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NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: October 1, 2004 **Category:** Star Forming Regions

The COMPLETE Density Structure of Star Forming Cores: IR-extinction mapping in Ophiuchus

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)***:**
The COMPLETE (COordinated Molecular Probe Line Extinction Thermal Emission) Survey of Star-forming Regions is painting a uniquely comprehensive picture of large, nearby star-forming regions. Through a public database, this collaboration will help researchers answer key questions about star-formation for years to come. A vital component of this picture is near-infrared extinction mapping, which traces dense regimes in star-forming cores more reliably than any other method. We have already used 2MASS and the NICER (Near-Infrared Color Excess Revisited) technique to broadly map extinction in the Ophiuchus star-forming region. The proposed observations will provide 5 pixels for every one in the 2MASS-based maps, and offer improved dynamic range. These twin improvements will allow us to trace the density structure of star-forming gas from the highly-turbulent "dark cloud" regime to a smooth "coherent core". This "transition to coherence" remains one of the least understood aspects of star formation. No single study before COMPLETE has traced this entire process for many star-forming sites in the same region.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	CT-4m	ISPI	4	bright	May - Jun	May - Jul
2						
3						
4						
5						
6						

Scheduling constraints and non-usable dates *(up to four lines).*

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

The molecular cloud complex in Ophiuchus is an ideal laboratory in which to study star formation. Relatively close (160 pc), it contains star formation over a wide range of physical parameters, from the dense central region to isolated cores in nebulous filaments. This cloud is a target of the Spitzer Space Telescope Legacy program "From Molecular Cores to Planet Forming Disks" (c2d), which will uncover new young stars. The COMPLETE (COordinated Molecular Probe Line Extinction Thermal Emission) Survey of Star-forming Regions is taking advantage of this natural laboratory, mapping molecular lines, thermal emission, and extinction broadly on large scales and deeply in selected regions in order to understand the star formation process on a wide range of scales (0.1 -10pc). Extinction mapping gives unique information about the density structure in clouds, and when combined with molecular and dust emission data, it can tell us the masses, extinction laws, and molecular depletion of these clouds. With deep, wide observations we will reach the scale of core-coherence (0.1 pc), with detailed knowledge about the surrounding turbulent medium.

Near-infrared extinction mapping is an extension of the revelatory work of Barnard (1919), who used optical star counting to measure extinction. Lombardi & Alves (2001) extended the pioneering work of Lada et al. (1994) with NICER (Near-Infrared Color Excess method Revisited), which taught us much about star-forming cores: that the structure of dark cloud cores like B68 is often characterized by a Bonnor-Ebert sphere (Alves et al. 2001), that the density profiles of filamentary clouds are much less steep than predicted, and that, in combination with millimeter emission, we can trace molecular depletion deeply into clouds (Kramer et al. 1999). The resolution of an extinction map is proportional to the density of stars used in its construction. This makes near-infrared maps ideal, since the light from stars penetrates the dust more easily than in the visible (see Figure 1). Stars also have low intrinsic color in the near-infrared, so we can use the colors of each star as a measure of extinction without needing detailed stellar types. While the mid- to far- infrared cameras on Spitzer see through the dust even better, stars are intrinsically significantly fainter at these wavelengths and hence the optimum place to map extinction remains the near-infrared.

The key to COMPLETE is coordination: combining different methods produces new insight. We have already made broad extinction maps of Ophiuchus using NICER applied to 2MASS data, but the sensitivity of 2MASS limits us to an effective resolution of $\sim 3'$— the whole size of dense star forming cores. We propose new observations to make higher resolution extinction maps of selected dense parts of Ophiuchus with a resolution of $\sim$ 80/arcsec, enabling us to resolve density structure inside individual cores. Molecular line and millimeter continuum observations are being obtained for COMPLETE. The proposed extinction maps combined with our IRAM 30-m COMPLETE molecular line maps will allow us to separate density structure from chemical (depletion) structure; combined with COMPLETE's IRAM 30-m MAMBO dust continuum maps they will allow us to separate density structure from (dust) temperature structure. One curious discovery we have already made is that in Perseus, another region being studied by COMPLETE, ^{13}CO emission appears to be a poor tracer of the true density at low extinctions ($A_V < 2$) where it is often used, especially by those studying the role of turbulence in stars formation, as a reliable tracer. We do not see as much of an effect in Ophiuchus, so we are very interested to compare ^{13}CO and extinction at high resolution and uncover why these regions differ.

With all of COMPLETE's data, we will be able to chart the temperature and density of star-forming dust and gas over a large range of spatial scales, and to interpret kinematics of those distributions. Nearly all of the data needed to reach this goal of a "COMPLETE" physical picture of star-forming regions is in-hand, or is being obtained. The high-resolution extinction observations requested here will give density profiles for many different cores — a critical final piece of the picture.

References

Alves, J., Lada, C. J., & Lada, E. A. (2001), Nature, 409, 159.

Barnard E.E. (1919), ApJ, 49, 1.

Lada, C.J., Lada, E.A., Clemens, D.P. & Bally, J. (1994), ApJ, 429, 694.

Lombardi, M. & Alves, J. (2001), A&A 377, 1023.

Kramer, C., Alves, J., et al. (1999), A&A, 342, 257

Kramer, C., Alves, J. et al. (1998), A&A, 329L, 33

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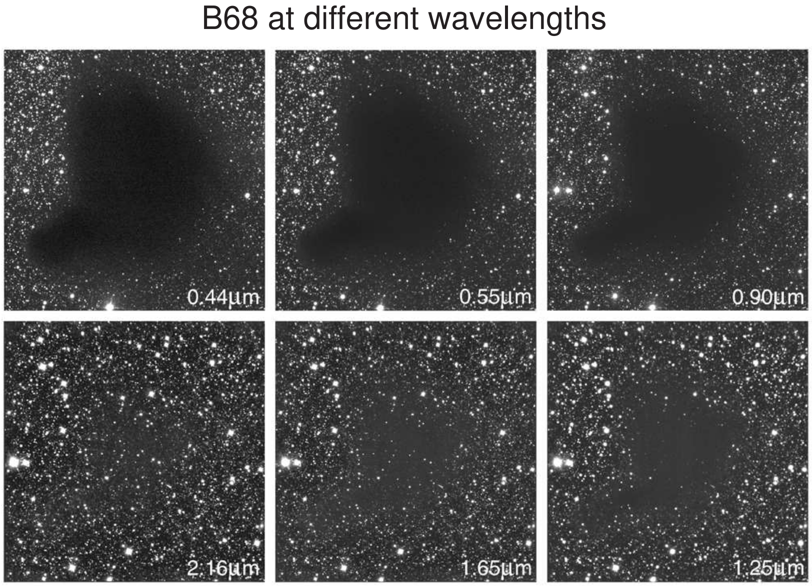

Figure 1: At longer wavelengths, more and more stars peer out from behind the cloud, allowing us to probe into denser and denser regions with higher spatial resolution.

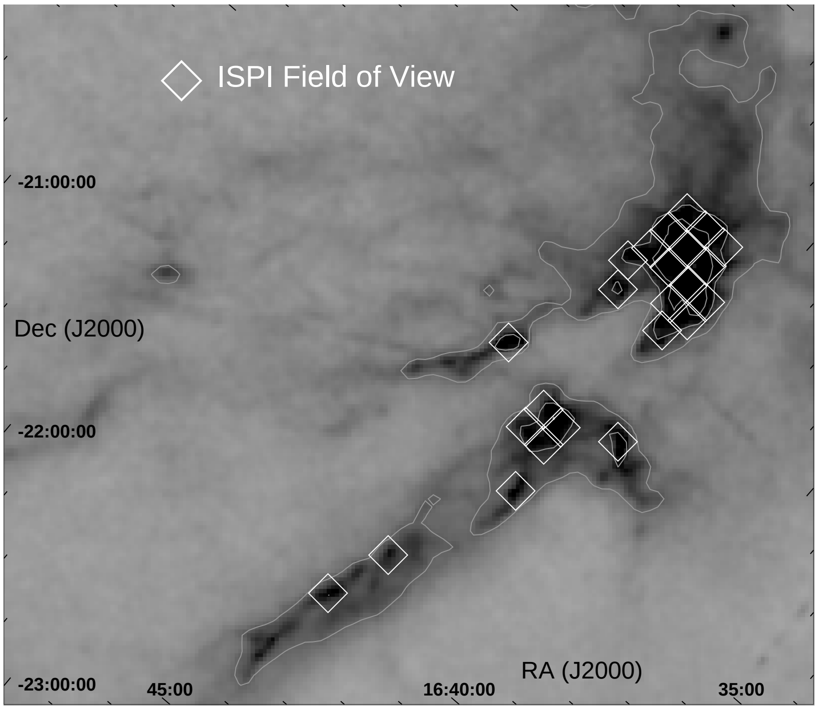

Figure 2: NICER extinction map of Ophiuchus using 2MASS data. The contours are at A_V = 5,10,15 mag. The squares are where we propose to obtain deeper infrared images, providing better resolution, a higher limiting A_V and detailed comparison with other COMPLETE observations.

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

We will observe 24 ISPI frames within Ophiuchus. A large number of these frames are dedicated to the central region, while the rest cover most of the dense cores with an $A_V > 10$ embedded in the filaments. Fields were chosen using using the broad but shallow extinction map made from NICER applied to 2MASS J,H, and K colors (see Figure 2). The new observations will provide much greater resolution than is possible with 2MASS, so we will achieve similar resolution and coverage in extinction, millimeter emission, and CO emission for a large number of individual cores.

The proposed JHK observations can be achieved through simple "shift-and-add" NIR techniques. With a FOV= $10.25' \times 10.25'$ we plan a total of 24 science pointings (with small overlap to allow for mosaicing) and 4 control fields. The method that will be used to derive infrared extinction relies strongly on the observation of these control fields, from which we derive the normal stellar background and any extinction that is foreground to the entire complex. Since the Ophiuchus complex stretches over a fairly broad region, we will obtain control fields at four locations around the edge of the complex where we expect there is no gas and dust, as evidenced by a lack of CO emission, and zero extinction in the 2MASS extinction map. One control field each night will provide for accurate calibration.

From estimated cumulative star counts provided by Martin Cohen for Ophiuchus in H and K using the SKY4 model (Cohen 1994), we are able to estimate the stellar density we expect to see as a function of magnitude. At a proposed depth of H = 20.6 magnitudes and using our experience from the 2MASS maps, we hope to reach a resolution of $\sim 80''$(further details available in the technical section). This corresponds to ≈ 0.06 pc at the distance of Ophiuchus, and should allow us to resolve the density profiles of individual cores.

This study will thus shed valuable light on: the transition to coherence, by resolving density structure both within, and in a wide field around cores; molecular depletion, by comparison with molecular tracers such as N_2H^+; and temperature versus density structure, by comparison with IRAM 30-m MAMBO dust continuum. Although each of these has previously been studied for individual regions, this project will be the first case in which all methods are used on a large number of cores within one complex, allowing us to develop a notion of a "typical" core versus ones which appear to be unusual.

Proprietary Period: 18 months

Use of Other Facilities *Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program.*

The COMPLETE project makes use of a wide range of telescopes, and we expect to combine our infrared extinction maps with this data to study star formation in novel ways. In the radio, FCRAO is being used to map ^{13}CO, the IRAM 30-m is mapping N_2H^+, and we have used the GBT to map HI self-absorption. In the millimeter/sub-millimeter regime, we are using SCUBA and MAMBO to map thermal emission and dense, starless cores. 2MASS colors have allowed us to obtain large-scale infrared extinction maps. In space, the COMPLETE team has used re-reduced IRAS data to identify a previously little studied ring in Ophiuchus. As previously mentioned, the c2d (Cores to Disks) legacy project on the Spitzer Space Telescope will search for embedded stars in Ophiuchus, adding virtually all the young stars to our picture of star-forming clouds. Spitzer will also provide images of the extended emission in Ophiuchus in the IRAC and MIPS wavebands.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

None

Observing Run Details for Run 1: CT-4m/ISPI

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

Ophiuchus is an ideal place to study star formation. The ideal instrument to observe it for extinction mapping is at a 4-meter telescopes with a wide-field near-IR camera. This combination is a judicious weighting of our desire to cover a large number of cores (requiring a large field of view) with our desire to resolve cores at a scale of $\sim 80''$ (requiring very deep exposures to have enough background stars). Thus the ideal site for Ophiuchus extinction-mapping observations is CTIO, with ISPI (Infrared Side Port Imager) on the 4-m.

Martin Cohen provided us with estimated cumulative star counts for the center of Ophiuchus in H and K using his SKY4 model (Cohen 1994). The number of stars observed limits the resolution of the map. From our experience with the 2MASS extinction map we discovered that to make a map with no holes after we spatially smooth required an average of $\approx$ 12 (stars)/(pixel), a criteria we adopt here.

The limiting factor in dense cores at this galactic latitude is seeing enough stars in H (which is, at an A_V of 10, 0.6 magnitudes dimmer than K). We aim for $80''$ resolution which corresponds to $\approx$ 0.06 pc at the distance of Ophiuchus. To achieve the necessary stellar density, the SKY4 model predicts we will have to reach a magnitude of H $\approx$ 20 (20.6 mag with an A_V of 10 obscuring stars in the densest regions). Based on the ISPI exposure calculator we can reach 5σ photometry to this magnitude in H in 20 minutes of exposure time, or 40 minutes of observing, assuming 50% efficiency.

A similar stellar density in K is reached at 19.75 mag, which can be reached in 15 minutes of integration, or 30 minutes of observing. At regions of high extinction we will see few stars at J, so this frame is used mainly to obtain color-color diagrams of the region for calibration purposes. We plan to reach a J of 19 mag in 2.5 minutes of integration time, or 5 minutes of observing. In total then, a science frame will require 75 minutes of observing (accounting for overhead).

Our source is observable (above an airmass of 2) for about 9 hours during the optimum time requested in this proposal. We propose to do 6 science frames and one calibration region each night. Our 24 frames will thus require 4 nights.

Instrument Configuration

Filters: J,H,K	Slit:	Fiber cable:
Grating/grism:	Multislit:	Corrector:
Order:	λ_{start}:	Collimator:
Cross disperser:	λ_{end}:	Atmos. disp. corr.:

R.A. range of principal targets (hours): 16 to 17

Dec. range of principal targets (degrees): -30 to -18

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

NOAO observing proposal LaTeX macros v2.9.

Table 1: Ophiuchus Targets

Designation	RA	Dec	J mag	H mag	K mag
Oph1	16:31:51.4	24:54:19.2	20.6	19.75	19
Oph2	16:25:59.8	24:17:41.5	20.6	19.75	19
Oph3	16:26:00.8	24:26:53.6	20.6	19.75	19
Oph4	16:26:41.2	24:17:07.9	20.6	19.75	19
Oph5	16:26:43.4	24:26:34.6	20.6	19.75	19
Oph6	16:27:21.3	24:16:18.9	20.6	19.75	19
Oph7	16:27:24.8	24:26:00.2	20.6	19.75	19
Oph8	16:26:01.8	24:36:05.5	20.6	19.75	19
Oph9	16:26:43.4	24:36:03.1	20.6	19.75	19
Oph10	16:27:26.0	24:35:43.2	20.6	19.75	19
Oph11	16:28:46.7	24:17:12.2	20.6	19.75	19
Oph12	16:34:40.4	24:37:36.7	20.6	19.75	19
Oph13	16:31:48.2	23:59:43.7	20.6	19.75	19
Oph14	16:33:11.9	24:24:55.4	20.6	19.75	19
Oph15	16:33:14.5	24:34:20.0	20.6	19.75	19
Oph16	16:32:32.0	24:25:50.2	20.6	19.75	19
Oph17	16:32:35.6	24:34:58.2	20.6	19.75	19
Oph18	16:27:28.1	24:44:37.9	20.6	19.75	19
Oph19	16:28:07.4	24:35:07.9	20.6	19.75	19
Oph20	16:28:09.6	24:44:02.4	20.6	19.75	19
Oph21	16:28:48.9	24:39:31.5	20.6	19.75	19
Oph22	16:28:00.8	24:12:51.8	20.6	19.75	19
Oph23	16:38:12.8	24:17:18.3	20.6	19.75	19
Oph24	16:40:02.0	24:09:28.9	20.6	19.75	19