Title
Review: Understanding galaxy formation and evolution with long wavelength observations

Journal
ASTROPHYSICS WITH INFRARED SURVEYS: A PRELUDE TO SIRTF, 177

Author
Malkan, MA

Publication Date
1999

To be published in:
"Astrophysics with Infrared Arrays: A Prelude to SIRTF"
ASP Conference Proceedings

Review: Understanding Galaxy Formation and Evolution with Long Wavelength Observations

Matthew A. Malkan
U.C.L.A. Astronomy, Los Angeles CA 90095-1562

ABSTRACT

It is well established in the local Universe that regions of high star-formation rate are dusty. As a result of this physical causal link, galaxies of increasing current star formation activity emit a larger proportion of their bolometric luminosity via dust absorption and re-radiation in the thermal mid- to far-infrared. Several new observations indicate that this trend continues back to earlier cosmic times, when star formation rates were very high, and a large fraction of the resulting UV power was reprocessed by dust into the infrared. For studying the more luminous, (and therefore more dusty) galaxies, infrared spectroscopy is crucial even at moderate redshifts. For the less dusty galaxies, we are still driven strongly to longer wavelengths as their redshifts increase from 5 to 10. On the observational side, infrared astronomy is about to start catching up with optical astronomy in sensitivity, spatial resolution and field-of-view. Therefore, long-wavelength observations will play the key role in our understanding of galaxy formation and evolution in the "Immature Universe."

Subject headings: Galaxy Formation, Evolution, Dust

1. Dust in the Universe: Now

Figuring out how galaxies formed and evolved a long time ago is one of the supreme challenges for theorists and, especially, observers. We will need all the help we can get. As a great coach might have said: "When the going gets tough, the tough get empirical."

It is good advice to review our empirical knowledge of star-forming galaxies in the local Universe if we want to have a good shot at understanding them in the early Universe. Since the highly successful IRAS mission, no one (at least in astronomy) can be ignorant of the fact that many galaxies are moderately to extremely dusty. Operationally, this means that a significant, to a dominant fraction of their bolometric energy is reradiated at long wavelengths after absorption by dust grains.

Many astronomers are also aware of the next lesson from IRAS: the effects of dust are strongest in the most luminous galaxies. As the current star formation rate increases, so does the fraction of stellar photons that are absorbed by dust. This could have been predicted from the simple fact that young stars are generally closer to the dusty molecular clouds out of which they were born than are older stars. So naturally the youngest stars have the highest "dust covering fractions", and this trend is strong when integrated over a galactic scale.

This is shown in Figure 1, reproduced from Malkan and Stecker 1998. It simply presents the average observed far-infrared-to-optical spectra of galaxies of varying luminosities, based on the large multiwavelength database of Spinoglio et al. (1995). The lines are average spectra of galaxies differing by factors of ten in bolometric luminosity. At higher luminosities, the "valley" around log $\nu = 13$, between the light of red giant stars on the right (peaking around log $\nu = 14.5$) and the cold dust bump on the left (around log $\nu = 12.5$) is progressively "filled in" from more and more thermal emission from warm dust grains associated with H II regions. And the relative power in the dust emission grows to be much stronger than that of the starlight, as the dust peak shifts to shorter wavelengths. At the same time, the relative power at short wavelengths (log $\nu = 15$, off the right end of the graph) is collapsing due to dust absorption. The dominant factor in making galaxies in the local universe more luminous is not their larger masses, but their lower Mass/Light ratios– the result of a higher proportion of recently formed stars.

In the extreme ultraluminous starburst galaxies, the average dust absorption becomes so large that much of the galaxy is effectively optically thick at wavelengths of 10μm or longer. ISO is providing dramatic new evidence for this proposition. Figure 2 shows a montage of Long Wavelength Spectrometer grating-scan spectra of luminous galaxies from the LWS Infrared-Bright Galaxies team (Fischer et al. 1998). Even at the resolution of about 200, the strong forbidden lines from neutral and ionized gas are evident in the normal galaxies. Most of this emission becomes weaker *relative to the thermal dust continuum* in the more luminous objects, while at the same time molecular *absorption* lines become more and more prominent. For the molecular lines, and even [OI] 63μm to be detected in absorption requires very high column densities of cold gas. There is a tendency for dust absorption to be stronger in the more luminous galaxies, but it is not strictly monotonic.

2. Dust in the Universe: Then

It has been said that the Universe is difficult to understand because "there's nothing to compare it with." Much accumulating observational evidence indicates that we *can* compare the Immature Universe with our current epoch and locale– the same trends we find at z=0 continue at high-redshifts. The main observational evidence for this view is:

- a) **Detections of distant dusty galaxies in ultra-deep ISO fields;** It is always scary when unexpected sources are detected right at the sensitivity threshold of new instruments, and this concern hovers around most of the evidence to be described here. Nonetheless, several groups have now begun to converge on estimates of very deep infrared galaxy counts, using ISOCAM at 7 and 15μm (Oliver, et al. 1997; Taniguchi, et al. 1997; Desert, et al. 1998), and ISOPHOT at 175μm (Kawara, et al. 1998). The surface densities are relatively high: 0.7 to 1.7 per square arcmin in the ISOCAM images and 0.011 per square arcmin in the ISOPHOT map. Especially at the longer wavelengths, many of the faint sources are probably starburst galaxies at redshifts of 1 or greater. High rates of star formation are implied by the required high luminosities in the mid-infrared. Whatever the exact redshifts of these distant galaxies are, in many cases their *ratio* of infrared/optical luminosity is so large, that it requires over half of their power to be reprocessed by dust grains (Rowan-Robinson et al. 1997). The large number of detections (for such small areas covered so far) suggests that this may be the rule rather than the exception for high-redshift galaxies. The longer wavelength observations also highlight the importance of observing regions of low cirrus contamination from the Milky Way. Fluctuations in the column density of local interstellar matter on sub-arcminute scales are a significant, if not dominant source of noise at these faint levels. The real solution, however, lies with improved spatial resolution from larger telescopes, which is also essential for confident cross-identifications at other wavelengths.

- b) **High surface densities of star-forming galaxies in narrow-band infrared searches;** Figure 3 shows the estimated star-formation rates from recent detections of $H\alpha$ emitting galaxies at redshifts of 2 to 2.5 from Teplitz, Malkan and McLean (1998a). The same narrow-band imaging technique has also recently been used to detect a [OIII]λ5007 line-emitting galaxy at z=3.31 (Teplitz, Malkan and McLean 1998b).

Table 1 lists the implied surface density of galaxies per square arcminute, for comparison with other search methods, but it is also necessary to account for the very different redshift windows of each one. Although the surveys are not yet large, and the fluctuations from one to another are substantial, it appears that near-infrared selection finds several times more galaxies than optical methods, which are based on detecting spectral features in the rest-frame ultraviolet. The highly successful Lyman break search technique can only find galaxies that have 1) *blue continuum colors.* Most of the confirmed U-band dropouts in the HDF have V-I$\leq$0.5 (e.g. Dickinson, 1998); and 2) *strong far-UV continuum.* If Lyα is not strong in emission, (and this can be prevented by very minor amounts of dust), then the spectroscopic confirmations hinge almost completely on identifying key interstellar *absorption* lines between 1200 and 1400$\AA$.

Is it reasonable to suppose that a major proportion (half or even more?) of high-redshift galaxies are missed by optical searches, but detectable in the near-infrared? Yes, especially when one considers that the integrated luminosity of those galaxies *detected* in the optical surveys (i.e. the *least* dusty ones) needs to be corrected upward for extinction by a factor of five to seven (Dickinson 1998; Pettini et al. 1998). Some studies have suggested even larger corrections (Meurer, et al. 1997; Sawicki and Yee, 1998). On the other hand, extensive spectroscopy of a K-magnitude-limited galaxy sample has been used to argue that the correction should be only a factor of three, and that the incompleteness is not extremely large (Cohen et al 1998). There are tentative indications that the effects of extinction are stronger in the more luminous galaxies. This question will be answered definitively when near-infrared spectrographs on large telescopes (NIRSPEC on Keck, for example) can measure the rest-frame optical spectra of high-redshift galaxies as accurately as current optical spectrographs are measuring their rest-frame ultraviolet spectra.

- c) **Detection of strong Diffuse Infrared Background (DIRB) emission** (that requires substantial luminosity evolution in the infrared); Several recent calculations have attempted to predict the DIRB emission from galaxies. Figure 4 shows one of the relatively conservative estimates, based on a simple *empirical* assumption: that the trend for more luminous galaxies to emit a larger fraction of their power in the thermal infrared continues back to z=1–2, when galaxies were more than an order of magnitude more luminous than today. The smooth curves are the predictions from Malkan and Stecker (1998), which extrapolate from the best present-day IRAF luminosity functions. Note that the predictions are very similar using either the IRAS luminosity functions at 12μm (upper dashed line, excludes Seyfert galaxies) or at 60μm (upper solid line, includes Seyfert galaxies). The two upper solid lines assume the best guess evolution law inferred from deep IRAS counts, $L \propto (1+z)^3$, out to z=2 (upper curve) or z=1 (next upper solid line). The lower lines are conservative lower limits assuming small luminosity evolution. The error bars show new claimed *detections*, from the DIRBE and FIRAS experiments on COBE and from ISOCAM number counts described above (Fixsen et al. 1998; Puget et al. 1996; Dwek et al. 1998). We see that our empirical assumption is broadly consistent with the reported detections at 7–500μm. If the new DIRBE detections at 140 and 240μm are confirmed (they are formally consistent with the lower FIRAS estimates (triangular region), given the large error bars), they will require even *more* dusty galaxies than are included in our simple empirical model. The wavelength of this exess is sufficiently longward of the peak in low-redshift galaxies that for nearly any model it requires a large population of dusty galaxies at redshifts of 1 or more. (Traditional active galactic nuclei–Seyfert 1's and 2's– make a small (10%) addition to these totals–shown by the dotted lines– but they are not sufficiently numerous to alter the overall conclusions significantly.) Independent calculations (e.g., Guiderdoni et al. 1998) lead to similar conclusions.

- d) **Millimeter line and continuum detections of distant galaxies.** In a few systems where a distant background object (e.g., a Seyfert galaxy: FSC10214+4724, or a quasar: H1413+117, the Cloverleaf) is gravitationally lensed, sensitive searches have detected molecular emission lines (Barvainis et al. 1997; Downes et al. 1995: Frayer et al. 1998). High-redshift quasars, or galaxies grouped with them, have also been detected in the 1.3mm continuum and CO line emission (Ohta et al. 1996; Omont et al. 1996a; Omont et al. 1996b). It is generally assumed that the millimeter line and continuum emission is associated with star formation in the host galaxy, and is not related to the active nucleus. If so, and if these objects are representative of many high-redshift galaxies, then dust grains and the molecules that they help to form may be common at high redshifts.

- e) **Detection of a high surface density of faint submillimeter sources by SCUBA on the JCMT.** Making deep source counts (to mJy levels at 850μm) was one of the chief goals for building SCUBA. Some of its first day-long pointings under good sky conditions were made by Smail, et al. (1997), who targeted Abell clusters, in the hope that they would gravitationally amplify the faint background sources they were seeking. They were rewarded with detections which imply 0.6 sources per square arcminute down to 4 mJy, though it is not certain how strong the lensing effects were. Hughes et al. (1998) have 5 detections in the Hubble Deep Field, and Barger et al. (1998) have one detection each in the Lockman Hole and in SSA13. As with ISO, there is some judgement in deciding what to identify as a significant detection, but most groups appear to be proceeding fairly cautiously. It is the same situation as in the other surveys described above: one might not have too much confidence in the results of just one or two deep fields, but as different groups, independently studying different regions, continue to find comparably large densities of faint sources at 850μm, the significance of the conclusion builds. [1] Assuming some of these sources are at cosmologically interesting distances, and that most of their continuum emission is powered by star formation rather than a nonstellar AGN, they must be the tip of the young galaxy iceberg: tremendous starbursts with SFR's of hundreds to a thousand $M_\odot$ /year (e.g., Franceschini et al. 1998). Major improvement in the number statistics will require larger detector arrays; pushing to deeper sensitivities will probably require interferrometry, to avoid the looming confusion limit (Blain, et al., 1998). In any case, some near-IR spectroscopy will again be required, to confirm their redshifts, and to prove that they are not powered by AGN.

3. "In Today's Rapidly Evolving World of the Future:" Bright Prospects for Coming Infrared Observatories in Space

Based on the above considerations, I can confidently make this prediction: In the upcoming decade, infrared/long-wavelength astronomy(s) [2] will play the leading role in advancing our understanding of galaxy formation and evolution. The support for this conclusion gets stronger at every successive (almost quarterly!) conference on anything containing the phrase "Young Universe", including the October 1997 Monteporzio meeting with that name. The prediction stands on two legs: 1) where the most observational gains are; and 2) where the distant sources emit. The first point, the *unique* instrumentation gains that infrared astronomers are on the verge of reaping (as they in effect "catch up" with more mature wavebands such as the optical), are widely appreciated, but are so dramatic they merit re-summarizing:

- 1) orders of magnitude gains in sensitivity, particularly from airborne and space-based telescopes with greatly reduced sky backgrounds;

---

[1] I am assuming there are *not* many equally sensitive (unpublished) observations with *no* detections (i.e. that we are not just sleeping through a Bayesian nightmare).

[2] In fact, the long-wavelength observational techniques will soon become so necessary in this field that the phrase "infrared astronomer" will soon be an anachronism. Instead, there will be "observers" who study high-redshift galaxies, and it will simply be assumed that infrared instruments are a prime part of their arsenal.

- 2) orders of magnitude increases in the number of pixels, which will be particularly useful to exploit the next gain:
- 3) orders of magnitude improvement in spatial resolution, often pushing right up to the diffraction limit of the telescope (or beyond in the case of sub-millimeter interferrometers); combined with
- 4) favorable K corrections, at least relative to shorter wavelengths. At the longer wavelengths and high redshifts, the K corrections actually can become zero, or even (longward of 60μm) *positive.*

Even beyond all these fabulous gains, it is a truism that we need to study red objects at red wavelengths. Many of these distant galaxies are largely or totally opaque at rest wavelengths shortward of several microns, and nearly all of their power emerges at 2–100μm. Given their huge visual extinctions, their most useful diagnostic emission lines from their neutral and ionized gas have rest wavelengths of 2μm to longward of 35μm. By far the strongest spectroscopic features (in equivalent width) are the PAH bands at 3.3, 7.7 and 11.3μm (not included in the calculations of Figures 1 and 4). The strongest emission line at long wavelengths, [CII]158μm (e.g., Colbert et al. 1998), will be detectable at *high* redshifts by upcoming ground-based millimeter arrays.

To take a specific example, for each galaxy we can use the ratios of infrared emission lines to estimate what proportion of the bolometric energy output comes from young stars, and what proportion comes from a (possibly hidden) active galactic nucleus. Both processes coexist in low-redshift galaxies (such as NGC 1068 and NGC 7469), and also in high-redshift galaxies (e.g. Malkan, Teplitz and McLean 1996; Frayer et al. 1998). The strength of high-ionization forbidden fine-structure emission lines from 2 to 50μm is predicted to be a powerful indicator of the relative contributions of starbursts and AGNs (Spinoglio and Malkan 1992). Recent ISO spectroscopy with the Short Wavelength Spectrometer shows that this can be done in practice (see review by Genzel in this proceeding).

To what redshift will we continue to find many dusty galaxies emitting strongly in the infrared? The answer depends on the trade-off between two opposing effects:

- 1) the higher past star formation rates, which are empirically linked with a larger bolometric fraction of power reprocessed by dust grains (discussed above), *VERSUS*
- 2) the tendency for more metal-deficient systems to be less dusty. We do not know how strong this trend is, even in the local Universe. We do know that most visible parts of the Immature Universe became enriched with at least some metals (up

to Population II abundances of 1 to 10% solar) in a short time. This is merely a restatement of the "G dwarf" problem in the Milky Way (the virtual absence of extremely metal poor old stars), or the absence of direct evidence for the fabled "Population III." The evolutionary phase before any dust grains had a chance to form could be extremely brief.

My suspicion is that 1) will tend to dominate 2) at least back to a redshift of 5 to 10.

Even at the highest redshifts when the first galaxies were forming, infrared spectroscopy will be absolutely essential to study the fraction of young galaxies which will be less dusty than the luminous IR galaxies. Their strongest, most powerful spectroscopic features, in emission and absorption, start at [OII]3727 and extend up to the CO absorption and H recombination lines in the 2μm window. More and more of these key features are shifted longward of $\lambda_{obsvd} \sim 5\mu$m at cosmologically interesting lookback times (z increasing from 2 to $\geq$ 10) and most of them will not in general fall into any of the atmospheric "windows" for ground-based telescopes.

As usual, spectroscopy [3] of the strongest features is the single most important tool available for studying these galaxies. It is needed to identify them and measure their redshifts, measure the kinematics, masses and dynamics of their stars and interstellar medium, determine the ionization and excitation mechanism(s) in their gas (i.e., active nucleus, young stars, shocks, etc.) This then allows estimates of elemental abundances, and ultimately determination of their evolutionary status.

For these reasons, much of the action in studies of the "Immature Universe" for the next 10 years will come from long-wavelength spectroscopy, especially with SOFIA and SIRTF. Those same reasons make an overwhelmingly strong case for extending the capabilities of a Next Generation Space Telescope beyond 5μm, preferably to 35μm.

P.G. Wodehouse's immortal Bertie Wooster summed up the current situation best, when he exclaimed: "Half of the world has *no idea* how the other two-thirds lives!" This is going to change dramatically in the next few years.

I wish to thank the colleagues who shared their work on ISO data in advance of publication. ISO research at UCLA has been supported by NASA grant NAG 5-3309. Harry Teplitz also provided help with Figure 3.

---

[3] A spectral resolution of a few hundred km/sec is reasonably matched to the intrinsic width of most of these features. Even when they are unresolved, e.g. in slitless spectroscopy grism surveys, they are still extremely useful for answering most of the above questions.

REFERENCES

Barger, A. et al. 1998, Nature, 394, 248

Barvainis, R. et al. 1997, A&A, 484, 695

Bechtold, J. et al. 1998, in “The Young Universe”, eds. D’Odorico, S., Fontana, A. and Giallongo, E., p. 241

Beckwith, S. et al. 1998, ApJ, 504, 107

Blain, A. et al. 1998, MNRAS, 296, L29

Bunker, A. et al. 1996, MNRAS, 273, 513

Cohen, J. et al. 1998, astro-ph preprint No. 9809067

Colbert, J. et al. 1998, ApJ, in press

Desert, F. et al. 1998, astro-ph preprint No. 9809004

Dickinson, M. 1998, in “The Hubble Deep Field”, eds. Livio, M., Fall, S. and Madau, P.

Downes, D. et al. 1995, ApJ, 453, L65

Dwek, E. et al. 1998, astro-ph preprint No. 9806129

Fischer, J. et al. 1998, in preparation

Fixsen, D. et al. 1998, ApJ, in press

Franceschini, A. et al. 1998, MNRAS, 296, 709

Frayer, D. et al. 1998, ApJ, in press

Gallego, D. et al. 1995, ApJ, 455, L1

Genzel, R. et al. 1998, in this proceedings

Guiderdoni, B. et al. 1998, MNRAS, 295, 877

Hughes, D. et al. 1998, Nature, 394, 241

Malkan, M. and Stecker, F. 1998, ApJ, 496, 13

Malkan, M., Teplitz, H., McLean, I. 1996, ApJ, 468, L9

Mannucci, F. et al. 1998, ApJ, 501, L11

Meurer, G. et al. 1997, AJ, 114, 54

Ohta, K. et al. 1996, Nature, 382, 426

Oliver, S. et al. 1997, MNRAS, 289, 471

Omont, A. et al. 1996a, Nature, 382, 428

Omont, A. et al. 1996b, A&A, 315, 1

Pettini, M. et al. 1998, ApJ, in press

Puget, J. et al. 1996, A&A, 308, L5

Rowan-Robinson, M. 1997, MNRAS, 289, 490

Rush, B., Malkan, M. and Spinoglio, L. 1993 (RMS93), ApJS, 89, 1

Sawicki, M. and Yee, H. 1998, AJ, 115, 1329

Smail, I. et al. 1998, ApJ, 490, L5

Spinoglio, L. and Malkan, M. 1992, ApJ, 399, 504

Teplitz, H., Malkan, M. and McLean, I. 1998a, ApJ, in press

Teplitz, H., Malkan, M. and McLean, I. 1998b, ApJ, submitted

This preprint was prepared with the AAS LaTeX macros v4.0.

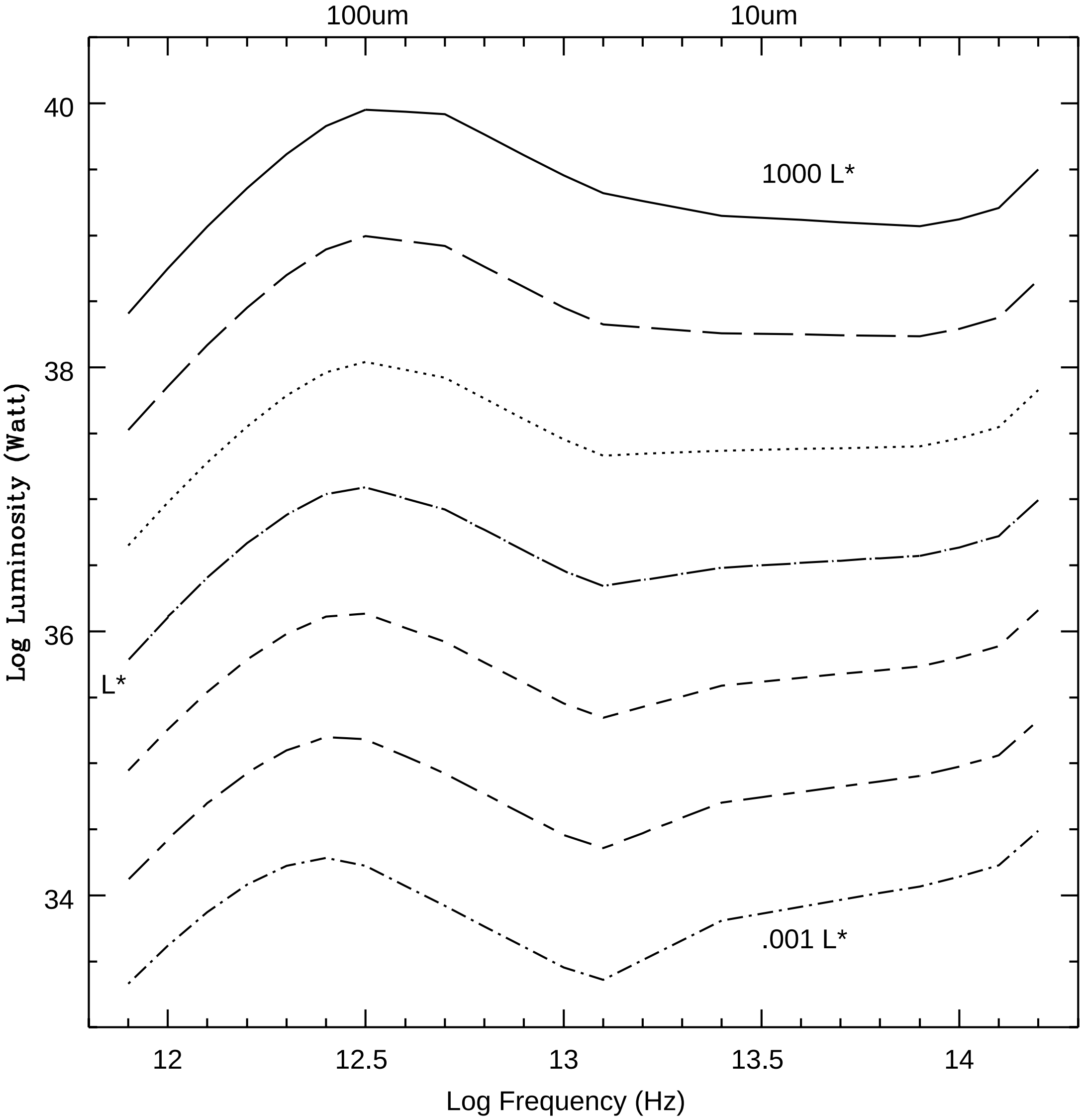

Fig. 1.— Average Observed Infrared Spectra of Galaxies of Varying Luminosity (Malkan and Stecker 1998).

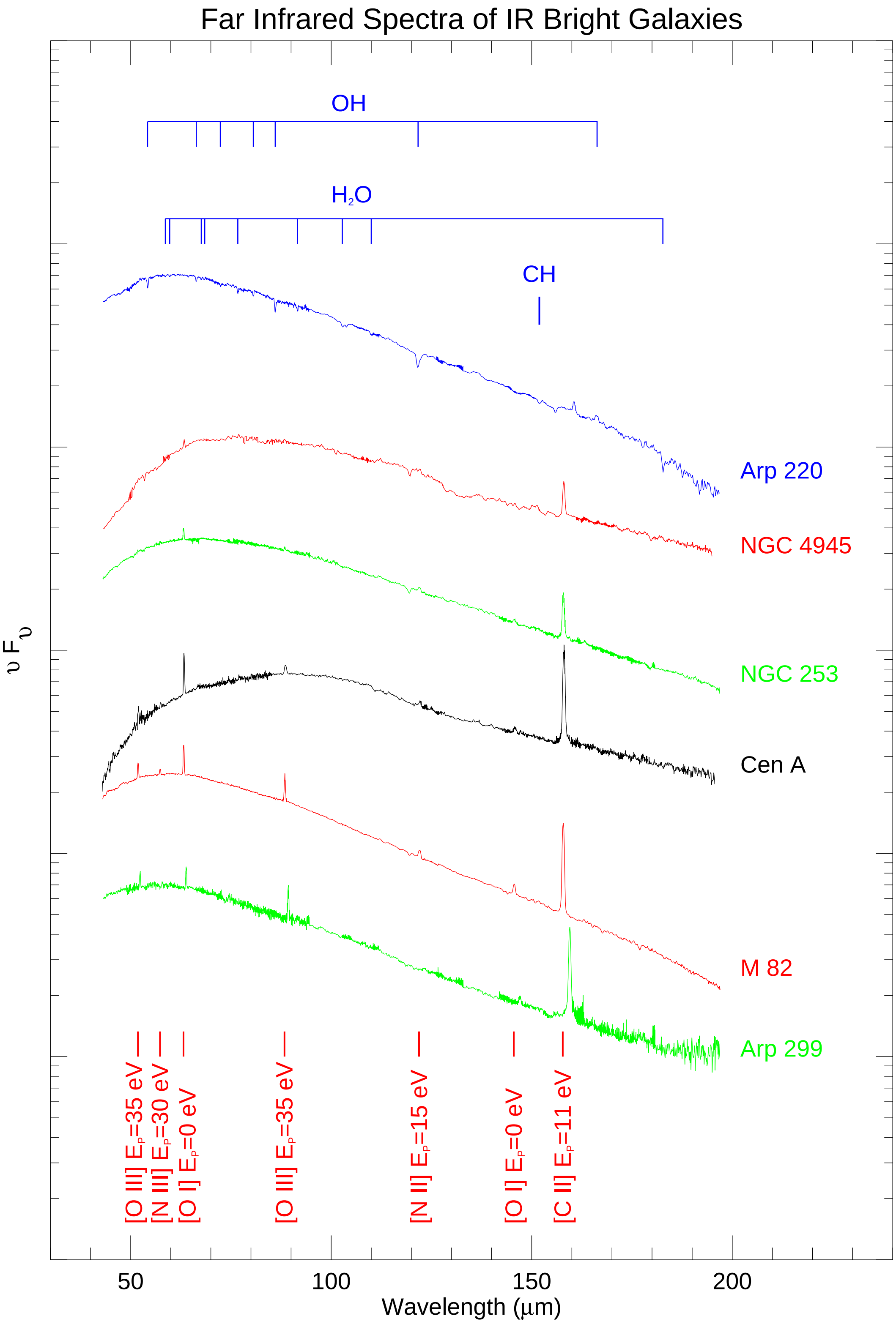

Fig. 2.— ISO LWS Full Grating Scan Spectra of IR-Bright Galaxies (Fischer et al. 1998).

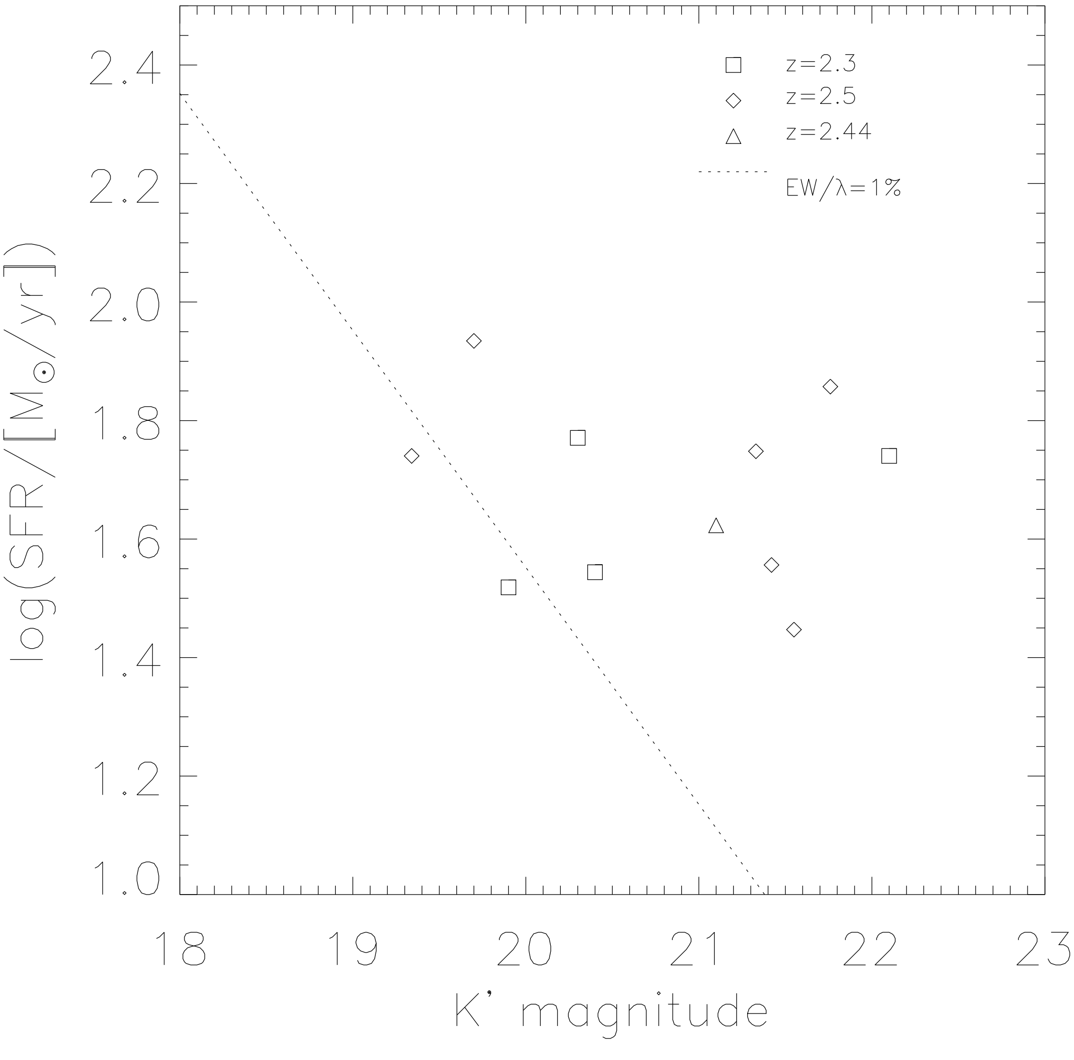

Fig. 3.— Hα-emitting galaxies detected at z=2.3–2.5 (TMM 98a).

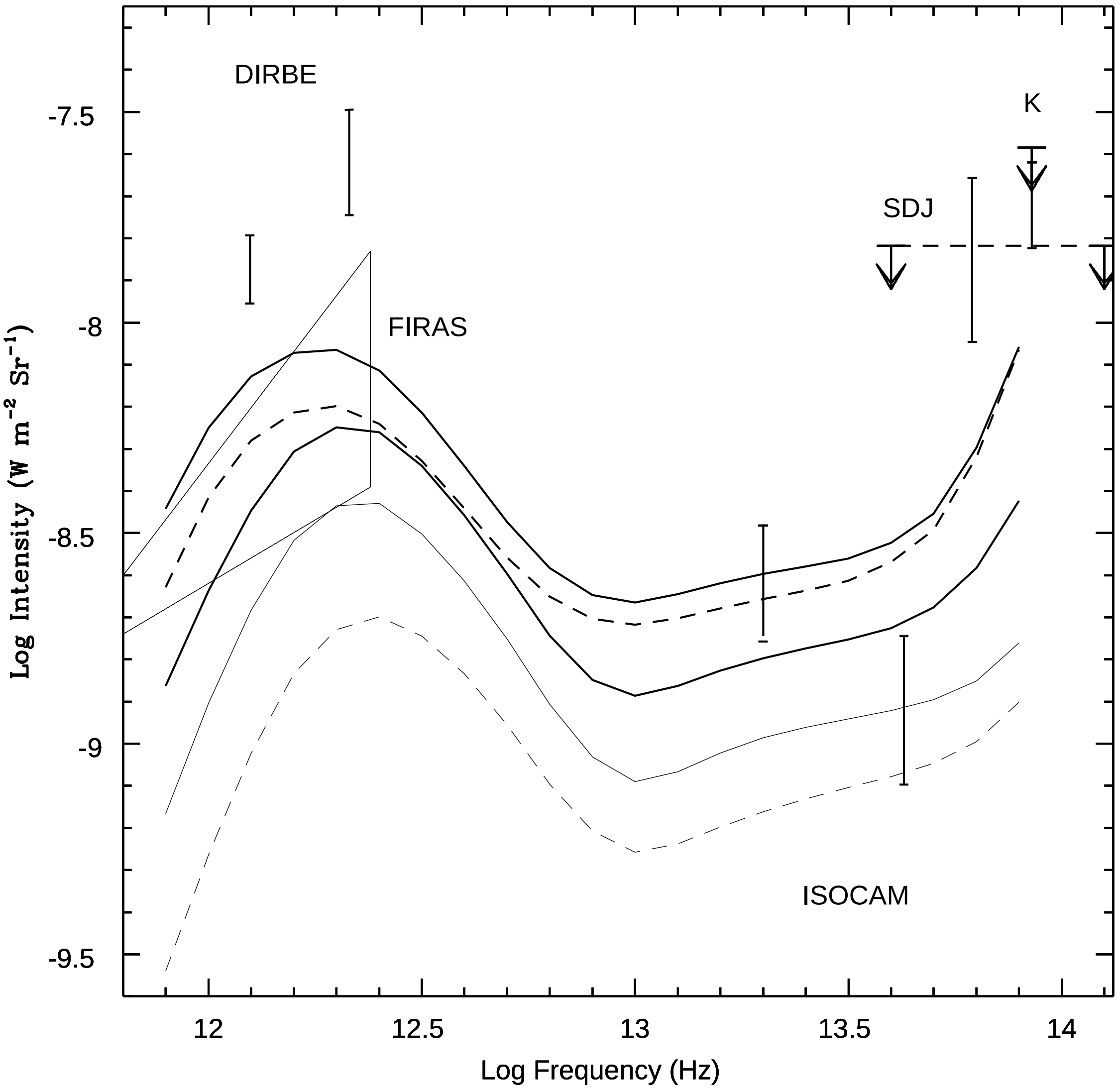

Fig. 4.— Estimates of the Cosmic Diffuse Infrared Background Radiation: Models and Data.

Table 1: Surface Densities of High-Redshift Galaxies.

Surf.Density[1]	Limiting Flux[2]	Survey	Targeted Where?	Avg. z	Δz
1.2	0.5–0.8	TMM 98a	QSO ABSN	2.3–2.5	0.04
0.5	2.0	Bechtold et 98	DLA	2.3	0.04
0.035	2.0	Bunker et 95	DLA	2.3	0.04
0.004	3.0+	Beckwith et 98	QSO Ze	2.3	0.04
0.15	3.0-	Mannucci et 98	DLA	2.3	0.04
0.3	0.3–0.4	TMM 98b	QSO Ze	3.3	0.04
1	1?	UV Dropouts	Field	2.8–3.3	0.5
0.00001		RMS 93	IRAS All Sky	0–0.04	0.02
0.0001		Gallego et al	Field	0–0.1	0.04

---

[1] Objects per square arcminute

[2] in units of $10^{-16} erg/sec/cm^2$