The COMPLETE Nature of the Warm Dust Shell in Perseus

Abstract

We propose to make IRAC and MIPS observations of a remarkable warm dust shell in the Perseus molecular cloud complex region. The shell is clearly visible as a complete, almost perfectly circular ring of emission in IRAS images of the region, and dominates over emission from the cloud complex itself at all of the IRAS bands. Limited previous observations of the shell have shown it is most likely an expanding H\textsc{i} region or stellar wind from the early B-star HD278942, one of the nearest known massive stars. Our proposed Spitzer observations will enable us to construct a 3-color 4.5/8/24\textmu m composite image, from which we will be able to clearly differentiate between shocked material, the photo-dissociation front of the H\textsc{i} region and warm material within. Longer wavelength MIPS observations will enable us to accurately determine the mass and temperature of the material in the shell. The presence of shocks and/or photo-dissociation regions combined with atomic and molecular line observations already obtained as part of the COMPLETE Survey of Star-Forming Regions will help us determine what effect the shell has had on star-formation in the molecular cloud complex.

Background

The interaction of newly formed stars with their parent cloud, particularly in the case of massive stars, can have significant consequences for the subsequent development of the cloud. While supernovae and bipolar outflows have received much attention in this regard, the energy input from B-star winds may be as (or more) important over the lifetime of a molecular cloud. (e.g. Matzner 2002).

The Perseus Molecular Cloud complex has a mass of ~1.3x10\textsuperscript{4} M\textsubscript{Sun} at a distance of 260pc, although actual distance estimates range from 230pc (Cernis 1990) to 350pc (Herbig & Jones 1983). Star formation is ongoing in several parts of the complex, most obviously around the two reflection nebulae IC348 and NGC1333. Several surveys (e.g. Ladd, Lada & Myers 1993, Lada & Lada 1995, Aspin, Sandell & Russell 1994) have established that there is a population of pre-main sequence stars located both within the clusters and throughout the complex, but relatively few high-mass stars have been found. The molecular cloud complex is a target of the Spitzer Legacy program “From Molecular Cores to Planet Forming Disks” (hereafter c2d; Evans et al. 2003), while the two clusters NGC1333 and IC348 are included in a Spitzer GTO program. These programs aim to determine the distribution of young stars and clusters, and investigate their association with known dense cores.

The ongoing COMPLETE\textsuperscript{1} Survey has coordinated its observations with the c2d program. COMPLETE provides a comprehensive multiwavelength database of observations complementary to c2d, including large scale molecular line, submillimeter continuum and near-infrared extinction maps of Perseus.

However, the Perseus complex is not just interesting for its star-forming properties. An almost complete shell of enhanced emission can be seen in IRAS data toward the center of the molecular cloud complex (fig. 1a). The shell has a radius of 0.75\textdegree, or 10pc at the distance of the molecular cloud. Although its existence has been known for almost 15 years\textsuperscript{2} — it was first described by Pauls & Schwartz (1989) in a conference proceedings and further discussed by Fiedler et al. (1994) — it has been mostly ignored by studies of star-formation in the region. Based on radio data, Fiedler et al. argued that the feature is caused by a supernova remnant (SNR), which if true, would have the highest known Galactic latitude for such an object. More recently de Zeeuw et al. (1999) associated the shell with the B star HD 278942, located at its geometric center. Andersson et al. (2000) performed a multi-wavelength study of the star and its surroundings. They reclassified HD 278942 as an O9.5—B0 V star with an age of 8Myr, and found weak radio continuum emission with a spectral index consistent with an optically thin H\textsc{i} region filling the shell. At its Hipparcos distance of 207±52pc, HD278942

\textsuperscript{1} CoOrdinated Molecular Probe Line, Extinction and Thermal Emission; http://cfa-www.harvard.edu/COMPLETE

\textsuperscript{2} In fact, a careful eye would spot an approximately circular region of faint nebulosity filling the area of the IRAS ring in optical photographs published by Barnard in 1907!
would be the most massive and luminous star in the region, and would likely have an important impact on the star forming gas.

As part of the COMPLETE Survey, we have recently recalibrated 60 and 100µm IRAS Sky Survey Atlas (ISSA) maps of the Perseus region, and used them to create new high-sensitivity temperature and thermal-emission maps (fig. 1a; Schnee et al, in prep.). The shell is clearly seen as an enhancement in column density (left panel). Although on careful inspection, the known dark cores in Perseus are visible in our thermal emission map, the general morphology is very different from molecular line or extinction maps of the region (right panel), which are likely to provide a more reliable estimate of the true column-density distribution. In the right panel (fig. 1b) we show Hα emission overlaid with contours of visual extinction. The Hα emission filling the shell confirms that it is an H II region, and is clearly located behind the molecular cloud material.

There is no evidence for an enhancement in true column density at the position of the shell in either our CO observations (Ridge et al., submitted) or in our 2MASS/NICER extinction maps. The extinction map shows the more familiar view of Perseus as a chain of molecular clouds.

---

**Figure 1:**

a) Dust thermal emission (interpreted here in units of \(A_V\)) in the Perseus region, constructed from IRAS 60 and 100µm images. The positions of the well-known star-forming regions IC348 and NGC1333 are indicated. The cross marks the position of the B0 star HD278942. b) Hα emission (from Skyview), indicating the shell is likely due to an H II region, overlaid with contours of visual extinction (calculated using the NICER technique).

**Figure 3:** 8.3µm image of the shell from MSX. The bright region to the east of the shell is the IC348 star-forming cluster.
Spitzer Cycle-2 GO Proposal

map (fig. 1b). The shell appears so dominant in the IRAS maps because it is warm.

The shell was the subject of a pointed observation by the Midcourse Space Experiment (MSX) satellite, which provided images at four mid-infrared wavebands. It was clearly detected in the first two bands at 8.3µm (figure 3) and 12.1µm (Kraemer et al. 2003). The non-detection in the 14.7 and 21µm bands is most likely due to the lower sensitivity of those bands, as it is clearly present in the 12 and 25µm bands of IRAS. The higher resolution of the 8µm MSX observations reveals structures not apparent in the IRAS image. In particular there are two enhancements in the 8µm emission, to the south and southwest. These enhancements correspond spatially to a small local enhancement in the visual extinction, and some unusual velocity features seen in $^{13}$CO emission (Ridge et al., submitted), suggesting that they may be due to shocked molecular cloud material. This is strong evidence that the shell is having an impact on the molecular cloud complex, and its proximity to the star-forming cluster IC348 (the bright emission to the northeast of the ring in figure 3) may not be coincidence.

Proposed Observations

The shell is one of the most nearby examples of an HII region around a young massive star, and it is especially exciting to see a rare complete circumstellar shell. We are extremely lucky to have such a nice example of this phenomenon so nearby, enabling us to study it in intimate detail. The potential for this program is already displayed by the spectacular (preliminary) MIPS image mosaic of the southern portion of the shell (figure 5) showing complex, filamentary structures and even a possible second smaller shell within. Additionally, the shell’s association with the Perseus molecular cloud complex makes this an ideal laboratory for studying the impact that such a star can have on molecular cloud material, and the implications for the star-forming properties of the region.

Current observations of the region have concentrated on the molecular cloud complex which overlaps with only the lower portion of the shell. Without knowledge of the shell’s influence it is difficult to disentangle the properties of the star-forming gas from that of the shell itself. It is therefore imperative that any study of this region includes an exploration of the impact of an interaction between the HII region and the cloud complex.

As a natural extension to the COMPLETE survey, we have recently started a program of observations to investigate the shell. We have already obtained observations at the Greenbank Telescope and Five College Radio Astronomy Observatory (FCRAO) 14m telescope to make sensitive H$\alpha$, $^{12}$CO and $^{13}$CO maps at selected positions in the shell, while the Canadian Galactic Plane Survey collaboration are in the process of extending their program of high resolution HII mapping to include Perseus and its surroundings. We have already begun to use these atomic and molecular gas observations to look at the kinematics of the shell, and determine its rate of expansion.

Mid- and far-infrared observations are required to constrain the temperature, detailed structure and mass of the warm gas in the shell, as well as to search for shocked gas that may serve as the “smoking-gun” for an interaction between the expanding shell and the clouds. The Spitzer c2d program has covered about half the area of the shell with IRAC mapping observations (figure 4), while c2d MIPS observations include about two-thirds of the shell (figure 5). We now propose to extend the Spitzer coverage to include the remainder of the shell. This will enable us to determine the properties of the shell to the north, where we believe no interaction is occurring. We will then compare the emission to that in the southern portion, and determine whether there is evidence for additional shocked material in regions that overlap with the molecular clouds.

At 8µm the flux is dominated by poly-aromatic hydrocarbon (PAH) emission bands, superimposed on an underlying plateau of emission between 6 and 9µm attributed to small dust grains. The interface between an ionization front and the ambient interstellar medium leads to a photo-dissociation region (PDR), a neutral zone surrounding the ionized gas, in which PAHs emit strongly and small dust grains become heated. This is a transient effect and denotes the passing of a shock or ionization front. Therefore, in an HII region emission at 8µm is primarily tracing the ionization front. 24µm emission is usually due to thermal emission from larger dust grains and will therefore trace the warm dust within. The shorter wavelength 4.5µm IRAC band has already been shown to be an excellent tracer of shocks. Hence, by making a 3-color 4.5/8/24µm composite image we will be able to clearly differentiate between shocked material, the PDR and warm material within the ring. We expect to see an enhancement in shocked material in the southern portion of the ring with respect to the north,
Spitzer Cycle-2 GO Proposal
indicative of an impact onto the molecular clouds. Where the shocks appear strongest we will look in our $^{13}$CO data for velocity features which seem unusual.

The longer wavelength MIPS bands at 70 and 160μm, provide important constraints on the temperature and composition of the more tenuous warm dust. Using a standard dust model for a temperature range of 30-40K, we expect the wavelength of the peak of thermal emission to be around 70μm, between the two IRAS bands. As part of his thesis work Scott Schnee has developed an algorithm that uses a combination of IRAS 60 and 100μm emission and near-infrared extinction mapping to accurately constrain dust temperature (Schnee et al., in prep.). The addition of both 24 and 70μm (as well as 160μm data where possible) information from MIPS will enable us get a good handle on smaller scale dust temperature variations and also test for variation in the dust emissivity index, indicating variations in the grain size distribution or composition. Such differences, if spatially coherent would provide additional evidence for the passing of a shock, and hence an interaction with the molecular cloud.

Summary
Perseus is often seen as a vital link between Taurus and Orion, the two extremes of nearby star-forming regions. Located at ~260pc and containing both star-forming clusters and a population of distributed young stars, it seems to provide an excellent laboratory for testing models of star formation. It is no surprise that the entire molecular cloud complex is the target of a Spitzer Legacy Program (From Molecular Cores to Planet Forming Disks; c2d), while several of the clusters are targeted by Spitzer GTO programs. Additionally, the COMPLETE Collaboration have been obtaining a wealth of complementary multiwavelength observations of the Perseus region which will provide vital information about the gas and dust from which the new stars are forming.

Unfortunately, Perseus may not be as straightforward as it seems. IRAS data shows a 10pc warm shell located towards the center of the complex, an HII region powered by one of the most nearby OB-stars known (200pc). If the shell is physically connected to the star-forming region then it would be expected to significantly affect the manner in which the molecular cloud is able to form stars. An MSX 8.3μm image of the shell provides tantalizing evidence that it may in fact be impacting on the cloud complex, and hence we propose to use IRAC and MIPS to map the top half of the shell that is not included in the c2d program. The proposed region extends out of the area dominated by emission from the molecular cloud complex and will therefore make it simpler to disentangle the properties of the shell from those of the clouds. MIPS observations will provide strong constraints on the temperature and emissivity of the warm dust we see with IRAS. The 8μm IRAC observations will enable us to look for the presence of PAHs and transiently heated small dust grains indicative of a photodissociation region, while at the shorter mid-infrared wavelengths strong CO band-head and/or H$_2$ emission may indicate the presence of recently shocked gas. The Spitzer observations will be combined with atomic and molecular gas observations we have obtained for the COMPLETE Survey, enabling us to determine the temperature, density, dust properties and expansion rate of the shell.

References
Spitzer Cycle-2 GO Proposal

Pauls, T., Schwartz, P.R. 1989, in The Physics and Chemistry of Interstellar Molecular Clouds, ed. T.J. Armstrong

Figure 5: 24 (blue) and 70μm (red) composite MIPS image from c2d. Courtesy of Karl Stapelfeldt.
Spitzer Cycle-2 GO Proposal

**Technical Justification**

Our strategy requires a total time of 19.8 hours, utilizing IRAC and MIPS mapping. We plan to follow the c2d program in our IRAC mapping strategy, so our observations can be easily mosaiced with their maps of the lower half of the shell. With MIPS we hope to make use of 160µm data, and hence our mapping strategy is slightly different to c2d.

Six IRAC maps are required to cover the extent of the shell not included in the c2d program. We have allowed a minimal overlap in order to mosaic the fields satisfactorily. Each map is observed over two epochs, so that asteroids can be identified and removed. The second epoch is constrained within 3-6 hours of the first, hence that asteroids will have had time to move, but not move out of the map field of view. Two dithers are used for each epoch, and an offset of 10” is applied to the second epoch maps, such that 4 dithers are effectively obtained. The small overlaps between maps require that all six of the maps be made within 7 days of each other to prevent gaps due the change in scan direction. We therefore request the observations be made within one instrument campaign.

Three MIPS scan maps are sufficient to cover required area. The c2d program used a fast scan-rate and hence the 160µm data are under sampled. For this reason we include a larger overlap with the c2d program than we chose for the IRAC mapping, ensuring that we obtain 160µm observations for as much of the shell as possible without requiring any extra observing time in addition to that required to extend the coverage of the 24 and 70µm maps to include all of the shell. A cross-scan step of 276” is used, providing fully sampled maps at 24 and 160µm. A second epoch is again required in order to identify asteroids in the 24µm images. The second epoch maps will be offset by 148” in the cross-scan direction, therefore providing fully sampled maps at 70µm. A medium scan rate is required for fully sampled maps at 160µm. Again, a minimal overlap between maps is used to allow mosaicing of the images, and this requires that the observations be made within 30 days of each other.

Table 1 lists the peak and median fluxes for each of the IRAS bands within the area we plan to map with IRAC and MIPS. We assume that the 25µm and 60µm IRAS bands provide a good estimate of the expected flux at 24 and 70µm respectively. The 100µm IRAS flux places a conservative upper limit on the expected emission at 160µm.

<table>
<thead>
<tr>
<th>IRAS Band</th>
<th>12µm</th>
<th>25µm</th>
<th>60µm</th>
<th>100µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Flux (MJy/Sr)</td>
<td>5.38</td>
<td>17.03</td>
<td>55.27</td>
<td>139.43</td>
</tr>
<tr>
<td>Median Flux (MJy/Sr)</td>
<td>3.15</td>
<td>6.86</td>
<td>14.41</td>
<td>63.73</td>
</tr>
</tbody>
</table>

Table 1: Peak and median fluxes in the four IRAS bands within the area we plan to map.

Using the online Performance Estimation Tool, we have determined the expected extended-source sensitivity for our planned mapping strategy, and this is summarized in table 2, along with the expected extended-source saturation limits for MIPS and the estimated background from zodiacal light in each of the seven bands, determined using SPOT. We ignore the contribution to the “background” by the ISM in our calculations, as it is exactly this emission that we are interested in. From our recalibrated ISSA maps we have determined that the true underlying background emission from the diffuse ISM is a small contribution (≤5MJy/Sr) to the total flux in this region.

<table>
<thead>
<tr>
<th>Waveband (µm)</th>
<th>3.6</th>
<th>4.5</th>
<th>5.8</th>
<th>8.0</th>
<th>24</th>
<th>70</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended Source Sensitivity (MJy/Sr)</td>
<td>0.04</td>
<td>0.05</td>
<td>0.15</td>
<td>0.17</td>
<td>0.12</td>
<td>0.45</td>
<td>1.71</td>
</tr>
<tr>
<td>Exposure time per pixel (s)</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>40</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>Max. Zodiacal Light Background (MJy/Sr)</td>
<td>0.16</td>
<td>0.23</td>
<td>0.91</td>
<td>5.57</td>
<td>52.1</td>
<td>14.1</td>
<td>2.77</td>
</tr>
<tr>
<td>Extended Source Saturation in 10s</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>260</td>
<td>101/292*</td>
<td>See text.</td>
</tr>
</tbody>
</table>

Table 2: Instrument and background properties for the region we plan to observe.
Spitzer Cycle-2 GO Proposal

It is clear from tables 1 and 2 that our planned mapping strategy will be sufficient to obtain excellent sensitivity observations of the shell in all of the wavebands, and that saturation should not be a problem at 24 or 70μm. This is confirmed by the beautiful MIPS 24 and 70μm composite image shown in figure 5. There is no in-flight performance estimate for the extended source saturation limit at 160μm yet. However, the pre-launch limit was estimated at 14MJy/Sr for a 10s exposure (equivalent to the slow scan rate). Early reports have suggested that the 160μm performance is ~2 times less sensitive than pre-launch predictions, while a medium scan rate will allow saturation limits 2.5 times higher. We therefore estimate that the 160μm extended-source saturation limits will be ~70MJy/Sr. The spectrum of thermal emission falls beyond ~70μm, and hence we expect the 160μm flux to be significantly lower than the 100μm flux from IRAS. We therefore believe that although there may be saturation at positions of peak 160μm emission, we will be able to make use of the 160μm observations of extended emission over much of the region.
Alyssa A. Goodman

Education

Recent Academic Experience
1999- Professor of Astronomy, Harvard University
2001-2002 Visiting Fellow, Yale University (Sabbatical)
1996-1999 Associate Professor of Astronomy, Harvard University
1992-1996 Assistant Professor of Astronomy, Harvard University
1995-1997 Head Tutor, Harvard University Astronomy Department
1995- Research Associate, Smithsonian Astrophysical Observatory
1989-1992 President’s Fellow, University of California, Berkeley

Recent Honors and Awards
2004 Sturm Lecturer, Wesleyan University
1998 Bok Prize, Harvard University
1997 Newton Lacy Pierce Prize, American Astronomical Society
1994-1999 National Science Foundation Young Investigator
1994 Pedagogical Innovation Award, Harvard University
1993-1995 Alfred P. Sloan Fellow

Society Memberships
AAS; IAU; URSI Commission J (Radio Astronomy); AAAS; AAUP

External Advisory & Review Committee Work (Past 5 Years)
AAS Publications Board; NSF-Galactic Astronomy Panel Reviews (Chair); National Academy of Science’s Committee on Astronomy and Astrophysics; SIRTF Legacy Projects for Galactic Astronomy (Panel Chair); AAS Committee on Astronomy and Public Policy; NRAO Director Search Committee; M4 Satellite Science Advisory Group (Chair); NRAO VLA-VLBA Proposal Reviewer; US Square Kilometer Array Consortium (Harvard Representative); Spitzer Science Center Oversight Committee (2003-)

Relevant Recent Publications:
**Observation Summary Table**
Not required.

**Status of Existing Observatory Programs**
The P.I. is not an investigator or technical contact on any current Spitzer programs.

**Proprietary Period Modification**
No modification is requested.

**Justification of Duplicate Observations**
Our MIPS observations overlap with c2d observations of the Perseus molecular cloud complex. However, c2d used a fast scanning rate, and hence their 160μm data is not fully sampled. We hope to make use of the 160μm data, and therefore include a significant overlap with the c2d MIPS coverage, such that we obtain 160μm coverage of the majority of the shell, without requiring any additional observing time on top of that required to extend the 24 and 70μm coverage to include the previously unobserved northern portion of the shell.

**Justification of Scheduling Constraints**
In order to ensure that there are no gaps between our submaps, we request that the each of the sets of observations are completed within a single instrument campaign.

**Data Analysis Funding Distribution**
P.I. A. Goodman 100%

**Financial Contact Information**
Mary Mitchell or Robert Bloomberg  
Director of Awards Management  
Harvard University Office for Sponsored Research  
Holyoke Center 4th Floor  
1350 Massachusetts Ave.  
Cambridge, MA 02138

Telephone: (617) 495-5501  
Fax: (617) 496-2524  
Email: mary_mitchell@harvard.edu, bob_bloomberg@harvard.edu