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Future Observations with SIRTF and Other Mid-Infrared/Sub-mm Missions

Peter Eisenhardt

Jet Propulsion Laboratory, California Institute of Technology, MS 169-327, 4800 Oak Grove Drive, Pasadena, CA 91109

Abstract.

Infrared observations are crucial for studies of high redshift galaxies. I summarize the capabilities of three future infrared space observatories, and give a few examples of applications to the study of galaxy formation and evolution. SIRTF, with its 85 cm, 5.5 K telescope, will be launched in December 2001, providing natural background limited imaging from $3 - 180\mu$m and spectroscopy from $5 - 40\mu$m over its expected 5 year lifetime. The Next Generation Sky Survey was a proposed (but not selected) Medium Explorer surveying the entire sky at 3.5, 4.7, 12 and 23μm with a thousand to a million times better sensitivity than previous all-sky infrared surveys. The larger (3.5 m) but warmer (70 K) Far Infrared and Sub-mm Telescope is planned for launch in 2007, providing imaging and spectroscopy from $80 - 670\mu$m over its 3 year lifetime.

1. Introduction

Hy Spinrad's career intersects with my own life in several important ways: my parents met in International House, the site of this conference, in the year Hy came to Berkeley as a freshman. In fact the only time in Hy's astronomical career away from Berkeley was a 2 year stint at JPL, when he was one of the first three people hired into the JPL astrophysics group - the group in which I plan observations of high redshift galaxies with the Space Infrared Telescope Facility (SIRTF) today. I began working on SIRTF with Hy's sponsorship at Berkeley a dozen years ago.

I performed some archival research on Hy's years at JPL and came across the image shown in Figure 1. The data were obtained in 1963, making the lookback time over half Hy's curent age. It is evident that Hy is among the more luminous members of the astronomical community, since he's evolved relatively little since then. All the major features seem to be in place, although the bar structures are more pronounced.

2. Infrared Observations and Galaxy Formation

There are several fundamental reasons why infrared observations are crucial for studies of galaxy formation and evolution. These include the cosmological redshift, the ubiquity of the H^- ion as a dominant opacity source in stellar

Figure 1. Hyron Spinrad at JPL in 1963

populations, and the importance of dust in modulating the spectral energy distribution of star forming regions. Such considerations have motivated a wide variety of planned and proposed space infrared missions, including the three I discuss here: SIRTF, NGSS, and FIRST.

It is almost a tautology to state that infrared data are necessary to understand evolutionary effects in high redshift galaxies. Comparisons of galaxies at different lookback time must be made at constant rest frame wavelengths to be meaningful. For starlight the most relevant wavelengths are from the Lyman break at $912Å$ to the CO absorption bands at 2.3μm.

The Lyman break technique has now been extended to the point ($z \gtrsim 7$) that galaxies at the high redshift frontier are undetectable without infrared observations (Lanzetta et al. 1998, Dickinson et al. 1999). The Lyman break technique samples rest frame UV light emitted by the hottest stars and hence is an excellent guide to unobscured star-forming populations. Extending this technique to even higher redshifts is likely to require NGST.

But the spectra of the garden variety stars and galaxies we know most about peak in the near infrared, because of the H^- opacity minimum at 1.6μm (John 1988). Identifying large samples of high redshift galaxies in the rest frame near IR has been one of the defining scientific programs for SIRTF (see Figure 2).

Finally, star formation, at least locally, is strongly associated with dust and hence with high levels of UV extinction. Meurer, Heckman, & Calzetti (1999) and Steidel et al. (1999) have used the correlation of UV spectral index with far IR emission to estimate that extinction corrections to estimates of the global star formation rate are a factor of 5. Recent far-infrared detections

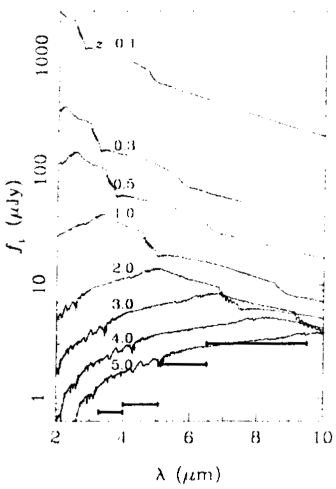

Figure 2. Model spectra as a function of redshift for a maximally old L^* galaxy in which all stars formed in an instantaneous burst at $z = \infty$, and evolve passively thereafter, in an $H_o = 50, q_o = 0.1$ cosmology. The flux is normalized to $M_K = -25.1$ today (Gardner et al. 1997). Also shown are the IRAC sensitivities (1σ in 500 seconds).

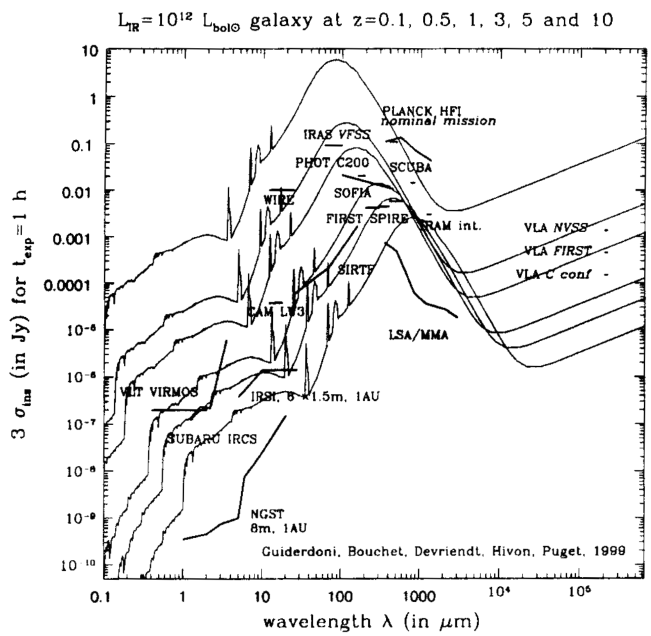

Figure 3. Model spectra of an IR luminous galaxy at various redshifts, from Guiderdoni et al. (1999). Also plotted are the sensitivities of various existing and proposed instruments.

of the cosmic background (Hauser 1998), and far-infrared and submillimeter detections of field galaxies with *ISO* and SCUBA (Kawara at al. 1998, Puget et al. 1999, Barger et al. 1998, Hughes et al. 1998) also hint at a heavily dust enshrouded starburst population in the early universe. Whether these sources are in fact starbursts or are powered by AGN, what their luminosities are, and what their redshift distribution is, are very much open questions. The identification and characterization of distant ultra-luminous infrared galaxies (ULIRG's - see Figure 3) requires space infrared missions which directly sample the bulk of their bolometric luminosity.

3. SIRTF

Studies of galaxy formation and evolution have been one of the chief motivations for SIRTF since its inception. After many years of conceptual design studies, SIRTF has entered its final construction phase (Fanson et al. 1998). SIRTF will consist of a 0.85-meter cryogenically-cooled telescope and three science instruments capable of performing imaging and spectroscopy in the $3 - 180\mu m$ wavelength band. With launch planned for December 2001, SIRTF will complete NASA's family of Great Observatories. Large format infrared detector arrays, coupled with innovative choices in orbit and system architecture will give SIRTF a large increase in sensitivity across its wavelength range, compared to previous missions such as IRAS and ISO. Over 75% of the observing time during its 2.5 year-minimum (5 year goal) lifetime will be awarded to general investigators. A call for Legacy Proposals (large projects of both immediate scientific interest and lasting archival value, and with no proprietary data period) is planned for July of 2000. For the most up-to-date information on SIRTF, see http://sirtf.caltech.edu.

Several innovative design features have enabled SIRTF to retain the majority of the originally envisioned science capability at a fraction of the original cost and mass. SIRTF's 85-cm aperture Cassegrain telescope is cooled by helium vapor to 5.5 K. The telescope primary and secondary mirrors are constructed of beryllium, and the f-ratio of the system is f/12. The telescope is a Ritchey-Chretien design, diffraction limited at a wavelength of $6.5\mu m$. Three science instruments share the 32 arcminute diameter focal plane, and are located in a chamber cooled to 1.4 K by superfluid helium. A major technical development of the SIRTF mission has been the implementation of a "warm-launch architecture," in which SIRTF's telescope assembly is launched at ambient temperature and allowed to cool radiatively (passively) to ≈ 30K, and only then thermally connected to the helium tank. Only the focal-plane instruments and the compact liquid helium cryostat are enclosed in a vacuum shell. This has led to a dramatic reduction in the volume of liquid cryogen required (360 liters) for the 5-year mission.

A Delta 7920-H rocket will be used to launch SIRTF directly into an Earth-trailing heliocentric orbit, which drifts away from the Earth at approximately 0.1 AU per year. No orbit corrections or adjustments are envisaged. This orbit removes the thermal load and viewing constraints imposed by the Earth, providing much simpler operations than are possible in an Earth orbit. SIRTF's window of visibility on the celestial sky will form an annulus, perpendicular to sensitivities expected for NGSS were 55, 60, 320, and 1120μJy respectively at these four wavelengths, and the image quality was specified as 5″ FWHM (10″ at 23μm). *NGSS* would have $> 2\times$ better sensitivity over the 2500 square degrees nearest the ecliptic poles due to the lower zodiacal background and increased number of passes. NGSS planned to scan the sky in a polar, sun-synchronous orbit with a 50 cm telescope, using the MIPS scan mirror to freeze a 34′ field onto four 1024^2 arrays cooled with a solid hydrogen cryostat similar to WIRE. Although it was not selected in the current round of Medium Explorers for launch in 2003/2004, NGSS may be reproposed in the future. For further information see http://www.astro.ucla.edu/~wright/NGSS.

5. *FIRST*

The Far Infrared and Sub-mm Telescope (FIRST) is cornerstone number 4 of the European Space Agency's 'Horizon 2000' science plan. FIRST will perform photometry and spectroscopy in the $80 - 670\mu$m range. Using an architecture reminiscent of SIRTF, NASA will supply the 3.5 m diameter Cassegrain telescope which is passively cooled to < 70 K, while the three science instruments are housed in a superfluid helium cryostat. Launch of FIRST on an Ariane 5 into an orbit around the L2 point (1.5 million km from the Earth in the anti-solar direction) is planned for 2007. FIRST will be a general purpose observatory, with a minimum operational lifetime of 3 years.

The FIRST instruments are the Heterodyne Instrument for FIRST (HIFI - Th. de Grauuw, SRON, PI); the Photoconductor Array Camera and Spectrometer (PACS - A. Poglitsch, MPE, PI); and the Spectral and Photometric Imaging REceiver (SPIRE - M. Griffin, QMW, PI). HIFI offers R $= 10^3 - 10^6$ heterodyne spectroscopy over the $110 - 625\mu$m range, using Superconductor-Insulator-Superconductor (SIS) and Hot Electron Bolometer (HEB) mixers. The line sensitivity is $\sim 10^{-17}$ W/m^2 (5σ in 1 hour). PACS uses two 25×16 Ge:Ga arrays simultaneously covering $80 - 130\mu$m and $130 - 210\mu$m with full sampling at 90 and 180μm respectively, providing $\sim$ 5mJy point source detections. As a spectrometer PACS covers $\sim$ 1500 km/sec at R $\sim$ 150, with a line sensitivity of $\sim 2 \times 10^{-18}$ W/m^2. SPIRE will use bolometer arrays cooled to 0.3K to image a $4' \times 4'$ field simultaneously at 250, 350, and 500μm to $\sim$ 3mJy. The arrays contain 32^2, 24^2, and 16^2 pixels respectively, and are refrigerated by a closed-cycle ^{3}He sorption cooler. SPIRE also includes a Fourier Transform Spectrometer operating over a $2' \times 2'$ field with adjustable resolution from $0.04 - 2$ cm^{-1}, corresponding to R $= 20 - 1000$ at 250μm. Figure 4 summarizes the performance of the *FIRST* instruments. Additional information about *FIRST* can be found at http://astro.estec.esa.nl/First.

6. Future Space Missions and Galaxy Formation and Evolution

Relative to ISO, SIRTF's detector arrays provide typically $1 - 2$ orders of magnitude better sensitivity, coupled with $1 - 2$ orders of magnitude more pixels. The gains of NGSS and FIRST are even more substantial. These gains are sufficient to bring vast numbers of distant galaxies at large lookback times within the grasp of the new geenration of space infrared missions.

the ecliptic plane, with allowed solar elongations ranging from 80 to 120 degrees. All regions of the sky will be visible to SIRTF twice a year, for a minimum of ≈ 40 days each period (at the ecliptic equator). The visibility periods increase to $\gtrsim 200$ days per year at an ecliptic latitude of 60°, and constant viewing is possible within 10°of the ecliptic poles. About a third of the sky will be instantaneously visible to SIRTF at any given time.

3.1. SIRTF Instruments

The SIRTF instruments are the Infrared Array Camera (IRAC - G. Fazio, SAO, PI, Fazio et al. 1998); the Infrared Spectrograph (IRS - J. Houck, Cornell, PI, Roellig et al. 1998); and the Multiband Imaging Photometer for SIRTF (MIPS - G. Rieke, U. Arizona, PI, Heim et al. 1998).

IRAC provides imaging at 3.6, 4.5, 5.8, and $8\mu m$, with predicted point source sensitivities (5σ in 500 sec) of $\approx$ 3, 4, 10, and 15μJy respectively. All bands use arrays with 256^2 $1\farcs2$ pixels, with InSb detectors for the two shorter wavelengths, and Si:As IBC detectors for the two longer longer wavelengths. Dichroic beamsplitters allow the 3.6 and $5.8\mu m$ arrays to view the same $5\farcm1 \times 5\farcm1$ field while an adjacent field is simultaneously imaged at 4.5 and $8\mu m$. A shutter allows dark current and absolute sky brightness measurements, and its mirrored inner surface can also be illuminated by calibration sources.

The IRS uses a 128^2 pixel Si:As IBC array and a 128^2 pixel Si:Sb IBC array to provide low resolution (R $\approx$ 50) long-slit ($1' - 2\farcm5$) spectroscopy from $5 - 40\mu m$. A second pair of these arrays provides moderate resolution (R $\approx$ 600) echelle spectroscopy with $12'' - 22''$ slits from $10 - 40\mu m$. The low resolution sensitivity is $\sim$ 1 mJy (5σ in 500 sec), while the line sensitivity in the echelle mode is $\approx 3 \times 10^{-18}$ W/m^2. Part of the low resolution Si:As array is used to obtain "peak-up" images over two $1' \times 1\farcm2$ fields: one covering $13 - 18\mu m$, the other $18 - 26\mu m$. Onboard centroids are determined from these peak-up images to offset the source directly onto the selected slit with sub-arcsecond accuracy.

The MIPS provides imaging over a $5\farcm3$ field using a 128^2 pixel Si:As IBC array at $24\mu m$, and a 32^2 pixel Ge:Ga photoconductor array at $100\mu m$. A 2×20 pixel stressed Ge:Ga photoconductor array images a $0\farcm5 \times 5\farcm3$ field at $160\mu m$. Predicted 5σ in 500 second sensitivities are 0.37, 1.4, and 22.5 mJy respectively in the three bands (the $160\mu m$ value is limited by confusion). A scan mirror derived from the design proven in *ISO*'s SWS instrument allows sources to be chopped on and off the detectors. The scan mirror also enables MIPS to efficiently survey large areas, by freezing an image of the sky on the three detectors for several seconds while the observatory continuously scans in the opposite direction at a constant rate. Other settings of the scan mirror enable a fully-sampled, higher magnification mode at $70\mu m$, and an R $\approx$ 15 spectral energy distribution mode from $52 - 99\mu m$.

4. NGSS

The Next Generation Sky Survey (NGSS) was a proposed NASA Medium Explorer to survey the entire sky at 3.5 and $4.7\mu m$ with a million times better sensitivity than COBE, and at 12 and $23\mu m$ with a thousand times better sensitivity than IRAS. E.L. Wright of UCLA was the PI. The minimum 5σ point source

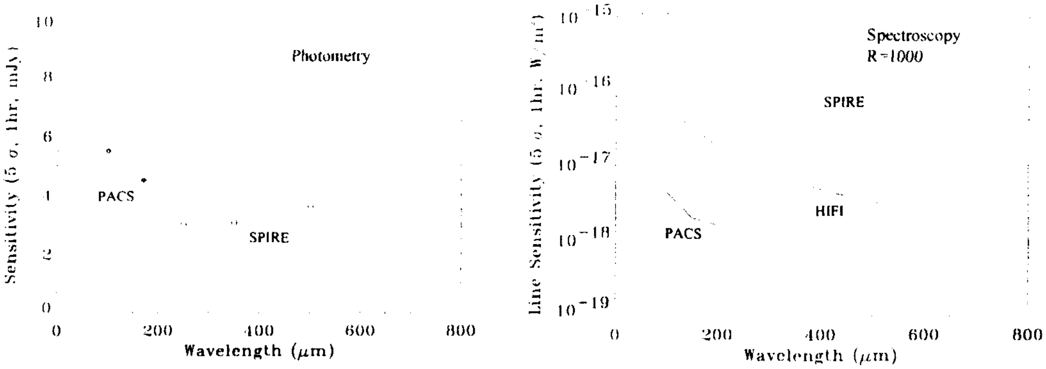

Figure 4. Photometric and spectroscopic sensitivity of *FIRST* instruments.

6.1. Redshifted Starlight

One of the defining scientific programs for SIRTF is the study of galaxies to $z > 3$ by means of deep surveys at $3 - 10\mu$m. This limit was selected because it is apparently beyond the peak in the space density of luminous quasars (Schmidt, Schneider, & Gunn 1995). Not only will IRAC's excellent sensitivity in this wavelength region allow such galaxies to be detected (Figure 2), but the H^- opacity minimum at 1.6μm (John 1988) is expected to be a major tool in photometric redshift determination at $1 < z < 5$ (Wright, Eisenhardt, & Fazio 1994; Simpson & Eisenhardt 1999), since it is a ubiquitous feature of stellar atmospheres.

UV-bright examples of such galaxies have already been detected by means of the Lyman break technique (Steidel et al. 1996, 1999), and they play an important role in the overall star formation history of the Universe (Madau et al. 1996). By detecting galaxies on the strength of their UV emission, however, LBG samples are necessarily biased in favor of those with both active star formation and relatively modest extinction. Such samples will not reveal if there is an underlying population of galaxies which have already assembled the bulk of their stellar mass. In the absence of ongoing star formation, even massive galaxies will be too faint in the rest-frame ultraviolet to be picked up by optical surveys. The stellar mass already present at an early epoch constrains the star formation rate to that point, a quantity which is still uncertain due to the possibility of significant dust extinction. Hence an accurate picture of the star formation history of the universe can only be determined by making an accurate census of *all* galaxies, not just star-forming ones with low extinction. Since the luminosity in the rest-frame near-infrared correlates linearly with mass (Gavazzi, Pierini, & Boselli 1996) and is relatively unaffected by dust obscuration, this is clearly the spectral region in which to make such a census.

Figure 2 shows that IRAC sensitivity is sufficient to sample around the rest frame 1.6μm peak to $z > 3$. NGSS could construct a similar sample at $z = 1$ over 2500 square degrees around the ecliptic poles. Scaling from existing K selected samples, Simpson & Eisenhardt (1999) estimate that IRAC could generate a sample containing roughly one thousand $z = 3L^*$ galaxies in 100 hours of observation. Beyond generating a sample selected primarily on mass,

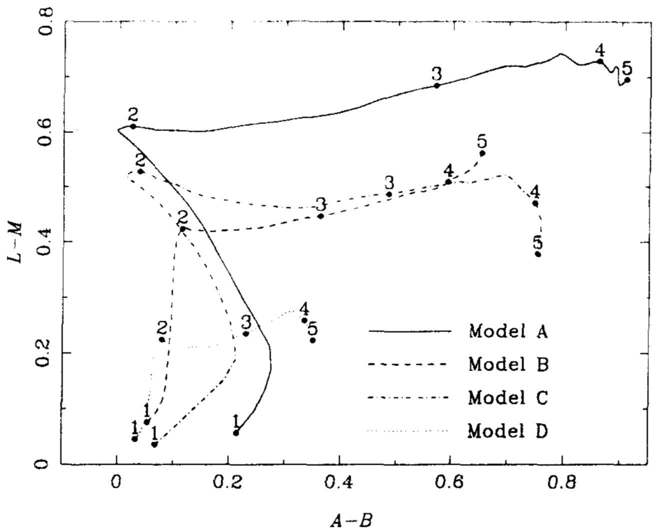

Figure 5. Loci of the four galaxy models discussed in [23] in the $L - M$ *vs* $A_p - B_p$ ($3.6 - 4.5\mu$m vs. $5.6 - 8.0\mu$m) color-color diagram. The locations of the models at z = 1,2,3,4,5 are indicated.

IRAC sampling of the $1.6\mu m$ peak can be used to obtain photometric redshifts. The 5.8 and 8μm IRAC filters were optimized for photometric redshifts of $z \approx 3$ galaxies (Simpson & Eisenhardt 1999). If supplemented by comparably deep groundbased K data (e.g. with the planned UKIRT wide field camera), NGSS could use a similar approach to identify many thousands of $z \sim 1$ galaxy clusters.

As an illustration of how photometric redshifts can be derived from IRAC data, Figure 5 shows a $3.6 - 4.5\mu$m vs. $5.6 - 8.0\mu$m color-color plot for the galaxy models considered in Simpson & Eisenhardt (1999) in the redshift range $1 < z < 5$. It can be seen that the color in the two Si:As filters is generally able to provide an excellent measurement of the galaxy redshift for $z \gtrsim 2$. For $1 \lesssim z \lesssim 2$, the $3.6 - 4.5\mu$m color provides most of the photometric redshift signal. Only Model D has a very limited range of colors which might hamper analysis, since we are observing the Rayleigh–Jeans tail of a recent starburst with only weak metal line blanketing; however, this is exactly the sort of UV-bright galaxy which would be detected in surveys for UV dropouts, and so this does not pose a problem.

6.2. Infrared Luminous Galaxies

In the local universe, 30% or more of the bolometric energy of galaxies is emitted at $> 10\mu$m (Lonsdale 1999, Sanders & Mirabel 1996). The ratio of IR to UV/optical luminosity increases with star formation rate and luminosity, and can exceed 100:1 in extreme cases. As derived from UV luminosity, both the incidence of high SFR galaxies and the global SFR were much higher at $z \gtrsim 1$ than today (Madau et al. 1996). Hence it is plausible to expect that ultraluminous IR starburst galaxies such as Arp 220 were also much more common at high redshift.

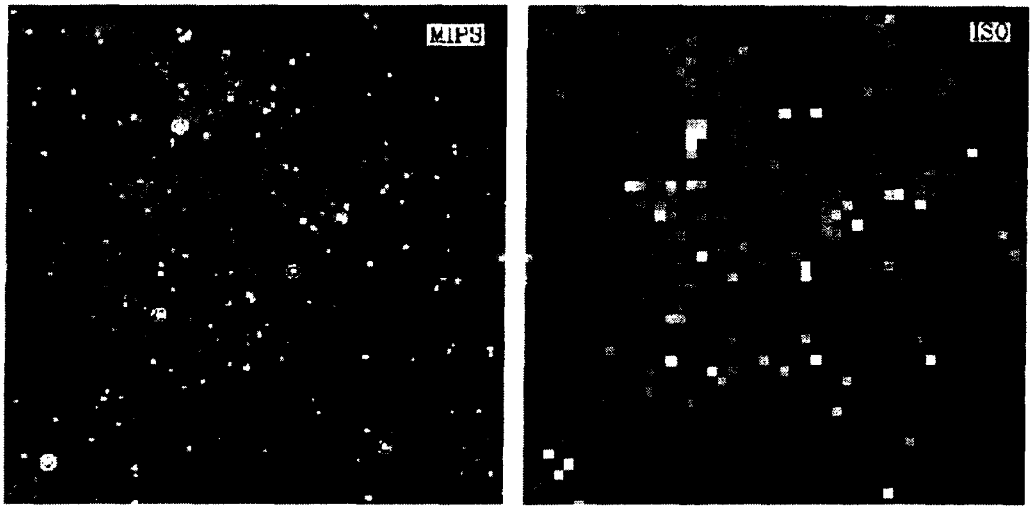

Figure 6. Simulated 70μm map of 35×35' region with MIPS (left) vs. ISO (right).

The detection of the cosmic infrared background (CIB) at 140 and 240μm by DIRBE (Hauser et al. 1998) demonstrates that at least half of the bolometric energy integrated over the age of the Universe is found in the IR-submm range (Dwek et al. 1998). Deep observations with SCUBA reveal a population of 850μm sources with fluxes > 1 mJy which can account for much of the CIB (Hughes et al. 1998, Barger et al. 1998), while *ISO* surveys to 100 mJy at 175μm reveal a population which accounts for roughly 10% of the CIB (Reach et al. 1999).

Figure 3 from Guiderdoni et al. (1999) plots the spectrum of an IR starburst galaxy with luminosity similar to Arp 220 at various redshifts. The sensitivity of a number of existing, planned, and proposed instruments is shown for comparison.

SIRTF's MIPS instrument can obtain photometry for sources similar to Arp 220 to $z \sim 2$, and should be able to identify the bulk of the discrete sources comprising the CIB at 160μm. FIRST's SPIRE instrument will extend this to 500μm with better angular resolution, probing more deeply into the confusion expected at these wavelengths. Targeted far-IR observations of luminous LBG galaxies on the one hand, and of SCUBA sources on the other will allow the construction of complete spectral energy distributions for these objects, and show whether there is any significant overlap between objects which contribute to the UV/optical cosmic background and those which make up the CIB.

The MIPS scan mirror enables large areas to be surveyed efficiently. Figure 6 illustrates the type of data expected from 24 hours of MIPS observation, as compared to the same time with ISO. With its very large arrays, NGSS would survey even more efficiently: the mosaic shown in Figure 6 corresponds to a single NGSS field, although only at wavelengths $\leq 23\mu$m. Surveys such as these will allow the identification of large enough samples to search for rare and perhaps presently unknown classes of objects.

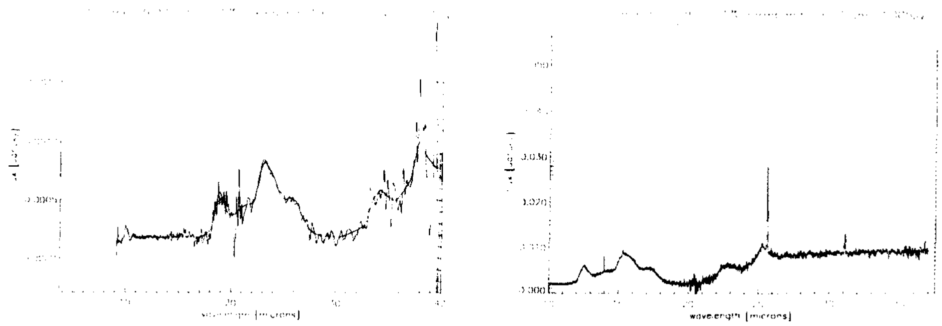

Figure 7. Simulated low-resolution IRS spectrum of an ultraluminous IR galaxy at $z = 2$ (left), and high-resolution spectrum at $z = 1$ (right).

6.3. Starbursts vs. AGN

While surveys can reveal previously unsuspected populations and determine global parameters, spectroscopy is necessary to understand the physical nature of the infrared luminous objects IR surveys will discover. For heavily extincted objects with extreme ratios of IR to UV/optical luminosity, the IRS is likely to be the only tool to obtain the redshift until the advent of NGST and FIRST. Figure 7 shows simulated IRS spectra of an Arp 220-like ULIRG with the low resolution modules at $z = 2$ and with the high resolution modules at $z = 1$. The complete low resolution spectrum would require a few hours of IRS observing, while the high resolution spectrum corresponds to 1000 seconds of integration.

One of the fundamental questions regarding ULIRG's is whether they are powered by starbursts or by AGN. The broad peak at an observed wavelength of 23μm in the low resolution spectrum is the rest-frame 7.7μm PAH feature. ISO observations have established that the strength of this feature provides good discrimination between the AGN and starburst mechanisms (Lutz et al. 1998). More luminous systems tend to have a higher incidence of AGN (and weak or non-existent 7.7μm PAH emission).

More quantitative information about excitation conditions and abundances can be obtained by measuring the strengths of the gas-phase emission lines visible in the high resolution spectrum in Figure 7. In particular ratios of the forbidden neon lines including [NeII] 12.8μm, [NeV] 14.3μm, and [NeIII] 15.6μm can readily distinguish starbursts, shocks, and AGN, and are very insensitive to extinction (Voit 1992). The high ratio of [NeII]/[NeIII] and [NeIII]/[NeV] in Figure 7 is clear evidence for a starburst.

Finally, for sources with known redshift, PACS will measure features to $> 200\mu$m, and for sources with adequate flux, HIFI will resolve the velocity structure of lines such as [CII] 158μm, which is thought to be the primary cooling line in star-forming galaxies.

7. Conclusions

SIRTF's and *FIRST*'s advances over previous IR capabilities will enable dramatic progress to be made on some of today's most pressing questions regarding galaxy formation and evolution. In the broadest terms, they will provide the data needed to understand the connection between the starlight making up the UV/Optical cosmic background and the dust responsible for the CIB.

Surveys with IRAC will enable the generation of field galaxy samples selected on the rest-frame $1.6\mu m$ peak out to $z = 4$. Such samples are complementary to those based on the Lyman break, because they are relatively insensitive to dust and to the current star formation rate. These samples will be selected approximately on mass, assuming the local linear scaling of the $1.6\mu m$ peak with dynamical mass (i.e., the Tully-Fisher relation) continues to hold at high redshift. By sampling around the rest frame $1.6\mu m$ peak, we expect that IRAC will be able to estimate photometric redshifts to 10% for galaxies as bright as L^* to $z > 3$. MIPS and SPIRE observations will allow the study of ULIRG's to $z \sim 3$ and beyond out to $> 100\mu m$ in the rest frame. The resulting spectral energy distributions will define the bolometric luminosities of sources recently found by SCUBA, and establish the degree of overlap between the sub-mm and UV selected populations. IRS observations will provide redshifts for populations too red to measure using ground-based telescopes, and reveal the extent to which AGN vs. starbursts are responsible for the ULIRG component as a function of lookback time. High resolution spectra of more luminous sources with HIFI will reveal the temperature, density and kinematics of the high redshift ISM.

Finally, with these advances in the capability, it is highly likely that previously unsuspected phenomena will be discovered. The first opportunity for the astronomical community to make such discoveries is fast approaching: the first proposals for *SIRTF* time will be due in September 2000, with launch a little over a year later.

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