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SIRTF: PROBING THE DARK CORNERS OF THE GALAXY

Michael W. Werner
NASA Ames Research Center
and
Dora S. Willoughby
Information Management International

ABSTRACT

SIRTF - the Space Infrared Telescope Facility - is planned for launch by NASA in the mid-1990's. It will be a cryogenically-cooled observatory for infrared astronomy and will carry several focal plane instruments which will provide a wide range of imaging, photometric, and spectroscopic capabilities. SIRTF will build on the scientific and technical progress of the successful IRAS mission and take the next step in the exploration of the Universe at infrared wavelengths.

Most of the observing time during the five-to-ten year SIRTF mission will be available to General Investigators, so there will be ample opportunities for the pursuit of problems originating from within the Space Life Sciences community. This paper will review the capabilities of SIRTF for this style of investigation, using the study of carbon in the Galaxy as a specific example. The very high sensitivity of SIRTF's spectrometers to diffuse emission will allow studies of carbon in both the gaseous and solid phase in the interstellar medium and should be of particular importance for the identification of the carbon-bearing macromolecules believed to be responsible for the emission features identified in the near infrared. SIRTF will also carry out studies of a wide variety of evolved stars which are returning gas and solid phase carbon to the interstellar medium and contribute to our understanding of the carbon "budget" in the Galaxy. These studies in the area of galactic astronomy will be complemented by detailed investigations of carbon-bearing compounds in solar system objects, including the surfaces of distant asteroids and cometary nuclei which are too faint to be studied in any other way.

INTRODUCTION

This paper will look into the future to discuss the use of SIRTF, the Space Infrared Telescope Facility, for the study of problems discussed at this conference and similar problems in Space Life Sciences. SIRTF should permit a specific style of investigation in this area, described in greater detail below, which I refer to as "probing the dark corners of the Galaxy." The paper includes a general description of SIRTF and examples of specific problems where SIRTF should have a major impact. The opportunities for general participation in the SIRTF program will also be described.

SIRTF, THE OBSERVATORY

SIRTF, the Space Infrared Telescope Facility, is a cryogenically cooled telescope for infrared astronomy to be launched in the mid 1990's, perhaps 1996 or 1997 on the present schedule. SIRTF will have a long lifetime, of the order of five years, which will be achieved by on-orbit replenishment of its liquid helium cryogen at two-to-three year intervals. There will be an extensive guest investigator program -- SIRTF is envisioned as an observatory for the entire scientific community, and is being developed as such at NASA Ames Research Center.

The unique capabilities of a cryogenic telescope for infrared astronomy from space give SIRTF tremendous power for the types of scientific problems which are being discussed at this conference. Figure 2 illustrates this in two ways. The upper curve shows the atmospheric transmission at infrared wavelengths from 2 to 1000 microns as it would be on a good mountain top site. Even on a good mountain like Mauna Kea the entire wavelength band from 30 to 300 microns, which includes many transitions of carbon-bearing molecules as well as the critical fine structure line of the C^+ ion, is totally unobservable from the ground. Radiation in several other infrared bands, including the 5-8 micron window where solid state and gaseous absorption features can be studied, also doesn't get through to the ground, nor does radiation in the region around 3 microns. One can get above some of this absorption by using an airplane such as the Kuiper Airborne Observatory, but not above all of it; so there is a great advantage in going into space just to get above the atmospheric absorption.

The other major advantage of going into space is shown in the lower set of curves in Figure 2, which show the brightness of the sky -- that is to say, the brightness of the background against which one is trying to detect infrared sources -- as a function of wavelength for several situations. From the ground, or from an airplane using an ambient temperature telescope, the background is quite bright, basically that of a 250-300 K black body with emissivity ~ 0.1. The background is contributed both by the atmosphere and by the telescope itself. However, if one goes into space, the natural

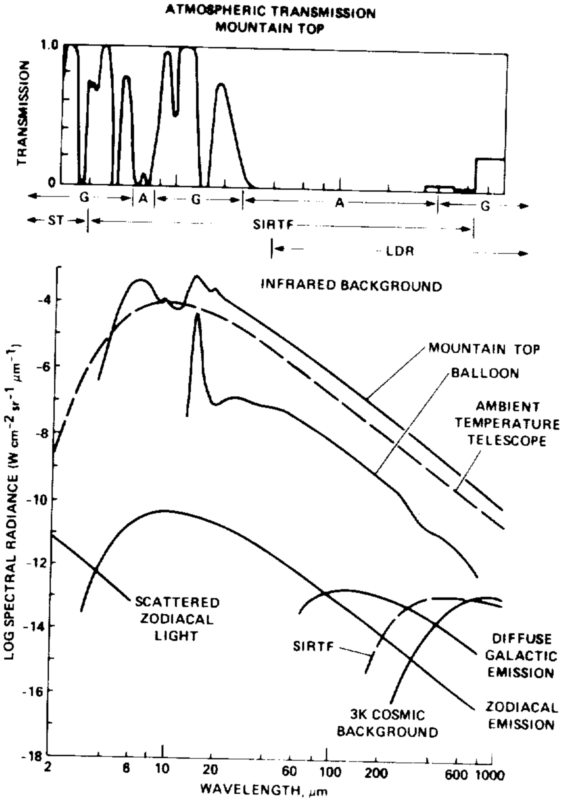

Fig. 2. Atmospheric transmission of infrared radiation at mountain top altitude (upper curve), and background radiation due to the atmosphere and ambient temperature telescope at mountain top and balloon altitudes, compared with the much lower astrophysical and instrumental backgrounds which characterize the SIRTF operating environment.

background -- primarily due to scattered sunlight or emitted radiation from the tenuous zodiacal dust cloud -- is about six or seven orders of magnitude lower. Very faint infrared sources stand out much more prominently against this background, and the limiting noise, which is due to the fluctuations in the rate of photon arrival, is reduced by three to four orders of magnitude as compared to an ambient temperature telescope. If the telescope is cooled so that it doesn't produce appreciable infrared emission, as will be done with SIRTF, very low backgrounds and exceedingly high sensitivity can be achieved. So a cryogenic telescope like SIRTF promises a three or four orders of magnitude increase in sensitivity over current capabilities over much of the infrared spectrum. The tremendous potential of SIRTF has been tantalizingly foretold by the Infrared Astronomical Satellite (IRAS) survey mission, which has demonstrated the power of a cooled telescope in space. IRAS worked primarily in just four broad spectral bands at 12, 25, 60, and 100 μm, while SIRTF will provide both photometric and spectroscopic capabilities across the entire infrared.

The characteristics of the SIRTF mission and telescope are shown in Table A. The telescope aperture will be 85 cm, making it a one meter class telescope. The wavelength range will be from 2-700 microns with 1 arcsec images in the near infrared. The pointing accuracy and stability will be ~ 0.15 arcsec, consistent with the short wavelength images. Mission duration will be in excess of five years. In addition, there will be planetary tracking capability so one can study solar system phenomena. Further details concerning the SIRTF facility and instruments are given in a paper by Werner and Eisenhardt (1988)[1], and the broad scope of SIRTF science is discussed by Reike et al. (1986)[2].

Three instruments, an infrared array camera, a spectrometer, and a multiband imaging photometer, are under development for SIRTF by different university teams. These are described in Table B. SIRTF's instruments will exploit the rapid progress now occurring in the development of monolithic arrays for infrared astronomy (Wynn-Williams and Becklin, 1987)[3].

SIRTF will be capable of mapping and photometry throughout the 2-700 micron band. Its imaging capabilities will be particularly impressive at the shorter wavelengths where large arrays will provide images ~ 5 arcminutes in extent with arcsec resolution. A variety of filters will be available for use with the imaging arrays, including filters which might be tuned to some of the features of interest in studying carbon compounds. SIRTF will have capability for polarimetry and an emphasis on obtaining the highest possible spatial resolution.

In addition, SIRTF will have spectroscopic capability in two modes, a low resolution mode at resolving power of about 100 from 2-120 microns, and a higher mode with resolving power of about 2000 from 4 to about 200 microns. Again, detector arrays will be used for spectroscopy, obtaining spectra at several points along the slit as well as dispersing the spectrum perpendicular to the slit.

Figure 3 shows a comparison of the sensitivity which SIRTF will achieve in low, medium and high resolution modes compared with the sensitivity which IRAS was able to achieve, with the current capabilities of ground based and airborne facilities and with the signals from some astronomical objects of potential interest. In broad spectral bands, SIRTF will be one to ten thousand times more sensitive than IRAS. Of particular importance for the problems discussed at this conference is SIRTF's spectroscopic capability. SIRTF will be able to obtain quite quickly detailed spectra of any IRAS source. For example, SIRTF spectra of the 700 carbon stars discovered by IRAS would permit determination of the molecular content of their atmospheres.

TABLE A

SIRTF -- SPACE INFRARED TELESCOPE FACILITY

SYSTEM CHARACTERISTICS

APERTURE: 85 CM
WAVELENGTH RANGE: 2-700 μm
DIFFRACTION-LIMIT: <4 μm
FIELD OF VIEW: 7 ARCMINUTES
ANGULAR RESOLUTION: 1 ARCSEC @ 4 μm
POINTING ACCURACY/STABILITY [ARCSEC]: 0.15/0.15
MISSION DURATION: >5 YEARS
PLANETARY TRACKING CAPABILITY

TABLE B

SIRTF INSTRUMENTATION

INSTRUMENT	PI	CHARACTERISTICS
INFRARED ARRAY CAMERA (IRAC)	G. FAZIO, SAO	Wide field and diffraction-limited imaging, 2-30 μm, using arrays with up to 128 x 128 pixels. Simultaneous viewing in 3 wavelength bands, selectable filters. Polarimetric capability.
INFRARED SPECTROMETER (IRS)	J. HOUCK, CORNELL	Grating spectrometers, ~ 2-200 μm, using two-dimensional (~ 10x50) detector arrays. Resolving power from 50 to > 1000. Low and high resolution options at most wavelengths.
MULTIBAND IMAGING PHOTOMETER (MIPS)	G. RIEKE, ARIZONA	Photometry, 3-200 μm, using small arrays with pixels sized for complete sampling of Airy disk. Wide field, high resolution imaging, 60-120 μm. Broad band photometry and mapping, 200-700 μm. Polarimetric capability.

THE DARK CORNERS OF THE GALAXY

From the astrophysical point of view SIRTF is often thought of as a discovery instrument. Its great sensitivity will allow new phenomena to be discovered by the imaging instruments and followed up with the spectrograph. A number of SIRTF's most important science goals have this character. But thinking about the use of SIRTF to study the problems discussed at this conference reminds me of the story about the drunk who was searching for a lost dollar bill under a light post. Some guy came along and said "Where'd you lose it?" He said "I lost it over there, but the light's

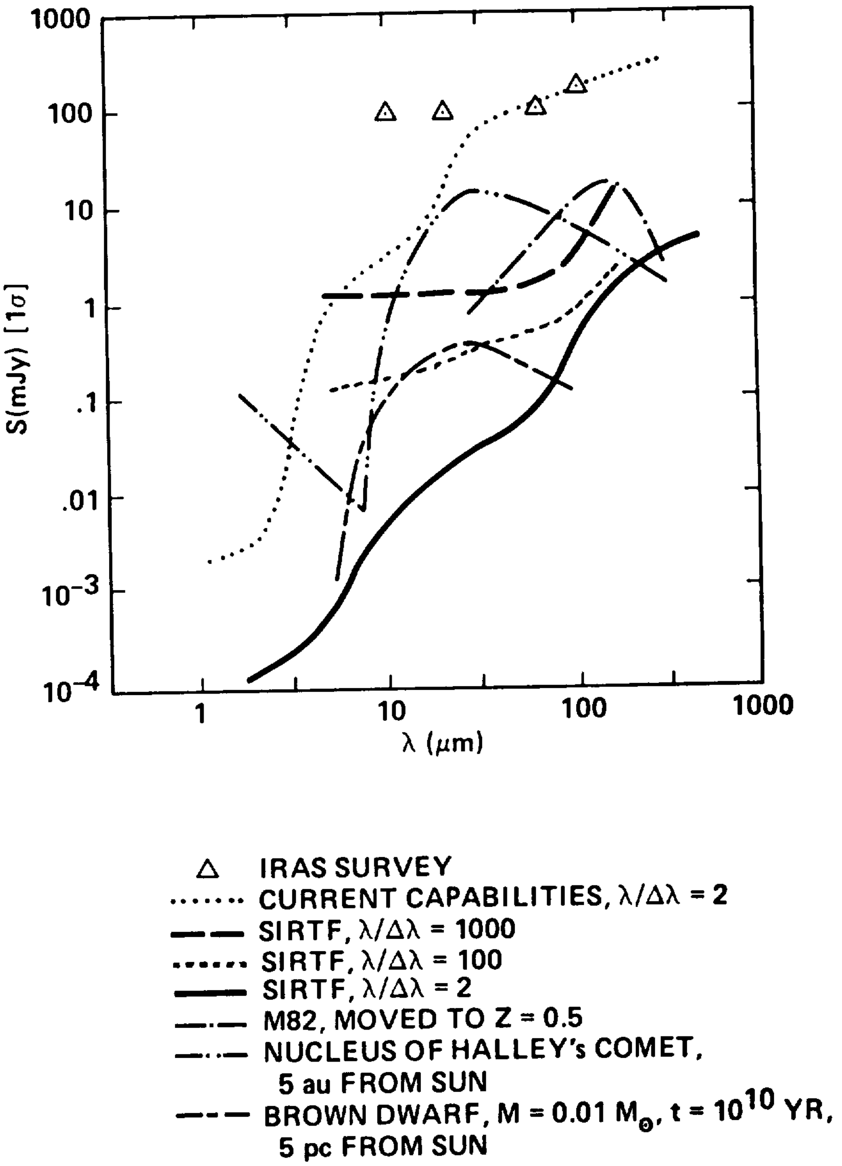

Fig. 3. The sensitivity of SIRTF in photometric and spectroscopic modes compared with the sensitivities of current telescopes and IRAS. Also shown are computed signals expected from a galaxy similar to M82 at a distance of z=0.5, Halley's comet at 5 AU from the sun, and a brown dwarf 15 light years away, typical of objects which SIRTF might study.

a lot better here." With SIRTF, however, we can look for the dollar at the place where it was lost. In other words, SIRTF will allow us to look into the dark corners of the Galaxy to see where most of the matter and most of the carbon reside, and to see the fainter and less dramatic manifestations of phenomena for which we can see only one or two unusual cases with our current capabilities. SIRTF will vastly increase the dynamic range over which these interesting phenomena can be studied.

A. Absorption by Grain Mantles

Figure 4 shows the extremely nice spectrum of the infrared absorption by icy grain mantles along the line of sight to W33A (Tielens and Allamandola, 1987).[4] Figure 5 shows a cartoon version of the cloud of dust and gas which surrounds W33A. W33A, an extremely bright object, is presumably having a tremendous perturbing effect upon the local grain mantle composition and chemistry, and its influence is

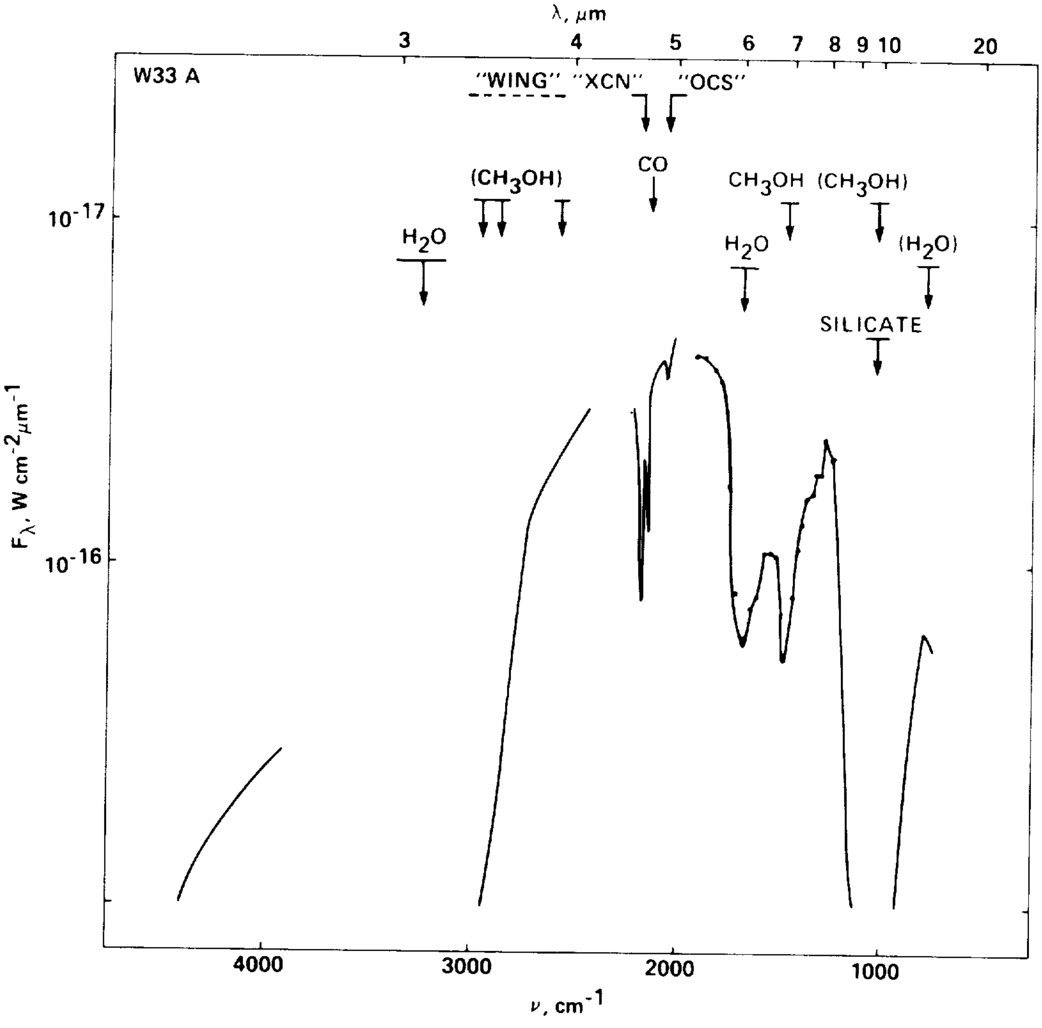

Fig. 4. The 2-13 μm spectrum of the protostar W33A, (from Tielens and Allamandola, 1987), showing absorption features at 3.08, 4.61, 4.67, 4.9, 6.0, 6.85, and 10 μm. The peak frequencies and widths of likely identifications for these features are shown as arrows and bars. Except for the 10 μm silicate, all of the other features are ascribed to molecules in icy grain mantles in the dust cloud surrounding this source.

inextricably folded into the observed spectrum. With current observing capabilities, however, this perturbation is unavoidable. With SIRTF, however, one could look not only at W33A, a very bright source, but also at random background stars behind this dark cloud, which have no effect whatever upon the material within it. One could study the grain composition at various positions across the cloud as a function of density density and temperature, and get a much better understanding of how the icy mantles evolve. To show that this is feasible, consider that the SIRTF limit for 1% resolution spectroscopy at five microns is about 10,000 times (10 stellar magnitudes) fainter than W33A, corresponding to 13th or 14th magnitude. The density of stars of that brightness in a random direction in the sky is such that behind a typical dark cloud there should be five to ten stars sufficiently bright to be used as probes to assess the absorption in the cloud and determine the mantle materials. Such background stars could be found very easily using SIRTF's cameras to image the cloud -- objects which can be detected spectroscopically are quite bright to SIRTF in its photometric mode. One could complement these observations by gas phase spectroscopy at higher resolution, and by continuum observations in the far infrared and submillimeter. These would permit determination of the dust and gas content along the

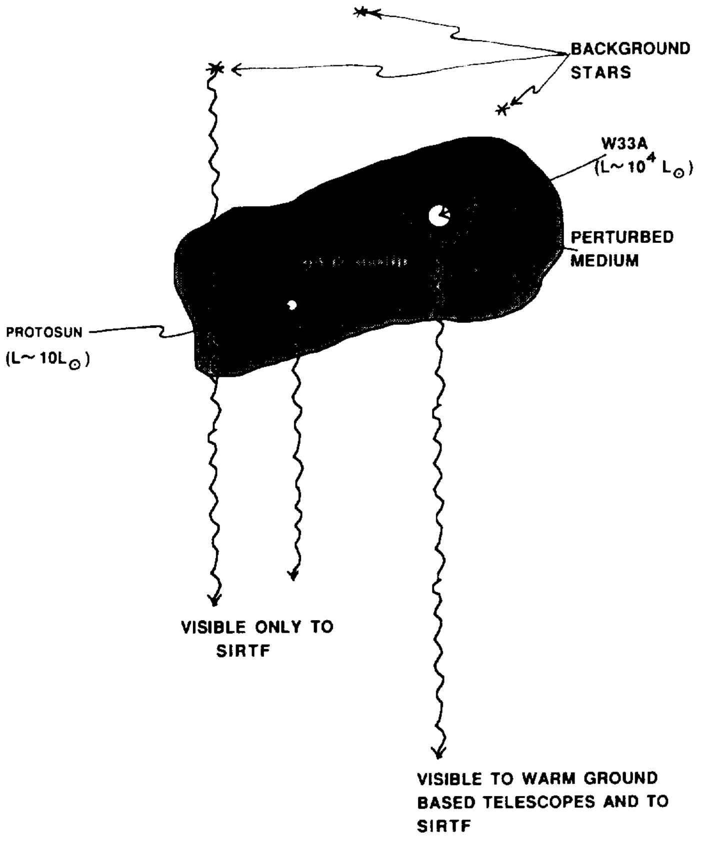

Fig. 5. This cartoon depicts a dense molecular cloud surrounding the highly luminous protostar W33A, which seriously perturbs the cloud material close to it. At present, the only way to study the cloud composition is by its effect on radiation from W33A which has passed through the perturbed region around the protostar. To study the unperturbed cloud material by observing the spectra of stars behind the cloud, or to study less luminous solar-type protostars within the cloud requires telescopes more sensitive than those currently available. SIRTF, however, will be able to do spectroscopic studies of both such objects.

line of sight for which the absorption has been measured. This is one dark corner that SIRTF can look into.

B. Gas Phase Spectroscopy

It will also be possible to do interesting gas phase spectroscopy of the biogenic elements with SIRTF. A number of lines in the far infrared are of interest for abundance determinations. These include the 63 and 145.5 μm lines of neutral oxygen, the 52 and 88 μm lines of O^{++}, the 57 μm line of N^{+}, the 122 μm line of N^{++}, the 158 μm line of C^{+}, and the 370 and 609 μm lines of neutral carbon. Many of these have been discussed at this conference. It has already been possible to look at the ratio of oxygen to nitrogen in the brighter ionized regions at various points through the galaxy, to get some idea of how the history of nuclear evolution has varied throughout the galaxy. Some of the data that have been obtained are shown in Figure 6 (taken from Lester et al. 1987),[5] where the abundance ratio of doubly ionized nitrogen to doubly ionized oxygen is plotted as a function of the distance of the ionized region from the center of the galaxy. These data show evidence for an increase in the nitrogen to oxygen ratio as one moves toward the center of the galaxy. This has been interpreted as indicating more star formation and thus more nuclear processing in the inner regions of the galaxy over the past 10 billion years. With SIRTF one will easily be able to extend this type of study to distant galaxies using the same infrared lines, which provide very good abundance determinations. In this way, we can look at the history of star formation and thus at the return of processed matter to the interstellar medium in other galaxies.

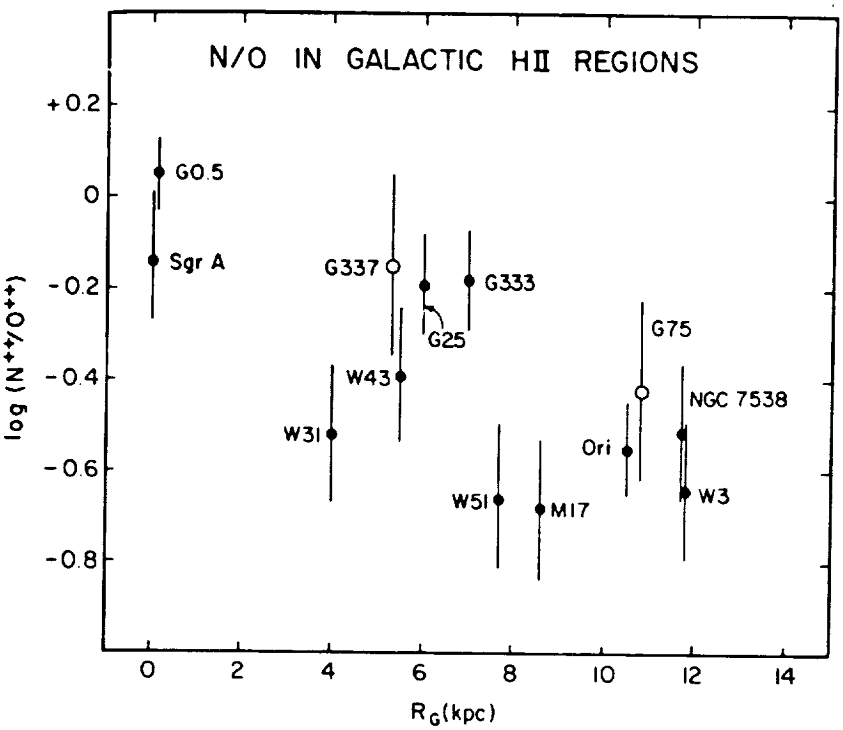

Fig. 6. The N/O ratio in galactic H II regions plotted vs. distance from the galactic center (from Lester, et al., 1987). The higher ratio of nitrogen to oxygen near the galactic center is indicative of more star formation and more nuclear processing in the inner regions of the galaxy.

Also in the area of gas phase spectroscopy is the possibility of looking at the C^+ line in circumstellar shells, discussed earlier as of importance in the chemistry of such regions. Figure 7 shows the spectrum of the 158 μm line of C^+ in NGC 7027, the brightest planetary nebula in the sky (Ellis and Werner, 1984).[6] A planetary nebula consists of a bright hot star, an ionized shell (seen in the radio continuum and in lines characteristic of ionized material), and an exterior molecular shell which is seen in emission lines of CO and other molecules. Clearly there must be an intermediate atomic region in which the gas is undergoing a transition from being ionized to being molecular. The transition region will be heated and partially ionized by the low energy ultraviolet photons from the central star; such a region should be bright in the C^+ line. That's exactly what one sees in the case of NGC 7027. The masses of material in each of these three regions are, approximately: 0.1 solar mass in the ionized shell, 0.25 solar masses in the atomic region, and 0.5 solar masses in the molecular shell. In this particular case the atomic region, which cannot be easily detected in any other way except through the 63 μm line of neutral oxygen, is comparable in mass with the molecular and the totally ionized portions of the circumstellar shell. Thus the C^+ line in this case is a diagnostic of the rate of return of matter to the interstellar medium, matter enriched in carbon, nitrogen and oxygen. Its abundance in such shells is also of importance because of its effect on chemical processes and thus on the chemical composition of the returned matter. SIRTF's capability to detect C^+ lines with a flux of 1.5×10^{-18} watts per square meter (0.01 percent of the brightness of the line in NGC 7027) will make it possible to detect as little as 10^{-5} solar masses of ionized carbon in an object at the distance of the galactic center, which is 30,000 light years away. Thus, instead of having to look only at the brightest and nearest planetary nebulae, one could easily study all of the planetary nebulae that are now known.

Since the mass that one can see scales inversely as the square of the distance, in the solar neighborhood at 300 light years from the sun, one could see as little as

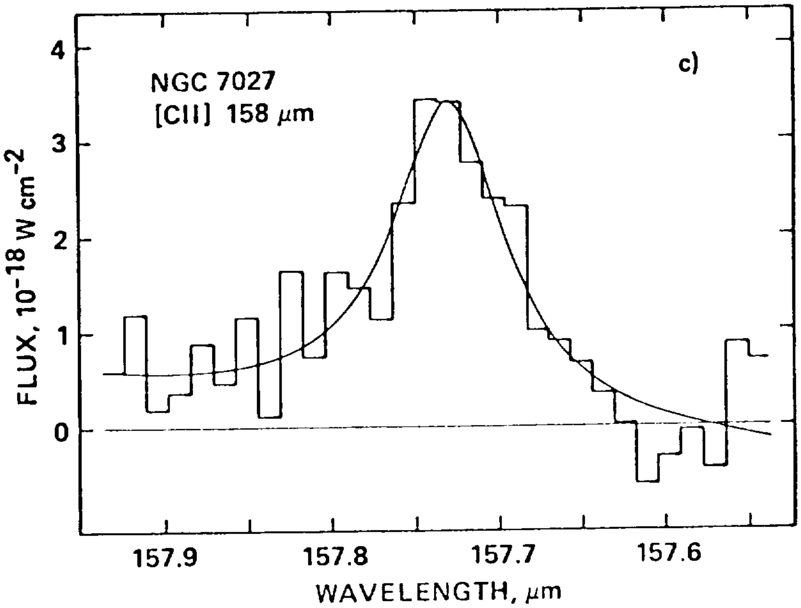

Fig. 7. The spectrum of the 158 μm line of C^+ in the planetary nebula NGC 7027 (from Ellis and Werner, 1984). The strength of this line in planetary nebulae is a measure of the return of biogenic elements to the interstellar medium.

10^{-9} solar masses of carbon, which is much less than the mass of carbon in the solar system. This assumes that the carbon is ionized and that the upper state of the C^+ line is well populated, which will occur over a substantial range of density and temperatures. With SIRTF's ability to detect 10^{-9} solar masses of C^+, or even smaller amounts for closer objects, one should think about looking for gas in "Vega shells", clouds of debris around stars, which may be relics of a planetary formation phase. Vega and Beta Pictoris provide the best known examples of this phenomenon, but IRAS discovered such shells around approximately 20% of nearby stars of masses $\leq 2M_{\odot}$. Based on statistical extropolations of the results from IRAS, Backman and Gillett (1987)[7] estimate that most solar type stars are circled by particle clouds which emit in the far infrared. The IRAS number of 20% is set not because that's all there are, but by the dynamic range of our ability to detect them. So here is a whole new area of science which SIRTF can explore. There is material around stars which may well be the debris of the planetary formation phase, and studying its composition in the infrared either through gas phase or solid phase spectroscopy should be extremely interesting. This would be a very potent application of SIRTF because it can resolve the Vega shell, which is some 20 arcsec in diameter, and because it could detect objects of the scale of the Vega shell around stars thousands of light years away, and more modest examples around nearer stars.

C. Comets

A third exciting area is the study of comets. Some very nice ground-based spectroscopy by Baas et al. (1986)[8] discovered in the spectrum of Halley's comet a complicated feature, shown in Figure 8, at a wavelength of about 3.25 μm. They suggest that this is due to UV-pumped fluorescence of organic molecules, either molecules on small grains or free molecules. SIRTF could have detected this particular brightness from Halley's comet at a distance of 3 AU from the sun (out past the asteroid belt) as the comet approached the inner solar system. SIRTF could study the development of this feature, verify the excitation mechanism, and perhaps

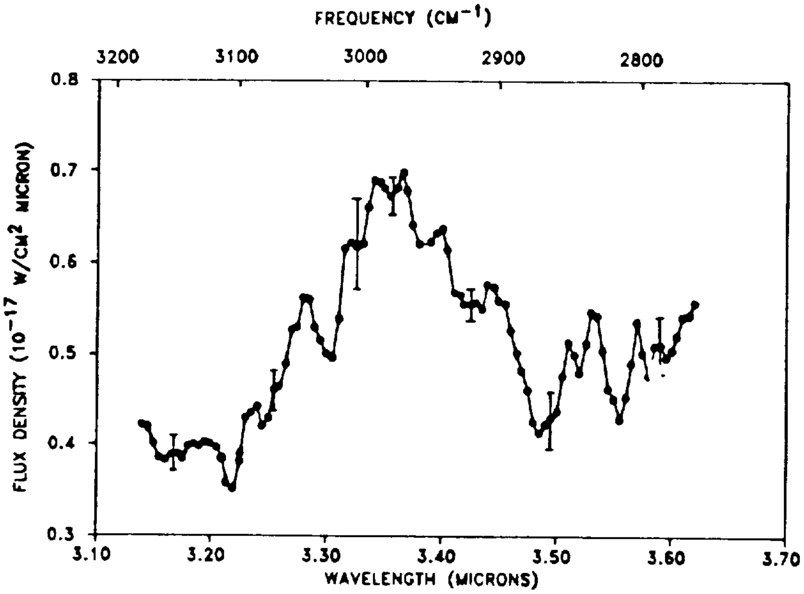

Fig. 8. The spectrum of Halley's comet in the wavelength region around 3.35 μm (from Baas et al. 1986). The presence of this peak in the spectrum can be interpreted as evidence for UV-pumped fluorescence of organic molecules, either on small grains or as free molecules.

determine the temperature at which this material, whatever it is, starts to come off the cometary grains. This is the sort of project which could be done with spectral resolving power of about 100, consistent with the SIRTF instrumentation.

D. Diffuse Emission from the Interstellar Medium

A cryogenic telescope like SIRTF is particularly sensitive to low surface brightness extended emission, and SIRTF will be intensively used in studies of diffuse infrared emission from the interstellar medium. One of the main phenomena to be explored in this fashion is the non-equilibrium emission seen from 2 to 30 μm in many interstellar regions; it was to explain this non-equilibrium emission that polycyclic aromatic hydrocarbons (PAHs) were postulated as an abundant carbon-bearing constituent of the interstellar medium (Leger and Puget (1984)[9]; Allamandola, Tielens, and Barker (1985)[10]).

This non-equilibrium emission was first discovered in bright reflection nebulae like NGC 7023 (Sellgren et al. 1985).[11] Figure 9 shows the infrared spectrum of the bright inner region of NGC 7023. At wavelengths longward of 30 μm there is an emission peak which is consistent with thermal emission from grains in equilibrium

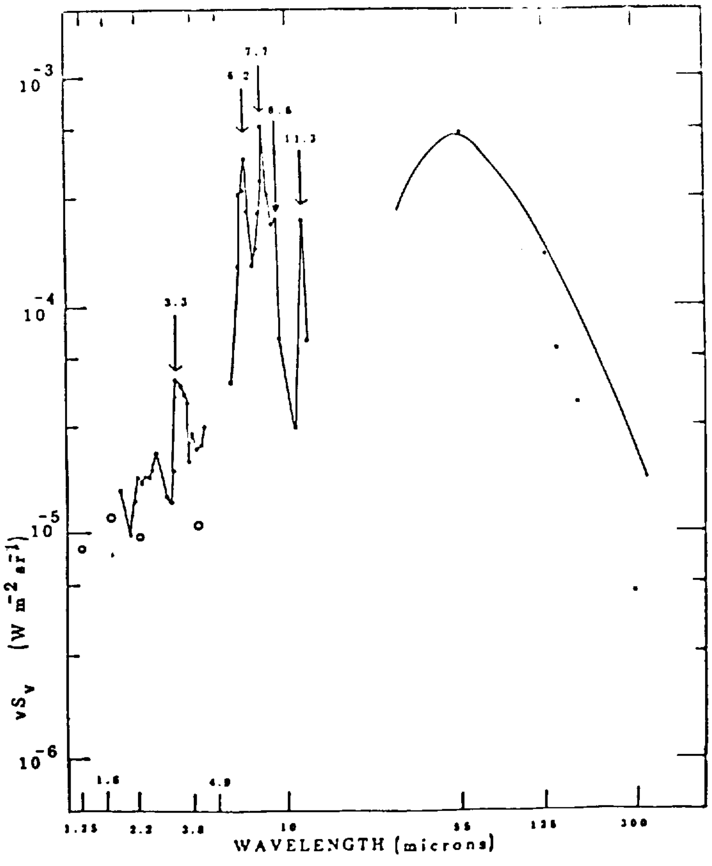

Fig. 9. The infrared spectrum of the reflection nebula NGC 7023 (from Sellgren et al. 1985, and Whitcomb et al. 1981[12]) showing a peak longward of 30 μm, attributed to thermal emission from grains in equilibrium with radiation from the illuminating star, and showing peaks in the range 2-11 μm due to non-equilibrium emission from polycyclic aromatic hydrocarbons (PAHs).

with the radiation from the star which illuminates this nebula. At shorter wavelengths we see the very pronounced emission features which are attributed to the PAHs, and perhaps some continuum as well. If one extrapolates the thermal emission curve to shorter wavelengths, it falls far below these emission features, and since there is nothing exotic going on in the reflection nebula, one is forced by these data to infer that this emission is excited in some kind of non-equilibrium way. What IRAS saw when it looked in a region like this was just the four broad points at 100, 60, 25 and 12 microns; where it averaged over whatever spectral structure there might be. SIRTF will be able to resolve the features in this part of the spectrum and take an inventory of the emission features seen in regions of various types and under differing excitation conditions. In addition, SIRTF can obtain spectra of many such regions, as opposed to the handful now accessible.

An example of the type of region which SIRTF can study in this fashion -- another type of region in which IRAS found infrared emission which may have this non-equilibrium character at the shortest wavelengths -- is Cas A, which is a supernova remnant. In Figure 10, IRAS maps of Cas A at 12, 25, and 60 microns are compared with an X-ray map of the same region (Dwek et al. 1987a).[13] The emission seen in the X-ray clearly comes from a very hot plasma, and the infrared emission comes from dust particles mixed within that plasma. The dust particles are heated not by photons, which is the normal way that dust is heated in our galaxy, but by collisions with energetic particles in the plasma, which has a temperature of about 10^7 K. As these particles pass through the dust grains they lose energy by ionization losses which

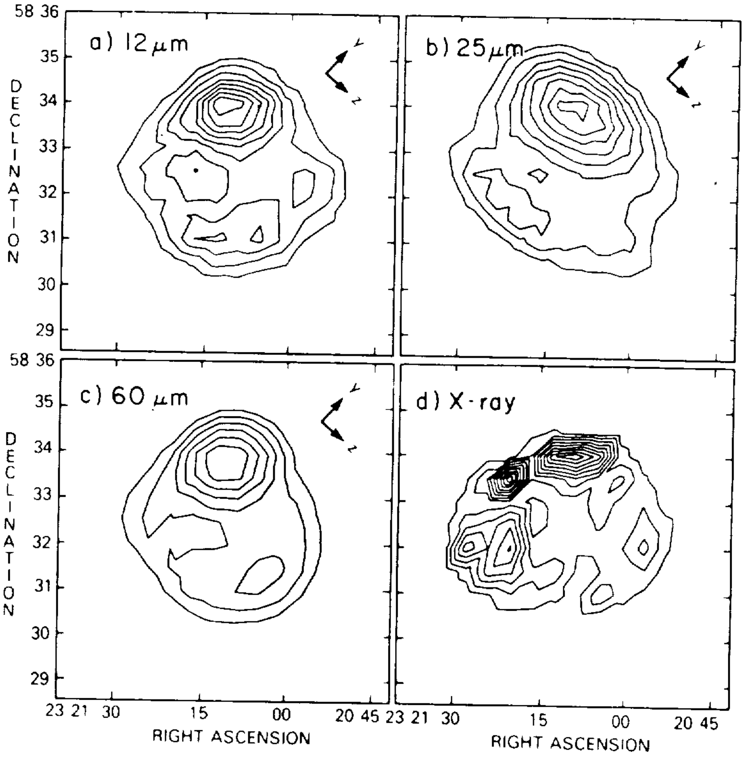

Fig. 10. IRAS-measured contours of Cas A at 12, 25, and 60 μm compared with X-ray contours of the same region (from Dwek, et al. 1987a). The X-ray emission is from hot plasma; the infrared emission is from dust grains embedded in the plasma, and heated by collisions with hot plasma particles.

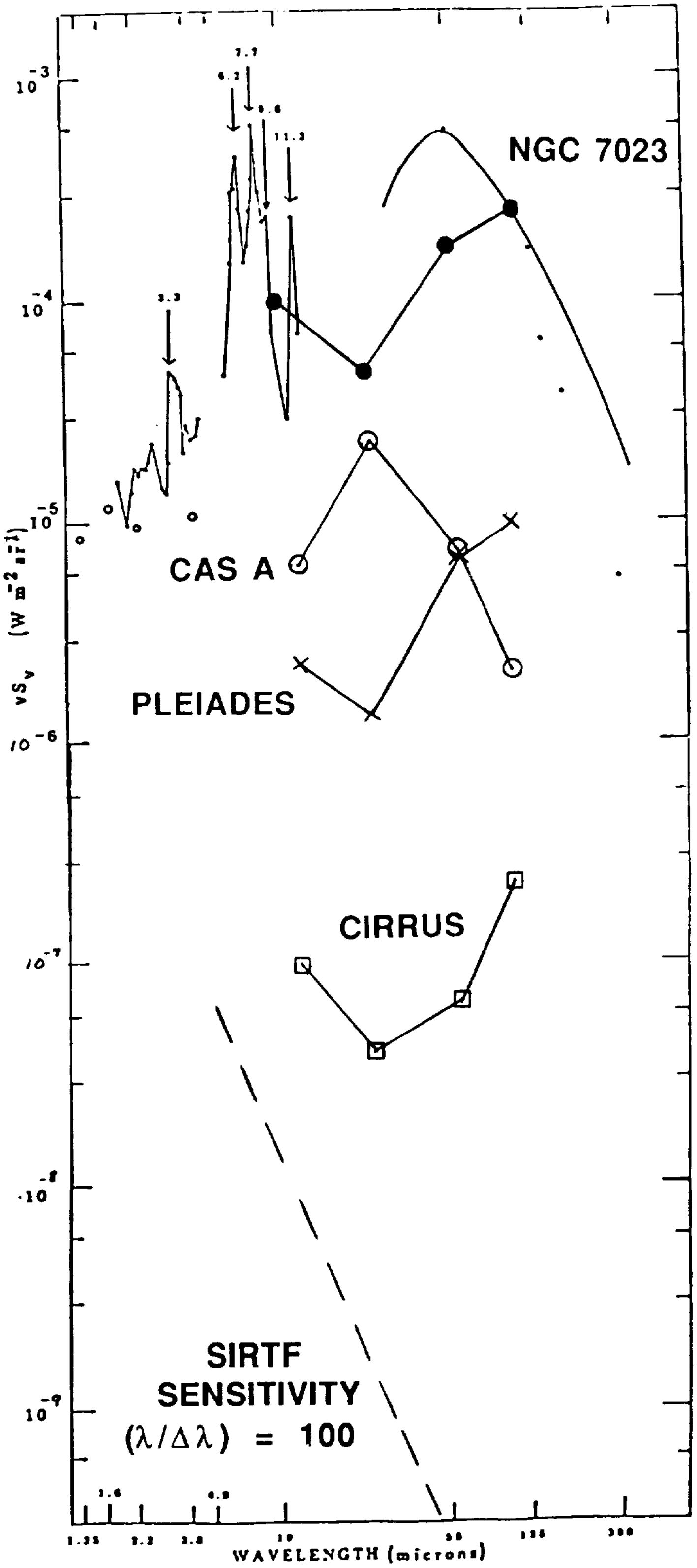

Fig. 11. The spectrum of NGC 7023 (from Sellgren et al. 1985 and Whitcomb et al. 1981) and IRAS observations of NGC 7023, Cas A, reflection nebulae in the Pleiades, and the galactic cirrus, compared with the sensitivity with which SIRTF will be able to make spectroscopic studies of these and similar objects with a resolution of λ/Δλ of 100.

heats the dust particles and causes the observed radiation. There is a series of very nice papers on this process by Dwek et al. (1987b)[14] on the data from IRAS. Clearly, if one is interested in grain destruction and what happens to grains in supernova shocks, then certainly the spectrum of the emission from these regions must be studied.

Another type of region of interest for SIRTF to study is the infrared cirrus, wisps of radiation seen away from the galactic plane, which have been given the name "cirrus" because they look like the cirrus clouds which astronomers are all too familiar with from ground-based work. The cirrus appears to be emission from fairly random patches of dust in the interstellar medium illuminated by ambient starlight. These patches reside in what must be the most benign environment in which particles can exist in the interstellar medium.

Figure 11 shows a comparison of expected fluxes from these three types of regions with what the capabilities of SIRTF will be. NGC 7023 is shown as the brightest region of this general type; the solid circles show the average (as opposed to peak brightness of NGC 7023 based on IRAS data; the open circles, x's, and squares show the IRAS observations of the emission from Cas A, moderately bright reflection nebulae in the Pleiades (Castelaz, et al. 1987),[15] and the IR cirrus respectively. The cirrus is about as faint a region as IRAS can see, and is far fainter than can be seen from the ground or with warm telescopes. Even the bright reflection nebulae in the Pleiades are inaccessible to currently available instruments. The sensitivity which SIRTF will achieve with a resolving power of 1% is shown by the dashed curve at the bottom of the figure. Clearly, SIRTF will have the ability to obtain spectra of any of these regions at the 1% level. One can then look for the presence and the structure of the emission features and see how they vary as one goes from a supernova remnant where there is shock processing to regions like the Pleiades where the radiation density is quite high, and finally -- to the darkest corners of the galaxy -- to regions where the radiation density is low and the material undisturbed.

CONCLUSIONS

SIRTF will be operated as an observatory-class facility. Beginning four months after launch, 50% or more of the observing time will be used by general investigators selected competitively from the broad community.

SIRTF has great potential for the study of carbon in space, and of other problems in the area of Space Life Sciences. More active involvement of the Space Life Sciences Community in the SIRTF project definition would be most welcome. Specific suggestions or requests for more information concerning SIRTF are solicited, and should be passed on to the author of this article. Ultimately, members of this community should be thinking about proposing observing programs for SIRTF.

This talk has concentrated on SIRTF, but the European Space Agencies are developing a project called ISO, the Infrared Space Observatory, which will be intermediate in capability between IRAS and SIRTF, and come along earlier than SIRTF, perhaps as early as 1993. The Space Telescope, and other major U.S. astrophysical observatories also will have great potential for studying various aspects of these problems.

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