STAR FORMATION IN TAURUS:

Preliminary Results from 2MASS

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Abstract.
Data with the 2M ASS prototype camera were obtained in a 2.3 sq. deg region in Taurus containing Heiles Cloud 2, a region known from IRAS observations to contain a number of very young solar type stars. Data at 1,25 (J), 1.65(H), and 2.2 (K_s) μm are presented. These data are representative of the type and quality of data expected from the planned near-IR surveys, 2MASS and DENIS. Near-IR surveys will be useful for determining the large scale variation of extinction with clouds, for determining the luminosity function in nearby clouds down to ranges of 0.1-1.0 LO, and for finding highly extincted T Tauri stars missed by IRAS because the bulk of their luminosity is emitted shortward of 12 pm.

Key words: Star Formation — Taurus — 2MASS — Near-infrared

1. Introduction

In this talk we aim to give an impression of the research that will be possible when data from the new 2 μm surveys, 2MASS and DENIS, become available. A region in Taurus served as a test area for observations with the 2MASS prototype camera (Kleinmann *et al.* 1994a).

Taurus is one of the closest, best studied region of low *mass* star formation. The IRAS census is complete down to $\sim 0.1 L_\odot$ (Kenyon *et al.* 1990; Beichman, Boulanger and Moshir 1992) for objects emitting most of their luminosity at color temperatures cooler than a few hundred K. Optical surveys of T Tauri stars are complete to a similar luminosity level for modest ($A_v << 5$) visual extinctions (Herbig and Bell 1988). Extensive CO (Ungerechts and Thaddeus 1987) and other molecular line surveys (Benson and Myers 1989) are also available to identify potential sites of star formation. The combination of these data suggests that stars form in small clusters, centered on dense, opaque cores of molecular gas with extinctions of $A_v \sim 5 - 20$ msg. However, near-IR surveys of Taurus are very limited. The classic survey was carried out by Elias (1978), who found 215 objects down to a limiting magnitude of $K \sim 8$ in some 15 sq. deg. A handful of sources showed near-IR excesses indicative of extreme youth. Benson *et al.* (1984) carried out limited near-IR surveys toward dense *NH3* cores. These observations were augmented by IRAS data (Beichman *et al.* 1986) covering the entire Taurus cloud instead of the few arcminute-sized regions that could be surveyed with single element photometers: Near-IR data proved invaluable as follow-up observations of specific IRAS sources (Myers *et al.* 1987; Kenyon *et al.* 1993).

The advent of sensitive array cameras, and of surveys like 2MASS and DENIS, will soon make large scale surveys of nearby star forming regions possible with a sensitivity comparable in limiting luminosity for young stellar objects (YSOs) to those available at longer and shorter wavelengths. in understanding the role of near-IR surveys it is useful to understand the division of YSOS into three classes (Adams, Lada and Shu 1987): deeply embedded Class I objects emitting mostly longward of 12 μm; Class 2 objects which have begun to disperse the surrounding cloud and disk, enabling photospheric light in the near-IR to shine through; relatively unobscured Class 3 objects with little or no infrared excess.

2. 2MASS Observations of Taurus

Observations were made on two separate observing runs using the 2MASS prototype camera. 11 band data were obtained on October 1 G, 1992; J and K_s data were obtained on March 6, 1993. Three overlapping scans were made in each of the three bands covering $\sim 0.5° X6°$ centered on the Taurus Molecular Ring (in Heiles Cloud 2; Terebey *et al.* 1990). The region scanned in all three bands lies within the following range of coordinates (1950): $4^h35^m26^s < \alpha < 4^h37^m17^s$; 22°54'< δ <28°30' for a total area of full overlap of 2.3 sq. deg.

Data were run through the 2MASS prototype software at IPAC, producing both images and point sources, Point sources were extracted down to levels below $K_s \sim$ 15, consistent with a source of $K_s \sim$ 14 having a signal to noise ratio of 14. in total there were 6854 extractions at J (< 15.5), 8417 objects at H (< 15.0) and 6968 objects at K_s (< 14.5). On the basis of multiple scans made over a separate test region (the cluster M92), we estimate that the 2MASS data are >99% complete and highly reliable (> 99%) down to a limit of K_s=1 4.0 (Kleinmann *et al.* 1994 b). We expect comparable quality at J ~15 and 11 ~14.5, but this has not yet been demonstrated. Figure 1 shows source counts as a function of K_s magnitude, compared with predictions from a galactic structure model (§4).

The data were calibrated with respect to UKIRT faint standards observed periodically throughout the night and appear to be accurate to 7%. '1'here is insufficient calibration data at multiple wavelengths to derive any color corrections for these data. In the software used to reduce these data, saturation of the NICMOS array is a problem for very bright sources, $K_s < 8$. Some 65 sources have been excluded from the color-color diagrams presented below for this reason. New software present] y under development will enable

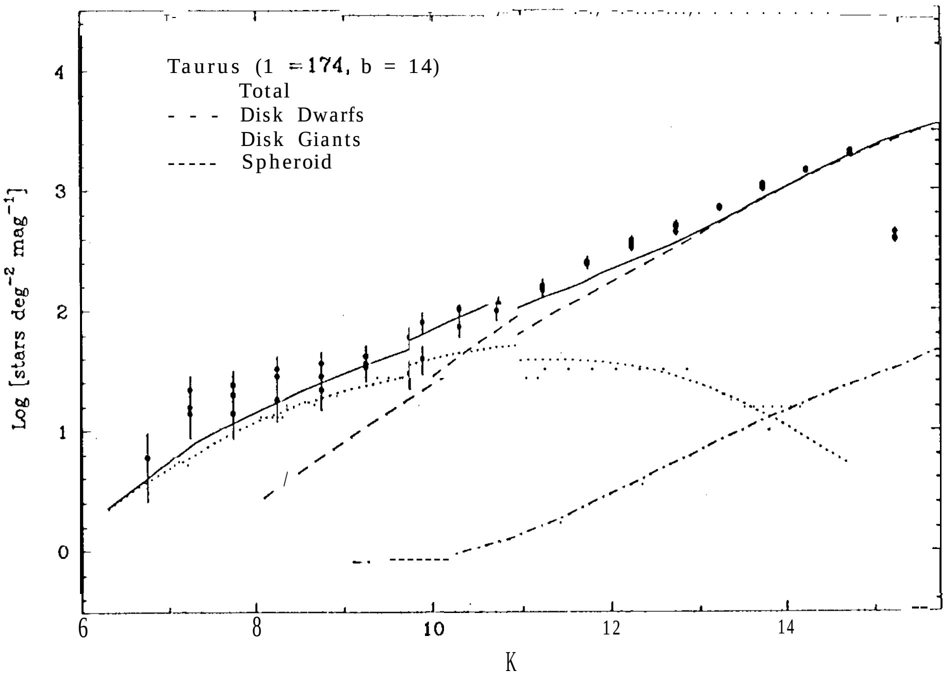

Fig. 1. Comparison of source counts at K_s with a modified Bahcall-Soneira model. The slope of the relation is -0.32, consistent with the distribution of disk dwarf stars. Also shown are the counts expected for giants and spheroidal stars.

accurate (< 10%) photometry for sources as bright as $K_s \sim$ 4-5.

To create a final "catalog" for the purposes of this investigation, we demanded that there be at least one *High Quality Measurement* in one of the three bands, defined here as being brighter than J< 15, H< 14.5 or, K< 14, A source with at least one high quality band was allowed to accept lower quality measurements in other bands, arbitrarily defined to be within 0.5 mag of the above thresholds. Table 1 gives the band-by-band statistics of sources detected in Taurus with at least one high quality measurement, The fact that most objects (85%) are seen in three bands, and that almost all (94%) are seen in two or more bands implies that the sensitivities of the three bands are well matched.

3. 2MASS Objects in Other Catalogs

The 2MASS sources were compared with the GSC and IRAS catalogs to learn about the nature of the 2MASS sources. Only 838 2MASS objects

TABLE I

Table 1. Band Combinations Detected in Survey

Bands	Number	Bands	Number
$\_\_K_s$	73	J_K_s	89
_H_	101	JH_	36
$\_HK_s$	274	JHK_s	4698
J_.	143		
All J	4242	All H	5012
All J{.	4316	Total	5414

($\sim$ 15%) matched stars in the GSC with a match radius of $2''$. As will be shown in the next section the reason for the relatively low fraction is the effect of extinction over much of the cloud.

Seventeen matches were also found in the IRAS Point Source (PSC) and Faint Source (FSC) catalogs. IRAS sources detected only at 100 μm were excluded from the comparison, as these are likely to be coincidences between stars and ubiquitous cirrus sources. The matches found within the quoted IRAS error ellipses include nine 12 pm-only sources (typically cataloged SAO or GSC stars); five 12 & 25 μm sources; one 12, 25 & 60 μm source; and two 12, 25, 60, & 100 μm sources. The 2MASS sources matching the IRAS objects arc usually bright in the near-Ii{, with a typical 1{-[12] of about 4 msg. The non-stellar sources, i.e. the embedded objects showing up at the long IRAS wavelengths, are considerably redder with 1{-[12] of 6-10. Of particular interest is onc IRAS source not detected by 2MASS. L1527 (04368+2557) is an extremely red (class I) object seen only at 25, 60 and 100 μm. The extinction or intrinsic cold color temperature that precludes a detection at 12 μm, also prevents detection of a near-IIL point source, However, faint nebulosity and a jet extending to the West is apparent in the 2MASS data (cf. Kenyon *et al.* 1993).

4. Source Counts and Colors

Figure 2 shows that the source counts vary considerably as a function of position within the scan because of the effects of extinction in the cloud. The number of GSC matches drops to nearly zero at the cloud center, while the 2M ASS counts pcr band drop by 50% at cloud center (only counts at V, J and K_s are shown for clarity), This region of Taurus differs from a region of high mass star formation like NGC 2264 (Lada *et al.* 1993) which

Source Counts

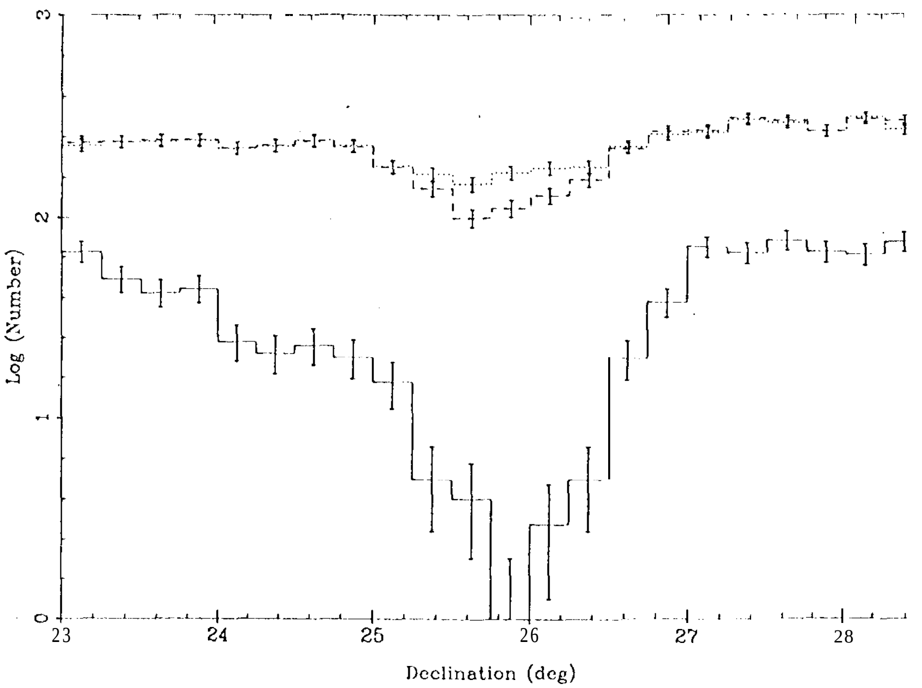

Fig. 2. The source counts from the Guide Star Catalog (solid line), at J (dashed line), and at K_s (dotted line) plotted as a function of declination along the scan, showing the marked effect of extinction toward the center of the cloud even in the near-IIL The data arc binned in $\sim 0.5 \times 0.25°$ bins.

shows a large, dense cluster of young stars. There is no increase in source density evident in these data. There is also a striking change in properties of the band merge properties of the 2MASS sources, with a sharp jump in the number of sources without a J counterpart toward the cloud core, Note that in highly obscured regions, the DENIS survey with coverage at 1, J and K, will detect a large number of sources only at K.

Figure 1 shows the K_s source counts compared with the counts predicted for various types of stars using a Bahcall-Soneira (198j) model (modified to include the effects of extinction and AGB stars). The model suggests that the majority of the 2MASS sources are disk dwarfs. The color information (Figure 3) support this interpretation as well.

Figure 3a shows the J-H-K_s colors for sources at the periphery of the scanned region, away from the molecular cloud; figure 3b shows the colors for the sources in the central 1° of the cloud. Also shown is locus of main sequence stars and representative colors of T Tauri stars and embedded YSOS (Kenyon *et al.* 1993). Figure 3c and 3d show the predicted colors for

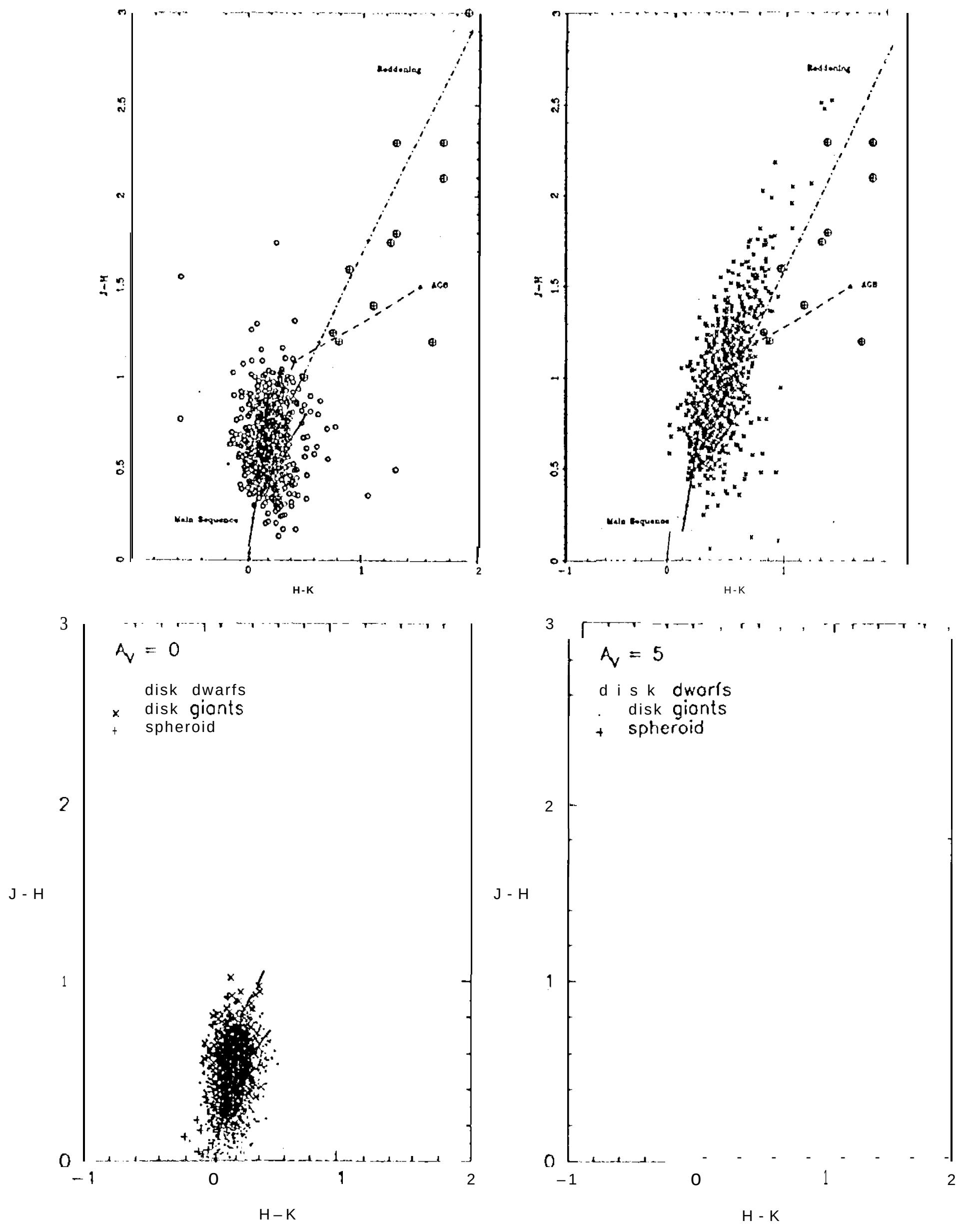

Fig. 3. Top: The J-II-K, color-color diagram for the 2MASS data in the outer part of the cloud (left) and for the central 10 (right). The main-sequence is shown, as is the location of AGB stars (dashed line and triangles), of selected T Tauri stars and embedded sources (⊕, Kenyon *et* al. 1993). The dash-dotted line shows the effect of A_V of 5,10,20 mag to an object with the average colors in the unreddened part of the cloud. Bottom: A theoretical (J-11)-(11-K,) color-color diagram, based on the modified Bahcall-Soneira model for two different amounts of extinction (left A_v=O; right A_v=5 mag).

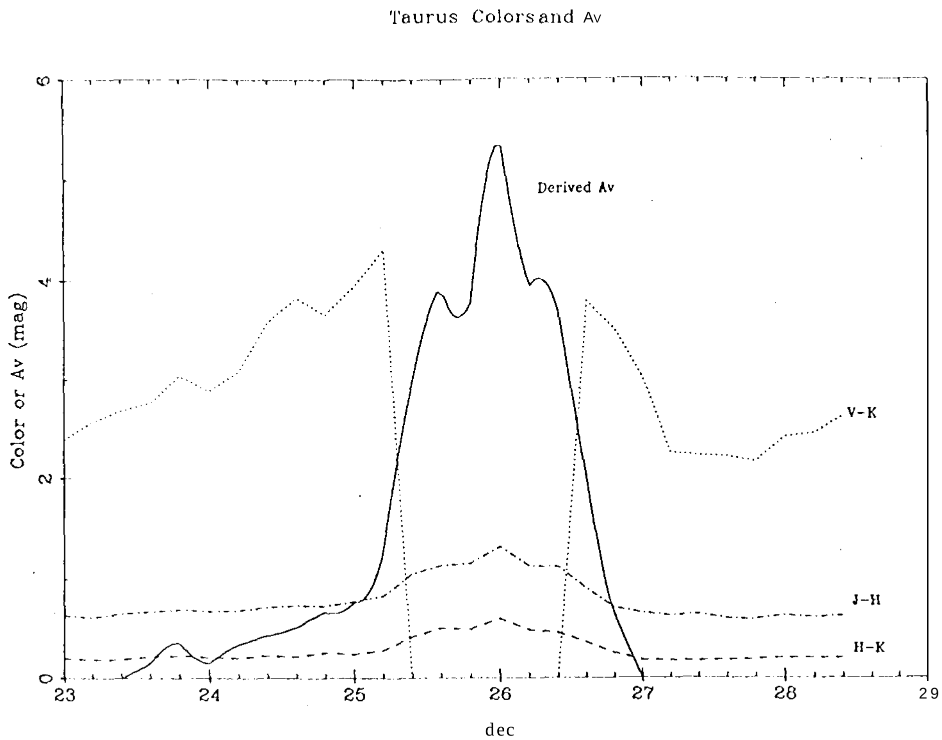

Fig. 4. The reddening in the scanned region can be inferred from the variation of V-K_s (for stars with GSC matches), (J-11), and (11-1 <,) colors as a function of declination.

A_V=0 and A_v=5 mag, based on the Bahcall-Soneira model discussed above. It is evident that the vast majority of stars are K or M stars reddened by as many as 5-10 msg. There arc, however, a few sources that must either be reddened by A_v> 20, or have intrinsically redder colors than the rest. Sonic of these objects might be T Tauri stars or another type of YSO. As Neil] Reid pointed out at this conference, the J-H-K_s color-color plane is relatively insensitive to stellar type for cool stars and follow-up observations such as longer wavelength photometry or visible spectroscopy will be needed to determine the nature of these sources.

It is possible to use these background stars to infer the extinction within the cloud from the 2MASS data, First, onc can adopt the colors seen at the ends of the scan as representative of the entire population and attribute any reddening as due to extinction. The extinction, A_v, can then be inferred from a standard reddening law (Draine and Lec 1984). Figure 4 shows that the A_v inferred from the colors approaches $A_V \sim$ 7, consistent with seeing 1-2 optical depths into the cloud, One can also infer the extinction from the variation

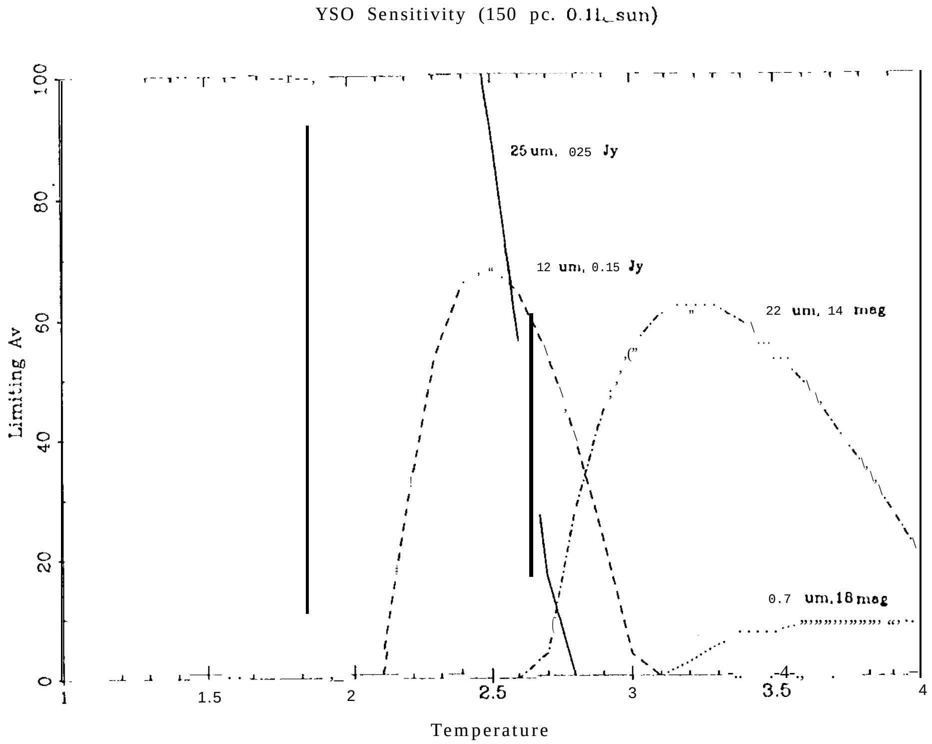

Fig. 5. The figure shows the limiting temperature and extinction at which a 0.1 LO object can be seen in Taurus, for IRAS, 2MASS and an R-band image.

of source counts. This technique gives almost an identical extinction profile. With more than >1000 sources / sq. deg. in this region, it is possible to measure the extinction on angular scales much smaller than a degree, Both techniques suffer from the obvious selection effect that very opaque regions will be missed since they will have few, if any, sources, even at K.

5. *2MASS* and Star Formation

What sort of objects will 2MASS find that are not identified at other wavelengths? Figure 5 plots the sensitivity of the IRAS Faint Source catalog (at 12 and 25 μm), of 2MASS, and of an R-band image for a 0.1 $L_\odot$ object obscured by some amount of extinction, and emitting all of its luminosity at a particular temperature. The figure shows that TRAS with a limit at [12] $\sim$ 6 is the most sensitive catalog for objects with color temperatures between 100-500 K over any range of extinctions expected in Taurus. '1'bus, lRAS is most likely to detect Class 1 and 2 objects (embedded or partially embedded sources with disks). However, 2MASS will be more sensitive than

IRAS or optical surveys to late Class 2 and all Class 3 objects (T Tauri stars with modest K-band excesses and ages between 0.1 -3x 106 yr) suffering more than a few magnitudes of extinction. Some of the very red objects found in the 2MASS sample may be YSOS not detected by IRAS. There will be a well-defined niche for 2MASS and DENIS in surveying complete regions, not just the dense cores, to find YSOs. Another important role of these data will be to correct near-IR luminosity functions of YSO clusters for the effects of background sources and extinction (Lada *et al. 1993).*

6. Conclusions

The 2MASS and DENIS surveys will play an important role in revealing the global properties of star forming regions. With near-IR surveys it will be possible to deduce the reddening and background stellar densities needed to derive luminosity functions and reveal the presence of embedded clusters. Near-lR surveys can also identify embedded T Tauri stars and YSOS which have moved beyond the active disk stage and so arc undetectable by IRAS. Various types of nebulosity associated with star formation activity will also be detectable,

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