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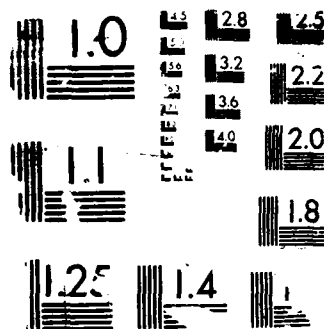
ANALYSIS OF DEEP SKY SOURCES FOUND BY THE INFRARED  
ASTRONOMY SATELLITE (U) MASSACHUSETTS UNIV AMHERST  
DEPT OF PHYSICS AND ASTRONOMY S KLEINMANN 15 DEC 87  
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| <p>This program was aimed at understanding the number and types of sources found in the fields observed with greatest sensitivity by the IRAS satellite. The initial phase of the study emphasized observation and analysis of sources found in the less sensitive all sky survey carried out with IRAS. Significant differences between the bright and faint 12 um sources were found, which constrain their relative spatial distributions and luminosities. A study focussed on one, large population of infrared-bright stars -- those whose atmospheres are rich in carbon -- yielded measurements of their space distribution range of mass loss rates, and lifetimes. An analysis of 60 um sources from the IRAS survey showed that eighty-five percent of those located more than thirty degrees above the plane of the Galaxy are extragalactic objects, provided a measure of the space density of galaxies of different infrared luminosities, and showed that there are significant differences in the environment and infrared properties of the most luminous and least luminous galaxies. Studies of galaxies with particularly strong mid-infrared emission resulted in the discovery of ultra-luminous objects. Initial studies of results from the IRAS pointed observations show effects of contamination by low-surface-brightness interstellar clouds.</p> |                                                   |                                                                                                    |                          |
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**FINAL TECHNICAL REPORT**

**for**

**"Analysis of Deep Sky Sources Found by the Infrared Astronomy Satellite"**

**which was supported under  
AFOSR Grant No. 85-0057**

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**Submitted on:** December 15, 1987

**SUMMARY:** Results are summarized for a program aimed at understanding the number and types of sources found in the fields observed with greatest sensitivity by the *IRAS* satellite. The initial phase of this study emphasized observation and analysis of sources found in the less sensitive all sky survey carried out with *IRAS*. Significant differences between the bright and faint 12  $\mu\text{m}$  sources were found, which constrain their relative spatial distributions and luminosities. A study focussed on one, large population of infrared-bright stars -- those whose atmospheres are rich in carbon -- yielded refined measurements of their space distribution, range of mass loss rates, and lifetimes. An analysis of 60  $\mu\text{m}$  sources from the *IRAS* survey showed that 85% of those located  $>30^\circ$  above the plane of the Galaxy are extragalactic objects, provided a measure of the space density of galaxies of different infrared luminosities, and showed that there are significant differences in the environment and infrared properties of the most luminous and least luminous galaxies. Studies of galaxies with particularly strong mid-infrared emission resulted in the discovery of ultra-luminous objects. Our initial studies of results from the *IRAS* pointed observations show effects of contamination by low-surface-brightness interstellar clouds.

## I. Introduction

This report summarizes work done under the project "Analysis of Deep Sky Sources Found by the Infrared Astronomy Satellite", which was funded by the *Air Force Office of Scientific Research* under Grant No. 85-0057. The objective of this program was to determine what classes of infrared sources had been detected by NASA's *Infrared Astronomy Satellite (IRAS)*. That satellite carried a liquid Helium cooled telescope of ~57 cm diameter, equipped with an array of 62 detectors operating at effective wavelengths of 12, 25, 60, and 100  $\mu\text{m}$ . About half of its 9-month operational lifetime was used to carry out an all-sky survey. Much of the remaining time was used to obtain more sensitive observations of selected regions of the sky; this was done by scanning the telescope slowly over regions of interest; greater sensitivity was achieved by co-adding the results of many repeated scans. A particular goal of the program described here was to learn the properties of the sources found in the fields observed by *IRAS* in this pointed mode, especially in those "deep" fields where the greatest sensitivity had been achieved by 20 or more repeated scans.

In order to understand the types and numbers of sources found in the deepest fields observed with *IRAS* it is essential to begin with a clear understanding of the sources found in the less sensitive all-sky survey, since this represents a uniform and unbiased sampling of the entire sky. The *IRAS Point Source Catalog* (hereafter, PSC) lists nearly 250,000 unresolved sources that were detected in at least one of the 4 bands of the survey. Results from our analyses of stellar objects in the PSC are summarized in Section II. These objects can be distinguished by the fact that they are typically brighter at 12  $\mu\text{m}$  than at the other wavelengths observed by *IRAS*.

Results from our analyses of extragalactic sources found in the *IRAS* survey are summarized in Section III. These sources are typically brightest in the far-infrared ( $\lambda > 50 \mu\text{m}$ ), because the emission from the stars they contain is completely overwhelmed by emission from large, dense clouds that are warmed by stars recently formed within them. Work done in the program described here shows the number and infrared properties of galaxies in the local Universe. Another program focussed on galaxies with strong mid-infrared emission. These results provide the basis for estimating the number and properties of galaxies that might be detected in surveys that reach much fainter flux levels than the faintest galaxies listed in the PSC.

Our program to study the sources found in the fields observed in pointed mode by the *IRAS* satellite had a number of milestones. Completion of the *IRAS Serendipitous Survey Catalog* (Kleinmann *et al.* 1986a; hereafter, SSC) was an important step. 44,000 sources found in two repeated scans of 1813 fields observed in the pointed mode are listed in this catalog. The SSC represents a level of sensitivity between that of the *IRAS* PSC and the very deepest fields observed in pointed mode. Our initial analyses of the contents of the sky at this level of completeness are included in Section IV. Also reviewed in that Section are our initial studies of sources found in the fields observed 20 or more times in pointed mode. These studies have revealed the need for extensive additional processing of the *IRAS* deep sky observations, and indicate some techniques that might be used to pursue further studies of the faintest sources found within them.

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## II. Observations and Analysis of Stars Found in the IRAS Survey

### a) A Flux-Limited Sample of 12 $\mu\text{m}$ Sources

About 6000 unresolved sources were detected at 12  $\mu\text{m}$  in the *IRAS* survey at high galactic latitudes ( $|b| > 30^\circ$ ). We undertook an observational program to determine the optical properties of all of these objects (except those few which were identified with galaxies). To do this, we initially used measurements of star diameters on photographic plates from the Palomar Observatory Sky Survey. Calibration of the micrometer measurements to absolute fluxes was accomplished by comparison to similar measurements of "standard" stars whose brightnesses had been previously measured at the telescope with an optical photometer. All measurements were carried out with the 2-axis Grant measuring engine at the headquarters of the National Optical Astronomy Observatory. The accuracy of this technique was limited by variations in the characteristics of different plates. This program revealed a number of *IRAS* sources that deserved further study because of their extremely high ratios of infrared to optical flux. However, it had insufficient accuracy to determine whether the optical color of a source (ratio of blue light to yellow light) was consistent with the ratio of optical to 12  $\mu\text{m}$  light. More importantly, it lacked the accuracy to show whether the optical properties of bright infrared stars differed systematically from those of faint infrared stars.

Subsequently, we initiated an observing program to obtain accurate photoelectric photometry of the high latitude 12  $\mu\text{m}$  *IRAS* sources. This program utilized a highly automated photometer system, attached to one of the 36-inch telescopes at Kitt Peak National Observatory. Specifically, the system was used to obtain measurements in two broad bands ( $B$ ,  $\lambda_{\text{eff}} \sim 0.44 \mu\text{m}$ ) and ( $V$ ,  $\lambda_{\text{eff}} \sim 0.55 \mu\text{m}$ ) of stars within  $\sim 1$  arcminute of the *IRAS* position.

As of July 31, 1987, approximately 25% of the sample (1500 sources) had been observed with this technique. A preliminary report on these results was given by Goodrich *et al.* (1987). They showed

- A star brighter than 25  $\text{mJy}^1$  was found within the required 1 arcmin distance from the infrared positions of 90% of the *IRAS* sources. The remaining objects are the targets of further study.
- The optical colors of most of these stars are consistent with their being "giants", i.e., luminous stars that could be detected by *IRAS* out to distances much greater than the thickness, or scale height of the Galaxy. This observation is consistent with the fact that the number of faint sources detected by *IRAS* is much less than would have been deduced if most of them were low luminosity sources detectable only out to distances much less than the scale height of the Galaxy.
- About a third of the stars detected by *IRAS* have strong infrared "excesses", i.e., more infrared emission than expected from their photospheres. Most of these objects are cool stars which

1.  $1 \text{ mJy} = 10^{-29} \text{ W m}^{-2} \text{ Hz}^{-1}$

are undergoing rapid mass loss. Dust particles condense in the outflowing, cooling gas in their circumstellar envelopes, and this dust is heated by the central star to a sufficient temperature that it produces strong infrared emission.

- A greater fraction of the bright infrared sources have strong infrared excesses than the faint infrared sources. This result can be understood by considering the flattened and finite structure of the Milky Way. If the stars with large infrared excesses have sufficiently high infrared luminosity, then the IRAS survey would be able to detect them at distances beyond the edges of the Milky Way, so that no more stars of this type would be detected at flux levels below some limit, say,  $F_0$ . If, at the same time, sources without infrared excesses have sufficiently low infrared luminosity, then the number detected by IRAS could increase as  $(F/F_0)^{-3/2}$ , where  $F$  is the flux level of the faintest source in the sample. Thus, the stars without excesses would increasingly dominate the total population of detected infrared sources in surveys at low infrared flux levels.

The foregoing results have direct implications for the types and number of sources that are expected in the deep fields observed by IRAS. If the observed distribution of optical/infrared flux densities characterizes sources even fainter than the faintest sources in the PSS, then a predictable and large (97%) fraction of the SSC sources should have optical counterparts brighter than 5 mJy. A program to measure the optical brightnesses of objects identified with 12  $\mu\text{m}$  sources in the SSC was recently initiated; the ratio between the actual and expected number of optical counterparts with the required optical brightness should provide a good measure of the reliability of that catalog.

#### *b) A Flux Limited Sample of Carbon Stars*

In addition to studying IRAS results with the goal of learning the number and types of sources that were detected in the survey, we have also begun exploiting the sky coverage and sensitivity of the survey to investigate the properties of large previously known classes of infrared-bright stars. We began by studying the IRAS properties of carbon stars -- cool ( $T < 4000$  K) stars with more carbon than oxygen in their atmospheres. Since these stars have high luminosity and distinctive optical spectra, they can be detected at very large distances. Because of their high mass loss rates, they are an important source of enrichment for the interstellar medium, so an understanding of the evolution of the Galaxy depends both on the amount of mass they lose each year and on their distribution within the Galaxy. Our study of a complete sample of carbon stars (all of those detected in the *Two Micron Sky Survey* (Neugebauer and Leighton 1969) was reported by Claussen *et al.* (1987).

The spatial distribution of carbon stars could be determined by noting that the carbon stars found in the Large Magellanic Cloud (hereafter, LMC) exhibited a small range in apparent flux at 2.2  $\mu\text{m}$ . Since all of the stars in the LMC are at nearly the same distance from us, carbon stars must have a small range in absolute 2.2  $\mu\text{m}$  luminosity. Thus, the distances to all of the carbon stars detected in the TMSS could be deduced by comparing their apparent brightness to the absolute luminosity of the carbon stars in the LMC. This procedure showed that the carbon stars detected in the TMSS are confined to the galactic plane, with a scale height of about 200 pc, and have a surface density projected onto the galactic plane of about

100 kpc<sup>-2</sup>.

To determine the rate of mass loss by each carbon star to the interstellar medium, it is necessary to know the distance, the brightness of the star at some wavelength where the emission of the dust is significant, the properties of the dust grains in their atmospheres, and the typical size and outflow velocity in their envelopes. At mid-infrared and longer wavelengths ( $\lambda > 12 \mu\text{m}$ ), the emission from carbon stars greatly exceeds that due expected from their photospheres, and is therefore attributed to cool dust in the circumstellar envelope. Photometry for nearly all of the carbon stars in our sample is available at this wavelength from the IRAS survey. Thus, using previous estimates of the properties of the dust grains, we could determine the total mass of the dust and (assuming a typical ratio of gas to dust) gas in their envelopes. Existing measurements of the sizes and outflow velocities in the envelopes of carbon stars then yields their rates of mass loss.

This effort showed that there is a wide (factor of  $> 1000$ ) range in mass loss rates among carbon stars. Thus, most of the mass contributed by carbon stars to the interstellar medium comes from a small subset of carbon stars. Those with highest mass loss rates are so heavily enshrouded in dust that they are exceedingly faint at optical wavelengths, and not even readily detectable at near-infrared wavelengths. These stars are highly variable and typically have near-infrared amplitudes greater than a factor of 10. Recent work has shown that the circumstellar dust envelopes of these stars should be resolvable on scales of  $> 1$  arcmin at  $\lambda > 50 \mu\text{m}$ . Details of their structure are sensitive to properties of the dust grains and to variations in their mass loss rates with time. Re-examination of available *IRAS* data is being carried out to assess their spatial properties and thereby test our current models.



### III. Observations and Analysis of Galaxies Found in the IRAS Survey

#### *a) A Flux-Limited Sample of 60 $\mu$ m Sources*

In regions of the sky more than  $\sim 10^\circ$  from the plane of our Galaxy, most of the 60  $\mu$ m sources detected by *IRAS* are galaxies.

Unlike stars, the distances to galaxies can be estimated directly, from a measurement of the redshifts of the emission or absorption lines in their spectra, using the "Hubble" relation,  $\text{distance} = [\text{velocity of recession}] / H_0$ , where we have adopted the value  $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . This is based on the assumption that all galaxies are taking part in the general expansion of the Universe, so that the distance between any two galaxies is linearly proportional to their relative speed of recession. It is well-supported for galaxies moving at recessional speeds greater than  $\sim 1000 \text{ km/s}$ .

We have used the *IRAS* survey and the Hubble Law to determine the luminosities of infrared-bright galaxies, and the space density of galaxies of various infrared luminosities; this is the so-called "luminosity function". It is computed by selecting a "complete" sample of galaxies whose apparent brightness exceeds some flux limit, then ranking the galaxies according to absolute luminosity (computed from their brightness and redshift), and computing the volume of space within which galaxies in a given range of luminosity could be detected above the pre-specified flux limit.

The results of this program were published by Smith *et al.* (1987). This study was based on a complete sample of 60  $\mu$ m sources listed in the *IRAS* PSC with brightnesses  $F(60) > 2 \text{ Jy}$ , and lying within a certain region in the sky. This region had been selected for comparison with results from an earlier study, designed to measure the space distribution of galaxies drawn from an optical survey. Smith *et al.* concluded:

- 85% of the 60  $\mu$ m sources brighter than 2 Jy at high galactic latitudes ( $b > 30^\circ$ ) are galaxies; most of the remainder are stars.
- Most of the galaxies in the sample have a spiral morphology, like the Milky Way. Such galaxies typically have a high content of interstellar gas and dust, conditions essential for the formation of new stars. It is the heating effect of new-born stars on the clouds in which they formed that produces most of the observed infrared emission.
- Though the median infrared luminosity for *IRAS* galaxies is high (about 10 times higher than the Milky Way), the sensitivity of the *IRAS* survey is insufficient to detect them at distances beyond  $\sim 100 \text{ Mpc}$ . This distance corresponds to a small "look-back time" compared to the age of the Universe. Therefore, no significant effects due to evolution in the luminosities of galaxies are expected within this volume. In fact, no evolutionary effects are observed.
- The infrared luminosity function differs from the luminosity function derived from optically selected galaxies, in its lack of an exponential cutoff in the number density of galaxies at high luminosities. Thus, the mechanism that produces high luminosity infrared galaxies must be different from that which produced optically-selected galaxies. It now appears (see below) that high infrared luminosity may be a short-lived phase that

occurs during (some) galaxy-galaxy interactions.

- Galaxies in our infrared-selected sample show a much smaller tendency to exist in clusters than do galaxies in an optically-selected sample. This is consistent with the fact that most of the galaxies in our sample are spirals, whereas most of the galaxies in clusters are ellipticals. This result implies that an infrared-selected sample of galaxies may not trace the mass density in the Universe, as assumed by current cosmological interpretations of the *IRAS* survey.
- Most of the galaxies with high luminosity are found in interacting pairs, while most of the low luminosity galaxies are isolated. This result implies that the interaction between two galaxies tends to accelerate the rate of star formation. Since most of the high luminosity galaxies have unusually high ratios of flux density,  $F(25\ \mu\text{m})/F(60\ \mu\text{m})$ , since they can be detected to very large distances, and since the rate of interactions between galaxies should have been higher in the early Universe than it is now, the number of galaxies with relatively high mid-infrared ( $25\ \mu\text{m}$ ) flux density should increase more rapidly than other galaxies as the sky is surveyed at greater infrared sensitivity.

Ms. Bev Smith is completing a Ph.D. these aimed at estimating the rate of increase in interacting galaxies in infrared surveys at deeper flux limits than the *IRAS* PSC. Her results will be compared with results in the SSC, and, eventually, with results in the deepest regions observed in the pointed mode with *IRAS*.

#### *b) Studies of Mid-Infrared-Bright Galaxies*

A study of *IRAS*  $60\ \mu\text{m}$  sources with unusually faint optical counterparts resulted in the discovery of the most luminous galaxy detected by the *IRAS* survey. For our adopted value of  $H_0$ , the total luminosity of this galaxy is 6 trillion times that of the sun. This discovery was reported by Kleinmann and Keel (1987), and further observations were reported by Kleinmann *et al.* (1987b).

The galaxy, *IRAS* 09104+4109, is unusual in its spectrum, its morphology, and its environment. At optical wavelengths, it has a powerful emission line spectrum, resembling that of "Seyfert 2" galaxies, which have exceedingly bright nuclei thought to contain massive objects. This galaxy is more luminous than any member of the Seyfert class; in fact, it is well within the range of quasars. Its continuous spectrum is characterized by an unusually high mid-infrared flux, like the most luminous galaxies studied by Smith *et al.* (1987).

*IRAS* 09104+4109 has an elliptical shape, and is surrounded by an extensive ( $> 80\ \text{kpc}$ ) envelope. Only a few galaxies of this type (designated "cD") are known; they were discovered in studies of celestial radio sources. This galaxy has 50 times more luminosity than any of the prototypical cD radio galaxies.

Finally, *IRAS* 09104+4109 sits near the center of a rich cluster of galaxies which is apparently flattened. Further observations are planned to test whether this cluster indeed has a significant angular momentum, which will raise intriguing questions regarding the formation of such large structures. In any case, the presence of the cluster has led to the suggestion that the current high luminosity of *IRAS* 09104+4109 is due to an interaction between it and one

(or more) member galaxies of the cluster in which it is located.

The extraordinary properties of IRAS 09104+4109 have motivated a more systematic study of galaxies detected by *IRAS* with similar infrared colors. Preliminary results from this program were reported by Kleinmann *et al.* (1987a). Using an infrared flux ratio criterion, we have discovered many additional high-luminosity galaxies; most of these have optical spectra similar to Seyfert galaxies and quasars. No galaxies having a luminosity as high as IRAS 09104+4109 or a similar morphology or an associated cluster have been found in this program. However, the discovery of so many previously unknown quasars suggests that previous surveys for quasars may be highly incomplete, and indicates the need to re-evaluate estimates of the rate of evolution of the Universe based on these surveys.

#### IV. Studies of Results From IRAS Pointed Observations

##### *a) Study of the Contents of the SSC*

The *IRAS* SSC consists of all sources seen in at least two pointed-mode *IRAS* observations of the same field. In general, the pointed observations were targeted on a specific object of particular astrophysical importance. Thus, the sources detected in these observations do not represent an unbiased sampling of the sky. Further, the pointed observations were carried out with a large variety of scan rate, scan direction (important for extended or confused sources), sampling, and sky coverage. This complicates any effort to determine the completeness of the SSC. Finally, low-surface-brightness interstellar clouds (infrared "cirrus") may have introduced a significant number of spurious sources. Despite these problems, preliminary analyses of the SSC have been undertaken (Kleinmann *et al.* 1986b; Cutri *et al.* 1987). They show

- In most areas, the SSC reached a limiting flux density that is 3 times lower than the completeness limit of the PSC, at 12, 25, and 60  $\mu\text{m}$ . The limiting flux of the SSC at 100  $\mu\text{m}$  is only about 2 times lower than the completeness limit of the PSC at that wavelength, possibly due to effects of confusion by infrared cirrus.
- The SSC is characterized by very high photometric accuracy. The colors of stars known not to have large infrared excesses, and the agreement between the SSC and PSC indicate a photometric accuracy  $< 5\%$  at 12, 25, and 60  $\mu\text{m}$ .
- Because of the limited sky coverage in each of the fields of the SSC, the positional accuracy of the SSC is not as high as the PSC. The errors are about a factor of 2 larger.
- Nearly twice as many sources as expected were found in the SSC than were expected by extrapolation of the PSC; this problem is particularly obvious at 60  $\mu\text{m}$ . This suggests that the reliability of the PSC is not as high as expected on the basis of comparisons between the SSC and results from deeply co-added fields. Studies are in progress to determine the cause and magnitude of the observed over-density of sources at faint levels.

Our initial studies of the 12  $\mu\text{m}$  sources listed in the SSC has resulted in the discovery of an extremely red object, now known to be a carbon star (Cutri *et al.* 1986). This star has an infrared continuum similar to that of the carbon star, TMSS +10216, which may have the most massive circumstellar envelope of any star in this class. The most peculiar feature of the red carbon star found in the SSC is that it is extremely faint. If it has the same luminosity as TMSS +10216, it must lie at a distance of  $> 10,000$  pc, 50 times the scale height of carbon stars. Alternatively, it may be an example of a class of "dwarf" carbon stars, formed by "contamination", when matter from one component of a binary star system sheds enriched matter to the other component. Further study is being carried out to understand the relationship between this object and previously known carbon stars.

*b) Study of the Fields Observed  $\geq 20$  Times with IRAS*

Our study of the deepest fields observed by *IRAS* in pointed mode had the scientific goals of testing current models of the structure (extent) of the Milky Way and of the rate of evolution of galaxies. Optical photometry, if not spectra, of the sources detected by *IRAS* in its most sensitive observations is needed to achieve these goals. Thus, the first step in our program was to find optical counterparts for each of the *IRAS* sources.

Our approach in this task was to develop a data base containing all objects detected on the blue-sensitive ('O') and red-sensitive ('E') plates of the Palomar Observatory Sky Survey, in  $1.5 \times 1.5$  square degree regions centered on the fields of interest. The automated scanning photodensitometer at the headquarters of the National Optical Astronomy Observatories was used to do this. This system could detect objects brighter than 2 times the faintest objects recorded on the Palomar Plates, and provide accurate measurements of their diameters (from which we deduced their optical flux densities) and positions. Calibration of the object diameters in terms of optical flux density was accomplished by comparison to similar photodensitometry scans of stars of known brightness. The scanning process was used on 8 fields, all of which were located at high galactic latitudes, and had been observed 20 or more times by *IRAS* in pointed mode.

The work just described was actually carried out *before* the *IRAS* data became available for this program. That is, the positions of the centers of the fields that had been observed frequently in the *IRAS* pointed observation program were publicly available, but the contents of those fields not. Access to the *IRAS* data was made available in early 1987 through a collaborative arrangement.

Comparison of the positions of *IRAS* sources with the optical data base showed few cases where the *IRAS* sources had bright optical counterparts; typically, several faint optical counterparts were found within the *IRAS* "error box" of each source.

Our inability to find reasonable optical identifications for many of the *IRAS* sources raised a question regarding the reliability of the data base of sources from the *IRAS* deep sky fields. To check this, we requested that the *IRAS* data be re-processed: Each group of 20 scans of each field was sub-divided into 2 groups of 10 scans each. The 10 scans in each group were then co-added. Comparing the co-added sets of 10 scans each, we found that very few sources were seen on both sets. Even some very bright sources were not seen on both sets. The non-repeatability of the two sets of data has been attributed to effects of low-surface brightness clouds (the "infrared cirrus"; Low *et al.* (1984)), since the directions of the scans were quite different for the two sets of data. These effects could be eliminated by additional processing, now underway at NASA's Infrared Processing and Analysis Center.

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## VI. Publications

S. G. Kleinmann, R. M. Cutri, E. T. Young, F. J. Low, and F. C. Gillett; "IRAS Serendipitous Survey Catalog", distributed in Microfiche and magnetic tape form by NASA/JPL.

S. G. Kleinmann, R. M. Cutri, E. T. Young, F. J. Low, and F. C. Gillett; "Explanatory Supplement to the IRAS Serendipitous Survey Catalog", Washington, D. C., U. S. Government Printing Office, 1986; 99 pp.

B. J. Smith, S. G. Kleinmann, J. P. Huchra, and F. J. Low; "A Study of A Flux-Limited Sample of IRAS Galaxies", *Astrophysical Journal*, **318**, p. 161-174.

S. G. Kleinmann and W. C. Keel; "Properties of the Unusual Galaxy PSC 09104+4109", *Star Formation in Galaxies*, Washington, D. C., NASA Conference Proceedings, 1987, p. 559-562.

M. J. Claussen, S. G. Kleinmann, R. R. Joyce, and M. Jura; "A Flux Limited Sample of Galactic Carbon Stars", *Astrophysical Journal Supplement Series*, **65**, p. 385-404.

S. G. Kleinmann, D. Hamilton, W. C. Keel, C. G. Wynn-Williams, S. A. Eales, E. E. Becklin, and K. D. Kuntz; "The Properties and Environment of the Giant, Infrared-Luminous Galaxy IRAS 09104+4109"; *Astrophysical Journal*, (submitted August 7, 1987) (37 p.)

**VII. Personnel**

|                                   |                                                                                                                 |
|-----------------------------------|-----------------------------------------------------------------------------------------------------------------|
| Principal Investigator            | Susan G. Kleinmann<br>Associate Professor<br>Department of Physics and Astronomy<br>University of Massachusetts |
| Research Associate                | Mark J. Claussen                                                                                                |
| Graduate Research Assistant       | Beverly J. Smith<br>Thesis title: "Structure in Infrared-Bright Galaxies"                                       |
| Undergraduate Research Assistants | Wendy Conrad<br>James Sottile<br>James Belfiore                                                                 |



## VIII. Interactions

### *a) Papers Presented at Meetings*

Cutri, R. M., Low, F. J., Young, E. T., Kleinmann, S. G., and Gillett, F. C.; "A Search for Brown Dwarf Candidates Among IRAS Serendipitous Sources", presented at the 167<sup>th</sup> Meeting of the American Astronomical Society, January, 1986.

Smith, B., Kleinmann, S. G., and Huchra, J.; "A Redshift Survey of IRAS Galaxies", presented at the "Star Formation in Galaxies" Conference, Pasadena, CA, June, 1986.

M. J. Claussen, S. G. Kleinmann, and R. R. Joyce; "A Study of A Flux-Limited Sample of Galactic Carbon Stars", presented at the 169<sup>th</sup> Meeting of the American Astronomical Society, January, 1987.

R. M. Cutri, F. J. Low, E. T. Young, S. G. Kleinmann, and F. C. Gillett; "An Analysis of the Constituents of the IRAS Serendipitous Survey Catalog", presented at the 169<sup>th</sup> Meeting of the American Astronomical Society, January, 1987.

S. G. Kleinmann, J. P. Huchra, F. J. Low, R. M. Cutri, and F. C. Gillett; "Search for Infrared Quasars", presented at the 169<sup>th</sup> Meeting of the American Astronomical Society, January, 1987.

S. G. Kleinmann, J. S. Young, M. J. Claussen, V. C. Rubin, N. Z. Scoville; "Optical and Millimeter Wave Studies of NGC 2146", presented at the 170<sup>th</sup> Meeting of the American Astronomical Society, June, 1987.

B. D. Goodrich, J. L. Africano, W. Binkert, and S. G. Kleinmann; "Optical Photometry of High Latitude 12  $\mu$ m IRAS Sources", presented at the 170<sup>th</sup> Meeting of the American Astronomical Society, June, 1987.

### *b) Consulting*

During 1987, S. G. Kleinmann consulted for M.I.T. Lincoln Laboratory (Group 38) in regard to their plans to obtain ground-based mid-infrared photometry of infrared-bright stars in selected fields.

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