The star-forming content of the W3 giant molecular cloud


1Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead, CH41 1LD, UK
2Subaru Telescope, National Astronomical Observatory of Japan, 650 North A'ohoku Place, Hilo, HI 96720, USA
3Harvard College Observatory, 60 Garden Street, MS 42, Cambridge, MA 01238, USA
4Department of Physics and Astronomy, University of Leeds, LS2 9JT, UK
5Cavendish Laboratory, J J Thompson Avenue, Cambridge, CB3 0HE UK

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ABSTRACT
We have surveyed a \( \sim 0.9 \)-square-degree area of the W3 giant molecular cloud and star-forming region in the 850-\( \mu \)m continuum, using the SCUBA bolometer array on the James Clerk Maxwell Telescope. A complete sample of 316 dense clumps was detected with a mass range from around 13 to 2500 \( M_\odot \). Part of the W3 GMC is subject to an interaction with the H\( ii \) region and fast stellar winds generated by the nearby W4 OB association. We find that the fraction of total gas mass in dense, 850-\( \mu \)m traced structures is significantly altered by this interaction, being around 5% to 13% in the undisturbed cloud but \( \sim 25 - 37\% \) in the feedback-affected region. The mass distribution in the detected clump sample depends somewhat on assumptions of dust temperature and is not a simple, single power law but contains significant structure at intermediate masses. This structure is likely to be due to crowding of sources near or below the spatial resolution of the observations. There is little evidence of any difference between the index of the high-mass end of the clump mass function in the compressed region and in the unaffected cloud. The consequences of these results are discussed in terms of current models of triggered star formation.

Key words: stars: formation; ISM: clouds; ISM: individual: W3; submillimetre

1 INTRODUCTION

The most general observable quantities in star-forming regions that can be related to predictive models are the star-formation efficiency (SFE) and the initial mass function (IMF). The average SFE is generally low (\( \lesssim 1\% \), Duerr, Imhoff & Lada 1982) in molecular clouds in the Galaxy and in normal external galaxies but can increase dramatically (by up to \( \sim 50 \) times) in starburst galaxies (Sanders et al. 1991) and galaxy mergers, an effect which has been linked to strong feedback and enhancements in average gas density (e.g. Rownd & Young 1999).

The origin of the stellar IMF is not yet clear, but one possibility is that it is directly physically related to the rather similar mass function of the dense clumps that are formed in the turbulent environment of star forming regions (e.g. Clarke 1998 and references therein; Nutter & Ward-Thompson 2007). If so, then the stellar IMF is determined by the physics of star formation and the basic nature of molecular clouds. While the observed mass function in dense clumps is somewhat variable from region to region (e.g. Johnstone et al. 2000; 2001), there is little strong evidence of significant variations in the stellar IMF (Massey 2003).

Turbulent fragmentation models of star formation (e.g. Padoan & Nordlund 2002) predict that complete Salpeter-like mass functions of gravitationally bound dense clumps will form spontaneously in molecular clouds with driven turbulence. Such models also suggest that the SFE is determined by a combination of the scale on which the turbulence is driven and the Mach number of the driven turbulence (e.g. Vázquez-Semadeni et al. 2003). This is the paradigm of spontaneous star formation.

Investigating the physical basis for the idea of triggered star formation, Whitworth et al. (1994) modelled the shocked, compressed cloud layers formed by interactions. They concluded that the dynamical instabilities in the shocked gas generate new density structure, some of which subsequently collapses, and predicted that higher-mass stars should be preferentially formed under these conditions. Lim, Falle & Hartquist (2005) modelled the evolution of a cloud containing a significant magnetic field subject to a sudden increase in external pressure. Their simulation predicts the
formation of new dense structures, in which the thermal and magnetic pressures are comparable, which are potential sites of high-mass star formation.

Surveys of Giant Molecular Clouds (GMCs), the sites of cluster formation, provide the observational constraints within which theoretical models must operate. Thermal emission from the cold dust present in molecular clouds peaks in the submillimetre, and is a reliably optically thin tracer of column density. Hence observations in the sub-millimetre continuum are ideally suited to locating and quantifying the dense structure which contains the current and incipient star formation (e.g. Johnstone et al. 2000).

The W3 GMC is a high-mass star-forming region located in the outer Galaxy, in the Perseus spiral arm, at $l \approx 134^\circ$ and a distance of $\sim 2.0$ kpc (e.g. Hachisuka et al. 2006) from the Sun. The cloud occupies a well defined 1.5 $\times$ 1.5 degree area and is one of the most massive molecular clouds in the outer Galaxy (Heyer & Terebey 1998).

Figure 1 shows the location of the W3 cloud, its proximity to the IC1805 OB association, the boundary of the W4 HII region and the location of the high-mass star formation within the cloud itself as traced at 8$\mu$m by MSX.

Approximately 40% of the cloud’s total mass (Allsopp et al., 2007) is located in a layer of strong CO emission referred to as the high-density layer (HDL) by Lada et al. (1978). The HDL occupies the eastern edge of the GMC and runs parallel to the edge of the W4 HII region. It is likely to have formed from compression of the cloud gas resulting from the expansion of the HII region and/or the ram pressure from the fast stellar winds from the W4 OB association. The luminous, massive star-forming regions within the HDL, (W3Main, W3(OH) and AFGL333), are likely to be examples of triggered star formation. The rest of the

\begin{figure*}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Overview of the W3 GMC and the area immediately to the east. The grey scale shows MSX 8-$\mu$m emission delineating the edge of the W4 HII region and the luminous star-formation regions in the eastern layer of W3. The white contours are integrated $^{12}$CO J=1–0 emission from the FCRAO Outer Galaxy Survey (Heyer et al. 1998). The positions of the O stars of the IC1805 cluster (Massey et al. 1995) are shown as circles.}
\end{figure*}
cloud is apparently unaffected by this or any other major interaction with the surrounding medium. The W3 GMC thus provides a useful specimen for studying the differences between induced and spontaneous star formation independent of initial conditions.

This paper presents the results of a census of star-formation activity and dense structure in the W3 GMC, made to test the predictions of models such as those mentioned above and to look for differences in the mass distribution and fractional mass in dense structures that can be related to the spatial variation in local conditions.

2 OBSERVATIONS AND DATA REDUCTION
The observations were made during 2001 July 17–24 and 26, using the Submillimetre Common-User Bolometer Array (SCUBA) receiver (Holland et al. 1999) on the 15-m James Clerk Maxwell Telescope (JCMT). SCUBA is a dual-camera system, with 91 bolometers optimized for performance at 450 µm and 37 bolometers for 850 µm. The spatial resolution at 450 µm is 8 arcsec at FWHM and at 850 µm it is 14 arcsec. The two arrays observe simultaneously but the atmospheric opacity at the time of the observations was too high for photometric 450-µm data to be obtained. Consequently, only the 850-µm data are considered in what follows. The SCUBA field of view is ~2.3 arcmin across. An area of 3150 arcmin$^2$, encompassing the HDL and the southern portion of the W3 GMC, was surveyed (Figure 2).

Since the W3 GMC is considerably larger than the array field of view, the data were obtained in scan-mapping mode using the “Emerson II” observing technique. A differential map of the source was generated by scanning the array across individual 10-arcmin square fields whilst the secondary mirror chopped in right ascension or declination by one of three small chop throws – 30 arcsec, 44 arcsec or...
68 arcsec. Thus each 10-arcmin square submap comprises six component maps of three chop throws in two directions.

Pointing observations were made toward W3 (OH) every ~90 minutes, and found to vary by less than 6 arcsec in Right Ascension and Declination. The zenith atmospheric opacity was estimated by performing skydips approximately every hour. The average atmospheric opacity at 850 µm was 0.356, whilst the minimum and maximum values were determined to be 0.702 and 0.185 respectively.

Data reduction was done using the software package surf (Jenness & Lightfoot 1998). The data were flat-fielded, extinction corrected and despiked. Noisy bolometers were identified and blanked. Due to the difficulty inherent in identifying emission-free regions for the purposes of signal baseline removal, the median level was removed from each scan (Johnstone et al. 2000). A model of the sky atmospheric emission was calculated and removed from the scan-map data.

The data were flux calibrated using observations of Uranus and the planetary nebula CRL 618. The Starlink program fluxes was used to calculate flux densities for Uranus, whilst the flux density of CRL 618 was assumed to be 4.56 ± 0.17 Jy at 850 µm. The derived flux conversion factors were applied to the individual chop-maps prior to rebinning. Calibration is estimated to be accurate to 6%, based on the root mean square deviation of the flux conversions factors. The rebinned chop-maps were then mosaicked together with other maps taken with the same chop configuration. The resulting six large maps were Fourier-transformed and combined in Fourier space; a filter was applied to remove data at spatial frequencies above SCUBA’s sensitivity threshold (ie structure smaller than the beam). An inverse FT then generated the reconstructed map (Figure 2).

### 2.1 Suppression of extended structure

In SCUBA’s scan-mapping mode, spatial scales more extended than a few times the maximum chop throw are measured with significantly reduced sensitivity. However, the observing and map reconstruction methods described above produced semi-periodic apparent structure on scales similar to the size of the individual scan maps (10 arcmins) with amplitude ~ 0.15 – 0.2 Jy per pixel (4 to 5 times the unsmoothed pixel-pixel rms noise; see below).

In order to suppress this spurious extended structure, a template was constructed by subtracting and interpolating over all strong steep-gradient sources from the reduced map and smoothing the result with a Gaussian function of FWHM 80 arcsec (a little larger than the maximum chop throw). This template was subtracted from the original reduced map and the resulting image was smoothed to the resolution of the telescope (14 arcsec) to yield the final processed map (Figure 3). Removal of the extended structure from the map is largely cosmetic and introduces additional flux measurement uncertainties and necessarily deletes a certain amount of real low-frequency structure. It also tends to produce slight negative ‘dishing’ around the brightest sources. The latter is difficult to avoid in the more crowded regions where merged sources and the artifacts become difficult to distinguish, and sources are difficult to remove accurately in the creation of the background template.

The mean pixel-to-pixel rms noise in the processed, smoothed map was found to be ~13 mJy, which is equivalent to 56 mJy per beam.

### 3 RESULTS AND ANALYSIS

#### 3.1 General features of the processed map

Figure 3 shows that the strongest 850-µm emission is located in the HDL region along the eastern edge of the cloud. The conspicuously bright sources in the northern part of this strip correspond to the known star-formation regions W3 Main (at RA ≈ 2h25m38s, DEC ≈ +62°05’58”) and W3 (OH) (2h27m05s, +61°52’05”). There is a considerable amount of strong emission in the environs of these two sources. The W3 North star-forming region is also distinguishable (2h25m54s, +62°16’06”). Further to the south along the HDL, the AFGL 333 region (2h28m09s, +61°30’00”) has a beaded, filamentary appearance. North east of AFGL 333 there is a bright pointlike source corresponding to the position of the known outflow IC 1805-W (2h29m03s, +61°33’29”) associated with IRAS point source 02252+6120.

In the south-western portion of the map the continuum emission is of much lower average intensity. Many compact features are detected, however, including a group of sources near (2h25m39s, +61°13’16”) and a sinuous filament which runs from RA ~ 2h22m25” to ~ 2h20m30”, DEC ~ +61°06”. Immediately west of this filament is a loop of sources associated with, and possibly formed by the expansion of the KR 140 compact Hii region (Kerton et al. 2001). North of KR 140, a prominent group of sources is located at (2h21m06”, +61°27’28”).

#### 3.2 Source detection

Individual 850-µm sources were identified using clfind2d (version of 6/10/04) a two-dimensional adaptation of the Williams, de Geus and Blitz (1994) clump-finding algorithm, clfind. This technique decomposes the data into a set of discrete clumps by first (virtually) contouring the map at a series of levels set by the user. The clumps are then located by identifying emission peaks and tracing closed contours down to lower intensities. Williams et al. (1994) provide a detailed description of the algorithm’s methodology and performance testing with simulated data. The advantages of clfind are that it does not assume any a priori source profile and that it is an objective technique. Its weaknesses are mainly those associated with the separation of crowded objects and the inclusion of spurious sources at low levels, which are common to all object-detection routines.

CLFIND defines a clump boundary as the least significant contour surrounding the parent emission peak. This boundary is signal-to-noise dependent and not necessarily related to any physical outer radius. This should introduce a bias against extended, low-surface-brightness objects. If the detection contour is set low so as to minimise this bias, this will result in the overestimation of the fluxes of faint sources, relative to standard aperture photometry, since source fluxes are integrated over all pixels within this boundary.

CLFIND2D was run with input contour levels at 1σ (13 mJy), 2σ (27 mJy) and 3σ (40 mJy) then at 3-σ intervals.
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The SCUBA 850-µm continuum map after flattening (see text). The continuum emission is shown in negative logarithmic grey scale and the cloud boundary is marked in grey contours, as in Figure 2.

Figure 3.

up to the peak signal of 14.2 Jy per pixel. The low sigma levels were included in order to ensure detection of faint but significant sources. With ~18 pixels inside the half-maximum radius of an unresolved source, a 5-sigma detection may have a peak flux surface brightness that is barely above the 1-σ level. It also enables us to examine the spectrum of noise in the data and to measure the source detection and completeness limits, since these can not immediately be inferred from the pixel-to-pixel noise. In any case, adjacent pixels are not independent because of the data reconstruction process. ‘Detections’ less than 68 arcsec (the maximum chop throw) from the map edges were rejected since, in these marginal regions, the residual noise is greatest, coverage is incomplete and reconstructed fluxes are unreliable.

The distribution of the resulting sample, which is dominated by noise, is presented in Figure 4 as a histogram of equal-width flux bins. Also shown in Figure 4 is the distribution of an equivalent sample obtained with the object detection routines in the Starlink GAIA package (which uses SExtractor: Bertin & Arnouts 1996). This extraction used elliptical isophotal fitting with the same detection limit. The two distributions are very similar except at very low flux levels well below the completeness limit.

3.3 Completeness

Figure 4 shows the combined noise spectrum and source flux distribution. It also shows that it is not easy to distinguish the boundary between noise sources and real detections in these data by simple inspection.

In order to define a completeness limit, we introduced 50 artificial point sources, repeatedly and at random positions, into each of two otherwise blank regions of the reduced and flattened image (Fig. 3) and used CLFIND2D to recover them and measure fluxes. By doing this, we find that the recovery rate is 100% down to flux densities of 113 mJy per beam, dropping to 50% at 28 mJy per beam.

The 1-sigma rms noise in the processed, smoothed map
is 13.3 mJy per pixel or 56 mJy per beam. A completeness limit of 113 mJy therefore corresponds to a 2-sigma detection and represents the total flux density of an unresolved source which can be reliably recovered from the image using CLFIND2D. Clearly, extended sources must have higher completeness limits.

This is not the end of the story, however, since we also need to know the flux level at which all detected sources are real. In other words, the limit of effectively zero contamination by spurious noise sources. By running CLFIND2D on the same two apparently empty regions of the image, we extracted a spectrum of detections resulting only from noise. Scaling these spectra by relative area to the total source flux distribution in Fig. 3, we find that contamination is 25% or around 1 detection per 10 square arcminutes) at flux densities of 225 mJy per beam and below, but effectively zero at 280 mJy and above. The latter is 2.5 times the completeness limit obtained from the source recovery tests and around five times the nominal 1-sigma noise (in mJy per beam). The latter flux density limit, which gives us a sample of 316 real sources, is adopted in what follows. The location of these sources within the survey area is plotted in Figure 5.

\[ M_{\text{clump}} = 29.61 \, S_{850} \left[ \exp \left( \frac{17K}{T_d} \right) - 1 \right] M_\odot \]

where \( D \) the assumed distance, \( B_\nu(T_d) \) the Planck function evaluated at dust temperature \( T_d \) and \( \kappa_\nu \) is the mass absorption coefficient or opacity.

In accordance with Mitchell et al. (2001), the value of the (gas plus dust) mass absorption coefficient at \( \lambda = 850 \mu m \) was taken to be \( \kappa_{850} = 0.01 \, cm^2 \, g^{-1} \), including an assumed gas-to-dust mass ratio of 100. Adopting a distance of 2.0 kpc to the W3 GMC (Hachisuka et al. 2006), the above equation takes on the form

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where \( S_{850} \), the total 850-\mu m flux density within the clump boundary, is measured in Janskys.

Dust temperatures were estimated from gas kinetic temperatures obtained from our own ammonia inversion-line measurements of a subsample of 44 clumps (Allsopp et al. 2007). \( T_d \) values were assigned in two ways, in order to investigate the effect on the measured clump mass function. In the first, we assigned a single dust temperature to all sources, equal to the median \( T_d \) value in the measured subsample for the relevant cloud region. These values were 18 K for the HDL and 14 K for the diffuse region. Uncertainties in these temperature estimates can cause large errors in calculated masses. A 30% uncertainty in the above values creates an error of around –30%, +100%, in calculated mass. In the second method, measured \( NH_3 \) gas temperatures were assigned to specific clumps, where available. The rest of the sample was assigned temperatures randomly from the set of \( NH_3 \) temperatures in the relevant section of the cloud (Diffuse region or HDL). Figure 6 shows the distribution of \( NH_3 \) temperatures used.

The properties of all 850-\mu m sources above the contamination limit are listed in Table 1. The source coordinates correspond to the peak flux positions and the total flux densities are without background subtraction, since the latter is insignificant after the removal of large scale structure in the map.

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3.4 Dust temperatures and clump masses

Under the assumption that the 850-\mu m emission is optically thin, gas masses can be estimated from source flux densities \( S_\nu \) using

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

where \( D \) the assumed distance, \( B_\nu(T_d) \) the Planck function evaluated at dust temperature \( T_d \) and \( \kappa_\nu \) is the mass absorption coefficient or opacity.

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3.5 The clump mass spectrum

Figure 7 shows the distribution of clump masses, for sources with integrated 850-\mu m flux densities above the 280-mJy contamination limit, in both the HDL and diffuse cloud region. The masses entering these distributions are calculated using both a fixed dust temperature and actual and randomly-assigned \( NH_3 \) temperatures (see above), averaged over 20 repeats in the latter case. These histograms have, as near as possible, equal population bins (and hence unequal bin widths) and are plotted as the log of the bin population per unit log bin width. The distributions in the latter case turn over below log \( M \sim 1.1 \) for the HDL clumps and \( \sim 1.3 \) for the diffuse cloud data. This is due to the combination of the flux completeness limit and the distribution of temperatures.

The single-temperature mass functions obviously follow the flux distribution and are far from a single, simple power law in either of the two subsets. There is distinct structure around log \( M = 1.8 \) in both subsamples. This structure is still evident in the HDL data when actual and random temperatures from the \( NH_3 \) distribution are assigned to clumps
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Figure 5. The SCUBA 850-µm source positions indicated by circles. The circle diameters are proportional to the log of the source flux density. The continuum survey area is shaded in light grey and the cloud boundary, traced in 12CO J=1–0 as in Figure 2, is marked in dark grey contours.

(Figure 7b). It does not appear in the diffuse cloud sample in the latter model.

Above the completeness turnover masses, a single, linear fit to the averaged HDL logarithmic mass function produced by the distributed-temperature model has a negative power-law index of 0.50 ± 0.05. This fit includes the log $M = 1.8$ structure and does not represent the data well. The equivalent fit for the diffuse-cloud sample produces an index of 0.66 ± 0.06. Above the apparent structure at log $M = 1.8$, the HDL mass function is steeper (index 0.85 ± 0.02) and more consistent with a single power law. The equivalent part of the diffuse-cloud data gives the same fitted index, within the uncertainties, i.e. 0.80 ± 0.06. Note that, in this form of the mass function, the canonical Salpeter stellar IMF has an index of 1.35.

In the single-temperature model (Figure 7a), a fit to all the data gives results similar to those above. Fitting only to data with log $M > 1.8$ gives 0.92 ± 0.06 for the HDL sample index and 1.19 ± 0.07 for the diffuse cloud sample. The former is consistent with the distributed-temperature model, but the latter is steeper, and rather closer to the Salpeter-like mass functions found in other studies.

If we consider only clumps with measured NH$_3$ gas temperatures, and use these as dust-temperature estimates, the mass-function fits have indices of 0.5 ± 0.2 for the HDL and 0.50 ± 0.06 for the diffuse cloud. These are consistent with the fits to all data in both temperature models, the larger error on the HDL result reflecting the persistent appearance of structure in the mass function in this subsample.

Many other determinations of clump mass functions use only those sources without evidence of star formation. For consistency in the W3 sample, all we can do in this regard is remove the few clumps with IRAS and MSX Point Source catalogue detections. There are 29 MSX point sources with 8-µm detections within 10″ of a SCUBA 850-µm source and a further 27 within 20″. The former should be a reasonable
association criterion given the nominal pointing accuracy of MSX (< 3′′; but see Lumsden et al. 2002). If the $10''$ associations are removed from the sample, using the single-temperature model and fitting to $\log M > 1.8$, we get indices of $0.92 \pm 0.06$ and $1.5 \pm 0.1$ for the HDL and diffuse-cloud clumps, respectively. The former is not significantly different from the result using the whole sample, while the latter is. Removing the $20''$ associations as well produces $0.94 \pm 0.07$ and $1.7 \pm 0.4$.

### 3.6 The fraction of gas mass in dense structures

The total gas mass in the HDL and diffuse cloud regions was estimated from maps of the whole W3 GMC in the $^{13}$CO J=1–0 rotational transition made at the FCRAO 14-m telescope (Allsopp et al. in preparation). In order to calculate $H_2$ column densities, the LTE approximation was assumed with a single excitation temperature of 30 K. The latter value is consistent with the colour temperature of the diffuse dust emission in IRAS extended emission maps (Bretherton 2003) and adopting a higher temperature for the diffuse CO-traced gas than the dense ammonia-traced clumps accounts for the likely greater penetration of the diffuse gas by radiation. At temperatures above ~10 K, the column density calculated from CO 1–0 is roughly proportional to the assumed excitation temperature. The probable error introduced by our assumption of 30 K here is therefore no greater than other uncertainties in calculating absolute column densities (see below). The $^{13}$CO/$H_2$ relative abundance was assumed to be $1.25 \times 10^{-6}$ and, for the purposes of this estimate only, the $^{13}$CO emission was assumed to be optically thin everywhere.

Correcting for spatial oversampling and telescope beam efficiency, the total gas mass of the GMC was found to be $3.8 \times 10^5 M_\odot$. The mass in the HDL and the entire diffuse cloud region west of the HDL was $1.5 \times 10^5$ and $2.3 \times 10^5 M_\odot$, respectively. These estimates have a systematic uncertainty which is a factor of order 2–5 arising largely from the assumed relative abundances and CO excitation temperature. The corresponding CO-traced mass in the portion of the diffuse cloud region mapped with SCUBA is $1.15 \times 10^5 M_\odot$.

The estimated total cloud mass gives an average gas density for the whole GMC of only $4 \times 10^7$ m$^{-3}$, assuming the cloud is as deep along the line of sight as it is wide. This is rather typical of GMC’s and means that the volume filling factor is < 5%, if the CO-traced molecular gas density is above the critical density for the 1–0 transition ($\sim 10^9$ m$^{-3}$ for $T \geq 30$ K).

The total mass in dense clumps with 850-μm flux densities above the contamination limit of 280 mJy per beam is $3.8 \times 10^4$ and $6.1 \times 10^3 M_\odot$ in these two regions, respectively.

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**Figure 6.** Distribution of $NH_3$ gas kinetic temperatures used in estimating clump dust temperatures. The solid line denotes the HDL clump data, the dashed line is the data for sources in the diffuse cloud.

**Figure 7.** Distribution of masses of detected clumps above the noise contamination limit: HDL (triangles) and Diffuse cloud (circles) samples. Top: masses calculated using a single dust temperature equal to the median of the gas temperatures in Figure 6 error bars are $\sqrt{N}$. Bottom: using actual $NH_3$ gas temperatures, where available, otherwise a randomly assigned temperature from the distributions in Fig 4 and is the average over 20 temperature assignments (errors are standard deviations of the 20 results. One has been added to mass bins to remove the possibility of taking the log of zero in an empty bin.
These figures assume the single-temperature model. Using the temperature-distribution model the mass estimates are around 10% higher. The uncertainty in these masses is dominated by errors in the assumed values of dust emissivity (see Henning et al. 1995) and dust temperature, and are a factor of order 2-3. This uncertainty is, again, largely systematic since we are dealing here with the sum over the sample. These mass values indicate that the detected fraction of gas in the form of dense clumps is 0.26 in the HDL and 0.05 in the diffuse cloud. These values are subject to the systematic errors in the mass estimates, which combine into a factor of 4 or 5 but the difference between them is robust.

4 DISCUSSION

4.1 General results

The reduced 850-µm map of W3 (Figure 3) reveals that the brightest sub-millimetre sources and a large fraction (86% by mass; 69% by number) of the detected sources above the contamination limit of ~13 M⊙ are located in the HDL. This is not surprising, since the HDL contains the majority of the infrared sources associated with the cloud, several well-known massive star-forming regions (W3 IRS5, W3(OH), NGC333) each containing clusters of (ultra) compact H II regions, and other phenomena associated with massive star formation, such as masers (e.g. OH and methanol; Etoka, Cohen & Gray 2005) as well as energetic bipolar molecular outflows (e.g. Mitchell, Hasegawa & Schella 1992). This region of the cloud is apparently compressed by the expanding H II region and/or the stellar winds from the W4 OB association and is likely to be the site of significant triggered star formation.

Less predictably, we have found that there is a significant amount of dense structure in regions of the W3 GMC which are far less affected by interactions. 14% by mass and 31% by number of the dense clumps were found in the portion of the surveyed area away from the HDL (Figure 5). The objects in this diffuse cloud region are all rather low mass, the brightest being almost an order of magnitude fainter than the brightest source in the HDL sample, but the lack of high-mass clumps is consistent with statistics, as demonstrated by the similarity in the high-mass slope of the mass function (see above). The sources in the diffuse cloud are much less densely packed than in the HDL. It therefore appears that there is active, albeit far less dramatic, star formation activity in the cloud away from the regions where triggering by external interactions is dominant. This star formation is likely to be associated with the natural turbulence in the cloud as predicted by, e.g., Padoan & Nordlund (2002), although it is not possible to say that the diffuse cloud region is free of external interactions. The KR 140 H II region at least appears to have triggered the formation of a few small condensations by expanding into the southwest corner of the cloud (Kerton et al. 2001).

Given that the observing technique is insensitive to emission that is extended on scales larger than the largest chop throw, 68 arcsec, we can only be concerned with the point-like sources in this study. Despite this, there is some evidence in Figure 2 of a ridge of extended emission running through the middle of the HDL region, south from W3(OH).

This putative feature may have partly motivated the method because it is rather narrow in this region, but it has been further reduced by the large-scale background removal that produces the final map (Fig. 3) and its significance is not considered further here.

The northern half of the western section of the cloud is not covered by the present survey. We can assume that it is similar in its physical state and star-formation content to the surveyed southern half but none of the conclusions we draw is dependent on this assumption. There is evidence of star formation activity in this northern region (Breherton 2003) and there have been suggestions that this part of the cloud interacts with the HB3 (G132.6+1.5) supernova remnant (Roulledge et al. 1991).

4.2 The clump sample

These observations give us a complete census of the dense, potentially star-forming structures in the W3 GMC. We have used the resulting sample to construct the two basic quantities which define the star-forming content: the distribution of masses (mass function) and the fraction of the total cloud mass in dense structures that may produce stars. The fact that this particular GMC is experiencing a major feedback interaction which affects only a well-defined section of the cloud has allowed us to look for quantitative differences in these two parameters that we might relate to the effects of the interaction.

The conservative limit to the sample reliability is the noise-contamination limit at 280 mJy. Given our dust temperature and other assumptions above, this gives the sample a lower mass limit of around 13 M⊙. The sample of Enoch et al. (2006) from Perseus overlaps this, extending from a completeness limit of 0.8 M⊙ to around 30 M⊙.

Above this limit, we have detected 316 sources, including 15 out of 20 of the relatively faint objects found in the southwest corner of the cloud by Kerton et al. (2001), who also used SCUBA scan-mapping at 850µm. However, the 850-µm fluxes we obtain using clfind2d are three times larger, on average, than the values Kerton et al. (2001) measured using photometry within polygonal apertures. The 850-µm fluxes are correlated, but flux ratios vary between 1 and 5, with a standard deviation of 1.3. The systematic discrepancy is partly due to the different photometry method (§3.2) which will have the greatest effect on the weakest sources.

4.3 The dense clump mass function

The observed mass function in W3 is not a simple, single power law. There is evidence of a persistent feature, a slope reversal or peak, at masses of around 60 M⊙ (Figure 7). The origin of this feature appears to be in the combination of the scale on which sources are clustered (both physical clustering and superimpositions by chance along the line of sight) and the spatial resolution of the data. It should be noted that most, if not all, of the clumps detected in W3 are likely to form or be forming embedded clusters of stars. All objects above the completeness limit are more massive than those in Motte et al. (1998) that contain substructure. The W3 clump mass function may, therefore, be more analogous to a stellar cluster mass function.
The complex shape of the mass distribution measured in the HDL clumps (Figure 7), including slope reversal and peak, is reproduced qualitatively when the clustering scale becomes comparable to the spatial resolution.

- As the clustering becomes more severe, the position of the peak in the mass distribution moves toward higher mass bins.

- The most likely origin of the observed reversal feature is in clustering of sources at and below the spatial resolution, and not in any physical effect such as a second population of clumps with a lower-mass cutoff around 60 $M_\odot$.

A more detailed analysis of this effect may enable us to estimate the physical clustering at scales near and below the spatial resolution limit but this is beyond the scope of this paper. In the mean time, it is interesting to point out that a just-resolved object with a mass equal to our sample limit (13 $M_\odot$) would have a thermal ($T = 20$ K) Jeans length of $\sim 0.05$ pc, close to the apparent clustering scale implied by the simulation.

As mentioned above, we might expect the highest mass clumps to be not significantly affected by crowding at the resolution scale. We might thus expect to recover the original clump mass function index at the high-mass end of the distribution. Except where a single temperature is applied, the fitted power laws to the upper end of the mass functions in the two subsamples (§3.5) have exponents $\sim 0.84$, significantly flatter than that of a Salpeter IMF (1.35).

Similarly flat mass distributions have been found in CO studies of cloud structures (e.g. Williams et al. 2000), but those of the dense clumps traced by mm and submm wavelength data have generally yielded high-end power laws consistent with the Salpeter stellar IMF (e.g. Motte et al. 1998; Johnstone et al. 2000; Enoch et al. 2006) or steeper (e.g. Johnstone et al. 2001; Kirk et al. 2006). The reasons for the discrepancy between the molecular-line and (sub)mm continuum data are not clear. There has been much speculation in the literature of a direct connection between these submillimetre clump mass functions and the stellar IMF via turbulent fragmentation models of star formation. The discrepant results have not yet been fitted into such a picture but note that determinations of stellar cluster mass functions yield power-law exponents between 0.95 and 1.4 in our formulation, slightly flatter, on average, than Salpeter (Zhang & Fall 1999, Lada & Lada 2003, Hunter et al. 2003).

It is worth noting that the observed mass function will tend towards the cluster mass function in the limit of strong clustering, and towards the clump mass function in the limit of zero clustering. Further, in the intermediate case, the existence of a cluster distribution similar to the clump mass function (ie with fewer high-mass clusters) will tend to steepen the observed clump spectrum (Weidner & Kroupa 2005). This occurs when the slope of the mass function of individual clumps is preserved within clusters. Then many low-mass, and therefore truncated clump mass functions are superimposed on just a few high-mass clusters that extend over the whole mass range.

No clear difference has been found in the index at the high-mass end of the clump mass function (above 60 $M_\odot$) between the HDL and the diffuse cloud subsamples. A difference does emerge when objects associated with MSX 8-$\mu$m point sources are removed. In this case the diffuse-cloud
The star-forming content of the W3 GMC

mass function steepens into a power law consistent with Salpeter (§3.5). This could mean that the fraction of clumps with embedded stars (and so evolutionary status) is more mass dependent in the diffuse cloud. However, this result must be treated with some caution as it may be the result of the MSX flux limit falling relatively high up in this lower-mass subsample. Any other differences between the two mass distributions can be accounted for by the increased density of sources and the greater degree of crowding in the HDL region.

The foregoing analysis, and the likelihood of unresolved clustering, shows that decoding the observed mass spectrum in W3 is a complex problem. Until the spatial resolution available at these wavelengths is significantly improved, few strong constraints can be placed on the underlying distribution of clump masses, other than that they may be distributed as a power law with a negative exponent.

4.4 The fraction of mass in dense clumps

Using $^{12}$CO J=1–0 data, Lada et al. (1978) found the total mass of the W 3 GMC to be $\sim 7 \times 10^4 M_\odot$. They estimated masses of $\sim 4 \times 10^4 M_\odot$ and $\sim 3 \times 10^4 M_\odot$ for the HDL and the diffuse cloud region west of the HDL, respectively. There are a factor of $\sim 5$ lower than the estimates we use to calculate the mass fraction in dense clumps. This can probably be accounted for by optical depth effects, choice of excitation temperature, undersampling in the older data, and assumed abundance ratios. Our figure of $\sim 4 \times 10^5 M_\odot$ appears more consistent with the estimate of $\sim 10^8 M_\odot$ for the whole W3/4/5 GMC complex by Heyer & Terebey (1998).

The fraction of gas mass in dense, potentially star-forming structures detected in these observations is around 26% in the HDL region and only $\sim 5\%$ in the diffuse cloud area surveyed with SCUBA. These mass fractions are lower limits since there must be a component of dense structures that is either extended and has been ‘resolved out’ by the observing and reduction techniques and/or consists of compact sources below the detection limit. The latter portion of this missing mass can be estimated by projecting the clump mass functions in Figure 7 back to an assumed turnover mass of a little below 1 solar mass (e.g. Motte et al. 1998). The result of this depends on the exponent of the mass function at lower masses. Adopting a very flat power-law exponent of $-0.5$, consistent with the fit to the whole of the HDL sample, suggests that $\sim 8\%$ of the total mass in dense clumps is undetected. The equivalent missing fraction in the diffuse cloud sample is $23\%$. This implies a corrected mass fraction in dense clumps of $28\%$ in the HDL and $6.5\%$ in the diffuse cloud. If the exponent were as large as $-1.5$, these corrected mass fractions would rise to $37\%$ and $13\%$, respectively.

There is a large uncertainty (discussed above) in these absolute efficiency values, arising from adopted CO abundances and excitation, dust emissivity and temperature. The two mass fractions are, however, robust relative to each other. We therefore conclude that there is a significant enhancement in the efficiency with which dense, potentially star-forming, structures are formed from the cloud gas where that gas has been shocked by the external interaction. This enhancement is by a factor of at least 3 and possibly as high as 5.

Since the HDL has apparently been subject to a compressive interaction due to the expanding W 4 HII region, this result is consistent with either of two scenarios. The first is that the effects of the interaction cause existing structures in the cloud to accrete more material and grow more massive. This may be due to an increase in the signal speed in the compressed gas and, hence, in the accretion rate, or an increase in the effective Jeans mass, both of which may be caused by an increase in turbulent velocities. The second possibility is that new dense structures are formed in the interaction, in the shocks between turbulent flows or in local gravitational instabilities. An increase in the fraction of total cloud mass contained in dense clumps is not consistent with a model in which feedback from previous generations of high-mass stars simply raises the ambient pressure and so increases the probability that existing structures collapse to form stars. Feedback mechanisms must create new dense structure from which stars can form or must force more of the cloud gas into accretion flows onto existing bound objects. This has a bearing on the question of how star formation efficiency is enhanced by feedback and is a clue to the origin of the large increase in star-formation efficiency observed in starburst galaxies, for example.

This result is consistent with models of triggered star formation in which entirely new structure forms as the result of an interaction (e.g. Whitworth et al., 1994, Lim et al., 2005). It is also consistent with AMR simulations of the interaction of fast stellar winds with turbulent clouds (Jones et al. in preparation). These models predict that density enhancements which form in the turbulent gas prior to the passage of the shock tend to continue to dominate in the post-shock gas. The existing clumps are either stripped (if they are small) or accrete more material if they are massive and tightly bound. This process might be expected to flatten the spontaneously formed dense clump mass function.

5 CONCLUSIONS

We have surveyed two thirds of the area of the W3 Giant Molecular Cloud in the 850-µm continuum at 14″ resolution, resulting in a complete census of the star-formation activity in the surveyed region. The observations produced a sample of 316 dense clumps above a flux limit determined by contamination of spurious noise sources at 280 mJy per beam. This limit is around five time the nominal 1–σ noise level and gives a lower mass limit of around $13 M_\odot$, depending on temperature assumptions. Analysis of the distribution of masses in the sample shows that adopting a single temperature for all clumps produces a somewhat different result from using a distribution of temperatures based on NH$_3$ gas temperatures.

The mass function is flatter than found in many other studies and is not a simple, single power law but contains significant structure. Simple modelling indicates that this structure can be explained by crowding of sources near or below the spatial resolution of the data. Whether the implied characteristic scale ($\sim 0.1$ pc) of this crowding is meaningful is not yet clear, but it is similar to the thermal Jeans length of just-resolved objects at the low-mass end of the sample.

The W3 GMC is subject to feedback from a previous generation of OB stars, having been compressed on one side by the expansion of the HII region generated by the W4 OB
association, while the rest of the cloud is largely unaffected. The W3 cloud therefore provides a useful insight into the processes of triggered star formation and into the differences between this and spontaneous star formation.

We have analysed the mass distribution and mass fraction in dense clumps in the compressed region and the natural cloud. There is little evidence of any difference in the mass distribution, although more severe crowding in the compressed cloud layer may be having an effect. The main difference comes in the fraction of the cloud that has been converted to dense, potentially star-forming clumps. This is 26 – 37% in the compressed region and only 5 – 13% in the diffuse cloud. This difference suggests that the enhanced star-formation efficiency associated with feedback and triggering is not simply a process of increasing the probability that existing dense clumps will collapse to form stars (e.g. by increasing the ambient pressure). It is consistent with new structure being created in the compressed shocked gas and also supports a model in which structures in the pre-shocked gas survive but accrete more efficiently in the post-shock environment.

ACKNOWLEDGMENTS

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REFERENCES

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This paper has been typeset from a ΥTEX/ ΥΠΞ file prepared by the author.
Table 1. The 50 brightest sources from the W3 850-µm source sample. The full list of 316 objects is available in the on-line version.

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\(^a\)Object number from full on-line source table
\(^b\)possible MSX association at separation < 10″
\(^c\)possible MSX association at separation < 20″
\(^d\)possible IRAS association at separation < 60″