The Spitzer c2d Survey of Large, Nearby, Interstellar Clouds.

III. Perseus Observed with IRAC

Jes K. Jørgensen¹, Paul M. Harvey², Neal J. Evans II³, Tracy L. Huard¹, Lori E. Allen¹, Alicia Porras¹, Geoffrey A. Blake³, Tyler L. Bourke¹, Nicholas Chapman⁴, Lucas Cieza², David W. Koerner⁵, Shih-Ping Lai⁴, Lee G. Mundy⁴, Philip C. Myers¹, Deborah L. Padgett⁶, Luisa Rebull⁶, Anneila I. Sargent⁷, William Spiesman², Karl R. Stapelfeldt⁸, Ewine F. van Dishoeck⁹, Zahed Wahhaj⁵ & Kaisa E. Young²

ABSTRACT

We present observations of 3.86 degree² of the Perseus molecular cloud complex at 3.6, 4.5, 5.8 and 8.0 μm with the Spitzer Space Telescope Infrared Array Camera (IRAC). The maps show strong extended emission arising from shocked H₂ in outflows in the region and from polycyclic aromatic hydrocarbon (PAH) features, in particular in the prominent Perseus ring. More than 120,000 sources are extracted toward the cloud. Based on their IRAC colors and comparison to off-cloud and extragalactic fields, we identify 400 candidate young stellar objects. About two thirds of these are associated with the young clusters IC 348 and NGC 1333, which account for 14% of the surveyed cloud area, while the remaining third is distributed over the remaining cloud, including a number of

¹Harvard-Smithsonian Center for Astrophysics, 60 Garden Street MS42, MA 02138, jjorgensen@cfa.harvard.edu

²Department of Astronomy, University of Texas at Austin, 1 University Station C1400, Austin, TX 78712

³Division of Geological and Planetary Sciences, MS 150-21, California Institute of Technology, Pasadena, CA 91125

⁴Department of Astronomy, University of Maryland, College Park, MD 20742

⁵Department of Physics and Astronomy, Northern Arizona University, NAU Box 6010, Flagstaff, AZ 86011-6010

⁶Spitzer Science Center, MC 220-6, California Institute of Technology, Pasadena, CA 91125

⁷Division of Physics, Mathematics, and Astronomy, MS 105-24, California Institute of Technology, Pasadena, CA 91125

⁸Jet Propulsion Laboratory, MS 183-900, California Institute of Technology, Pasadena, CA 91125

⁹Leiden Observatory, PO Box 9513, NL 2300 RA Leiden, The Netherlands
smaller groups around B1, L1448 and L1455. We classify the young stellar objects according to the traditional scheme based on the slope of their spectral energy distributions from near-infrared 2MASS $K_s$ through mid-infrared IRAC and MIPS 24 $\mu$m wavelengths. Significant differences are found for the numbers of embedded Class I objects relative to more evolved Class II objects in IC 348, NGC 1333 and the remaining cloud with the embedded Class I and “flat spectrum” YSOs constituting 14%, 36% and 47% of the total number of YSOs identified in each of these regions. These numbers suggest a difference in evolution over the cloud: NGC 1333 previously has been suggested to be younger than IC 348 based on near-infrared studies of the YSO populations and the larger number of Class I objects in NGC 1333 supports this. The high number of Class I objects in the extended cloud (61% of the Class I objects in the entire cloud) suggests that a significant fraction of the current star formation is occurring outside these two clusters. Finally we discuss a number of outflows and identify their driving sources, including the known deeply embedded Class 0 sources outside the two major clusters. The Class 0 objects are found to be detected by Spitzer and have very red $[3.6]-[4.5]$ colors but do not show similarly red $[5.8]-[8.0]$ colors. The Class 0 objects are easily identifiable in color-color diagrams plotting these two colors but are, in some cases, problematic to extract with automatic source extraction routines due to the extended emission from shocked gas or scattered light in cavities related to the associated outflows.

Subject headings: star: formation — infrared: stars — ISM: clouds

1. Introduction

Low-mass stars such as our own Sun are formed in a wide range of different environments ranging from isolated cores to large, dense clusters. To fully understand the differences in the formation processes amongst these environments, large unbiased surveys and compilations of young stellar objects are necessary. A major goal of the Spitzer Space Telescope legacy project “From Molecular Cores to Planet Forming Disks” (c2d; Evans et al. 2003) is to characterize star formation in a variety of environments through a combination of mapping and spectroscopic observations utilizing the full palette of Spitzer instruments.

The Perseus molecular cloud is a prime example of a low-mass star forming region. Low-mass protostars are found in a number of dense clusters, such as NGC 1333 and IC 348, looser groups associated with smaller dark clouds, including Barnard 1, Barnard 5, L1448 and L1455, and a number of dense cores. Although no massive stars are currently formed in
the cloud, OB stars have been formed previously in the vicinity, as witnessed by the Per OB2 association (e.g., de Zeeuw et al. 1999). This paper presents Spitzer Infrared Array Camera (IRAC) maps of 3.86 degree$^2$ of Perseus from the c2d legacy project. This paper is the third in a series of papers presenting the basic results for the five large clouds in the c2d survey. The two previous papers in this series presented MIPS observations of Chamaeleon (Young et al. 2005) and IRAC observations of Serpens (Harvey et al. 2006b). We will present the results for all clouds in a fairly standard format to facilitate comparisons. While this paper is based on IRAC data, some information from MIPS observations of Perseus by c2d (Rebull et al. 2006) is used in source classification and in discussion of particular sources.

Perseus was first mapped, in full, in CO by Sargent (1979). Ladd et al. (1993) identified 23 candidate young stellar objects (YSOs) from the IRAS point source catalog and surveyed these at 2 µm. Ladd et al. found that the YSO candidates were distributed throughout the cloud with higher numbers toward the prominent clusters in IC 348 and NGC 1333: 87% of the YSOs were located within 1 degree of these two clusters, but only 30% within 30'. Subsequent near-infrared studies have focused on the regions around NGC 1333 (Lada et al. 1996; Wilking et al. 2004) and IC 348 (Lada & Lada 1995; Luhman et al. 2003), identifying a large number of infrared excess sources (about 60 sources in each region – corresponding to 50% and 20% of the total number of cluster members in NGC 1333 and IC 348, respectively).

The exact distance to Perseus remains uncertain. It is not clear whether the cloud is located in the vicinity of the Per OB2 association (at a distance of 320 pc inferred from Hipparcos parallax measurements (de Zeeuw et al. 1999)) or whether the cloud is closer, in front of the OB association at 200–250 pc such as suggested by extinction studies (e.g., Černis 1990). Whether a single distance to the entire cloud is valid or whether the Perseus cloud in fact has a distance gradient (similar to an observed line of sight velocity gradient (Sargent 1979)) or is a conglomeration of smaller clouds is another issue. In any case, following Enoch et al. (2006), a distance of 250 ± 50 pc is adopted in this paper.

2. Observations

In total, 4.29 degree$^2$ of Perseus was observed with the IRAC camera in each of 4 bands at 3.6, 4.5, 5.8 and 8.0 µm on 2004 September 7 and 8. The IRAC camera observes these four bands simultaneously with one field of view imaged by the 3.6 and 5.8 µm filters and a nearby field imaged by the 4.5 and 8.0 µm filters. Mosaics of our Perseus observations overlap in all four IRAC bands in a region covering 3.86 degree$^2$. The mapped area was selected based on the $^{13}$CO maps of Padoan et al. (1999), including the entire region with $A_V \gtrsim 2$ mag. Fig. 1 shows an overlay of the observed region on a dust column density map based on IRAS 60
and 100 µm thermal emission (Schnee et al. 2005). The cloud was mapped in two epochs to help in the elimination of transient objects such as unknown asteroids. The regions around NGC 1333 and IC 348 were mapped in Guaranteed Time Observations (GTO; Gutermuth et al. (2006) and Lada et al. (2006), respectively) and observed in one epoch within the c2d program. Two smaller gaps (per_gap1, per_gap2 in Table 1) between the fields mapped by the GTO and c2d were added later and only observed in one epoch. MIPS observations of the Perseus cloud from c2d are discussed in a separate paper (Rebull et al. 2006).

Furthermore 6 off-cloud fields, each of 0.08 degree$^2$, were observed for statistical comparisons with 0.05 degree$^2$ overlap between all four IRAC bands. These regions were selected as having a relatively low extinction ($A_V < 0.5$ mag) from the large scale CO maps by Dame et al. (2001) and chosen to cover a range of galactic latitudes around Perseus. Table 1 provides a summary of the observations, including the distribution of the on- and off-cloud fields.
Fig. 1.— Coverage by the c2d IRAC maps. The thick black line indicate the region covered by all 4 IRAC bands from which the source catalogs are extracted. The off-cloud fields are likewise shown (black solid fields) and numbered 1 through 6. The grey scale map is the dust column density distribution based on IRAS 60 and 100 μm thermal emission from COMPLETE (Schnee et al. 2005) encompassed by the black rectangle. The prominent ring seen in the map of Schnee et al. is not a true column density feature but rather reflects a different, warmer dust population in this region (Ridge et al. 2006).
Table 1: Summary of observations.

| Field | Position (α, δ)$_{2000}$ | Position (l, b) | AOR epoch 1 | AOR epoch 2 |
|-------|--------------------------|----------------|--------------|-------------|
| per.1 | (03:47:44.0,+32:44:44.0) | (160.6, -16.9) | 0005783552   | 0005790464  |
| per.2 | (03:46:01.0,+32:29:16.0) | (160.5, -17.4) | 0005783808   | 0005790720  |
| per.4 | (03:44:53.3,+31:39:00.0) | (160.9, -18.2) | 0005784064   | 0005791232  |
| per.5 | (03:41:59.0,+31:48:34.0) | (160.3, -18.4) | 0005784320   | 0005791488  |
| per.6 | (03:40:12.0,+31:26:41.0) | (160.2, -18.9) | 0005784576   | 0005791744  |
| per.7 | (03:38:27.0,+31:22:11.0) | (159.0, -19.2) | 0005784832   | 0005792000  |
| per.8 | (03:36:23.0,+31:08:41.0) | (159.7, -19.7) | 0005785088   | 0005792256  |
| per.9 | (03:33:36.0,+30:36:36.0) | (159.2, -20.1) | 0005785344   | 0005792512  |
| per.10| (03:31:00.0,+30:36:50.0) | (159.1, -20.8) | 0005785600   | 0005792768  |
| per.11| (03:30:09.0,+31:31:48.0) | (158.4, -20.2) | 0005785856   | 0005793024  |
| per.13| (03:28:41.0,+30:34:02.0) | (158.7, -21.2) | 0005786112   | 0005793536  |
| per.14| (03:27:12.0,+30:11:49.0) | (158.7, -21.7) | 0005786368   | 0005793792  |
| per.15| (03:25:20.0,+30:30:01.0) | (158.2, -21.6) | 0005786624   | 0005794048  |
| per.16| (03:27:08.0,+30:39:42.0) | (158.4, -21.3) | 0005786880   | 0005794304  |
| per.17| (03:29:39.0,+30:55:28.0) | (158.7, -20.8) | 0005787136   | 0005794560  |
| per.18| (03:31:05.0,+31:04:42.0) | (158.8, -20.4) | 0005787392   | 0005794816  |

- **AORs mapped in two epochs by c2d**

- **AORs mapped in one epoch by GTO team and in one epoch by c2d.**

- **AORs to cover gaps between c2d and GTO areas. Mapped in one epoch by c2d.**

- **Off-cloud regions mapped in two epochs by c2d.**
3. Data reduction

The data reduction started from the IRAC basic calibrated data (BCD) images supplied by the Spitzer Science Center (SSC) from their S11.4.0 pipeline. The SSC pipeline BCD data are delivered with dark and bias levels subtracted and flat field corrected. Instrumental signatures, bad pixels or pixels saturated by bright sources are furthermore masked. Finally the BCD images are flux calibrated into physical units (MJy sr$^{-1}$). To arrive at the final source catalogs our data reduction continues from the BCD images by 1) correcting additional background and image effects, 2) creating a mosaic from individual frames, 3) extracting sources from the final mosaic and 4) merging the catalogs across bands. A detailed description of the processing is described in the documentation for the delivery of c2d data (Evans et al. 2005) and further discussed in Harvey et al. (2006b).

In the first step, the c2d pipeline improves the BCD images by additional masking of bad pixels not picked up by the SSC pipeline reduction, correcting muxbleed and column pull-down defects occurring near moderately bright sources and finally correcting the so-called “first frame” effect for the band 3 (5.8 µm) images (see Harvey et al. (2006b) for further discussion of these corrections). In the second step, mosaics are created from the frames from observations in the two different epochs and from short exposure (0.4 second) data. The combination of the two epoch observations eliminates transient effects including most asteroids in the mosaics. The inclusion of the short exposure data allows masking of likely saturated areas in the longer integration frames.

As a third step, sources are extracted using a c2d developed tool, $c2dphot$ (Harvey et al. 2006a). $c2dphot$ extracts sources using digitized source profiles and calculates photometry for each source including uncertainty in the derived fluxes. The source extractor recognizes “small” extended sources (i.e., sources better fit by a two-axis ellipsoid than a point source profile) and provides an estimate of the size of these. These extended sources (sources with “image type” 2 in the delivered c2d catalogs Evans et al. 2005) are included in our general catalog with fluxes extracted from aperture photometry. However, we leave them out of the color-color/color-magnitude diagrams and discussions in Sect. 5 and onwards in this paper for consistent photometry of sources in our high quality catalogs (i.e., when comparing unresolved and extended sources). The accuracy of the flux calibration for the sources is estimated to $\approx 15\%$. The extraction is applied to each of the single epoch datasets together with the combined mosaics. A uniform flux cut-off of 0.05 mJy is applied across the regions and bands. The source lists from each dataset are cross-checked serving as an additional test of transient detections.

In the fourth step, the lists are merged by cross-identifying sources from each of the IRAC bands followed by merging with the MIPS 24 µm (Rebull et al. 2006) and 2MASS
catalogs. In the band merging an IRAC source is accepted as identified in two bands if the positional agreement is better than 2.0″. Cross identifications with MIPS 24 μm require positional agreement better than 4.0″ and with 2MASS better than 2.0″.

4. Results

4.1. Description of the overall cloud environment

A three color composite of the Perseus region is presented in Fig. 2, showing IRAC bands 1 (IRAC1; 3.6 μm), 2 (IRAC2; 4.5 μm) and 4 (IRAC4; 8.0 μm). For display purposes the image in this figure does not include the short integration data which otherwise are used for photometry of saturated sources. For comparison, the extinction contours from Enoch et al. (2006) are overlaid on the band 2 image in Fig. 3, and prominent regions identified. Fig. 4 shows greyscale images (logarithmic stretch) of the cloud for each of the IRAC bands. As pointed out above, the field observed by the IRAC1 and IRAC3 bands is offset from the field observed by the IRAC2 and IRAC4 bands which is clearly seen by comparing the panels of Fig. 4. Only the overlap region is shown in Fig. 2 and used in the subsequent analysis. The emission seen in the IRAC bands highlight different features of the cloud: band 1 shows the largest fraction of stars, band 2 is, in particular, sensitive to H$_2$ rotational transitions arising in shocked gas associated with the outflows, whereas bands 3 and 4 includes emission from the polycyclic aromatic hydrocarbon (PAH) features at 6.2 and 7.7 μm.

Besides the two main clusters, NGC 1333 and IC 348, a striking feature in the image is the Perseus ring (sometimes referred to as G159.6-18.5) in the eastern part of the cloud, which is seen in all bands - most prominent in the 8.0 μm (likely PAH) emission. It has been suggested to be a supernova remnant (Fiedler et al. 1994) or an H II region associated with a late O/early B star, HD 278942 (de Zeeuw et al. 1999; Andersson et al. 2000). Ridge et al. (2006) argue that the shell is located behind the cloud (although it may be “touching” it).

The western part of the cloud shows less PAH emission than the eastern part, but harbors a number of prominent outflows, in particular in the B1, L1448 and L1455 regions (see inserts). We will return to a discussion of some of these outflows in Sect. 6. The extinction map (Fig. 3) demonstrates, however, that regions of medium-high column density are not isolated to a particular part of the cloud. In contrast, the Serpens cloud exhibits smaller and more isolated regions of high extinction, where also the highest number of Class I YSOs are found (Harvey et al. 2006b). In Perseus, regions of high extinction are likewise found close to IC 348 and NGC 1333 but these are in no way unique. There is also no clear correlation between the regions of high extinction and the extended emission seen in the
IRAC images.

4.2. Catalogs and statistics

In total 123327 sources were detected by the Spitzer observations in at least one IRAC band. Table 2 summarizes the number of sources detected in the Perseus maps with S/N ratios of at least 7. Sources which have multiple counterparts within the radius used in the bandmerging are excluded from this “high quality” catalog, which we use in the subsequent sections. This corresponds to selecting all sources with detections of quality “A” or “B” in one of the IRAC bands from the delivered c2d catalogs (Evans et al. 2005). Of all the sources in the catalog the largest fraction is most likely background stars picked up in the most sensitive 3.6 and 4.5 μm bands. This is clearly illustrated in Table 3 where the number of detected sources are split up in the different IRAC bands: with 70,000–110,000 sources detected in IRAC bands 1 and 2 and 10,000–15,000 in band 3 and 4. Of all the reliable detections, about 6700 sources were detected in all four IRAC bands with about 20% of these not previously detected by 2MASS. Conversely, 65 of the 7933 2MASS sources (0.8%) included in the Perseus mosaic were not detected in any IRAC band. Most of these 65 sources are located at the edge of the Spitzer maps explaining why they are not included in the catalog. Finally about 541 of the four band detections are found to be extended in one or more bands (classified with “image type” 2 in the c2d catalogs). These are left out of the color-color and color-magnitude diagrams in the following sections and our high quality catalog therefore consists of 6192 four band detections.
Fig. 2.— Three color image of the Perseus region with IRAC1 (3.6 μm; blue), IRAC2 (4.5 μm; green) and IRAC4 (8.0 μm; red).
Fig. 3.— IRAC2 image with prominent clusters and cores indicated. The dashed contours indicate an extinction map with levels corresponding to $A_V = 2, 4, 6, 8, 10$ mag.
Fig. 4.— Black/white maps of the entire region (shown with a logarithmic stretch) in (a) IRAC band 1 (3.6 μm), (b) band 2 (4.5 μm), (c) band 3 (5.8 μm), and (d) band 4 (8.0 μm).
Table 2: Detection of sources with S/N ≥ $7\sigma$ toward Perseus (total numbers).

| Detection in at least one IRAC band | 123327 |
|------------------------------------|--------|
| Detection in all 4 IRAC bands       | 6733   |
| Detection in 3 IRAC bands           | 8438   |
| Detection in 2 IRAC bands           | 50925  |
| Detection in 1 IRAC band            | 57231  |
| Detection in 2MASS only$^a$          | 65     |
| Detection in IRAC only              | 114975 |
| Detection in 4 IRAC bands and not 2MASS$^a$ | 1380   |

Excluding extended sources:

| Four band detections                | 6192   |
| Four band detections with 2MASS association$^a$ | 5115   |
| Detected in IRAC1+2 and 2MASS$^a$      | 7487   |

$^a$A source is counted as detected by 2MASS if it has a S/N of at least 10 in both $H$ and $K_s$.  

Table 3: Detection of sources toward Perseus (per band).

|                      | 3.6 µm | 4.5 µm | 5.8 µm | 8.0 µm |
|----------------------|--------|--------|--------|--------|
| Detections with      |        |        |        |        |
| ...S/N of at least 7 | 110585 | 76425  | 14999  | 9318   |
| ...S/N of at least 10| 85913  | 60042  | 10189  | 7010   |
| ...S/N of at least 15| 53592  | 34619  | 6644   | 4810   |
| Final sample (excluding extended sources) | 104341 | 74877  | 14832  | 8997   |
| ...2MASS ass. (S/N at least 10 in H and K$_s$) | 7532   | 7778   | 7206   | 5434   |
Fig. 5 shows the differential source counts for the cloud and “off-cloud” areas. The turn over at faint magnitudes illustrates the completeness limit for each IRAC band: 17.5 mag for IRAC1, 16.5 mag for IRAC2, 14.5 mag for IRAC3 and 13.5 mag for IRAC4. An interesting feature is clearly seen in the comparison between the on- and off-cloud fields: the populations in the two agree well in the bright tail of the distribution, but in the faint end there is a clear excess of sources in the off-cloud fields.
Fig. 5.— Differential source counts for the on- and off-cloud regions (grey and black, respectively).
Naturally some difference could be expected between the on- and off-cloud fields: the off-cloud fields are selected to have low extinction whereas most of the on-cloud area has $A_V \gtrsim 2$ mag. Fig. 6 compares the differential source counts from a high extinction ($A_V \gtrsim 6$ mag) and a low extinction ($A_V \lesssim 2$ mag) field based on the extinction map in Fig. 3. This figure shows that there is an excess of faint sources in the low extinction field, similar to that seen in the off-cloud fields, relative to the counts in the high extinction fields, i.e., extinction in the cloud shifts the differential source count distribution toward fainter magnitudes.

The double peak seen most clearly in the distribution of IRAC band 1 sources at 17–18 mag. in both the on- and off-cloud fields appears to be real. It is not an artifact of the calibration or combination of the different mosaics or frames (e.g., long and short exposures); it is not associated, e.g., with sources only detected in one epoch; and it is seen across the cloud and not related to any specific region. It therefore seems to reflect either the distribution of stars or background galaxies toward Perseus, but based on this dataset it is not possible to say which is more likely. Deep observations and a detailed comparison to a larger sample of fields could possibly shed further light on this issue.

Finally Fig. 7 compares the on-cloud differential source counts to the predicted galactic star counts from the models of Wainscoat et al. (1992) calculated using the C-version of the models by J. Carpenter. The model predictions agree well with the observed star counts at bright magnitudes, but underestimate the source counts at brightnesses fainter than 13–15 mag. The reason is likely contributions from background galaxies which start to dominate the counts there. For this comparison and our subsequent analysis, the stars are separated from the remaining sources by fitting a (possibly reddened) photosphere (Lai et al. 2006) to the 2MASS and IRAC measurements. This method relies on 2MASS measurements and does not properly identify fainter stars only picked up in the IRAC bands. It is seen that the observed population of stars agree well with the predictions of the Wainscoat et al. (1992) models but also that the background galaxies outnumber the predicted star counts by more than 3:1 at faint magnitudes in some of the bands. This effect is naturally more pronounced for these data than corresponding Serpens data (Harvey et al. 2006b) since Perseus is located further from the Galactic plane and the stellar density therefore is lower than in Serpens.

5. The YSO population

5.1. Colors of the sources

With more than 6000 sources in the final high quality catalog detected in all four IRAC bands it is of great interest to establish general criteria for selecting samples of candidate
Fig. 6.— Differential source counts for a low and high extinction field (black and grey lines, respectively).
Fig. 7.— Differential source counts for all on-cloud sources as in Fig. 5 (grey) and objects which can be classified as stars through fits to their 2MASS and IRAC measurements by a (reddened) photosphere (black). Also shown are the predictions for the star counts from the models of Wainscoat et al. (1992) (black dashed line). An excess of background galaxies is clearly seen at faint magnitudes from the comparison between the distribution of stars from the model predictions and the actual number counts. Note that the fainter stars in the Spitzer observations are not classified as such due to lack of 2MASS data. The difference between the black solid and dashed lines at faint magnitudes therefore reflect the completeness of the 2MASS data rather than an actual discrepancy between the IRAC observations and the model predictions.
young stellar objects. A number of such schemes have been suggested based on IRAC colors alone or in combination with 2MASS or MIPS colors (e.g., Allen et al. 2004; Megeath et al. 2004; Gutermuth et al. 2004; Muzerolle et al. 2004). With the Spitzer observations, a high number of photometric data points are obtained that provide strong constraints on the loci in the color-color and color-magnitude planes characterizing young stellar objects.

A first task is to separate the YSO population from the remainder of the sources toward the cloud, “contaminating the sample”, mainly stars and background galaxies. Figs. 8-10 show color-magnitude and color-color diagrams for the Perseus cloud compared to the off-cloud and catalogs and data from the SWIRE Elais N1 data set (Surace et al. 2004), which is used to estimate the extragalactic component of our catalogs. The SWIRE catalog was processed exactly like the cloud datasets resulting in a catalog consisting of 103557 sources distributed over 6.3 degree². For a better comparison to the Perseus data the SWIRE catalog was trimmed down to the same area as covered by the Perseus observations by randomly selecting sources. The SWIRE data also go somewhat deeper due to longer integration time, so the catalog of SWIRE sources was furthermore trimmed to a similar completeness limit as the Perseus data. In the analysis only sources with high quality detections (as described in Sect. 4.2) have been included. In each of the diagrams the group of stars constitute a distinct group centered around zero colors. Comparing the [8.0] vs. [4.5] − [8.0] color-magnitude diagram for the Perseus on-cloud region to the off-cloud regions and SWIRE data there obviously is a significant excess of sources with [4.5] − [8.0] > 0.5 and [8.0] magnitudes brighter than 14 − ([4.5] − [8.0]) as indicated by the dashed lines in the top right panel. In total, 400 such objects are found that as a first cut represent the candidate YSOs toward Perseus. In the “on-cloud” and, in particular, the SWIRE diagrams a large population of fainter red objects is seen, which are likely dominated by background galaxies. At faint magnitudes the diagram becomes inadequate for separating these three basic group of objects and it becomes necessary to look at the full photometric data for classification. In particular, stars are separated from the remaining objects by fitting a (possibly reddened) photosphere (Lai et al. 2006) as described above.

Some sources do not show an excess in the IRAC bands but do show an excess in the MIPS 24 µm observations discussed by Rebull et al. (2006). The combination of the long wavelength IRAC and MIPS observations are expected to be particularly sensitive to infrared excesses since photospheric colors are expected to be zero and has previously been applied to the selection of young stellar objects (Muzerolle et al. 2004). As above, sources with excesses in the MIPS band can be selected from [24] − [8] > 0.7 and [24] < 12 − ([24] − [8.0]). This selection adds another 37 candidate YSOs to our catalogs. These include objects with faint excesses only detectable at longer wavelengths (i.e., more evolved “Class III” objects). Embedded YSOs, with some degree of PAH emission contributing to the IRAC band 4
emission (shifting them rightward in Fig. 8 to the faint side of the magnitude cut-off) or with certain geometries of their circumstellar envelopes, can also fall into this category, however. Still, this is a small fraction \( \approx 9\% \) compared to our total list of 400 YSO candidates but illustrates how the inclusion of even longer wavelength data adds to the information about the sample of YSOs.

A small fraction, 3–4\%, of the non-star objects in the SWIRE and off-cloud diagrams are bright enough at 8 or 24 \( \mu \text{m} \) to be misclassified as YSOs. If the same fraction applies to the Perseus diagram, about 24 \( \approx 6\% \) of the YSOs in the on-cloud region might in fact be extragalactic objects. This number is an upper limit, though: any extragalactic object will be behind the cloud, extingued, and thus moved in the direction of the extinction vector toward the faint side of the magnitude cut-off (non-vertical, dashed) line in the \([8.0] \) vs. \([4.5] \) diagram in Fig. 8.

Fig. 9 and Fig. 10 show the location of the different groups of sources in two other diagrams that have been used for classifying YSOs from samples of Spitzer sources, the \([3.6] \) vs. \([5.8] \) vs. \([8.0] \) (Megeath et al. 2004) and \( H-K_s \) vs. \( K_s-[4.5] \) (Gutermuth et al. 2004) color-color diagrams. The locations of the YSO candidates agree well with the predicted locations in these two diagrams: in the \([3.6] \) vs. \([5.8] \) vs. \([8.0] \) diagram, the YSOs are expected to fall in a group with colors around \((3.6]-[4.5], [5.8]-[8.0]) = (0.7, 0.5)\) or redder according to Allen et al. (2004) and Megeath et al. (2004). It is also clear, however, that this diagram in itself is not sufficient to separate the YSO candidates from, i.e., the background galaxy populations. In contrast, the \( H-K_s \) vs. \( K_s-[4.5] \) diagram appears to be better suited for selecting YSO candidates. The detected galaxies and stars are largely overlapping with colors close to zero (compare, e.g., to the SWIRE diagram) whereas the YSO candidates have redder \( H-[4.5] \) colors, in particular. The drawback to this diagram is the requirement that the YSOs are all detected at \( H \) and \( K_s \). It turns out that only 280 (70\%) of the YSO candidates have 2MASS associations, i.e., 10\( \sigma \) detections in both \( H \) and \( K_s \) (305 or 76\% of the YSO candidates are associated with 2MASS sources with 5\( \sigma \) detections in \( H \) and \( K_s \)). The sources not detected by 2MASS are likely more deeply embedded sources or brown dwarfs and therefore the selection of YSO candidates using 2MASS criteria is somewhat biased against such objects. One could, on the other hand, suspect that the \( H-K_s \) vs. \( K_s-[4.5] \) diagram would identify sources not included in the other diagrams, given that only detections in IRAC bands 1 and 2 are required. This, however, seems not to be the case as only a few “other” sources are identified in the red part of the diagram - as also shown by the comparison to the off-cloud diagram. The best way to separate faint YSOs from galaxies seems to be with much deeper JHK data.
Fig. 8.— [8.0] vs. [4.5] − [8.0] color-magnitude diagrams based on the high quality catalogs (see text) with the Perseus “on-cloud” regions (left), “off-cloud” region (middle) and trimmed SWIRE catalog (right). In each panel stars have been indicated by dark grey dots, YSO candidates by black plus signs and other sources by light grey dots. The distinction between YSO candidates and other sources was predominantly made based on this diagram with YSO candidates taken from the upper right part of the diagram above and right of the two dashed lines with a few additional sources added based on their [8.0] − [24] colors (see discussion in text). Two extinction vectors are shown corresponding to $A_K = 5$ mag. The gray vector was derived for diffuse ISM regions by Indebetouw et al. (2005). The black vector, appropriate for the dense regions found in molecular clouds and cores, was derived from deep near-infrared and Spitzer observations of dense cores (Huard et al. 2006).

Fig. 9.— [3.6] − [4.5] vs. [5.8] − [8.0] color-color diagram for the “on-cloud” (left), “off-cloud” (middle) and SWIRE (right) fields. Sources, symbols and extinction vectors as in Fig. 8.
5.2. Classification of YSO candidates

With a sample of candidate YSOs selected, a next natural step is to search for trends in evolution between these. The most used classification scheme for YSOs is based on their spectral slope, \( \alpha = \frac{d \log L}{d \log \lambda} \) (Lada 1987), dividing the YSOs into Class I, II and III with increasingly blue SEDs. This classification scheme is thought to represent (roughly) the evolution of YSOs from their embedded protostellar phases through their pre-main sequence stages. The Lada classification scheme has subsequently been expanded with a group of “flat spectrum” YSOs suggested to represent a transitional phase between the Class I and II stages (André & Montmerle 1994; Greene et al. 1994). Earlier in the evolution of low-mass protostars, the so-called “Class 0” objects (André et al. 1993), are thought to represent the most deeply embedded YSOs. This class of objects is defined by the SEDs at submillimeter wavelengths where they emit more than 0.5% of their total bolometric luminosity at wavelengths longer than 350 \( \mu \text{m} \) and not by their mid-infrared signatures: previously these objects were in general not detected at mid-infrared wavelengths. A number of Class 0 objects are known in Perseus and we will return to these in Sect. 6. In the remainder of this section, however, we will not distinguish these deeply embedded protostars from the Class I objects.

For each of the sources in the Perseus YSO catalog, a spectral index is assigned based on its photometry from 2MASS \( K_s \) through MIPS 24 \( \mu \text{m} \). Fig. 11 plots the sources with different spectral indexes in the \([3.6]−[4.5] \) vs. \([5.8]−[8.0] \) diagrams following the division by Greene et al. (1994) where Class I objects have \( \alpha \geq 0.3 \), “flat spectrum” objects have \(-0.3 \leq \alpha < 0.3 \), Class II objects \(-1.6 \leq \alpha < -0.3 \) and Class III objects \( \alpha < -1.6 \). With this scheme 243 of the YSOs in Perseus are classified as Class II, 71 as “flat spectrum” and 54 as Class I YSOs.

Based on a theoretical study, Allen et al. (2004) suggested that the Class II objects, i.e., pre-main sequence stars with disks, would have colors \( 0.0 < [3.6]−[4.5] < 0.8 \) and \( 0.4 < [5.8]−[8.0] < 1.1 \) whereas the Class I objects, i.e., objects still embedded in a circumstellar envelope, would have colors \([3.6]−[4.5] > 0.8 \) and/or \([5.8]−[8.0] > 1.1 \). This division between Class I and II objects is seen to be in good agreement with the \( \alpha \) classification described above for 219 (90\%) of the Class II and 50 (93\%) of the Class I objects. 42 (59\%) of the “flat spectrum” sources fall in the region of Class I objects in the scheme of Allen et al. (2004) and 28 (39\%) in the region of Class II objects underscoring that this group lies between the Class I and II objects. It may not be that surprising that these trends are found, given that the estimate of \( \alpha \) and the color diagrams essentially are based on the same measurements. The classification is also not unambiguous: Class II objects with edge-on disks for example have colors similar to the Class I objects.
A cross-check with the SIMBAD astronomical database reveals that 217 (or 54%) of the YSO candidates from the list in this paper are associated with known objects - almost all YSO-like - within a search radius of 5′′. Expanding the search radius to 10′′ only increases this number slightly to 228. Interestingly only 35% and 39% of the Class I and “flat spectrum” sources are associated with known sources, whereas the numbers for the Class II and III objects are 60% and 72%, respectively. It therefore appears that the new YSO candidates in our catalog are predominantly faint, embedded sources with significant mid-infrared excesses, as should be expected from the high sensitivity of Spitzer compared to previous surveys included in SIMBAD - in particular those based on IRAS data.

Our selection of YSO candidates does not properly identify Class III objects: of our YSO candidates, 32 objects have α <-1.6 consistent with Class III objects (16 of these 32 are selected as YSO candidates on basis of the criterion involving their IRAC4 and MIPS 24 μm colors, a high fraction compared to the only ≈ 9% of the entire YSO population selected in this way). Given that the emission from such objects is largely photospheric and therefore difficult to distinguish from stars, this sample is not complete. Additional data from other wavelengths are necessary to address these issues and properly cross-identifying YSOs (Lai et al. in prep.). One of the goals for c2d is to include such data - also to refine the classification schemes and thus our understanding of the evolution of YSOs.

5.3. Spatial distribution of YSOs

Fig. 12 shows the identified Class I and II YSO candidates plotted over the 4.5 μm IRAC image. The two clusters around NGC 1333 and IC 348 clearly stand out with a high density of sources. Fig. 13 shows the color-color and color-magnitude diagrams for the extended cloud (excluding the clusters) compared to each of these two clusters. The NGC 1333 region was defined as ranging from 03:28:00 to 03:30:00 in Right Ascension and +31:06:00 to +31:30:00 in Declination while the IC 348 region was defined as ranging from 03:43:12 to 03:46:00 in Right Ascension and +31:48:00 to +32:24:00 in Declination (all J2000) including the areas studied in the GTO programs. The numbers of total YSO candidates and numbers of Class I and II objects in each of these regions are summarized in Table 4. Significant differences exist between IC 348, NGC 1333 and the remaining cloud. The two clusters contain similar numbers of YSO candidates and contain about half of the total YSO candidates in the surveyed area. The spatial density of YSO candidates is 5–6 times higher in each of the clusters compared to the extended cloud. In the extended cloud most of the YSOs appear to be following the extinction with concentrations of predominantly Class I objects around B1, B5, L1448 and L1455 and an additional number of Class II objects about 40′ southwest of
the main concentration of sources in IC 348. Cambrésy et al. (2006) recently suggested the existence of a cluster separate from the main IC 348 cluster at this location through maps of the spatial density of sources derived from 2MASS data. This cluster is not included in the statistics for IC 348 below but rather together with the remaining cloud.

Table 4 also shows that there is a significant difference in the relative numbers of Class I/“flat spectrum” and Class II objects among the two clusters and the extended cloud with the more embedded Class I objects being more numerous in NGC 1333 compared to IC 348 whose YSO population predominantly consist of Class II YSOs. A difference between the two clusters is consistent with near-infrared studies suggesting an age of about 2 Myr for IC 348 (Luhman et al. 2003) and < 1 Myr for NGC 1333 (Lada et al. 1996; Wilking et al. 2004). The relative number of Class I and “flat spectrum” objects compared to the overall YSO candidates is significantly higher in the extended cloud compared to these two clusters, however, suggesting that a significant fraction of the recent and current star formation in Perseus is going on in the extended cloud including the smaller groups surrounding B1, L1455 and L1448. In fact 61% of the Class I YSOs toward Perseus are located outside the two main clusters compared to only 28% of the Class II YSOs. Even within the group of Class I and “flat spectrum” sources it seems that the extended cloud contains more of the red Class I objects compared to the numbers in NGC 1333. A more detailed study of the clustering properties of the different groups of YSOs in these regions - and comparison to other similar selections of YSOs in other cloud regions - could shed further light on differences in YSOs formed in large clusters compared to objects formed in small groups or in relative isolation.
Fig. 10.— As in Fig. 8 and 9 but for a $H-K_s$ vs. $K_s-4.5$ color-color diagram. All sources with high quality detections in the IRAC bands 1 and 2 (see text) and 10σ detections in $H$ and $K_s$ included. Otherwise sources and symbols as in Fig. 8 and 9; extinction vectors shown are for $A_K = 2$ mag.
Fig. 11.— [3.6]−[4.5] vs. [5.8]−[8.0] color-color diagrams for the YSO sample. The symbols are colored according to their classification based on their spectral slope $\alpha$ ($\alpha = \frac{d \log F_{\lambda}}{d \log \lambda}$) in the scheme of Lada (1987): Class I objects ($\alpha \geq 0.3$) and “flat spectrum” ($-0.3 \leq \alpha < 0.3$) sources are shown in the left panel with grey and black symbols, respectively. Likewise Class II ($-1.6 \leq \alpha < -0.3$) and Class III objects ($\alpha < -1.6$) are shown in the right panels with grey and black symbols, respectively. The box delineating Class II objects from Allen et al. (2004) has furthermore been indicated in the right panel (black/grey dashed rectangle).
Fig. 12.— Distribution of Class I objects (upper) and Class II objects (lower) plotted on top on a 4.5 μm image of Perseus with an extinction map overlay (see also Fig. 3). The adopted boundaries for IC 348 and NGC 1333 have been indicated by the dashed lines.
|                       | Total surveyed area | IC 348  | NGC 1333 | Remaining cloud |
|-----------------------|---------------------|---------|----------|-----------------|
| Area                  | 3.86 deg$^2$        | 0.36 deg$^2$ | 0.17 deg$^2$ | 3.33 deg$^2$   |
| YSO candidates        | 400                 | 158     | 98       | 144             |
| YSOs per sq. degree   | 103.6               | 438.9   | 576.5    | 43.2            |
| Class I               | 54 (14%)            | 11 (7%) | 10 (10%) | 33 (23%)        |
| “Flat spectrum”       | 71 (18%)            | 11 (7%) | 25 (26%) | 35 (24%)        |
| Class II              | 243 (61%)           | 116 (73%) | 58 (59%) | 69 (48%)        |
| Class III             | 32 (8%)             | 20 (13%) | 5 (5%)   | 7 (5%)          |

Table 4: Number of YSO candidates in IC 348 and NGC 1333 compared to the remaining cloud. Numbers in parentheses indicate the relative fraction of YSOs of different classes compared to the total number of YSOs in the specific regions.
6. Deeply embedded protostars and associated outflows

Perhaps the most spectacular features in the maps are the prominent outflows clearly seen in bands 2 and 3 where molecular hydrogen emission from shocked gas dominates. Fig. 14 shows band 2 images of a selection of the outflows outside the two main clusters in Perseus. Since the outflow activity is thought to be related to the accretion onto the central star/disk system, it has been suggested that sources with such strong outflow activity represented the earliest, most deeply embedded stages of low-mass protostellar evolution (Bontemps et al. 1996), the Class 0 stage (André et al. 1993). On the other hand, the exact same outflows pose a problem for the source catalogs above. The deeply embedded protostars driving these outflows likely show extended emission at 4.5 and 5.8 \( \mu m \) from which it may be problematic to extract the embedded sources.

6.1. L1448

Fig. 14a shows the outflows in the L1448 region with known embedded protostars over-plotted. The L1448-C source is one of the best studied Class 0 protostars at a range of wavelengths and is known to drive a parsec scale outflow in the North-South direction. This outflow is clearly identified in our maps extending to the north where the outflow emission makes a break at the positions of another known Class 0 protostar, L1448-N (or L1448-IRS3). L1448-N is a binary with a separation of about 7\( \prime \) (e.g., Looney et al. 2000). Two sources are seen at the position of L1448-N(A) and L1448-N(B) with the Eastern, L1448-N(A), corresponding to the brighter source in the IRAC maps with the exception of band 1 (Fig. 15). Interestingly the western source, L1448-N(B), is the stronger of the two in 2.7 mm observations by Looney et al. (2000). The Spitzer maps also show some indication of two fan-shaped outflows emerging from the central source in the north direction, and separating the point source fluxes is subject to significant uncertainties. Only faint extended emission is seen at the location of a third source, L1448-NW (L1448-IRS3C), northwest of the L1448-N(A) and -N(B). Almost parallel to the L1448-C outflow, about 8\( \prime \) to the west, the outflow from the Class 0 source L1448-IRS2 (O’Linger et al. 1999) is seen. Another outflow is observed close to L1448-IRS2 in the north-west direction. This outflow is associated with the L1448-IRS1 source, which is located outside our mosaic in IRAC bands 2 and 4 but clearly identified in bands 1 and 3. The outflows from L1448 are likely extending even further south: between L1455 and L1448 two prominent knots associated with shocked gas are identified at (03:25:51; +30:35:13) and (03:26:04; +30:39:02), the latter is associated with HH 277, and further south at the position of HH 278 (03:26:59; +30:25:58) pointing back toward the L1448 region. Shocks are seen on similar scales pointing back toward the NGC 1333 region.
Fig. 13.— Color-color and color-magnitude diagrams from the extended cloud excluding NGC 1333 and IC 348 (left), NGC 1333 only (middle) and IC 348 only (right). As in Fig. 8-10 stars have been indicated by dark grey dots, YSO candidates by black plus signs and other sources by light grey dots.
Fig. 14.— Images of outflows in Perseus in band 2. Upper panels, L1448 (left) and B1 (right). Lower panels: B1-ridge (left) and L1455 (right). In the L1448 panel the location of L1448-IRS1 (seen in the band 1 and 3 images) is indicated with a black star. In the B1-ridge panel the directions of the outflows from IRAS 03292-3039 and IRAS 03282-3035 are indicated by black arrows. Similar arrows are shown for L1455-IRS1 and L1455-IRS4 in Fig. 16 where the location of HH 318 also is indicated.
in our maps around the position of HH 746 at (03:28:32; +30:52:10).

Toward L1448-C, two sources are clearly seen in the IRAC images separated by about 8\arcsec (Fig. 15), which we will refer to as L1448-C(N) (at the position of the millimeter source L1448-mm) and L1448-C(S). Of these only one source is identified in all four IRAC bands in our source extraction. The source recognized from millimeter interferometric observations as the driving source of the outflow - and which is detected in the millimeter continuum interferometric measurements - is only detected in IRAC band 3 and MIPS 24 \( \mu \)m by the source extraction software even though it is clearly identified as a separate point source. The reason is likely the confusion with the extended emission from the outflows in the other bands. We extract a flux for this source from aperture photometry in a 2 pixel radius (2.4\arcsec) aperture with a sky annulus extending from 2 to 6 pixels (2.4\arcsec to 7.2\arcsec) using the aper procedure from the IDL Astronomy User’s library. L1448-IRS2 also does not make it to the high quality catalog; it shows extended emission in IRAC2 and IRAC3 and is therefore not included in our high quality catalog used in the color-color and color-magnitude diagrams above. The source extractor does identify this source and it is included in the overall catalog of sources from c2d.

### 6.2. L1455

The outflows in L1455 pose an interesting puzzle. Previously three young stellar objects had been identified in this region (Juan et al. 1993): L1455-IRS1 (IRAS 03245+3002), L1455-IRS2 (IRAS 03247+3001) and L1455-IRS3 (IRAS 03249+2957). L1455-IRS2 is driving a North-South outflow and associated with the red nebular object, RNO 15. An outflow is stretching roughly northwest-southeast in CO observations (Goldsmith et al. 1984) and is likely associated with a number of Herbig-Haro objects (Bally et al. 1997). The driving source of this outflow is not clear: Juan et al. (1993) suggested that L1455-IRS1 was the driving source of the entire complex CO outflow observed by Goldsmith et al. (1984), but Bally et al. (1997) argued that two separate outflows had to be responsible for the NW/SE outflow and an outflow extending in the East-West direction (also responsible for HH 317). Indeed Davis et al. (1997) showed from CO 3–2 observations that L1455-IRS1 was associated with an outflow in the NE/SW direction and likely responsible for HH 318.

In the IRAC2 image the NW/SE outflow is clearly identified together with a number of the Herbig-Haro objects observed by Bally et al.: HH 279 (03:27:19; +30:17:16), HH 317 (03:27:11; +30:11:59) and HH 318 (03:27:44.6; +30:14:17). In addition a nebulosity is seen south of HH 279 delineating the southern part of the blue-shifted lobe of the CO outflow. About 15\arcmin south-west of the central L1455 cluster another nebulosity is seen, which could
Fig. 15.— Zoom-in on the IRAC2 image around L1448-C and L1448-N (note that the scaling of the image is slightly different from Fig. 14). The separation of L1448-N into L1448-N(A) and L1448-N(B) and L1448-C into L1448-C(S) and L1448-C(N) is clearly seen.
represent the other lobe of the NW/SE outflow. Two additional infrared sources are observed close to L1455-IRS1 and -IRS2: one in between the two sources, which we name L1455-IRS4\(^1\) and one slightly northwest of L1455-IRS1 which we name L1455-IRS5. The close proximity of these sources suggest an interaction, which may have caused the precession of the NE/SW outflow as discussed by Davis et al. (1997). Of the four sources, L1455-IRS2 is clearly the strongest at mid-infrared wavelengths followed by L1455-IRS5. On the other hand L1455-IRS1 and L1455-IRS4 are associated with the strongest dust continuum peaks in maps of the (sub)millimeter emission as shown in a map at 350 \(\mu\)m taken with the SHARC II bolometer array at the Caltech Submillimeter Observatory (Fig. 16; J. Wu et al., (in prep.) - see also Hatchell et al. (2005) and Enoch et al. (2006)). From the color criteria discussed above, L1455-IRS1 and L1455-IRS4 would both fall in the Class I group whereas L1455-IRS2 and L1455-IRS5 would be more evolved Class II objects. It is therefore also likely that L1455-IRS1 and L1455-IRS4 are responsible for the NE/SW and NW/SE outflows respectively and their association with the dust continuum peaks furthermore suggest their deeply embedded natures. L1455-IRS3 is likewise classified as a Class I source but no continuum peak is seen toward this source in the SCUBA maps of Hatchell et al. (2005) (unfortunately it falls just outside the field observed by Enoch et al. (2006)). A companion, L1455-IRS6, is seen 40'' north of L1455-IRS3 with an SED typical of a Class II source. Of the two candidate embedded protostars, L1455-IRS1 and L1455-IRS4, L1455-IRS1 has full photometry in our high quality catalog from 3.6 to 24 \(\mu\)m whereas L1455-IRS4 only is recognized at the two longer wavelengths.

Finally, two knots are seen at (03:26:27; +30:16:01) and (03:26:49; +30:14:54) in the IRAC2 maps associated with HH 280 and HH 493 distributed symmetrically on a east/southeast-west/northwest axis through IRAS 03235+3004 which Walawender et al. (2004) suggested was the driving source of this outflow. IRAS 03235+3004 is detected as a candidate Class I object in our catalogs and associated with a strong continuum peak in the maps of Hatchell et al. (2005) and Enoch et al. (2006).

6.3. B1 and beyond

Finally we would like draw the attention to the outflow activity around the B1 region which has recently received much attention as one of the very active regions of star formation in the Perseus complex with a number of submillimeter clumps with embedded protostars and Herbig-Haro objects (Hirano et al. 1999; Matthews & Wilson 2002; Walawender et al.\(^1\))

\(^1\)Note that Froebrich (2005) erroneously identified a source close to this position with the RNO 15 nebula.
Fig. 16.— Zoom-in on the IRAC2 image of the central region of L1455 from Fig. 14. Overlaid in white contours are a 350 μm continuum image from the SHARC II bolometer array at the Caltech Submillimeter Observatory (J. Wu, in prep.). The contours are plotted at 15%, 30%, 45%, . . . of the peak flux (at the position of L1455-IRS1). The approximate directions of the outflows from L1455-IRS1 and L1455-IRS4 are indicated by black arrows.
A number of these prominent outflows are observed in the IRAC data. The most striking is the precessing outflow clearly associated with the B1-c source. This source stands out very clearly in the RGB image (Fig. 2) with a very red color suggesting the embedded nature of this object. Of the other sources in this region, B1-a shows extended emission that dominates the source at 3.6 μm. The source is therefore not included in the high quality catalog used for the color-magnitude diagrams above.

The B1-b and B1-d submillimeter cores suggest an interesting interaction: toward the B1-b position a point source with colors consistent with an embedded YSO is clearly seen with a jet extending southwest of the core toward the position of the other submillimeter core, B1-d. On the other side of this core the jet seems to be making a break and thereafter extends further south with weaker emission. The break occurs at the exact position of the B1-d submillimeter core suggesting some interaction between the outflows and the core. An outflow extending from a source embedded in the B1-d core can of course also not be ruled out: no point source is seen in the IRAC bands but a faint MIPS source is seen toward the position of the submillimeter core. Previously no outflow had been associated with the B1-b sources, but this may have been due to the confusion in the region. Based on maps of the dust continuum emission from SCUBA and 3 mm interferometric measurements from the Nobeyama Millimeter Array, B1-b was found to be a binary by Hirano et al. (1999) with a separation of ≈ 20″, but it does not show up as two separate sources in the Spitzer images.

In addition to these sources the emission line star, LkHα327, is clearly the strongest source in the IRAC bands located northwest of the submillimeter cores. LkHα327 is identified as a Class II object by our criteria. Four additional candidate Class I YSOs are identified southwest of the main concentration of submillimeter cores. These sources are weak compared to the sources associated with the central cores, but might be associated with faint dust continuum emission.

The region southwest of the main B1 core, the B1-ridge, is also interesting with two strong outflows associated with the two IRAS sources, IRAS 0328+3035 and IRAS 03292+3039. Both of these sources are associated with peaks in dust continuum emission in the maps of Hatchell et al. (2005) and Enoch et al. (2006), but neither is picked up in the high quality catalog above. A weak IRAC source is associated with IRAS 0328+3035 which is somewhat extended in a number of the IRAC bands. IRAS 03292+3039 is not detected in IRAC band 1 by the source extraction algorithm but recognized as a faint (1.2 mJy) source with an arcshaped nebulosity in the images. In addition to these two candidate deeply embedded protostars, two other IRAS sources, IRAS 03281+3039 and IRAS 03276+3042 are found in this region. The former was previously classified as a candidate galaxy based on its IRAS colors (de Grijp et al. 1987), but has colors consistent with a Class I YSO in our data. It
is located in close proximity to a group of HH filaments, HH 770, 771 and 772 (Walawender et al. 2005) and a group of sources classified as Class II objects in our analysis. It shows strong emission at all IRAC and MIPS wavelengths and is detected in 2MASS, but is not associated with any dust continuum peaks. The latter, IRAS 03276+3042, is likely associated with a candidate Class II source from our catalog also detected at all wavelengths.

6.4. Colors of embedded protostars

As discussed above, each of the known Class 0 objects discussed above is driving outflows. Table 6.4 lists the mid-infrared measurements of each of the Class 0 objects, together with the candidate outflow driving sources discussed above. This compilation does not include sources in the areas covered by the guaranteed time observations of NGC 1333 and IC 348 discussed by Gutermuth et al. (2006) and Lada et al. (2006). The detection of mid-infrared counterparts for these deeply embedded protostars nicely demonstrates the high sensitivity of the Spitzer observations, since previously only a few deeply embedded protostars had been measured in the mid-infrared. Fig. 17 singles these objects out in the $[3.6] - [4.5]$ vs. $[5.8] - [8.0]$ diagrams and Fig 18 shows the SEDs of each of them. Each of these objects would easily be picked out as Class I objects from this diagram with IRAS 03292+3039 at the bluest end of the distribution. These objects actually are somewhat separate from the overall population of Class I objects with in general the reddest colors. It is clear from the diagram that the Class 0 objects have much redder $[3.6] - [4.5]$ colors than $[5.8] - [8.0]$ colors. In the models of Allen et al. (2004) the explanation is that the 10 µm silicate absorption feature overlaps with the IRAC4 (8.0 µm) band. Objects with progressively more massive envelopes will have an increasing silicate absorption feature and therefore less red $[5.8] - [8.0]$ colors, as the 8.0 µm flux is absorbed. The objects in Fig. 17 fall outside the range spanned by the models of embedded YSOs by Allen et al. (2004) with even redder $[3.6] - [4.5]$ colors. Judging from the diagrams of Allen et al. (2004) this could imply larger values of the centrifugal radius (300 AU) which would provide less line of sight absorption, similar to the modeling results of the Class 0 protostar IRAS 16293-2422 (Jørgensen et al. 2005). However, we emphasize that this is based on simple 1D models not taking the more detailed source structures into account. Whitney et al. (2003) for example showed that the presence of outflow cavities likewise would lead to bluer colors - although this effect should be important for both $[5.8]-[8.0]$ and $[3.6]-[4.5]$ colors according to the models of Whitney et al. (2003). Additional factors important for these colors could also be that the (proto)stellar photosphere starts dominating at shorter wavelengths: this could cause a double peaked structure of the SED and can explain the SEDs that have a turnover between the IRAC2 and IRAC3 measurements (Fig. 18). Also the contribution from the shocked H$_2$ emission
to the 4.5 \( \mu m \) band or deep absorption due to ice features included in the IRAC bands will affect the interpretation of these colors. Combinations of all these effects could be the explanation for the scatter seen in the \([5.8] - [8.0]\) colors of the Class 0 objects in Fig. 17. A more detailed dust radiative transfer treatment of the full SED from mid-infrared through (sub)millimeter wavelengths for individual objects is needed to shed further light on these issues.

The above discussion also illustrates that some of these potentially very interesting objects may not be singled out directly by the source extraction procedures due to confusion with nearby sources and extended \( \text{H}_2 \) emission. Of the 13 known protostars listed in Table 6.4 only 5 (L1448-C(S), L1455-IRS1, B1-b, B1-c and IRAS 03235+3004) are included in the high quality catalog (Sect. 4.2). It should also be emphasized that the above discussion is not a complete or an exhaustive discussion of all the information available about the outflows in the IRAC maps. For example, information about the shock structure could be obtained by comparing the ratios between the fluxes in different bands. This is outside the scope of this paper, however.
Fig. 17.— As the left panel of Fig. 11 (Class I objects with grey and “flat spectrum” sources with black symbols) but including the candidate deeply embedded protostars (plus signs).
Fig. 18.— Overview of the 3.6–24μm SEDs for each of the Class 0 objects from Table 6.4 with additional 70 and 160 μm fluxes from Spitzer/MIPS observations from c2d (Rebull et al. 2006). Note: we assume that L1448-C(N) and L1448-C(S), L1448-N(A) and L1448-N(B), respectively each contribute half of their observed MIPS fluxes and therefore the plotted value for each corresponds to half the number listed in Table 6.4.
Table 5. Deeply embedded objects/outflow driving sources in Perseus with IRAC and MIPS 24 fluxes. For details about the MIPS data see Rebull et al. (2006).

| Source        | RA        | DEC        | $S(3.6\ \mu m)$ [mJy] | $S(4.5\ \mu m)$ [mJy] | $S(5.8\ \mu m)$ [mJy] | $S(8.0\ \mu m)$ [mJy] | $S(24\ \mu m)$ [mJy] |
|--------------|-----------|------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| L1448-C(N)$^a$ | 03:25:38.9| +30:44:06.0| 4.2±0.4                | 13.5±0.8               | 11.7±0.8               | 19.6±1.2               | 1560±43                |
| L1448-C(S)    | 03:25:39.1| +30:43:58.9| 2.5±0.08               | 23.6±0.6               | 77.2±0.8               | 123±1                  | 485±4                  |
| L1448-IRS2    | 03:25:22.4| +30:45:13.6| 0.31±0.02              | 2.8±0.2                | 4.5±0.2                | 10.2±0.1               | 3530±104               |
| L1448-N(A)    | 03:25:36.5| +30:45:23.2| 1.2±0.2                | 10.5±0.3               | 43.0±0.5               | 124±1                  | 1560±43                |
| L1448-N(B)    | 03:25:36.2| +30:45:17.1| 1.6±0.3                | 4.7±0.5                | 5.9±0.6                | 57±2                   | 1560±30                |
| B1-a$^c$      | 03:33:16.7| +31:07:55.1| 5.4±0.3                | 50.0±0.6               | 84.6±0.5               | 105±0.9                | 1560±30                |
| B1-b          | 03:33:29.3| +31:07:21.4| 4.1±0.04               | 16.8±0.1               | 25.0±0.2               | 29.6±0.2               | 164±2                  |
| B1-c          | 03:33:17.9| +31:09:31.8| 0.17±0.004             | 6.6±0.08               | 34.3±0.2               | 90.3±0.8               | 676±10                 |
| L1455-IRS1    | 03:27:39.1| +30:13:02.8| 0.64±0.02              | 8.7±0.2                | 18.8±0.3               | 23.3±0.1               | 1760±34                |
| L1455-IRS4    | 03:27:43.3| +30:12:28.9| 0.76±0.03              | 3.4±0.1                | 13.6±0.2               | 25.0±0.2               | 761±9                  |
| IRAS 03235+3004$^c$ | 03:26:37.5| +30:15:28.2| 1.6±0.07               | 9.9±0.1                | 11.2±0.08              | 11.1±0.04              | 400±3                  |
| IRAS 03282+3035 | 03:31:21.0| +30:45:30.0| 0.17±0.006             | 0.66±0.02              | 0.74±0.02              | 14.6±0.2               | 3530±104               |
| IRAS 03292+3039 | 03:32:18.2| +30:49:46.9| 1.4±0.2                | 2.3±0.1                | 2.7±0.07               | 1.4±0.04               | 13.1±0.1               |

$^a$L1448-C(N) is also referred to as L1448-C and L1448-mm in the literature, being associated with a strong millimeter source in aperture synthesis observations (see discussion in text).

$^b$L1448-C(N) and L1448-C(S) are not separated by the source extraction software at MIPS 24 µm. Likewise for L1448-N(A) and L1448-N(B).

$^c$B1-a and IRAS 03235+3004 are detected by 2MASS in the $K_s$ band: B1-a with a $K_s$ flux of 1.4±0.1 mJy (upper limits of 0.089 mJy in $J$ and 0.38 mJy in $H$) and IRAS 03235+3004 with a $K_s$ flux of 1.2±0.08 mJy (upper limits of 0.18 mJy in $J$ and 0.50 mJy in $H$). None of the remaining sources have 2MASS associations.
7. Summary

We have presented a survey of 3.86 square degrees of the Perseus cloud at 3.6, 4.5, 5.8 and 8.0 \(\mu m\) using the Spitzer Space Telescope Infrared Array Camera (IRAC). More than 120,000 sources are identified across the field. Based on their mid-infrared colors and comparison to off-cloud and extragalactic control fields, 400 candidate young stellar objects are identified in this sample. About two thirds of these YSO candidates are located in two clusters, NGC 1333 and IC 348, constituting 14\% of the surveyed area. The young stellar objects are divided into Class I and II objects using the slope of their SEDs from their 2MASS \(K_s\) through IRAC and MIPS 24 \(\mu m\) fluxes: a clear difference is seen with few embedded Class I and “flat spectrum” YSOs in IC 348 (14\% of the YSO population) compared to NGC 1333 (36\% of the YSOs) and the remaining, extended cloud (47\% of the YSOs). This suggests an evolutionary difference, with NGC 1333 consisting of a younger population of YSOs compared to IC 348 (consistent with previous near-infrared observations) but also that a significant fraction of the current star formation might be going on outside these clusters in the extended cloud where 61\% of the Class I objects toward Perseus are found. Finally we discuss a number of the outflows showing up predominantly through shocked \(H_2\) emission in the IRAC2 maps and identify the mid-infrared counterparts for the deeply embedded Class 0 objects in the region. All known Class 0 objects in Perseus have mid-infrared counterparts. The Class 0 objects are found to have very red \([3.6] - [4.5]\) colors compared to \([5.8] - [8.0]\) colors, but are spread out over a wide range of colors in this diagram.

We are grateful to the staff at the Lorentz Center at Leiden University for hospitality during a three week meeting in July 2005 where a large part of this work was pursued. We thank Mike Dunham for supplying the SHARC II image of the L1455 region. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. The research of JKJ was supported by NASA Origins Grant NAG5-13050. Support for this work, part of the Spitzer Legacy Science Program, was also provided by NASA through contract 1224608, 1230782, and 1230779 issued by the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract 1407. Astrochemistry in Leiden is supported by a NWO Spinoza grant and a NOVA grant. KEY was supported by NASA under Grant NGT5-50401 issued through the Office of Space Science. The SHARC II data were obtained with support from NASA Origins grant NNG04GG24G to NJE.

REFERENCES

Allen, L. E., et al. 2004, ApJS, 154, 363
Andersson, B.-G., Wannier, P. G., Moriarty-Schieven, G. H., & Bakker, E. J. 2000, AJ, 119, 1325

André, P., & Montmerle, T. 1994, ApJ, 420, 837

André, P., Ward-Thompson, D., & Barsony, M. 1993, ApJ, 406, 122

Bally, J., Devine, D., Alten, V., & Sutherland, R. S. 1997, ApJ, 478, 603

Bontemps, S., André, P., Terebey, S., & Cabrit, S. 1996, A&A, 311, 858

Cambrésy, L., Petropoulou, V., Kontizas, M., & Kontizas, E. 2006, A&A, 445, 999

Černis, K. 1990, Ap&SS, 166, 315

Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, ApJ, 547, 792

Davis, C. J., Eislöffel, J., Ray, T. P., & Jenness, T. 1997, A&A, 324, 1013

de Grijp, M. H. K., Lub, J., & Miley, G. K. 1987, A&AS, 70, 95

de Zeeuw, P. T., Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blaauw, A. 1999, AJ, 117, 354

Enoch, M., et al. 2006, ApJ, 638, 293

Evans, N. J., et al. 2003, PASP, 115, 965

Evans, N. J., et al. 2005, "Delivery of Data from the c2d Legacy Project: IRAC and MIPS (Pasadena, SSC)"

Fiedler, R., Pauls, T., Johnston, K. J., & Dennison, B. 1994, ApJ, 430, 595

Froebrich, D. 2005, ApJS, 156, 169

Goldsmith, P. F., Snell, R. L., Hemeon-Heyer, M., & Langer, W. D. 1984, ApJ, 286, 599

Greene, T. P., Wilking, B. A., André, P., Young, E. T., & Lada, C. J. 1994, ApJ, 434, 614

Gutermuth, R., et al. 2006, ApJ, in prep.

Gutermuth, R. A., Megeath, S. T., Muzerolle, J., Allen, L. E., Pipher, J. L., Myers, P. C., & Fazio, G. G. 2004, ApJS, 154, 374

Harvey, P., et al. 2006a, ApJ, in prep.
Harvey, P., et al. 2006b, ApJ, in press.

Hatchell, J., Richer, J. S., Fuller, G. A., Qualtrough, C. J., Ladd, E. F., & Chandler, C. J. 2005, A&A, 440, 151

Hirano, N., Kamazaki, T., Mikami, H., Ohashi, N., & Umemoto, T. 1999, in Proceedings of “Star Formation 1999”, ed. T. Nakamoto, 181

Huard, T., et al. 2006, ApJ, in prep.

Indebetouw, R., et al. 2005, ApJ, 619, 931

Jørgensen, J. K., et al. 2005, ApJ, 631, L77

Juan, J., Bachiller, R., Koempe, C., & Martin-Pintado, J. 1993, A&A, 270, 432

Lada, C., et al. 2006, AJ, 131, 1574

Lada, C. J. 1987, in IAU Symp. 115: Star Forming Regions (D. Reidel Publishing Co., Dordrecht), Vol. 115, 1

Lada, C. J., Alves, J., & Lada, E. A. 1996, AJ, 111, 1964

Lada, E. A., & Lada, C. J. 1995, AJ, 109, 1682

Ladd, E. F., Lada, E. A., & Myers, P. C. 1993, ApJ, 410, 168

Lai, S.-P., et al. 2006, ApJ, in prep.

Looney, L. W., Mundy, L. G., & Welch, W. J. 2000, ApJ, 529, 477

Luhman, K. L., Stauffer, J. R., Muench, A. A., Rieke, G. H., Lada, E. A., Bouvier, J., & Lada, C. J. 2003, ApJ, 593, 1093

Matthews, B. C., & Wilson, C. D. 2002, ApJ, 574, 822

Megeath, S. T., et al. 2004, ApJS, 154, 367

Muzerolle, J., et al. 2004, ApJS, 154, 379

O’Linger, J., Wolf-Chase, G., Barsony, M., & Ward-Thompson, D. 1999, ApJ, 515, 696

Padoan, P., Bally, J., Billawala, Y., Juvela, M., & Nordlund, A. 1999, ApJ, 525, 318

Rebull, L., et al. 2006, ApJ, in prep
Ridge, N. A., et al. 2006, ApJ, in press. (astro-ph/0601692)
Sargent, A. I. 1979, ApJ, 233, 163
Schnee, S. L., Ridge, N. A., Goodman, A. A., & Li, J. G. 2005, ApJ, 634, 442
Surace, J. A., et al. 2004, VizieR Online Data Catalog, 2255, 0
Wainscoat, R. J., Cohen, M., Volk, K., Walker, H. J., & Schwartz, D. E. 1992, ApJS, 83, 111
Walawender, J., Bally, J., Kirk, H., & Johnstone, D. 2005, AJ, 130, 1795
Walawender, J., Bally, J., Reipurth, B., & Aspin, C. 2004, AJ, 127, 2809
Whitney, B. A., Wood, K., Bjorkman, J. E., & Wolff, M. J. 2003, ApJ, 591, 1049
Wilking, B. A., Meyer, M. R., Greene, T. P., Mikhail, A., & Carlson, G. 2004, AJ, 127, 1131
Young, K. E., et al. 2005, ApJ, 628, 283