

UCLA

UCLA Previously Published Works

Title

An Empirically Based Calculation of the Extragalactic Infrared Background

Permalink

<https://escholarship.org/uc/item/2tq023qx>

Journal

The Astrophysical Journal, 496(1)

ISSN

0004-637X

Authors

Malkan, MA

Stecker, FW

Publication Date

1998-03-20

DOI

10.1086/305384

Peer reviewed

**AN EMPIRICALLY BASED CALCULATION OF THE
EXTRAGALACTIC INFRARED BACKGROUND**

M. A. Malkan

Department of Physics and Astronomy, University of California, Los Angeles,
Los Angeles, CA 90095-1562

F. W. Stecker

Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center,
Greenbelt, MD 20771

The Astrophysical Journal, in press.

Received _____; accepted _____

ABSTRACT

Using the excellent observed correlations among various infrared wavebands with 12 and $60\mu\text{m}$ luminosities, we calculate the 2-300 μm spectra of galaxies as a function of luminosity. We then use 12 μm and 60 μm galaxy luminosity functions derived from IRAS data, together with recent data on the redshift evolution of galaxy emissivity, to derive a new, empirically based IR background spectrum from stellar and dust emission in galaxies. Our best estimate for the IR background is of order 2-3 $\text{nW m}^{-2} \text{sr}^{-1}$ with a peak around 200 μm reaching $\sim 6\text{-}8 \text{ nW m}^{-2} \text{sr}^{-1}$. Our empirically derived background spectrum is fairly flat in the mid IR, as opposed to spectra based on modeling with discrete temperatures which exhibit a pronounced “valley” in the mid-IR. We also derive a conservative lower limit to the IR background which is more than a factor of 2 lower than our derived flux.

Subject headings: infrared: general – diffuse radiation – infrared: galaxies

1. Introduction

The extragalactic diffuse IR background has long been recognized to contain important information about the evolution of galaxies. More recently, studies of the IR background have become important to very-high-energy γ -ray astronomers because pair-production interactions of multi-TeV γ -rays with extragalactic IR photons are an important source of extinction of extragalactic γ -rays (Stecker & De Jager 1977a and references therein). Indeed, one empirical way to determine the IR background flux is to look for absorption of TeV γ -rays in the spectra of blazars (Stecker, De Jager & Salamon 1992).

Stecker, Puget & Fazio (1977) made an early estimate of the extragalactic IR background and showed that if galaxies radiate a significant fraction of their energy from stellar nucleosynthesis in the mid to far IR range, the background flux would be of the order of $10 \text{ nW m}^{-2}\text{sr}^{-1}$. The COBE-DIRBE detector has now obtained extragalactic residual flux measurements which approach or reach this range (Hauser 1996). There have been many attempts to model the expected IR background from galaxies; they have recently been reviewed by Lonsdale (1996).

In this letter, we take an alternate approach. Rather than modeling the IR emission from galaxies using assumptions such as theoretical dust temperature distributions, we base our calculations on empirical studies of the IR spectra of galaxies with a wide distribution of intrinsic luminosities, and on empirically determined luminosity functions for these galaxies.

2. Infrared Spectra of Galaxies

The starlight spectra of all but the youngest galaxies have a peak in νL_ν from red giants around $1\text{--}1.5\mu\text{m}$, and drop as a Jeans tail at wavelengths longer than $2\mu\text{m}$. At wavelengths longer than $3\mu\text{m}$, spiral galaxies emit by thermal radiation from dust grains,

which are warmed to a very wide range of temperatures, from a minimum of 15–20 K to a maximum which can exceed 800 K (Joseph, Meikle, Robertson & Wright 1984). Because of this very large temperature range, modelling of the diffuse mid-IR and far-IR background from thermal dust emission from a large sample of galaxies by choosing one, or even two temperatures is not realistic. This is why our empirical approach is preferable to what has been done previously.

Observations with the Infrared Astronomy Satellite (IRAS), combined with other data, have indicated that the infrared (10^{12} to 10^{14} Hz) spectra of all types of spiral galaxies depend systematically on their total luminosity. There are well-determined relations between the luminosity emitted in a given infrared waveband with the luminosity at $60\mu\text{m}$. Spinoglio, *et al.* (1995) established tight empirical correlations relating 100, 60, 25, $12\mu\text{m}$ and $1.2\text{--}2.2\mu\text{m}$ (NIR) luminosities with the bolometric luminosity of Seyfert and non-Seyfert galaxies. We have combined these relations so that for any given value of L_{12} or L_{60} , we can predict the luminosities at all other infrared wavelengths. The luminosities at 2.2 and $3.5\mu\text{m}$ in WHz^{-1} were estimated from the relation for L_{NIR} (given in Watts), as $L_{3.5} = 1.50L_{2.2} = 2.05 \times 10^{-14}L_{NIR}$ for Seyfert 1 galaxies, $L_{3.5} = 1.08L_{2.2} = 1.20 \times 10^{-14}L_{NIR}$ for Seyfert 2 galaxies, and $L_{3.5} = 1.06L_{2.2} = 1.01 \times 10^{-14}L_{NIR}$ for non-Seyfert galaxies. We have extrapolated to wavelengths longer than $100\mu\text{m}$ using the correlation of far-infrared color temperature with the parameter α_{60-100} given by Spinoglio, *et al.* (1995) in their Appendix B, derived from far-infrared photometry data obtained from the Kuiper Airborne Observatory. Luminosities at all other wavelengths were then estimated by linear interpolation in $\text{Log}(\nu)$ versus $\text{Log}(L_\nu)$.

The largest proportions of hot dust are found in galaxies with the highest rates of current star formation. This results in a systematic trend for more luminous galaxies to emit relatively hotter infrared spectra. We illustrate this gradual trend in Figure 1, which shows

the IR spectra of galaxies with luminosities taken differing by various factors of 10 from $L_* = 10^{22.2} \text{ W Hz}^{-1}$, ranging from $10^{-3} L_*$ to $10^3 L_*$. The luminosity correlations among the various IR wavebands are very tight for all kinds of non-Seyfert spiral galaxies ($\sim 90\%$ of spirals), including those classified as “normal”, “LINER”, and “Ultraluminous”. Thus over more than four orders of magnitude of luminosity, the infrared spectra of galaxies change gradually and continuously. The data do not support any clear quantitative distinction into separate categories of galaxies (such as “starbursts” or “hyperluminous” or “dwarfs”). For this reason, we can use a single luminosity function (LF) obtained from $60\mu\text{m}$ surveys to represent all IR emitting galaxies. (Elliptical galaxies, being dust-poor, are not significant enough mid-IR and far-IR emitters to be included in our calculation).

3. Galaxy Luminosity Functions

The total diffuse IR background at a given frequency is calculated by integrating over the luminosity function of galaxies and then integrating over redshift. (See, *e.g.*, the formalism in Stecker & Salamon (1996) for a derivation of diffuse background flux from unresolved point sources). We have used two different assumed galaxy luminosity functions, both of which are derived directly from IRAS source catalogs having complete spectroscopic redshift measurements. The first is the Extended 12 Micron Galaxy Sample (Rush, Malkan & Spinoglio 1993), which is based on a $12\mu\text{m}$ flux-limited sample of 893 galaxies. The second is the sample of 2818 galaxies selected at $60\mu\text{m}$ by Saunders *et al.* 1990). Both differential luminosity functions are adequately fitted by a double-power-law function of the form:

$$\phi = C(L/L_*)^{1-\alpha}[1 + (L/\beta L_*)]^{-\beta} \quad (1)$$

with low-luminosity slopes of $\alpha = 1.35$ and 1.7 for the respective $12\mu\text{m}$ and $60\mu\text{m}$ LF’s, steepening by $\beta = 2.11$ and 3.6 respectively, around a “knee” at $L_* = 10^{24.22} h_{50}^{-2} \text{ W Hz}^{-1}$

and $10^{23.0} h_{50}^{-2} \text{W Hz}^{-1}$, respectively. The value given by Saunders, *et al.* (1990) for the normalization constant of the $60\mu\text{m}$ LF is $C_{60} = 3.25 \times 10^{-3} h_{50}^3 \text{Mpc}^{-3} \text{dex}^{-1}$. The value for the $12\mu\text{m}$ normalization constant, obtained from the data of Rush, *et al.* (1993), is $C_{12} = 2.7 \times 10^{-3} h_{50}^3 \text{Mpc}^{-3} \text{dex}^{-1}$.

The Saunders, *et al.* (1990) luminosity function is similar to that of the QDOT survey (Lawrence, *et al.* 1986) and the BGS (Soifer, *et al.* 1987). In particular all of these LF's agree extremely well on the volume density of galaxies within an order-of-magnitude of L_* . We confirmed that our results are hardly changed (by less than 10% at any frequency) by substituting any of these $60\mu\text{m}$ LFs into our integration.

4. The Background Calculation

In order to calculate the total contribution to the IR background from sources emitting at various redshifts, we must extrapolate the luminosity function data, obtained mainly for low-redshift galaxies, all the way to the redshift of initial galaxy formation, z_{max} . At present, IR observations of galaxies at high redshifts are severely limited. Although optical and ultraviolet searches tend to discover high-redshift galaxies with apparent visual absorptions of less than half a magnitude, near-infrared searches are capable of finding substantially dustier galaxies (Malkan, Teplitz and McLean 1995; 1996). A recent deep ISOCAM $7\mu\text{m}$ image of the Hubble Deep Field appears to have reliably detected 13 galaxies at $z \leq 0.5$ (Rowan-Robinson, *et al.* 1997). Assuming these identifications are correct, they imply a very high rate of mid-infrared emission from luminous IR galaxies at $z=1$.

The redshift evolution of the infrared galaxy LF is only weakly constrained at present. Saunders, *et al.* (1990) found that their data could be fitted by a luminosity evolution with $Q = 3 \pm 1$. A more recent analysis of a deep sub-sample of the IRAS Faint Source

Survey by Bertin, Dennefeld & Moshir (1997) finds evidence for strong evolution of IRAS galaxies with $Q = 3.2 \pm 0.2 \pm 0.3$ out to a redshift of 0.3. Previous studies by Soifer, *et al.* (1987), Lonsdale, *et al.* (1990) and Pearson & Rowan-Robinson (1996) have come to similar conclusions regarding the redshift evolution of IRAS sources. The analysis of Gregorich, *et al.* (1995), which indicated even stronger evolution, and which would lead to predictions of a higher IR background, appears to disagree with other analyses; their sample may have been contaminated by false detections (Bertin, *et al.* 1997).

Lilly, *et al.* (1996) found strong galaxy evolution at 280 nm, a wavelength which reflects instantaneous (rather than cumulative) star formation activity. Their value for Q was in the range of 3 to 4, depending on the cosmological model chosen. If, as is generally believed, short-wavelength emission from hot, young O and B stars is reradiated by dust in the far IR, a consistency with the IRAS and ISO studies emerges. Pei & Fall (1995) analysed the evolution of neutral hydrogen gas in damped Ly α systems seen in quasar spectra. Their study indicated that the star formation rate in the universe peaks at a redshift between 1 and 2, evolving roughly as $(1+z)^{3\pm 1}$ at lower redshifts and falling off at higher redshifts. Such evolution is consistent with recent studies of the redshift distribution of galaxy emissivity and corresponding star formation history by Lilly, *et al.* (1996), Cowie, Songaila, Hu & Cohen (1996), Madau, *et al.* (1996), and Connelley, *et al.* (1997).

We have therefore evolved the locally-determined galaxy LF to higher redshift assuming (1) pure luminosity evolution of the form $L(z) = L_0(1+z)^Q$ for $z \leq z_{flat}$, (2) no evolution, *i.e.*, $L(z) = L_0(1+z_{flat})^Q = \text{const}$, for $z_{flat} \geq z \geq z_{max}$, and (3) no emission, *i.e.*, $L(z) = 0$, for $z \geq z_{max}$. Since it has been fairly well established that the stellar emissivity from galaxies peaks at a redshift between 1 and 2 (see above), we assumed values for z_{flat} of 1 and 2, $z_{max} = 4$, and $Q = 3$ for our “best upper and lower estimates”. (We checked that pure density evolution $\propto (1+z)^7$, which has less physical plausibility, gave very similar

results.)

The upper two (heavier) solid curves in Figure 2 show the result of our computation with $Q = 3$ for values of z_{flat} of 1 and 2 and a z_{max} of 4. (The solid lines are based on the $60\mu\text{m}$ LF, while the dashed lines were obtained using the $12\mu\text{m}$ LF with only the $z_{flat} = 2$ case and the conservative lower limit shown.) The estimated IR background is on average $\sim 20\%$ higher using the $60\mu\text{m}$ LF. (Note that, as given in the discussion following Eq. (1), C_{60} is greater than C_{12}). This might be attributed partly to some possible incompleteness in the $12\mu\text{m}$ survey versus the $60\mu\text{m}$ surveys with better sensitivity. We also note that the $12\mu\text{m}$ LF refers only to non-Seyfert galaxies, and therefore has a very steep high-luminosity cut-off. The $60\mu\text{m}$ LF, which does not separate out the Seyferts, therefore includes some extremely red galaxies with peak luminosities around $60\mu\text{m}$ that were not included in the $12\mu\text{m}$ calculation.

Seyfert galaxies make up approximately 10% of the IR background at $12\mu\text{m}$ and even less at longer wavelengths where non-Seyfert galaxies are relatively brighter. A crude indication of the relative contributions to the $12\mu\text{m}$ background from low-redshift Seyferts can be inferred from the fact that 53 of the 893 (6%) 12 Micron Galaxies are classified as type 1, and 63 (7%) are classified as type 2. We have calculated their contribution to the diffuse background and determined that it is less than 10%, assuming the same evolution as non-Seyferts.

A very conservative lower limit on the IR background spectrum was derived by assuming the least amount of galaxy luminosity evolution consistent with the IRAS galaxy counts, *i.e.*, $Q=2$ and a maximum redshift $z_{max} = 1$. This is the smallest z_{max} and evolution exponent which are allowed (*e.g.*, Rowan-Robinson *et al.*, 1997). The conservative lower limit is shown by the lower light lines in Figure 2 (with the $60\mu\text{m}$ LF calculation as the solid line and the $12\mu\text{m}$ calculation as the dotted line). The amplitude of this lower limit

flux is less than half of that calculated for the $z_{flat} = 1$, $z_{max} = 4$ estimate and less than one third of that calculated for the $z_{flat} = 2$ $z_{max} = 4$ estimate. The predicted shape of the lower-limit background spectrum is similar to that of our $z_{flat} = 1$ estimate; it differs from the $z_{flat} = 2$ case because the peak is shifted to slightly shorter wavelengths owing to the redshift cut-off. For similar reasons, the $3\mu\text{m}$ bump from redshifted starlight is relatively weaker, since we have cut off emission beyond $z = 1$.

5. Discussion and Conclusions

We can compare our best-estimate IR background spectra (the darker solid lines in Figure 2) with the presently existing data, and with previous calculations based on modelling. Figure 2 shows the COBE-DIRBE residuals given by Hauser (1996), upper limits determined from a fluctuation analysis of the COBE-DIRBE maps by Kashlinsky, *et al.* (1996), and the upper limit obtained from the lack of significant absorption in the γ -ray spectrum of Mrk 421 up to ~ 3 TeV by Stecker and De Jager (1993). Our results are also consistent with upper limits obtained by Dwek & Slavin (1994), also using TeV γ -ray data from Mrk 421. A power-law extrapolation of our results to wavelengths greater than $500\mu\text{m}$ would be consistent with upper limits obtained in that range from the FIRAS data by Fixsen, *et al.* (1996). Our best-estimate background spectrum agrees quite well with the claimed detection levels at wavelengths greater than $150\mu\text{m}$ obtained by Puget, *et al.* (1996) (not shown) based on an analysis of FIRAS data.

There are several uncertainties which could affect our results:

- (1) The redshift corresponding to the maximum star formation rate is, at present, not well defined.
- (2) Uncertainties in the galaxy LF at low luminosities do not affect our result much

because the integrated infrared luminosity is dominated by the contributions of galaxies within an order of magnitude of the luminosity knee at L_* .

(3) The contributions from galaxies at redshifts greater than those where the luminosity function is strongly evolving are substantially reduced by the cosmological factors involving geometry and energy redshifting. For this reason, our choice of the maximum redshift does not influence the results much. There is a more significant dependence on the redshift, z_{flat} , below which we assume $(1+z)^3$ luminosity evolution and beyond which we assume that no evolution occurred.

Our results are within 50% of previous results obtained by theoretical modeling (see review by Lonsdale 1996). They are in general agreement in flux level with the most recent calculation of Franceschini, *et al.* (1997). However, our spectrum, being based on empirical data, is somewhat different from many previous results which are based on theoretical modeling, *e.g.*, Franceschini *et al.* (1997) and previous work). In particular, the “valley” between stellar emission at a few μm and dust emission at $\sim 100\mu\text{m}$ is almost non-existent in our spectrum, because our empirical galaxy spectra automatically account for the very wide range of dust temperatures present.

The extragalactic infrared background fluxes calculated in this paper have been used to make new calculations of the absorption of extragalactic high energy γ -rays. The results of those calculations will be presented elsewhere (Stecker & De Jager 1997b,c).

REFERENCES

- Bertin, E., Dennefeld, M. & Moshir, M. 1997, A&A, in press preprint astro-ph/9610218
- Connelley, *et al.* 1997, preprint astro-ph/9706255
- Cowie, L.L., Songaila, A., Hu, E.M. & Cohen, J.G. 1996, A.J. 112, 839
- Dwek, E. & Slavin, J. 1994, ApJ 436, 696
- Fixsen, D.J., *et al.* 1996, ApJ 473, 576
- Franceschini, A., Mazzei, P. De Zotti, G., & Danese, L. 1994, ApJ 427, 140
- Franceschini, A., Andreani, P., & Danese, L. 1997, preprint astro-ph/9706022
- Franceschini, A., *et al.* 1997, preprint astro-ph/9707080
- Hauser, M.G. 1996, in *Unveiling the Cosmic Infrared Background*, ed. E. Dwek (AIP 348)
(New York: Amer.Inst.Phys.), p. 11
- Joseph, R.D., Meikle, W.P., Robertson, N.A., Wright, G.S. 1984, MNRAS 209, 111
- Kashlinsky, A., Mather, J.C., Odenwald, S. & Hauser, M.G. 1996, ApJ 470, 681
- Lawrence, A., *et al.* 1986, MNRAS 219, 687
- Gregorich, D.T., *et al.* 1995, AJ 110, 259
- Lilly, S.J., Le Fevre, O., Hammer, F. & Crampton, D. 1996, ApJ 460, L1
- Lonsdale, C. 1996, in *Unveiling the Cosmic Infrared Background*, ed. E. Dwek (AIP 348)
(New York: Amer.Inst.Phys.), p. 147
- Lonsdale, C. *et al.* 1990, ApJ 358, L60

- Madau, P., *et al.* 1996, MNRAS 283, 1388
- Malkan, M. A., Teplitz, H. I., McLean, I.A. 1995, ApJ 448, L5
- Malkan, M.A., Teplitz, H. I., McLean, I. A. 1996, ApJ 468, L9
- Pearson, C. & Rowan-Robinson, M. 1996, MNRAS 283, 174
- Pei, Y.C. & Fall, S.M. 1995, ApJ 454, 69
- Puget, J.-L., *et al.* 1996, A & A 308, L5
- Rowan-Robinson, M., *et al.* 1997, preprint astro-ph/9707029
- Rush, B., Malkan, M.A. & Spinoglio, L. 1993, ApJS 89, 1
- Saunders, W., *et al.* 1990, MNRAS 242, 318
- Soifer, *et al.* 1987, ApJ 320, 238
- Spinoglio, L., *et al.* 1995, ApJ 453, 616
- Stecker, F.W. & De Jager, O.C. 1993, ApJ 415, L71
- Stecker, F.W. & De Jager, O.C. 1997a, ApJ 476, 712
- Stecker, F.W. & De Jager, O.C. 1997b, *Proc. Kruger National Park Workshop on TeV Gamma-Ray Astrophysics*, to be published
- Stecker, F.W. & De Jager, O.C. 1997c, submitted to ApJ Letters.
- Stecker, F.W., De Jager, O.C. & Salamon, M.H. 1992, ApJ 390, L49
- Stecker, F.W., Puget, J.-L. & Fazio, G.G. 1997, ApJ 214, L51
- Stecker, F.W., & Salamon, M.H. 1996, ApJ 464, 600

Figure Captions

Figure 1. Observed dependence of infrared spectra of non-Seyfert galaxies on luminosity, based on relations from Spinoglio *et al.* (1995). Spectra are plotted for luminosities between $10^{-3} L_*$ and $10^3 L_*$ by factors of 10 in luminosity.

Figure 2. Predictions of diffuse IR background from galaxies. Solid lines were calculated using the $60\mu\text{m}$ LF; dashed lines are from the $12\mu\text{m}$ LF. The upper two solid lines show the results of our “best estimates” using values of z_{flat} of 2 (upper solid line) and 1 (middle solid line) as described in the text. The lower light lines are based on our conservative lower limit assumptions about galaxy evolution. We also show the COBE-DIRBE residuals given by Hauser (1996) as vertical ranges, the upper limit in the L band ($\log\nu=13.93$) given by Kashlinsky, *et al.* (1996) (K), and the upper limit band given by Stecker & De Jager (1993) (SDJ).



