COMPLET(E)ING THE STAR-FORMATION HISTORY OF THE RHO-OPH REGION

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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.

Located only 160pc from the Sun, the Ophiuchus molecular cloud is one of the most conspicuous nearby regions where low- and intermediate-mass star formation is taking place (e.g. Wilking 1992 for a review). The Ophiuchus cloud consists of two massive, centrally condensed cores, L1688 and L1689, from each of which a filamentary system of streamers extends to the north-east over tens of parsecs (e.g. Loren 1989). While little star formation activity is observed in the streamers, the westernmost core, L1688 (figure 1), harbors a rich cluster of young stellar objects (YSOs) at various evolutionary stages and is distinguished by a high star-formation efficiency (Wilking & Lada 1983 - hereafter WL83). This young stellar cluster and the cloud core in which it resides are commonly referred to as the ρ-Oph star-forming region. Both the gas/dust content and the embedded stellar population of ρ−Oph have been extensively studied for more than two decades. The distribution of the low-density molecular gas was mapped in $C^{18}O$(1-0) by WL83, revealing a ridge of high column density gas. Loren (1989) observed the entire cloud (including the streamers) in ^{13}CO(1-0), while the emission from cold dust was mapped extensively in the millimeter continuum by Motte et al. (1998).

The stellar content of the ρ−Oph cloud core has also been observed at wavelengths ranging between the x-ray and the radio band. In x-rays, Einstein and ROSAT surveys revealed highly variable sources associated with magnetically-active young stars (Montmerle et al. 1983, Casanova et al. 1995). In the near-infrared, several surveys (e.g. Greene & Young 1992, Barsony et al. 1997) have discovered more than 200 low-luminosity embedded sources. In the centimeter radio continuum range, several VLA surveys have resulted in the discovery of more than 20 radio-emitting YSOs (e.g. Leous et al. 1991).

Because of the wealth of data available and small distance enabling it to be studied at small spatial scales, the ρ-Oph region has come to be seen as a reference laboratory to which other regions of low- and intermediate-mass star formation are compared. The main cloud offers both the nearest example of a region of induced (or triggered) star formation (e.g. Vrba 1977) and the nearest example of a young embedded cluster (WL83). It is the phenomenon of triggered star-formation that we address in this proposal.

ρ−Oph vs. ρ−Ophiuchi

As part of the COMPLETE Survey of Star Forming Regions[1] we have recently constructed new temperature and thermal-emission (column density) maps of the Ophiuchus region from IRAS Sky Survey Atlas (ISSA) 60 and 100μm images, and were surprised to find ring of warm (37K) dust located approximately 1° to the north of the ρ-Oph star-forming region (figure 1; Li et al. in prep.). Comparison with the extinction map shows that the ring sits neatly inside a "nook" of high-extinction (i.e. cold dense material) on the northern edge of ρ-Oph. In fact, this ring was reported by Bernard et al. (1993) in a discussion of the far-infrared emission from Ophiuchus and Chamaeleon, but they did not investigate its nature or possible progenitor. The ring is centered on the young BIV star, ρ-Ophiuchi[2], which also powers

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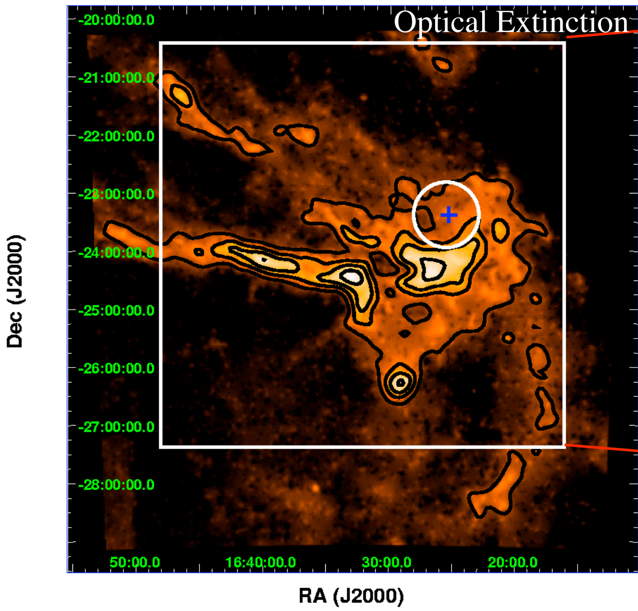
[1] **C**o**O**rdinated **M**olecular **P**robe **L**ine, **E**xtinction and **T**hermal **E**mission; http://cfa-www.harvard.edu/COMPLETE

[2] To prevent confusion, we will refer to this star as 5−Oph throughout the remainder of this proposal, while the (confusingly named) star-forming region 1° to its south will be referred to as ρ-Oph.



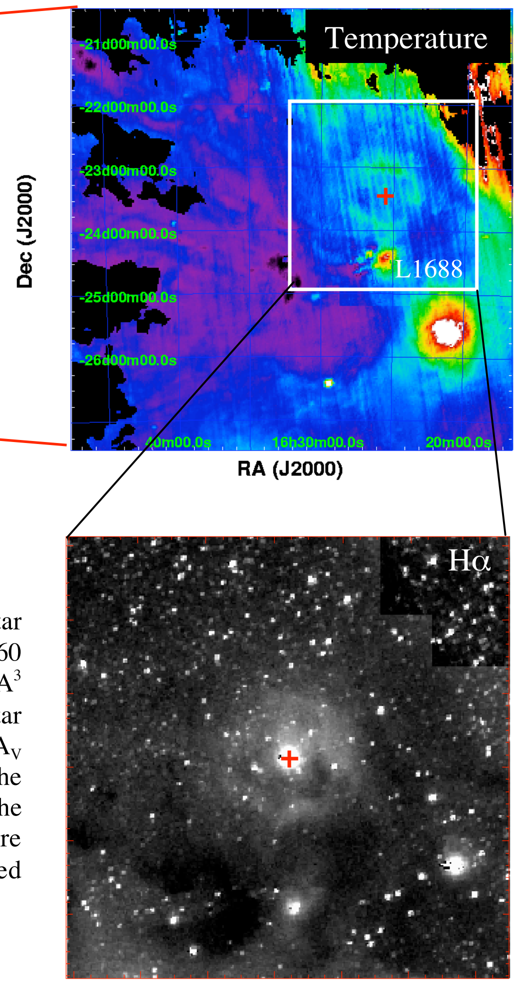


Figure 1: The Ophiuchus region in extinction from R-band star counts (above; Cambresy et al. 1999), temperature from IRAS 60 and 100μm emission (above right) and H-α from SHASSA[3] (right). In each figure the cross indicates the position of the star 5-Oph. The contours in the extinction map are spaced at A_V intervals of 2, starting at an A_V of 2. The position and size of the ring are indicated by a white circle in the extinction map. The position of L1688 (aka ρ-Oph) is indicated in the temperature map. The bright source to the south west is an unrelated foreground star.

This figure should be viewed in colour.

an oft-photographed bright nebula. The SHASSA[3] H-α image shows a circular limb-brightened nebulosity, indicating that the IRAS dust ring is almost certainly due to a powerful stellar wind or HII region, most likely from 5-Oph itself.

The presence of an HII region suggests that 5-Oph is probably still relatively young, and it would therefore be located near to its birthplace and, assuming a Salpeter-like IMF, within a cluster of several hundred low or intermediate mass stars. If this is the case, then this cluster would comprise a significant fraction of the total young stars in the Ophiuchus region, and provide strong evidence for an earlier epoch of star formation in Ophiuchus which could be impacting on the current star-formation activity of the region. With Ophiuchus located so nearby, we have an unprecedented opportunity to study sequential star formation. 5-Oph and the HII region provide us with an accurate timescale for the progression of the compression wave through the dense gas, clearly demonstrating the time at which star-formation started in the ρ-Oph cluster.

While the possibility of triggered star formation in ρ-Oph poses an interesting topic on its own, the location of a massive star so close (the ring diameter is just 2pc) to a young cluster of lower mass stars may also provide us with a clue to the early evolution of our own pre-solar nebula. Studies of primitive meteoritic material formed in the early solar system have frequently found the decay products of several relatively short lived extinct radionuclides, e.g. ^{26}Al. These nuclides are generally thought to be produced in supernovae or AGB star winds, and transporting them into the pre-solar nebula before they decay would require such a phenomenon to have occurred within just a few parsecs at the time of the Sun's formation (e.g. Cameron et al 1995). Other authors (e.g. Glassgold et al. 2000 and refs. therein) have

[3] Southern H-alpha All Sky Survey Atlas; http://amundsen.swarthmore.edu/SHASSA/

suggested that the nuclides could have been formed by the irradiation of early solar system material by flares of extremely high energy x-ray flux common in T-Tauri stars. This explanation has become favoured because it does not require the more complex scenario of an evolved (rare) massive star located so close to the Sun's birthplace. However, in the case of Ophiuchus we now have direct evidence for a relatively massive star, with a lifetime of the order of the pre-main-sequence evolution time-scale of a G star (30-100Myr) within just a few parsecs of possibly hundreds of young solar analogues.

Why Chandra?

In order to test the hypothesis of sequential star formation, we need to measure the ages of young stars near 5-Oph, and determine if the older cluster is uniform in age, or if the stars become progressively younger towards the (younger) ρ-Oph cluster.

The existence of the optical nebula and high extinction in the region has historically made it difficult to search for a cluster associated with 5-Oph. An H-α survey by Wilking et al. (1987) found just a few stars close to 5-Oph, but the more recent SHASSA H-α image and 2MASS K-band images of the area surrounding the star seem to show an over-density of stars. However, neither H-α or 2MASS observations can be used as an unbiased method to identify young stars – both H-α and K-band excess are strong evidence for the presence of disks, but this criterion will miss "older" pre-main-sequence stars (e.g. weak line T-Tauri stars, wTTs) which have already shed most of their circumstellar material. WTTSs are well-known to have x-ray emission due to energetic processes on their surfaces, thought to be related to their dynamic magnetic fields, and x-rays have the added advantage of being able to penetrate the high line-of-sight extinction towards regions of recent star formation. For these reasons it has become customary to search for young stars in the x-ray (see e.g. Glassgold et al. 2000 and refs. therein).

The region surrounding 5-Oph was serendipitously included in a ROSAT pointed observation (Snowden et al. 1994). These data show about twenty x-ray point sources within the ring, all with heavily reddened hardness ratios, suggesting that the sources form a loose embedded cluster associated with the B star. Several of these sources seem to lie on another ring, interior to the ring traced by the HII region. Interestingly, one of the x-ray sources detected by ROSAT close to the centre of the ring has well-determined hardness ratios consistent with it being a compact object, possibly a neutron star. Although we don't believe that the ring is a supernova remnant, the serendipitous inclusion of this source within our proposed x-ray observations will enable us to rule this scenario out conclusively.

Meanwhile, the ρ-Oph cluster has been observed in x-rays, including by *Chandra*, many times (e.g. Casanova et al. 1995, Grosso et al. 2000, Imanishi et al. 2001, Vuong et al. 2003; table 1). These observations have revealed more than 100 x-ray sources, almost 70% of which have been confirmed as young stars by e.g. optical or infrared spectroscopy (e.g. Martín et al. 1998).

These and other surveys have shown that x-rays provide the only unbiased way to find young (pre-main-sequence) stars in regions of high visual extinction, while the small point spread function (PSF) of *Chandra* make it ideal this type of study, where we expect a field crowded with x-ray sources.

Additionally, the x-ray observations will be uniquely sensitive to any diffuse hot plasma that may be caused by a wind from 5-Oph. Such plasmas have been observed in more distant massive star-forming regions by e.g. Townsley et al. (2003). If such a plasma exists, its temperature and density can constrain the mass load against it, while knowledge of the luminosity of the B-star constrains the total kinetic energy available to the wind. By comparison to models (e.g. Cantó et al. 2000) we will be able to strongly constrain the evolution of the dust ring.

Proposed Observations

We expect to make use of archival data from 3 previous *Chandra* programs: T. Montmerle made extensive survey observations of the ρ-Oph cloud and two deep observations of the centre of the cloud core have been made. These observations are summarised in table 1 and overlaid on the optical extinction map of the region in figure 2. However, in order to achieve our scientific goals, we require new observations of the region between ρ-Oph and 5–Oph.

It is unfeasible to map the entire region surrounding 5-Oph with *Chandra*. We therefore propose to make a set of representative observations which should give an accurate indication of the overall population of young stars. Our strategy is to use ACIS to perform survey observations (10ks) of 7 fields, indicated by cyan boxes in figure 2. We have chosen the fields such that we have continuous coverage from the B-star to the region where archival data is available. This will allow us to explore the ages of young stars across the boundary between the ring and the active star-forming region. We will observe two additional fields to the north-west of the star, in order to test for spherical symmetry of the young stellar population. The seven fields can be co-added to increase sensitivity to extended emission, although limb darkening may make this unnecessary.

From figure 6.27 of the Proposer's Observatory Guide, a 10ks ACIS-I exposure achieves on-axis sensitivity of about 4×10^{-15} ergs/cm^2/sec. This is the incident flux at ACIS after absorption. To convert this to unabsorbed flux, we assume N_H is fairly high in this cloud, about 10^{22} cm^{-2}. Using PIMMS we model the corona of the stars as a 1.5keV thermal Bremsstrahlung plasma and assume the cluster is at 160pc to derive a luminosity limit at the source of 4×10^{28} ergs/sec. This is a similar depth to the HRC image of the Orion Nebula (Flaccomio et al. 2003) who detected all stars down to 0.5M_{sun} and 66% of stars between 0.03 M_{sun} and 0.5 M_{sun}.

P.I.	Proposal #	Exposure time per field (ks)	Fig. 2 colour
Montmerle	01200572	5	blue
Koyama	01200705	100	green
Gagne	01200767	100	green
Goodman	This proposal	10	cyan

Table 1: Summary of previous and proposed observations of the Ophiuchus region. The last column indicates the colour used in figure 2 to display the observations.

This figure should be viewed in colour.

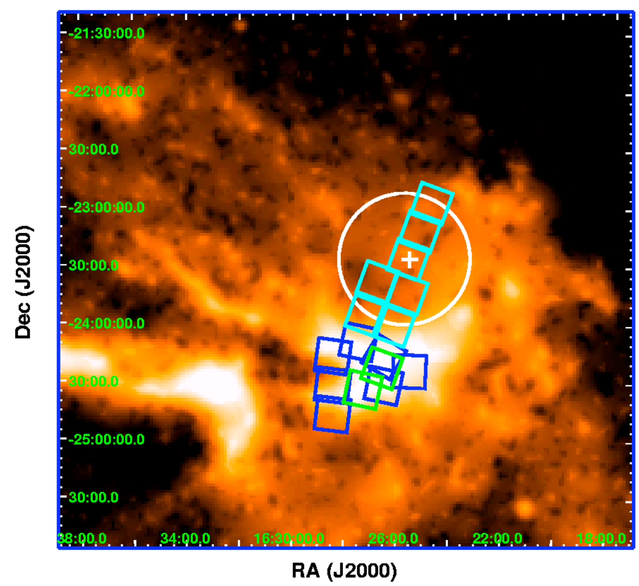


Figure 2: Extinction map from figure 1, overlaid with the outlines of previously observed Chandra fields in ρ-Oph (blue and green; see table 1 for an explanation) and proposed fields near 5–Oph (cyan). The white circle and cross show the position of the IRAS ring and the star 5-Oph respectively.

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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.

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Previous *Chandra* Programs

Neither the P.I. (Goodman) or the Observing Co.I. (Ridge) have previously been awarded Chandra observations.