The COMPLETE Nature of the Warm Dust Ring in Perseus

Abstract

We propose to make IRAC and MIPS observations of the poorly-studied warm dust ring in the Perseus molecular cloud complex region. The ring is clearly visible 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 ring have failed to determine beyond doubt either its nature (HII region, stellar wind or supernova remnant) or driving source. Our proposed Spitzer observations will enable us to accurately determine the mass of material in the ring, and search for the presence of shocks and/or photo-dissociation regions which will help us distinguish between the possible scenarios. These data, combined with atomic and molecular line observations being obtained as part of the COMPLETE Survey of Star-Forming Regions will enable us to finally determine the nature of the ring and its likely consequences for studies of the star-forming properties of Perseus, providing a vital contribution to the Spitzer Legacy Program "From Molecular Cores to Planet Forming Disks."

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. Hot, massive stars will cause cloud disruption through their ionizing flux as well as through the momentum in their stellar winds. Alternatively, given the right conditions in the cloud, stellar winds may also cause the collapse of cloud cores and induce further star formation.

The Perseus Molecular Cloud complex has a mass of ~1.3×10^4 M_{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 c2d program will also use extinction mapping to determine the density structure of individual cores.

The ongoing COMPLETE[1] Survey, a large international effort utilizing telescopes such as GBT, FCRAO, JCMT and IRAM has coordinated its observations with the c2d program. COMPLETE will provide 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 ring of enhanced emission can be seen in IRAS data toward the center of the molecular cloud complex (fig. 1). The ring has a radius of 0.75°, or 10pc at the distance of the molecular cloud. Although its existence has been known for almost 15 years[2] — it was first described by Pauls & Schwartz (1989) in a conference proceedings and further discussed by Fiedler et al. (1994) — there has been little investigation into the nature or source of the ring, and 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 ring 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 HII region filling the ring. They could not, however, rule out the possibility that the radio continuum is due to synchrotron emission from

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[1] **C**o**O**rdinated **M**olecular **P**robe **L**ine, **E**xtinction and **T**hermal **E**mission; http://cfa-www.harvard.edu/COMPLETE

[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!

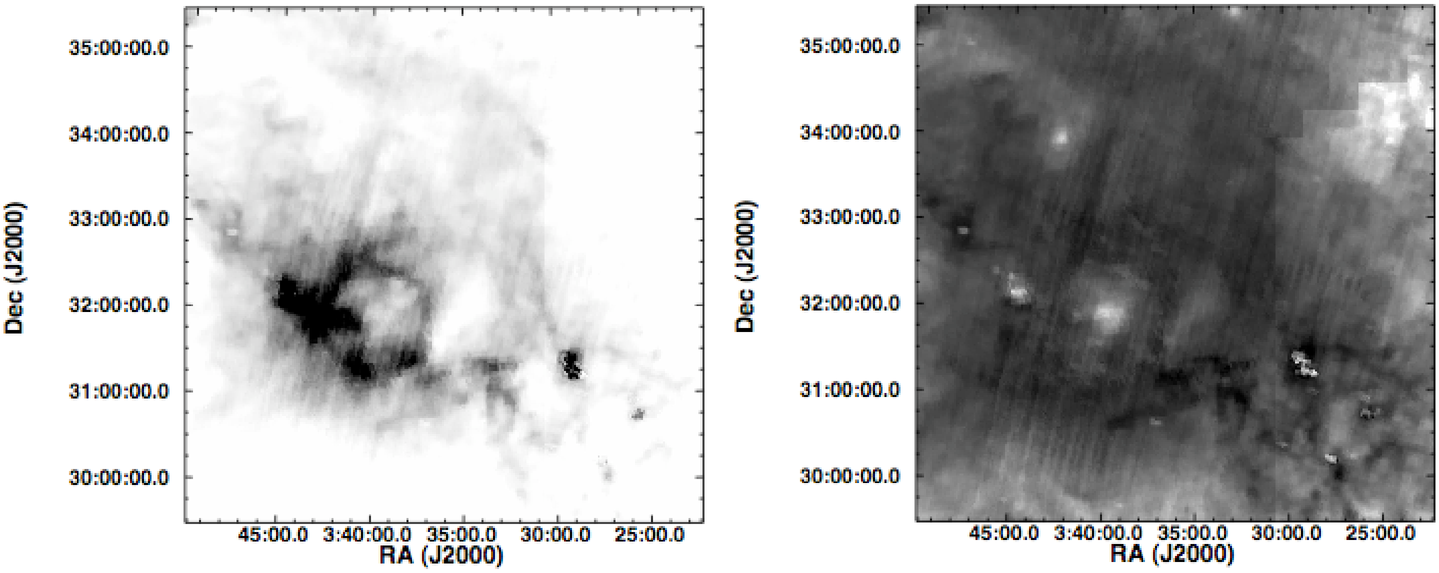

Figure 1: Left: Dust thermal emission derived from IRAS 60 and 100μm emission. High values of column density are dark. Right: Dust temperature derived from IRAS 60 and 100μm emission. Higher temperatures are indicated by white regions. The ring appears as a column density enhancement filled with warm dust.

the interaction between a stellar wind and the molecular cloud. Their other observations concentrated on HD278942 itself, and hence provide little insight into the nature of the actual ring.

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. 1). The ring is clearly seen as an enhancement in column density (left panel), and is filled with warm material evident in the temperature map (right 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 ^{13}CO or extinction maps of the region, which are likely to provide a more reliable estimate of the true column-density distribution. In this respect Perseus is intermediate in its properties between Taurus, where there are no massive stars and the IRAS emission traces the column density well, and Orion, where the presence of a large cluster of young stars leads to a population of heated dust and the IRAS emission bears little morphological similarity to other column density tracers.

In a study of the optical polarization of background stars, Goodman et al. (1990) found a bimodal distribution of polarisation angles in the Perseus region which they attributed to two separate dust distributions along the line of sight, each associated with a different magnetic field orientation. This hypothesis is supported by the presence of two distinct velocity components seen in CO maps of the same region (Ungerechts & Thaddeus 1987), although at the time Goodman et al. could detect no meaningful spatial distinction between the two distributions.

In figure 2 we show polarization vectors from Goodman et al. overlaid on the IRAS thermal emission map (left) and a ^{13}CO map (right). The weaker polarisation component identified by Goodman et al. is clearly aligned along the major axis of the molecular cloud, but on comparison with our new thermal emission maps it now becomes evident that the second polarisation component is preferentially located within and aligned with the warm ring and associated arm to the west (Ridge et al., in prep). Further evidence of two dust populations is provided in figure 3, where we show thermal emission (interpreted here as column density in units of A_v) plotted against temperature derived from the 60 and 100μm emission. Two distinct populations are seen in the emission. The grey crosses represent points selected to be located within the ring, while the black squares represent the remainder of the data. The division was purely based on physical position and without reference to the two populations visible in figure 3. There is no evidence for an enhancement in true column density at the position of the ring in either our CO observations or in our extinction maps of the region constructed from 2MASS using the NICER algorithm (Lombardi & Alves 2001). Therefore, the only explanation for the ring to be so prominent in the IRAS maps, and for it to appear as a distinct population in figure 3 is that the ring really contains dust with a different emissivity to the dust throughout the rest of the complex.

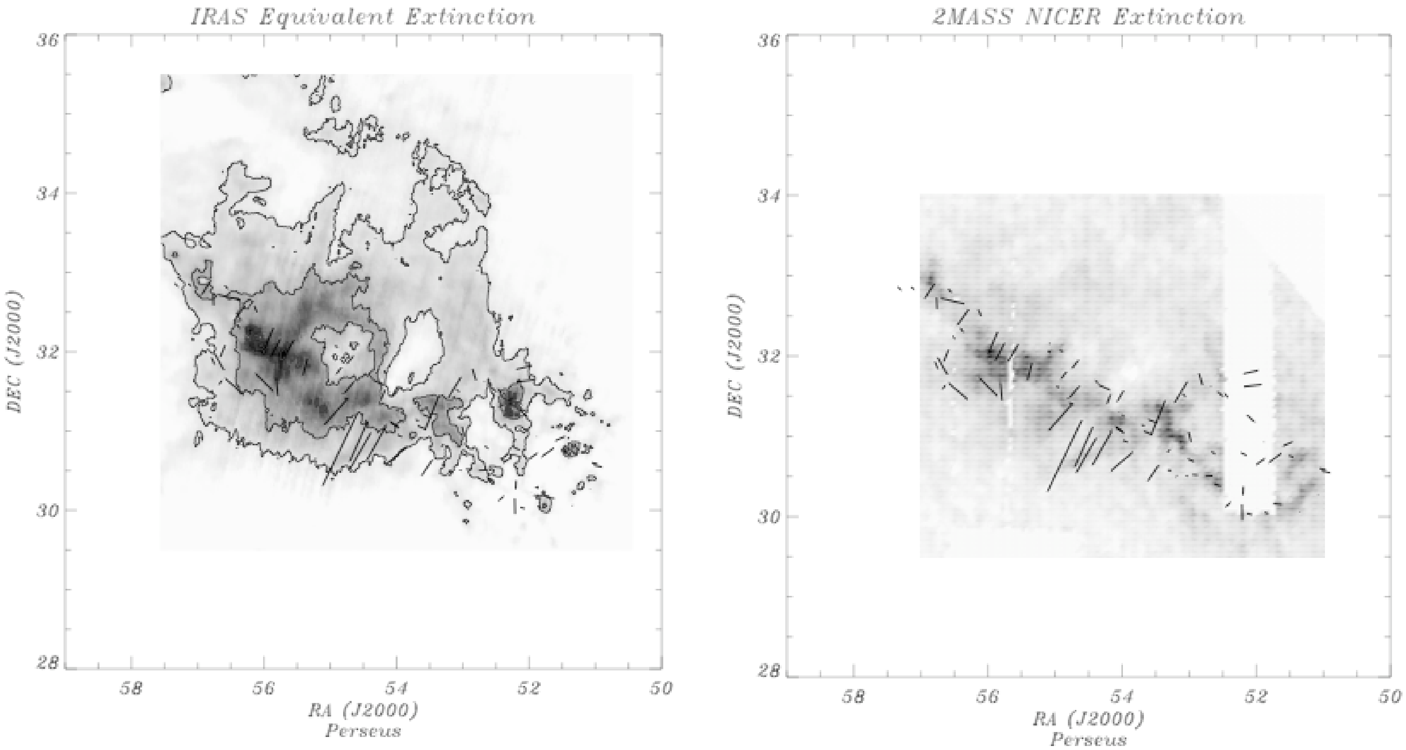

Figure 2: Vectors indicating direction and magnitude of the polarization of background starlight (from Goodman et al. 1990), overlaid on "extinction" derived from IRAS 100μm emission (left) and extinction derived using 2MASS and the NICER algorithm (right). The longer polarization vectors appear to be preferentially associated with ring emission (left), while the weaker vectors are aligned with the major axis of the molecular cloud complex, seen in the 2MASS derived extinction map, which traces true column-density.

If the ring is the source of the second dust component proposed by Goodman et al., there is no reason to assume that it is any way physically connected to the rest of the molecular cloud complex, and may in fact be at a completely different distance. This is supported by an elongated shadow, spatially coincident with a filament of ^{13}CO emission, which can be seen in silhouette in front of the circle of nebulosity visible in Barnard's 1907 optical photograph. This would place at least the eastern end of the molecular cloud complex in front of the ring. We cannot, however, determine an accurate distance to the ring, and hence rule out an interaction with the molecular cloud complex — if HD278942 is the progenitor of the ring, its Hipparcos distance of 207±52pc puts it ambiguously close to distance estimates for the molecular cloud complex.

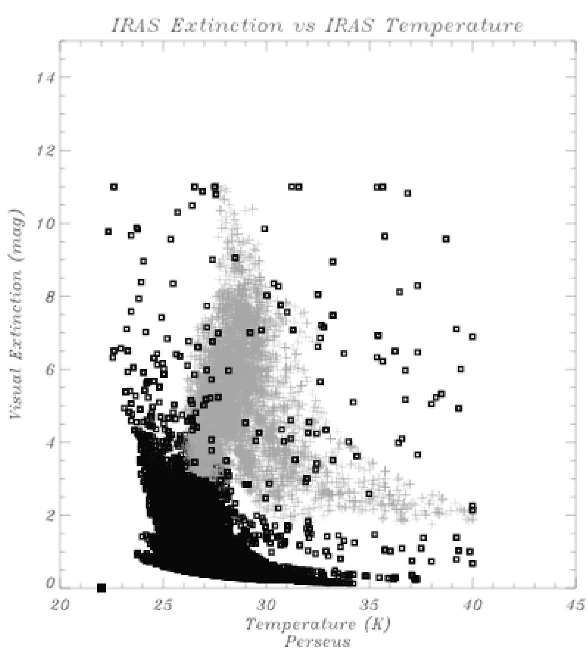

Figure 3: Extinction vs. temperature determined from IRAS 60 and 100μm emission. Grey crosses denote emission from selected to lie within the ring

Proposed Observations

Whether due to a stellar wind, expanding HII region or (now unlikely) supernova remnant, if the ring is in fact interacting with the complex, then this will have major implications for any study of the star-forming properties of Perseus. Current observations of the region have concentrated on the molecular cloud complex which overlaps with only the lower portion of the ring. Without knowledge of the ring's influence it is difficult to disentangle the properties of the star-forming gas from that of the ring itself. It is therefore imperative for the other Spitzer programs, studying this region, and in particular the c2d Legacy program, that the nature of the ring is established beyond doubt.

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

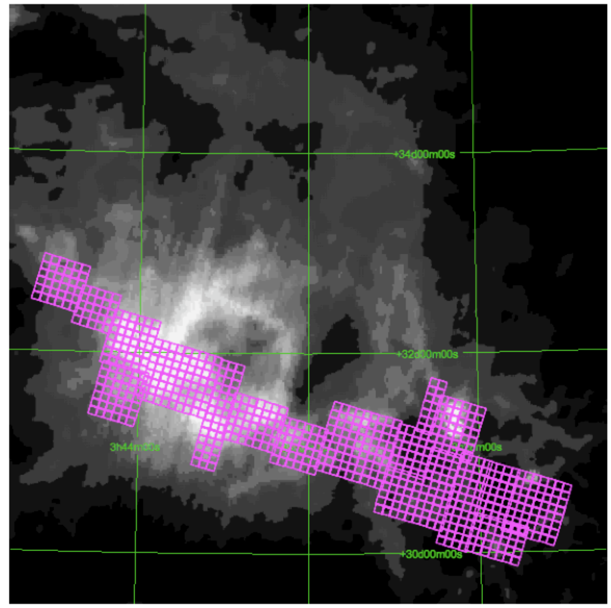

Figure 4: SPOT image showing the c2d and GTO IRAC coverage overlaid on our thermal emission image of the ring. The MIPS coverage is similar.

Mid- and far-infrared Spitzer observations are now required to constrain the temperature and mass of warm gas in the ring. The c2d program will cover about half the area of the ring with both IRAC and MIPS mapping observations (figure 4). Here we propose to extend the coverage to include the top half of the ring, where we will be able to disentangle the ring from the molecular cloud complex and star forming gas.

The interpretation of extended emission seen in the mid-infrared is still in its infancy, and as such we expect our observations to provide us with many exciting surprises, just as the images we have seen from the Early Release Observations (EROs) have done. However, observations of similar regions by the MSX satellite can give us a clue as to what we can expect to see.

Figure 5 shows MSX 8 and 21μm images of a more distant suspected HII region, G28.82—0.23. The size of the circle of emission appears to decrease as the wavelength increases. This is because we are seeing different physical phenomena producing the emission at the two wavelengths. 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, primarily composed of carbon. 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. The longest MSX band, at 21μm, is likely to be tracing thermal emission from larger dust grains. Therefore, in this source PAH emission at 8μm is tracing the ionization front from the HII region, while the 21μm emission traces the warm dust within. If the Perseus

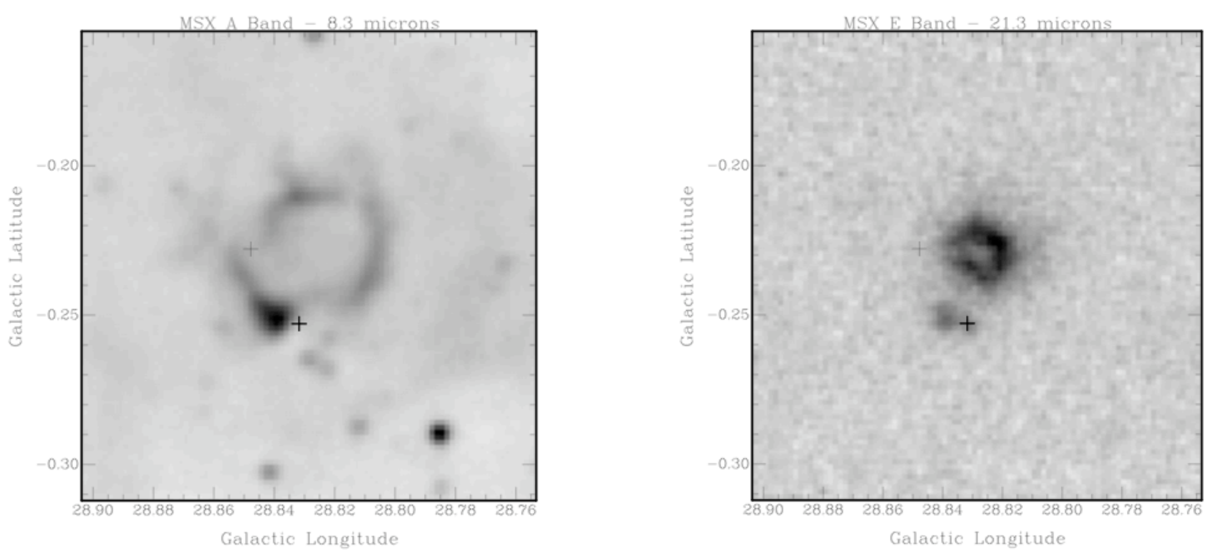

Figure 5: MSX 8.3μm (top) and 21.3μm emission from a suspected HII region. The crosses denote the positions of masers.

ring is the result of an H II region expanding into the dense ISM then we would expect to see a similar morphological trend between the IRAC 8µm and MIPS 24µm bands.

ISO-SWS has identified emission bands between 3 and 8µm from e.g. water ice and solid CO_2 (e.g. Rosenthal et al 2000). With the better sensitivity and wavelength coverage available with IRAC we will detect these features in the extended dust emission of the ring. We will then be able to compare the dust within the ring with that in the molecular cloud and determine conclusively whether the ring contains a different dust population to the cloud.

The longer wavelength MIPS bands at 70 and 160µm, although possibly saturated at the positions of peak emission (see technical justification), will be able to provide important constraints on the temperature of the more tenuous extended warm dust we see with IRAS at 60 and 100µm. 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. With both 24 and 70µm coverage of the ring from MIPS we will get a good handle on dust temperature variations, while the 160µm observations will enable us to investigate variations in dust emissivity.

Summary

Perseus is often seen as a natural stepping stone between Taurus and Orion, the two extremes of nearby star-forming regions. Located at ~300pc 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 then 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 ring located towards the center of the complex. Limited previous observations of the ring have failed to establish either its nature or progenitor, although it is likely that it is due to an expanding H II region. If the ring 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. It is therefore essential to the success of the Spitzer Legacy Program and any other study of the region that the nature of the ring be established beyond doubt.

Hence we propose to use IRAC and MIPS to map the top half of the ring 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 ring 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 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 finally unravel a 15 year old mystery!

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Technical Details

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 ring. 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 ring not included in the c2d program. We have allowed a minimal overlap in order to mosaic the fields satisfactorily. The small overlaps require that all six of the maps be made within 7 days of each other to prevent gaps due the change in scan direction. Our planned coverage is shown in figure 6.

Four MIPS scan maps are sufficient to cover the same area. In order to make full use of the 70μm observations a cross-scan step of 148″ is used. 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. We will use a medium scan rate to obtain a fully sampled map in all three of the MIPS bands, while minimizing the risk of saturation.

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.

IRAS Band	12μm	25μm	60μm	100μm
Peak Flux (MJy/Sr)	5.38	17.03	55.27	139.43
Median Flux (MJy/Sr)	3.15	6.86	14.41	63.73

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 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.

Waveband (μm)	3.6	4.5	5.8	8.0	24	70	160
Extended Source Sensitivity (MJy/Sr)	0.04	0.05	0.18	0.19	0.12	0.37	0.85
Exposure time per pixel (s)	12	12	12	12	40	40	4
Max. Zodiacal Light Background (MJy/Sr)	0.16	0.23	0.91	5.57	52.1	14.1	2.77
Extended Source Saturation in 10s	—	—	—	—	260	125*	See text.

Table 2: Instrument and background properties for the region we plan to observe.

* fine scale mode

It is clear from tables 1 and 2 that our planned mapping strategy will be sufficient to obtain excellent sensitivity observations of the ring in all of the wavebands, and that saturation should not be a problem at 24 or 70μm. 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.

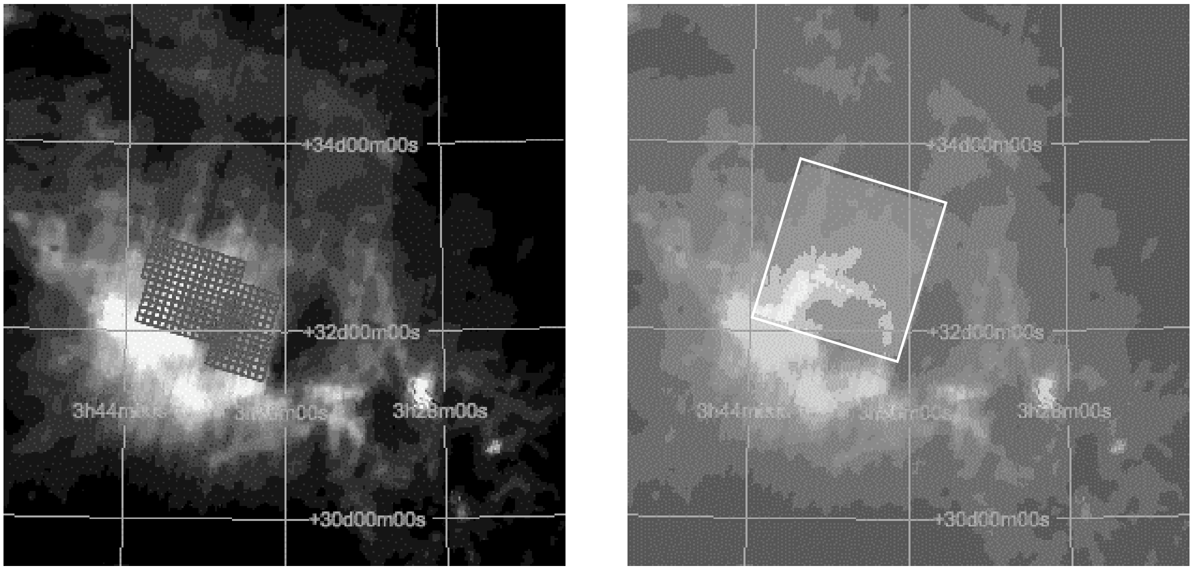

Figure 6: Outline of proposed IRAC (left) and MIPS (right) observations.

Data Reduction and Analysis

Data reduction and analysis will be carried out primarily by the COMPLETE Postdoctoral Fellow, Naomi Ridge with assistance from graduate student Scott Schnee. The SSC pipeline will provide calibrated and mosaiced images, and therefore relatively little post-pipeline data processing is expected to be required. Schnee was primarily responsible for producing the new dust-emission maps from the ISSA plates, and will apply these well-understood techniques to the long wavelength data (24-160μm) in order to investigate the thermal dust properties. As such, it is expected that this program will contribute significantly to his PhD Thesis. Ridge will lead the interpretation of the short wavelength (3-8μm) observations. Data analysis support is requested by the P.I. for salary support to Ridge.

Alyssa A. Goodman

Education

Sc.B. in Physics, MIT, 1984; A.M. in Physics, Harvard, 1986; Ph.D. in Physics, Harvard, 1989

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:

Arce, H.G. & Goodman, A.A. 1999, *An Extinction Study of the Taurus Dark Cloud Complex*, ApJ, 517, 264.

Arce, H.G. & Goodman, A.A. 2001, *The Mass-Velocity and Position-Velocity Relations in Episodic Outflows*, ApJ, 551, L171.

Arce, H.G. & Goodman, A.A. 2002, *Bow Shocks, Wiggling Jets, and Wide-Angle Winds: A High-Resolution Study of the Entrainment Mechanism of the PV Cephei Molecular (CO) Outflow*, ApJ, 575, 928.

Arce, H.G.& Goodman, A.A. 2002, *The Great PV Cephei Outflow: A Case Study in Outflow-Cloud Interaction*, ApJ, 575, 911.

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Goodman A.A. et al. 2004, *The COMPLETE Survey of Star-Forming Regions at Age 2,* to appear in the Proceedings of the 60th Birthday Celebration for F. Shu, D. Hollenbach & C.McKee.

Goodman, A. A. & Arce, H. G. 2004, *PV Ceph: Young Star Caught Speeding?*, ApJ, to appear May 10

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Observations Summary

Total number of AORs: 10
Total Time Requested: 14.8 hours
Instruments Requested: IRAC, MIPS

AOR #	Instrument	Observing Mode	Time Required (s)
1	IRAC	HDR/Mapping	2569
2	IRAC	HDR/Mapping	2569
3	IRAC	HDR/Mapping	2569
4	IRAC	HDR/Mapping	3360
5	IRAC	HDR/Mapping	3359
6	IRAC	HDR/Mapping	2569
7	MIPS	Scan Map	9035
8	MIPS	Scan Map	9037
9	MIPS	Scan Map	9034
10	MIPS	Scan Map	9035

Total of IRAC observations: 4.7 hours
Total of MIPS observations: 10 hours

Involvement in Previous Spitzer Programs

The principal investigator is not involved as investigator in any existing Spitzer Space Telescope research program.

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