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A Study of the Large-Scale Infrared Emission from a Selected Dark
Cloud

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(NASA-CR-192775) A STUDY OF THE
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I. INTRODUCTION

This final report summarizes an investigation of the infrared emission energetics and embedded population in the ρ Ophiuchi dark cloud. With a distance of ~ 140 pc, the ρ Ophiuchi cloud is one of the closest regions of recent star formation. It is also one of the best studied such regions with numerous observations at all wavelengths. The IRAS data of the cloud provided a new glimpse of the overall structure of the cloud. In particular, the interaction of radiation from the Sco-Oph OB Association on the external heating of the cloud was very evident on Skyflux and Survey Co-Add images produced by IRAS. The infrared survey also revealed a number of new embedded sources in the cloud which have subsequently been observed from the ground (e.g., Wilking, Lada, and Young 1989). An earlier study by us (Greene and Young 1989) explored the overall energetics of the cloud using the IRAS data. The main conclusions of that work were: 1) The overall luminosity of the cloud is well explained by the emission of the known B-stars, HD 147889, SR-3, and S1, along with a 15% contribution from the external radiation field. 2) The dust physical temperatures were significantly lower than the observed CO gas temperatures. 3) Dust grains are heated to only 10% to 20% of the total depth into the cloud. The goal of the present study was to extend this analysis by drawing on data from large-scale CO maps by Loren (1989) and from near-infrared surveys of the embedded population.

II. DATA SETS

a) IRAS Data

The primary IRAS data sets used in this analysis were the SKYFLUX extended emission product, Survey Co-Add maps, and the Pointed Observations of the ρ Ophiuchi dark cloud. The existing data all suffered from a number of artifacts that required image processing to remove. Although we were able to correct these problems to first order, a significantly more involved re-calibration would be needed to extract the full information from the observations.

The first correction needed was the gross removal of the zodiacal emission. Since the SKYFLUX and Survey Co-Add images are combinations of scans with a variety of epochs and solar elongation angles, the resulting images represent a crude average of the varying background emission. We approximated the average zodiacal emission by fitting a plane surface to the background emission. Since the region of interest was only about 1° in diameter, much smaller than a $16^\circ \times 16^\circ$ SKYFLUX plate, this approach worked reasonably well. We then forced the emission of corresponding regions in the higher resolution Survey Co-Add images to match the SKYFLUX plates.

The second major adjustment in our use of the IRAS data resulted from observations made with the Cosmic Background Explorer Satellite (COBE). Since IRAS was not originally designed to perform absolute background measurements, there was some uncertainty concerning the calibration of the extended emission observations. By February 1990, the COBE results from Diffuse Infrared Background Experiment (DIRBE) showed a significant deviation from the IRAS results in the 60 and 100 μm bands. Specifically, the sky brightness at the North Galactic Pole was 3 times lower at those wavelength. The COBE results at 12 and 25 μm , on the other hand, were in good agreement. Since the DIRBE used the IRAS point source flux densities as the primary calibration, the discrepancy was dependent on the angular scale observed. Because our region of interest was in the intermediate size scale where the correction was uncertain, we made no calibration changes to the data per se. Instead, we concentrated on quantities such as the 60 μm to 100 μm flux ratios that apparently did not depend on scale dependent calibration factors.

b) Near Infrared Observations

One of the goals of this investigation was to correlate the embedded stellar population with more extended emission. One of the major limitations of studying the embedded population in a molecular cloud with IRAS is the modest angular resolution. In a complicated region like the ρ Oph cloud, confusion due to high source densities and extended emission limited the attainable sensitivity. The availability of the 128x128 pixel NICMOS near infrared camera at Steward Observatory (Rieke *et al.* 1989) gave us the opportunity to map the ρ Ophiuchi region in the J, H, and K photometric bands. The array combined excellent sensitivity with arc second angular resolution. This grant supported, in part, the reduction and analysis of these imaging data, and their correlation with the IRAS data.

The individual frames from the survey are ~ 3.84 arc minutes on a side, and the region was covered with a mosaic of 156 frames. Although much of the data reduction was performed with standard routines available in the Image Reduction and Analysis Facility (IRAF), we had to develop specialized routines to do the mosaicing. The requirement for preserving high precision positional information led us to an iterative mosaicing approach where sources with known high quality positions were used as fiducials for the remainder of the frames. The frames with no previously known sources were mosaiced using sources in the overlap regions. The resulting map has an estimated positional uncertainty of 1.3 arc seconds.

An effort was also made to match background levels by forcing the overlap regions in adjacent frames to be the same. This approach was only marginally successful because of illumination non-uniformities in the infrared camera. This non-uniformity was traced to an improperly placed pupil in the camera, which has subsequently been rectified. This problem in the optical system is not corrected by the normal flat field procedures. Instead

we applied an empirical position dependent (in pixel coordinates) correction to the source fluxes, but did not attempt to correct the background emission.

III. RESULTS

Our analysis of the IRAS data confirm the general conclusions of Greene and Young (1989). Based on $12\ \mu\text{m}$ - $25\ \mu\text{m}$ and $60\ \mu\text{m}$ - $100\ \mu\text{m}$ colors, the typical radiation field in the ρ Oph region is significantly higher than for the solar neighborhood. The observed dust temperatures are significantly lower than the observed CO kinetic temperatures. Consequently, the gas must have an additional heating mechanism.

A total of $650\ \text{arcmin}^2$ ($1.4\ \text{pc}^2$) of the ρ Ophiuchi cloud was mapped in the J, H, and K photometric bands. In this region, 481 sources were detected. Figure 1 shows the survey

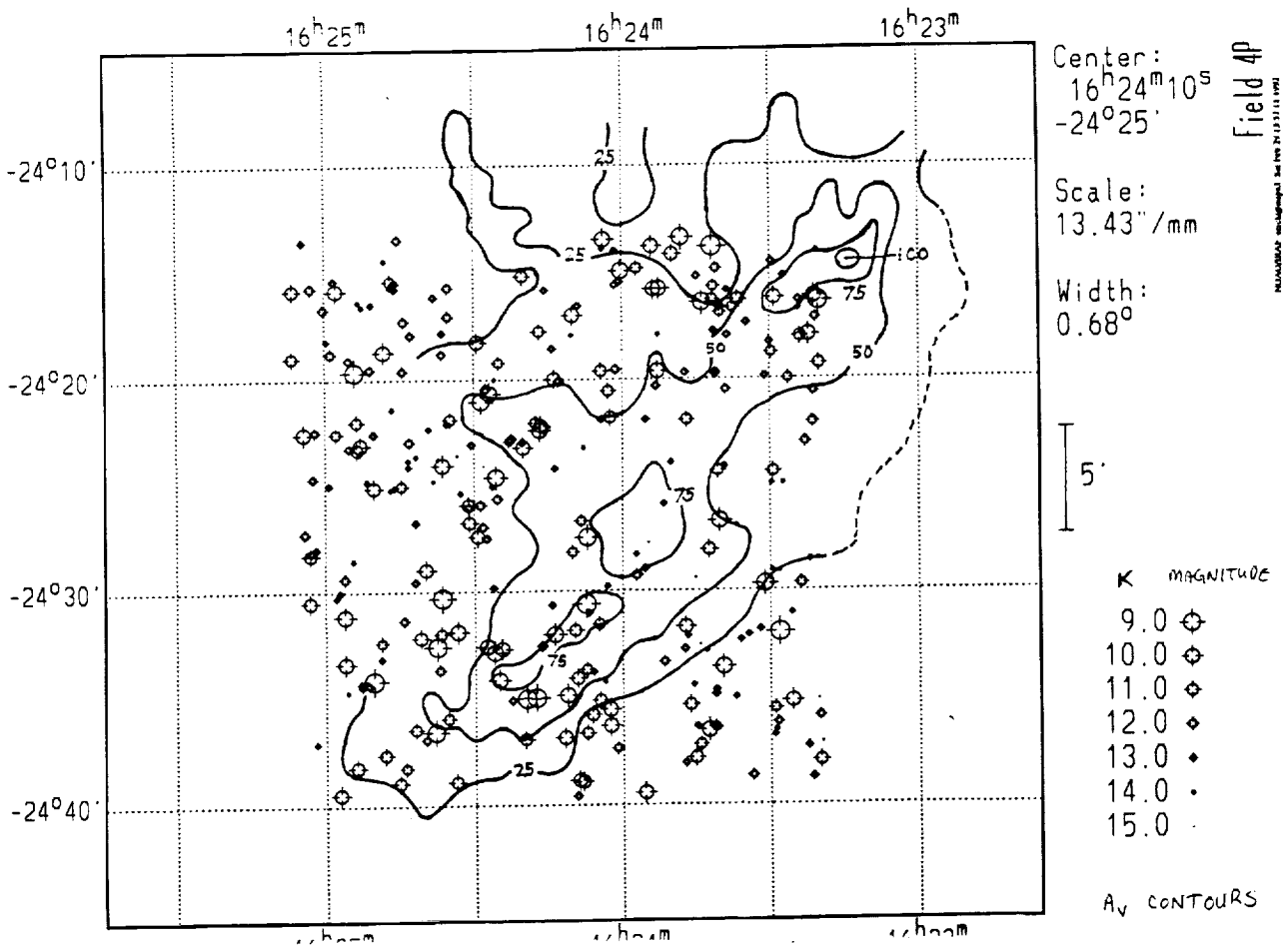


Figure 1. Sources detected in the K-survey. A_v contours based on $C^{18}O$ are indicated.

results at K along with contours of visual extinction based on CO column density. The source distribution highly clumpy, although it shows no clear correspondence with A_V contours except for an apparent avoidance of the dense core of the cloud. This avoidance could be due simply to the very high extinction in that region.

Associations with the IRAS sources in the survey region have been made. All the IRAS sources have plausible near infrared candidates with $K < 14$ mag.

An analysis of the (J-H) - (H-K) color-color plot (Figure 2) shows that many of the sources line within the region expected for reddened main-sequence stars (within the dashed lines in the figure). The suggested extinctions are as high as $A_K > 2.5$ or $A_V > 25$. A significant fraction of the sources, however, have colors that are better explained by infrared excesses produced by circumstellar disks. Our observations suggest as many as 48% of the sources have excesses.

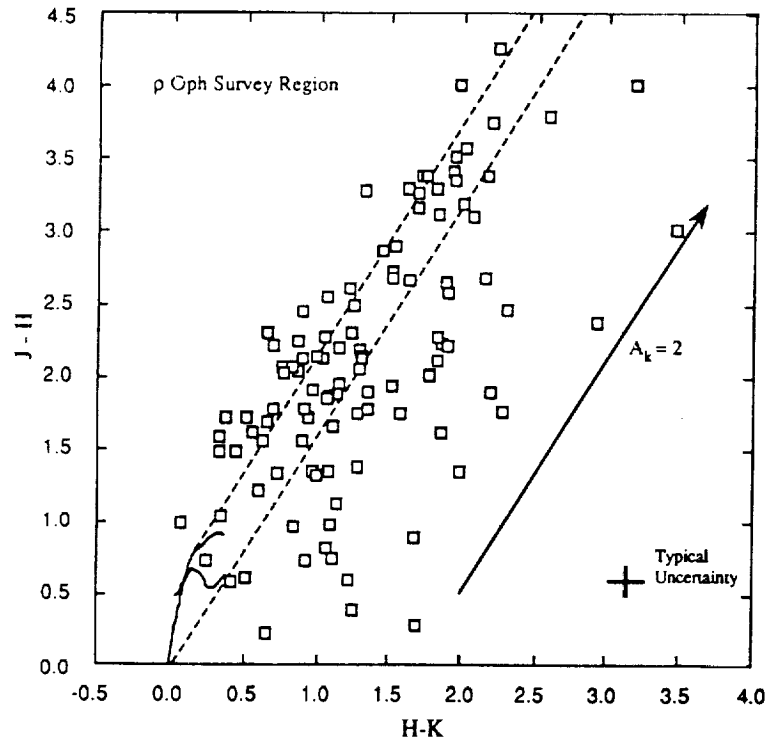


Figure 2. (J-H) - (H-K) Color-color plot. Reddening line is indicated

IV. PUBLICATIONS

This grant partially supported the Ph.D. thesis research of Thomas P. Greene at Steward Observatory. This work is presented in much more detail in:

T.P. Greene 1991, "Infrared Studies of Star Formation in the Rho Ophiuchi Dark Cloud", Ph.D. Thesis, Steward Observatory, University of Arizona.

The results produced under this grant have been published in:

T. P. Greene and E.T. Young, 1992, "Near-Infrared Observations of Young Stellar Objects in the ρ Ophiuchi Dark Cloud", *Astrophysical Journal*, **395**, 516-528.

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