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FINAL REPORT

To the National Aeronautics and Space Administration
Ames Research Center
for
Cooperative Agreement NCC 2-407

"Supporting Research and Technology Activities in the Preparation of a Three-Dimensional Map of the Infrared Sky"

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Submitted by

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FINAL REPORT FOR COOPERATIVE
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The purpose of this Cooperative Agreement was to collaborate with NASA civil servant and contractor personnel, and other Institute personnel in a project to use all available cataloged astronomical infrared data to construct a detailed three dimensional model of the infrared sky.

This report covers the work of the following SETI Institute personnel:

Dr. Arati Chokshi
Ms. Deborah E. Schwartz
Dr. Kevin M. Volk
Dr. Richard J. Wainscoat
Dr. Helen J. Walker

The group had complementary skills and actively collaborated on many of the tasks involved in this project. Therefore, even though individuals are identified with the tasks, there was a high degree of collaboration. The individual who is identified with a task took the lead in accomplishing it.

Dr. Arati Chokshi

Before leaving the project, Dr. Chokshi participated in a study of the IRAS colors of normal stars and the infrared excesses in Be stars. Both studies resulted in two publications[1,2], and the results on Be stars were also presented at the 169th meeting of the American Astronomical Society in Pasadena[3].

Using stars from the Bright Star Catalog (BSC), supplemented by cool dwarf stars from the Gliese catalog, that were detected by IRAS, the intrinsic visual-to-infrared color indices for "normal" stars as a function of IRAS wavelength (at 12, 25, 60 and 100 microns), spectral type (between O5 and M8), and luminosity class (all classes between I and V) were defined empirically[1]. In this study normal stars are defined as stars without significant infrared emission beyond their photospheric radiation. The results of this study were used in two ways. First is to identify other than normal stars in the IRAS survey for further study. Second is to use generic IRAS low resolution spectra (LRS) for each normal type of star to extrapolate the star's flux to other wavelengths.

The IR excesses of a sample of bright, well studied Be stars drawn from the literature using IRAS data were investigated. The previously established correlation between infrared luminosity and the H-alpha luminosity indicated that the L(IR)/L(H-alpha) ratios significantly deviated from the theoretical relationship. The contribution is from infrared free-free and free-bound continuum[2,3]. This investigation decreased the apparent deviations by up to an order of magnitude. Inclusion of temperature and optical depth effects led to the decrease in L(IR)/L(H-alpha) ratios.

Dr. Arati Chokshi resigned from the project for personal reasons at the end of year one. A nationwide advertisement appeared in the Job Registry of the American Astronomical Society, and the response was very positive. In conjunction with the NASA technical monitor, Dr. Kevin M. Volk was selected.

Dr. Helen J. Walker

Dr. Walker worked on two main areas, the IRAS colors of stars and the (logN,logS) data, both of which were needed to investigate galactic structure.

Using only the IRAS fluxes, various types of normal stars were plotted on a [12]-[25], [25]-[60] color diagram. The bright stars, the evolved carbon rich stars, and the evolved oxygen rich stars tend to separate into almost non-overlapping boxes in the IRAS color-color diagram. A study of the Low Resolution Spectra (LRS) has revealed that the [12]-[25] color is related to the slope of the underlying continuum in the LRS domain, rather than depending upon the dust features.

From parametric fits of the (logN,logS) plots, Dr. Walker set up a scheme for quantifying these graphs. The next step was to compare these plots with empirical models of the distribution of infrared point sources in the galaxy. From these comparisons, we determined if the known elements of galactic structure, disk, halo, spiral arms, could be traced in the IRAS data, and to what distance, in the plane and out of the plane. The M giants/supergiants are intrinsically very luminous and can be seen by IRAS to great distances, certainly as far as the galactic center. The M giants/supergiants provided us with a good test of this approach.

The color-color analysis and reclassification of misclassified Low Resolution Spectral (LRS) spectra resulted in publications in the astronomical literature. As part of this study on color-color classification, Dr. Walker participated in observing trips to Lick Observatory where she assisted the project in obtaining CCD (charge coupled detector) spectra of interesting stars. Another study involved a critical analysis of differential (logN,logS) plots. The differential (logN,logS) program proved very useful in isolating "features" in the cumulative distributions. We tracked the individual sources responsible for apparent "excesses" in the cumulative distributions, and locate these sources in the IRAS two-color planes. The study of differential (logN,logS) plots and their association with different types of sources in the color-color diagrams played a key role in modeling the different types of radiators in the infrared sky[4,5,6].

Another important study was the collaborative work of Drs. Walker and Volk with the Ames Artificial Intelligence (AI) group headed by Dr. Peter Cheeseman. The use of AI techniques yielded valuable results when applied to the analysis of the IRAS Low Resolution Spectral Catalogue (LRSC) This project investigated an independent way of classifying the LRS spectra, and a set of over 300 spectra has revealed this is to be a very powerful way of sorting the spectra into groups. Preliminary results were presented at the Third International IRAS Conference[7]. The final results of the AI work were published[8].

Dr. Kevin M. Volk

Dr. Volk worked on how to use the observed IRAS source counts as a function of position to deduce the physical structure of the galaxy. The sky distribution of IRAS sources is a function of both the range of 12 microns fluxes chosen and the [12] - [25] color range considered. In most ranges the galactic disk is by far the dominant component seen by IRAS. Selected color and flux ranges showed the galactic bulge as well as the disk. The galactic halo proper must also be present but is much less obvious in the data. It was necessary to understand why different color and flux slices of the IRAS data show very different sky distributions and to find what information about the overall structure of the galaxy, (scale lengths for the various components, the relative numbers of sources from the disk, bulge and halo components, possible contributions from a thick disk) are available from these sky distributions.

The first component studied was the galactic bulge, which is seen cleanly in certain color and flux ranges. To study the radial density function of the bulge sources and the bulge ellipticity a Monte Carlo program was developed to produce model sky distributions. Comparison with the IRAS data allowed inference of the structure of the bulge, which was found to be distinct from the larger galactic halo in radial structure. It was also possible to get some information about the 12 microns luminosity function of the bulge sources by comparison of the model fluxes to those actually observed for selected bulge areas.

Having modeled the galactic bulge the next step was to study the component or components seen by IRAS.

Dr. Volk studied a new subset of the IRAS data which is the set of nearby stars compiled by Gliese. This study was essential to provide the basic data for galaxy simulations, his own as well as Dr. Wainscoat's, which previously had to be assumed from the conversion of stellar properties as observed at optical wavelengths to the infrared. By carrying out this study the input data for the models were put on a solid observational footing. He also developed a Monte Carlo simulation of the bulge, disk and spheroid of the Galaxy. All were integrated into a large Cray-based simulation in which arbitrary proportions of bulge, spheroid and disk can be accommodated[9].

The group made an analysis of the sources in the IRAS data that are associated with galaxies. Such sources comprise about 8% of all point sources observed by the IRAS satellite. At high galactic latitudes galaxies are the dominant type of source observed by IRAS. To model this contribution to the infrared sky required a study of the infrared luminosity function of galaxies of various types as well as a study of the sky distribution of galaxies. Some work of this sort had been carried out elsewhere and was adapted for our needs. Study of elliptical galaxies, which are relatively faint infrared sources compared with spiral galaxies, was carried out. A study of whether any large-scale galaxy clustering is observed by IRAS was also carried out. Finally the IRAS spectra of those few galaxies that were bright enough to be observed were studied. The full spectral data provided a few more galaxy spectra helpful in this study.

The computer program was extended to allow modeling of a galaxy with the galactic bulge, the halo and one or more disk components. The program allows simulation of the sky distribution of sources and of (logN,logS) plots for selected sky areas. These models differ from the galactic models of Dr. Wainscoat in that they deal strictly with the IRAS data instead of starting from the galaxy as seen at optical wavelengths and transforming to 12 microns or 25 microns. Comparison of these two approaches allowed the identification of any groups of sources which are luminous at 12 microns or 25 microns but inconspicuous at optical wavelengths. These models are also useful to understand why different color ranges in the IRAS data show dramatically different sky distributions.

Dr. Richard J. Wainscoat

Dr. Wainscoat concentrated on the IRAS properties of metal-poor stars. In order to properly construct a model of our Galaxy, a number of separate components had to be considered. The primary components are the disk and the spheroid. The disk may be considered as comprising three parts: the young disk, with approximately solar metallicity, and commonly referred to as population I; the old disk, which contains a large part of the disk's stellar mass, with a metallicity ranging from solar down to [Fe/H]~-0.5 (i.e. one third solar); and the more recently discovered thick disk, whose metallicity ranges down as low as [Fe/H]~-1.5. The spheroid may be regarded as consisting of the galactic bulge, with a metallicity roughly solar, and the galactic halo (Population II) - the first component of the Galaxy to be formed and that component to which the globular clusters belong - with a metallicity which ranges as low as [Fe/H]<-2.0.

The study of "Normal Stars"[1], concentrated on a sample of stars selected from the bright star catalogue. By the nature of this selection, a significant fraction of this sample are Population I stars, and the average metallicity of this sample is therefore probably roughly solar. Since our Galaxy consists of some components with different abundances, it was important to investigate the effects of changing metallicities on the results obtained by Cohen et al.[1], so that an accurate model of our Galaxy could be constructed. Metallicity changes were expected to produce such effects as inhibition of grain formation in metal poor stars during the late stages of their evolution thus altering their infrared spectrum.

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There are two possible approaches by which the applicability of the Cohen et al.[1] results to metal weak stars were tested:

a) Globular clusters:

Globular clusters are some of the oldest and most metal-weak objects in the Galaxy. A number of globular clusters were seen by IRAS; however, the point source fluxes are of little value since the globular clusters are too extended for inclusion in the Point Source Catalog, whilst the globular clusters are not extended enough (with the exception of 47 Tuc and w Centauri) to be included in the Small Scale Structure Catalog. Therefore, Dr. Wainscoat searched the IRAS pointed observations for observations of globular clusters, and found approximately ten globular clusters. He determined far-infrared fluxes for these clusters from these pointed observations. All globular clusters are seen most easily at 12 microns, but are also seen at 25 microns. Only 47 Tuc is seen at 60 microns, and none of them are detected at 100 microns. Only in 47 Tuc and w Centauri is it possible to resolve individual stellar sources within the cluster in the IRAS image. Dr. Wainscoat has taken color-magnitude diagrams (CMD) for selected globular clusters in this sample, and attempted to synthesize their IRAS fluxes from these CMD's and luminosity functions, and lookup tables derived from Cohen et al.[1]. This has been successfully completed for 47 Tuc (one of the more metal rich globular clusters, and also one of the best studied), with a very good 12 micron magnitude and V-[12] color being derived. A large fraction of the 12 micron flux comes from the red end of the giant branch. Dr. Wainscoat extended this work to less metal-rich.

b) Metal-weak (halo) stars:

Although the dominant galactic component in the solar neighborhood is the disk, there are also halo stars present (a much smaller number). Dr. Wainscoat has taken a sample of known halo stars from the literature and identified those which were detected by IRAS (about 80). Due to their nature (stars formed very early in the life of the Galaxy, and metal-poor), these stars have only a limited range of spectral types (dwarfs ~F5 or later, giants ~G0 to M0). In a B-V vs V-[12] color-color diagram, it appears that these metal poor stars have an excess of 12 micron radiation for their B-V color compared to a normal sample of stars taken from the bright star catalog (e.g. Waters et al.,[10]). This can perhaps be better explained as being a deficit in the B-V color for the spectral type, with this deficit being caused by the low metallicity.

He modeled our Galaxy at the IRAS wavelengths. The IRAS catalog forms an almost complete and relatively unbiased database, thus providing a useful tool for the study of the Galaxy. This research involved determining the distributions and brightnesses of many types of infrared sources. The distribution of optically bright stars away from the plane of the Galaxy is already well understood, but until now we knew little about their distribution closer to the plane, where dust absorption is high at optical wavelengths. The distributions of "infrared-bright" sources (e.g. dust-shrouded stars, Carbon stars, gaseous nebulae) were less well known. This project embarked on an optical identification program for some of these objects, with the aim of a more thorough knowledge of the constituents of the Galaxy which are seen by IRAS. This research is of value in the understanding of the distribution of both normal stars and infrared bright sources, and therefore enrich our understanding of our Galaxy.

He also studied external edge-on galaxies, using 2-dimensional array detectors. This work was carried out at near-infrared wavelengths (2 microns), where the light is dominated by the old stars. Edge-on galaxies are the only sources in which we can study the vertical distribution of stars (i.e. out of the plane). Since these galaxies have dust lanes, it has been impossible to study their stellar distributions at the classical optical wavelengths, and it has only recently become possible to pursue this question in the near-infrared, where the dust absorption is much diminished. The structure determined is important in understanding the formation and dynamical evolution of galactic disks. This work was quite closely related to that described in the previous paragraph and both address the same fundamental questions of Galactic structure, but from different approaches[11].

Ms. Deborah E. Schwartz

Ms. Deborah Schwartz divided her time equally between the IRAS database studies and studies of a microgravity experiment and, more recently, of a possible Mars Rover/Sample Return experiment conducted in conjunction with NASA scientist Chris McKay. The report for Ms. Schwartz's activities is divided into two areas, the IRAS database studies and the microgravity, Mars studies.

IRAS Studies:

Ms. Schwartz used the INGRES relational database management program in two major studies of the IRAS data. The first study, in conjunction with Dr. Walker, investigated stars in the IRAS Point Source Catalog that are identified in other catalogs. The second study, in conjunction with Dr. Wainscoat, began the modeling of globular clusters.

The study of stars was divided into several subtasks. Ms. Schwartz participated in the study of star colors as a function of spectral type and luminosity class. The results of this study have been published[1]. She has also made a statistical determination of the distribution of the number of stars in specific IRAS catalogs as a function of spectral type and luminosity class, and galactic latitude, longitude, and distance. She obtained (logN,logS) plots, and plots of the log of the fluxes versus the cumulative fluxes of high quality IRAS sources in all latitudinal ranges. These results were used to infer overall longitudinal trends in star density for the galactic sky.

Ms. Schwartz has performed statistical analyses and curve fitting of IRAS high quality detections that are listed in the General Catalog of Variable Stars (GCVS) as M stars, Bright stars, or Carbon stars. The results of these studies were used to recognize and select stars with IR excess for further study. The ultimate goal of these types of studies was to define IRAS characteristics of specific categories and sub-categories of point and extended sources that can be extrapolated to other categories.

Ms. Schwartz also was involved with identifying sources within low metal, high metal, and intermediate metal-rich globular clusters. This identification was a necessary first step before a model of globular clusters could be constructed. The results of these studies presented a set of visual-to-infrared color indices for low metal sources.

Ms. Schwartz also identified anomalous galactic structures and interesting areas of cirrus from the HCON (hours confirmed) images. Since the cirrus is a component of the celestial background in the far infrared, any flux extrapolation needed to take the cirrus into account. In addition, anomalous galactic structures needed to be distinguished from the ever present cirrus structure.

Ms. Schwartz provided general support for the other members of the project. Ms. Schwartz participated in observing trips to Lick observatory where she assisted the project in obtaining CCD spectra of interesting stars. Prior to observing trips, she made finding charts for approximately 300-400 selected sources, helped examine and make final selection of sources on the basis of the character and brightness of their photographic counterparts. Using the 40 inch telescope with the CCD spectrograph, she obtained spectra of the objects selected to test the ability to classify IRAS sources by their PSC (Point Source Catalog) colors. In addition, she assisted in using a differential (logN,logS) program which proved very useful in isolating "features" in the cumulative distributions. We thus were able to track the individual sources responsible for apparent "excesses" in the cumulative distributions, and locate these sources in the IRAS two-color planes. Ms. Schwartz also set up and process numerous INGRES queries to search the IRAS database for other members of the project.

Solar System Exploration:

Ms. Schwartz also devoted about half of her time to two other projects. These projects include the Space Station Gas-Grain Simulator (GGS) and the Mars Rover/Sample Return Mission.

For the GGS project, she was involved in the final preparation of a report for a workshop held in the summer of 1987[12,13]. In addition, she participated in the final definition and engineering studies for the microgravity experiments. These studies answered the questions of what in-house experiments can be done to simulate the Space Station environment, as well as how microgravity will effect the different experiments and the equipment used for these experiments. For many of these questions, she used the equations of motion in a rotating field to derive the magnitude and direction of the gravity forces at different places on the Space Station.

She was also involved in defining the goals and top level concept for a Mars sample return mission. She was also involved in developing an implementation schedule. In particular, she studied how AI techniques could be used in the design of a sample recovery vehicle.

Ms. Schwartz was involved in a number of laboratory experiments and literature searches for the Mars Rover experiment. The laboratory experiments included the study of growing primitive organism in various level of N_2 which simulate the primitive Martian atmosphere. Another area for experimentation was to test the hypothesis that organic forms affected the relative abundance of metals found on the Martian surface. These experiments included extensive searches of the chemical literature to find the possible reactions for metals likely to be found on Mars. Ms. Schwartz also used her extensive knowledge of geology to participate in selecting sites on the Martian surface for the rover and to understand the evolution of the Martian surface.

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