SMOKE SIGNALS FROM OPHIUCHUS

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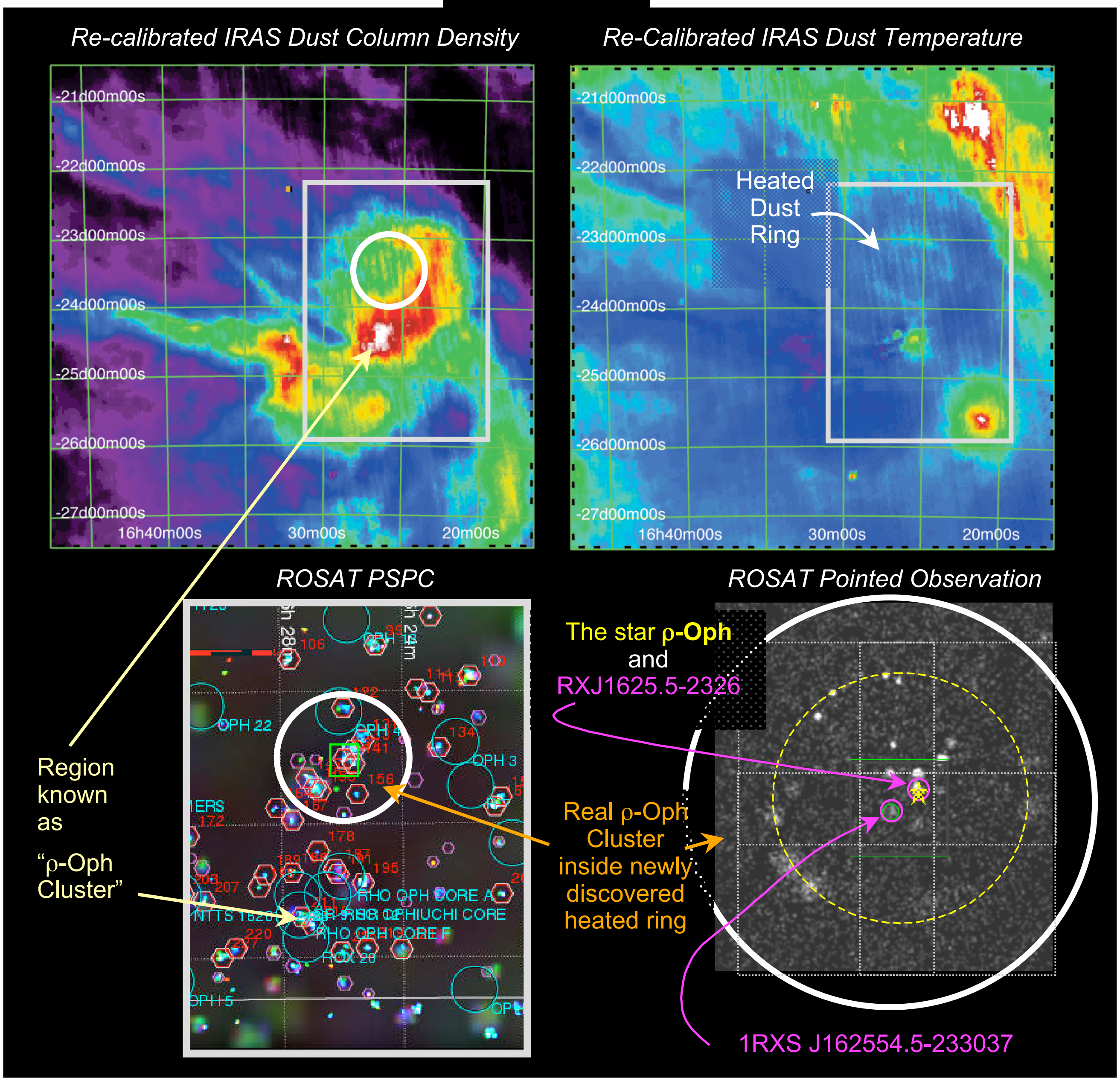
This proposal offers Chandra a chance to solve a mystery. The composite figure below, explained in this proposal, takes us through the first many chapters of an obviously exciting story—all about giant rings of smoke being blown into the interstellar medium. When completed, the story will tell a great tale of many generations of stars forming in Ophiuchus. Trouble is, without some help from Chandra, we still don't know much about the protagonist(s).

Figure 1



*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.*

Background Information: Will the Real ρ-Oph Cluster Please Stand Up?

Ophiuchus is one of a handful of well-studied star-forming regions within 200 pc of the Sun. The distance to Ophiuchus is ~160 pc, so the 1-degree grid boxes shown in Figure 1 correspond to about 2 pc in our region of interest. The area labeled "Region known as ρ-Oph Cluster" in Figure 1 contains more than 400 forming stars, the most massive of which is a B star (Bontemps et al. 2001; Wilking, Lada & Young 1989). Trouble is, it turns out this region is only known as the "ρ-Oph Cluster" because it is *near* the young BIV star ρ-Oph—not around it (see the labeled yellow star in Figure 1's lower right panel). Now, though, thanks to a ring of warm smoke revealed by new IRAS maps and a gaggle of embedded sources revealed by ROSAT (see Figure 1), we have found the *real ρ-Oph Cluster*, and we would like to study it[1].

The new IRAS-based column density and temperature maps shown in Figure 1 (from Goodman, Li & Schnee 2003) were created in conjunction with the ongoing **CO**ordinated **M**olecular **P**robe **L**ine **E**xtinction **T**hermal **E**mission (**COMPLETE**) Survey of Star Forming Regions. COMPLETE is a large, international, coordinated effort to map three >10-pc-scale star forming regions being mapped under the SIRTF Legacy Cores-to-Disks (c2d) program with every relevant ground-based method of measuring density, temperature and velocity structure.[2] In order to create the new IRAS maps, we re-calibrated the zero points of the IRAS Sky Survey Atlas (ISSA) 60 and 100 micron plates, to facilitate their use down to very low flux levels.

Upon examining the "new & improved" IRAS maps made for COMPLETE, we *discovered* the 2-pc diameter heated dust ring shown in Figures 1 and 2. The temperature of that ring is only about 37 K, or 7 K hotter than its immediate environment. After further investigation, we determined that the unusual X-ray source 1RXSJ162554.5-233037 (discussed below) lies very near the ring's center. We also noticed that the elevated-temperature ring fits neatly inside a crook of dust emission extending North from the ρ-Oph region (see Figure 1).

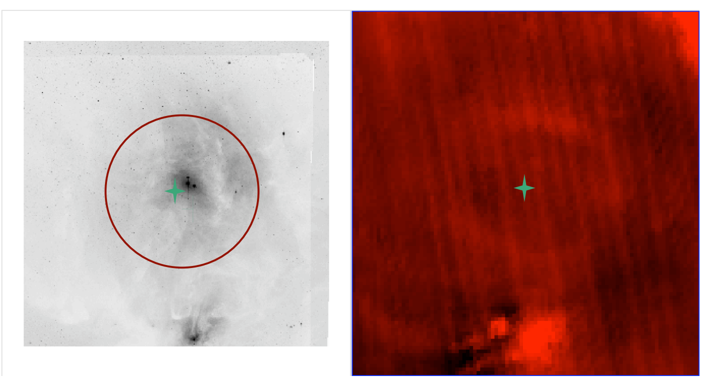


Figure 2: *Left panel:* Nebulosity around ρ-Oph (DSS); *Right Panel:* IRAS temperature image of shell (colors from 26 to 39 K only). The maroon ring shows the same 2 pc diameter shell as on the previous page, and the green star shows 1RXS J162554-233037. ρ-Oph is apparent in the left panel with diffraction spikes.

With great surprise, we also realized that the ring we detected in IRAS encircles the famous star ρ-Ophiuchi, for which the (famous, but fraudulently named) "ρ-Oph cluster" a full degree south of (the real) ρ -Oph is named. ρ-Oph itself is a BIV star, and it powers an oft-photographed very beautiful bright nebula, shown in black and white in Figure 2. This existence of this nebula historically made it difficult to search in the optical for a cluster *really* associated with ρ -Oph, and *until now, none was known*.

Fortuitously, the region around (the real) ρ -Oph, interior to the IRAS ring, was serendipitously included in a ROSAT pointed observation made by Snowden et al. in 1994. The data from the pointed observation show about twenty ROSAT-detected point sources within the IRAS ring, all with heavily "reddened" hardness ratios, suggestive that the sources form a loose embedded cluster associated with ρ-Oph. One source, **1RXSJ162554.5-233037** has a well-determined Hardness Ratio 2=1.0, and Hardness Ratio 1=0.6, making it an excellent candidate to be some kind of "exotic" compact object (e.g. neutron star, accreting binary). Furthermore, with only a small dose of imagination, one can see that most of

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[1] Do not be fooled by papers in print with titles like "CHANDRA Observations of the ρ-Ophiuchi Cloud" (Imanishi et al. 2001). Every Chandra observation of this region to date has been of the southern, well-known cluster, not the one around the "real" ρ-Oph.

[2] Please see http://cfa-www.harvard.edu/COMPLETE for more information.

the ROSAT sources discovered around ρ-Oph lie on another ring, interior to the IRAS ring (see the light dashed line in Figure 1). The Chandra observations proposed below will easily reveal whether or not this ring in the pattern the ROSAT sources was an illusion or not.

What caused the ring in Ophiuchus, and what might it have to do with sequential star formation?

The most obvious astronomical hypothesis when a warm nearly-perfect circle is found potentially centered on an exotic X-ray source is that a powerful wind, maybe even a supernova, created a shell in the interstellar medium which we observe as a limb-brightened ring.

To evaluate the plausibility of the Ophiuchus ring being a supernova, we can use the simple formalism set out in Mike Shull's "Signature of a Buried Supernova" paper of 1980, to calculate that a 0.5 x 10^{51} erg supernova ejecting a mass of 1 solar mass into a medium, like the dense parts of Ophiuchus, with a density of 10^5 cm^{-3} would reach the size apparent in the Figures (~2 pc) in about 200,000 years. At that time, the temperature of the shell would be 38 K—eerily like the color temperature we observe. The velocity of this shell at 200,000 years would be only 1.7 km s^{-1}, which is only slightly larger than the ^{13}CO line widths in this region, and thus nearly undetectable as an expansion—unless one were explicitly looking for such a signature. The (well-known, southern) "ρ-Oph" cluster contains some stars as old as ~1 Myr, so we do *not* think that this hypothetical 200,000-year-old supernova would have directly "triggered" the formation of the (well-known, southern) "ρ-Oph" cluster—but the calculation certainly makes one wonder whether the ρ-Oph molecular cloud complex has at least been struck by at least one supernova since it began forming stars.[3] Also, the (possibly accidental) ring-like pattern of the ROSAT sources apparent in Figure 1, which is concentric with and interior to the IRAS ring, leads one to dream that perhaps this hypothetical supernova could even have "exploded" its host cluster, sending stars to the (constant) radial distance from the explosion's center where we see them now.

But, SNe are not the only way to drive powerful winds into the ISM—a substantial wind should be associated with the B star ρ-Oph itself. At this time, though, without more information on the sources around (the real) ρ-Oph, and more information about the mass[4] and velocity of the ring, it is hard for us to evaluate the host of possible hypotheses. *Identifying the creator of the IRAS ring, and constraining its former identity (SN progenitor, star with wind, accreting binary, etc.) is the primary goal of our proposed Chandra observations.*

Our longer-term goal, which also justifies much of the COMPLETE Survey, is to *evaluate the role of previous generations of stars on the long-term productivity of star-forming molecular gas*. For example, with COMPLETE and SIRTF data, we will be able to use molecular-line observations along with a point-source census to statistically evaluate the role of pc-scale bipolar outflows from young stars in churning and destroying their natal clouds. By studying large shells like the one described in this proposal, we are investigating the influence of prior generations of stars on their associated molecular clouds on very large (>>1 pc) spatial scales, and honestly unknown timescales. Imagine, for example, that star-formation in one region (e.g. the southern well-known "ρ-Oph cluster") is accelerated by increased pressure caused by the expansion of a neighboring shell (e.g. the one associated with 1RXSJ162554.5-233037). This hypothesis, similar to the one put forward as "sequential star formation" by Elmegreen and Lada (1977), implies that one *cannot* legitimately calculate star-formation rates and/or efficiencies, in our Galaxy or anywhere else, without taking environmental effects—on large scales—into account.

Why Chandra?

The missing chapters of the story we described at the outset tell what protagonist(s) caused the warm dust ring around 1RXSJ162554.5-233037, and how and when the shell was created. The research for these

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[3] On the longer time scale, and larger spatial scale, de Geus and colleagues argued very convincingly that the bubbly and filamentary nature of the entire Sco-Cen-Oph region of the ISM can be explained as due to the effects of stellar associations and their winds upon each other (de Geus 1992; de Geus, Bronfman, & Thaddeus 1990; de Geus & Burton 1991; de Geus, de Zeeuw, & Lub 1989).

[4] As part of COMPLETE, we have been awarded a large amount of time on the JCMT, where we are using the SCUBA instrument to map out dust mass. The region of the IRAS ring in Ophiuchus was observed in March 2003, and the data are currently being reduced.

missing chapters necessitates a multi-wavelength approach. Existing radio continuum data are insufficiently sensitive to find the synchrotron emission that might be associated with this shell, so we are in the process of proposing to search for it later this year. Radio-wavelength molecular or HI-absorption spectral-line data might reveal expansion in the shell, and we are in the process, as part of COMPLETE, of acquiring the relevant data at FCRAO and the GBT. Far-IR data gave us the introductory chapter to our mystery, by revealing the Ophiuchus ring. Existing (almost released!) 2MASS and upcoming SIRTF near-IR data will give much needed information about the age and mass distribution of the cluster associated with (the real) ρ-Oph, as well as the extinction structure within the shell.[5] The near-IR data are critical, since optical images of this region are dominated by the nebulosity around ρ-Oph. And, last but certainly not least, X-rays may well hold the key to unlocking the mystery. The ROSAT data have already strongly hinted that 1RXSJ162554.5-233037 may well be our protagonist(s), but we need to know much more about this character before writing more of our story.

Observations Planned

Our strategy is to map enough of the (real) ρ-Oph cluster region to accurately determine the positions of all cluster members, while simultaneously covering a large enough area to survey nearly all of the ring discovered in the new IRAS temperature maps. ACIS is not appropriate for these goals, because of its limited field-of-view, and the severe pile up from which the bright sources in this field will suffer. We therefore propose to utilize the HRC-I detector, observing in four overlapping 30'-square fields, shown as outlined squares in Figure 1's bottom right panel. Each HRC pointing will last 15 ksec, so we will be able to detect on-axis sources as faint as 2×10^{-14} ergs sec^{-1}. This is about 20 times deeper than the ROSAT data. The HRC observations will have adequate resolution and sensitivity to separate close pairs and multiples that would not be apparent at ROSAT resolution (see Figure 1). Also, if 1RXSJ162554.5-233037 is as exotic as the ROSAT observations suggest it may be, HRC-I will allow us to put some initial constraints on the presence of pulsations from this source. We are also submitting a proposal, very similar to this one, to XMM, to do spectroscopy of the sources we will map out with Chandra/HRC, and to search for any extended hot gas that may fill the bubble indicated by the IRAS-detected circle. The XMM observations alone would not provide the spatial resolution of HRC-I, which is critical in the identification of all the individual cluster members.

ROSAT saw a count rate in 1RXSJ162554.5-233037 of about 0.016 cps. We used PIMMS to scale this to our expectations for Chandra/HRC assuming a single source. For flux estimation we assumed a 1.5 keV blackbody and $N_{\rm H} = 10^{22}$ cm^{-2}. The projected Chandra count rate is 0.068 cps, which would provide about 1000 photons per exposure This is a lower limit as the hot component is probably much hotter. For a sinusoidal pulse profile, our sensitivity will allow us to detect a periodicity in a blind search down to a pulsed fraction of 30%, or 15% if the pulse is narrow. We may do even better, if the 4 observations are consecutive (our preference). In this case we would see about at least 4000 photons in a fairly coherent time frame.

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[5] As part of COMPLETE, we are using a sophisticated star-counting algorithm known as "NICER" to map extinction without the bias caused by dust temperature when using thermal dust emission measurements (see Lombardi & Alves 2001 and references therein).