $\Sigma_{\text{obs}} = 2 \times \Sigma(r)$. In both NGC 2023/2024 and NGC 2068/2071, the mean cloud...
column density over the area observed by SCUBA-2 is $9 \times 10^{23} \text{ cm}^{-2}$. For each core, we measure the local cloud column density as the maximum value of the Lombardi et al. (2014) column density map within the core’s footprint (there are typically only a few resolution elements within each core footprint). If we make the assumption that the cores can be well represented by an isothermal sphere model, the critical radius and mass of each core can be written as

$$R_{\text{crit}} = 0.49 \frac{c_s^2}{G \rho} \tag{6}$$

and

$$M_{\text{crit}} = c_s^4 \sqrt{\frac{1.4}{G \rho}} \tag{7}$$

where $c_s$ is the sound speed and $G$ the gravitational constant (equations adapted from Hartmann 1998). In Figure 11, we show the relationship between core sizes and masses and the total cloud column density at the core positions. We see a strong correlation between the cloud column density and the core masses, and a weak correlation between the cloud column density and the core sizes, in contrast with Sadavoy et al. (2010), who compared SCUBA-based dense core properties with extinction-based column density measures in five nearby molecular clouds, including Orion. Given the large scatter in the relationships that we observe, we expect that the discrepancy with Sadavoy et al. (2010) is the result of the much larger number of dense cores in our present analysis, and the larger parameter space that they occupy.

With the pressure of the overlying cloud material estimated using the spherical-cloud assumption discussed above, many of the cores have sizes and masses larger than can be thermally supported given this external weight of the cloud. By size, all protostars and 522 of 826 starless cores lie above the critical value, while by mass, 50 of 60 protostars and 101 of 826 starless cores lie above the critical value (note that cores in L1622 are not included in this analysis). The fraction of cores deemed unstable by this simple pressure analysis is a significant change from the apparent thermal stability of the dense cores seen in Figure 9 (24 of 60 protostellar cores lie above the thermal Jeans mass compared to 9 of 826 starless cores; see Section 4.2) and shows that the pressure from the ambient molecular cloud plays a strong role dense core stability. A similar result has been seen in other dense core analyses (e.g., Kirk et al. 2007; Lada et al. 2008; Pattle et al. 2015). Beyond stability considerations from a hydrostatic equilibrium model, non-thermal forces may be contributing significantly to the pressure on individual cores, which might help to explain the large scatter apparent in Figure 11.

While we identify dense cores inhabiting a wide range of cloud column densities, we note that the correlation between the cores’ size or mass with the cloud column density also implies that there is a minimum column density value at which pressure-unstable cores are found. This minimum column density is approximately $10^{22} \text{ cm}^{-2}$, which is somewhat higher than the cloud density threshold observed in nearby star-forming regions, which is usually around $5-7 \times 10^{21} \text{ cm}^{-2}$ (e.g., Onishi et al. 1998; Johnstone et al. 2004; Enoch et al. 2006, 2007; Kirk et al. 2006; Könyves et al. 2013).

### 4.5. Cloud Structure and Core Lifetimes

In Figure 12, we compare the cumulative mass fractions of dense cores (using the total mass estimated) and cloud mass as functions of the cloud column density from Lombardi et al. (2014) for NGC 2023/2024 and NGC 2068/2071. For a fair comparison between the dense core mass and cloud mass fractions, we consider only areas observed with SCUBA-2. For the dense cores, we take the column density at each pixel that lies within a dense core footprint (excluding other pixels as noise). Figure 12 shows that the dense cores seen by SCUBA-2 are associated with the highest column density material. For example, roughly 24% and 43% of the mass in SCUBA-2 cores in NGC 2023/2024 and NGC 2068/2071 respectively is associated with total column densities above $10^{23} \text{ cm}^{-2}$, whereas only a small fraction of the cloud material (3% and 5% respectively) lies within this range. We also compare in Figure 12 the protostar number fraction with the column density at the locations of protostars from Megeath et al. (2012) and Stutz et al. (2013). Assuming that all protostars have similar masses, the fractional number of protostars within a column density contour is equivalent to their fractional mass within that same contour. We find that the protostars are also...
concentrated in regions of high column density, although
slightly less so than the dense cores in NGC 2068/2071. Since
the protostellar list from Megeath et al. (2012) likely includes
some slightly older protostars that have drifted from their
birthsites, it is not surprising for a YSO population to have a
slightly wider range of column densities than the dense cores.

We can also consider the above distributions in terms of total
masses, as shown in Figure 13. The total mass in NGC 2023/
2024 and NGC 2068/2071 within the areas observed by
SCUBA-2 is 10600 $M_\odot$ and 9000 $M_\odot$, respectively, while the
total mass in dense cores is 780 $M_\odot$ and 340 $M_\odot$, respectively.
Again, we emphasize that the dense core masses are estimated
assuming a constant temperature of 20 K. Both NGC 2023/
2024 and NGC 2068/2071 have several large and massive
protostellar dense cores for which this assumption will cause
the mass to be overestimated. These particular dense cores are
coincident with the highest total column densities in the
Lombardi et al. (2014) map, which is responsible for making
the total dense core mass strangely appear larger than the total
gas and dust mass at the highest column densities in Figure 13.
It is also likely that, due to their slightly lower resolution
(compared to SCUBA-2), Lombardi et al. (2014) may slightly
underestimate the total mass in the highest column density and
smallest scale structures. Even with these caveats, it is
interesting to note that above $1-2 \times 10^{23}$ cm$^{-2}$, nearly all of
the high column density material is already in dense cores.
Below this column density, the dense cores represent an ever-
decreasing fraction of the total mass.

At the highest column densities, 10%–20% of the dense core
material is already located within protostars, if we make the
assumption that each protostar has a mass of 0.5 $M_\odot$. At lower
column densities, the mass in YSOs is only around 6% of the
dense core mass in NGC 2023/2024 while it is 16%–22% in
NGC 2068/2071. In both regions, the mass within YSOs is
less than 1% of the total cloud mass. There is no indication of a
strong relationship between the total column density and the
ratio of YSO mass to dense core mass, though it is possible that
systematic biases in our simple mass estimations which hide
such a trend (e.g., if YSOs tend to be more massive in high
column density environments). At lower column densities, the
ratio of YSO mass to dense core mass in NGC 2023/2024 is
roughly a factor of 4 lower than in NGC 2068/2071. This
result could imply that NGC 2023/2024 is younger, and that
the protostars there have only started to form recently.
Although the total numbers of sources are small, Stutz et al.
(2013) also found a higher proportion of the youngest
protostellar candidates (“PBRs”) in NGC 2023/2024 than in
NGC 2068/2071 relative to YSOs found in the Spitzer-based
catalog of Megeath et al. (2012). This result also supports the
scenario of NGC 2023/2024 being younger, as does the
relatively larger percentage of YSOs that we see at lower
column densities in NGC 2068/2071 (Figure 12).

The ratio of starless cores to protostellar cores has also been
used as a tool to estimate the relative lifetimes of the two
stages, with the estimated protostellar lifetime then used as an
anchor to obtain absolute lifetimes. Previous analyses of dense
cores detected with SCUBA and similar instruments have
suggested lifetimes of both to be several tenths of a Myr, with a
similar number of protostellar and starless cores identified (e.g.,
Kirk et al. 2005; Hatchell et al. 2007; Enoch et al. 2008), while
earlier analyses, such as that of Jessop & Ward-Thompson
(2000) suggested the starless core lifetime decreases with the
core’s volume density. With our more sensitive census of cores
detected with SCUBA-2, we identify a much larger population
of starless dense cores, and can re-visit this question, although
we caution that examining only cores within a single cloud may
introduce some bias. Furthermore, some of the dense cores in
our sample may be transient features which never evolve to
form a star. In our full sample, we have 851 starless cores and
64 protostellar cores, i.e., a ratio of 13:1. If we sub-divide the
dense cores into bins of varying mean density, we find a
roughly 1:1 ratio for starless to protostellar cores above mean
densities of $10^3$ cm$^{-3}$ and a rapidly increasing ratio beyond
that, as shown in Table 3. In Table 3, we include the ratio of
protostellar cores for both the full dense core sample, as well as
when the cores are restricted to those more massive than
0.1 $M_\odot$ (i.e., those which presently have sufficient mass to
form a star and may therefore be less likely to be transient
features). While the protostellar ratios differ in the lower
density bins, depending on which sample is examined, both
show the same trend of a protostellar ratio that decreases
rapidly with protostar density. This result is qualitatively in
agreement with Jessop & Ward-Thompson (2000) in that dense
core lifetimes do indeed appear to be longer for cores with
lower mean density. We caution, however, that our assumption
of a constant temperature tends to bias the protostellar core
masses (and hence mean densities) to higher values, which
would therefore serve to increase the fraction of protostellar
cores in the higher density bins from their true value. Similarly,
if some starless cores were colder than 20 K, their masses and
densities would be underestimated which would increase the
number of starless cores in the higher density bins.

The concentration measured for each core is likely to be less
biased by a non-constant temperature than density/mass
estimates are. Separating the dense cores into those with high
and low concentrations (above and below the nominal
maximum stable value of 0.72) shows that more concentrated
dense cores are more likely to be protostellar. The starless to
protostellar core ratio for high concentrations is 7:1 (299 versus
42) while the ratio for low concentrations is 24:1 (551 versus
23). We note that these ratios are very similar when only dense
cores more massive than 0.1 $M_\odot$ are considered: there, the
ratios are 6:1 and 22:1 respectively.

Both the concentration and mean density results support the
simple picture that as dense cores evolve, they tend to become
denser and more centrally concentrated before they are able to
form a protostar.

5. DISCUSSION

Lada et al. (1991) identified roughly 300 YSOs in each of the
NGC 2023/2024 and NGC 2068/2071 regions, corresponding to
an additional 150 $M_\odot$ for each region beyond the YSO
masses discussed in the previous section. With an efficiency of
converting dense core mass into YSOs of 30%, approximately
235 $M_\odot$ and 100 $M_\odot$ of YSOs in NGC 2023/2024 and
NGC 2068/2071, respectively, may be created from the
current population of dense cores. This number would roughly
double the existing stellar populations in both regions, and is
several times larger than the existing YSO population in either
region. The total amount of mass at lower densities in each
region is around 10,000 $M_\odot$, if even 1% of this mass ends up
also contributing to future stars, it would contribute about the
same amount of stars again. Both of these regions therefore
may one day harbor stellar clusters containing many hundreds
of stars. At the present star formation rate, it will take several million years to deplete the current population of dense cores. Since the most massive dense starless cores present reach only about 10 $M_\odot$, it is likely that B stars will be the most massive that can eventually form and help to drive the dissipation of the remaining cloud material.

L1622 appears to have less material available to form additional YSOs with a total dense core mass of 18 $M_\odot$ and...
roughly 6 $M_\odot$ presently in YSOs. The total cloud mass cannot be estimated to the same precision as NGC 2023/2024 and NGC 2068/2071 since a full column density map is not presently available. Based on the CO maps of Maddalena et al. (1986), however, L1622 appears to be a factor of at least several less massive than NGC 2023/2024 or NGC 2068/2071. This too suggests that a limited amount of star formation may occur in the future in L1622. As outlined in the introduction, the distance to L1622 is less certain, and some observations suggest a distance of <200 pc (see discussion in Reipurth et al. 2008). If this closer distance is indeed correct, then L1622 would be an even more quiescent region than our analysis here suggests. For example, all of the core sizes would increase by a factor of ~2, while the masses would decrease by a factor of ~4. Also, the shorter distance would push all of the cores below the thermal Jeans line in Figure 9, while the cores’ central concentrations would remain unchanged. Since L1622 cores represent a small fraction of the total core population analyzed here, there would be minimal impact on our overall conclusions.

6. CONCLUSION

We have presented a first-look analysis of SCUBA-2 observations of the Orion B molecular cloud taken as part of the JCMT Gould Belt Survey. The improved sensitivity and larger detector size of SCUBA-2 compared to SCUBA has allowed for significantly larger and more sensitive maps, with these SCUBA-2 observations reaching an rms of 3.7 mJy bm$^{-1}$, four to six times lower than previous SCUBA observations. Approximately 0.6, 2.1, and 1.7 square degrees were mapped in L1622, NGC 2023/2024, and NGC 2068/2071, respectively. In addition to the catalogs presented here, all of the reduced data sets analyzed in this paper (850 and 450 $\mu$m emission maps, the CO-subtracted 850 $\mu$m map, and the 850 $\mu$m based FellWalker core footprint, along with maps of the variance per pixel, and the external mask applied) are available at (Kirk 2015, see https://doi.org/10.11570/16.0003).

We used the FellWalker algorithm to identify 915 dense cores within the 850 $\mu$m map, and analyzed their basic properties. Protostellar dense cores are identified through association with a protostar in the Spitzer (Megeath et al. 2012) or Herschel (Stutz et al. 2013) catalogs. Assuming a constant temperature of 20 K yields a starless core mass function similar to that derived in other studies, with the high-mass end following a roughly Salpeter slope. Comparing the core masses and radii showed that most cores have mean densities between $10^4$ cm$^{-3}$ and several $10^5$ cm$^{-3}$. Dense cores with masses above the thermal Jeans mass for the assumed temperature of 20 K tend to be protostellar, although there are both starless cores and protostars on both sides of this relationship. A larger number of cores appear to be unstable when the bounding pressure due to the weight of the overlying cloud material is accounted for. We measure a range of central concentrations for the dense cores which tends to have larger values than previous SCUBA analyses (Johnstone et al. 2003, 2006), which we speculate is due to our deeper sensitivity. At the highest mean densities, the lifetimes of the starless and protostellar stages of dense cores appear to be fairly similar, consistent with previous observations, while the least dense cores in our sample may be longer-lived entities, if they are destined to form stars at all. Comparison of the distribution of dense cores we identified to the overall cloud column densities in NGC 2023/2024 and NGC 2068/2071 measured by Lombardi et al. (2014) shows that at high column densities, above $1-2 \times 10^{23}$ cm$^{-2}$, nearly all of the material is contained in the dense cores, while at lower cloud column densities, dense cores comprise a much smaller fraction of the material. Based on the amount of dense gas available, we predict that each of NGC 2023/2024 and NGC 2068/2071 will form at least as many stars as are currently present, while L1622 has little dense material available to supplement the present-day small protostellar population. We will present an in-depth analysis of the clustering properties of the dense cores in Kirk et al. (2015).

The authors thank the referee for a constructive report. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. The JCMT has historically been operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the National Research Council of Canada and the Netherlands Organisation for Scientific Research. Additional funds for the construction of SCUBA-2 were provided by the Canada Foundation for Innovation. The identification number for the programme under which the SCUBA-2 data used in this paper is MJLSG41. The authors thank the JCMT staff for their support of the GBS team in data collection and reduction efforts. The Starlink software (Currie et al. 2014) is supported by the East Asian Observatory. These data were reduced using a development version from 2014 December (version 516b455a). This research used the services of the Canadian Advanced Network for Astronomy Research (CANFAR) which in turn is supported by CANARIE, Compute Canada, University of Victoria, the National Research Council of Canada, and the Canadian Space Agency. This research used the facilities of the Canadian Astronomy Data Centre operated by the National Research Council of Canada with the support of the Canadian Space Agency. Figures in this paper were created using the NASA IDL astronomy library.

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### Table 3

<table>
<thead>
<tr>
<th>Density Range (cm$^{-3}$)</th>
<th>All Cores</th>
<th>Cores $&gt; 0.1 M_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_d$</td>
<td>$N_p$</td>
</tr>
<tr>
<td>$&gt;10^3$</td>
<td>34</td>
<td>31</td>
</tr>
<tr>
<td>$10^{3.5}-10^5$</td>
<td>270</td>
<td>29</td>
</tr>
<tr>
<td>$10^5-10^4$</td>
<td>546</td>
<td>5</td>
</tr>
</tbody>
</table>

**Notes.**

- *a* Mean core densities calculated using the total mass and effective radius.
- *b* Number of starless cores, protostellar cores, and their ratio for the full dense core sample.
- *c* Number of starless cores, protostellar cores, and their ratio for dense cores above 0.1 $M_\odot$.  

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38 One scan in NGC 2023/2024 (target OrionB_450_S) is presently mislabelled in CADC with the project code MJLSG31 (the designation for Orion A). Observations taken during science verification across all GBS regions falls under the project code MJLSG22.

APPENDIX A
DENSE CORE IDENTIFICATION

Here, we describe our identification of dense cores, which was based on Starlink’s Fellwalker algorithm (Berry 2015). The FellWalker algorithm is based on the idea of hiking through a set of hills: peaks are defined as local maxima, with their extents based on the routes that a hiker could ascend to reach the top of each peak. Users can set parameters in the algorithm such as the minimum peak size, minimum dip between neighboring peaks, minimum ascent slope, etc. Prior to running FellWalker, we made a qualitative comparison between our 850 μm maps and the publicly available Herschel 500 μm map (Schneider et al. 2013). This comparison revealed that surprisingly faint structures in the 850 μm map all have counterparts in the Herschel 500 μm data. Given this correspondence, we adopted less stringent FellWalker
parameters than the default recommended values. In particular, the parameters we modified from the default values are:

1. `FellWalker.AllowEdge = 0` (eliminate objects touching a map edge)
2. `FellWalker.Noise = 0.5 * rms` (extend object search deeper into the noise)
3. `FellWalker.MaxJump = 2.5` (reduce area for identifying shared peaks)
4. `FellWalker.MinPix = 5` (allow smaller objects to be identified)
5. `FellWalker.CleanIter = 5` (tidy up jagged source edges).

We then ran the FellWalker source list through a second program to eliminate spurious sources, which were numerous with the relaxed criteria above. Since the noise at the edges of the maps and mosaics is larger than in the center, a large number of spurious sources were identified with FellWalker, which assumes a constant noise level across the map. We tested a variety of criteria to weed out spurious sources, and found the following set of criteria to be the most effective at removing...
noise sources while retaining real sources. We removed: (1) sources smaller than the effective beamsizes, (2) sources which had fewer than three pixels above twice the local noise level, and (3) sources which, when slightly smoothed, had fewer than fifteen pixels above the local noise level. In addition, sources identified very near to the map edge (where the noise was highest) were eliminated if they had fewer than 22 pixels above the local noise level, when the image was slightly smoothed (i.e., 50% more pixels than the third criterion). All of the remaining sources passed our visual inspection. In general, the 3rd criterion eliminated the most sources. The first criterion almost never rejected any sources since FellWalker itself eliminates sources smaller than the beam. FellWalker identified 260, 1383, and 1020 sources in L1622, NGC 2023/2024, and NGC 2068/2071, respectively, which reduced to 29, 564, and 322 reliable cores after the cuts described above.

APPENDIX B
COMPARISON TO SCUBA

Parts of both the NGC 2023/2024 and NGC 2068/2071 regions were observed with the original SCUBA instrument, and analyses of these observations, which include independently derived core catalogs, are given in Motte et al. (2001), Mitchell et al. (2001), Johnstone et al. (2001, 2006), Nutter & Ward-Thompson (2007), and Di Francesco et al. (2008). Both Nutter & Ward-Thompson (2007) (hereafter NWT07) and the SCUBA Legacy Catalog of Di Francesco et al. (2008) (hereafter SLC) include all observations taken during SCUBA’s operation of Orion B, and so we use these two works to compare the sensitivity of SCUBA and SCUBA-2 in Orion B.39

Figures 14 and 15 show the SCUBA-2 850 µm images of the portions of NGC 2023/2024 and NGC 2068/2071 that were covered by SCUBA, based on the “coverage maps” from the SLC.40 The left panels of Figures 14 and 15 show the cores listed in NWT07, while the right panels show the SLC cores. Since both NGC 2023/2024 and NGC 2068/2071 have clustered and complex emission, we expect differences to arise in core boundaries and the level of fragmentation. To compare the core catalogs quantitatively, we associate the peak position of each SCUBA core with the FellWalker core whose boundary it lies within. Indeed, Figures 14 and 15 show that all of the cores in NWT07 have a match in our SCUBA-2 core catalog, while several of the SLC cores do not have a match. Table 4 shows the number of cores matched for each catalog. Comparing the number of cores in the two SCUBA-based catalogs which do and do not have a match in the SCUBA-2 catalog suggests that the SLC probes deeper than NWT07 in NGC 2023/2024 while the reverse is the case in NGC 2068/2071. In both cases, the SLC is more susceptible to falsely identifying cores. The SCUBA-2 catalog includes several times more cores than seen with SCUBA over a comparable area: roughly 300 additional cores were found in the SCUBA-2 map of the part of NGC 2023/2024 observed with SCUBA (compared to 60–90 cores identified with SCUBA), while roughly 150 additional cores were found in NGC 2068/2071 (compared to 90–100 identified with SCUBA).

Figures 16 and 17 show comparisons of the peak fluxes, total fluxes, and sizes measured for cores in NGC 2023/2024 and NGC 2068/2071 respectively. The SCUBA Legacy maps were created with a resolution of 19"8 (Di Francesco et al. 2008), degraded from the nominal best value to better handle noise features in their processing of multiple data sets of differing quality. We roughly correct for differences expected in the SLC values caused by this lower resolution: we decrease the SLC peak flux by the ratio of beam sizes, and deconvolve the SLC peak flux with the 19"8 beam, and reconvolve it with the SCUBA-2 14"6 beam (given typical core sizes, the radius correction tends to be very small). The NWT07 catalog had a similar effective radius to our SCUBA-2 map, so corrections are not needed for that comparison. Most of the core catalog values agree reasonably well between the two SCUBA measurements and the SCUBA-2 measurement, although there is significant scatter around a perfect one-to-one relationship. We expect the peak flux to show the best agreement, and indeed that is generally true. Note that the scatter in the comparison with the NWT07 peak fluxes is likely due to the lower precision of their published catalog values, which were only given in tenths of a Jy mm$^{-1}$. Since generally cores become more numerous at lower flux levels (when above the detection limit), we expect that most of the cores shown at each of the several tenths of a Jy mm$^{-1}$ level in peak flux would in fact have slightly lower true values, lowering the apparent scatter. The total flux and size plots tend to show a larger scatter between the SCUBA and SCUBA-2 values, as these measures are more sensitive to precisely how the dense core boundaries are defined, which tends to vary more between core identification methods in regions of complex emission. We do not see any indication of systematic calibration issues between the SCUBA and SCUBA-2 maps: the median ratio of peak or total flux in SCUBA and SCUBA-2 cores is not consistently higher or lower than the published catalog values.

<table>
<thead>
<tr>
<th>Region</th>
<th>NWT07a</th>
<th>SLCb</th>
<th>FW-NWT07c</th>
<th>FW-SLCd</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 2023/2024</td>
<td>59</td>
<td>90</td>
<td>57</td>
<td>80</td>
</tr>
<tr>
<td>NGC 2068/2071</td>
<td>100</td>
<td>87</td>
<td>90</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 4: Number of Cores Matched between SCUBA and SCUBA-2 Maps

Notes.

a Number of cores in Nutter & Ward-Thompson (2007) which were and were not matched to a SCUBA-2 FellWalker core.
b Number of cores in the SCUBA Legacy Catalog (Di Francesco et al. 2008) which were and were not matched to a SCUBA-2 FellWalker core.
c Number of SCUBA-2 FellWalker cores associated with one or more cores in Nutter & Ward-Thompson (2007).
d Number of SCUBA-2 FellWalker cores associated with one or more cores in the SCUBA Legacy Catalog.

39 For completeness, we note that one single small “jiggle map” (pointed observation) was taken in the L1622 region, but given the small quantity of data, we do not make comparisons in this region.
40 http://www4.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/community/scubalegacy/
lower than one across both regions in the NWT07 or SLC catalogs. Barring the problem with the lower precision in the peak flux values given in NWT07, we find generally good agreement between the measured core properties from SCUBA-2 and those in NWT07 and the SLC. The SCUBA Legacy processed images have some negative features (“bowls”) around bright cores. Also, the NGC 2023/2024 and NGC 2068/2071 regions happened to be split between two “tiles” in the SLC data set, which appears to have caused a particularly poor automated reduction of these regions. The resulting large scale bowls and pedestals make the resulting core catalog less accurate. This difference likely accounts both for the large scatter away from the one-to-one relationship in the total flux comparison, as well the presence of SLC cores which have no match in our SCUBA-2 catalog. Visual inspection of the SLC cores which are unmatched show they are either caused by noise spikes at map edges, or are small-scale noise features coincident with a large-scale pedestal that raised them above the global flux cutoff used.

For our comparison with the SLC, since the 850 \( \mu m \) maps and source boundaries are publicly available, we can explicitly also test the cause of the un-matched FellWalker sources. In Figure 18, we show the SCUBA Legacy flux at the position of each unmatched FellWalker core peak position. As can be seen in the figure, there is generally a good correspondence between the FellWalker core peak flux and the SCUBA Legacy flux at the same location. We additionally find that the majority of the brighter unmatched FellWalker cores have peak positions which lie within an SLC source boundary. In these cases, it is clear that the reason that the FellWalker core was unmatched is differences in source boundaries in regions of complex emission: the SLC source which the FellWalker core peak lies within was matched to a different FellWalker core. We also examined the brightest unmatched FellWalker cores whose peak positions did not lie within any SLC source boundaries, and in all cases we found that there were sources visible in the SCUBA Legacy map that were excluded from the final SCUBA Legacy catalog. There were two causes for this exclusion. First, there were several bright emission peaks lying very close to a SCUBA Legacy map edge (these correspond to the brightest few open squares in each panel of Figure 18). Since many SCUBA Legacy maps suffer from significant edge artefacts, the SLC used strong criteria to eliminate potentially spurious objects identified near a map edge, and evidently on occasion those criteria also removed several real sources from their catalog. Second, some peaks of emission were located within strong negative bowls in the SCUBA Legacy map: while the peaks themselves were bright enough to be easily discernable, their extents were truncated by the surrounding negative bowl to such an extent that these sources were likely eliminated by minimum size criteria imposed on the SLC. The apparent presence of bright unmatched FellWalker cores in Figures 16 and 17 are therefore not indicative of major inconsistencies between the SCUBA Legacy map and the SCUBA-2 map.

Finally, we show the effective completeness levels in the SCUBA catalogs by determining the fraction of SCUBA-2 cores found. Figure 19 shows the fraction of cores NWT07 identified in our SCUBA-2 catalog as a function of peak flux (left panel) and total flux (right panel). The bin sizes adopted were chosen to ensure most bins were reasonably populated, while still showing sufficient detail at low fluxes. The vertical lines in both panels show the statistical/counting uncertainty based on the number of NWT07 cores in each bin, illustrating that most bins are not strongly populated. Still, it is clear that at higher peak and total flux values, the fraction of matches is generally good. We visually inspected the instances of fewer correspondences at higher peak and total fluxes and found that these were attributable to differences in how the FellWalker and ClumpFind algorithms divided complex emission structures into individual cores.

In the lower peak and total flux regimes, we find that the NWT07 catalog is complete to roughly 40%-60% of the cores in our catalog at their nominal completeness level. For the peak flux, the completeness level shown (vertical dashed line) is five times the SCUBA noise level as listed in NWT07, which they state was used as the minimum ClumpFind threshold. The total flux completeness level is more difficult to determine, since it varies with core size. We roughly estimated the completeness...
level by taking a flux of three times the noise level across the average area of their cores.\textsuperscript{41} Although there is a significant amount of uncertainty introduced by the complex emission structure, these comparisons suggest that the NWT07 catalog would be roughly 90% complete at a completeness limit of approximately 50% higher than quoted in their paper. These comparisons show that the SCUBA-2 data of Orion B analyzed here provide significantly more sensitive coverage than the SCUBA data (as well as also covering a larger area, as is evident comparing, e.g., Figures 3 and 14). With a typical noise level of $\sim 3.7$ mJy bm$^{-1}$, our nominal 3$\sigma$ completeness is roughly 11 mJy bm$^{-1}$ in peak flux, although we expect the actual value to be slightly larger, since faint cores lying outside of our external mask will have somewhat diminished flux levels.

\textsuperscript{41} Normally, ClumpFind includes pixels within cores that have fluxes down to $2\sigma$ below the specified minimum peak flux value.

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