IRAS AND STAR FORMATION IN DARK CLOUDS

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ABSTRACT. As a first step in systematically studying star formation in dark clouds we report a search for IRAS Point Source Catalog detections lieing within the boundaries of Southern Dark Clouds in the catalog of Hartley et al.(1986). To aid in further classifying the 1099 objects by their infrared colours the colours of the whole IRAS Point Source Catalog are discussed and plotted, and the regions occupied by various types of objects tabulated. The presence of Cirrus makes it difficult to confidently identify protostellar like objects from IRAS data alone. Nevertheless 247 sources have colours characteristic of objects deeply embedded in the dark clouds and are probably at least young stars of low mass. These sources appear to be located at random positions within the dark cloud volumes and there is no evidence to suggest that formation of low mass stars in this dark cloud sample is externally triggered.

1. INTRODUCTION

The search for a true protostar in which the majority of energy is produced by gravitational accretion rather than nuclear fusion has been described as "the Holy Grail of infrared astronomy" (Wynn-Williams 1982). As yet there is no clear example of such an object, although a strong case has been made for B335 (Gee et al. 1985). As the rate of evolution of a star increases with its mass, and the initial mass function increases towards lower mass there will be more low than high mass protostars around at any time. Low mass stars form in dark clouds without necessarily being accompanied by the high mass stars which form in giant molecular clouds and later develop HII regions. We wish to study the stellar content of dark clouds to look for possible protostars and young stellar objects and to understand what processes determine their numbers, location and properties in dark clouds.

The Infrared Astronomical Satellite (IRAS) performed an all sky infrared survey at wavelengths of 12,25,60 and 100 microns from which the IRAS Point Source Catalog (IRAS, 1985) was derived (IRAS Explanatory Supplement, 1985, henceforward Supplement). The IRAS catalog is potentially a uniquely useful tool because it is, at first sight, a

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statistically complete survey of most of the sky. Even if objects are deeply embedded in dark clouds and optically invisible IRAS can potentially locate and characterise them by detecting the thermal emission from the surrounding dust. However one must be cautious about interpretation of statistics of such galactic objects because of the effects of confusion, shadowing and cirrus, all of which are important near the galactic plane (Supplement).

The purpose of this contribution is to give a progress report on an attempt to get an overrall view of the contents of dark clouds from the IRAS catalog, concentrating on the criteria used for defining a sample of IRAS objects to be studied. Preliminary results from IRAS on star formation in dark clouds were given by Beichman et al.(1984) for B5, by Emerson et al.(1984) for L1551 and ESO 210-6A, and by Baud et al.(1984) for Chamaeleon I and showed that IRAS was a powerful instrument for detecting even low luminosity objects in nearby dark clouds. Beichman et al.(1986) discuss IRAS detections of candidate protostars in nearby molecular cloud cores and Myers and colleagues (this volume) are completing a ground based follow-up program to clarify the nature of these objects. Many papers in preparation or press by various authors interpret IRAS data often in conjunction with observations at other wavelengths but these detailed studies of individual IRAS sources or follow-up observations will not be further discussed here.

2. SELECTION OF DARK CLOUD SAMPLE

We define Dark Clouds as those that are optically discernible as such, and thereby exclude molecular clouds that are too distant to have optical counterparts. This definition also ensures that the clouds are mostly relatively nearby which should aid in detecting low mass stars.

The first problem is to find which IRAS sources are associated with dark clouds. This is non-trivial as there are 245,839 objects in the IRAS catalog, and dark clouds are neither point like nor uniform in shape and hence their positions and extents are difficult to catalog. Ultimately we will make overlay plots for the sky surveys and look for the IRAS sources lieing within the optical cloud outlines, but this is a long term undertaking. To make short term progress a computerised association between IRAS sources and dark clouds is needed.

The IRAS catalog already contains a crude attempt at associations with the Lynds (1962) dark cloud catalog and with Wesselius' globule list (Supplement) which was a preliminary and incomplete version of the Southern Dark Cloud (henceforward SDC) catalog of Hartley et al.(1986). These associations were made by taking each cataloged dark cloud as circular with area equal to its actual area, and searching for associated IRAS sources out to the equivalent circular radius or to 60′ whichever was smaller. Because dark clouds are not generally circular this does not ensure that the IRAS sources actually lie within the boundaries of the optical dark clouds. Thus the use of these associations for statistical work must be considered dubious.

A better set of associations can be made if a catalog of dark clouds lists the cloud major and minor axes so that the search radius can be set equal to the cloud semi-minor axis. Such a search should more closely guarantee that the IRAS objects found are truly seen towards the dark clouds. Of the major dark cloud catalogs only the SDC catalog (Hartley et al. 1986) gives major and minor axes so it was used as the sample of dark clouds for this study.

The SDC catalog lists 1055 individual dark clouds and 46 cloud complexes found south of declination -33 degrees on ESO/SERC J survey plates. As individual members of cloud complexes are generally listed the 46 complexes were excluded from consideration. The remaining 1055 dark clouds cover an area of 42 square degrees and we searched all of the area that lay within circles of radius equal to the semi-minor axis of each cloud. This corresponds to searching an area of 25 square degrees or 60% of the total cataloged area. A total of 1099 IRAS sources were associated with 436 of the dark clouds by this criterion. The corresponding source surface density is 44.1 per square degree of dark cloud area searched. The remaining 619 dark clouds did not have any IRAS sources lieing within the search radius. Although only 41% by number of clouds searched contained IRAS sources this corresponds to 85% of the area searched. Note that, although our search method should ensure that most of the IRAS sources are truly seen towards dark clouds, we will not find all sources associated with each cloud by this method, unless a cloud appears circular.

3. CLASSES OF SOURCE IN THE IRAS CATALOG

It is useful to classify the IRAS sources using their measured infrared colours [100-60], [60-25] and [25-12] defined as the logarithm of the ratio of the IRAS catalog flux densities (S(l) in Janskies at wavelength l in microns) at a long and shorter pair of adjacent wavelengths. (For example for the 100 to 60 micron colour [100-60] = Lg[S(100)/S(60)]). No colour corrections (Supplement) have been applied.

We take an empirical approach of plotting colour-colour plots of the IRAS catalog to find the regions of these plots occupied by various object of known type.

The left hand sides of Figures 1 and 2 show the [25-12] versus [60-25] and [100-60] versus [60-25] colour-colour plots for all sources in the IRAS Catalog with medium or good quality detections at three adjacent wavelengths. The coldest objects will lie in the top right of each plot and the hottest in the bottom left.

Colour-colour plots (not shown here) were constructed for a few types of object and the densest clustering of objects of each type used to define the colour regions discussed below and summarised in Table I. Figures 1 and 2 should be viewed with the aid of Table I.

The colours given for blackbodies take into account the IRAS bandpasses and so are directly comparable with the IRAS catalog fluxes, avoiding the complexities of color corrections (Supplement).

The stars' colours are based on objects associated with a stellar catalog according to the IRAS catalog and cluster in the bottom left hand corners of Figs 1 and 2 as expected for relatively warm 300-2000 K objects (Chester 1986).

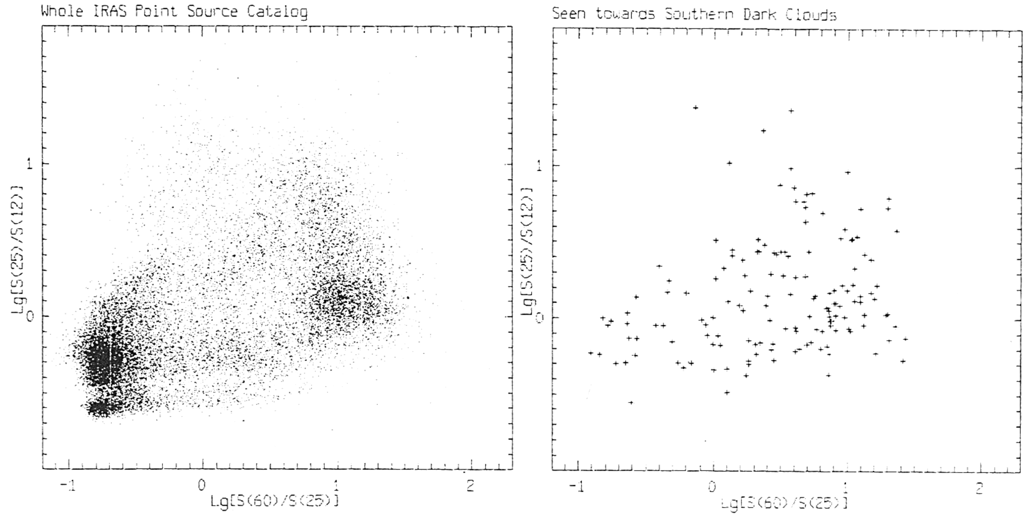

Figure 1. [25-12] versus [60-25] micron colour-colour plots for IRAS detections at 12, 25 and 60 microns. The regions populated by some known types of object are given in Table I. Left: 19,576 IRAS catalog sources. Right: 153 sources seen towards southern dark clouds.

In Figure 1 the clustering at [25-12] = -0.6 corresponds to the Rayleigh Jeans tail of photospheric emission from stars and is clearly separated by a boundary at [25-12] = -0.5 from the major clustering at [25-12] = -0.25 which is mostly due to emission from late type giant and supergiant stars surrounded by circumstellar dust shells. Hacking et al. (1985) discuss in more detail the regions of the colour-colour diagrams occupied by K and M stars without circumstellar dust shells, by M stars with circumstellar shells and by carbon stars. Figure 2 indicates that [100-60] is not very well determined for stars as few of them are bright enough to be detected at 100 microns.

Bulge stars are taken from Habing et al.(1985) and are probably evolved late type M stars near the tip of the red giant branch.

Planetary nebulae colours are taken from Pottasch et al. (1984).

TABLE I
Colour ranges occupied by some known types of object

Object Type	IRAS Colours		
	[25-12]	[60-25]	[100-60]
1000 K blackbody	-0.47	-0.70	-0.50
100 K blackbody	+1.64	+0.44	-0.17
50 K blackbody	+3.69	+1.79	+0.23
30 K blackbody	+6.39	+3.52	+0.70
Stars	-0.7 to -0.2	-0.9 to -0.4	-0.2 to -0.6
Bulge stars	-0.2 to +0.3	-0.8 to -0.2	-
Planetary Nebulae	+0.8 to +1.2	0.0 to +0.4	-0.4 to 0.0
T Tauri Stars	0.0 to +0.5	-0.2 to +0.4	0.0 to +0.4
Cores	+0.4 to +1.0	+0.4 to +1.3	+0.1 to +0.7
Galaxies	0.0 to +0.4	+0.6 to +1.2	+0.1 to +0.5

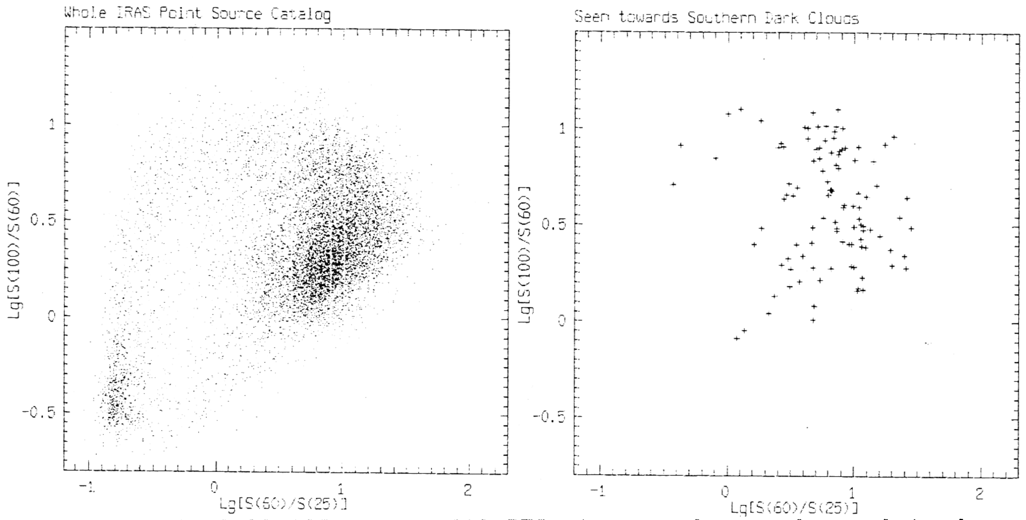

Figure 2. [100-60] versus [60-25] micron colour-colour plots for IRAS detections at 25, 60 and 100 microns. The regions populated by some known types of object are given in Table I. Left: 10,216 IRAS catalog sources. Right: 106 sources seen towards southern dark clouds.

Note that OH/IR stars (Olnon et al. 1984) lie along a track running between the stars and planetary nebulae regions of Figure 1.

T Tauri star colours are based on 338 IRAS sources associated with known T Tauri stars (Emerson et al. 1986), and confirm the IRAS colours found for T Tauri stars in Taurus by Harris (1985).

Cores are based on the sample of IRAS objects found associated (Beichman et al. 1986) with dense molecular cloud cores studied by Myers et al. (1983) and Myers and Benson (1983). Many of these objects also populate the T Tauri region.

Galaxy colours are based on objects associated with an extragalactic catalog according to the IRAS catalog.

Molecular cloud hot spots, HII regions, reflection nebulae, star formation regions, which we shall collectively call embedded sources, all occupy an area similar to that of galaxies and cores.

The left hand side of Figure 3 shows a histogram of the numbers of all IRAS catalog sources with detections at two adjacent wavelengths as a function of [100-60]. It contains many more sources than the colour-colour plot as a source need only have medium or good quality detections at 2 adjacent IRAS wavelengths for inclusion in a histogram, whereas 3 adjacent detections are necessary for inclusion on a colour-colour plot. The importance of Cirrus (Low et al. 1984, Gautier 1986) may be clearly seen from the strong peak at [100-60] = +0.8 in Figure 3. Cirrus does not clearly appear on either the colour-colour plots as it is too cold to be detected at 25 microns. The equivalent histogram for the sample of IRAS sources seen towards Southern Dark Clouds is given in the right hand side of Figure 3 for comparison. Similar histograms (not shown) for [60-25] and [25-12] colours confirm the features of the colour-colour diagrams, but for a larger sample.

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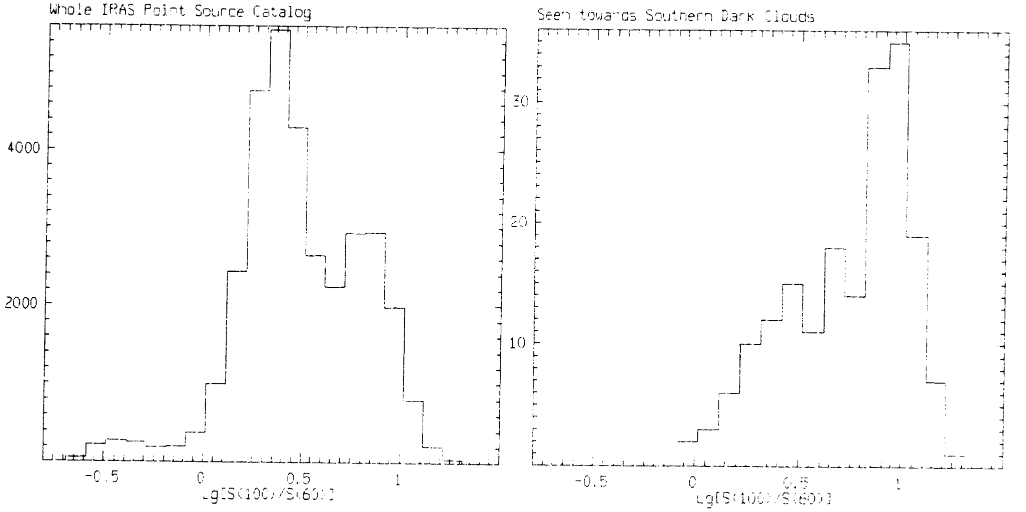

Figure 3. Histogram of the number of detections at 60 and 100 microns as a function of [100-60] colour. The colour ranges populated by some known types of object are given in TABLE I. Left: 33,438 IRAS catalog sources. Right: 186 sources seen towards southern dark clouds.

For illustration we now point out the location in the colour-colour diagrams of two often discussed objects, L1551 and B335.

L1551 IRS5 the prototypical premain sequence object with prominent bipolar outflow is at [100-60] = +0.1, [60-25] = +0.5 and [25-12] = +1.0 in the Cores region. There are many other objects with similar colours.

In fact the IRAS source in B335 is not on the colour-colour plots as it appears in the catalog only at 60 and 100 microns, but its fluxes are known from special pointed observations (Beichman et al. 1986) and it would have been found at [100-60] = +0.7, [60-25] = +1.6, [25-12] = +0.3. Clearly there are very few objects with cold colours similar to B335 and detected by IRAS at 25 microns. Assuming B335 to be at 230 pc identical objects would have to be closer than 140 pc to be in the IRAS catalog at 25 microns. There are only 5 sources with this, or more extreme colours in Figure 2 so that the local surface density of B335 type objects is not more than 100 kpc^{-2} or about 25% of the surface density of 10^2 to 10^4 solar mass molecular clouds (Elmegreen 1985). The rarity of B335 type objects perhaps strengthens the case for B335 being a real protostar, but also, by the same token, indicates the difficulty of easily finding many real protostars from the IRAS catalog.

4. CLASSES OF IRAS SOURCE SEEN TOWARDS SOUTHERN DARK CLOUDS

Comparing Figures 1-3 for the whole IRAS catalog with those for the SDC sample one notices that the SDC sample is relatively poor in stars and relatively rich in embedded and cirrus-like objects as might be expected for a population of objects physically associated with dark clouds in which star formation is occuring, or has recently occured, and for which dust clouds are also heated externally by the interstellar radiation field.

We split the 1099 IRAS sources seen towards southern dark clouds into 5 categories based on the wavelengths at which detections were made and their observed colours. These categories are mainly based on Table I and Figures 1-3.

529 sources (48%, surface density 21.2 per sq. deg.) have "Star colours" defined as a detection at 12 microns, and with [25-12] < 0 if also detected at 25 microns. At longer wavelengths there are either no detections (461 sources) or the flux density continues to fall (17 sources). Additionally in this class we have included 51 similar objects but with an apparent flux density rise at longer wavelengths based ONLY on MODERATE quality detections. Many of these latter are likely to be stars with cirrus contamination. We have not differentiated between stars where photospheric emission is seen and those where emission from dust shells is predominant.

119 objects (11%, surface density 4.8 per sq. deg.) are designated as having "Thick dust shell colours peaking at 25 microns" defined as a detection at 25 microns, and with [25-12] > 0 if also detected at 12 microns. At longer wavelengths either there are no detections (101 sources) or the flux density falls (8 sources). Additionally we include 10 sources where there is a flux density rise at 100 micron based ONLY on a MODERATE quality detection. We assume these cases represent contamination by cirrus.

160 sources (15%, surface density 6.4 per sq. deg.) are designated as having "Cirrus colours" defined as a detection only at 100 microns (91 sources) or detection at 60 and 100 microns only with [100-60] > +0.6 (69 objects). In fact only 4 of all the objects detected only at 60 and 100 microns failed to fall into this class.

247 sources (22%, surface density 9.9 per sq. deg.) are designated as having "Embedded colours" defined as a detection at 25 and 60 microns with [60-25] > 0 and with [25-12] > 0 if also detected at 12 microns (154 sources). Also we include 89 sources detected only at 60 microns and 4 sources with detections at 60 and 100 microns only with [100-60] < +0.6. Because we have demanded that these objects be seen at 60 and 25 microns, or if not seen at 25 microns that they not have cirrus like colours, they should not contain much cirrus, but be objects locally heated by an internal energy source. This is the sample in which we expect to find our young and proto stars.

The remaining 44 sources (4%, surface density 1.8 per sq. deg.) are not readily assigned to any of the above classes. Many of them probably have unusual colours due to the presence of more than one type of source in the IRAS beam at the same time or other difficulties. They will not be further considered here.

These classifications, and our interpretation of their significance, are consistent with the associations and with the classification of the 8-22 micron Low Resolution Spectrometer spectra (Supplement) given, where available, in the IRAS Catalog.

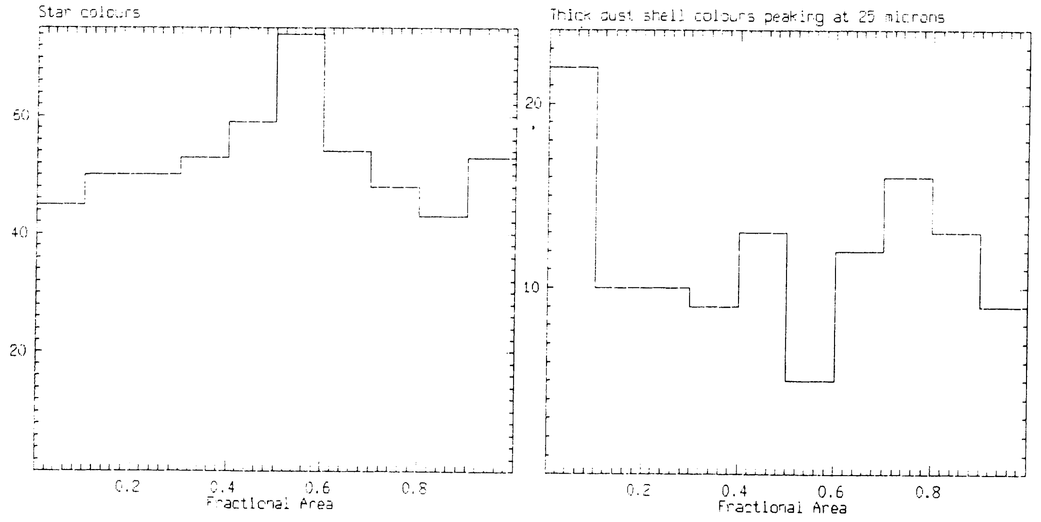

Figure 4. Histograms of the number of sources associated with southern dark clouds as a function of the fractional projected circular area, measured from the cloud centre, at which they were found. Left: sources with star colours. Right: sources with thick dust shell colours peaking at 25 microns.

5. LOCATION OF IRAS SOURCES SEEN TOWARDS SOUTHERN DARK CLOUDS

The positional search criteria and classification establish 4 samples of sources seen towards the southern dark clouds, but some of the sources will be field objects not associated physically (merely by projection) with the dark clouds. The physically unassociated sources should be distributed randomly, in projection, over the cloud area with the number found projected within fractional cloud area f to f+df being constant. For sources physically associated with the dark clouds and located randomly throughout the volume of the clouds the number found projected within fractional cloud area f to f+df should be proportional to $(1-f)^{0.5}$ df. Here we have taken the volume searched to be spherical. In reality the clouds are more likely to be ellipsoidal than spherical so the volume searched should really be defined by the intersection of the search circle with an ellipsoid, but as the search circle radius is equal to the ellipse semi-minor axis this volume approximates to a sphere. The true geometry is not anyway well enough known to justify a less approximate approach. For sources physically associated with the dark clouds but randomly distributed over the surface of a spherical cloud, rather than throughout its volume, the number of sources found projected within fractional area f to f+df should be proportional to $(1-f)^{-0.5}$df.

To try and determine which sources are physically associated with the southern dark clouds we used the distance of each IRAS source from its associated dark cloud centre to calculate the fractional area of the cloud at which each IRAS source was found. Histograms of the number of

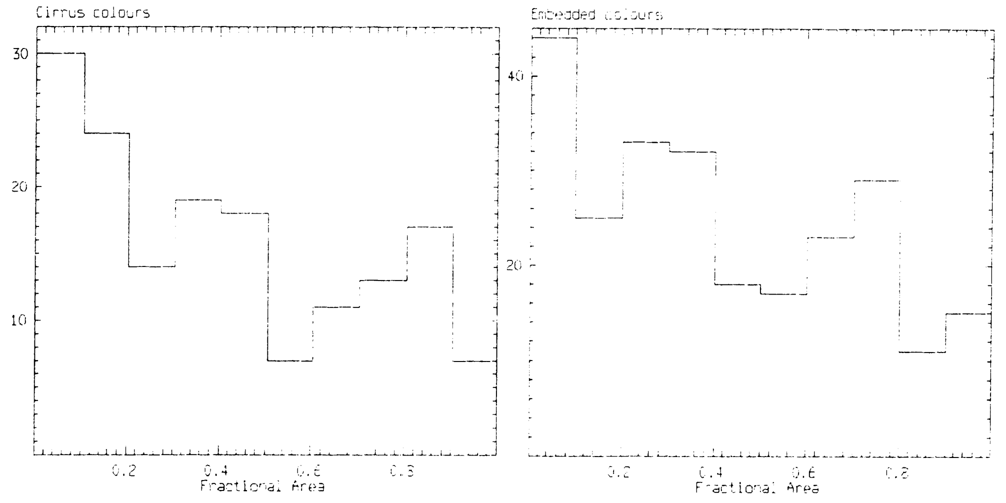

Figure 5. Histograms of the number of sources associated with southern dark clouds as a function of the fractional projected circular area, measured from the cloud centre, at which they were found. Left: sources with cirrus colours. Right: sources with embedded colours.

sources as a function of fractional area are shown for the four classes in Figures 4 and 5.

The sources with Star colours and with thick dust shell colours peaking at 25 microns are presumed to be mostly stars of various types. If most are field stars their distribution over the cloud's fractional area should be uniform and we interpret Figure 4 as indicating, within the uncertainties that the majority of sources in these two classes are indeed field sources. This conclusion can be made more strongly for the more numerous objects with star colours. The peak at fractional area 0.55 on their histogram has no obvious explanation and is being further investigated. It is mainly caused by some of the 263 sources detected only at 12 and 25 microns with [25-12] < 0. The peak at small fractional area for the thick dust shell colours peaking at 25 microns suggests that there may be a small numerical component of these sources embedded in the dark clouds, possibly concentrated towards their centres.

As the objects we are associating IRAS sources with are dark clouds and cirrus emission arises from dust heated externally by the local interstellar radiation field (Low et al 1984, Gautier 1986) we expect to find cirrus colour sources associated with these dark clouds. We might also expect the very youngest embedded protostars which are heating the dust clouds from inside to produce very cool dust which, like cirrus, would be usually detectable only at 100 microns. Cirrus thus reduces our ability to locate protostar candidates unambiguously using the IRAS catalog. Discrimination between cirrus and protostars will have to be based on careful examination, on a source by source basis, of the environment of the source (cirrus will tend to be seen part of extended structure) and other available data. Here we conservatively assume that all objects with cirrus colours are in fact cirrus, recognising that this may be throwing the baby out with the bath water! We would expect the structure in the dust clouds that is detected as point like sources in the IRAS in scan direction to be randomly distributed throughout the clouds volumes and thus that the number of cirrus colour sources will fall off (see above) with increasing fractional area. Figure 5, left, shows the histogram which, within the uncertainties, is consistent with this expectation.

We are now left with 247 sources with embedded colours. Galaxies would have these colours, but at the relatively low galactic latitudes of the dark clouds they should be far outnumbered by galactic objects and we will therefore ignore them (additionally they would be uniformly distributed with fractional area as they are not physically associated with the dark clouds). Because of the low galactic latitudes involved many of these objects also could be field objects. The histogram of their number as a function of fractional area in Figure 5, right, however falls to larger fractional area suggesting that the majority of them are likely to be physically associated with the dark clouds.

The conclusions above about whether the sources are field objects or physically associated with the dark clouds were based on the shape of the histogrmas in Fig 4 & 5 and are confirmed by comparing the expected and actual values of the median, mode and mean of each histogram.

Assuming a typical distance of 0.5 kpc for these dust clouds the luminosities of most of these embedded objects are characteristic of low mass stars. The formation of high mass stars is often considered to be externally triggered, although such a trigger is not thought necessary for low mass stars (eg Israel 1978, Elmegreen and Lada 1977). If in fact low mass star formation was also triggered externally we would expect a distribution of source with fractional area rising towards the cloud edge (see above) which is clearly inconsistent with the observed trend. This confirms that there is no reason to suppose that low mass star formation in an existing dark cloud generally requires strong external triggering which would result in stars forming at the edge of the cloud. A possible exception to this generalisation is that in L1551 the NE IRAS source (Emerson et al.1984) is located at a CO maximum (Snell and Schloerb 1985) of the gas shell swept up by the outflow from IRS5 and its formation may have been triggered by this flow.

We conclude that the majority of the sources with embedded colours are associated with the dark clouds towards which they are seen, and that they are equally likely to be found anywhere throughout the cloud volume.

Note that we have assumed uniform cloud densities in our intepretation. A more realistic centrally condensed cloud produces a more pronounced peak in the number of sources found towards the centre, and makes it more difficult to detect any external triggering effects. We feel that such sophistication is not warranted by the histograms.

6. DISCUSSION

We have discussed the method of extracting from the IRAS catalog a sample of objects that are physically associated with dark clouds and which we intend to use to study the statistics of star formation in dark clouds. Before using this data to study star formation in detail we need to know the cloud distances, gas densities and to examine the sources individually on the sky survey plates. These determinations are not yet available so we merely present order of magnitude estimates of the likely age of the embedded objects and the star formation efficiency in these dark clouds.

The typical turbulent velocity of molecular cloud cores that have recently formed low mass stars is 0.3 km s^{-1} (Myers 1986). Assuming this value is also appropriate to our sample it will give the likely magnitude of the peculiar velocity of recently formed objects. Taking a typical cloud with embedded sources to have a minor axis of 10 arcmin and to be at a distance of 0.5 kpc then objects with peculiar velocity 0.3 km s^{-1} will leave the cloud after about 2 10^6 years suggesting that this is an upper limit to the age of a typical source. Thus the IRAS sources are indeed at least young stars.

Taking a mean gas density of 3 10^3 cm^{-3} in the clouds the typical cloud mass is 170 solar masses so that if the embedded objects are typically of mass 3 solar masses the overrall star formation mass efficiency in the clouds which are currently forming stars is about 2%. About 16% by number and 51% by area of the dark clouds searched currently seem to have star formation activity going on so the star formation efficiency averaged over all the dark clouds in the sample is lower than 2%. It will be of interest to determine what differences exist between the dark clouds that are currently forming stars and those that are not.

7. CONCLUSIONS

We have discussed the selection criteria for finding a sample of IRAS sources physically associated with dark clouds. In doing so we have indicated the location of various types of objects in IRAS 25-12, 60-25 and 100-60 micron colour space. This information should be useful for those trying to select any type of source by IRAS colour criteria.

For the Southern Dark Cloud catalog (Hartley et. al. 1986) we find that 16% by number and 51% by area of the clouds searched contain embedded objects that are presumed to be at least recently formed objects. The confusing effects of cirrus make recognition of objects likely to be true protostars very difficult using IRAS data alone. Objects such as B335 or with more extreme IRAS colours are very rare at least within 140 pc of us. The embedded objects are mostly low mass stars and seem to form at random positions throughout the dark cloud volumes. There is no indication of widespread external triggering of star formation in these clouds.

Further investigations of the sample selected here are necessary before further conclusions can be drawn.

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STROM: I just wish to point out that the ratio of far-IR to near-IR luminosity need not necessarily provide a reliable signature of "protostars". L(FIR)/L(NIR) >> 1 certainly suggests a cool, optically thick dust envelope. However, L1551/IRS5, cited as a "prototypical" example of a "protostellar" object with L(FIR)/L(NIR) >> 1 actually can be viewed, via scattered light, from light escaping from the poles of a circumstellar disk surrounding IRS5; a spectrum of a scattered light patch associated with HH102 reveals IRS5 to be a late-type star (perhaps of the FU Ori type). Other sources characterized by large L(FIR)/L(NIR) (*e.g.* VLA-1 in the HH1-2 system and perhaps even B335) have associated reflection nebulae which appear to scatter radiation from an optically (or near-IR) visible object, obscured along the line of sight (but producing a scattered light region as light escapes from the "poles" of a circumstellar disk). My warning: do not ignore geometrical effects in evaluating the evolutionary status of an embedded star. We must find some way of assessing the ratio of accretion luminosity to "quasi-static" contraction luminosity.

EMERSON: I agree with your point. I showed the positions of L1551 IRS5 and B335 on the IRAS color-color diagrams mainly as points of reference to show where such frequently discussed young dust embedded objects, regardless of their intrinsic nature, are located. Given the nature of the IRAS data colors are the best way to pick candidate protostars, but other observations and careful interpretation are needed before one can claim to have found true protostars.

LADA: This is a very good point with which I agree. Sources with steeply rising energy distributions must both include "protostellar candidates" as well as objects in transition to PMS stars. The sequence of energy distributions from the negatively shaped spectra of T-Tauri stars to the steeply rising spectra of "protostellar" candidates is, I believe, a continuous one. In fact L1551 IRS5 is not nearly as steep as many other sources, including many without molecular outflows. However, I do think that its energy distribution indicates that hot dust exists very close ($\sim$ 1 AU) to the surface of the star, and my guess is that L1551 IRS5 is not a "typical" T-Tauri star or FU Ori object, but rather an extremely young example of one of these classes of objects.