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STARBURST GALAXIES

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ABSTRACT. The infrared properties of star-forming galaxies, primarily as determined by IRAS, are compared to X-ray, optical, and radio properties. New luminosity functions are reviewed and combined with those derived from optically discovered samples using 487 Markarian galaxies with redshifts and published IRAS 60μ fluxes, and 1074 such galaxies in the Center for Astrophysics redshift survey. It is found that the majority of infrared galaxies which could be detected are low luminosity sources already known from the optical samples, but non-infrared surveys have found only a very small fraction of the highest luminosity sources. Distributions of infrared to optical fluxes and available spectra indicate that the majority of IRAS-selected galaxies are starburst galaxies. Having a census of starburst galaxies and associated dust allows several important global calculations. The source counts are predicted as a function of flux limits for both infrared and radio fluxes. These galaxies are found to be important radio sources at faint flux limits. Taking the integrated flux to $z = 3$ indicates that such galaxies are a significant component of the diffuse X-ray background, and could be the dominant component depending on the nature of X-ray spectra and source evolution. The dust which must be associated with the known infrared galaxies obscures a significant portion of the universe beyond $z = 3$. Depending on the scale size of dusty galaxies, this effect may prevent the observation of distant quasars and primordial galaxies.

1. INTRODUCTION

Infrared astronomers can be defined as those individuals whose primary source of reward is hot dust. Studying hot dust might be considered as just another one of those things people do in California, but the census of this dust revealed by the IRAS has dramatic implications, at least for astronomy. In this paper, I summarize some implications of IRAS discoveries for understanding various astronomical problems, including consequences for X-ray, optical, and radio astronomy as well as fundamental cosmological interpretations of galaxies and quasars. In all cases, the results discussed arise because the extra-galactic sources seen by IRAS are predominantly star forming regions visible in the infrared by re-radiation from dust heated by the hot, massive, young stars. It is now obvious that this is the most efficient locator of star forming regions, so that these new data give us the most complete accounting yet available of star formation in the universe.

This paper emphasizes the starburst galaxies because it is clear that the great majority of the most luminous infrared galaxies are made luminous by star-bursts. This was already suspected from ground based observations, but was quantified by studies of IRAS sources (e.g. Lawrence et al. 1986, Rieke and Lebofsky 1986). Galaxies whose fundamental power sources are non-thermal, such as Seyfert galaxies, can be notable infrared sources, but do not exceed 10% of the infrared-luminous galaxies in any surveys. Even some bright Seyferts, such as NGC 1068, are found when observed carefully to have their infrared luminosity arising primarily from starbursts rather than non-thermal processes (Telesco et al. 1984). Consequently, I am not going to distinguish any further in this review between thermal and non-thermal infrared sources, and will simply group all galaxies into a single infrared luminosity function.

The term "starburst" connotes an object in which star formation is proceeding at a rate that cannot be maintained in equilibrium over the life of a galaxy. A corollary is that the observed properties of a galaxy undergoing a starburst are dominated in many wavebands by radiation originating in the starburst: X-rays from supernova remnants and compact accretors associated with massive stars, ultraviolet and optical continua from the hot stars themselves, emission lines from ionization by these stars, infrared continua from dust re-radiation, and radio continua from the hot gas and the supernova remnants.

It is no surprise that starburst galaxies show up on lists of interesting objects derived in many different ways. While the most luminous infrared galaxies fulfill this definition of starburst galaxy, there are many fainter infrared galaxies which are luminous because of star formation processes proceeding at more or less their equilibrium rate. There is no defined luminosity at which such "normal" galaxies separate from starburst galaxies. To facilitate my analysis, I will group all galaxies into a single 60μ luminosity function, whether starburst or not.

I feel there is no real purpose in defining precisely when the star formation rate is abnormally high, but if one wishes a rigorous definition of a starburst system, it could probably best be derived using the ratio of infrared to optical flux. In the discussion below, I consider the infrared properties of some optically derived samples--the bright, generally normal galaxies in the Center for Astrophysics redshift survey (Huchra et al. 1983) and the Markarian galaxies, most all of which are detected because excessive star formation makes their optical continua unusually blue. Utilizing the ratio "r" of infrared to optical flux as defined by Soifer et al. (1984), the distribution of r in these samples is as in Table I for those CfA and Markarian galaxies detected by IRAS. It is seen that Markarian galaxies are systematically about four times as luminous in the infrared relative to the optical. This is comparable to the distribution of r for galaxies discovered as infrared sources by Wolstencroft et al. (1985). My primary objective in the remainder of this paper is to consider some overall consequences of star formation in the universe as revealed by infrared results, so I worry no further about precise definitions for the various galaxies in which such star formation is revealed via the infrared luminosity.

2. LUMINOSITY FUNCTION FOR GALAXIES AT 60μ

The correct way to determine the luminosity function for any sample of celestial objects is to define the sample on the basis of a flux limit and then determine the actual fluxes and redshifts of every object in the sample. This procedure has begun for samples of infrared galaxies found by IRAS, utilizing primarily the 60μ fluxes at which detections are optimized. Two such studies based primarily on new redshift data have already appeared (Lawrence et al. 1986, Soifer et al. 1986). The importance of continuing these efforts is so obvious that I should not bother to mention it. It would be useful if authors

Table I
Distribution of Infrared to Optical Flux Ratio r

bin of log r	# of Markarian galaxies	# of CfA galaxies
-1.6 to -1.2	1 (0.2%)	3 (0.28%)
-1.2 to -0.8	1 (0.2%)	21 (1.20%)
-0.8 to -0.4	5 (1.0%)	125 (11.6%)
-0.4 to 0	62 (12.7%)	531 (49.4%)
0 to +0.4	188 (38.6%)	307 (28.9%)
0.4 to 0.8	177 (36.3%)	71 (6.6%)
0.8 to 1.2	43 (8.8%)	15 (1.4%)
1.2 to 1.6	9 (1.8%)	0 (0%)
1.6 to 2.0	1 (0.2%)	1 (0.1%)
2.0 to 2.4	0 (0%)	0 (0%)

always include their redshift and flux values in papers, because it is impossible otherwise to reproduce calculations of luminosity functions, and comparison between different samples then involves interpolation to other luminosity bins, normalizing of different cosmologies, and a lot of wondering as to whether I or one of the other parties did it wrong in the first place.

In Table II are shown the results for the two studies mentioned, normalized to the best of my ability to the same luminosity intervals and H_o = 75 km s^{-1} Mpc^{-1}. Both studies derive from faint IRAS sources in small areas of the sky and refer to relatively luminous galaxies. The results do not agree particularly well, but the average of them should give a real luminosity function that does not err by more than a factor of two in any bin.

Table II
Space Densities of Galaxies for 60μ Luminosities

d log L_ν (erg/s/Hz)	d log νL_ν (erg/s)	Lawrence #Mpc^{-3} (294 galaxies)	Soifer #Mpc^{-3} (141 galaxies)	CfA #Mpc^{-3} (1051 galaxies)	Markarian #Mpc^{-3} (487 galaxies)
28.6-29	41.3-41.7	-	-	-	-
29 -29.4	41.7-42.1	-	-	3.2×10^{-2}	1.2×10^{-2}
29.4-29.8	42.1-42.5	9.7×10^{-3}	-	9.6×10^{-3}	9.7×10^{-4}
29.8-30.2	42.5-42.9	5.5×10^{-3}	-	3.2×10^{-3}	3.5×10^{-4}
30.2-30.6	42.9-43.3	4.7×10^{-3}	-	10.6×10^{-4}	2.0×10^{-4}
30.6-31	43.3-43.7	1.8×10^{-3}	-	3.0×10^{-4}	1.2×10^{-4}
31 -31.4	43.7-44.1	6.2×10^{-4}	3.5×10^{-4}	5.7×10^{-5}	3.8×10^{-5}
31.4-31.8	44.1-44.5	2.1×10^{-4}	5.6×10^{-5}	5.7×10^{-6}	6.8×10^{-6}
31.8-32.2	44.5-44.9	4.1×10^{-5}	8.5×10^{-6}	1.2×10^{-7}	6.6×10^{-7}
32.2-32.6	44.9-45.3	6.5×10^{-6}	2.0×10^{-6}	1.7×10^{-8}	3.6×10^{-8}
32.6-33	45.3-45.7	9.4×10^{-7}	1.9×10^{-7}	1.0×10^{-9}	8.7×10^{-10}
33 -33.4	45.7-46.1	1.8×10^{-7}	5.1×10^{-8}	-	-

To supplement these results at low luminosities, it is necessary to have nearby galaxies, which are found spread over the entire sky. Limiting values to the space densities at low luminosities can be derived from the CfA sample, using IRAS fluxes for those galaxies. This sample contains redshifts for the approximately 2500 brightest galaxies, defined by their optical magnitude, in the most accessible 9000 deg^2 of the sky. I found 60μ fluxes for 1074 of them excluding Markarian galaxies (to be discussed separately) in the catalog of Lonsdale et al. (1985). Calculating distances and luminosities is problematical for some because of the very low redshifts. To keep the procedure simple, I ignored those with $cz < 500$ km s^{-1} and determined distances to the rest using $H_o = 75$ km s^{-1} Mpc^{-1}. The CfA sample is a large and important data base for use with IRAS results; there are many more sophisticated things which could be done.

Most of the CfA galaxies are found in low luminosity 60μ bins. The space densities of such galaxies in the infrared luminosity function only represent a lower limit to the true space densities, because they are defined by an additional optical selection effect that may or may not affect the infrared selection. That is, there may be more low luminosity infrared galaxies Mpc^{-3} than have already been found as optically bright galaxies. On the other hand, the fact that these low luminosity infrared galaxies exist in the CfA sample as known objects means that they must be included in the complete infrared luminosity function; that function cannot be truncated at only those luminosities seen in the samples derived from IRAS discoveries alone.

The largest other sample of optically discovered galaxies having redshifts is the Markarian sample, which gives another set of minimum limits to the infrared-luminous galaxies which must exist. Of the 1500 known Markarian galaxies, I found 487 with both redshifts and 60μ fluxes. Existing data on Markarian galaxies including 60μ fluxes are summarized by Mazzarella and Balzano (1986); their catalog was completed after my calculations so may include a few more redshifts than I utilized. Space densities from the CfA and Markarian samples are also listed in Table II, calculated assuming an IRAS 60μ flux limit for source detection of 0.5 Jy.

In Table III, the space densities of Table II are summarized into a single luminosity function that is adopted for the remainder of this paper. This Table also shows the proportion of galaxies in any luminosity bin that would already have been known from the optically derived samples compared to the number found from IRAS-derived samples. There are two interesting conclusions from this comparison; a few examples of the most infrared luminous galaxies were already known among optically discovered galaxies (such as Markarian 231, 171, NGC 7469, IC 4553), but infrared discovery observations find an increasingly higher percentage of the most luminous galaxies. This is a simple demonstration of the importance of IRAS for finding many examples of the most dramatic starburst systems. (It is fair to note that these percentages greatly underestimate the potential of optical techniques for finding such galaxies. No completeness corrections have been applied to the Markarian sample, and no allowance has been made for improved objective prism observations such as in Wasilewski (1983) that can significantly increase compared to Markarian's search the number of starburst galaxies found optically.)

Table III
Space Densities and Luminosity Function Adopted at 60μ

d Log L_ν	Space Density # Mpc^{-3}	minimum known optically	log L_ν	log Ψ Ψ has units # $Mpc^{-3} > L_\nu$
29 -29.4	$>4.4x10^{-2}$	100%	29	>-1.18
29.4-29.8	$>1.0x10^{-2}$	100%	29.4	>-1.64
29.8-30.2	$5.5x10^{-3}$	65%	29.8	-1.90
30.2-30.6	$4.7x10^{-3}$	28%	30.2	-2.15
30.6-31	$1.8x10^{-3}$	23%	30.6	-2.61
31 -31.4	$4.8x10^{-4}$	20%	31	-3.19
31.4-31.8	$1.3x10^{-4}$	9%	31.4	-3.80
31.8-32.2	$2.5x10^{-5}$	3%	31.8	-4.52
32.2-32.6	$4.3x10^{-6}$	1%	32.2	-5.30
32.6-33	$5.7x10^{-7}$	0.3%	32.6	-6.16
33 -33.4	$1.2x10^{-7}$	0%	33	-6.92

3. SOURCE COUNTS IN INFRARED AND RADIO, AND THE X-RAY BACKGROUND

3.1. Results at 60μ

The luminosity function in Table III, derived from various uses of IRAS fluxes, provides a starting point for predictions for how many star-forming galaxies should be seen in the universe with various observing techniques. Such predictions are commonly presented in terms of source counts as a function of flux limit, or "log N - log S" plots. The easiest way to make such calculations is as a sum of the number of galaxies seen in successive volume shells of the universe. Let dN(z) be the number of galaxies within a redshift interval dz having volume interval dV seen to a given flux limit. Then $dN(z) = \Psi[L(z)]dV$, for L(z) the minimum luminosity which can be reached for observations at z with the flux limit used. All of the results presented use a cosmology with q_o = 0.1, although the precise form is not important for most results, and H_o = 75. The methodology and necessary cosmological equations are summarized in Weedman (1986). All calculations for the infrared use a continuous spectrum of form $f_\nu \propto \nu^{-2}$, an index corresponding to that between 25μ and 60μ for typical galaxies in the samples used to construct the luminosity function.

Expectations for observations at 60μ are in Table IV, carried to a final flux limit of 0.5 mJy. Not surprisingly, the number of sources to be found increases rapidly with flux limit. The characteristic redshift of sources also increases but does not reach very large values even for faint flux limits because source counts are contaminated by the many low luminosity, nearby objects. If the most luminous objects could be traced, they would be visible to great distances. This is shown by the values of maximum redshift at which a galaxy with log L_ν = 33 could be seen.

Table IV
Predicted Source Counts and Redshifts for 60μ Flux Limits

Flux limit (Jy)	# deg^{-2} >f(60μ)	most probable z	highest z
11	0.01	0.0030	0.07
4.4	0.038	0.0045	0.10
1.8	0.15	0.0070	0.15
0.7	0.53	0.011	0.23
0.28	1.9	0.017	0.33
0.11	6.5	0.026	0.48
0.045	21	0.040	0.66
0.018	67	0.065	0.90
0.0072	200	0.095	1.22
0.0029	580	0.14	1.61
0.0012	1540	0.21	2.10
0.0005	3800	0.28	2.70

3.2. Relation to Radio Source Counts

Contrary to some expectations, deep radio surveys with the VLA did not reveal progressively increasing fractions of radio sources to be faint and distant quasars. Instead, a new population of intrinsically faint but relatively nearby galaxies begins to appear at flux levels of a few times 10^{-4} Jy (Condon 1984, Windhorst et al. 1985). From their blue colors, these seem to be starburst galaxies. The radio properties of starburst galaxies and IRAS sources in general deserve increased attention, and are getting it (see papers by Dressel, Wielebinski, Fich, and Eales and Wynn-Williams, this meeting). Data so far available indicate very similar ratios of infrared to radio flux, as would be expected if both are the consequence of the same starburst (e.g. Helou, Soifer and Rowan-Robinson 1985). For my calculations, I adopt the mean ratio f(60μ)/f(20cm) = 350 from the 8 starburst systems measured with both the VLA and IRAS from Sramek and Weedman (1986). Applying this to the luminosity function of Table III predicts the radio counts at 20 cm given in Table V. Fluxes associated with the counts in Table V can be rescaled proportionally if another value is adopted for the f(60μ)/f(20cm) ratio.

These expectations are consistent with the observed radio counts to the extent that the infrared galaxies predict a significant portion of but do not exceed the observed source counts. For example, Windhorst, Kron and Koo (1984) find 50 sources deg^{-2} to 6×10^{-4} Jy at 20 cm. There is much room and great potential for new and exciting results in correlating the infrared and radio properties of faint starburst systems. These may prove to be the dominant component for the faintest radio counts. Conversely, the radio counts can provide useful constraints to deductions from infrared data, which encourages further efforts at improved correlations between data from the two wavebands.

3.3. The Extragalactic Diffuse X-ray Background

The most outstanding puzzle in observational X-ray astronomy is that of the source of the diffuse X-ray background at energies above one KeV (Boldt 1981). This background seems to fill the extragalactic sky evenly and so must

Table V
Radio Source Counts of Starburst Galaxies at 20 cm

Flux limit (Jy)	# deg^{-2}>f(20cm)
0.29	0.0003
0.12	0.0014
0.047	0.006
0.0019	0.023
0.0075	0.088
0.0030	0.34
0.0012	1.2
0.0005	4.5
0.0002	16

arise from very distant sources. (The lower energy background has structure that correlates with the Milky Way Galaxy, so is attributed to various Galactic sources.) Much effort has gone into asking what sources could explain this background. Quasars, for example, could with sufficient evolution arise in adequate numbers to explain the background, except that the observed steep X-ray spectra of quasars are in gross disagreement with the flatter, seemingly thermal, spectrum of the background. Perhaps the background is associated with diffuse processes in the early universe, or perhaps it hints at an as yet unobserved population of objects. The exciting result from the infrared data is that starburst galaxies can play a significant, perhaps dominant, role in explaining this X-ray background.

Once again, I start with the starburst galaxy luminosity function in Table III. The answer for the predicted background will simply be a lower limit. The reasons are several. Low luminosity galaxies in large numbers could be significant for any background, which is by definition the integrated flux from many sources too faint to be resolved. Yet, the infrared luminosity function in Table III is truncated at log L(60μ) = 29, with no allowance for fainter galaxies that could conceivably exist in large numbers, given the steepness of the luminosity function. Furthermore, star formation should have been more common in the early universe, but no evolution is included in my calculation. Finally, the sum of sources is carried only to z = 3, because that is where the high redshift observables (quasars) cease, even though the presence of heavy elements in those same quasars shows that star formation must have predated their epochs.

It is possible empirically to ratio infrared and X-ray fluxes using a few star-forming systems with both Einstein and IRAS fluxes. The result I adopt arises from 12 galaxies in Fabbiano, Feigelson and Zamorani (1982) whose mean ratio f(60μ)/f(2keV) = 2.7×10^8. Extremes of this value range from 4.7 to 0.4. An improved determination of this ratio could be folded into the calculation simply by scaling the predicted X-ray background in proportion, as long as the ratio is not taken as a function of luminosity. Another uncertainty lies in the X-ray spectrum of starburst systems, of which nothing is known. (This ignorance may be considered an advantage for the modeler since that lessens demands on one's model.) Because existing galaxy observations are at 2 keV, that is the energy of the background calculation made. It is necessary to adopt a spectrum to account for K-corrections at high redshifts; because matching the background is the target, I adopt a spectral index of -0.4 to resemble that observed for the background near this energy.

The results are quite exciting, predicting without source evolution a 2 keV background from faint, unresolved X-ray sources of 1.3×10^{-7} Jy deg^{-2}, or 13% of the observed background. The sources are so common (over 10^6 deg^{-2}--see next section) that this background would appear unstructured. Applying source luminosity evolution proportional to $(1+z)^2$, not unreasonable since quasars evolve as about $(1+z)^4$, approximately doubles the background. The most critical need at the moment to pursue this idea further is improved X-ray data on starburst galaxies; it is obvious, however, that with relatively minor modifications to the parameters used the starburst galaxies could prove to be the primary source of the extragalactic X-ray background.

4. THE SHROUD OF THE UNIVERSE

Among the more pressing cosmological mysteries are the issues of why no primordial galaxies can be seen (e.g. Sunyaev et al. 1978) and why quasar numbers rapidly diminish beyond redshift of about 2.5 (Osmer 1982, Schmidt, Schneider and Gunn 1986). Various speculators have wondered if one or both of these effects might be caused by dust obscuring the background universe. Here, as well, the infrared galaxy luminosity function is a necessary step toward learning the answer. For this use, we no longer care what is heating the dust, but simply use the infrared-luminous galaxies as tracers of dust. Obviously, the results will be lower limits, because we omit objects containing dust that is not heated enough to radiate and omit objects with luminosities too low to be included in Table III.

To consider dusty galaxies as obscurers rather than emitters requires some modifications in cosmological considerations. Fluxes and luminosities no longer are relevant; all that counts is the total area of the sky covered up by all galaxies to a given redshift, regardless of the luminosities of these galaxies. A very important cosmological effect enters, which is that the angular diameter of galaxies decreases very little with redshift beyond z about unity. Unlike its contribution to flux, the obscuring ability of a galaxy changes little with redshift in those redshift regimes where the total number of galaxies is increasing dramatically. For example, with $q_o = 0.1$ and $H_o = 75$, the angular diameter subtended by 10 kpc remains almost constant at 1.3" for all $z>1$.

As was done for the source count calculations, the numbers of galaxies per shell of volume are summed to the cutoff redshift, also taken here as $z = 3$. Truncating the luminosity function at the luminosity in Table III, there are at least 6.6×10^{-2} dusty galaxies Mpc^{-3}. Carrying these to $z = 3$ with the cosmology assumed yields 1.1×10^6 galaxies deg^{-2}. It is easy enough to weight each of these by actual size, because the great majority of them are at $z>1$ where their angular size no longer changes with z. From this result, it is found that the fraction of the universe beyond $z = 3$ which is obscured by these galaxies closer than $z = 3$ is $4.5 \times 10^{-3} R^2$, for R the effective radius of the absorbing material in kpc.

This result illustrates the critical importance of obtaining infrared imaging data on galaxies to determine reasonable values for R. Note presentations at this meeting by Telesco, Low, and Rice. Recalling that most of the galaxies in the luminosity function are normal spirals, R may approach 10 kpc. In that case, the obscured fraction approaches unity, and could easily exceed unity if allowance were made for the faint or cold but dusty galaxies not included in the luminosity function used. Regardless of the conclusions finally reached, the IRAS data give us unambiguous proof that dust plays a significant role in governing the observable properties of the distant universe.

5. PUZZLES AND PROGRESS

There are many other aspects of investigating starburst galaxies whose importance is not diminished by the fact that I did not review them thoroughly. For example, I trust that A. Toomre will give what is due to those theorists who are struggling commendably with understanding why starbursts happen at all. Work by Struck-Marcell and Scalo discussed at this meeting is particularly relevant and diligent. Another area exciting in its own right is the molecular radio astronomy which attempts to understand how the presence of giant molecular clouds couples to the starburst phenomenon. There is no question that extensive CO emission correlates with infrared flux, as discussed in the literature and at this meeting by Young et al., Lo et al., and Solomon. Which ingredient was needed first; did the dust have to be there to make the molecules, or are the stars which made the dust there because of the raw material in the molecular clouds?

Another intriguing molecular observation is that of the megamasers such as originally emphasized by Baan and Haschick (1984) and discussed here by Bottinelli et al. and by Norris. These require not only dense molecular clouds between the observer and galactic nucleus, but also strong continuum radio sources in those nuclei. Such sources, as the ones in IC 4553, NGC 3079 and NGC 3690, are usually unresolved and accompanied by strong infrared sources (see the paper by Becklin and Wynn-Williams). To me, these sources are great puzzles. It is hard to understand how a starburst of the luminosity required, especially to explain the radio fluxes, can be compressed in such a small volume. These objects may prove to be important hybrids of starbursts plus something more mysterious. The entire question of why there are starbursts in and near galactic nuclei and how these relate to other forms of active nuclei is a basic one. Observationally, note papers here as well as earlier work by Turner, Keel, and Wilson which illustrate the various techniques being used to probe these nuclei; Norman has been worrying about the theory to explain these events and their consequences.

Various programs underway for intensive spectroscopic follow ups of IRAS sources are reported here by Houck, Savage et al., Dennefeld, and Smith et al. Beyond making major progress toward understanding the luminosity function and distributions of galaxy types, such observations are also the opportunity for finding really weird things. For example, are there more galaxies out there like Markarian 231? We knew 15 years ago that this object has a very strange optical spectrum, having a Seyfert 1 broad line region, absorption lines from young stars, and blueshifted absorption lines from dense interstellar material. I thought initially it was a more or less normal Seyfert galaxy with an absorbing cloud which happened to be in front of the nucleus, but the exceptional infrared luminosity now known implies that the absorption is much more widespread. Optical observers have found no other similar objects. Are there many hidden in the IRAS lists?

Seeking to answer such questions illustrates a basic value of surveys such as that of IRAS: these produce a treasure trove that keeps astronomers in many specialties busy and excited for years. Closing on that note, the IRAS teams deserve much commendation for their efficiency in making this marvelous data base so quickly and easily available to the rest of us.

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DISCUSSION

MONTMERLE:

You made the suggestions that starburst galaxies could explain the diffuse x-ray background. However, this background extends out to several 10 kev, whereas, to my knowledge, such high energies in our Galaxy, relate only to x-ray sources like compact binaries, etc. The Galactic star forming regions themselves may be associated with temperatures of 10-12 kev at most (see the recent 'Tenma' results). Therefore, what kind of observational evidence in our Galaxy may support your suggestion? Or are you thinking in terms of special processes not observed in Galactic star-forming regions?

WEEDMAN:

I don't know the answer for our Galaxy. Because there are no extragalactic starburst systems with 10 kev data, I didn't consider that energy in my analysis.

LOW:

Have you used the new infrared luminosity function to re-calculate the diffuse infrared background? It is possible to extract a diffuse extragalactic component from the IRAS data at $100\mu m$.

WEEDMAN:

I have determined a number, but did not present it because I wasn't aware of any meaningful measurements that could extract the extragalactic background from Galactic and zodiacal backgrounds.

BURBIDGE:

Since you have a $60\mu m$ luminosity function, can you look at the production of helium in galaxies? In effect, the amount of helium produced by hydrogen burning in galaxies is now greater than we originally expected it to be because the bolometric luminosity of galaxies integrated over the age of the universe is greater.

WEEDMAN:

What you suggest is an important consistency check that I have not done.

SCOVILLE:

Could you comment on the relative shapes and number densities of the IRAS galaxy and quasar luminosity functions.

WEEDMAN:

I have not compared them to determine the luminosity at which the space densities are comparable. At most luminosities, the galaxies greatly dominate, but at the very highest luminosities, there are only quasars. My definition of quasars includes Seyfert 1 galaxies, so the real issue should be to try to produce thermally vs. non-thermally derived luminosity functions.

GALLAGHER:

In considering the issue of 'extra' bolometric luminosity that has been found by IRAS (e.g., with regard to Geoff's questions about He production), don't you have to distinguish between blue, near constant SFR systems that surprise us by radiating much of their power in the infrared, and true bursts which surprise us by having a much larger bolometric luminosity than we would have expected from optical data? Do you have any estimates for the relative infrared luminosity contributions of these two classes of Markarian systems?

WEEDMAN:

I have not tried to distinguish starbursts at various levels from more equilibrium star formation in the luminosity function given. The hope is that we are observing a representative statistical sample of the total $60\mu m$ luminosity at a given epoch of the universe, and that the average would remain the same even as individual galaxies come and go.