Surveys with SIRTF and IRAC

Giovanni G. Fazio, Joseph L. Hora, and John R. Stauffer

Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138-1516

Peter Eisenhardt

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109

Abstract. SIRTF will be the first mission to combine the high sensitivity achievable from a cryogenic space telescope with the imaging and spectroscopic power of the new generation of infrared detector arrays. Within its lifetime, SIRTF will have the capability to conduct an extensive number of survey programs and be able to perform follow-up observations of the sources discovered. We discuss in detail one of SIRTF's focal plane instruments, the Infrared Array Camera (IRAC), and its capabilities to carry out such surveys. Two of the most important scientific objectives of IRAC will be to carry out surveys to study galaxy formation and evolution in the early Universe, and to search for brown dwarfs and superplanets.

1. Introduction

SIRTF, the fourth of NASA's Great Observatories, will be a cryogenically-cooled telescope for infrared astronomy from space that is planned for launch in December, 2001 (Fanson et al. 1998). It features an 85-cm aperture telescope at 5.5 K, and three focal-plane instruments that provide background limited imaging and spectroscopy covering the spectral range from 3 to 180 μm. SIRTF will be in a solar orbit, trailing the Earth, and will have a lifetime of 2.5 years, with a goal of 5 years. This will give SIRTF the capability to conduct extensive surveys and to perform follow-up observations of the sources discovered. Here we describe SIRTF's Infrared Array Camera instrument (IRAC) and its capabilities to carry out such surveys.

2. Infrared Array Camera (IRAC)

IRAC is a four-channel camera that provides simultaneous 5.12×5.12 arcmin broadband images at 3.6, 4.5, 5.8, and 8 μm (Fazio et al. 1998). The pixel size is 1.2 arcsec in all bands. Two adjacent fields of view in the SIRTF focal plane are viewed by the four channels in pairs (3.6 and 5.8 μm; 4.5 and 8.0 μm) through the use of dichroic beamsplitters (Figure 1). All four detector arrays in the camera are 256×256 pixels in size, with the two short wavelength channels using InSb

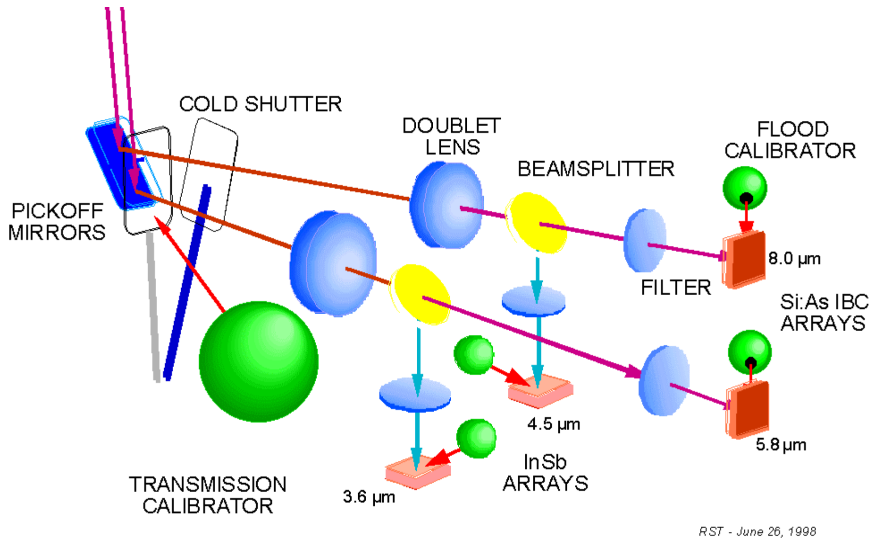

Figure 1. IRAC Conceptual Layout

and the two longer wavelength channels using Si:As IBC detectors. Table 1 defines the IRAC bands and gives the top-level sensitivity requirements. The array detector characteristics and performance requirements are summarized in Table 2. The performance numbers listed are the ones necessary to reach the sensitivity requirements that are listed in Table 1, given the total SIRTF and IRAC combined system throughput and performance of the telescope and IRAC optics.

Table 1. IRAC Top-Level Sensitivity Requirements

Channel No.	Center Wavelength (μm)	Total Bandwidth (%)	Broadband Sensitivity (μJy) (5σ, 200s)
1	3.6	20	6
2	4.5	23	7
3	5.8	25	36
4	8.0	38	54

The only moving part in IRAC is a shutter located near the entrance aperture of the camera. The rear of the shutter blade contains a reflective surface which, when the shutter is closed, allows light from a transmission calibration source in IRAC to enter the instrument optics. With the transmission calibrator off, the closed shutter also serves as a dark slide, blocking all radiation from entering the camera. Each array also has associated with it a flood calibrator which is used to test the array operability.

Development, construction and flight of IRAC is a joint project of the Smithsonian Astrophysical Observatory, NASA/Goddard Space Flight Center,

Table 2. Summary of IRAC Detector Array Characteristics and Requirements

Parameter	InSb Detector Arrays	Si:As Detector Arrays
Format	256×256	256×256
Pixel Size	30 μm	30 μm
Well Size (minimum)	10^5 e$^-$	10^5 e$^-$
Quantum Efficiency (mean)	>80% @ 3.6 and 4.5 μm	>23% @ 6.3 μm
Read Noise (mean)	<10 e$^-$	<20 e$^-$
Dark Current (maximum)	≤1 e$^-$/s	≤10 e$^-$/s
Operability (minimum)	99.5%	99.5%
Electrical pixel-pixel crosstalk (maximum)	5%	5%
Operating power (maximum)	1 mW	1 mW
Operating temperature	15 K	6 K
Radiometric stability (1σ rms) in 12 hr	1.0%	1.0%
Radiation Susceptibility to 70 MeV protons,	Operability:	Operability:
- Single 100 Rad exposure, pre-anneal	>90%	>90%
- 100 Rad total exposure and post-anneal	>99%	>99%
- After 800 Rad total exposure, post-anneal	>95%	>95%

NASA/Ames Research Center, the University of Rochester, and the University of Arizona. The infrared arrays will be constructed by the Raytheon/Santa Barbara Research Center and will be tested and evaluated by the University of Rochester, NASA/Ames Research Center and the NASA/Goddard Space Flight Center. Further information about IRAC and SIRTF can be obtained from the papers in the SPIE Conference on Infrared Astronomical Instrumentation, Vol. 3354, and from the IRAC Home Page at the following URL:

`http://cfa-www.harvard.edu/cfa/oir/Research/irac/firstpage.html`

3. IRAC Survey Capabilities

IRAC on SIRTF offers numerous and very powerful survey capabilities. Among these capabilities are:

1. **Simplicity of Operation and Calibration**
IRAC is a very simple camera, with only four fixed wavelength bands, no filter wheels and no changes in magnification. The only moving part is the entrance shutter. IRAC contains its own blackbody sources for calibration, linearity measurements, and flat-fielding, and has stimulators on each array to test their functionality.

2. **High Sensitivity and High Speed**
As shown in Table 1, IRAC is extremely sensitive, limited only by noise due to the diffuse infrared background radiation from the zodiacal dust and by confusion due to the random distribution of unresolved faint galaxies. IRAC's high increase in sensitivity over past and current infrared capa-

bilities allows surveys to extremely low flux levels to be carried out in relatively short periods of time.

3. **Large Field-of-View**
   IRAC's 256×256 pixel detector arrays provide a relatively large 5.1×5.1 arcmin FOV while the 1.2 arcsec pixels maintain spatial sampling similar to ground-based optical surveys. Large areas on the sky can be surveyed quickly with these arrays.

4. **Accurate Positional Registration**
   Since the geometry of the array pixels are fixed in space relative to one another, the relative position of sources in all four bands can be registered to high precision, enabling absolute positions to be measured accurately with respect to objects with known positions.

5. **Accessibility of a Large Area of the Sky**
   SIRTF's solar orbit and boresight orientation between 80° and 120° from the observatory-Sun line allows a large area of the sky (35%) to be viewed at any given time, a region around the ecliptic pole to be viewed continually, and a given region for at least 40 days consecutively. From an operational point of view, these capabilities are ideal for surveying.

6. **Long Lifetime**
   SIRTF's lifetime goal of 5 years will allow very significant amounts of time to be devoted to surveys early in the mission, yet allow both photometric and spectroscopic follow-up observations.

7. **Efficient Observing Mode**
   The single IRAC observing mode is simple: "step-and-integrate" (see §5 below). IRAC's dichroic beamsplitters allow imaging surveys to be carried out in two bands simultaneously, and the location of the two fields-of-view in the SIRTF focal plane, aligned in the survey direction, allow for rapid observation of a given area on the sky in all four bands.

4. IRAC Operational Modes

IRAC has three operational modes: Off, Observe/Calibrate, and Diagnostic.

1. **Off Mode**
   In this mode no power is dissipated in the cold assembly and all the electronics are off. Only one instrument can be on at any time on SIRTF; therefore, IRAC will be off when the other instruments are in use.

2. **Observe/Calibrate Mode**
   This mode is used for normal data taking. All four channels will operate in parallel and simultaneously image the two field-of-views in the four IRAC bands. The four arrays are read out using multiple (Fowler) sampling to reduce the effective read noise. In addition to the full frame mode (256×256 pixels), there is a subarray mode in which a 32×32 pixel region is read out at a faster rate (minimum readout time of 10 ms). This mode

is primarily for observing bright sources that would otherwise saturate the array even at the shortest full-array readout times, or for observing time critical events where a finer time resolution is required.

During calibrations the shutter can be closed to obtain darks, and the calibration sources operated to confirm responsivity, linearity, and IRAC's flat field.

3. **Diagnostic Mode**
   Several test functions are available in the Diagnostic mode, including the ability to transmit test patterns to evaluate the digital signal processors and transfer electronics. An annealing function is available to temporarily raise the temperature of the detectors if necessary to reduce dark current after large solar flares.

5. Observing with IRAC

IRAC has one basic observing function: "step and integrate". This means that the telescope will move and settle at a new position, and then the camera will take one or more images in all four channels. Several of these operations can be combined to map out regions larger than the IRAC field-of-view. This observing function can be done in either the full- or subarray-mode, and there will be a number of selectable parameters such as integration times and number of images at each position. The baseline full array frame times for normal observing, including 0.2 sec per array readout, are: 12, 30, 100 and 200 sec. To increase dynamic range using the full array, frame times of 0.4, 1.6, or 12 sec can be taken in conjunction with a longer normal observing frame.

The maximum signal without saturation in the full array mode (0.4 sec) is 1 Jy (3.6 and 4.5 μm); 4 Jy (5.8 μm) and 3 Jy (8.0 μm). The maximum signal in the subarray mode is 20 times the above values.

The observer will specify the observation by filling out an Astronomical Observation Template (AOT) form with the desired parameter values. The observer will have the capability on the AOT form to choose mapping parameters such as map field size, mapping step size, dither pattern, orientation, etc. and the form will provide a flexible means of specifying a observation. The scheduling of the observation will depend on the visibility of the field, given the pointing constraints of SIRTF. The visibility of a field is a function of its ecliptic latitude, with the highest visibility being within 10° of the ecliptic poles (the continuously viewable zone). However, all parts of the sky will be visible at least twice a year for 40 days at a time.

6. Surveys with IRAC

The IRAC instrument will address the four major scientific objectives that define the SIRTF mission. These objectives are (a) to study the birth and evolution of galaxies in the early universe, (b) to search for and study brown dwarfs and superplanets, (c) to study ultraluminous galaxies and active galactic nuclei, and (d) to discover and study protoplanetary and planetary debris disks.

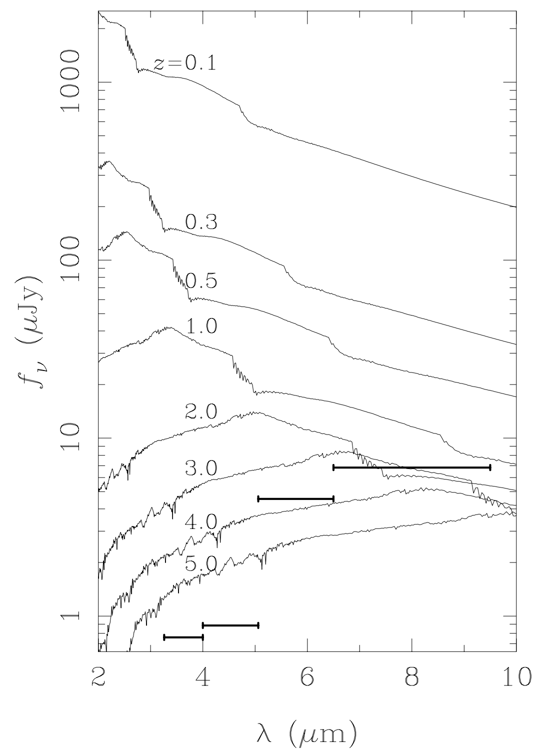

Figure 2. Model maximally-old $L*$ galaxy spectra as a function of redshift (z). The flux is normalized to an absolute K mag of -25.1 today. Also shown are the sensitivities (1 sigma in 500 sec) and filter bandpasses for the four IRAC channels (Fazio et al. 1998).

In this paper we will consider two of these objectives for which IRAC is particularly capable: deep, small area surveys to study galaxy formation and evolution during the early stages of the Universe, and larger area surveys to search for brown dwarfs and superplanets.

6.1. Early Universe

To carry out the studies of the early Universe, IRAC can be used to perform deep surveys in all four bands to detect normal $L*$ galaxies to redshifts $z > 3$. Although ultraviolet-bright $z = 3$ galaxies have now been detected via the "UV-dropout" technique, IRAC observations will sample, for the first time, the rest-frame near-infrared spectral region of normal galaxies at high redshift (Figure 2). Of particular importance is the 1.6 μm feature due to H^- absorption in late type stars and the 2.3 μm absorption edge due to CO (Figure 2), which can be used to determine photometric redshifts. Sufficient numbers of these galaxies will be detected to construct the luminosity function at different redshifts, permitting discrimination between density evolution, luminosity evolution, or a combination

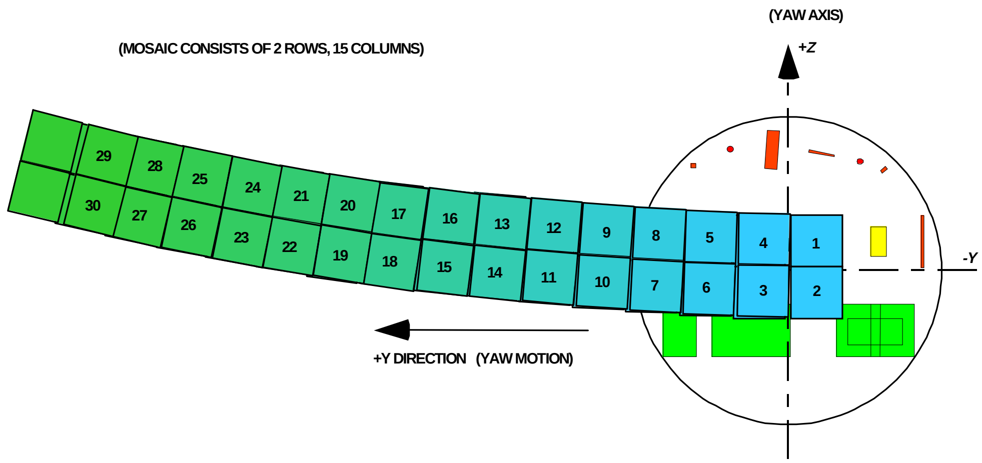

Figure 3. Map pattern for the early Universe survey.

of the two. These rest-frame near-IR selected normal galaxies must be observed to at least z = 3 to measure the star formation rate as a function of redshift as compared to that derived from observations of UV-dropout galaxies. The UV-dropout galaxy observations may have missed high-z dust-enshrouded galaxies that will be readily observable in the infrared.

A possible IRAC investigation would determine the number counts of normal galaxies as a function of redshift by using four-band imaging and photometric redshift determination. IRAC would be used to survey an area of about 0.2 square degrees at high galactic latitude (e.g., in the Lockman Hole) to achieve 10 sigma detections of $L*$ galaxies at z = 3 (a 1 sigma noise of approximately 0.6 μJy, at all wavelengths). This would require an estimated 14 hours per position. Thirty positions are required to map a 0.2 sq deg field, resulting in a total time of 420 hours or 18 days. A possible mapping pattern is illustrated in Figure 3, showing the SIRTF focal plane and the sequence of fields observed. Approximately 700 galaxies will be detected in each 5×5 arcmin field-of-view. These numbers will vary depending on the actual counts of galaxies at these faint IR flux levels, which are presently unknown.

Using photometric redshift estimates for each galaxy obtained from the IRAC colors (Figure 4), it will be possible to determine the luminosity function for each redshift bin to $L < L*$, and therefore measure luminosity/density evolution as a function of redshift. In conjunction with ground-based optical/near IR observations, this will enable measurement of the star formation rate as a function of redshift.

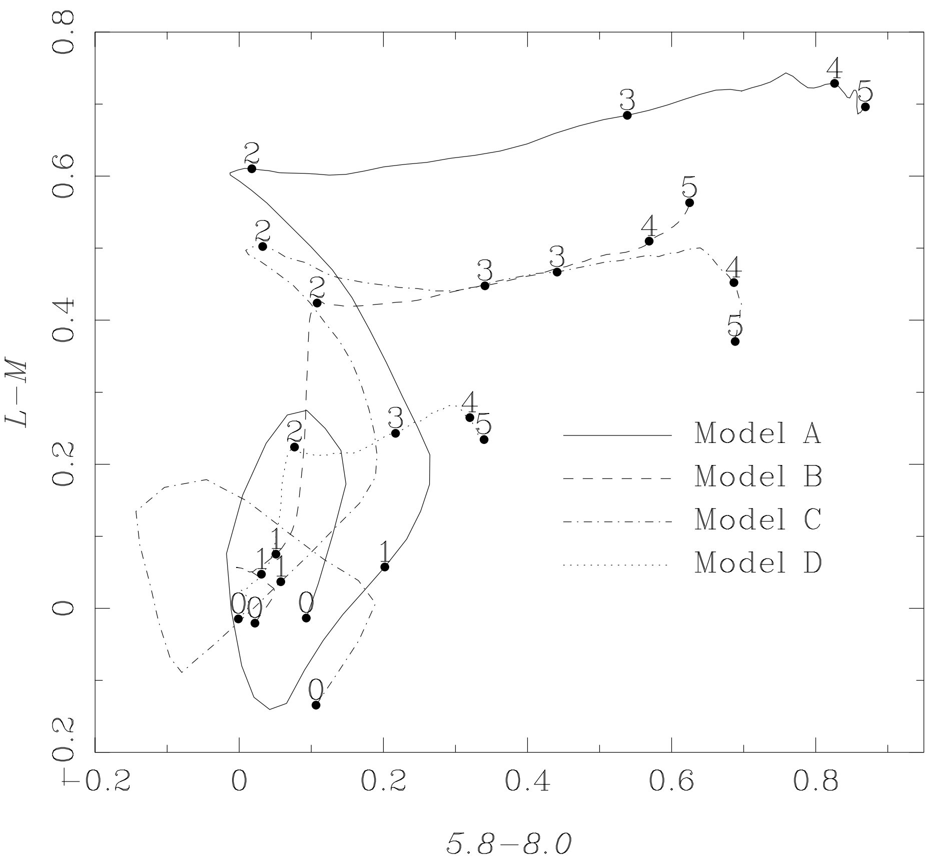

Figure 4. Color-Color diagram for determining photometric redshifts. The four models correspond to (A) a maximally old galaxy, solar metallicity, instantaneous starburst at z = ∞; (B) same as (A) with 1/50 solar metallicity; (C) a young galaxy with solar metallicity, and constant star formation rate over 100 Myr prior to redshift considered (i.e. a young non-evolving spectrum); (D) same a (C) with 1/50 solar metallicity (Simpson and Eisenhardt 1998).

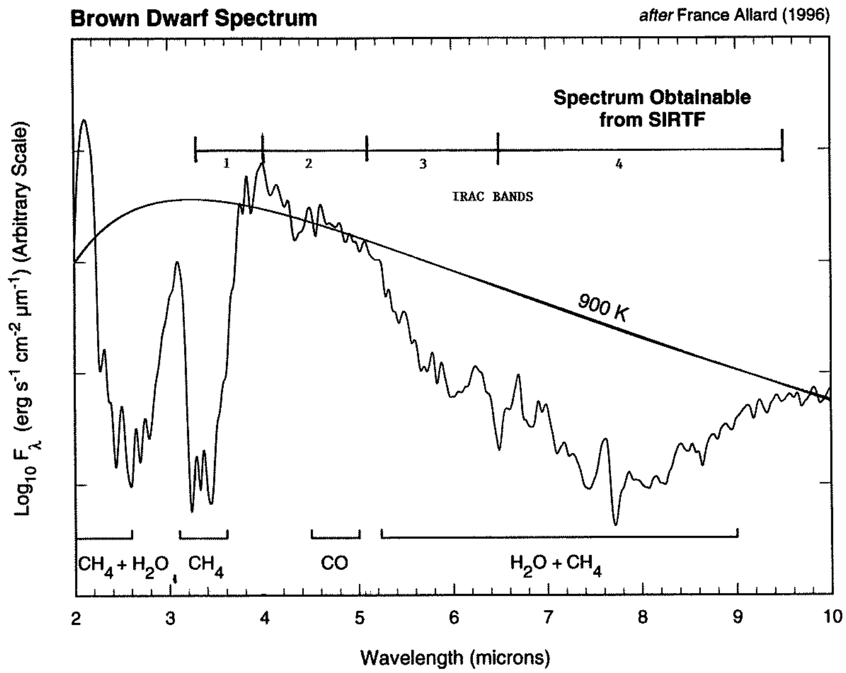

Figure 5. The IRAC bands are shown in relation to a model brown dwarf spectrum and a 900K blackbody.

6.2. Brown Dwarfs and Superplanets

During the past two years, ground-based surveys have begun to succeed in identifying large numbers of relatively young, nearby brown dwarfs in star-forming regions, young open clusters and the field. IRAC will be able to extend those efforts to older and lower mass brown dwarfs and superplanets. In nearby star-forming regions like Taurus, IRAC should be able to detect isolated objects down to near the mass of Jupiter. In the nearest and best-studied open clusters – in particular, the Pleiades and the Hyades – IRAC should be able to detect brown dwarfs down to 0.01 solar masses. As Figure 5 illustrates, the ratio of the IRAC bands at 3.6 and 4.5 μm is a very good means of selecting brown dwarfs.

The method of observation would be to carry out a large area survey of several open star clusters (e.g. NGC 2264, Pleiades, Hyades). The survey area is approximately 5 sq deg for NGC 2264 and the Pleiades, and approximately 10 sq deg for the Hyades. The integration time would be 30 sec per position, observing each position three times (90 sec total), which would achieve a sensitivity of 10 μJy, 5 sigma at 4.5 μm. The total observing time for all three fields would be about 160 hrs. The brown dwarf candidates would be selected by 3.6/4.5 μm color, based on model predictions and known objects from the 2MASS and DENIS surveys. The lowest mass objects will be detected only at 4.5 μm in 90 sec. The 4.5 μm only objects would need to be re-observed with much longer integrations to provide a detection at 3.6 μm. Figure 6 shows the

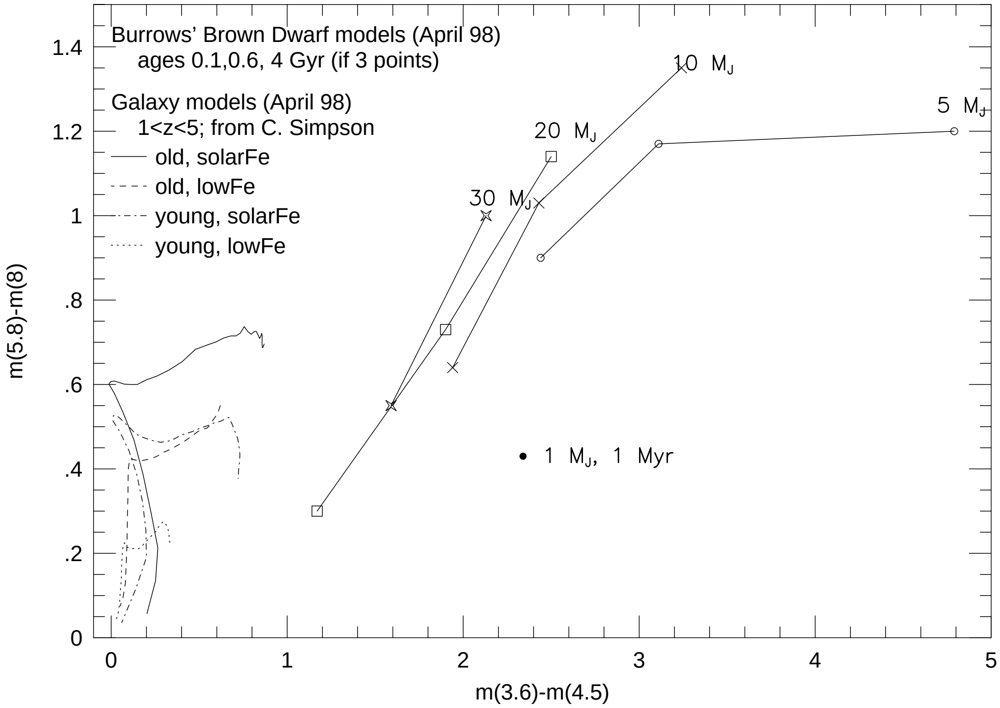

Figure 6. IRAC color/color diagram showing galaxies (lower left corner) and brown dwarfs of different masses and ages (upper right).

IRAC color/color diagram for objects with masses of 5, 10, 20, and 30 times the mass of Jupiter at various ages. The IRAC color/color diagram for galaxies in the field is shown in the same diagram. The galaxies are well-separated from the brown dwarfs, appearing in the lower left corner of the color/color plot.

7. Conclusions

Surveys by IRAC and the other SIRTF instruments, MIPS and IRS, are an integral and important part of the SIRTF observing program. The combination of high sensitivity, large area arrays, long lifetime, access to a large area of the sky at one time, stable observing conditions, and simple and efficient observing modes will allow SIRTF to rapidly survey the infrared sky to new depths.

Perhaps the most important results of these surveys will be discoveries that we never would have anticipated.

References

Simpson, C. and Eisenhardt, P. 1998, PASP, submitted

Fanson et al. 1998, in *Space Telescopes and Instruments V*, Proc. SPIE 3356, 478

Fazio et al. 1998, in *Infrared Astronomical Instrumentation*, Proc. SPIE 3354, 1024