NEW SAMPLE OF YOUNG STELLAR OBJECTS

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ABSTRACT. In recent years there has been much interest in the study of large samples of molecular cloud cores and related infrared sources in an attempt to observe true protostars - objects in transition between a molecular cloud core and a young stellar object (YSO). We present here a survey of 48 possible protostellar objects chosen initially by their IRAS colours and subsequently observed in (1–0) HCO^+ emission at Onsala in Feb 1990. Future observations in (3–2)^{13}CO & (3–2)^{12}CO will be made with the JCMT and in (1,1) and (2,2) NH_3 emission with the Bonn 100m telescope.

1. Introduction

A search for possible protostars can be undertaken in one of two ways: candidate objects can be chosen in regions of high visual obscuration containing known dense molecular cores (Myers & Benson, 1983), or, more commonly, objects can be selected by their infrared (IRAS) colours. (Beichman 1986, Myers 1987, Heyer 1987 and Scalise 1989). In both cases follow-up observations can be made using molecular line emission and/or further mid- to near- infrared photometry.

A protostar can be defined as a region within a molecular cloud where the star forming efficiency approaches 100%; thus all the gas and dust present within that region will collapse to form a star. This proceeds from the inside out, increasing the temperature and pressure of the protostar until the initiation of deuterium 'burning'. To date observations have failed to detect such an object, with most detections revealing outflow material with little or no sign of collapse. No object has been detected with simply inflow alone: this may be because such activity occurs over a very short time span compared with the outflow liftime, requiring a large sample of objects to be observed. A further reason may be that œOxisolated inflow occurs over a region that cannot be properly resolved, thus 'diluting' any otherwise detectable velocity shifts due to collapse.

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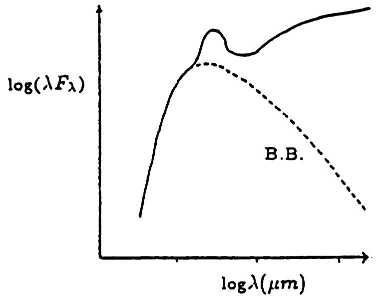
2. The IRAS Sample

The core of a protostellar object is shrouded by a thick optically opaque envelope of gas and dust which is heated initially by the release of gravitational energy and then later by the radiation energy emitted by deuterium 'burning'. The dust within the envelope re-radiates this energy at infrared wavelengths.
One can define a spectral index α for a given spectral energy distribution (SED), (Lada, 1987), as

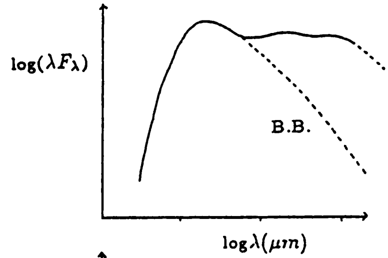
$$\alpha = \frac{\mathrm{dlog}\lambda \mathrm{F}_\lambda}{\mathrm{dlog}\lambda} .$$

Lada classifies young stellar objects (YSO's) according to their spectral energy distribution into three classes:-

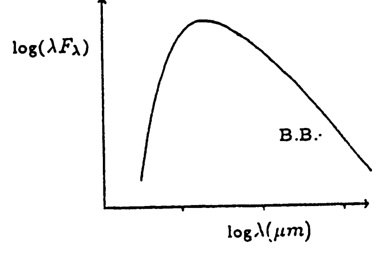
Class I.
These have a SED broader than for a single blackbody, with a positive spectral index between 12 to 100μm. This can be attributed to large amounts of circumstellar dust.



Class II.
These have negative spectral indices from 12 to 100μm. Again these have SED's broader than for single blackbodies. Their spectral index is due to some circumstellar dust. These objects are usually found to be embedded T-Tauri stars.



Class III.
Again these have a negative spectral index but SED's that correspond to a single black body which is only slightly reddened.



It is assumed that these classes represent an evolutionary sequence starting at the young, heavily shrouded class I objects and proceeding through class II to the older class III sources. Real sources are found to have a whole range of SED's that vary

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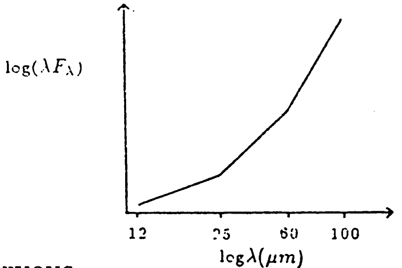
continuously in shape from class I to class III. Starting from this hypothesis, we selected all sources in the IRAS point source catalogue with positive spectral indices between all four wavelengths, not associated with possible extragalatic objects, and with all flux measurements being of at least moderate quality. These selection criteria produced ~4,500 sources, the vast majority of which had never been previously observed in molecular line emission.

Two further selection criteria were imposed to produce a smaller, yet complete, sample of 48 objects, these were:-

i) All spectral indices had to be greater than 2.
($\alpha_{12,25} > 2$, $\alpha_{25,60} > 2$, $\alpha_{60,100} > 2$) and

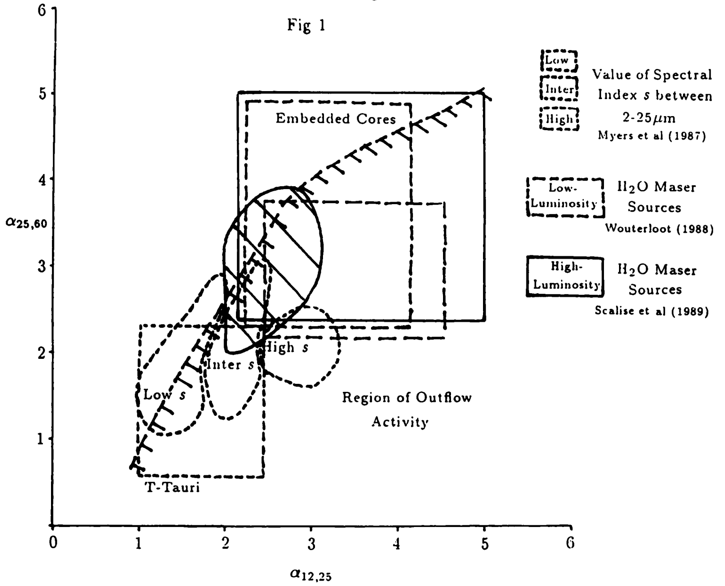
ii) Spectral indices increased with increasing wavelength.
($\alpha_{12,25} < \alpha_{25,60} < \alpha_{60,100}$)

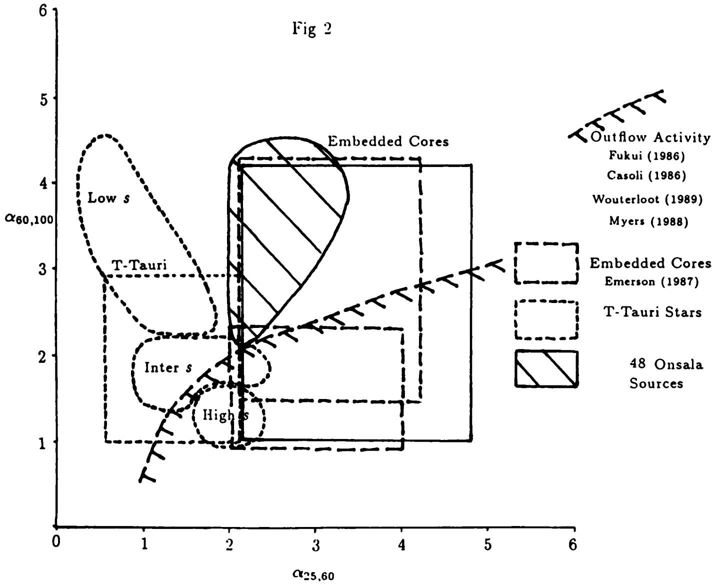


3. Previous Surveys

By bringing together many of the IRAS sources included in other surveys and plotting them on colour-colour diagrams, we investigated whether particular types of objects were confined to given regions in colour space. Caution must be exercised when combining sources from so many surveys - not only do they lie in different regions of space but they will have been selected in different ways , although the selection criteria will have been chosen to select possible YSO's and protostars and therefore be similar.
Looking at figs 1 & 2 it is apparent that certain phenomena are confined to areas of colour space; all the sources except those of Scalise (1989) have IRAS luminosities low to intermediate (~0.1 to ~200 $L_\odot$), although most are less than ~20 $L_\odot$.
Sources with maser and outflow activity predominately are found in similar regions: Wouterloot (1989) concluded that the two are correlated, and that sources with a higher far-infrared luminosity have generally higher H_2O maser luminosity. There appear to be close correlations between IRAS colours and near infrared and optical fluxes. Myers et al. (1987) found that objects that had a high spectral index s between 2 and 25μm were more likely to be optically invisible and near molecular cores than those with a low value of s, whilst extinction reaches a maximum when s=2 to 3, and implies a gas and dust density much greater than that deduced from molecular line observations, suggesting that the gas within the cores may be clumped,or have a non-spherical geometry. Similar results were obtained by Beichman (1986) who found a correlation between the presence of an optical counterpart and distance from the associated cloud core. The IRAS colours at 12 and 25μm

IRAS Colour-Colour Diagrams





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tend to show that the more obscured of these objects lie in the region of embedded sources defined by Emerson (1987), whilst those having optical counterparts tend to lie within the T-Tauri region. In figure 2, in which a third dimension is added to colour- colour space with $\alpha_{60,100}$, the simple evolutionary correlation, seen in fig 1, of decreasing s between embedded cores and T-Tauris is weaker. However, since IRAS fluxes at 100μm are subject to unknown amounts of 'cirrus' contamination, this evidence does not necessarily contradict the conclusions of Myers et al.

The mid-infrared flux between 2 to 25μm is dependent, according to theoretical calculations by Adams & Shu (1985), on the presence of material within a shell, or possibly a disk. This governs emission between 5 to 30μm, intercepting substantial amounts of radiation and allowing more distant grains to be warmed with a cooler distribution of photons than that from the star. The presence of such a structure would explain the cooler grain distribution required to fit far infrared observations. Thus the value of s (between 2 to 25 μm) may be indicative of the presence of the circumstellar disk; it should be noted that high and intermediate s value sources lie in a region associated with outflows and adjacent to one where masers occur. Using the same sample, a CO survey by Myers (1989), showed that outflows were only associated with IRAS sources near molecular cores.

From the IRAS colour plots no clearcut picture emerges. Although outflow sources predominately are found in the region enclosing embedded cores (Emerson, 1987), and that these sources border that enclosing T-Tauri stars, it is still not clear how a protostar moves in colour space as it evolves. Outflow is one of the easiest phenomena to detect, with adequate mapping, and is believed to last approximately half the life time of a protostar ($\sim 2 \times 10^5$yr, Snell et al.1988).

The accretion model of Adams and Shu (1986) predicts a protostar gaining mass and becoming warmer as it moves towards the region occupied by T-Tauri stars. From theoretical work by Stahler Shu & Taam (1980) accretion luminosity is proportional to the protostellar mass, thus luminosity and temperature should increase with time as the core assembles more material. Berrilli et al (1989), taking a large sample of known CO sources (outflows) and Herbig Haro excitation sources, found that there was no correlation between their luminosity and IRAS colours; they were evidently not becoming warmer as their luminosity increased. If the model of Adams & Shu is correct then such exciting sources cannot be described by a purely accretional model and are thus more evolved objects than true protostars.

4. Sample of 48 IRAS sources

4.1. CASE FOR PROTOSTARS

The sample of 48 IRAS sources, (Table 1), was found to occupy a very small area of colour space. Almost all lay outside the region predominately occupied by outflow and maser sources, and all have colour temperatures $T(\frac{60}{100}) \sim 20$ to 25K. They all have spectral energy distributions which peak longwards of 100μm, corresponding to temperatures less than 29K.

Table 1. 48 IRAS Source Fluxes and Spectral Indices

NAME	F_{12}	F_{25}	F_{60}	F_{100}	$\alpha_{12,25}$	$\alpha_{25,60}$	$\alpha_{60,100}$
00040+6742	0.55	1.33	9.77	47.66	2.20	3.27	4.10
00322+6315	0.29	0.65	3.51	12.50	2.10	2.93	3.49
00361+5911	2.64	5.68	14.20	33.48	2.04	2.05	2.70
00412+4132	0.37	0.87	6.42	21.56	2.20	3.28	3.37
00544+5609	0.49	1.26	6.65	28.12	2.29	2.90	3.82
02407+6029	1.20	4.51	29.07	90.17	2.80	3.13	3.22
02500+6905	0.52	1.10	7.66	29.12	2.02	3.22	3.61
03111+5938	0.38	1.27	5.73	17.17	2.64	2.72	3.15
03429+2423	0.42	1.14	4.68	10.91	2.36	2.61	2.66
04033+5103	0.28	0.76	4.58	14.67	2.36	3.05	3.28
04362+4913	0.42	1.20	5.03	17.79	2.43	2.64	3.47
04480+4530	0.93	2.23	14.93	46.96	2.19	3.17	3.24
04487+3942	0.38	0.84	2.45	8.77	2.10	2.20	3.50
05177+3636	0.74	1.59	4.29	15.90	2.00	2.10	3.60
05286+1203	0.78	1.19	9.35	70.37	2.22	2.81	4.95
05375−0040	0.73	1.72	5.00	27.98	2.17	2.22	4.37
05382−0324	0.25	0.53	5.66	35.46	2.02	3.71	4.59
05393+2248	1.10	2.94	11.25	25.09	2.34	2.53	2.57
05435−0015	1.93	5.13	20.87	67.93	2.33	2.60	3.31
05590+2008	0.41	0.90	5.72	23.03	2.07	3.11	3.73
06405−0356	0.31	0.65	4.38	13.75	2.01	3.18	3.24
06522−0350	1.45	3.56	23.12	69.62	2.22	3.14	3.16
18216+6418	0.19	0.40	1.13	2.16	2.01	2.19	2.27
18437−0216	3.87	14.86	146.81	640.72	2.83	3.62	3.88
18533+0750	2.56	5.55	25.84	363.55	2.05	2.76	6.18
19009+0204	0.61	1.42	8.09	24.10	2.15	2.99	3.14
19116+1155	2.69	6.28	43.47	370.44	2.16	3.21	5.19
19188+1400	1.52	6.20	71.65	443.40	2.90	3.79	4.56
19253+1748	3.33	11.30	52.49	136.06	2.66	2.75	2.86
19262+1924	3.86	12.39	70.63	468.50	2.58	2.98	4.70
19287+1816	1.21	3.80	21.22	99.11	2.56	2.96	4.02
19459+2558	0.36	1.34	6.93	24.86	2.79	2.88	3.50
19474+2637	4.21	14.75	92.02	319.28	2.71	3.09	3.44
19509+2725	0.48	1.06	3.50	16.76	2.08	2.36	4.07
20049+3326	0.97	2.26	6.74	24.18	2.15	2.25	3.50
20072+2720	0.78	2.19	14.30	44.87	2.41	3.14	3.24
20136+4025	0.77	1.90	13.34	50.64	2.23	3.23	3.61
21026+4932	1.38	3.98	15.29	37.51	2.44	2.54	2.76
21098+5358	0.40	0.88	7.05	28.79	2.07	3.37	3.75
21143+5159	0.38	0.85	5.07	19.20	2.10	3.04	3.61
21306+5733	0.65	1.44	9.01	38.47	2.08	3.09	3.84
21350+4943	0.32	0.74	5.48	18.44	2.14	3.29	3.38
22174+6042	0.46	1.67	9.27	35.81	2.75	2.96	3.65
22178+6317	5.16	14.37	61.59	212.67	2.39	2.66	3.40
22452+5835	0.31	0.66	3.40	23.94	2.00	2.80	4.80
22529+5704	0.34	0.83	2.51	10.53	2.22	2.26	3.81
23091+6211	0.33	0.88	3.16	18.85	2.38	2.46	4.50

We believe that this sample may represent a selection of extremely cool and still heavily enshrouded protostars. The SED's of our sample are very similar to IRS2 found in the dark cloud Barnard 5. This object has a colour temperature of ~25K and a mass which exceeds the calculated Jeans mass for this cloud. It is unlikely to be a density enhancement within the cloud heated by the interstellar radiation field (Beichman, 1984). A similar very cool object lies in the centre of B335, this also peaks longward of 100μm. (Keene et al, 1983).
From the NH_3 studies by Myers & Benson (1983) and Wouterloot & Walmsley (1988), almost all dense molecular cores associated with possible protostellar IRAS sources had kinetic temperatures less than 25K. Further, the study by Myers & Benson showed that even under the two extremes for supporting motion, thermal and Doppler, the cloud cores would at best be unstable and at worst, be undergoing collapse.

4.2. LUMINOSITY

Luminosity has been calculated where possible using the distance obtained from distance modulii of associated HII & OB clusters, using the expression for the infrared flux of Boulanger (Casoli, 1986). Most of the sources appear to be of intermediate luminosity, much lower than the outflow sources of Snell (1988) ~$10^4 L_\odot$, yet slightly greater than those of Beichman et al (1986) ~2-3$L_\odot$, (Table 3).

4.3. MASS

TABLE 2. Source mass comparisons

	Wavelength Range(μm)	Mass ($M_\odot$)	Number in Sample	
Sources with	12–25	$1\pm0.4\times10^{-6}$	(16)	
Optical	25–60	$4\pm2\times10^{-4}$	(9)	Beichman
Counterparts	60–100	$3\pm2\times10^{-5}$	(5)	1986
Sources without	12–25	$1\pm0.5\times10^{-5}$	(14)	
Optical	25–60	$4\pm1\times10^{-3}$	(22)	Beichman
Counterparts	60–100	$4\pm1\times10^{-1}$	(23)	1986
	12–25	1.4×10^{-5}	(16)	
	25–60	5.0×10^{-3}	(22)	Our Sample
	60–100	7.7	(22)	

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Following Beichman (1986) the mass of gas & dust in an optically thin region, emitting at a particular wavelength, may be calculated, assuming grain properties and temperatures of Hildebrand (1983).

TABLE 3. Source parameters and associated OB clusters

NAME	Assoc	D(kpc)	$L(L_\odot)$	$M_{12,25}$	$M_{25,60}$	$M_{60,100}$
05177	Aur OB1	1.32	42	5.7×10^{-6}	9.5×10^{-4}	0.21
00322	Cas OB14	1.10	19	2.8×10^{-6}	7.8×10^{-4}	1.91
	Cas OB4	2.88	128	1.9×10^{-5}	5.2×10^{-3}	12.9
00544	S184	2.20	154	2.8×10^{-5}	7.7×10^{-3}	25.7
02500	~CAM OB1	1.00	33	3.0×10^{-6}	9.7×10^{-4}	3.5
03111	CAM OB1	1.00	24	6.7×10^{-6}	2.3×10^{-3}	1.2
	S202	0.80	15	4.3×10^{-6}	1.5×10^{-3}	0.77
03429	~PER OB2	0.40	2.88	7.6×10^{-7}	3.0×10^{-4}	0.08
04033	CAM OB1	1.00	18.6	4.0×10^{-6}	1.1×10^{-3}	0.96
05375	ORI OB1	0.50	8.1	1.6×10^{-6}	4.3×10^{-4}	2.35
05435	ORI OB1	0.50	23	1.1×10^{-6}	1.6×10^{-4}	0.016
19459	~VUL OB1	2.00	117	3.6×10^{-5}	1.3×10^{-2}	12.6
20049	~CYG OB3	2.29	190	3.8×10^{-5}	1.0×10^{-2}	14
20136	CYG OB8	2.29	288	3.4×10^{-5}	1.1×10^{-2}	27.6
20555	CYG OB7	0.83	15.5	3.9×10^{-6}	1.1×10^{-3}	2.1
21026	CYG OB7	0.83	42.6	1.6×10^{-5}	4.5×10^{-3}	1.57
21143	CYG OB7	0.83	15.8	2.1×10^{-6}	5.8×10^{-4}	1.58
21306	CEP OB2	0.83	28.8	3.4×10^{-6}	9.9×10^{-3}	4.3
21350	CYG OB7	0.83	15.5	1.9×10^{-6}	5.7×10^{-4}	0.8
22178	CEP OB2	0.83	195	4.2×10^{-5}	1.6×10^{-2}	12.8
22529	CEP OB1	3.47	263	3.8×10^{-5}	1.2×10^{-2}	21.1
23091	CEP OB3	0.87	15	3.0×10^{-6}	1.0×10^{-3}	4.51
	CAS OB2	2.63	134	2.8×10^{-5}	9.9×10^{-3}	41.3
00040	~CEP OB4	0.84	34	3.4×10^{-6}	1.2×10^{-3}	7.7
02407	CAS OB6	2.19	501	1.4×10^{-4}	5.2×10^{-2}	29
	CAM OB1	1.0	112	6.3×10^{-5}	2.5×10^{-2}	6.1
18437	S66	3.2	6760	9.6×10^{-4}	3.8×10^{-1}	1045
21098	CYG OB7	0.83	21	2.1×10^{-6}	5.9×10^{-4}	2.2
22174	CEP OB2	0.83	29	7.1×10^{-6}	2.8×10^{-3}	2.9
22452	CEP OB2	0.83	15	2.2×10^{-6}	5.4×10^{-4}	0.32
	CEP OB1	3.47	263	3.9×10^{-5}	9.0×10^{-3}	5.6
05382	ORI OB1	0.5	7.5	4.7×10^{-7}	1.1×10^{-4}	2.7

~ Source just outside OB cluster boundary

Taking an average mass for each wavelength band, (neglecting 18437−0216 and all sources with ambiguous distances), gives results not too dissimilar from those obtained by Beichman for sources without optical counterparts, i.e. younger more embedded objects. Our 48 sources have around ten times more cool material emitting between 60 and 100μm; this is not particularly surprising judging from their enhanced SED's at these wavelengths, (Table 2).

4.4. HCO^+ OBSERVATIONS

HCO^+ (1–0) observations were made towards all 48 sources with the Onsala 20m telescope in Feb 1990, to determine if they were associated with molecular material. We obtained detections in 13 with T_A^* ranging from 0.2 to 0.8K with an average of 0.6K. Although this is more probably a distance effect rather than a reflection of the intrinsic source properties as non detections ocurred in nearby high, as well as low, IR luminosity sources.
Six of the stronger detections were then mapped on a 9 point grid , 5 of these proved to be extended with peaks not coinciding with the IRAS position. None showed high velocity wings, a sign associated with possible outflow activity and, according to Berrilli, associated with more developed YSO's.

5. Conclusions

We believe that these 48 sources represent a complete sample of protostellar objects, deeply embedded in their molecular clouds and still too young to be undergoing any large scale outflow.
NH_3 (1,1) & (2,2) observations will be made in December towards all 48 sources, enabling calculations similar to those of Myers & Benson (1983), to be made, determining if collapse is occuring in molecular cores. With sources of known distance an independent estimate can be placed on core masses allowing us to verify if the IR luminosities are proportional to their accreted mass, a sign that the object is still in a purely accretional, protostellar phase.
Time has been granted at the JCMT to observe all sources at high resolution $^{12}CO(3–2)$ & $^{13}CO(3–2)$, in an attempt to observe directly any infalling material, and to do far infrared photometry at 450 & 800μm, to fix the frequency range containing the emission peak.

6. Acknowledgments

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