AN INFRARED SEARCH FOR SUBSTELLAR OBJECTS

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ABSTRACT. Preliminary results from a systematic search for nearby substellar objects in the IRAS data bases has revealed only a single candidate among the 12 μm sources in the region of the polar caps. This object appears to be a distant carbon star. All 5700 sources were positionally associated with stars or galaxies.

INTRODUCTION

Studies of low mass stars in the solar neighborhood show that their space density decreases with mass below about 0.2 $M_\odot$. Extrapolation of this trend to masses below the end of the hydrogen burning main sequence (0.08 $M_\odot$) fails to predict enough unobserved objects to account for the local mass deficit discussed by Bahcall (1985, reference these proceedings for the most current discussion). It is quite possible, however, that substellar objects (SSO), such as the newly discovered companion to VB 8 (McCarthy et al, 1985), exist in very large numbers as individual systems with masses in the range 0.05 to 0.001 $M_\odot$; furthermore, these objects could radiate enough power at infrared wavelengths to be detected (Stevenson 1978). In this report preliminary results are given on a project to use the data bases from the IRAS sky survey in a systematic search for the closest members of this as yet undiscovered class of ubiquitous brown dwarfs.

THE IRAS DATA BASES

In 1983 the Infrared Astronomy Satellite (IRAS) performed the first deep survey of the sky in the infrared and produced a raw data base of more than 30 gigabytes. The IRAS catalog contains nearly 250,000 point sources detected at 12, 25, 60 and 100 μm and was released in November 1984 (Beichman et al.). New software is under development at Jet Propulsion Laboratory which will be used to co-add the redundant survey scans to produce a new data base with sources 2 to 3 times fainter. Both of these large scale data products are derived from the

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"all sky survey" which attained sky coverage of 96 percent, but, because of source confusion, it is unlikely that the co-addition will be extended to galactic latitudes below 30 degrees. A very much smaller data base is under construction which will contain sources about 5 times fainter than those in the point source catalog and will cover only a few percent of the sky. This "serendipity survey" utilizes the IRAS pointed observations of specific fields and should be released by mid 1986.* Table 1 summarizes the parameters of the three data bases as they pertain to the search for substellar objects.

When combined with Table I, Table II shows the applicability of the IRAS data products to a systematic search for substellar objects. Table II gives magnitudes at key wavelengths based on black body predictions for objects of the expected diameter at a distance of 1 pc. The V and R magnitudes include a possible 3 magnitude deficit below the blackbody values based on observations of the lowest mass M dwarfs (Probst 1983). For objects in the temperature range of interest the 12 μm IRAS band is the most sensitive. The reason that the higher galactic latitudes are much preferred over lower latitudes is two fold, first, the number of sources that must be processed is much smaller and, hence, more tractable and , second, the number of sources with circumstellar dust shells which mimic the temperatures of interest is found to be very much lower as the galactic latitude increases.

In order to estimate the number of SSO that might be within the roughly two cubic parsec volume surveyed by IRAS, the volume density of unobserved material from Bahcall's analysis can be combined with the ad hoc assumption of a flat mass spectrum. Then the total mass of 0.2 $M_\odot$ might be contained in approximately 5 objects with masses in the range 0.010 to 0.050 $M_\odot$ and temperatures in the range 500 to 1500 K. This is an optimistic view in the sense that the population must be quite young. If, instead, a vast population of SSO formed very early in the life of the galaxy, then their temperatures today would be too cold for IRAS to detect. For this reason Table I includes estimates of the performance of two possible searches in the IR to much deeper limits.

THE SEARCH METHOD

Since the 12 μm band of IRAS is the most sensitive for objects warmer than 200 K, and since even the closest SSO is unlikely to be detected at both 12 and 25 μm, it is necessary to reduce the number of possible candidates by a large factor prior to detailed studies from the ground. Fortunately, it has proved possible to positionally associate most 12 μm point sources detected by IRAS with optically bright sources, predominantly stars. The procedure used was as follows: (1) the machine readable catalogs of stars were matched with the IRAS sources of interest (2) overlays were made for the northern and southern photographic surveys for the remaining sources to carry out associations on an individual basis.

TABLE I. Properties of Infrared Sky Surveys at 12 and 2.2 μm

	Usable Sky Coverage (Sq. deg.)	No. of Pt. Sources	Limiting Magnitude
IRAS 12 μm			
Pt. Src. Catalog	>2 E 4	> 2 E 4	4.5
Coadded Survey	2 E 4	> 4 E 4	5.5
Serendipity Survey	500	1500	6.3
FUTURE			
2.2 μm	>2 E 4	> 1 E 6	13 to 15
SIRTF 12 μm	2 E 4	2 E 6	9 to 10

TABLE II. Brown Dwarf Magnitudes vs Temp. and Wavelength
Distance = 1 pc

T (K)	Wavelength (μm)			
	0.5	0.85	2.2	12
200			38	11
300			26	9
500		37	17	7
800	38	24	11.5	6
1000	30	19	9.5	5.5
1500	20-23	13-15	7	5
2000	15-18	10-13	6	4.5
2500	12-14	8-9.5	5	4

The reliability of this method remains to be demonstrated through further tests. However, it is already clear that the number of candidates is small enough to permit individual follow up from the ground. Of more concern is the possibility that a miss identification with a randomly placed star in the field will disguise the detection of a much cooler object. For these reasons the results reported here must be used as preliminary.

Once a candidate has been identified by its optical/IR properties, it must be observed from the ground to obtain accurate positions for proper motion and parallax determinations. Photometry in the near IR and spectroscopy at appropriate wavelengths may also serve to classify the source. Clearly, all objects found by this search are potentially interesting and should be followed up.

PRELIMINARY RESULTS

Under the direction of T. Chester at the IRAS Processing and Analysis Center (IPAC), the 12 μm point sources in the polar caps (defined here as $|b| > 50$ deg.) were searched for substellar candidates. The results are summarized in Table III. It is important to note that with special study of a few individual sources it was possible to positionally associate all 5776 12 μm sources with their optical counterparts. Only one source emerged as a clear substellar candidate and was observed from the ground to determine its spectral energy distribution, its proper motion and its spectral characteristics. The most likely interpretation of this singular object is that, despite its unusual temperature of 1300 K and its very high galactic latitude, 86 deg., it is probably a Carbon Star.

CONCLUSIONS

Preliminary results from analysis of the sources in the polar caps indicate that substellar objects are not easily found in the IRAS

TABLE III. IRAS 12 Micron Point Sources $|b| > 50^o$

Total Sample	5776
Unmatched	444
$T_c < 2500$ K	63
$2000 > T_c > 1000$	1
Sub-Stellar	0

point source catalog. However, it has also been shown that a viable method exists for extending the search to at least another quarter of the sky using the published data base. Two new data bases will become available for deeper searches and it seems clear that by exhaustive optical identification of the infrared sources a number of interesting objects will be found and even if no "ubiquitous brown dwarfs" are found, useful limits on their numbers will be determined.

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DISCUSSION

PACZYNSKI: A comment on brown dwarfs: AA Doradus is an eclipsing binary system whose dark companion has a mass of only 0.04 $M_\odot$ (Kudritzki et al. 1982, Astron. Astrophys., **106**, 254; Paczynski 1980, Acta Astron., **30**, 113). This is a spectroscopic binary; the dark companion is responsible for eclipses and the hemisphere heated by the companion is eclipsed. So the mass is very well established.

I also have a question to do with your last statement that there are so many bright infrared galaxies, which may be more numerous than quasars. Is it clear from the IRAS data that what is seen in the infrared is not nuclear activity? That it must be a starburst phenomenon?

LOW: I believe it to be a starburst phenomenon in an extreme limit in which so much gas has fallen into the nucleus that other processes, such as the Seyfert or quasar phenomenon, must be very closely related. Notice that the volume within ~ 100 Mpc of us contains several galaxies emitting $\geqslant 10^{12}$ $L_\odot$, but, as far as I know, not a single quasar.

J. BAHCALL: Isn't the IRAS spatial resolution inadequate to resolve the region from which the bright infrared emission comes? You don't know whether it comes from the nucleus or is distributed in the disk.

LOW: In the case of Arp 220, the 25 μ emission region is extremely compact. Data on that were presented at the Noordwijk symposium. It is also known that the emission from Mk 231 is extremely concentrated to the nucleus. So what I'm saying is that a large part of the mass reservoir, which is somehow preferentially present in the nucleus, gets converted extremely rapidly into stars to give the high luminosity that we see.

LYNDEN-BELL: Do you know that it comes from stars rather than something else?

LOW: I don't know that it comes from stars. But let me call to your attention something that I consider to be a very good test of this. That is the relationship between the total infrared brightness and the radio continuum emission. This relationship has been around for fifteen or twenty years, but the IRAS data have allowed it to be refined. We have found that the relationship is very tight all the way up to very luminous objects like Arp 220 or Mk 231 for a very large fraction of the total sample. If this is a true indicator of the conversion of mass into very luminous stars that produce supernovae, then I think that it is an indication that star formation is still at work.

OSTRIKER: A comment and a question on whether the emission is extended or nuclear. At least some subset of the infrared-bright galaxies must overlap with the galaxies observed by Condon, because he picked out a group of continuum-bright spiral galaxies, which I believe have shown up as IRAS sources. These galaxies were also studied spectroscopically and show emission extending over a good fraction of their disks. So it is known that at least that subsample has starburst activity going on over much of the disk. My question is: Have you cross-correlated your infrared-bright galaxies with the EINSTEIN results to see if there is any correlation with x-ray brightness?

LOW: I certainly have not, and I don't recall anything recent on that subject. I don't think that there is much of a correlation. Certainly we know for NGC 1068 that 95% of the infrared output comes not from the nucleus but from a very small, centrally condensed region of radius ~ 500 - 1000 pc. NGC 1068 is by far the closest and most easily studied infrared-bright galaxy, with an infrared luminosity about half that of the most luminous galaxies observed.

SOLOMON: Most of the very luminous infrared galaxies ($L_{IR} > 3\times10^{11}\ L_{\odot}$) have strong CO emission, indicating an origin for the infrared luminosity in active star formation within molecular clouds and not in very small sources in the galactic nucleus. However, these starburst regions may be concentrated in the inner galactic disk or even in the inner 1 or 2 kpc of the galaxies.

LOW: Yes. Mk 231 is an exception. It is also right at the top of the luminosity range and may be part quasar and part starburst galaxy. That might tell us something. The weight of evidence now is that the starburst phenomenon, if that's the term you like to use, takes place up to this $\geqslant 10^{12}\ L_{\odot}$ range. One of the interesting things the IRAS data tell us is that we can't stop there, we've got to study objects which put out hardly any optical photons at all. At Noordwijk, Mike Rowan-Robinson seemed to be convinced that he could build a model in which the luminosity from these systems is adequate to explain the 100 μ background of a few MJy steradian^{-1}. This could be a very important subject in the future. At the moment it is still premature to attach high significance to the 100 μ background measurement.

FABIAN: If Ω in baryons is several tenths and if this is uniformly distributed and makes the x-ray background, then the hot gas Compton scatters the microwave background, and we predict about 2 MJy steradian^{-1} at 100 μ. So you could rule out the x-ray background if you could explain the 100 μ background some other way.

BURSTEIN: Marcia Rieke and I have analyzed the IRAS fluxes for 2000 UGC Sc galaxies with diameters $\leqslant 3\overset{!}{.}5$. To make a long story short, we find that the detection of an Sc galaxy is a function of the inclination of the galaxy to the line of sight, as well as of wavelength. A chain of argument leads to the conclusion that most of the 60 μ and 100 μ flux from Sc's comes from near their nuclei, and is extincted by the dust in the disk when the galaxy is edge-on.

LOW: Yes, I think that is consistent with what we know from resolving individual galaxies of various luminosities. But I really can't overemphasize the fact that for our Galaxy we need to have a better handle on the outer parts in the infrared. Just because the nucleus contains so much luminosity doesn't mean we can neglect the infrared emission from processes going on in the outer parts that are so important for the rotation curves. For the most part IRAS is capable of telling us the answer. In some cases, we just have to open the catalogue.

DRESSLER: Did I understand you to argue that the idea that the blue luminosity is extinguished in infrared galaxies, resulting in a high ratio of infrared to blue luminosity, is ruled out by a correlation of this ratio with luminosity?

LOW: To my knowledge no-one has excluded the possibility of very dark, cold galaxies, i.e., objects which emit primarily in the infrared and have modest luminosities. These are hard to find. What leaps out at us are these extreme cases, the very high-luminosity objects. There will probably be a believable relationship between L_{IR}/L_B and L_{Tot} coming out of the data shortly. But this doesn't mean that there might not be large numbers of galaxies with low optical and infrared luminosities.

DRESSLER: This sounds like a classic Malmquist bias - those objects which are very luminous in the infrared are very distant.

LOW: I agree.

DRESSLER: May I point out something else? I was intrigued by your comment that most of the subluminous stars seem to be very young. I want to mention a paper by Poveda which suggests the possibility that these stars don't achieve fusion, and are all young and cooling down. I haven't heard that mentioned very much, but it's a way to have the mass function continue to climb below 0.2 $M_\odot$ even if the luminosity function turns over.

LOW: It's ideas like that which keep us sifting through the data.