CONTRIBUTION OF INFRARED GALAXIES TO THE COSMIC BACKGROUND*

Frank J. Low
Department of Space Science, Rice University, Houston, Texas,
and Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona

and

Wallace H. Tucker
Department of Space Science, Rice University, Houston, Texas
(Received 12 July 1968)

The far-infrared background due to a superposition of infrared galaxies of the type recently observed is computed. It is shown that these galaxies contribute an amount of energy to the universe roughly equal to that radiated by the other galaxies and produce a far-infrared background peaking beyond 50 μ. It is likely that they account for most of the observed extragalactic radio background but not the 3°K microwave background.

The origins of the diffuse cosmic background found in different spectral regions have recently been widely discussed. Here we calculate the far-infrared background caused by a superposition of infrared galaxies of the type observed by Kleinmann and Low[1] and Low.[2] Of particular interest is the possible explanation of the 3°K microwave background as the gray-body tail on this far-infrared background with peaks near 50 μ. We find that this possibility is excluded by the fact that the infrared galaxies have radio spectra which add up to the observed level of the radio background at 10^8 Hz before the 3°K level is reached. We show that the bright infrared galaxies, which apparently comprise only one percent of all observable galaxies, contribute an amount of energy to the universe roughly equal to that radiated by the other galaxies, and produce a far-infrared background peaking beyond 50 μ and possibly the observed extragalactic radio background. If the 3°K microwave background is in fact a black body, it remains the predominant source of radiant energy in the universe by a factor of 10.

Kleinmann and Low[1] have reported infrared observations of five Seyfert galaxies out to 22 μ and Low[2] has reported similar data on the quasar 3C273. Radio and microwave data can be found in the literature. All these objects display the same type of far-infrared spectral distribution, i.e., that shown in Fig. 1, a fact which constitutes the chief observational basis for the existence of a bright far-infrared cosmic background.

Here we do not attempt to explain either the energy source or the radiative mechanism producing this infrared phenomenon. Nor do we attempt to establish observational criteria for membership in the class of infrared galaxies. It may be that all galaxies and quasars display this same phenomenon on some scale. This can only be determined by further observations and should not strongly influence the conclusions of this paper unless widely different spectral energy distributions are found.

Strictly speaking, the integrated background in any frequency interval due to a particular class of galaxies is proportional to $\int Ln(L)dL = n_{\text{tot}}\bar{L}$. Here L is the source luminosity in the given frequency interval, $n(L)dL$ is the number density of the particular class of galaxies with L between L and $L+dL$, n_{tot} is the total number density of the class, and $\bar{L}$ is the average luminosity of that class. Since only six infrared galaxies have been observed, and their infrared luminosities vary over a wide range, it is impossible to estimate the average $\bar{L}$ as computed above. Our approach will be to take the arithmetical mean of

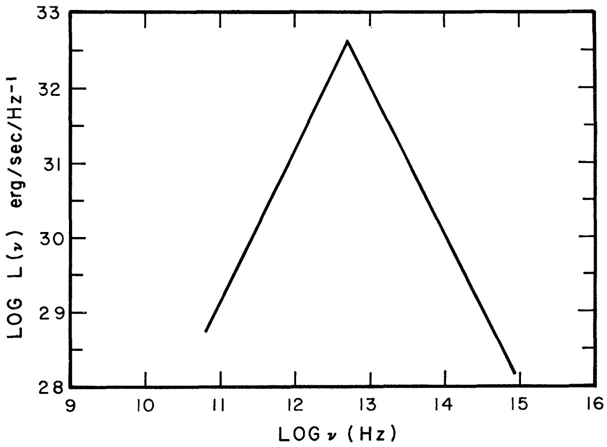

FIG. 1. Far-infrared spectral distribution of a typical infrared galaxy.

the infrared luminosity of the five Seyfert galaxies observed by Kleinmann and Low. Based on the observations of these galaxies, we have constructed a model infrared galaxy whose spectrum is shown in Fig. 1. This spectrum is described analytically as follows:

$$L(\nu)=A\nu^2 \text{ for } \nu \leqslant \nu_1,$$
$$=A\nu_1^2(\nu_1/\nu)^2 \text{ for } \nu \geqslant \nu_1,$$

where $\nu_1 = 5\times10^{12}$ Hz and $A=10^7$ Hz corresponding to a spectral luminosity at 5×10^{12} Hz of $L(5\times10^{12}\text{ Hz})=5\times10^{32}$ erg/sec Hz. The change in slope at 5×10^{12} Hz is necessary to join the microwave and infrared points. The radio spectrum is not shown because the radio luminosity varies so much from one infrared galaxy to another that it is very difficult to construct a model radio spectrum (see below).

The total number density of Seyfert galaxies has been estimated by Burbidge, Burbidge, and Sandage[3] to be about 1% of all galaxies, corresponding to a number density of 2×10^{-77} cm^{-3}. Schmidt's[4] observations of quasars indicate an excess (compared with the predictions of the usual relativistic cosmologies) of sources near redshift $z=\Delta\nu/\nu=2$. Schmidt shows that this can be interpreted as a density evolution relative to the cosmic expansion proportional to $(1+z)^m$ with a cutoff around $z=2$, where $m\approx3$. Since infrared galaxies appear to include both quasar and Seyfert galaxies, which are similar in many other respects, it is natural to assume that they might show such a density evolution too.

It has been shown[5] that the preponderance of redshifts around $z=2$ can be explained in terms of relativistic cosmologies with nonzero cosmological constants. Although it would perhaps be more satisfactory to compute the integrated flux for cosmological models of this type, we adopt here the procedure used by Silk[6] in his recent computation of the diffuse x-ray background. According to this procedure the effects of density evolution are taken into account by the introduction of a multiplicative correction factor into the usual integral for homogeneous Friedmann universes.[7] Therefore, the total integrated flux received from all infrared galaxies in the frequency interval between ν and $\nu+d\nu$ is given by

$$I(\nu)=(nR_{\mathrm{H}}/4\pi)\int_0^{z_{\max}}C(z)(1+z)^{-2}$$
$$\times(2q_0z+1)^{-1/2}L(\nu(1+z))dz.$$

Here n is the number density of infrared galaxies ($=2\times10^{-77}$ cm^{-3}), R_{H} is the Hubble radius ($=10^{10}$ light yr), q_0 is the deceleration parameter, and $z_{\max}$ is the redshift at which the optical depth due to Thomson scattering is equal to unity.[8]

In Fig. 2 the integrated spectral flux received from all galaxies is shown for the model infrared galaxies described in Fig. 1. Curve (1) is for a zero-pressure Friedman universe[7] having a deceleration parameter $q_0=\frac{1}{2}$ corresponding to a flat universe. Curve (2) represents the case $q_0=0.02$ corresponding to an open universe. This value of q_0 represents the lower limit to the mean matter density in the universe, i.e., that which is contained in ordinary galaxies and corresponds to $\rho_0=7\times10^{-31}$ g/cm^3.[9] On the other hand, the lifetime of the universe for general relativistic models with q_0 much greater than $\frac{1}{2}$ is uncomfortably close to the age of the earth[5,10]; so the values of q_0 used here are effectively the maximum and minimum values which this parameter can assume.

No density evolution relative to the cosmic expansion was assumed in computing curves (1) and (2). Curve (3) is for $q_0=0.02$ and a density evolution relative to the cosmic expansion proportional to $(1+z)^3$ for $z\leqslant2$, falling off as $(1+z)^{-3}$ for $2\leqslant z\leqslant9$, and no evolution relative to the cosmic expansion for $z\geqslant9$. Also shown in Fig. 2 are the observed radio background, the

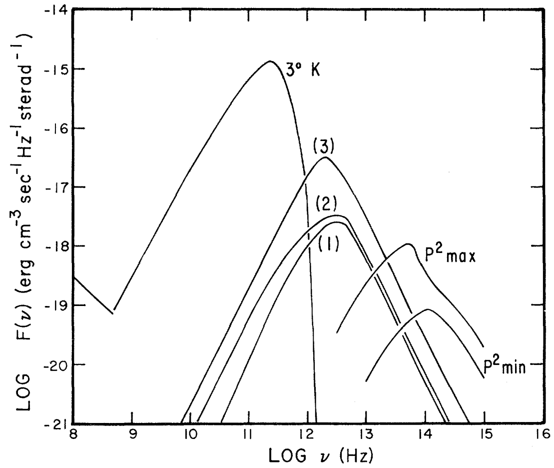

FIG. 2. Integrated background spectral flux due to infrared galaxies. The numbers refer to the different models discussed in the text. Also shown are the observed radio and microwave background, the 3°K blackbody curve, and the integrated flux from all other galaxies for two of the models computed by Partridge and Peebles which bracket all the models they considered.

3°K blackbody curve, and the integrated flux from all other galaxies for two of the models computed by Partridge and Peebles[10] which bracket all the models they considered.[11]

Several features of these curves are noteworthy. First, it is apparent that changing the cosmological model from one nonevolving model to another has little effect on the predicted flux (about 15%). Secondly, curve (3) shows that *if* the infrared galaxies have a density distribution with respect to z similar to that for quasars, the predicted flux is a factor 10 higher at the peak than for the models with no evolution. This correction *is* sensitive to the value of q_0. For $q_0=\frac{1}{2}$ the increase amounts to about a factor 6. Third, the predicted microwave flux is far below the 3°K blackbody value.

Also of interest is the radio flux from Seyfert galaxies. If one takes the arithmetical mean of the radio flux of the Seyfert galaxies observed by Kleinmann and Low, one obtains a radio spectrum which when treated in the same manner as the infrared yields a flux at 10^8 Hz which is a factor 5-50 (depending on the cosmological model) greater than the observed background. This discrepancy is no doubt due to the fact that the principal contributors to our average of the radio luminosities were NGC1275 and 3C120, both of which are a hundred times more luminous in the radio than most of the Seyferts. Since 3C120 and NGC1275 are the principal contributors to the infrared average, this suggests that our averaging procedure overestimates the flux by a large factor there as well. However, we do not believe this to be the case for the following reasons.

All the infrared luminosities lie within about a factor 10 of the average used here. Furthermore, the infrared emission appears to come from the nucleus of the galaxy, whereas the low-frequency radio emission comes from the halo. Thus there is not necessarily a connection between the two. A more relevant correlation would be expected to exist between the *optical* luminosity of the nucleus and the infrared luminosity. On this basis, at least two more of the 12 known Seyfert galaxies (NGC3516, NGC7469) should have infrared luminosities of the order of the value assumed here, even though they are weak radio emitters. Obviously, knowledge of the far-infrared flux from these objects is essential for an understanding of the far-infrared background.

In addition, it is important to know more precisely the radio properties of these objects and its relation to infrared emission. For, even if the average spectral luminosity of a Seyfert galaxy amounts to only 5×10^{30} erg/sec Hz at 10^8 Hz, they could account for most of the observed background at that frequency. Veron has recently examined the contribution to the radio background from radio galaxies and from normal galaxies.[12] He accounts for only 1/7 of the observed brightness. We suggest that Seyfert galaxies alone can account for the radio background. It appears that the 3°K background cannot be accounted for in any reasonable cosmological model without increasing the radio background above the observed level.

Figure 3 shows a plot of $\nu I(\nu)$ which has units of ergs cm^{-2} sec^{-1} sr, and therefore represents an approximation to the contribution in terms of total energy of the various types of electromagnetic radiation. Shown there are the contributions of the 3°K blackbody radiation, the infrared galaxies, the contribution of all other galaxies for the extremes of the models computed by Partridge and Peebles,[10] and the x-ray background. The contribution of the radio background is less than 10^{-10} erg/cm^2 sec^{-1} sr; so it is off the scale shown here. The figure shows that the infrared galaxies contribute an amount of energy to the universe roughly equal to that radiated by other galaxies and a factor 3-30 below the 3°K radiation.

There are two types of observations that can be made to confirm the reality of the predicted far-infrared cosmic background: (a) Direct observations near the peak at 100 μ using a wide

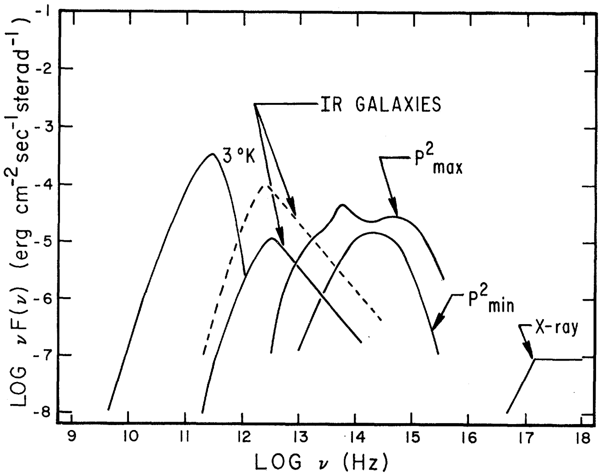

FIG. 3. Contribution of various types of electromagnetic radiation to the total radiant energy density in the universe.

field of view and a high throughput radiometer carried above the earth's atmospheric water vapor, and (b) a partial survey of the sky near 50 μ with a telescope capable of resolving and detecting large numbers of individual infrared galaxies. Method (b) is basically easier since it is much less sensitive to extraneous background radiation and deals with larger signals.

Once the spectral energy distribution is well determined for a representative sample of infrared galaxies, it should be possible to use the observations of method (a) as a sensitive test of cosmological models involving evolution.

---

*This work was supported by the National Science Foundation and the National Aeronautics and Space Administration.

[1] D. Kleinmann and F. Low, to be published.

[2] F. Low, Infrared Astronomy (Gordon and Breach Publishers, Inc., New York, 1968).

[3] G. Burbidge, E. Burbidge, and A. Sandage, Rev. Mod. Phys. 35, 947 (1963).

[4] M. Schmidt, Astrophys. J. 151, 393 (1968).

[5] V. Petrosian, E. Salpeter, and P. Szekeres, Astrophys. J. 147, 122 (1967).

[6] J. Silk, Astrophys. J. 161, L19 (1968).

[7] G. McVittie, General Relativity and Cosmology (University of Illinois Press, Urbana, 1965).

[8] J. Bahcall and E. Salpeter, Astrophys. J. 142, 1677 (1965).

[9] A. Sandage, Encyclopedia of Science and Technology (McGraw-Hill Publishing Company, Inc., 1966), Vol. 6, "Galaxy."

[10] R. Partridge and P. Peebles, Astrophys. J. 148, 377 (1967).

[11] It should be noted that Weymann [Astrophys. J. 145, 560 (1966)] has suggested that distortions of the blackbody curve could arise in the process of heating the intergalactic gas, if the heating occurred at a very early epoch when the intergalactic density was $\sim 10^2$ particles/cm^3. In that event, the emission from the intergalactic gas around 100 μ would be comparable with that predicted here.

[12] P. Veron, Ann. Astrophys. 30, 719 (1967).

PARTIAL PHOTOPRODUCTION CROSS SECTIONS UP TO 12 GeV*

J. Ballam, G. B. Chadwick, Z. G. T. Guiragossián, P. Klein, A. Levy,† M. Menke, E. Pickup, T. H. Tan, P. Seyboth,‡ and G. Wolf§
Stanford Linear Accelerator Center, Stanford University, Stanford, California

(Received 27 September 1968)

The Stanford Linear Accelerator Center 40-in. hydrogen bubble chamber has been exposed to positron-electron annihilation radiation at 5 and 7.5 GeV, which was superimposed upon a background of bremsstrahlung radiation with 12-GeV maximum energy. Reaction cross sections for events with no neutral particles are presented for all energies up to 12 GeV, for one neutral at 5 and 7.5 GeV, and for multineutral production at 7.5 GeV.

We report here the results obtained from a study of γp interactions produced by the Stanford Linear Accelerator Center (SLAC) annihilation beam in the SLAC 40-in. hydrogen bubble chamber. The special feature of this experiment is that the use of positron annihilation radiation allows a clean separation of events with a single neutral particle from multineutral events.

The experimental arrangement, and details of the analysis, have been given in another paper.[1] So far 10^6 pictures have been taken with this beam setup under various conditions and 180 000 have been analyzed to date: (I) 60 000 pictures with 10-GeV e^+, 5.2-GeV annihilation energy; (II) 60 000 pictures with 12-GeV e^+, 7.5-GeV annihilation energy; (III) 60 000 pictures with 12-GeV e^-, bremsstrahlung.

We present combined results from these three different exposures on the following reactions which can be completely analyzed:

$$\gamma p \to p\pi^+\pi^-, \tag{1}$$

$$\to p\pi^+\pi^-\pi^0, \tag{2}$$

$$\to n2\pi^+\pi^-, \tag{3}$$

$$\to p2\pi^+2\pi^-, \tag{4}$$

$$\to p2\pi^+2\pi^-\pi^0, \tag{5}$$

$$\to n3\pi^+2\pi^-. \tag{6}$$

The separation of reactions with a single neutral particle from those with more than one is made possible at 5 and 7.5 GeV by the small energy uncertainty of the annihilation peak in the photon-beam energy spectrum. For reactions with no missing neutrals in these topologies we are fur-