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SIRTF — The Shuttle Infrared Telescope Facility

Michael W. Werner and Fred C. Witteborn

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SIRTF - THE SHUTTLE INFRARED TELESCOPE FACILITY

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1. INTRODUCTION

Infrared observations from ambient temperature ground-based and stratospheric telescopes are now limited in sensitivity, in many instances, by the fundamental noise due to quantum fluctuations in the emission from the atmosphere and the telescope optics. A major advance in the sensitivity of infrared observations is therefore possible only with a cooled telescope operated in space, where the limiting background will be the very dilute emission of the zodiacal dust cloud. As shown in Figure 1, this is some seven orders of magnitude dimmer than the background seen by an ambient temperature telescope. (It is interesting to note that the decrease in infrared background between ambient ground-based telescopes and cryogenic space telescopes, about seven orders of magnitude, is also the factor by which the night sky is fainter than the day sky. Thus doing infrared astronomy with a warm telescope

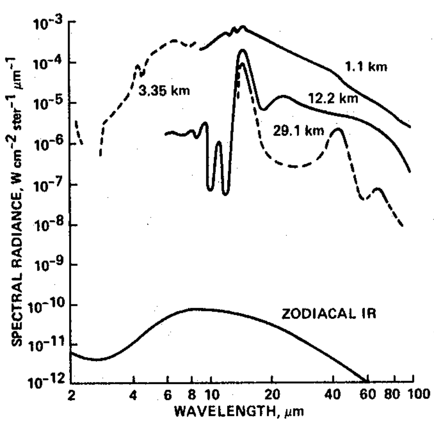

Fig. 1. Infrared Background Radiations at Various Altitudes. Atmospheric radiance is plotted vs. wavelength for various altitudes. The Kuiper Airborne Observatory operates at 12.2 km; balloon-borne telescopes operate up to about 30km. The zodiacal IR curve, representative of the background radiation in earth orbit, corresponds to radiation from the ecliptic plane, 90^{o} from the sun. It is based on data of Briotta (1976). The 6 to 100 micron atmospheric emission curves were derived from data of Moorwood et al. (1972). The 2 to 6 micron atmospheric curve is derived from data of Bell et al. (1960).

may be likened to doing optical observations in broad daylight!) Because the noise scales as the square root of the background photon flux, a cryogenically cooled space telescope of moderate size can be 100-to-1000 times more sensitive for infrared observations than even the largest ground-based telescope.

For the past ten years infrared astronomers, scientists, and engineers at the NASA Ames Research Center, and commercial aerospace and optics firms have studied the scientific requirements and design feasibility of a cryogenically-cooled infrared telescope to be operated from the Space Shuttle as an observatory-class facility for infrared astronomy. The resulting system, the Shuttle Infrared Telescope Facility (SIRTF) can achieve 100-to-1000 times the sensitivity of any existing telescope at wavelengths from 2μm to 200μm by exploiting the low background of the space environment. SIRTF's high sensitivity makes it a powerful tool for the study of known astrophysical problems and gives it great potential for the discovery of new and exciting phenomena in space. SIRTF has won consistently high ratings from scientific peer review groups, and its development as the first major infrared telescope in space was strongly supported by the National Academy of Sciences Astronomy Survey Committee (Field, 1982). In this report, we review the scientific requirements of SIRTF, the current design concept, and the scientific capabilities of the telescope. We also review recent experimental results showing that mirrors made of glassy materials may be suitable for use in large cryogenic telescopes such as SIRTF.

2. SIRTF SCIENCE REQUIREMENTS

The basic requirements placed on the SIRTF system by the scientific objectives it must meet are shown in Table 1. The basic sensitivity requirement - natural background-limited performance from 2 to 100 μm - translates into mirror temperatures of <10K and also an optical and baffling system with very good off-axis rejection. It is required that this sensitivity be achieved even when the line of sight passes as close as 45 degrees to the sun, the earth, or the Shuttle. The pointing stability requirement placed on the system assures that it is stable enough to use the highest angular resolution attainable from its aperture size (1.5" at 5μm). This is of special importance in view of the probable use of imaging infrared arrays on SIRTF. Although diffraction-limited performance is required only to 5μm, the desire to achieve still higher angular resolution, particularly through the minimum in the zodiacal background between 2 and 3μm, means that 2μm diffraction-limited performance is a desirable goal. Finally, it is required that the telescope be refurbishable and reflyable. Between flights, it will be possible to replace or upgrade instruments, or, if necessary, to install an entire new set of instruments which complement each other either scientifically or technically. The telescope can carry up to six instruments, although only two or three may fly on the first mission.

Table 1

SIRTF MAJOR SCIENCE REQUIREMENTS

NATURAL BACKGROUND LIMITED PERFORMANCE 2 - 100 μM
APERTURE DIAMETER > 0.8M
FIELD OF VIEW >, 7 ARCMINUTES
DIFFRACTION LIMITED IMAGE AT 5μM REQUIRED, 2μM GOAL
0.1 ARC-SEC OFFSET POINTING WITH .25 ARC-SEC RMS STABILITY
SPATIAL CHOPPING
VIEW AS CLOSE AS 45^{o} TO SUN AND EARTH
AT LEAST 2 INSTRUMENTS ON FIRST MISSION
DESIGN FOR UP TO SIX INSTRUMENTS
DESIGN FOR NOMINAL 14 DAY MISSION LIFE
REFURBISHABLE AND REFLYABLE

Repeated flights of SIRTF on the Shuttle will guarantee a flexible facility in an era of rapidly changing technology for infrared instrumentation. As illustrated below, a great deal of important scientific work can be accomplished by SIRTF even in a seven day Shuttle sortie mission. A long-life SIRTF with an advanced focal plane, operated from a permanent space station, is an attractive eventual goal. It is expected that the program will evolve in this direction following several years of operation of the Shuttle. The projected date for the first SIRTF mission on the Shuttle is 1989.

3. SIRTF DESIGN

The current design concept for SIRTF is shown in Figure 2, and the system parameters are listed in Table 2. The design is driven by the basic requirement of reaching the naturally occurring zodiacal infrared background emission from 2 to 100μm. This, in turn, places stringent requirements on the cryogenic environment, rejection of off-axis infrared radiation, and image quality. The telescope structure consists of an optical system surrounded by a large cryostat. Super-critical helium gas stored in large separate tanks is used to cool the instrument chamber, optics, baffles, and radiation shields of the telescope. Instruments and components requiring temperatures below 10K will be cooled by a small tank of superfluid helium located in the Multiple

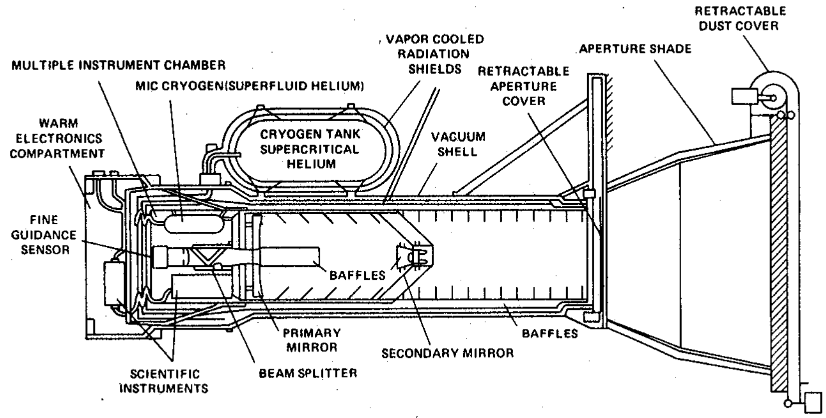

Fig. 2. SIRTF Telescope Concept. The primary mirror diameter is 90cm. The overall length is 7.4 meters.

Table 2

SIRTF Baseline Concept

Wavelength range	2 to 1000 Microns
Type	Ritchey-Chretien
Entrance Aperture	85 CM
Primary F/no	2.3
System F/no	24
Total Field of View	7.5 min
Secondary Magnification	10.4
Linear Obsuration	30-40%
Back Focal Distance	85 CM
Secondary Mirror Diameter	10.7 CM
Average Heat Load	3.6 Watts
Telescope Cryogen	SC He External tank
Instrument Cryogen	SF He Internal Tank

Instrument Chamber (MIC). The telescope will be installed in the Space Shuttle and cooled down several weeks prior to launch. The large, vacuum-tight aperture cover (essentially a gate valve) will be closed prior to vacuum pump-out and cool-down of the telescope interior. The valve will not be opened until about 24 hours after reaching orbit, so that any contaminants carried up by the Shuttle will have had time to disperse before the optics and baffles are exposed. The entrance to the telescope is protected further by an aperture shade which reduces the heat load on the cold telescope baffle by reflecting radiation from the earth and sun back out of the entrance. During launch and before observations commence, the aperture shade itself is protected by a dust cover, because emission from this surface is the largest heat load on the interior. Dust on the interior of the aperture shade would increase its diffuse scattering and emissivity above the desired 1% and 5%, respectively, and thereby decrease the cryogen hold-time of SIRTF. Long-life SIRTF missions (e.g., a 6 to 12 month operation on a space station) could utilize a separate cooler for the aperture shade as well as larger earth and sun avoidance angles.

The present concept incorporates Ritchey-Chretien optics with a 90 cm diameter primary mirror. Infrared and optical photons are reflected to a focus well past the beam splitter in the MIC. The beam splitter allows 50% or more of the visible light to pass through to a focus on a two dimensional CCD array used as a fine guidance sensor, and reflects infrared photons into any one of several instruments in the MIC. These instruments will include photometers, detector-array cameras, polarimeters and spectrometers operating in various bands throughout the 1 to 1000μm spectral range. The instruments will be built by Principal Investigator teams selected competitively. Observing time will be available to Guest Investigators as well as to the P.I. teams and the Facility Scientist.

SIRTF will be mounted on the Shuttle pointing mount (AGS or IPS), which will provide a basic pointing stability of a few arc seconds. Fine pointing to achieve the required 0".25 stability is achieved by an image motion compensation system in which high frequency disturbances sensed by the gyros but not totally corrected by the pointing mount are "fed forward" to the secondary mirror (Lorell, Barrows, and Matsumoto, 1981). This mirror pivots about two orthogonal axes normal to the optical axis to execute the pointing correction. The secondary mirror can, in addition, be oscillated about one of these axes to provide spatial chopping. The fine guidance sensor within the MIC is used to monitor the tracking and update the dygros to compensate for their drift; it also provides an image of the starfield for target identification and verification.

4. THE USE OF GLASSY MATERIALS FOR THE SIRTF PRIMARY

The foregoing discussion leads to the following requirements on the SIRTF primary mirror: (1) It must be capable of achieving a good optical figure (diffraction-limited performance to 5μm wavelength required; 2μm diffraction-limited performance as a goal) at a temperature of 10K. (2) It must not exhibit thermal variations large enough to produce excess noise at the focal plane. (3) It must have a smooth surface to minimize scattering of off-axis infrared radiation.

Early studies of SIRTF mirror materials favored the use of beryllium because of its high thermal conductivity and high strength-to-weight ratio. The IRAS primary, 60 cm in diameter, is the largest beryllium mirror to be used in an astronomical telescope, and the IRAS program results indicate that it may be difficult to achieve diffraction-limited performance at 2μm with a 90 cm beryllium mirror. Since beryllium in its natural form has anisotropic thermal expansion, optical grade beryllium must be finely milled and sintered before it can be used for a mirror. Residual inhomegeneities in the resulting material can distort the mirror figure when it is cooled to operating temperature. Another metal, aluminum, is sometimes used for large, cooled optics, but so far only in situations where precise figure quality is not essential. It therefore appears that no manufacturers can, at this time, promise large metal mirrors with the desired figure quality for SIRTF.

The use of glassy materials, particularly fused silica and quartz, in other space optics applications (such as GIRL, discussed in this volume) led us to consider fused quartz for the SIRTF primary. The density of fused quartz, $2.2 gm/cm^3$, is only a little higher than that of beryllium, but its thermal conductivity of 6×10^{-3} w/cmK near 10K compares poorly with values expected for a pure metal. On the other hand, fused quartz can be figured to much closer tolerances than beryllium. In addition, the high homogeneity of commercially available fused quartz offers the promise of low distortion after cooling to low temperature. Furthermore, glassy materials can be polished to much lower surface roughness than can bare beryllium, thus producing less scattering.

It has been shown elsewhere (Witteborn, Miller, and Werner, 1982) that the thermal properties of such a fused quartz mirror are satisfactory and do not introduce undesirable spatial or temporal gradients in optics temperature in the SIRTF application. Optical testing at low temperature of a sample fused quartz (Heraeus-Amersil T08E) mirror has also been carried out. The tests were performed in a liquid-helium-cooled vacuum test chamber. The 50 cm diameter spherical, f/2 mirror was ground, polished, and figured by the Optical Sciences Center, University of Arizona. Thermal contact to the mirror was provided by 48 copper straps arranged so that each would cool an equal volume of the mirror. The entire inside of the helium-cooled radiation shield surrounding the mirror was painted black to reduce the thermal load on the mirror caused by scattered radiation from the warmer sections of the dewar. Cooling from room temperature to 100K using LN2 required 96 hours. After LHe was added, cooling from 100K to 10.5K took 36 hours. The results of the optical tests (Miller, Witteborn, and Garland, 1982) are summarized in Figure 3, which shows that the

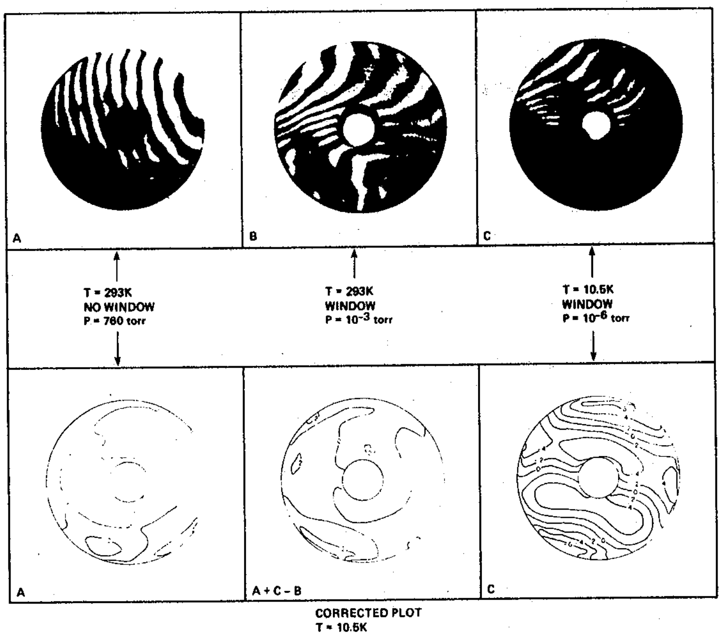

Fig. 3. Top: Interferograms of 50cm Diameter Fused Quartz Mirror using Optical Test Facility.
Bottom: Contour Plots of Mirror Surface Calculated from Interferograms. The contours at intervals of 0.2 (6328A) wave represent deviations from a perfectly spherical shape. Contour plot A + C - B represents the mirror condition at 10.5 K after dewar window distortions are subtracted.

figure changed by only about 1/30 of a 2μm wave in cooling from room temperature to 10.5K. Including the test at 10.5K, the mirror has been temperature cycled six times from room temperature to less than 100K. No degradation of figure quality has been observed during these cycles.

To date the mirror has been tested on a 3-point support which would not be adequate for the Shuttle launch environment. Later tests will utilize a mirror cell capable of holding the mirror in place against Shuttle vibration loads. Tests of at least one other glassy mirror material and other heat sinking techniques are planned. From results already obtained, however, we can conclude that a fused quartz mirror may permit the achievement of the SIRTF goal of diffraction-limited performance at 2μm and will also have acceptable thermal and surface quality characteristics.

5. SIRTF PERFORMANCE

The sensitivity of a telescope such as SIRTF can be compared with that of other infrared telescopes in a number of ways. In Figure 4 we compare the broadband point source sensitivity of SIRTF with that of the Kuiper Airborne Observatory and the NASA IRTF (representing the current state-of-the-art in the infrared) as well as with that predicted for the IRAS all-sky infrared survey satellite and for an infrared instrument on the 2.4m Space Telescope (ST). The assumptions used are detailed in the figure caption.

Figure 4 shows that with detector sensitivities which may reasonably be expected in 1990, SIRTF is two or three orders of magnitude more sensitive for broadband observations than present facilities such as the KAO and IRTF. The advantage extends to wavelengths well below 5µm and longward of 200µm. The potential gain with SIRTF if background-limited performance can be attained is even greater. SIRTF is also much more sensitive than the IRAS all-sky survey. Systematic follow-up of the IRAS survey will therefore be well within the capabilities of SIRTF but will be difficult or impossible with ambient-temperature telescopes. This follow-up can include 1% resolution classification-type spectra of the faintest sources in the all-sky catalog as well as broader band photometry, accurate positional determination, and spatial

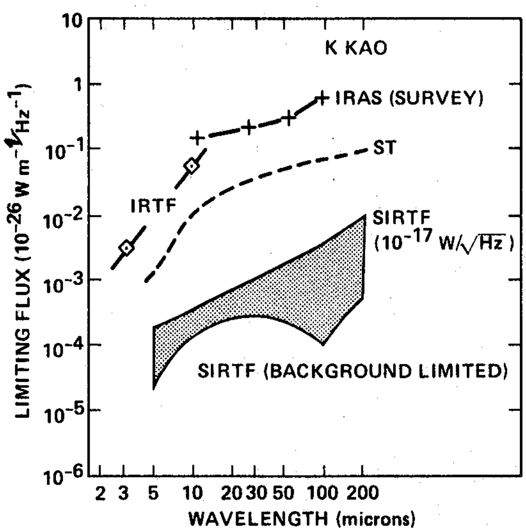

Fig. 4. Limiting fluxes Detectable at Infrared Wavelengths. The limiting fluxes plotted are those which can be measured in broad photometric bands with 10:1 signal-to-noise in integration times of 20 minutes for SIRTF and ST; 1 hour for the KAO and IRTF, and in the all-sky survey mode for IRAS. The IRTF and KAO points are based on current experience with these facilities. The IRTF points refer to measurements with a 6-arcsecond field of view; with smaller fields of view, the IRTF sensitivity approaches predicted for that ST. The expected IRAS numbers are based on current projections of satellite performance, and the ST and SIRTF number are projections assuming diffraction-limited fields of view and 10% instrumental efficiency in each case, 10% emissivity, T=293K, and background-limited performance for ST, and both background-limited and detector-limited performance, with 10^{-17} W/$\sqrt{Hz}$ detector sensitivity, for SIRTF.

mapping. Extensive follow-up from SIRTF will even be possible for sources detected in IRAS' deep-sky survey mode, which will go about ten times fainter than the all-sky survey performance shown in Figure 4. SIRTF is also one to two orders of magnitude more sensitive than even the idealized ST instrument assumed.

Other comparisons than that shown in Figure 4 are of course possible. For example, it is important to bear in mind that SIRTF attains its better point-source sensitivity in a field of view some 10 times larger than that of ST; thus in terms of surface brightness sensitivity rather than point source sensitivity, SIRTF is yet another order of magnitude more sensitive than the large ambient temperature telescopes. This is a natural consequence of the fact that SIRTF is detecting sources against a very low background. SIRTF's extremely high sensitivity to extended emission is of particular scientific importance because many infrared sources are spatially extended. On the other hand, if the comparison is made for observations at high spectral resolution, the warm telescopes begin to compete more favorably with SIRTF, because with narrow bandwidths the reduced background requires improved detector performance if the cryogenic telescope is to maintain its edge.

Although the detector NEP's of 10^{-17} $W/\sqrt{Hz}$ adopted in Figure 4 may seem rather optimistic, the likely advent of monolithic infrared arrays with on-chip integration capability over the next decade (Werner and McCreight, this volume) offers real promise that such performance can be achieved. For example, consider an array with a read noise of 500 electrons/pixel, operated at 10μm in an instrument with an overall efficiency of 10%. In 2 minutes of integration, assuming detector-noise limited operation, such an array would achieve a 1 σ detection of a source with power $8\text{x}10^{-19}$ watt per pixel, and the actual power detected by each pixel would be $8\text{x}10^{-20}$ watt. The NEP of a discrete detector giving similar performance is less than 10^{-18} $W/\sqrt{Hz}$.

6. OBSERVATIONS FROM SIRTF

SIRTF's 100-to-1000 fold increase in sensitivity translates into a 10^4 to 10^6 fold increase in the speed of data acquisition. Therefore observations which are literally impossible at present can be carried out in a few seconds from SIRTF. Consider, for example, infrared observations of quasars, which are important in determining the luminosities of quasars and in delineating the differences between radio-quiet and radio-loud quasars (Figure 5). At the present time, only two quasars have been detected at wavelengths between 20 and 1000μm (Harvey, Wilking, and Joy, 1982; Harper, 1982), and only a handful have been detected between 3 and 20μm (Rieke and Lebofsky, 1979; Soifer and Neugebauer, 1981). Assuming the performance shown in Figure 5, it will be

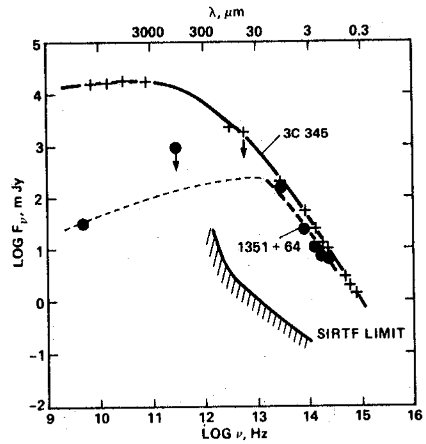

Fig. 5. The optical-to-radio energy distributions of a very bright radio-loud quasar, 3C345, and a very bright radio-quiet quasar, 1351+64; are compared with the limiting flux detectable from SIRTF (10 in 1000 sec) from 3 to 300μm. The fluxes are in units of mJy (1 m Jy = 10^{-29} W $m^{-2}Hz^{-1}$). The SIRTF performance assumes a detector sensitivity of 10^{-17} W/$\sqrt{Hz}$ for $\lambda \leq 100\mu m$ and 10^{-16} W/$\sqrt{Hz}$ at 300μm. The data for 3C345 are adapted from Harvey et al. (1980) and those for 1351 + 64 are from Enins et al. (1982).

possible in <12 hours of observing time from SIRTF to obtain broad band infrared energy distribution of several hundred quasars and 1% resolution spectra in the 10μm region of the 25 brightest. (A 50% duty cycle and energy distribution grossly similar to those shown in Figure 5 are assumed in this estimate.) This and similar examples illustrate how SIRTF, even in a short Shuttle flight, can make major contributions to the solution of outstanding atrophysical problems.

The unprecedented speed of observations from SIRTF puts a great premium on efficient orbital operations which will minimize the time lost to slewing and acquisition. It is anticipated that SIRTF observations, though monitored closely from both the Shuttle and the Payload Operations Control Center, will be carried out largely by following pre-programmed protocols (Werner and Lorell, 1981). These will include features, such as the ability to re-sequence targets in real time, designed to maximize the efficiency of the observing program.

In addition to targeted observations, SIRTF may be extensively used in a deep survey mode in which selected areas of the sky are surveyed down to the lowest attainable flux levels. Such a survey would complement the IRAS survey; the sky coverage of the SIRTF survey would be very limited compared to that of the IRAS all-sky survey, but it would look to 30 times the distance for objects of fixed luminosity.

It is useful to consider a specific example in more detail. One possible objective of such a deep survey would be "brown dwarfs", stars with masses less than 0.08 $M_{\odot}$. Theoretical considerations indicate that stars of this mass or less will not generate enough internal heat and pressure to initiate the nuclear burning of hydrogen. Such objects would, however, radiate the energy liberated in their gravitational collapse and would appear as faint, cool objects detectable only at infrared wavelengths. The existence and properties of brown dwarfs are of interest in connection with both the well-known missing mass problem and the definition of the faint end of the main sequence and the low mass limit of star formation (Bahcall and Soneira, 1981). These objects could be 10 or more times more numerous than ordinary stars in the solar neighborhood and still remain undetected by existing infrared techniques. SIRTF, with its high infrared sensitivity, offers a major improvement in our ability to detect brown dwarfs with temperatures in the range 250 to 1500K.

Figure 6 shows the maximum distance to which SIRTF could detect brown dwarfs as a function of the temperature of the brown dwarf - the relation between temperature and luminosity required to generate these curves was taken from the theoretical models of Stevenson (1978). Also shown are the distances to which the IRAS survey and an ambient temperature 3m ground or space telescope operating in the infrared could detect the same stars. The data shown in the figure can be used to design an observing program for SIRTF which would either detect an astrophysically interesting number of brown dwarfs or set useful limits on their properties.

Consider a halo around our Galaxy with a local density at the earth of 0.02 $M_{\odot}$ pc^{-3} (Bahcall and Soneira, 1981), and assume that the mass of each halo star is 0.05 $M_{\odot}$, the temperature 1000K, and the radius 0.1 $R_{\odot}$. With 10^{-17} $W/\sqrt{Hz}$ detectors, SIRTF can detect such stars as far away as 100 pc with 5:1 signal/noise. A deep survey at two wavelengths would be required to find these objects by their very red color. Assuming a 128x128 element near infrared array with 3" pixels, there would be 0.4 brown dwarfs in each survey exposure with little source confusion. A survey of 30 fields, taking 1 day from SIRTF, would be adequate to detect one dozen brown dwarfs of the specified type in each of two colors. The brown dwarfs would of course be only one of several objectives in such a deep survey. A considerably more extensive survey would be very feasible during a long-duration space platform mission.

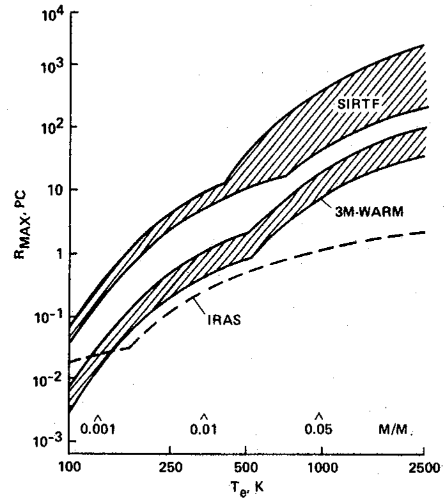

Fig. 6. The maximum distance, R_{max}, to which SIRTF could detect brown dwarfs (with S/N 10:1 in 1000 sec) of a given temperature, T_e, is compared with the performance of a 3-meter ground or space telescope at 273K and with that of IRAS all sky survey. The upper envelope of the SIRTF area corresponds to background-limited performance, while the lower assumes 10^{-17} W/$\sqrt{Hz}$ detector sensitivity. The "3m warm" band reflects an analagous range in assumptions regarding instrument capability for an uncooled, 3 meter telescope. For simplicity, only detection at 100μm, 10μm, and 3μm is considered; this accounts for the breaks in the curves. For temperatures T $\gtrsim$ 1500K, detection at $\lambda \lesssim 1\mu$m by the large ambient telescopes should also be considered. The numbers above the x-axis give the brown dwarf mass, in solar masses, corresponding to the given temperature, assuming a cooling time of 5 x 10^9 yr from the results of Stevenson (1978). We thank Dr. R. Probst for assistance with the preparation of this figure.

7. CONCLUSIONS

In addition to a general description of SIRTF design goals, we have discussed here just a few examples of the many astronomical problems that could be addressed by SIRTF with its 100 to 1000-fold sensitivity advantage over existing telescopes. It is important to realize that SIRTF will provide the same gain in infrared capability that other advanced facilities, such as the Space Telescope, Gamma Ray Observatory, AXAF, and the Very Large Array, are providing in other spectral bands. SIRTF complements these facilities and provides the essential capability for the study of astrophysical phenomena with high sensitivity across the entire electromagnetic spectrum. Finally, it is very clear from many recent examples of the effects of leaps in observing capability upon astrophysical exploration, that the most exciting discoveries which will result from SIRTF are those which cannot be anticipated.

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16. Abstract

The Shuttle Infrared Telescope (SIRTF) is a 1-m class cryogenically cooled telescope to be operated from the shuttle as a facility for infrared astronomy. By exploiting the very low infrared background of space, SIRTF will achieve 100 to 1000 times the sensitivity currently attainable at infrared wavelengths between 2 and 200 μm. This report reviews the scientific requirements of SIRTF, the current design concept, and the scientific capabilities of the system. We also review recent experimental results showing that mirrors made of glassy materials may be suitable for use in large cryogenic telescopes such as SIRTF.

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