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AN IRAS HIRES STUDY OF LOW MASS STAR FORMATION IN THE TAURUS MOLECULAR RING

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ABSTRACT The Taurus molecular cloud supposedly has no star clusters but only isolated star formation. However, the Infrared Astronomical Satellite (IRAS) shows us that a small star cluster is currently forming in Taurus. Most of the sources are deeply embedded and are probably low-mass protostars.

We use High Resolution (HiRes) images of the IRAS data from the Infrared Processing and Analysis Center (IPAC) to look for additional infrared members of the cluster. We also investigate the question of whether the infrared emission matches predictions for protostellar sources by examining whether the dust emission is resolved on scales of one arcminute ($\sim 10^{17}$ cm). With the exception of a luminous visible star, HD 29647, we find that the sources L1527, TMC1A, TMC1, TMC1C, TMR1, and IC2087 are unresolved in the HiRes images at 60 μm. Further analysis of IC2087 shows that it is unresolved at all four IRAS wavelengths.

INTRODUCTION

The nearest star forming regions are the Taurus and ρ Ophiuchus molecular clouds, both of which are located at a distance of approximately 160 pc. Both regions are currently forming low-mass stars, but otherwise have very different morphologies. The embedded star cluster in the ρ Oph cloud core has been viewed as an example of cluster formation while the Taurus cloud is often cited to contain only isolated star formation. Some authors have tried to explain the apparent difference in star formation content and cloud structure as due to differences in physical conditions in the clouds, such as magnetic field strength.

However the distinction between cluster or isolated star formation may be too simplistic. Recent near-infrared mapping of the Orion cloud has shown (Strom & Strom 1993) that star formation seems to be quite common in aggregates of 10 – 50 stars. It is important to understand the physical conditions in these regions, and relate them to current theories of isolated star formation. We undertake a study in nearby Taurus, where we identify a currently forming star cluster using the IRAS data.

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The IRAS data covering the densest part of the Taurus molecular cloud (sometimes called Heiles Cloud 2 or the Taurus Molecular Ring, hereafter TMR) reveals a 'ring' of embedded stars about 1 pc in radius. The projected stellar density corresponds to 4 – 8 stars pc^{-2}, which falls below the typical range considered to constitute a stellar cluster. However this is only a lower limit to the stellar density since there are likely to be other (visible) members than the seven far-infrared sources detected by IRAS.

To further investigate the infrared properties of the cluster we use High Resolution (HiRes) images of the IRAS data obtained from IPAC made using the Maximum Correlation Method (MCM) (Aumann, Fowler, & Melnyk 1990) as implemented by YORIC, the IPAC MCM processor. We use the improved resolution of roughly one arcminute in the HiRes images to search for additional infrared cluster members.

We also measure the sizes of the cluster sources. Models of the infrared emission from young embedded stars suggest that the mid-infrared (12 and 25 μm) comes primarily from a circumstellar disk, while the far-infrared (60 and 100 μm) comes from a circumstellar envelope. The circumstellar envelope is larger than the disk, and at 100 μm is expected to be roughly $10''$ (Butner et al. 1991) for low-luminosity (≤ 50 $L_\odot$) sources. Therefore only high luminosity protostellar sources are likely to be resolved by IRAS, even in the HiRes images. However sizes determined from HiRes images do provide an important check on the protostar models. In addition, most protostar models ignore the extended infrared component associated with outflows, such as has been observed around L1551 by IRAS at 60 μm (Edwards et al. 1986). Therefore it is interesting to use HiRes to measure whether protostellar sources are resolved.

GENERATION OF THE HIRES IMAGES

The HiRes images were generated at IPAC for a 2 degree field using the MCM algorithm with default parameters, including the now standard FBIAS processing. FBIAS processing provides for the addition of a small bias level to ensure the data are positive during the image reconstruction, and is particularly important for fields containing extended emission, such as star forming regions (*IPAC Users Guide 1993*).

AO Data

In addition to using standard survey data, HiRes images were generated using IRAS AO data (Additional Observations, also known as pointed observations). Each AO covers a skinny rectangular region running roughly north-south, but when mosaiced together they subtend the entire region of interest.

Spatial Resolution Studies Using the IRAS Simulator

To study the effective resolution of the HiRes images, extensive use was made of the HiRes IRAS Simulator. The simulation mode takes a model image and generates synthetic IRAS data that mimic what IRAS would have detected. The synthetic IRAS data is then processed as usual with the MCM algorithm (Surace et al. 1993).

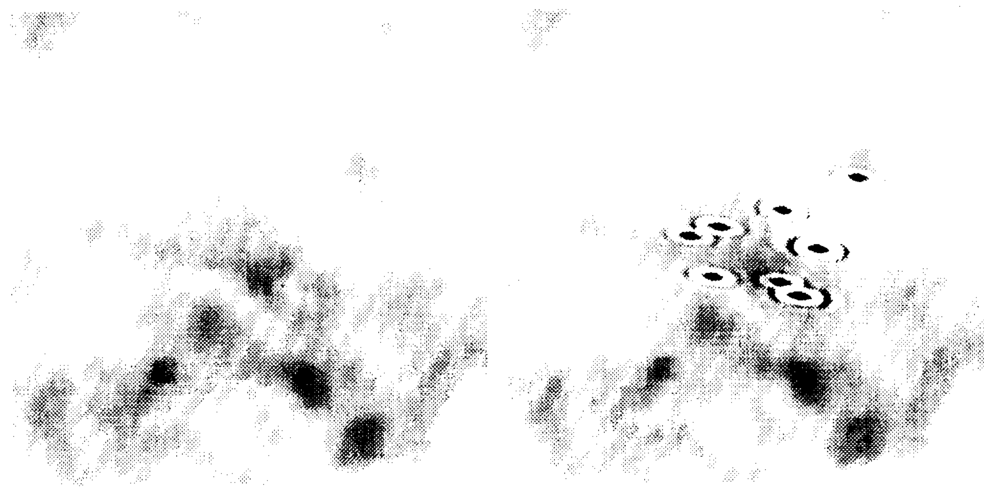

FIGURE 1 a) Spike model input image. Barely discernible spikes of the appropriate fluxes have been placed at the proper source locations, and added to a much smoothed version of the data. b) Spike model after HiRes processing.

The model images were meant to faithfully imitate the observed extended component of IRAS emission, while varying the treatment of the compact sources. The compact sources were alternatively treated as 1) unresolved spikes 2) Gaussians of various sizes and 3) a power-law distribution with intensity varying as θ^{-1} with angle.

The model for the extended component was based on the smoothed beam-sample model image that is normally produced during HiRes processing. The beam-sample model is a highly smoothed version of the 20th iteration HiRes image that has been further processed to exclude point sources found in the data. We further edited the smoothed images to remove any trace of pointlike sources which persisted.

The brightness of the stars in the original 60 and 100 μm maps were then measured, and the three types of compact models were placed on the smoothed maps at the known locations of the stars using the measured fluxes. The resulting maps were then processed using the IRAS simulator.

Figure 1a shows a model before processing, in this case a smoothed input map with barely discernible spikes at the position of the sources. Figure 1b shows the same map after HiRes processing at the 20th iteration. Comparison of the model image (Fig. 1b) with the actual HiRes data (Fig. 2b) shows the model indeed looks very similar to the data, down to the 'ringing' pattern seen around the compact sources.

Using Nearby Point Sources to Study Spatial Resolution

An alternative way to measure the effective spatial resolution achieved in the HiRes maps is to measure the spatial profile of a nearby point source. There are two cautions with this technique: first, the resolution depends on the local scan coverage, which can vary substantially over a degree particularly if there are gaps in the coverage, and second, it is not entirely clear how to identify which

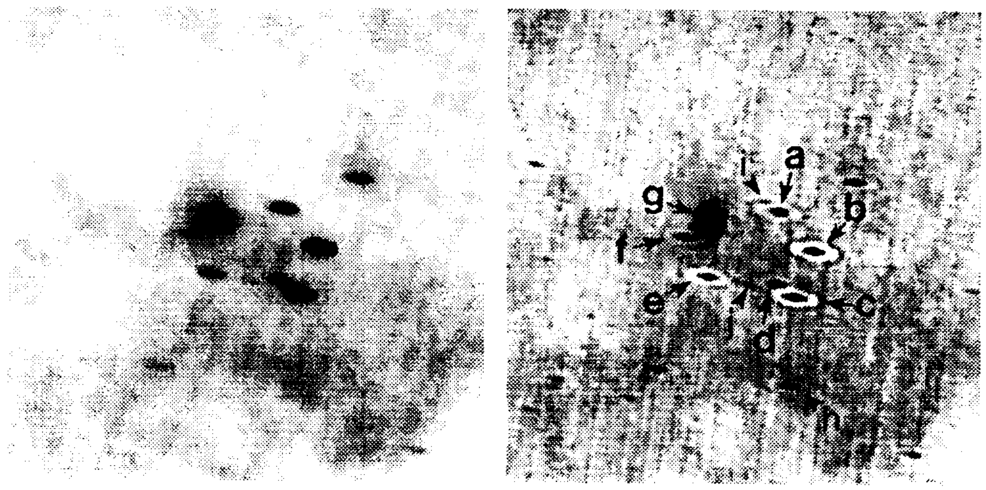

FIGURE 2 IRAS 60 μm image of the TMR embedded cluster. Images are 2 degrees on a side. a) Before HiRes Processing. b) The 20th iteration HiRes image.

sources are actually point sources.

We identified two likely point source candidates using the *IRAS Point Source Catalog, Version 2 (1988).* The sources RVTau and IUTau have falling spectral energy distributions that suggest they should be unresolved, namely they are strong at 12 μm and weak at 100 μm. These two particular sources were chosen because they were the only sources strong enough at 60 μm to do meaningful comparisons and which were also close to the field of interest (within 3 degrees).

HIRES IMAGES OF THE TMR FAR-INFRARED CLUSTER

Figures 2a-b show the the TMR region at 60 μm before and after HiRes processing. The IRAS data show the far-infrared cluster as a ring of seven bright sources near the center, less than a degree across. The IRAS detectors are rectangular, resulting in an elliptically shaped beam. The 'ringing' pattern evident around the stronger sources is an artifact of the processing, and reflects the typical behavior of the HiRes algorithm to pointlike sources, particularly to sources lying on a nonzero background.

Stripes are also visible in the images and are a consequence of the one dimensional scanning pattern of the IRAS satellite. Small errors in the gain, and residual errors in the baseline determination are strongly amplified during the HiRes processing and typically appear as stripes.

Individual Sources

The identifications of the cluster sources, clockwise from the north, are L1527 (a), TMR1 (b), TMC1A (c), IC2087 (d), TMC1 (e), TMC1C (f), and HD 29647 (g) (also known as SAO 76704). More information on individual objects can be

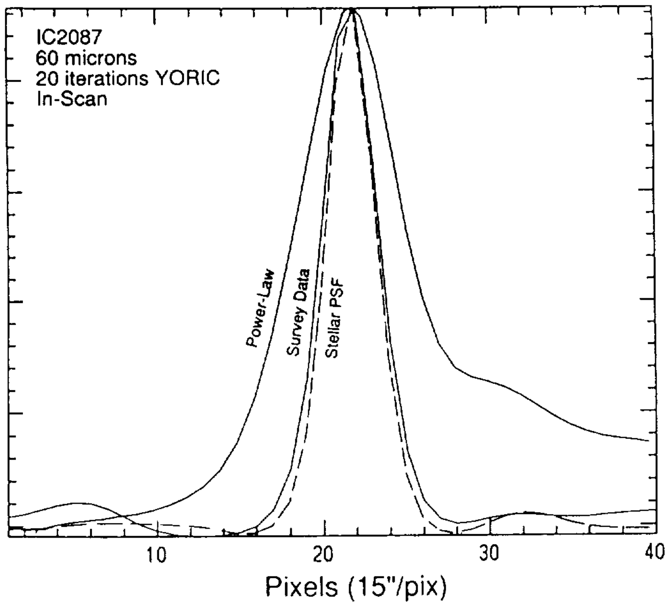

FIGURE 3 Sample one dimensional spatial profiles of the embedded source IC2087.

found in Crutcher (1984), Heyer, Snell, & Goldsmith (1987), and Terebey et al. (1989, 1990).

The lowest extinction is found in the north-east part of the ring containing TMC1C (f) and HD 29647 (g). In agreement with this general trend both sources are optically visible. TMC1C is a T Tauri star while HD 29647 is a bright star well known for its anomalous interstellar extinction properties. The IRAS data show HD 29647 is clearly extended.

IC2087 (d) has associated reflection nebulosity around it, suggesting it is moderately embedded. The other four objects are class I infrared sources and are thought to be protostars.

Molecular line mapping of the region indicates that several hundred solar masses of gas is concentrated around the embedded cluster and also extends to the south and south-east (Snell, Heyer, & Schloerb 1989).

SIZE DETERMINATION

Source size was examined in several ways. First the full-width at half-maximum (FWHM) sizes were estimated by fitting elliptical gaussians to the data. However the beam shape was not really gaussian enough to make this a good diagnostic. So instead, cuts were made along the major and minor axes. The data were averaged along this vector 3 pixels wide (45″) and the resulting one-dimensional profiles were graphically compared. For example Figure 3 displays several profiles for IC2087 along the minor axis. The stellar profile is seen to provide a good match to the data. As a measure of size we report the FWHM interpolated from the profiles.

It was found that the power–law models were, in every case, much more extended than the actual survey data. Typically, the FWHM of the power–law models (at 20 iterations) was 2.5 times that of the survey data.

We also attempted to fit the data against a sequence of radial gaussian models with varying sizes. However this approach was not successful because the gaussian models turned out to have beam shapes that were about 10 percent more elliptical than the actual data, so that different size gaussians were required to fit the major and minor axes.

This suggests that such model fits are too detailed given the imperfectly known IRAS detector response functions that enter into the IRAS simulator. The main result derived from the gaussian models was that the compact sources were most similar (to within $\sim 10''$) to the smallest sized model.

In the end we had two tools for assessing whether sources were resolved in the HiRes images. We used several candidate point sources found near our field to estimate an empirical point spread function. In addition we made extensive comparisons with the spike model. The input spikes had the same fluxes and locations as our compact sources, which allowed us to simulate the effects of source strength and local background level on the achieved resolution in the HiRes images.

Discussion of Measured Sizes

IC2087 was examined at all bands versus the two stars to look for extended flux. None was found. At all bands, both in-scan and cross-scan, it was found to have the same profile as the stars to within 1/3 pixel ($5''$) in-scan. Note that some uncertainty exists as the stars themselves did not have identical profiles. This is most pronounced in the cross-scan direction, as coverage variations are more pronounced and the sheer size of the profile leads to uncertainties as high as a full pixel ($15''$). The measured FWHM sizes are given in Table 1.

TABLE 1 Size of IC2087 at IRAS wavelengths.

Wavelength(μ m)	Flux(Jy)[a]	FWHM($'' \times ''$)[b]
12	5.0	48×34
25	6.8	72×35
60	7.3	113×54
100	18.2	210×150

[a]Fluxes from Point Source Catalog
[b]Cross-Scan by In-Scan direction

We then examined the other compact sources at 60 μm. The measured sizes are given in Table 2, starting with the two selected stars, RV Tau and IU Tau. The table shows roughly the expected behavior, that the achieved resolution is related to source strength. Weak sources, particularly those with significant local background have both lower signal to noise and take longer to converge than strong sources, which results in a lower achieved resolution.

As expected from the images, HD 29647 is found to be extended. However none of the other compact sources are extended compared with the pointlike stars. For example, TMC1C appears larger, but is weaker than other sources.

Examination of a source with the same flux and location in the spike model image indicates that the profile of TMC1C is consistent with that of a point source.

TABLE 2 Compact Source Sizes at 60 μm.

IRAS	Source	Flux(Jy)[a]	FWHM(″×″)[b]
04328+2824	IU Tau	3.5	98×51
04440+2605	RV Tau	6.5	82×49
04361+2547	TMR1	44.8	75×44
04365+2535	TMC1A	36.0	83×45
04368+2557	L1527	17.8	68×50
04369+2539	IC2087	7.3	113×54
04380+2553	HD 29647	11.0	274×112
04381+2540	TMC1	10.3	98×49
04385+2550	TMC1C	2.9	110×60

[a]Flux at 60 μm from Point Source Catalog
[b]Cross-Scan by In-Scan direction

NEW IRAS SOURCES IN THE HIRES IMAGES

We searched the HiRes Images for new compact infrared sources, in order to look for additional cluster members. In principle the PSC or FSC provide a list of all candidates. However in practice the two catalogs are not complete, while the FSC in particular suffers from reliability problems in confused regions. Incompleteness is important in star forming regions because it arises both for sources that sit inside dense cirrus emission, and for sources that that are confused with other nearby sources ($< 1'$).

As a first step we compared the HiRes images with a list of PSC sources. Figures 4a-d show the HiRes images at all four wavelengths. The positions of PSC sources are marked with circles. Only detections, not upperlimits, are marked in each band.

In general the PSC sources are easily detected by HiRes, except in the 100 μm images. At 100 μm, there are a number of 100 micron-only PSC sources that have no obvious or believable counterparts in the HiRes images. Since the image shows extensive cirrus emission throughout the field we suspect these PSC entries represent peaks in the cirrus distribution.

In the immediate vicinity of the cluster the 60 μm image shows seven likely members which define the TMR cluster. At 12 and 25 μm one easily identifies between two and four additional members of the cluster (which are also PSC sources), depending on where the cluster boundaries are drawn.

The 60 μm image also reveals a strong compact source (h, Fig. 2b) that is not found in the PSC, in the lower center of the image. This source has a counterpart in the 12 and 25 μm images, and also appears in the AO HiRes images. Therefore we judge this to be a new embedded source, although located outside the molecular ring and probably not a cluster member.

The 60 μm image also shows two new faint sources in the ring, one located

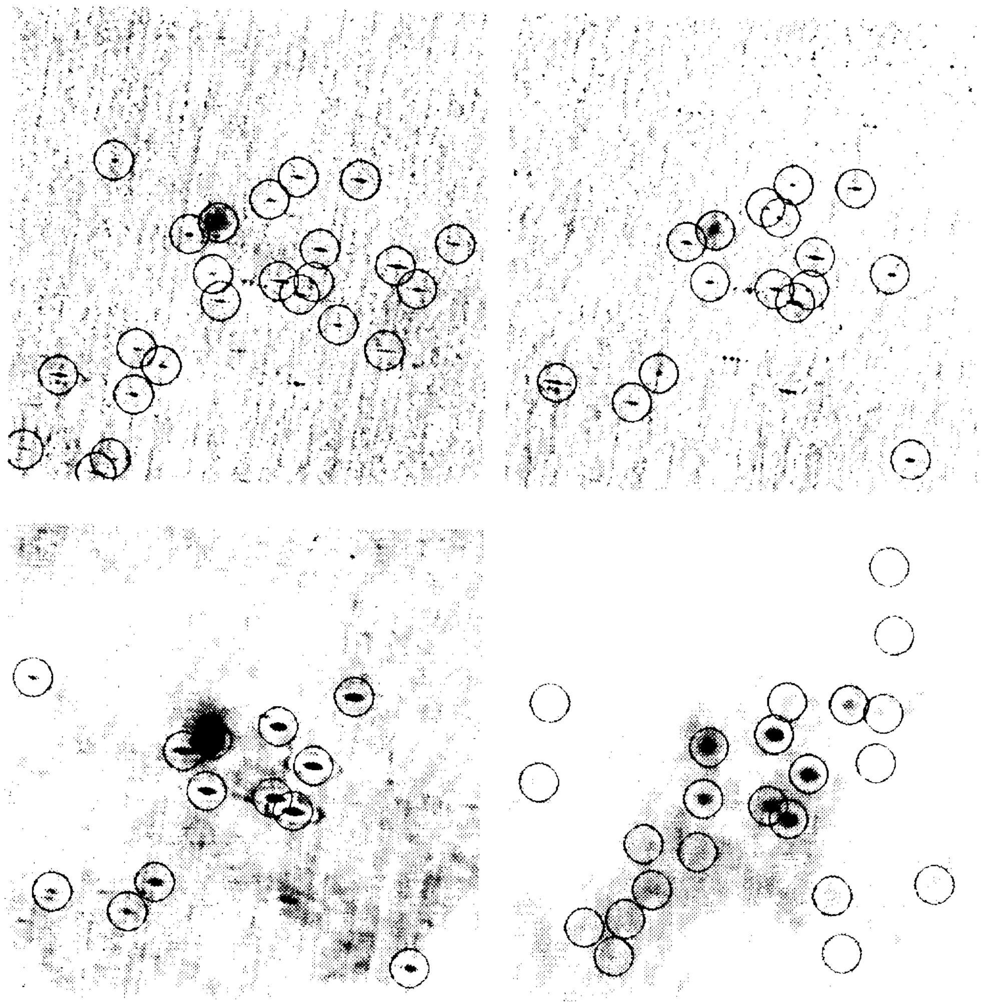

FIGURE 4 HiRes images of the TMR embedded cluster at all four wavelengths, 20th iteration. The positions of PSC sources are marked as circles. At each wavelength only PSC detections (not upperlimits) are shown. Nearly all PSC sources are obvious in the HiRes images. Exceptions are discussed in the text. a) Top-left 12 μm. b) Top-right 25 μm. c) Lower-left 60 μm. d) Lower-right 100 μm.

on the north (i), the other on the south (j). The northern source has a PSC counterpart in the 25 μm image, so in this case HiRes detects a PSC source at a wavelength that is given an upperlimit. The southern source in the ring is more problematic. Although it has a counterpart at 12 and 25 μm, it has no counterpart in the AO HiRes images. It is therefore either a variable source–a star, or bad data masquerading as a source. The case for bad data is strengthened by the fact that the source profile in the HiRes images looks very different from other compact sources.

Lastly, the AO HiRes images (not shown) reveal several new sources outside the ring that are fairly strong but are not visible in the survey data, and therefore are likely to be variable infrared sources (most likely stellar rather than embedded).

SUMMARY

We have examined the HiRes images in the vicinity of the Taurus Molecular Ring. The 60 μm image reveals an embedded cluster of seven strong infrared sources in a ring, which we suggest to be a low-density star cluster that is currently forming. Further investigation shows that the sources are unresolved at 60 μm at roughly one arcminute resolution in agreement with protostar models, with the exception of HD 29647.

Depending on how the boundaries of the cluster are drawn, at least two, and possibly four additional sources that are primarily seen at 12 and 25 μm are also likely to be members. Outside the cluster region the HiRes images reveal several new sources that are not found in the PSC. We conclude that the HiRes images are a powerful tool for studying infrared sources in star forming regions.

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