The Return of the Ring: What Happened in the Real ρ–Oph Cluster

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Objective

We propose to map a previously anonymous dust ring in the ρ Ophiuchi region with IRAC. Data from Spitzer will shed critical lights onto the origin and properties of this object. Only a quarter of the ring that coincides with dense gas will be covered by the “From Molecular Cores to Planet Forming Disks” (c2d) Legacy plan. A complete, highly sensitive and multi-band mid to far infrared data set is unique in helping us understand the interaction between stars and the ISM and the history of star formation in this important nearby region.

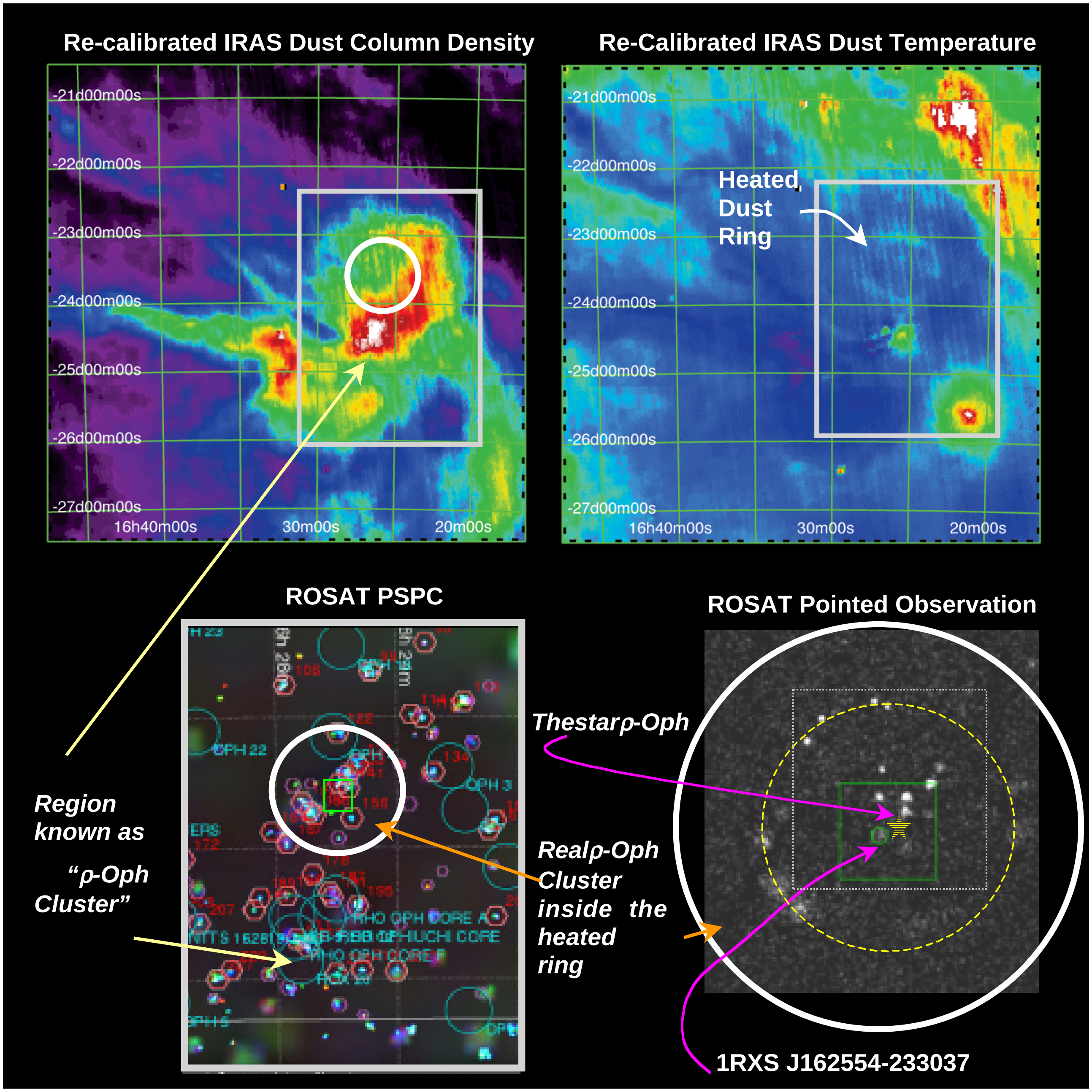

Figure1 In each panel where it is shown, the **white ring** shows a 2 pc circle, corresponding to the size and shape of the heated ring apparent in the IRAS Temperature Map. The smaller circles on the lower right are visual aids for the location of x-ray sources. Many of the X-ray point sources seems to occupy a smaller ring, almost concentric to the ρ-Oph dust ring.

COMPLETE and the Discovery of the Ring

The ongoing COordinated Molecular Probe Line Extinction Thermal Emission (COMPLETE) Survey (http://cfa-www.harvard.edu/COMPLETE) is aimed at building a comprehensive multi-wavelength database covering the same prominent nearby star forming regions included in the c2d Legacy survey. It is a large, international effort utilizing telescopes such as GBT, FCRAO, JCMT, and IRAM. The molecular and atomic spectroscopy provided by COMPLETE will reveal the kinematics of the star forming gas. The millimeter continuum maps will help define the dust properties and better understand the dust emission.

In preparing for the COMPLETE mapping efforts, we have re-calibrated the zero points of the 60 and 100 micron plates from the IRAS Sky Survey Atlas (ISSA). The re-calibration enables us to use the IRAS data down to low flux levels and to derive credible dust temperatures (Ridge et al. 2004). One surprising outcome is the existence of a dust ring with enhanced temperature surrounding the `real' ρ-Oph cluster. The name "ρ-Oph" is derived from the young BIV star ρ-Oph, which is near, but not inside the main clouds. In the context of star formation, the "ρ-Oph cluster" usually refers to embedded sources within dense gas (see Figure 1). The hot dust ring we seek to study, however, forms almost a perfect circle around ρ-Oph the star and is OUTSIDE the main cloud (Figure 1).

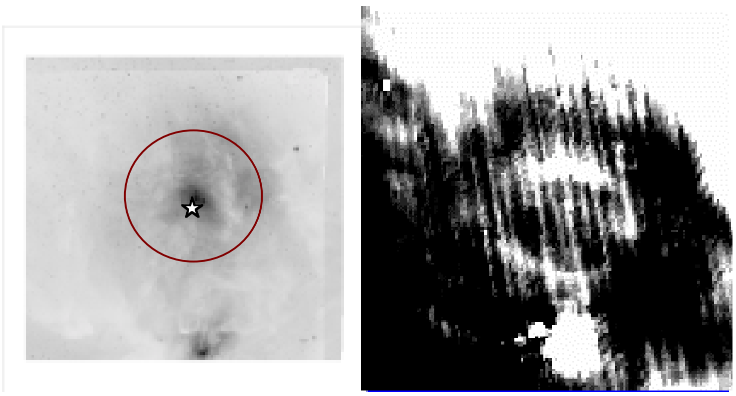

Figure 2: *Left panel:* Nebulosity around ρ-Oph (DSS); *Right Panel:* IRAS temperature image of shell (from 26 to 39 K only). The bright ring on the right panel shows the same 2 pc diameter shell as on the previous page. The star in the left panel shows 1RXS J162554-233037.

Is there a cluster located near the star ρ-Oph? A bright, oft-photographed nebula associated with the ρ Oph star prevents the optical search of one (Figure 2). Fortuitously, the region inside the dust ring was included in a ROSAT pointed observation made by Snowden et al. in 1994. ROSAT detects about 20 point sources with heavily reddened hardness ratios, suggestive of an embedded cluster associated with ρ-Oph (Goodman et al. 2004). We also have time at the XMM to follow up this discovery.

Can we identify the forces that shape the cluster and the dust ring?

Supernova or Stellar Wind?

Some of the ROSAT X-ray sources are located, seemingly, on a smaller, nearly concentric ring inside the IRAS ring (Figure 1). One of the X-ray sources near the ring center, 1RXSJ162554.5-233037, has peculiar Hardness Ratios consistent with being an exotic compact object, e.g. neutron star or accreting binary. Combined with the presence of ρ-Oph star itself, the likely hypothesis for the making of the ring should include both supernova explosion and/or a strong wind.

The size of the dust ring, is 1 degree across corresponding to about 2 pc diameter. A 0.5×10^{51} erg SN would eject 1 solar mass into dense medium (like ρ-Oph clouds ~10^5 cm^{-3}) to that size within 0.2 Myr. At this age, the shell would be about 38 K and moving at 1.7 km/s. Such a temperature is almost identical to the result (37 K) from our re-calibrated IRAS data! A supernova is not the only way to drive a shell into the ISM. A powerful wind, which could be produced by the B star ρ-Oph itself, can also impact the surrounding ISM. Further knowledge of the dust mass, velocity, and the nature of the encircled sources will be needed to recover the true history.

The interaction of stars with the ISM, in fact, may well be a key factor in shaping clouds and regulating star formation. Based largely on HI data on a much larger scale, de Geus (1992) suggested that stellar wind and supernova around stellar aggregates are responsible for the bubbles and filaments in the whole Sco-Cen-Oph region. The large-scale morphology, such as the alignment of filaments and location of shells, often suggest energy input from central sources. The collision of these ISM shells can create slow shocks at about 2 km/s (Meyers et al.1985), which possibly have induced core fragmentation and star formation (Motte et al.1998). Since the progenitors for large shells (bubbles) are usually not identied, these suggestions are very tantalizing, but not definitive.

Given the circular shape, the possible young age and its location, the ρ-Oph dust ring prensents a rare opportunity to study early-stage star-ISM interaction in an important nearby star forming region.

The COMPLETE Plan to Study the Ring

At only 125 pc from the sun (de Geus et al.1990), the ρ Ophiuchi region has been the subject of numerous mapping efforts (e.g. Wilking Lada 1983; Loren et al.1989) and is among the best studied star forming regions. Most of these efforts, however, do not extend far enough to cover the dust ring, which is around the “real” ρ-Oph star, about half a degree northeast to the dense molecular clouds boundaries.

Through COMPLETE, we are going to obtain a comprehensive data set on the ρ-Oph ring region using mostly ground based telescopes. As part of this plan, a Greenbank Telecope (GBT) to map the whole region in HI with high spectral resolution (dV < 0.2 km/s) program has been approved. Even with enhanced temperatures of the ring, the dust and the gas at the ring are still cooler than the galactic HI background emission. This raises the possibility of studying the kinematics of the ring through associated HI narrow self-absorption (or HINSA, see Li and Goldsmith 2003). There is an ongoing mapping project at FCRAO to cover the region in the 3mm transitions of ^{12}CO and ^{13}CO. We have also been granted SCUBA time to map the region in submillimeter continuum. Table 1 gives a brief summary of existing and upcoming data available for studying the dust ring in ρ-Oph.

Table 1 Complementary Data

Observations	Utilities	Telescopes	Source
HI (HINSA)	Atomic gas distribution and motion	GBT	COMPLETE
^{12}CO, ^{13}CO	Gas temperature and motion	FCRAO	COMPLETE
450 and 800 μm	Cold dust	JCMT	COMPLETE
60 & 100 μm	Dust temperature	IRAS	COMPLETE
NIR	Dust Extinction	2MASS	COMPLETE
SII Hα	Ionizing photon flux	SHASSA	J. Gaustad

The central pieces of this puzzle, the dust ring itself and the stellar objects it encircles, however, can only be studied thoroughly from space.

What Can Spitzer Tell Us?

With more than 2 orders of magnitude higher sensitivity than IRAS, the imaging arrays of Spitzer will be able to obtain data of good quality of the whole ρ-Oph ring region in a relatively small amount of time (< 5 hrs total).

In the Legacy c2d program, the ring region will be fully covered in three MIPS maps. The 160 μm band is expected to be saturated and the 70 μm band may be marginal. The 24 μm should provide accurate flux for extended emission and be helpful for finding point sources. Combined with IRAS and submillimeter continuum data, a good handle on dust temperature should be obtained.

Table 2 Proposed Spitzer Observations

λ (μm)	Instrument	Sensitivity (Mjy/Ster)	Utilities
3.6	IRAC	0.03	Stellar Radiation
4.5	IRAC	0.03	Shocked CO bands
5.8	IRAC	0.11	PAH
8.0	IRAC	0.11	PAH, VSG

The IRAC mapping in the c2d Legacy program, however, covers less than 50% part of the ring close to the side of the dense gas. We propose to complete the IRAC maps of the ρ-Oph ring in all four channels (see Figure 3).

Powered by transient heating of small dust grain by UV photons, the mid IR band are rich with PAH features. There are ample evidence of strong UV field in this region including the optical nebular (Figure 2) and the Hα image (see Table 1). Moreover, because the ρ-Oph ring is probably young, dense star forming materials are likely to still show the influence of UV irradiation and passing shocks. The ring-related shapes and effect of the progenitor event should manifest themselves in several different ways. The intensity will vary, particularly in bands sensitive to UV strength, such as the 8 micron band (Verstraete et al. 1996). The orientation of filaments, especially around dust knots, could show the preferred direction of the driving wind. The placement of protostars and other point sources is another important evidence as to the origin and condition of the ρ-Oph ring. For example, we can seek the reality and the meaning of the tantalizing inside ring marked by location of X-ray sources in Figure 1. Finally, the IR colors of protostars combined with luminosity will be a diagnostic of the ages. The relevance of the progenitor event of the ρ-Oph ring will be revealed by comparing these ages with that of the ring. Among many interesting topics that will be answered or raised by Spitzer data, the time scale and the collective effects of the ring will clearly be known for the first time.

For studying physical processes, the four IRAC bands provide good markers of outflows and photo-dissociation, which can either coexist or compete with each other for observable effects. Judging by newly available Early Release Observations (EROs), the 4.5 micron band will be particularly sensitive to shocked regions, with possible enhanced emission CO bands. The 5.8 and 8.0 micron bands, on the other hand, tend to be dominated by broad PAH features in photon-dominated regions (PDRs, also known as photon-dissociative region), which have been shown to be the case in several star forming regions through ISO observations (e.g. Henning et al. 1998). IRAC data, therefore, will likely identify regions of particular interest, such as strongly shocked ring boundaries and strong PDRs. These identifications will provide guidance for follow-up IRS spectroscopy studies with different focuses, such as the shocked H_2 lines and/or water ice absorption toward bright UV sources.

Summary

We propose to observe a largely unknown dust ring in the ρ Ophiuchi region. This ring has enhanced dust temperature best seen in our re-calibrated IRAS images. This ring is centered on a the B star ρ-Oph and a x-ray cluster. We have a comprehensive plan to obtain complemetary data to study this ring from radio to x-ray wavelengths. Information critical to understand the nature of this ring would come from Spitzer. The proposed IRAC observations (Table 2 and the Technical plan) will achieve better than 0.12 MJy/Ster sensitivity for extended sources (1 sigma) and L_{bol} ~ $0.5x10^{-3}L_{sun.}$ for point sources (3 sigma). Such a high sensitivity will provide a clear look at the ρ-Oph dust ring, the dust and young stellar content inside the ring, the impact of its progenitor, and guidance for future detailed studies.

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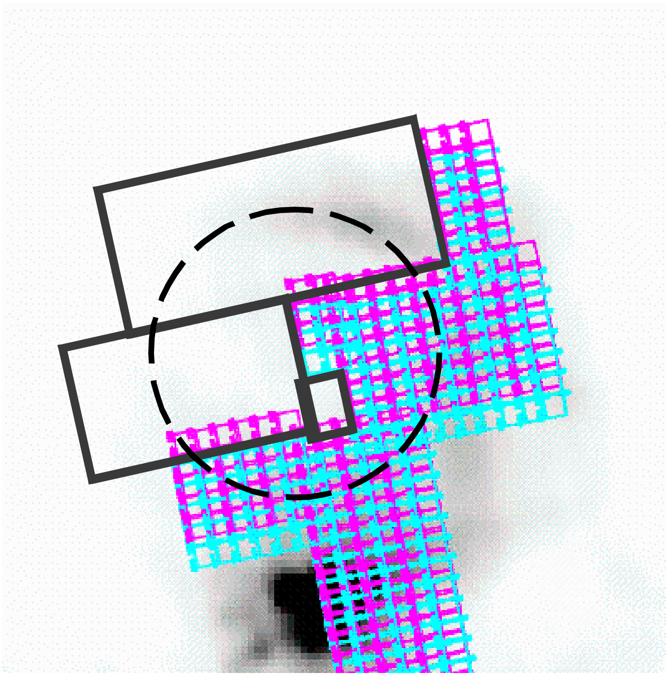
Technical Plan

We plan to use IRAC in HDR mapping mode. Three maps are needed to completely cover the ρ-Oph dust ring without unnecessary repetition of the area already included in the c2d Legacy program. For the best mosaicing product, these three maps (6 AORs) are to be done within 30 days to avoid significant rotation of the array.

Figure 3 illustrates the principle layout of our mapping strategies.



There cloud maps will employ two dithers and the total effective integration time is 24 seconds. Because of high probabilities of fast moving target, such as asteroids, in this area of the sky, each map region is to be done twice. This ensures credible detection of bright point source in our fields. The time requested and AORs are summerized in Table 3. The scan spacing is chosen to match that of the c2d AORs to facilitate eventual combination of both data sets to produce images of the full ring.

In the ρ-Oph region, the 8 micron band has by far the strongest background radiation, at about 21 MJy/Sr. This is still below the saturation limit for our short exposures. The expected sensitivity for extended sources is around ~0.03 MJy/Sr at 3.6 and 4.8 micron bands and around ~0.12 MJy/Sr at 5.8 and 8.0 micron bands (1 sigma). In terms of bolometric limit, IRAC scans will achieve 0.5×10^{-3} solar luminosities (point source, 3sigma) at the distance of ρ-Oph!

Figure 3 The IRAC coverage of the c2d program is shown in grids ovlaid with ISSA 100 micron image (based on output from the SPOT program). Only those adjacent to the proposed observations are shown. The black rectangles illustrate our proposed IRAC maps. The dashed circle shows the location of the ρ-oph dust ring.

Data Reduction

The PI will carry out the data reduction tasks with assitance from the graduate student Scott Schnee. Analying and modeling dust emission are critical parts of Mr. Schnee's PhD thesis. The data from Spitzer will be significant for that purpose. We plan to obtain calibrated and mosaiced images from the SSC pipeline.

Di Li

- **Education**

PhD in Astronomy, Cornell Univ. 2002, Master in Astronomy, Cornell Univ. 2000, Sc.B.. in Nuclear Physics and Sc.B. in Computer Software, Bejing Univ., 1995

- **Current Employment**

Astronomer, Havarvd-Smithsonian Center for Astrophysics

- **Professional Experience**

Planning and observing: SWAS satellite, CSO, SEST, FCRAO, Effelsberg, GBT, VLA, Arecibo
Data reduction: SWAS pipeline, Arecibo Class Calibration Software
Modeling: Dust temperature distribution, Radiative transfer

- **Grant and Award**

Small Research Grant, *American Astronomical Society*, 2002
First Class Fellowship, by *Beijing University*, 1992
GuangHua Scholarship, by *GuangHua Foundation*, 1992

- **Society Membership**

AAS, APS, CAS

- **Research Interest**

I am the PI of two GBT programs and several Arecbo program to study atomic gas in star forming clouds. I am the PI of a large scale mapping project using SWAS and FCARO to study carbon gas in the Ophiuchi region. I am a CoI in two survey projects, the COMPLETE-covering the same nearby star forming regions as those in the Spitzer Legacy program "From Molecular cores to Disks" and the ALPHA-TAU, covering Taurs. Both projects seek to build mulit-wavelength data base to catalgue the gas content in these star forming regions.

- **Relavent Recent Publication**

Zubko, V., Li, D., Lim, T. & Harwit, M. 2004, *Observations of Water Vapor Outflow from NML Cygnus*, Submitted to ApJ

Li D., Goldsmith, P.F. & Menten, K. 2003, *Massive Quiescent Cores in Orion I. Temperature Structure,* ApJ, 587, 262

Li, D. & Goldsmith, P. F. 2003, *HI Narrow Self Absorption in Dark Clouds*, ApJ, 585, 823

Goldsmith, P. F., Li, D., Melnick, G. J., Bergin, E. A., Howe, J. E., Snell, R. L., Neufeld, D. A. & Harwit, M., 2002, *Tentative Detection of Molecular Oxygen in the Rho Ophiuchi Cloud,* ApJ, 576, 814

Li, D., Melnick, G. & Goldsmith, P. F. 2002, *Large Scale Mapping of Rho Ophiuchi Cloud,* Conference Proceeding of the Astrochemistry and Star Formation Meeting in Waterloo, Canada

Li, D. & Melnick, G. 2002, *Submillimeter Wave Astronomy Satellite and Star Formation*, Conference Proceeding of the 6^{th} Pacific Rim Stellar Physics Meeting in Xi'an, China

Li, D., Goldsmith, P.F. & Xie, T. 1999, *A New Method For Determining the Dust Temperature Distribution*, ApJ, 522, 897

Spitzer Observations Summary

Total time: 4.4 hours

Number of AORs: 6

Instrument: IRAC (all bands)

Time Constraints: With 30 days

Table 3 AOR Summary

AOR Label	Instrument	Observing Mode	Time Required
IRAC-roph-ring1	IRAC/all bands	HDR/Mapping	4898
IRAC-roph-ring1a	IRAC/all bands	HDR/Mapping	4898
IRAC-roph-ring2	IRAC/all bands	HDR/Mapping	2443
IRAC-roph-ring2a	IRAC/all bands	HDR/Mapping	2443
IRAC-roph-ring3	IRAC/all bands	HDR/Mapping	646
IRAC-roph-ring3a	IRAC/all bands	HDR/Mapping	646

Previous Spitzer Programs: None.

Financial Contact Information

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