

# AMI-LA radio continuum observations of *Spitzer* c2d small clouds and cores: Perseus region<sup>★</sup>

AMI Consortium: Anna M. M. Scaife,<sup>1†</sup> Jennifer Hatchell,<sup>2</sup> Matthew Davies,<sup>3</sup> Thomas M. O. Franzen,<sup>3</sup> Keith J. B. Grainge,<sup>3,4</sup> Michael P. Hobson,<sup>3</sup> Natasha Hurley-Walker,<sup>3</sup> Anthony N. Lasenby,<sup>3,4</sup> Malak Olamaie,<sup>3</sup> Yvette C. Perrott,<sup>3</sup> Guy G. Pooley,<sup>3</sup> Carmen Rodríguez-Gonzálvez,<sup>3</sup> Richard D. E. Saunders,<sup>3,4</sup> Michel P. Schammel,<sup>3</sup> Paul F. Scott,<sup>3</sup> Timothy Shimwell,<sup>3</sup> David Titterton<sup>3</sup> and Elizabeth Waldram<sup>3</sup>

<sup>1</sup>*Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland*

<sup>2</sup>*School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL*

<sup>3</sup>*Astrophysics Group, Cavendish Laboratory, J J Thomson Avenue, Cambridge CB3 0HE*

<sup>4</sup>*Kavli Institute for Cosmology, Cambridge, Madingley Road, Cambridge CB3 0HA*

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## ABSTRACT

We present deep radio continuum observations of the cores identified as deeply embedded young stellar objects in the Perseus molecular cloud by the *Spitzer* c2d programme at a wavelength of 1.8 cm with the Arcminute Microkelvin Imager Large Array (AMI-LA). We detect 72 per cent of Class 0 objects from this sample and 31 per cent of Class I objects. No starless cores are detected. We use the flux densities measured from these data to improve constraints on the correlations between radio luminosity and bolometric luminosity, infrared luminosity and, where measured, outflow force. We discuss the differing behaviour of these objects as a function of protostellar class and investigate the differences in radio emission as a function of core mass. Two of four possible very low luminosity objects (VeLLOs) are detected at 1.8 cm.

**Key words:** radiation mechanisms: general – stars: formation – ISM: clouds – ISM: general.

## 1 INTRODUCTION

Since the advent of the *Spitzer Space Telescope*, direct infrared detection of the hot dust heated by an embedded protostar has become the most popular method for differentiating between starless and protostellar cores. However, *Spitzer* measurements of the luminosity distribution of protostars (Dunham et al. 2008) have aggravated the ‘luminosity problem’ first articulated by Kenyon et al. (1990). This problem arises from the increasing number of protostellar objects being discovered with internal luminosities  $L_{\text{int}} < 1 L_{\odot}$ , and furthermore  $L_{\text{int}} < 0.1 L_{\odot}$  in the case of very low luminosity objects (VeLLOs). Such low luminosities violate the lower luminosity limits set by steady accretion models for young stellar objects (Shu 1977; Evans et al. 2009) and imply that alternative processes, such as non-steady accretion (Kenyon & Hartmann 1995; Young & Evans

2005; Enoch et al. 2007), are required to explain this discrepancy. This luminosity problem is most difficult to rectify in very low luminosity objects (VeLLOs; Young et al. 2004; Dunham et al. 2008) with extreme luminosities  $L_{\text{int}} \leq 0.1 L_{\odot}$ . The nature of these objects is unclear, whether they are young Class 0 protostars which are just powering up, or are more evolved but in a low accretion state (Dunham et al. 2008; Evans et al. 2009).

Although the method is extremely reliable, *Spitzer* identification is not completely certain (Hatchell & Dunham 2009) as the response to extragalactic radio galaxies is known to mimic that of embedded protostellar cores and can cause false detections. In addition, a protostellar spectrum alone will not demonstrate that a core is truly embedded and, like many surveys, *Spitzer* is also flux-limited, with a luminosity completeness limit of  $0.004(d/140 \text{ pc})^2 L_{\odot}$  (Harvey et al. 2007; Dunham et al. 2008). Correctly determining the relative numbers of starless and protostellar cores in star-forming regions is essential for inferring time-scales for the different stages of protostellar evolution; for low-luminosity objects it is also necessary in order to determine the extent of the luminosity problem. Identifying embedded protostars by detecting their molecular outflows, either

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<sup>†</sup>Issuing author – e-mail: ascaife@cp.dias.ie

via high-excitation jet interactions (Herbig–Haro objects and shock-excited  $\text{H}_2$ ; e.g. Walawender, Bally & Reipurth 2005; Davis et al. 2008) or through low-excitation molecular lines such as  $^{12}\text{CO}$ , can immediately identify a source as an embedded protostar, avoiding the contaminants of infrared colour selection. However, in crowded star-formation regions, confusion from neighbouring outflows can frequently be an issue, as we discuss later. Outflows are particularly interesting for VeLLO scenarios by identifying if the protostar has shown more active mass ejection in the past, as momentum deposited at earlier times remains visible in the molecular outflow.

A further method for detecting protostars is through their radio emission (see e.g. André, Ward-Thompson & Barsony 1993). This radio emission provides not only a detection method, but also a potential mechanism for distinguishing protostellar class via its correlations with other physical characteristics. Radio follow-up of the Dunham et al. (2008) *Spitzer* catalogue of low-luminosity embedded objects at 16 GHz (AMI Consortium: Scaife et al. 2011) has provided clear evidence for distinct trends in the behaviour of the radio luminosity of these sources when compared with their bolometric luminosity, IR luminosity and outflow force where molecular outflows have been measured. Similar trends are well-documented at lower radio frequencies for higher luminosity sources ( $<10^3 L_{\odot}$ ); see e.g. Anglada (1995) or Shirley et al. (2007). In addition, the relationship between radio luminosity and the IR luminosity of these objects has shown that it may be possible to use the radio emission as a proxy for the internal luminosity of low-luminosity objects, a quantity which can otherwise only be derived through complex modelling of the IR spectra.

Here we present new data following on from the initial work of AMI Consortium: Scaife et al. (2011), hereafter Paper I. The candidates identified by *Spitzer* data in the catalogue of Dunham et al. (2008) were ranked as belonging to one of six ‘groups’, with Group 1 being those most likely to be true embedded objects, and Group 6 those least likely. These new data cover all objects classified as Groups 1–3 in Dunham et al. (2008) at  $\delta \geq 15^\circ$  not covered by Paper I. These sources lie predominantly in the area of the Perseus molecular cloud and significantly increase the available high-frequency radio data for this region. The Perseus molecular cloud is an exceptionally well studied star formation region with extensive complementary multifrequency data available (e.g. Hatchell et al. 2005, 2007a; Hatchell, Fuller & Richer 2007b; Hatchell & Dunham 2009). The sources investigated here all form part of the low and very low luminosity object population which has aggravated the ‘luminosity problem’. As such the detailed correlations and derivations of their physical properties are of particular interest.

The organization of this paper is as follows. In Section 2 we describe the sample of targets to be observed, and in Section 3 we describe the AMI Large Array (AMI-LA) telescope, the observations and the data reduction process. In Section 4 we comment upon the results of the observations and compare them to predictions. The nature of the radio emission and the correlations are derived in Section 5 and are discussed in Section 6.

## 2 THE SAMPLE

Previous centimetre-wave radio continuum follow-up (Paper I) of the *Spitzer* c2d catalogue of deeply embedded protostars (Dunham et al. 2008) covered all those objects which lay within clouds targeted by the AMI-SZA spinning dust sample (Scaife et al., in preparation). Candidates for embedded objects from this catalogue were ranked by Dunham et al. (2008) as belonging to one of six ‘groups’, with Group 1 being those most likely to be true embed-

ded objects, and Group 6 those least likely. The sample observed in this paper targets all the remaining candidates not observed in Paper I and identified as belonging to Groups 1–3 in Dunham et al. (2008), although we note that no Group 2 candidates are present, above  $\delta = 15^\circ$ . This declination limit is a consequence of the observing range of the AMI telescope; below this declination significant interference from geostationary satellites is experienced. The objects in this sample are predominantly found in the Perseus molecular cloud (22 cores) with a small number being located elsewhere (six cores). We identify the candidates from this catalogue by their catalogue number, i.e. [DCE08]-nnn, in column 1 of Table 1. The coordinates of the individual candidates are listed in columns 2 and 3 of Table 1, along with their Group and infrared luminosity from Dunham et al. (2008) in columns 4 and 5. They have been cross-referenced with the submillimetre star formation survey of the Perseus molecular cloud (Hatchell et al. 2005; Hatchell et al. 2007a, hereafter H07), the designations from which are listed in column 7 and the Class assigned to each object from those works is listed in column 8.

## 3 OBSERVATIONS

AMI comprises two synthesis arrays, one of 10 3.7-m antennas (SA) and one of eight 13-m antennas (LA), both sited at the Mullard Radio Astronomy Observatory at Lord’s Bridge, Cambridge (AMI Consortium: Zwart et al. 2008). The telescope observes in the band 13.5–17.9 GHz with eight 0.75-GHz bandwidth channels. In practice, the two lowest frequency channels (1 and 2) are not generally used due to a lower response in this frequency range and interference from geostationary satellites.

Observations of the 28 objects listed in Table 1 were made with the AMI-LA between 2010 July and 2010 August. Each target was observed as a single pointing, with the exceptions of [DCE08]-048 which is located within the [DCE08]-049 pointing (separation  $\approx 4$  arcsec), and [DCE08]-107 which is within the [DCE08]-108 pointing (separation  $\approx 6$  arcsec).

AMI-LA data reduction is performed using the local software tool *REDUCE*. This applies both automatic and manual flags for interference, shadowing and hardware errors, Fourier transforms the lag-delay correlator data to synthesize frequency channels and performs phase and amplitude calibrations before output to disc in *uv* FITS format suitable for imaging in *APS*.<sup>1</sup> Flux (primary) calibration is performed using short observations of 3C286 and 3C48. We assume I+Q flux densities for this source in the AMI LA channels consistent with the updated VLA calibration scale (Rick Perley, private communication); see Table 2. Since the AMI-LA measures I+Q, these flux densities include corrections for the polarization of the calibrator sources. A correction is also made for the changing intervening airmass over the observation. From other measurements, we find that the flux calibration is accurate to better than 5 per cent (AMI Consortium: Scaife et al. 2008; AMI Consortium: Hurley-Walker et al. 2009). Additional phase (secondary) calibration is done using interleaved observations of calibrators selected from the Jodrell Bank VLA Survey (JVAS; Patnaik et al. 1992). After calibration, the phase is generally stable to  $5^\circ$  for channels 4–7, and  $10^\circ$  for channels 3 and 8. The FWHM of the primary beam of the AMI-LA is  $\approx 6$  arcmin at 16 GHz. The data in this paper were taken with the AMI-LA using channels 4–7, which have superior phase stability. Therefore, the flux densities presented in what follows were measured with a total bandwidth of 3 GHz.

<sup>1</sup> <http://www.aips.nrao.edu/>

**Table 1.** The AMI-LA sample of embedded protostellar sources selected from the catalogue of Dunham et al. (2008). Columns are (1) source number from the Dunham et al. (2008) catalogue; (2) right ascension of source in J2000 coordinates; (3) declination of source in J2000 coordinates; (4) candidate group from Dunham et al. (2008); (5) IR luminosity from Dunham et al. (2008); (6) distance in kiloparsecs; (7) cross-identification with the catalogue of Hatchell et al. (2007a); and (8) protostellar class, where ‘S’ indicates a starless core.

[DCE08]	RA (J2000)	Dec. (J2000)	Group	$L_{\text{IR}}$ ( $L_{\odot}$ )	$D$ (kpc)	[H07]	Class
055	03 25 36.22	+30 45 15.8	1	0.061	0.25	28	0
056	03 25 39.12	+30 43 58.1	1	0.432	0.25	29	0
063	03 27 38.26	+30 13 58.8	1	0.347	0.25	39	I
064	03 28 32.57	+31 11 05.3	1	0.036	0.25	74	I
065	03 28 39.10	+31 06 01.8	1	0.015	0.25	71	0
068	03 28 45.29	+31 05 42.0	1	0.185	0.25	–	–
071	03 29 00.55	+31 12 00.7	1	0.105	0.25	65	0
073	03 29 12.07	+31 13 01.6	1	0.018	0.25	42	0
081	03 30 32.69	+30 26 26.5	1	0.033	0.25	Bolo62 <sup>a</sup>	0
084	03 31 20.98	+30 45 30.2	1	0.299	0.25	77	0
088	03 32 17.95	+30 49 47.6	1	0.135	0.25	76	0
090	03 32 29.18	+31 02 40.9	1	0.180	0.25	–	–
092	03 33 14.38	+31 07 10.9	1	0.098	0.25	–	–
093	03 33 16.44	+31 06 52.6	1	0.144	0.25	4	0
105	03 43 56.52	+32 00 52.9	1	0.310	0.25	12	0
106	03 43 56.83	+32 03 04.7	1	0.253	0.25	13	0
060	03 26 37.46	+30 15 28.1	3	0.462	0.25	80	I
080	03 29 51.82	+31 39 06.1	3	0.166	0.25	–	–
104	03 43 51.02	+32 03 07.9	3	0.172	0.25	15	0
107	03 44 02.40	+32 02 04.9	3	0.101	0.25	16/18?	S/S
108	03 44 02.64	+32 01 59.5	3	0.021	0.25	16/18?	S/S
109	03 44 21.36	+31 59 32.6	3	0.200	0.25	–	–
005	04 41 12.65	+25 46 35.4	1	0.383	0.14	–	–
044	22 30 31.94	+75 14 08.9	1	0.156	0.30	–	–
045	22 31 05.59	+75 13 37.2	1	0.077	0.30	–	–
048	22 38 46.15	+75 11 32.3	1	0.274	0.30	–	–
049	22 38 46.44	+75 11 28.0	1	0.081	0.30	–	–
043	22 29 59.52	+75 14 03.1	3	0.272	0.30	–	–

<sup>a</sup> Original designation from Enoch et al. (2007).

**Table 2.** AMI-LA frequency channels and primary calibrator flux densities measured in Jy.

Channel No.	3	4	5	6	7	8
Freq. (GHz)	13.88	14.63	15.38	16.13	16.88	17.63
3C48	1.89	1.78	1.68	1.60	1.52	1.45
3C286	3.74	3.60	3.47	3.35	3.24	3.14
3C147	2.85	2.71	2.57	2.45	2.35	2.24

Reduced data were imaged using the AIPS data package. CLEAN deconvolution was performed using the task IMAGR which applies a differential primary beam correction to the individual frequency channels to produce the combined frequency image. In what follows we use the convention:  $S_{\nu} \propto \nu^{\alpha}$ , where  $S_{\nu}$  is flux density (rather than flux,  $F_{\nu} = \nu S_{\nu}$ ),  $\nu$  is frequency and  $\alpha$  is the spectral index. All errors quoted are  $1\sigma$ .

## 4 RESULTS

The observations towards the 28 targets listed in Table 1 and described in Section 2 are summarized in Table 3. The details of each individual observation including both the primary and secondary calibration sources are listed. Maps were made using naturally weighted visibilities to ensure optimal noise levels, except

in those cases where sources were separated by less than one synthesized beam. In these instances uniform weighting was used in order to improve resolution and separate the sources. The resulting rms noise level in each map and the dimensions of the synthesized beam are listed in Table 3, and where uniform weighting has been employed it is indicated in the table. The rms noise level varies between fields due to the different levels of data flagging required following periods of poor weather conditions or interference from non-astronomical sources, such as geostationary satellites.

Source detection for these data was performed in the un-primary-beam-corrected maps, where we identified all objects within the FWHM of the AMI-LA primary beam with a peak flux density  $> 5\sigma_{\text{rms}}$ , as being true sources. A full list of the sources detected in these fields is given in Tables A1 and A2. The peak and integrated flux densities listed in both Tables 4, A1 and A2 were extracted from the primary-beam-corrected maps.

Integrated flux densities were determined by fitting a multivariate Gaussian and a background level to each source using the standard AIPS task JMFT. In addition, those objects which were poorly fitted by a Gaussian source model have integrated flux densities found using the FITFLUX program (Green 2007). This method calculates flux densities by removing a tilted plane fitted to the local background and integrating the remaining flux density. This is done by drawing a polygon around the source and fitting a tilted plane to the pixels around the edge of the polygon. Where an edge of the polygon

**Table 3.** AMI-LA observations. Sources found within the Perseus region are listed first, with those outside Perseus continued below the double line division. Columns are [1] source number from the Dunham et al. (2008) catalogue; [2] AMI-LA flux calibrator; [3] AMI-LA phase calibrator; [4] rms noise measured from recovered map; [5] major axis of AMI-LA synthesized beam; [6] minor axis of AMI-LA synthesized beam.

[DCE08]	1°	2°	$\sigma_{\text{rms}}$ ( $\frac{\mu\text{Jy}}{\text{beam}}$ )	$\Delta\theta_{\text{max}}$ (arcsec)	$\Delta\theta_{\text{min}}$ (arcsec)
055	3C286	J0329+2756	19	41.4	28.2
056	3C286	J0329+2756	22	41.8	28.6
063	3C48	J0329+2756	25	45.0	26.4
064	3C48	J0329+2756	18	40.5	26.3
065	3C286	J0329+2756	20	40.2	29.8
068	3C48	J0329+2756	18	42.7	27.5
071	3C48	J0329+2756	19	36.6	23.9
073	3C48	J0329+2756	26	37.3	24.7
081	3C48	J0329+2756	20	39.4	29.0
084	3C48	J0329+2756	30	36.3	25.2
088	3C48	J0329+2756	32	36.9	24.4
090	3C48	J0329+2756	25	36.1	26.1
092	3C48	J0329+2756	27	36.8	24.6
093	3C48	J0329+2756	22	36.4	24.5
105	3C48	J0329+2756	23	38.6	24.8
106	3C48	J0329+2756	20	41.0	29.7
060	3C48	J0329+2756	19	46.0	25.5
080	3C48	J0329+2756	19	42.5	28.4
104	3C48	J0341+3352	19	36.9	24.2
107	3C48	J2302+6405	22	41.9	29.0
108	3C48	J2302+6405	22	41.9	29.0
109	3C48	J0341+3352	25	35.8	23.7
005	3C286	J0435+2532	25	43.2	29.2
044	3C286	J2236+7322	24	40.5	25.3
045	3C286	J2236+7322	15	36.7	27.5
048	3C48	J2236+7322	25	30.8	24.7
049	3C286	J2236+7322	25	30.8	24.7
043	3C286	J2236+7322	24	40.7	28.0

crosses a region confused by another source, the background is subjective and this edge is omitted from the fitting. Since the extracted flux density is dependent to some degree on the background emission, we repeated this process using five irregular polygons, each varying slightly in shape. The final flux density is the average of that extracted from these five polygons. The error on these integrated flux densities is calculated as  $\sigma_s = \sqrt{(0.05S_{\text{int}})^2 + \sigma_{\text{fit}}^2 + \sigma_{\text{rms}}^2}$ , where  $\sigma_{\text{fit}}$  is the standard deviation of the flux densities found from the five polygonal apertures,  $\sigma_{\text{rms}}$  is the rms noise determined from the maps and  $0.05S_{\text{int}}$  is a conservative 5 per cent absolute calibration error. In the case of sources fitted using JMFFIT  $\sigma_{\text{fit}}$  is the fitting error returned by the task. Where the 5 per cent calibration uncertainty is not dominant, errors determined for this sample are in general heavily dependent on the rms noise,  $\sigma_{\text{rms}}$ , rather than the fitting error,  $\sigma_{\text{fit}}$ , which is found to be small.

The source list in Tables A1 and A2 was cross-referenced with the literature and where the position of a source coincides with a known object this has been indicated in column 7. For this identification we employed a search radius of 30 arcsec, although we note that most associations are within  $<2$  arcsec. The only source significantly separated from its association is [DCE08]-068 and this is commented upon in later discussions. Sources are identified as extragalactic radio sources where they have a counterpart in the NVSS (Condon et al. 1998) catalogue, and are denoted by ‘radio’.

#### 4.1 Expected contamination by extragalactic radio sources

At 16 GHz we expect a certain number of extragalactic radio sources to be seen within each of our fields. Following Paper I, to quantify this number we use the 15-GHz source counts model from de Zotti et al. (2005) scaled to the 10C survey source counts (AMI Consortium: Davies et al. 2010). The average rms noise from our data sets is  $\approx 25 \mu\text{Jy beam}^{-1}$  and from this model we predict that we should see  $0.07$  sources  $\text{arcmin}^{-2}$ , or  $\approx 2$  radio sources within a 6-arcmin FWHM primary beam above a  $5\sigma$  flux density of  $125 \mu\text{Jy}$ . Within the Perseus region we would therefore expect to detect  $\approx 26 \pm 5$  extragalactic radio sources, and in the remainder of the sample a further  $\approx 9 \pm 3$  sources. Tables A1 and A2 show the full source list for objects detected at  $>5\sigma$  in the fields. Making the assumption that all sources that cannot be identified with a previously known protostellar object are extragalactic, we find 21 radio sources in the Perseus fields, consistent with our prediction. In the fields outside the Perseus region we find only three non-protostellar sources. Although this is low compared to the prediction, we suggest that this is simply because the covered sky area is small and that this is a statistical outlier, consistent at  $2\sigma$ . Of these sources, seven are matched to known radio sources in the NVSS catalogue (Condon et al. 1998) at 1.4 GHz and six also have identifications in the WENSS catalogue at 327 MHz (Rengelink et al. 1997). Using these data we can identify all of these objects as steep spectrum radio sources with an average spectral index of  $\alpha_{0.327}^{16} = -0.88 \pm 0.15$ . Assuming a canonical spectral index for a non-thermal emission of  $\alpha = -0.7$ , and taking the completeness limit of the NVSS survey as  $3.4 \text{ mJy}$  (Condon et al. 1998), we find that all but three of the remaining unmatched radio sources have integrated flux densities below this threshold when extrapolating from 16 GHz.

Of the three sources which do not lie below the NVSS detection threshold, one is extended and has a much lower peak flux density making it unlikely to have been detected in NVSS. The remaining two are AMI-09 and AMI-44; both sources have flux densities above  $1 \text{ mJy}$  at 16 GHz and are relatively compact. AMI-09 is identified as VLA-10 in Rodríguez, Anglada & Curiel (1999) who surveyed the HH 7–11 region at 3.5 cm with the VLA. We also identify it with [EDJ09]-176 from Evans et al. (2009) who classify it as a YSO, and [GMM08]-3 from Gutermuth et al. (2008) who identify this YSO as an embedded Class I source. AMI-44 is also tentatively identified as a Class I protostar in the IC 348 nebula from the *Spitzer* catalogue of Muench et al. (2007).

## 5 PROTOSTELLAR SOURCES

### 5.1 Perseus region

Those fields which lie within the Perseus region surveyed in the sub-millimetre by H07 contain a number of known protostellar sources in addition to those selected from the *Spitzer* catalogue of DCE08. Table 4 lists all the protostellar sources within these fields from H07 and identifies them with sources detected in the AMI-LA catalogue in this work. Where a known object is not detected by the AMI-LA, an upper limit on the 1.8-cm radio flux density of that source is given. These limits take into account the position of the source within the AMI-LA primary beam. Since source detection is performed in the maps before correction for the primary beam this means that the true limit on the unattenuated flux density will be given by  $S_{\text{lim}} < 5 \sigma_{\text{th}}/A(r)$ , where  $A(r)$  is the primary beam attenuation at a radial distance  $r$  from the pointing centre.

**Table 4.** Physical parameters of protostellar sources within Perseus. Columns are (1) source number from the H07 catalogue; (2) source number from the DCE08 catalogue; (3) protostellar Class as identified in H07; (4) flux density predicted from vibrational dust emission at 16 GHz; (5) flag on presence of radio counterpart; (6) 1.8 cm radio flux density in excess of the thermal greybody emission measured by the AMI-LA; (7) envelope mass from H07 corrected to  $D = 250$  kpc; (8) bolometric temperature from H07; (9) bolometric luminosity from H07 corrected to  $D = 250$  kpc, unless otherwise indicated; (10) outflow force from H07b corrected to  $D = 250$  kpc; (11) flag on possible confusion of the outflow with other nearby objects.

[H07]	[DCE08]	Class	$S_{\text{pred},16}$ ( $\mu\text{Jy}$ )	Radio det. (y/n)	$S_{16}$ ( $\mu\text{Jy}$ )	$M_{\text{env}}$ ( $M_{\odot}$ )	$T_{\text{bol}}$ (K)	$L_{\text{bol}}$ ( $L_{\odot}$ )	$F_{\text{out}}$ ( $10^{-6} M_{\odot} \text{ yr}^{-1} \text{ km s}^{-1}$ )	Confused?
1		0	88	y	336.2	10.8	53	2.3	$1.3 \pm 0.8$	
2		0	140	y	499.9	15.9	<25	<1.5	$9.6 \pm 1.0$	
4	093	0	51	y	191.6	9.2	32	1.1 <sup>f</sup>	$1.4 \pm 0.3$	
7		I	9	y	128.5	1.7	158	0.8	$9.8 \pm 0.8$	
10		I	3	y	578.9	0.6	117	0.2	$3.4 \pm 0.4$	
12	105	0	71	y	911.1	14.0	31	1.8 <sup>f</sup>	$4.8 \pm 0.8$	
13	106	0	61	y	490.6	6.2	59	1.1 <sup>f</sup>	$4.0 \pm 0.5$	
15	104	0	12	n	<93	2.7	67	0.32 <sup>f</sup>	$0.5 \pm 0.2$	
16/18	107	S	16 <sup>c</sup>	n	<110	–	76 <sup>f</sup>	0.18 <sup>f</sup>	–	
16/18	108	S	16 <sup>c</sup>	n	<110	–	–	–	–	
27		0	128	y	1856.8 <sup>c</sup>	18.8	53	3.3	$21.5 \pm 3.0$	
28	055	0	67	y	1858.7 <sup>c</sup>	9.9	53	10.4	$28.4 \pm 2.9$	
29	056	0	55	y	473.0	11.1	49	3.8	$16.3 \pm 1.5$	
30		0	60	y	610.2	10.0	50	2.5	$7.9 \pm 0.8$	
31		0	59	n	<140	7.3	38	1.2	$2.8 \pm 0.5$	c
35		I	17	n	<1135	3.2	105	4.3	$7.3 \pm 0.6$	
36		0	31	y	– <sup>d</sup>	3.2	59	1.9	$5.1 \pm 0.5$	
37		I	27	n	<98	4.3	672	2.0	$2.5 \pm 0.4$	c
39	063	I	9(27 <sup>a</sup> )	n	<116(98)	1.2	394	1.1 <sup>f</sup>	$1.4 \pm 0.2$	c
41		0	231	y	1587.0	31.8	35	5.2	$35.5 \pm 2.9$	
42	073	0	77	y	391.3	15.4	39	4.6	$8.1 \pm 1.6$	
44		0	87	y	233.4	16.6	58	13.8	$56.7 \pm 4.4$	
48		0	36	n	<236	5.0	49	2.0	$2.1 \pm 1.6$	c
49		I	28	n	<217	4.5	140	4.1	H	
50		I	41	n	<245	4.4	88	3.4	$129.6 \pm 10.9$	c
52		0	33	y	– <sup>d</sup>	3.7	57	2.7	$25.4 \pm 2.6$	c
65	071	0	12(33 <sup>a</sup> )	y	227.7(206.7)	1.2	56	0.24 <sup>f</sup>	–	
69		I	3	n	<116	0.4	436	0.02	H?	
71	065	0	12	y	275.6	1.3	37	0.22 <sup>f</sup>	H?	
74	064	I	3	n	<87	0.4	144	0.20 <sup>f</sup>	H	
75		0	4	n	<96	0.7	67	0.06	H	
76	088	0	104	y	320.2	9.6	109	1.2 <sup>f</sup>	$0.9 \pm 0.5$	
77	084	0	19(37 <sup>a</sup> )	y	305.1(287.1)	3.8	60	1.1 <sup>f</sup>	$3.7 \pm 0.5$	
80	060	I	8(4 <sup>b</sup> )	n	<87(91)	1.5	86	1.1 <sup>f</sup>	–	
84		0	3	n	<223	0.5	74	0.04	–	
101		I	1	y	227.8	0.2	463	1.0	H	
Bolo62	081	0	2	n	<98	0.3	103	0.04	H <sup>ll</sup>	
–	068	0	4	n	<90	–	64 <sup>f</sup>	0.45 <sup>f</sup>	–	
–	080	–	10 <sup>e</sup> (6 <sup>b</sup> )	y	90.1	–	34 <sup>f</sup>	0.64 <sup>f</sup>	–	
–	090	–	3	y	114.0	–	114 <sup>f</sup>	0.57 <sup>f</sup>	–	
–	092	–	–	y	206.7	–	47 <sup>f</sup>	0.29 <sup>f</sup>	–	
–	109	–	17 <sup>e</sup> (9 <sup>b</sup> )	n	<125	–	345 <sup>f</sup>	0.26 <sup>f</sup>	–	

*Note.* Where no outflow force is given an ‘H’ indicates that an outflow has been detected by HARP, and ‘H?’ indicates a *possible* outflow (Hatchell et al. 2007b) but no outflow force value is available; a suffix of H<sup>ll</sup> indicates the lower line-wing detection criterion (Hatchell & Dunham 2009).

<sup>a</sup>Improved fit to modified greybody with  $\beta = 1.5$ .

<sup>b</sup>Improved fit to modified greybody with  $\beta = 2.0$ .

<sup>c</sup>Unresolved from neighbouring source.

<sup>d</sup>Flux density confused by neighbouring source.

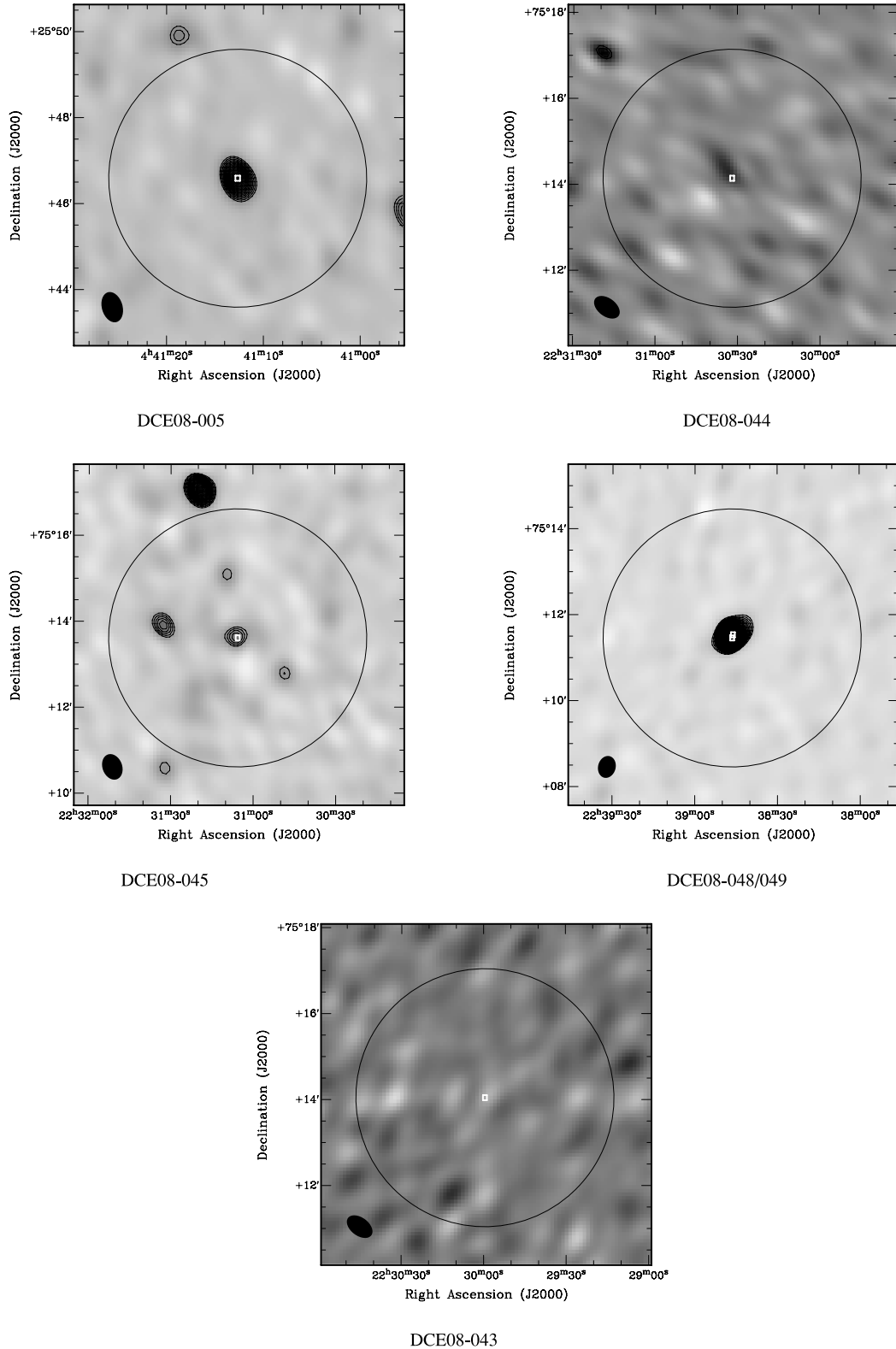
<sup>e</sup>Greybody fitted using flux densities from Di Francesco et al. (2008).

<sup>f</sup>From DCE08.

A number of the physical properties listed in Table 4 including the radio luminosity depend on the distance to Perseus. Although many studies assume a distance for Perseus of 320 kpc (e.g. H07), here we assume a distance of  $D = 250$  kpc in order to remain consistent with DCE08. Where necessary, physical quantities from the literature have been corrected accordingly.

## 5.2 Additional targets

There are six targets in our sample which lie outside the Perseus region (see Fig. 1). The first of these objects, [DCE08]-005, lies within the Taurus molecular cloud and is also known as IRAS04381+2540. We use the physical parameters derived for this core by Kauffmann



**Figure 1.** Sources lying outside the Perseus region. Grey-scale and contours at 16 GHz from the AMI-LA are shown with no correction for the primary beam attenuation. Contours are shown at  $5\sigma_{\text{rms}}$ ,  $6\sigma_{\text{rms}}$ ,  $7\sigma_{\text{rms}}$  etc., where values for  $\sigma_{\text{rms}}$  for each field can be found in Table 3. The position of each source from Table 5 is shown as an unfilled square. The FWHM of the AMI-LA primary beam is shown as a circle and the synthesized beam for each map as a filled ellipse in the bottom-left corner. A full set of maps for the remainder of the sources observed in this work can be found in Appendix B.

**Table 5.** Physical parameters of protostellar sources outside Perseus. Columns are (1) source number from the Dunham et al. (2008) catalogue; (2) association; (3) protostellar Class; (4) flux density predicted from vibrational dust emission at 16 GHz; (5) flag on presence of radio counterpart; (6) 1.8-cm radio flux density in excess of greybody emission measured by the AMI-LA; (7) envelope mass; (8) bolometric temperature; (9) bolometric luminosity from DCE08; (10) references for physical properties and class.

[DCE08]	Other names	Class	$S_{\text{pred},16}$ ( $\mu\text{Jy}$ )	Radio det. (y/n)	$S_{16}$ ( $\mu\text{Jy}$ )	$M_{\text{env}}$ ( $M_{\odot}$ )	$L_{\text{bol}}$ ( $L_{\odot}$ )	$T_{\text{bol}}$ (K)	Refs.
005	IRAS04381+2540	I	102	y	637.2	$2.8 \pm 0.05$	$0.67 \pm 0.02$	131	K08; DiF08
044	L1251-A IRS3	O	38	y	119.5	$11.09 \pm 0.44$	0.8	24	L10; W07
045	L1251-A IRS4	O	4	y	224.5	$16.46 \pm 0.68$	0.6	21	L10; W07
048/049	L1251-B IRS1/2	O/I <sup>a</sup>	141	y	1135.7	17.2 <sup>b</sup>	10/0.6	87/140	L06; DiF08; W07
043	L1251-A IRS2	I	23	n	<125	$14.15 \pm 2.10$	0.4	230	L10

References: Kauffmann et al. (2008) (K08); Di Francesco et al. (2008) (DiF08); Lee et al. (2010) (L10); Wu et al. (2007) (W07); Lee et al. (2006) (L06).

<sup>a</sup>As classified by this work, see text for details.

<sup>b</sup>As calculated by this work, from 850- $\mu\text{m}$  flux densities in Lee et al. (2006).

et al. (2008) from MAMBO 350- $\mu\text{m}$  data. The five remaining targets are all found within the L1251 dark cloud. [DCE08]-043, 044 and 045 are found in the vicinity of Core A, and [DCE08]-048 and 049 in the vicinity of Core B. Their precise identifications are listed in Table 5. [DCE08]-048 and [DCE08]-049 are not resolved by the AMI-LA and are therefore listed together. Lee et al. (2006) found that these sources were both borderline Class O/I based on their bolometric temperatures and the ratio of the submillimetre to bolometric luminosity. By also considering the ratio of 3.6 to 850  $\mu\text{m}$  flux density we classify [DCE08]-048, identified with L1251-B IRS1, as Class 0; and [DCE08]-049, identified with L1251-B IRS2, as Class I. The physical parameters and classifications of those objects in L1251-A are taken from Lee et al. (2010).

### 5.3 Expected vibrational dust contribution

For each of the sources listed in Table 4 we constrain the contribution of thermal dust emission to the measured flux density at 16 GHz by fitting to submillimetre data at 1.1 mm (Enoch et al. 2007), and 850 and 450  $\mu\text{m}$  (Hatchell et al. 2007). For the sources in Table 5 we use the submillimetre data from the references in that table. Following Paper I we fit a modified greybody spectra of the form

$$S_{\nu} = \nu^{\beta} B_{\nu}(T_{\text{d}}), \quad (1)$$

where  $\nu$  is the frequency of the data point,  $\beta$  is the opacity index for which we assume a canonical value of  $\beta = 1.8$  and  $B_{\nu}$  is the Planck function for a dust temperature  $T_{\text{d}}$ . A value of  $\beta = 1.8$  agrees with that used by Hatchell et al. (2007) and is close to the theoretically derived value of  $\beta_{\text{OH5}} = 1.85$  found for coagulated grains with thin ice mantles between 350  $\mu\text{m}$  and 1.3 mm (Ossenkopf & Henning 1994).

Tables 4 and 5 list the predicted flux density due to thermal dust emission at 16 GHz from these fits. Where a value of  $\beta = 1.8$  does not provide a good fit to the data we repeat these fits using alternative values of  $\beta = 1.0, 1.5$  and  $2.0$ . Where appropriate a second prediction for the 16-GHz flux density due to thermal dust and based on the minimum  $\chi^2$  value of  $\beta$  is also shown in Table 4. In practice a value of  $\beta = 1.0$  is not preferred for any of our sources. This is perhaps not surprising as the sample consists predominantly of young protostars with low  $T_{\text{d}}$  values, which as such are expected to have larger values of  $\beta$  in general (Planck Collaboration: Montier et al. 2011). For those objects which are only detected at one of the three submillimetre wavelengths, we simply extrapolate to 16 GHz using the canonical  $\beta$ . We note that there is a degree of uncertainty in these predictions, largely due to

the systematic uncertainties in submillimetre flux densities, which also in general limit the determination of  $\beta$  (Shirley et al. 2011a). In addition, a single value of  $\beta$  may not hold to cm-wave frequencies, notably in the case of objects with discs (Shirley et al. 2011a), but we consider this model to be a reasonable approximation in the absence of additional submillimetre and millimetre-wave data.

In what follows we use the measured flux density at 1.8 cm with the predicted greybody contribution *subtracted* to calculate the radio luminosity. This is to ensure that the values used are representative only of the radio emission and do not include contributions from the thermal dust tail which varies greatly between sources (see Tables 4 and 5) and which might therefore influence any conclusions being drawn from the distributions examined in the later stages of this paper.

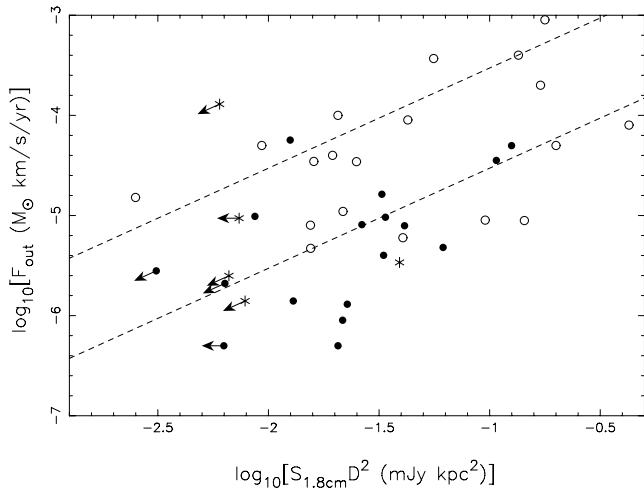
The average ratio of predicted thermal dust emission to residual radio emission is approximately 14 per cent. This shows that although the contribution is small it is not negligible. In addition we can see that the ratio is lower for detected Class I sources (9 per cent) compared with Class 0 sources (18 per cent). This might be expected due to their comparatively smaller dust envelopes, but could also indicate an increase in radio emission relative to thermal dust emission for these objects.

### 5.4 Luminosity and outflow force correlations

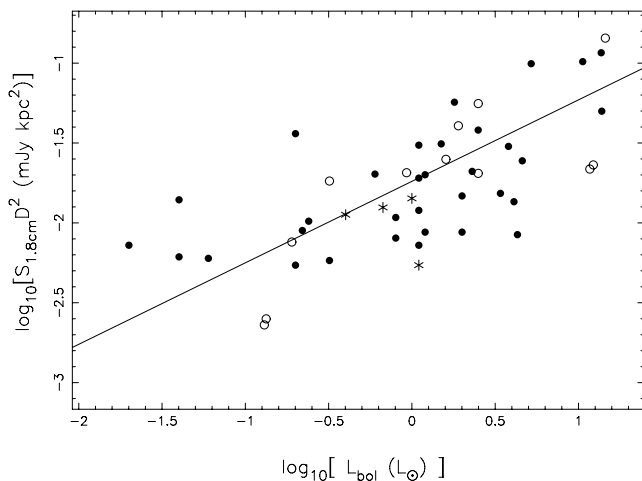
A detailed investigation of the possible causes for a correlation of the radio luminosity with the bolometric luminosity, infrared luminosity and outflow force was presented in Paper I and references therein. We do not revisit these discussions here but utilize the combined data from this work and Paper I to redraw these correlations. Values for the physical characteristics of these sources are listed in Table 4. In the case of outflow force the letter ‘H’ indicates that an outflow has been detected with HARP, but that no value for its momentum flux is available in the literature. The correlations between these parameters and the radio luminosity are shown in Figs 2–4.

The correlation of radio luminosity with outflow force is shown in Fig. 2. Although it is evident that no improvement in this correlation is made by the addition of these new measurements, these data are consistent with the loose trend determined in Paper I. As discussed at length in Paper I, the lack of a well-defined correlation in this case may be due to the errors inherent in the measurements of outflow force.

Although Class I objects are generally considered to have weaker outflows than Class 0 objects, there is no clear evolutionary division in the sources sampled here. Indeed the outflow force values for the



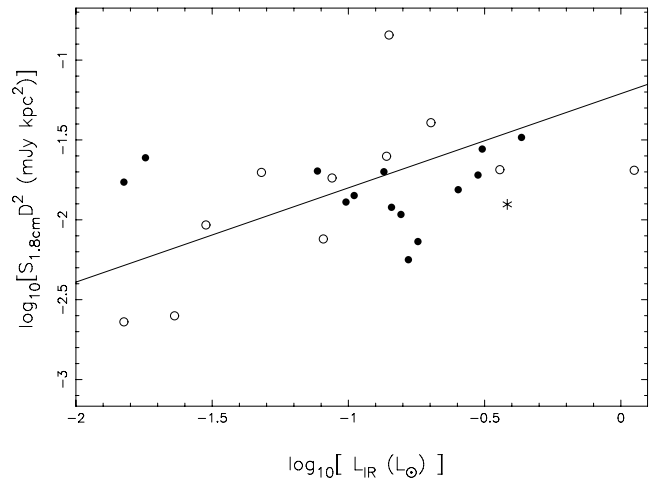
**Figure 2.** Correlation of 1.8-cm radio luminosity with outflow force. Data from Paper I are shown as unfilled circles, Class 0 objects from this work are shown as filled circles and Class I objects as stars. The dashed lines show the theoretical relationship between 1.8-cm radio luminosity and outflow force (Curiel et al. 1989) for an efficiency of  $\eta = 1$  (minimum required force; lower line) and an efficiency of  $\eta = 0.1$  (upper line).



**Figure 3.** Correlation of radio luminosity with bolometric luminosity for objects detected at  $>5\sigma$ . Class 0 sources from this work are shown as filled circles, Class I sources from this work are shown as stars and sources from Paper I are shown as unfilled circles. The best-fitting correlation is shown as a solid line.

Class I objects in this sample span almost as broad a range as those from Class 0. As in Paper I we plot the minimum outflow force required to explain the centimetre-wave emission as arising from shock ionization (Anglada 1995); see Fig. 2. Although the data seem to follow the general trend described by this model, not all objects lie above the limit indicated for an efficiency of  $\eta = 1$ , indicating that their radio emission cannot arise, at least solely, from shock ionization.

The correlation of radio luminosity with bolometric luminosity is shown in Fig. 3. All sources for which a bolometric luminosity exists in the literature are included, see Tables 4 and 5 for values and references. The data from this work are very consistent with those from Paper I. An improved correlation combining the data



**Figure 4.** Correlation of radio luminosity with infrared luminosity for objects detected at  $>5\sigma$ . Class 0 sources from this work are shown as filled circles, Class I sources from this work are shown as stars and sources from Paper I are shown as unfilled circles. The best-fitting correlation is shown as a solid line.

from this paper with those of Paper I, shown in Fig. 3, is

$$\log[L_{1.8\text{cm}}(\text{mJy kpc}^2)] = -(1.74 \pm 0.18) + (0.51 \pm 0.26) \log[L_{\text{bol}}(L_{\odot})]. \quad (2)$$

The correlation of radio luminosity with infrared luminosity is shown in Fig. 4. The data shown are those for which a source is found in DCE08, and which have an IR luminosity derived in that work. The correlation with IR luminosity found in Paper I, and shown as a solid line in Fig. 4, is a good fit to the combined data sets. Notable in this plot are the possible VeLLO sources [DCE08]-065 and [DCE08]-073, which both have radio luminosities in excess of the general trend. A further object which does not follow the correlation is [DCE08]-055; however, there is an obvious explanation for this behaviour. Although we associate [DCE08]-055 with [H07]-028 due to proximity, the radio detection is in fact also completely unresolved from [H07]-027. Since there is no infrared luminosity available in the literature for [H07]-027, we describe the  $L_{\text{IR}}$  of [DCE08]-055 ([H07]-028) as being a lower limit, and exclude it from the fitted data shown in Fig. 4.

The improved correlation combining the data from this paper with those of Paper I, is

$$\log[L_{1.8\text{cm}}(\text{mJy kpc}^2)] = -(1.23 \pm 0.39) + (0.59 \pm 0.34) \log[L_{\text{IR}}(L_{\odot})]. \quad (3)$$

### 5.5 Correlation with envelope mass

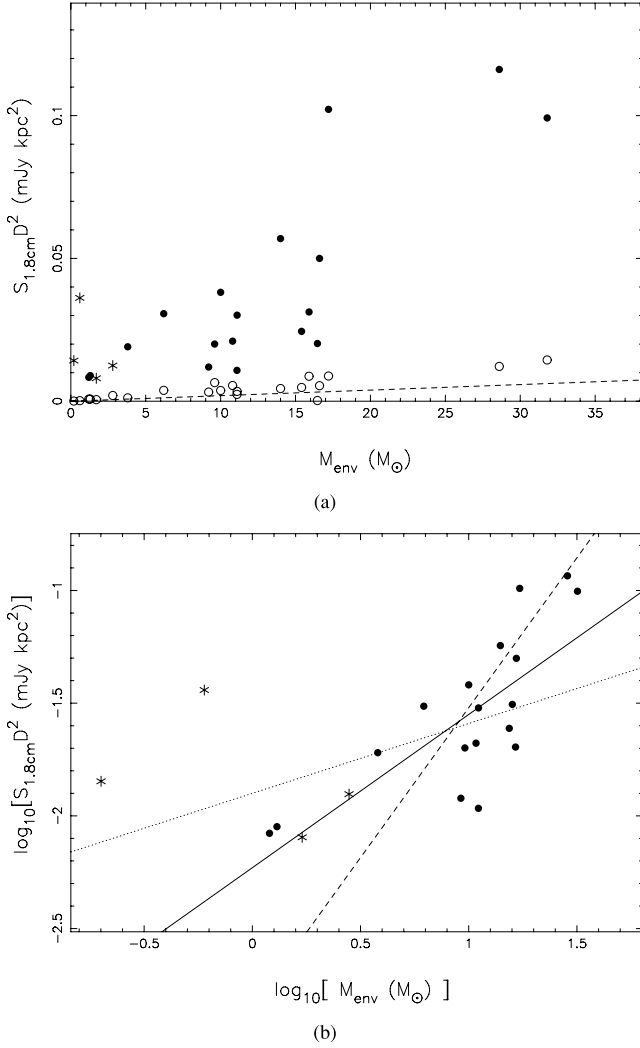
For each of the objects cross-identified with the 850- $\mu\text{m}$  Scuba catalogue of H07 we can also investigate the correlation of the radio luminosity with core envelope mass. These masses were determined using the 850- $\mu\text{m}$  flux density in the following way:

$$M = \frac{S_{\nu} D^2}{\kappa_{\nu} B_{\nu}(T_{\text{d}})}, \quad (4)$$

making the assumptions that the dust temperature  $T_{\text{d}} = 10\text{ K}$  and the dust opacity  $\kappa_{850\mu\text{m}} = 0.0012\text{ m}^2\text{ kg}^{-1}$ . The opacity is known to follow the distribution  $\kappa_{\nu} = \kappa_0(\nu/\nu_0)^{\beta}$ , where  $\beta = 2$ .

Reversing this relationship we can see that luminosity ( $S_{\nu} D^2$ ) is a linear function of core envelope mass,  $M$ . Using the envelope





**Figure 5.** Correlation of radio luminosity with envelope mass. (a) Linear correlation, and (b) logarithmic correlation. In (a), two data points are presented for each object: unfilled circles show the submillimetre greybody predictions for 16-GHz luminosities from thermal dust emission, filled circles and stars show the measured radio luminosities in excess of the greybody predictions for Class 0 and Class I objects, respectively; a 16-GHz luminosity prediction from envelope mass is shown as a dashed line; in (b) the radio luminosity data only are plotted; a best-fitting regression is shown as a solid line, the relationship  $L_{\text{rad}} \propto M^{4/3}$  is shown scaled to fit the Class 0 data as a dashed line, and the predicted relationship based on the radio and bolometric luminosity is shown as a dotted line; see text for details.

masses derived from the 850- $\mu\text{m}$  measurements and the known behaviour of  $\kappa_{\nu}$ , we can predict the radio luminosity from the dust mass at 1.8 cm. This prediction is shown as a dashed line in Fig. 5. The predicted luminosities for each object at 16 GHz based on a greybody fitted to submillimetre data, the flux densities for which are listed in column 4 of Tables 4 and 5, are shown as unfilled squares in this plot and the radio luminosities in excess of these predictions, i.e. the difference between the total radio luminosity and the greybody prediction, are shown as filled circles and stars for Class 0 and Class I objects, respectively. The submillimetre greybody predictions for the sample are well fitted by the mass prediction model, with perhaps some evidence for a lower average value of  $\kappa_{\nu}$ , which is known to vary, or alternatively a lower value of the emissivity index  $\beta$  used to calculate the greybody emission. For

a detailed comparison of current measured opacities for low-mass cores, we refer the reader to Shirley et al. (2011b). The value of  $\kappa_{850\ \mu\text{m}}$  used here agrees with that derived by Shirley et al. (2011b) for the low-mass Class 0 core B335, who found a range of values  $\kappa_{850\ \mu\text{m}} = (1.18 - 1.77)^{+0.36}_{-0.24} \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ .

It is clear from Fig. 5 that a correlation also exists between envelope mass and radio luminosity, with a Pearson correlation coefficient of  $r = 0.89$  indicating a strong positive correlation. However, this correlation does not seem to hold as strongly, if at all, for the detected Class I objects in this sample which are all found at the low-mass end of the relationship and deviate from the trend. Unlike the luminosity and outflow force correlations, this trend seems to show a dependency on protostellar evolution, with all Class I objects lying at the low-mass end. The fact that the Class I objects also deviate from the general correlation seen in the Class 0 sources suggests, similarly to the detection statistics (see Section 5.7), that the radio emission from Class I objects is heavily influenced by environmental factors rather than arising as a consequence of an intrinsic mechanism.

The correlation fitted to the Class 0 sources in this sample is

$$\log[L_{1.8\text{cm}}(\text{mJy kpc}^2)] = -(2.23 \pm 0.65) + (0.68 \pm 0.62) \log[M_{\text{env}}(M_{\odot})], \quad (5)$$

and is plotted as a solid line in Fig. 5.

It is known that a correlation exists between bolometric luminosity and core mass (see e.g. Planck collaboration: Montier et al. 2011) with the form  $\log L_{\text{bol}} = \log A + 0.67 \log M_{\text{env}}$ , where the constant  $A$  depends on the surface density. Combining this relationship with that fitted between radio and bolometric luminosity in this work, equation (2), we can predict a weak correlation between radio luminosity and core mass with the form  $\log L_{\text{rad}} = \log A' + 0.31 \log M_{\text{env}}$ . The relationship shown in equation (5) is broadly consistent with this correlation due to the large scatter in the data, and is shown in Fig. 5(b) as a dotted line. However, it is unclear why this relationship should fail to apply in the case of Class I objects. It can be seen from Fig. 3 that the bolometric luminosities of the Class I sources in this sample show no deviation from the general trend, nor with any evolutionary distinction evident in their distribution.

As sources evolve through the Class 0 and Class I stages, both the envelope mass and the average mass-loss rate in the outflow decrease (Bontemps et al. 1996; Fuller & Ladd 2002; Arce & Sargent 2006). The observed correlation of radio luminosity,  $L_{\text{rad}}$ , with envelope mass could also be seen as a correlation with mass-loss rate.

Models of radio emission from both ionized spherical stellar winds (Panagia & Felli 1975) and collimated winds (Reynolds 1986) predict a correlation between radio luminosity,  $L_{\text{rad}}$ , and the rate of stellar mass-loss,  $\dot{M}$ . In the canonical spherical case with  $n_e \propto r^{-2}$ ,

$$\left[ \frac{S_{\nu} d^2}{\text{mJy kpc}^2} \right] = 5.12 \left[ \frac{\nu}{10 \text{ GHz}} \right]^{0.6} \left[ \frac{T_e}{10^4 \text{ K}} \right]^{0.1} \left[ \frac{\mu}{1.2} \right]^{-4/3} \times \left[ \frac{v_*}{10^3 \text{ km s}^{-1}} \right]^{-4/3} \bar{Z}^{-2/3} \left[ \frac{\dot{M}}{10^{-5} M_{\odot} \text{ yr}^{-1}} \right]^{4/3} \quad (6)$$

(Panagia & Felli 1975). For the case of a collimated outflow, Reynolds (1986) also predicted the relationship

$$L_{\text{rad}} \propto \dot{M}^{4/3}, \quad (7)$$

where the constant of proportionality included weak dependencies on ionization fraction, collimation, temperature and outflow inclination. Although the best-fitting regression to the Class 0 data shown in Figs 5(a) and (b) is not exactly equal to this value, it can be seen that these data are not inconsistent with the predicted relationship, plotted as a dashed line in Fig. 5(b).

In recent models, mass accretion is suggested to be episodic, raising luminosities and temperatures and switching protostars back and forth between Class 0 and Class I (Dunham et al. 2010). If the variable accretion model were correct, and radio luminosities did correlate with mass-loss rate in the outflow, then Class I sources should have radio luminosities higher by an order of magnitude than Class 0 sources. We find that the small number of Class I sources which are detected in this sample have much higher radio luminosities relative to the correlation seen with envelope mass for Class 0. However, the high number of non-detections for Class I sources also suggests that mass-loss rate is not the only factor controlling the radio luminosity for these objects.

We also note that the observed correlation could also be explained by a population of dust with a similar mass but a higher opacity,  $\kappa_{850\ \mu\text{m}} \approx 0.006\ \text{m}^2\ \text{kg}^{-1}$ . This value is very high compared with the range of values collected by Shirley et al. (2011b) and, even considering the degenerate contributions of mass, opacity and temperature to this relationship, it would seem unlikely that the emission we see at centimetre wavelengths is not in fact free-free emission but thermal emission from a separate population of dust. Alternatively, the emission could also arise as a consequence of rotational emission from a population of very small dust grains (VSGs). If these VSGs were mixed through the dense dust core as a function of density then the amount of rotational emission would also be a function of dust mass. However, we do not explore this possibility further since we do not have additional supporting evidence.

### 5.6 Correlation with bolometric temperature

The bolometric temperature, values taken from H07, is representative of the dust temperature in the cores – rather than the temperature of any ionized gas. Consequently the lack of correlation with radio luminosity is perhaps not surprising.

On average the bolometric temperature is thought to increase with bolometric luminosity; however, within individual classes of protostellar object this trend is extremely weak and indeed it is possible that it is itself simply an effect of observational biases in the submillimetre (Kauffmann et al. 2008). Although MAMBO follow-up of the *Spitzer* c2d catalogue showed a correlation between bolometric temperature and envelope mass (Kauffmann et al. 2008), this was only really evident when combining objects in Classes 0, I and II. Individual classes did not portray a strong trend between these parameters and the same is true of the sample of objects considered here. When Classes 0 and I are considered together a weak negative correlation is found,  $r = -0.41$ ; however, if the Class 0 objects alone are considered then this correlation reduces even further, and in fact reverses, to  $r = 0.24$ .

When comparing bolometric temperatures determined using IRAC data (H07) and those found from fluxes calculated using *Spitzer* SEDs (DCE08), there is a marked difference for this sample, with those derived from IRAS being, on average, a factor of 1.6 higher than the corresponding *Spitzer* values. Bolometric temperature is one of the indicators for protostellar class and within this sample three sources with  $70 \leq T_{\text{bol}} \leq 150$  will have this indicator change from Class I to 0 when the *Spitzer* temperature is used. For two of these sources, [DCE08]-060 ([H07]-80) and [DCE08]-064 ([H07]-074), their overall classification will change from Class I to Class 0 when *Spitzer* temperatures are utilized rather than those from IRAC. However, neither is detected at 1.8 cm by AMI-LA. The third, [DCE08]-088 ([H07]-076), is already identified as Class 0 and is detected.

### 5.7 Detections and non-detections

Of the 28 objects targeted in the *Spitzer* catalogue of embedded sources (DCE08), nine are in the Perseus region which we do not detect. Of these, four are designated Group 1 by DCE08 and are therefore most likely to be true embedded protostars. Of these Group 1 objects two are Class I following the revised classifications from Section 5.6 ([DCE08]-063 and 064) and two are Class 0 ([DCE08]-068 and 081). [DCE08]-068 is identified as Class 0 following an identification with [H07]-75 in Hatchell & Dunham (2009); however, we note that the positions of these sources are in fact offset by 45 arcsec making their correspondence uncertain. This may be an example of a false protostellar identification due to confusion with an external galaxy in DCE08. [DCE08]-081 was initially identified as Class 0 by H07, but no outflow was detected by Hatchell et al. (2007b). An outflow was identified by Hatchell & Dunham (2009) using the ‘lower line-wing criteria’, with the caveat that it may have been confused with the outflow from [H07]-081. Five of the six Group 3 objects are not detected. Of these two are considered starless ([DCE08]-107 and 108), one is Class I ([DCE08]-060), one has no classification and no counterpart in H07 ([DCE08]-109). The remaining non-detection is [DCE08]-104, which is a Class 0 source.

Of the sources outside the Perseus region, all Group 1 objects are detected, although we note that [DCE08]-048 and 049 are unresolved and it is likely that the radio detection is dominated by [DCE08]-048. [DCE08]-043 (Class I), the only Group 3 object outside Perseus is not detected. In these numbers the radio detection rates are 81 and 29 per cent for the Group 1 and Group 3 objects, respectively.

The detection statistics for the whole sample divided by protostellar Class and candidate Group are summarized in Table 6. The results are very similar to those found in Paper I for VeLLO and Class 0 sources. For Class I sources the detection rate is lower in this work compared with that of Paper I (71 per cent). The consistency in detection for Class 0 sources, and lack of consistency for Class I sources, may indicate that the radio emission mechanisms for the two types of protostellar objects differ. Consistency indicates

**Table 6.** Summary of detection statistics for Table 4. The original sample includes only objects from DCE08, listed in Table 1. The extended sample includes all sources identified in H07 and listed in Table 4, inclusive of the original sample.

Class	Present	Detected	Per cent
Original sample:			
VeLLO	4	2	50
0	16(18)	13(13)	81(72)
I	6(4)	2(2)	33(50) <sup>a</sup>
Starless	2	0	0
Group 1	21	17	81
Group 3	7	2	29
Extended sample:			
0	25(27)	18(18)	72(67)
I	11(9)	3(3)	27(33) <sup>a</sup>
Starless	15	0	0

*Note.* Figures in brackets indicate revised numbers following reclassification of sources based on bolometric temperatures derived from *Spitzer* data in DCE08.

<sup>a</sup>By considering [DCE08]-049 as a non-detection, these figures are reduced to 17(25) per cent for the original sample and 18(22) per cent for the extended sample; see text for details.

that the emission from Class 0 objects is dependent on an intrinsic mechanism, whereas for Class I objects environmental factors are important leading to different detection statistics in different regions. We note that a comparison of the statistics for VeLLO sources is not conclusive due to the small number of these objects in this work. We also tabulate the detection statistics for the much larger number of protostellar sources which lie within our fields identified from the catalogue of H07; however, we note that the primary beam attenuation away from the pointing centre will bias these detections non-uniformly. We include starless cores identified in H07 in these statistics, but do not list the positions for these objects in Table 4 as they are uniformly not detected. In spite of the differences between these samples the detection statistics for Class 0 and Class I objects are very similar for the original DCE08 sample and the extended data set. We note that these numbers include [DCE08]-049 as a detection, although it is not possible to say conclusively whether it is contributing to the flux density of AMI-49, which combines [DCE08]-048 and [DCE08]-049. The effect of considering it a non-detection would be to reduce the Class I detection rate to 17(25) per cent for the original sample and 18(22) per cent for the extended sample.

Since the correlation of radio luminosity with bolometric luminosity is the most well defined, we examine the distribution of these non-detections with respect to this relationship. There are two distinct regions of non-detection. The first comprises low and very low bolometric luminosity objects. The non-detection limits for these sources lie entirely above the general correlation and we can therefore assume that the fact that they are not detected is biased by their low intrinsic luminosities. The second group is found at higher bolometric luminosities ( $L_{\text{bol}} > 1 L_{\odot}$ ) and lies predominantly below the general trend. For these objects there are two possibilities: first that their non-detection is simply an observational bias caused by the sensitivity limit of the observations, or secondly that they do not follow the general trend and have abnormally low, or zero, radio emission. There is no evident common characteristic between these sources which might be used to distinguish them from the general population, and in the absence of more sensitive observations it is not possible to say definitively if this is indeed the case as the sensitivity limit is not significantly removed from the general trend.

### 5.8 VeLLOs

There are three sources in this sample which can be defined as VeLLOs based on their modelled internal luminosities by DCE08; they are [DCE08]-064, 065 and 081. The source [DCE08]-073 has an infrared luminosity of  $L_{\text{IR}} = 0.018 L_{\odot}$ , well below the rough cut-off of  $L_{\text{IR}} = 0.05 L_{\odot}$  that generally indicates VeLLO status, which may also make it a VeLLO candidate or a borderline case. Of these sources, we detect [DCE08]-065 and [DCE08]-073 at 1.8 cm with the AMI-LA. Both of the detected sources are identified as Class 0 from H07. Of the undetected sources, [DCE08]-081 is identified as Class 0 and [DCE08]-064 as Class I by H07, although we note that [DCE08]-064 would be reclassified as Class 0 using its bolometric temperature from DCE08 as discussed in Section 5.6. [DCE08]-073 and [DCE08]-065 deviate from the general correlation trend of radio luminosity to infrared luminosity, having radio luminosities in excess of that expected, and this has already been noted in Section 5.4. However, with two sources of similar infrared luminosity from Paper I having radio luminosities below the general trend, it is likely that this is simply due to scatter in an undersampled luminosity range rather than representing a characteristic deviation.

[DCE08]-073 is the only VeLLO object with a measured outflow force and we note from Fig. 2 that the radio luminosity for this source is consistent with having arisen as a consequence of shock ionization, unlike the VeLLO source L1014 (Shirley et al. 2007) which has an outflow momentum significantly too low to explain its radio emission.

## 6 DISCUSSION AND CONCLUSIONS

The evidence for hot gas in low-mass protostars that could give rise to radio free-free emission has been strengthened by recent analyses of *Herschel*-PACS data (van Kempen et al. 2010) which have revealed spectral features indicative of small-scale shocks created along the cavity walls of protostellar outflows. Of these, *C*-type shocks give rise to  $\text{H}_2\text{O}$  emission, and *J*-type shocks within the lower density jet give rise to observed  $\text{O I}$  features. Combinations of these shocks can also give rise to observed OH emission. However, the gas in such shocks is heated to temperatures of up to only 3000 K (van Kempen et al. 2010), just sufficient to produce free-free emission. Typical temperatures for free-free emission are in the range  $4000 \leq T_e \leq 20\,000$  K, with a mean value of approximately 8000 K (Dickinson, Davies & Davis 2003). Below 5000 K emission through molecular lines and bands becomes significant. Indeed the theoretical lower limit that we show in Fig. 2 from Anglada (1996) for the amount of free-free emission from shock ionization for a given outflow force,  $F$ , assumes  $T_e = 10^4$  K. This relationship can be re-expressed to include a temperature dependence as  $L_{\text{rad}} \propto F_{\text{out}} T_e^{-0.45}$ , implying that for a lower temperature such as that found in van Kempen et al. (2010) a smaller amount of radio emission would be expected for a given outflow force. This would make it more difficult to explain the observed radio luminosities as arising from shock ionization.

It is unclear why free-free emission produced by shock ionization in such regions should be correlated strongly with envelope mass but less so with outflow force, as has been observed in this work. Since the stellar mass,  $M_*$ , determines the outflow velocity it could be supposed that emission from shock ionization in a molecular outflow might be correlated with  $M_*$ . If, as demonstrated by Chabrier & Hennebelle (2010), the stellar mass is a linear function of the core mass then this may lead to a correlation between envelope mass and radio luminosity from shock ionization. However, the formation of shocks along the length of an outflow is dependent not only on the velocity of that outflow, but also on the local environment. To establish a clear correlation would require uniformity not only of the local environment but also of the number of shocks formed by an outflow of particular velocity. In addition we note that the measured outflow force for protostellar objects is not necessarily a current value but instead represents the averaged historical accretion history of the source and therefore may not necessarily correspond to the radio luminosity, which depends on the ‘current’ protostellar state. The radio emission from protostars is also known to possess a degree of variability, as observed in the VeLLO source L1014 (Shirley et al. 2007), which may contribute to the spread in the correlations presented here. The data here are observed over only a single epoch, and a degree of decorrelation due to variability will be common to all the measured correlations.

Since the free-free emission (radio luminosity) observed here demonstrates a correlation with envelope mass, which is furthermore consistent with that expected from free-free emission as a consequence of partially ionised stellar winds (both spherical and collimated), it is possible that the thermal and non-thermal radio flux density (see e.g. Rodríguez et al. 1999) detected from

low-mass protostars arises as a consequence not only of different emission mechanisms, but also of different underlying astrophysical processes. In order to distinguish these mechanisms, which occur at separated locations within a protostellar system, much higher resolution observations are required than can be provided here.

In addition to free-free and synchrotron emission, we must also consider the possibility that the correlation of radio luminosity with mass is a consequence of the centimetre-wave emission being due to a population of very cold dust. To check this hypothesis, the emission observed is fitted by a modified blackbody representing a possible very cold dust component. However, in order to accommodate the amount of emission seen at 1.8 cm a dust temperature of  $T_d < 5$  K and a value of  $\beta \ll 1$  are required. Such a low cold thermal equilibrium temperature for big dust grains is unrealistic, as is the spectral dust emissivity index. Current observations suggest  $\beta$  to be in the range of 1–2.5 (e.g. Boulanger et al. 1996; Paradis et al. 2009) and the Kramers–König equations also suggest a value of 1 as a theoretical lower limit to  $\beta$  (Emerson 1988). The existence of very cold dust that would explain the observed centimetre emission therefore seems very unlikely.

In summary we find five main conclusions from this work as follows.

(i) We find that 72 per cent of Class 0 objects in the extended sample have detected radio counterparts at 16 GHz, compared with a lower detection rate of 27 per cent for Class I objects. No starless cores were detected. This detection rate for Class I sources differs from that of Paper I and we hypothesize that the discrepancy may be due to environmental effects causing localized differences in the radio emission from Class I objects, whereas radio emission from Class 0 objects arises as a consequence of an intrinsic emission mechanism.

(ii) These new data strengthen the correlations from Paper I of radio luminosity with bolometric and infrared luminosity in the low-luminosity limit and significantly increase the available radio data for low and very low luminosity protostars.

(iii) We find no improvement in the correlation of radio luminosity with outflow force from these new data. We suggest that for the low temperatures found in shocks along molecular outflow cavities the measured outflow forces cannot explain the observed radio luminosities.

(iv) We find a correlation of radio luminosity with core mass for Class 0 objects which does not hold for Class I objects. We suggest that this difference is broadly consistent with theories of episodic mass accretion, but requires additional data for Class I sources in order to be confirmed.

(v) We hypothesize that the observed correlation with core mass seen for Class 0 objects may be due to the predicted relationship between stellar mass-loss rate and radio luminosity, as suggested by Panagia & Felli (1975) and Reynolds (1986). With the currently available data it is not possible to distinguish the case of an ionized spherical stellar wind from a collimated outflow; however, this correlation suggests that such a mechanism is more likely to account for the observed free-free radio emission than the alternatively hypothesized mechanism of shock ionization.

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## APPENDIX A: SOURCE LIST

Sources detected in the AMI-LA fields are listed in Table A1. Column 1 indicates the AMI-LA source designation in increasing right ascension, column 2 indicates the field in which the source was detected, column 3 lists the right ascension in J2000 coordinates, column 4 lists the source declination in J2000 coordinates, column 5 lists the peak flux density of the source at 16 GHz in units of  $\mu\text{Jy beam}^{-1}$  and column 6 lists the integrated flux density in units of mJy; column 7 lists known associations for each source.

**Table A1.** Detected sources in the Perseus region at 16 GHz with the AMI-LA.

AMI	Field	RA (J2000)	Dec. (J2000)	$S_p$ ( $\mu\text{Jy beam}^{-1}$ )	$S_{\text{int}}$ (mJy)	Assoc.
01	DCE08-055	03 25 22.3	+30 45 10.8	470	670 ± 39	[H07]-30
02	DCE08-055	03 25 31.6	+30 44 35.8	174	396 ± 27	
03	DCE08-055	03 25 36.2	+30 45 20.8	1713	2059 ± 105	DCE08-055
04	DCE08-055	03 25 38.9	+30 44 00.8	470	537 ± 33	DCE08-056
03	DCE08-056	03 25 36.4	+30 45 18.1	1822	2045 ± 105	DCE08-055
04	DCE08-056	03 25 38.7	+30 44 03.1	510	519 ± 34	DCE08-056
05	DCE08-063	03 27 29.8	+30 14 48.8	2649	3178 ± 161	radio
06	DCE08-063	03 27 41.7	+30 11 43.8	3265	4337 ± 218	radio
07	DCE08-065	03 28 38.3	+31 06 06.8	154	288 ± 25	DCE08-065
08	DCE08-071	03 28 56.6	+31 14 20.9	273	320 ± 25	[H07]-44
09	DCE08-071	03 28 57.4	+31 14 12.1	658	1211 ± 63	
10	DCE08-071	03 29 00.2	+31 12 05.7	239	239 ± 22	DCE08-071
11	DCE08-071	03 29 10.7	+31 13 30.7	1685	1689 ± 87	[H07]-41
12	DCE08-071	03 29 11.8	+31 13 16.0	439	486 ± 31	DCE08-073
13	DCE08-073	03 29 03.1	+31 13 41.6	240	240 ± 22	VLA15?
11	DCE08-073	03 29 10.5	+31 13 31.6	1657	1733 ± 90	[H07]-41
14	DCE08-073	03 29 12.1	+31 13 01.6	468	516 ± 37	DCE08-073
15	DCE08-081	03 30 43.5	+30 27 21.5	561	590 ± 36	
16	DCE08-084	03 31 19.0	+30 47 25.2	9276	9580 ± 480	radio
17	DCE08-084	03 31 21.0	+30 45 15.2	276	324 ± 34	DCE08-084
18	DCE08-084	03 31 24.9	+30 44 15.2	285	445 ± 37	
19	DCE08-088	03 32 17.6	+30 49 47.6	346	424 ± 38	DCE08-088
20	DCE08-088	03 32 23.4	+30 49 42.6	648	712 ± 48	radio
21	DCE08-090	03 32 25.3	+31 05 10.9	5324	5408 ± 272	radio
22	DCE08-090	03 32 29.2	+31 02 35.9	102	117 ± 26	DCE08-090
23	DCE08-092	03 33 13.7	+31 07 07.6	207	207 ± 29	DCE08-092
24	DCE08-092	03 33 16.1	+31 06 57.6	215	235 ± 29	DCE08-093
25	DCE08-092	03 33 16.8	+31 08 02.6	138	138 ± 28	[H07]-7
26	DCE08-092	03 33 18.0	+31 09 32.6	449	490 ± 36	[H07]-1
27	DCE08-092	03 33 20.7	+31 09 12.6	258	283 ± 30	
28	DCE08-092	03 33 21.1	+31 07 32.6	515	684 ± 44	[H07]-2
29	DCE08-092	03 33 27.3	+31 07 07.6	442	629 ± 41	[H07]-10
23	DCE08-093	03 33 13.7	+31 07 07.6	207	207 ± 24	DCE08-092
24	DCE08-093	03 33 16.1	+31 06 57.6	243	243 ± 25	DCE08-093
25	DCE08-093	03 33 16.8	+31 08 02.6	138	138 ± 23	[H07]-7
26	DCE08-093	03 33 18.0	+31 09 32.6	419	424 ± 31	[H07]-1
27	DCE08-093	03 33 20.7	+31 09 12.6	267	304 ± 27	
28	DCE08-093	03 33 21.1	+31 07 32.6	548	640 ± 39	[H07]-2
29	DCE08-093	03 33 27.3	+31 07 07.6	424	582 ± 36	[H07]-10
30	DCE08-105	03 43 49.8	+32 00 32.9	215	343 ± 29	
31	DCE08-105	03 43 56.2	+32 00 52.9	207	535 ± 35	DCE08-105

**Table A1** – *continued*

AMI	Field	RA (J2000)	Dec. (J2000)	$S_p$ ( $\mu\text{Jy beam}^{-1}$ )	$S_{\text{int}}$ (mJy)	Assoc.
30	DCE08-106	03 43 51.7	+32 00 54.7	143	201 ± 22	
31	DCE08-106	03 43 55.7	+32 00 50.3	218	472 ± 31	DCE08-105
32	DCE08-106	03 43 58.0	+32 03 09.7	137	162 ± 22	DCE08-106
33	DCE08-060	03 26 28.6	+30 16 18.1	6321	7153 ± 358	radio
34	DCE08-080	03 29 52.2	+31 39 01.1	84 <sup>a</sup>	90 ± 19	DCE08-080
35	DCE08-104	03 43 43.5	+32 04 52.9	324	1543 ± 79	RIDGE
36	DCE08-104	03 43 53.0	+32 02 12.9	134	135 ± 20	
37	DCE08-104	03 43 57.3	+32 05 27.9	485	529 ± 33	
38	DCE08-104	03 43 56.5	+32 00 52.9	395	646 ± 38	[H07]-12
39	DCE08-104	03 43 57.3	+32 03 07.9	326	552 ± 34	[H07]-13
40	DCE08-104	03 43 59.7	+32 03 07.9	249	275 ± 24	IC348BN
38	DCE08-107	03 43 56.5	+32 00 49.9	433	982 ± 54	[H07]-12
39	DCE08-107	03 43 57.7	+32 03 09.9	360	534 ± 35	[H07]-13
41	DCE08-107	03 44 07.1	+32 03 59.9	258	1146 ± 61	
42	DCE08-107	03 44 13.0	+32 01 24.9	229	229 ± 25	[H07]-101
43	DCE08-107	03 44 13.8	+32 00 59.9	341	341 ± 28	
44	DCE08-109	03 44 20.5	+32 01 59.2	2010	2022 ± 104	

<sup>a</sup>Detected at  $4.4\sigma$ .**Table A2.** Detected sources outside the Perseus region at 16 GHz with the AMI-LA.

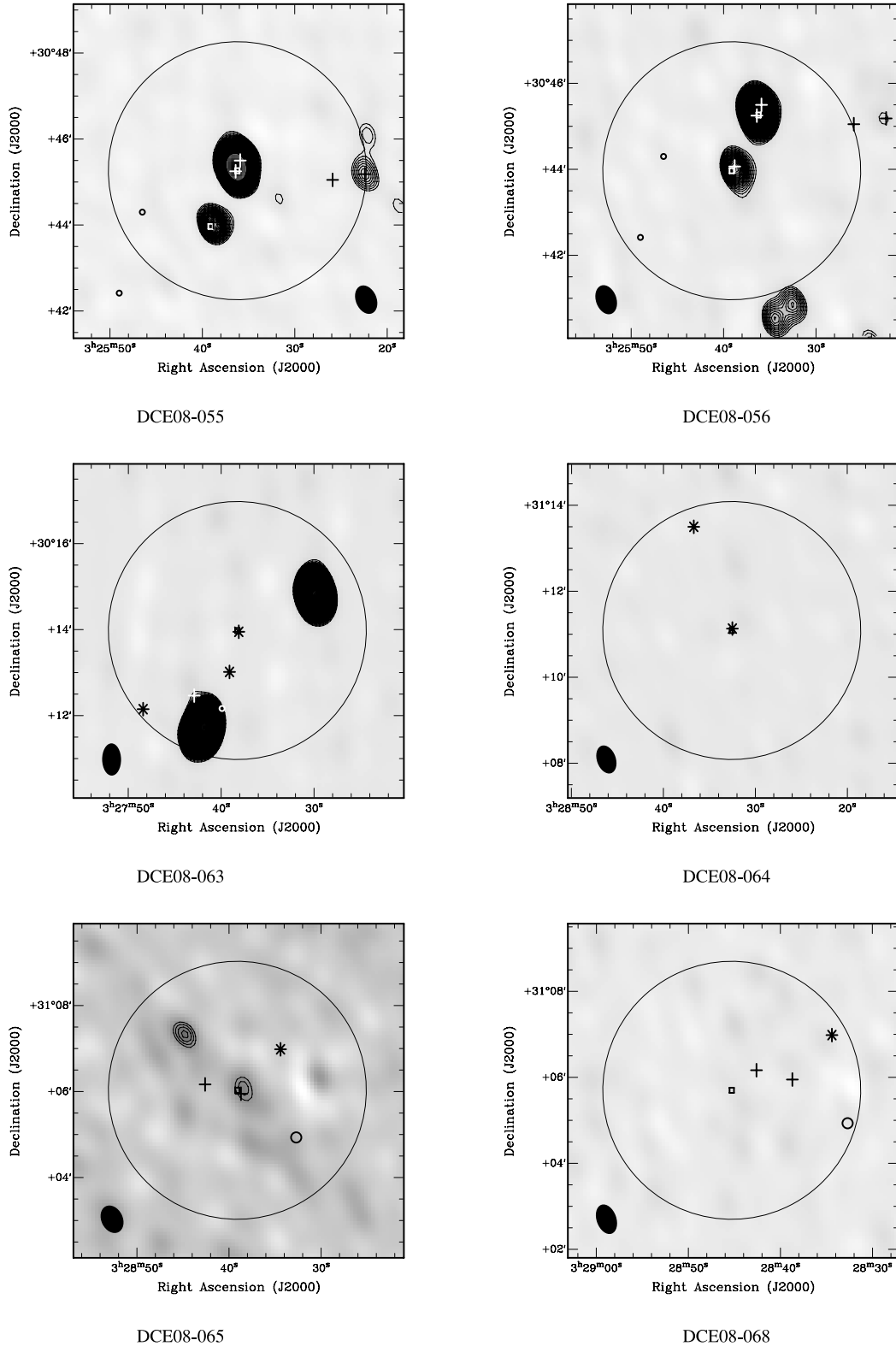
AMI	Field	RA (J2000)	Dec. (J2000)	$S_p$ ( $\mu\text{Jy beam}^{-1}$ )	$S_{\text{int}}$ (mJy)	Assoc.
45	DCE08-005	04 41 12.7	+25 46 35.4	523	645 ± 41	DCE08-005
46	DCE08-044	22 30 33.2	+75 14 18.9	116	167 ± 25	DCE08-044
47	DCE08-045	22 30 48.6	+75 12 47.2	127	159 ± 17	radio
48	DCE08-045	22 31 05.6	+75 13 37.2	125	179 ± 17	DCE08-045
49	DCE08-045	22 31 09.5	+75 15 07.2	127	146 ± 17	
50	DCE08-045	22 31 33.1	+75 13 57.1	184	189 ± 18	
51	DCE08-049	22 38 46.4	+75 11 33.0	854	1173 ± 64	DCE08-048/049

Sources are designated as ‘radio’ where they have a counterpart in the NVSS catalogue (Condon et al. 1998). Table A2 lists sources located outside the Perseus region.

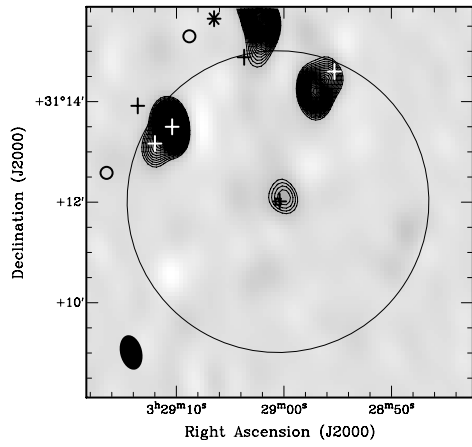
## APPENDIX B: AMI-LA MAPS

Maps of each field are shown in Fig. B1. AMI-LA data are shown uncorrected for the primary beam response in grey-scale and con-

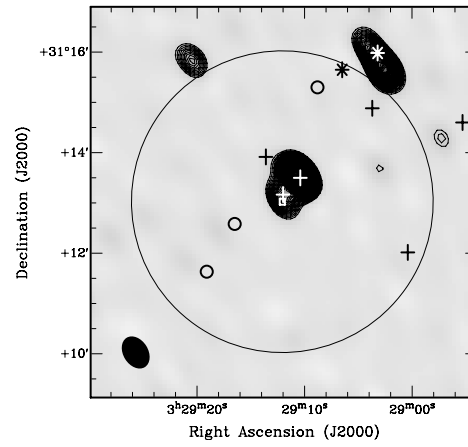
tours of  $5\sigma$ ,  $6\sigma$ ,  $7\sigma$ ,  $8\sigma$  etc to  $1 \text{ mJy beam}^{-1}$  and then in increments of  $1 \text{ mJy beam}^{-1}$ . The AMI-LA primary beam response is shown as a solid circle and the PSF for each data set as a filled ellipse in the bottom-left corner. The positions of *Spitzer* embedded protostellar cores (Dunham et al. 2008) are shown as unfilled squares, and the positions of Class 0, Class I and starless cores from Hatchell et al. (2007) are indicated as crosses (‘+’), stars and unfilled circles, respectively.



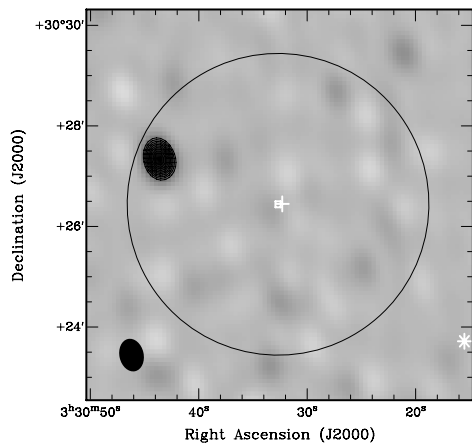
**Figure B1.** Sources lying inside the Perseus region. Grey-scale and contours at 16 GHz from the AMI-LA are shown with no correction for the primary beam attenuation. Contours are shown at  $5\sigma_{\text{rms}}$ ,  $6\sigma_{\text{rms}}$ ,  $7\sigma_{\text{rms}}$  etc., where values for  $\sigma_{\text{rms}}$  for each field can be found in Table 3. The position of each source from Table 5 is shown as an unfilled square. The FWHM of the AMI-LA primary beam is shown as a circle and the synthesized for each map as a filled ellipse in the bottom-left corner.



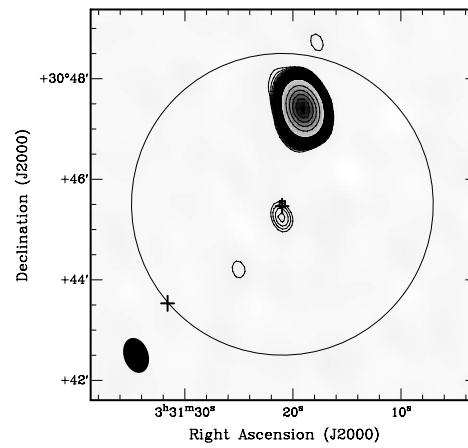
DCE08-071



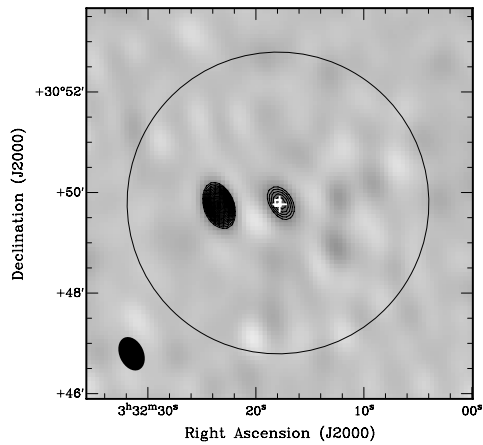
DCE08-073



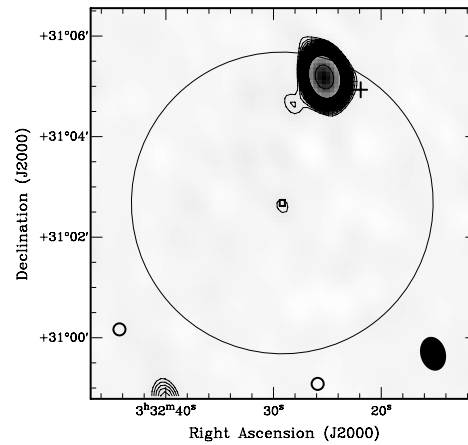
DCE08-081



DCE08-084



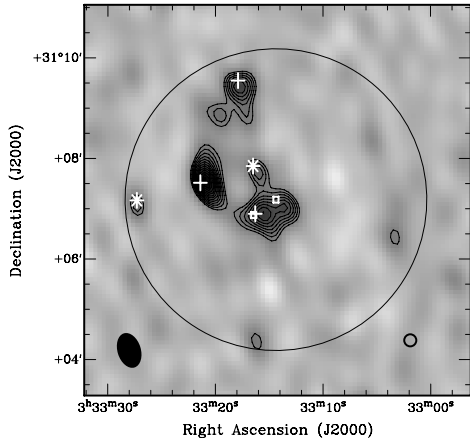
DCE08-088



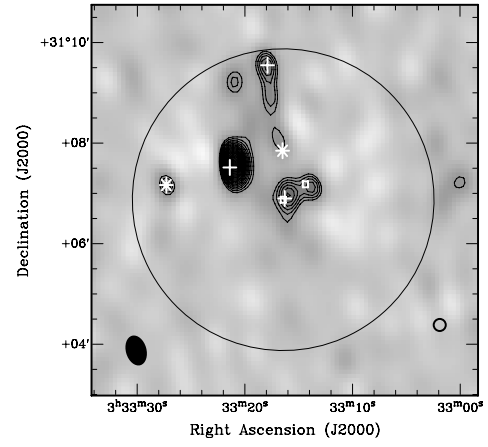
DCE08-090

Figure B1 – *continued*

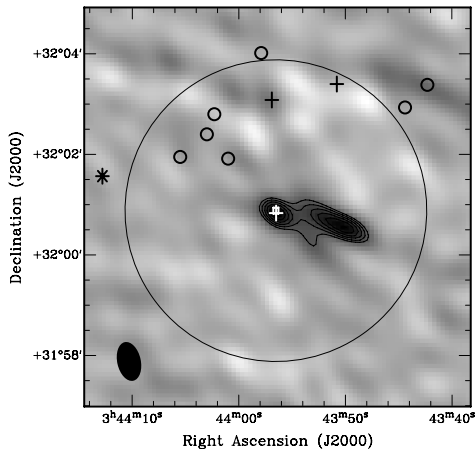




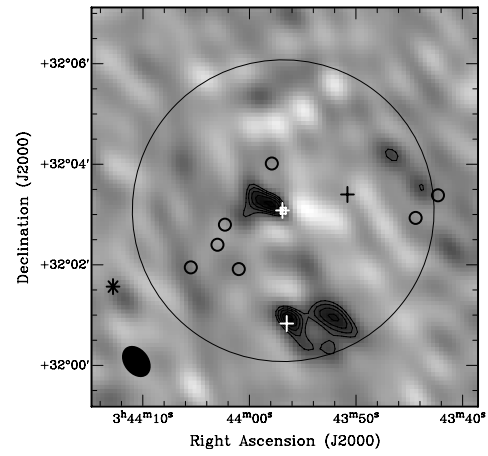
DCE08-092



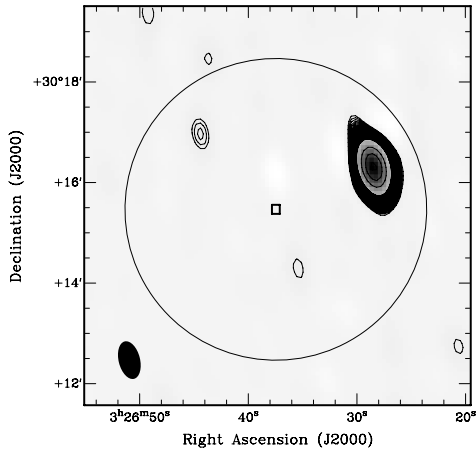
DCE08-093



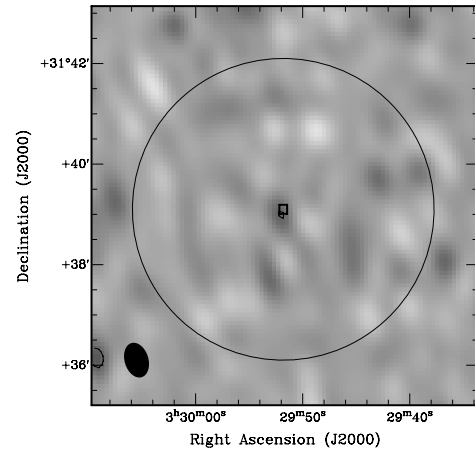
DCE08-105



DCE08-106

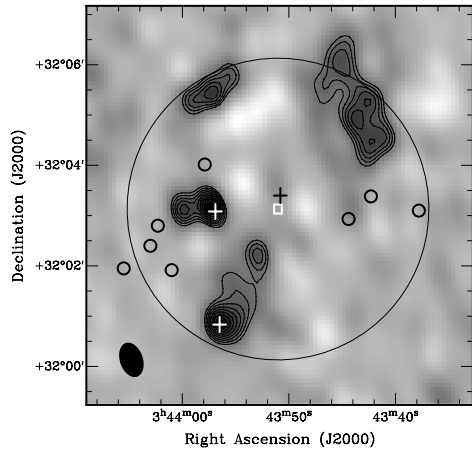


DCE08-060

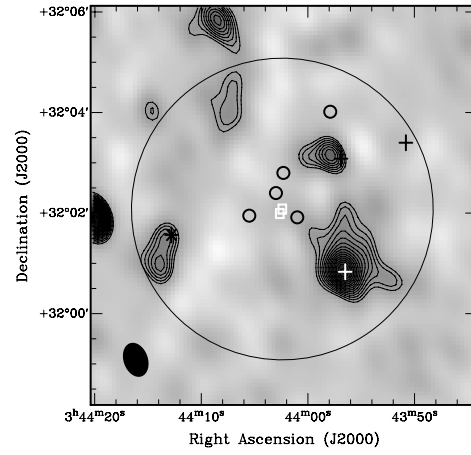


DCE08-080

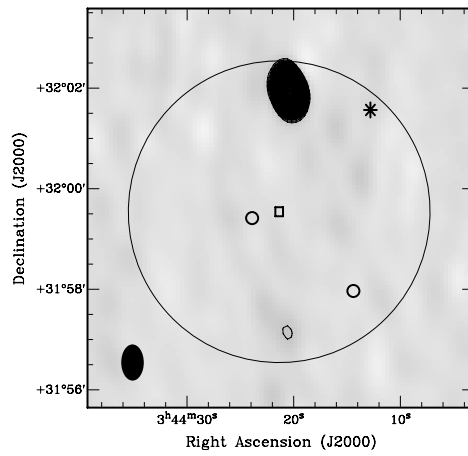
Figure B1 – continued



DCE08-104



DCE08-107



DCE08-109

**Figure B1** – *continued*

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