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Bruce Partridge
Haverford College, bpartrid@haverford.edu

P. J. E. Peebles

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Are Young Galaxies Visible? II. The Integrated Background

R. Bruce Partridge
Haverford College

P. J. E. Peebles

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ARE YOUNG GALAXIES VISIBLE? II. THE INTEGRATED BACKGROUND

R. B. PARTRIDGE AND P. J. E. PEEBLES
Palmer Physical Laboratory, Princeton University
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ABSTRACT

In a previous publication we presented a model for the formation of galaxies and for the properties of the young galaxies. In this article the time variation of the luminosity and spectrum of the model galaxy is used to compute the integrated background radiation due to the highly redshifted starlight from all the galaxies. This background is compared with the contribution from other sources, local and extragalactic. It is concluded that in the wavelength range from 5 to 15 μ it may be possible to pick out the integrated light of the distant galaxies. The intensity is within reach of present detection techniques.

I. INTRODUCTION

A central problem of cosmology is to find an acceptable picture for the formation and evolution of the galaxies. We have previously proposed a possible picture for how the galaxies formed, and we considered the possibility that it might be put to the test by a search for individual, highly red-shifted, young galaxies (Partridge and Peebles 1967). The purpose of this paper is to consider the possibility of a second kind of test of the proposed picture based on a measurement of the integrated light from all the distant young galaxies.

In recent years, a number of theoretical estimates have been made of the integrated background from the light from all distant galaxies (McVittie and Wyatt 1959; Law 1963; Whitrow and Yallop 1964, 1965). Because of the redshift of the light from numerous distant galaxies, the integrated background will reach a maximum in the infrared. Estimates of the spectrum and intensity of the background are of considerable current interest, since it appears likely that detailed infrared observations above the atmosphere will soon be possible, and also since it has been suggested that there may be an intergalactic plasma (Field 1959; Gunn and Peterson 1965) that would prevent observations of distant galaxies. The optical depth for scattering the light could reach unity at a redshift $1 + z = 8$ for acceleration parameter $q_0 = \frac{1}{2}$, and at a redshift $1 + z = 5$ for an acceleration parameter $q_0 = 1$ (Bahcall and Salpeter 1965).

In this paper, we have computed the integrated background from distant galaxies for two different cosmological models and for several assumptions about the evolutionary changes in the mean brightness and spectrum of the galaxies. The results are presented in Figures 6 and 7 (see below). An attempt to take account of the evolution of the galaxies was made by Whitrow and Yallop (1965), who assumed a black-body spectrum for the galaxies, with a time-dependent temperature. However, we believe it is important to calculate in some detail the luminosity and spectrum of galaxies as a function of time, using a particular model for galactic evolution. The basic assumptions of the model we will use are set out in the following section (see also Partridge and Peebles 1967) and are compared at a number of points with observations. The model predicts a highly luminous phase at an early epoch in the history of galaxies, followed by a slow decrease in luminosity and a gradual reddening of the spectrum (see Figs. 2 and 5 below). The derived background is compared with a number of other possible sources of infrared background. The comparison suggests that an experiment conducted above the atmosphere in the spectral region $5\ \mu \leq \lambda \leq 15\ \mu$ offers some chance of observing the light from distant galaxies. The expected brightness of the integrated background at 10 μ is in the range of 3×10^{-5} to 3×10^{-6} ergs/cm^2 sec sterad in a logarithmic frequency interval, a brightness within reach of present detection techniques.

II. THE INTEGRATED BACKGROUND FROM THE GALAXIES: BASIC ASSUMPTIONS

Our purpose in this section is to present some necessary general assumptions. In the next section we will describe a model for the evolution of galaxies. These assumptions and results are used in the fourth section to compute the expected integrated background.

a) Cosmological Model

In the calculation of the integrated light from the galaxies we adopt the conventional general relativity theory (without the cosmological constant), and we assume that the Universe is homogeneous and isotropic when averaged over a reasonable distance scale (perhaps 30 Mpc). Throughout this paper all lengths, times and so on are proper quantities as measured with ordinary rods and clocks.

The present value of the reciprocal of Hubble's constant is taken to be

$$H_0^{-1} = 1 \times 10^{10}\ \text{years}\,. \tag{1}$$

A fairly reliable lower limit to the mean matter density in the Universe is that contained in ordinary galaxies, 7×10^{-31} gm/cm^3 (Oort 1958; van den Bergh 1961). We assume that the mean mass density in radiation and neutrinos may be neglected. Direct measurements of the acceleration parameter (Sandage 1961) would admit a total mass density as high as 10^{-28} gm/cm^3 (acceleration parameter $q_0 \lesssim 3$). However, a mass density this high would make the expansion time of the Universe less than the age of Earth. We assume therefore that, if the Universe is closed, it is still in the early stages of expansion, with the acceleration parameter nearly equal to 0.5. The present value of the mean mass density ρ_0, then, is assumed to be in the range

$$2 \times 10^{-29} \gtrsim \rho_0 \gtrsim 7 \times 10^{-31}\ \text{gm/cm}^3\,. \tag{2}$$

From the assumed homogeneity and isotropy of the Universe it follows that the integrated intensity of the radiation from the galaxies is given by the formula

$$i(\nu_0,t_0) = \int_0^{t_0} \frac{\mathfrak{E}(\nu(t),t)\,c\,dt}{4\pi(1+z(t))^3}\,, \tag{3}$$

where

$$\nu(t) = \nu_0(1 + z(t))\,. \tag{4}$$

In equation (3), $i(\nu_0,t_0)$ is the present value of the radiation energy flux per steradian and per unit frequency interval, evaluated at the frequency ν_0. In the integral, $\mathfrak{E}(\nu(t),t)$ is the total luminosity of the galaxies per unit volume and per unit frequency interval, evaluated at the frequency $\nu(t)$ given by equation (4). As usual the redshift $z(t)$ in equations (3) and (4) is defined as the fractional increase in the wavelength of a photon in the time interval from t to the present time t_0.

When galaxies are not created or destroyed the mean number of galaxies per unit volume satisfies the equation

$$n(t) = n(t_0)\,(1 + z(t))^3\,. \tag{5}$$

Using this equation we can reduce equation (3) to the desired form:

$$i(\nu_0,t_0) = \mathfrak{E}(\nu_0,t_0)\int_0^{t_0} \frac{\mathfrak{L}(\nu(t),t)}{\mathfrak{L}(\nu_0,t_0)}\,\frac{c\,dt}{4\pi}\,. \tag{6}$$

Here $\mathfrak{L}(\nu(t),t)$ is a mean of the luminosity per frequency interval per galaxy at time t. Thus, to calculate the integrated background we need to find the present mean luminosity per unit volume from the galaxies, $\mathfrak{E}(\nu_0,t_0)$, and we need to estimate the ratio $\mathfrak{L}(\nu(t),t)/\mathfrak{L}(\nu_0,t_0)$, that is, to estimate how the mean luminosity of the galaxies has varied with time.

b) Mean Luminosity per Unit Volume

Values for the present total luminosity per unit volume of galaxies are listed in Table 1. There are three independent determinations, based on rather different methods, and they agree fairly well. We adopt the mean of the three values. Taking the absolute photographic magnitude of the Sun to be $M_{pg} = 5.16$, we find that the mean emission per unit volume and per logarithmic frequency interval is

$$\nu_0\mathfrak{E}(\nu_0,t_0) = 2.5 \times 10^{-32} \text{ ergs/sec cm}^3 \tag{7}$$

at the wavelength

$$\lambda_0 = 4300 \text{ Å} . \tag{8}$$

The galaxy counts are not complete to dwarf galaxies, and it might be conceivable that the dwarf galaxies are numerous enough to increase the value (7) appreciably. If we assume that this is not the case, and assume that we are not in an exceptionally rich

TABLE 1

MEAN PHOTOGRAPHIC LUMINOSITY OF GALAXIES PER UNIT VOLUME

	$\mathfrak{L}_\odot/M_{pc}^3$
Oort (1958)..	2.9×10^8
Van den Bergh (1961).... . . .	2.7×10^8
Kiang (1961)	$4\ 3\times10^8$

part of space, it appears that equation (7) is uncertain by less than a factor of 2. It will be shown below that an upper limit a factor of 5 greater than the value (7) is obtained from the limit on the extragalactic background at 5300 Å wavelength.

c) Mass-to-Luminosity Ratio of Galaxies

We have two lines of evidence on the time variation of the luminosity of galaxies: the total amount of hydrogen converted to helium and heavy elements, and a model for the mass-to-light ratio of the newly formed young galaxies (Partridge and Peebles 1967). For both of these we need to know the present value of the ratio of the average mass per unit volume in galaxies to the average luminosity per unit volume due to the galaxies.

Statistical results on the mass-to-light ratio have been given by Page (1962), and masses derived from rotation curves were summarized by Burbidge (1961). A recent review of the mass-to-light ratio of galaxies has been given by Roberts (1963). The mean value of the mass-to-light ratio for spiral galaxies appears to be about 10 solar units. For elliptical galaxies the ratio is higher by a factor of 5—10. We need a mean of the ratio, weighted according to the relative contribution to the total luminosity per unit volume. Since elliptical galaxies contribute roughly 10 per cent of the total light (van den Bergh 1961) we shall adopt the mean value

$$\mathfrak{M}/\mathfrak{L}_{pg} = 20 . \tag{9}$$

It is uncertain by a factor of 2 at least. The luminosity is measured at a wavelength of 4300 Å, and the ratio is expressed in solar units.

Equations (7) and (9) yield a value for the mean mass density which is 35 per cent smaller than the lower limit in equation (2). This modest inconsistency has been accepted so that we can use a conservative value for the mass-to-light ratio and the traditional value for the mean density of the matter in galaxies.

d) Total Helium and Heavy Element Production

If cosmic-ray and radio emission are unimportant means for radiating energy, the rate of conversion of hydrogen to helium and heavy elements is given by the formula

$$dX/dt = -1.0 \times 10^{-11} \frac{\mathfrak{L}}{\mathfrak{M}} \text{ year}^{-1} . \tag{10}$$

Here X is the hydrogen abundance by mass, $\mathfrak{L}$ is the total (bolometric) luminosity and the ratio $\mathfrak{L}/\mathfrak{M}$ is expressed in solar units. Given the total fraction of hydrogen burned, this equation fixes the integral of the light-to-mass ratio over time, and this together with the present value of the mass-to-light ratio (eq. [9]) provides a useful measure of the time variation of the luminosity of the galaxies.

If it were assumed that the mean luminosity of the galaxies had remained constant in time, we see from equations (9) and (10) that only 0.5 per cent of the hydrogen would have been consumed in the 10^{10} years available. By comparison the interstellar material in our own Galaxy contains about 3 per cent by mass heavy elements and 35 per cent by mass helium. We know that the heavy elements were produced in the Galaxy, but it is not yet clear that this was the case for the helium. The helium content in very old stars is not reliably established, although the spectroscopic evidence for the Population II stars on the horizontal branch seems to point to a low primordial helium abundance (Sargent and Searle 1966). A second uncertainty here is that we do not know whether the helium content in our own Galaxy is representative of the average. For the present calculation we shall assume that all the helium was produced in the Galaxy, and that the present interstellar helium abundance, 35 per cent by mass, is roughly equal to an average over galaxies. The first assumption is optimistic in the sense that lower helium production would permit a lower integrated background. Some justification for the second assumption is the agreement of the helium abundances in the Galaxy with several extragalactic nebulae (this is summarized by Roberts 1963, and more recently observations have been made by Mathis 1965).

e) Stellar Creation Function

Following Salpeter's original discussion of the evolution of the Galaxy, we shall suppose that the relative numbers of stars with different masses created at any time is given by a time independent stellar creation function (Salpeter 1955). We use a differential creation function such that in any time interval the relative number of stars created with absolute magnitude M_v to $M_v + dM_v$ is proportional to

$$dN = \psi(M_v)dM_v . \tag{11}$$

The function $\psi(M_v)$ is assumed to be independent of time.

The stellar creation function $\psi_1(M_v)$ given by Limber (1960) is shown as a solid line in Figure 1. It is based in part on the luminosity functions in galactic clusters and in part on Salpeter's argument connecting the luminosity function for field stars with the stellar creation function. It is useful to present the model results also for another possible form of the creation function. The function $\psi_2(M_v)$ shown as a dashed line in Figure 1 is based on the following considerations: For stars dimmer than $M_v = +5$ it seems reasonable to suppose that the field-star luminosity function has the same shape as the creation function, because none of the stars has evolved off the main sequence (Salpeter 1955). On the other hand, for stars brighter than $M_v = +2$ the lifetime is less than 10^9 years. Following Schmidt (1963), we can argue that since the mean stellar formation rate probably has changed very little in the past billion years, the form of the stellar creation function for these bright stars is simply given by the ratio of the luminosity function for the field stars (Schmidt 1959) to the stellar lifetime, $\phi(M_v)/\tau(M_v)$. Thus, in the logarithmic graph of Figure 1, the shape of the curve is determined to the left of $M_v = +2$ and to the right of $M_v = +5$, and the remaining problem is to move the curves the proper amount up or down relative to each other, and to join them smoothly. Some guidance is provided by the creation function derived by van den Bergh (1957) from galactic cluster data. Van den Bergh's results are shown as crosses in Figure 1. The creation function ψ_2 derived in this way is shown as a dashed line in the figure.

With a given stellar creation function the evolution of the model galaxy depends on the total rate at which gas is being incorporated in new stars. In the next section we present an argument fixing this rate and use it to compute the evolution of the model galaxy.

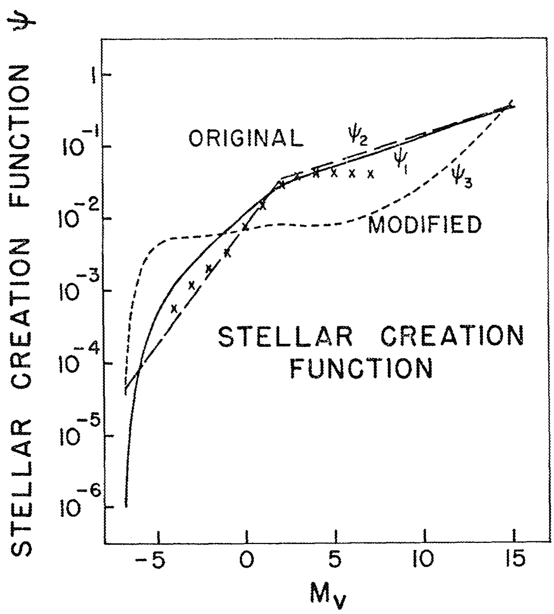

FIG. 1.—The stellar creation function. The solid curve is the original function, derived in part from the stellar abundances in young clusters and in part from the field star abundances in the solar neighborhood. The broken curve is derived from field-star abundances and estimates of stellar lifetimes. The crosses represent the observed luminosity function in galactic clusters (van den Bergh 1957). The third curve is a modified creation function (eq. [18]), chosen to yield the desired present values of the mass/luminosity ratio and the He abundance in new stars.

III. A MODEL FOR THE EVOLUTION OF THE GALAXY

We have shown (Partridge and Peebles 1967) that on the gravitational instability picture the galaxies must have formed as distinct gravitationally bound clouds of neutral atomic hydrogen at a fairly well-defined epoch,

$$t_p \simeq 1.5 \times 10^8 \text{ years} . \tag{12}$$

This corresponds to a redshift z in the range 10–30 for the density range given by equation (2). The time of formation is determined by the minimum mean density of the proto-galaxy, and in deriving equation (12) we have used the parameters appropriate for our own Galaxy. If the proto-galaxy were much larger than the halo of the present Galaxy, it would increase the formation time given in equation (12).

In this model the initial collapse of the proto-galaxy heats and ionizes the hydrogen, thus initiating the formation of the first generation of stars. It is important to recognize that a gravitationally bound hydrogen gas cloud with the size and mass of an ordinary galaxy could not last for more than a few hundreds of millions of years without suffering either widespread stellar formation or else catastrophic collapse. If the system were supported by random velocities of the individual atoms, the atoms soon would be collisionally ionized and the system could radiate and collapse at nearly the freefall time, a time of the order of 10^8 years. If the system were supported by turbulence it might last somewhat longer, but the turbulence would be expected to have dissipated in a few characteristic transversal times, that is, a few hundreds of millions of years (cf. Spitzer 1966).

Thus it appears that once the proto-galaxy has departed from the general expansion of the Universe and started to collapse, it must keep on collapsing until enough stars have formed to feed energy to the remaining gas as fast as the energy is being dissipated. The amount of interstellar gas remaining when this equilibrium has been achieved depends upon the energy transfer rates.

The temperature of the interstellar gas in the young galaxy is expected to have been in the range of 10^4—10^6 ° K. The upper temperature limit corresponds to the assumption that the energy of the gas required by the virial theorem is thermal energy. If it were assumed that the interstellar gas was uniformly distributed over a sphere of radius 10 kpc, bremsstrahlung radiation by the interstellar plasma would amount to 0.05—0.5 solar luminosities per solar mass of material. The gas is not expected to have been particularly uniformly distributed, and irregularities in the density would increase the mean bremsstrahlung luminosity. It is concluded that in the young galaxy massive hot stars must have been numerous enough to have been able to supply energy to the remaining interstellar gas at a rate of the same order as the present total luminosity of the galaxy. The efficiency with which energy would be transferred from stars to the interstellar gas presumably was not high. We note, for example, that for a star with a surface temperature of 30000° K about 80 per cent of its radiation energy would be at wavelengths longward of 912 Å, and so could directly leave the young galaxy, free-free transitions at longer wavelengths being unimportant.

Apparently, to support the remaining interstellar gas, a substantial fraction of the material must have been incorporated in the first generation of stars. We have assumed that in fact most of the material in the proto-galaxies ended up in stars during this initial period of rapid stellar formation. This leads to an initial luminosity several hundred times greater than the present value. Some justification of the assumption is that the model results described below agree with the present properties of our own Galaxy.

As this first generation of stars evolves, matter is returned to the interstellar medium. For the initial luminosity function ψ_1 shown in Figure 1 about 25 per cent of the mass would have been returned to the interstellar medium after 1.7×10^8 years. This material goes into later generations of stars. Consistent with the above assumption we suppose that new stars are formed as quickly as material is rejected from evolved stars. Thus, in the present state of the Galaxy, appreciable amounts of material are coming from the old stars in the galactic halo and nucleus, and we suppose that this material makes its way to the spiral arms, where the new stars are forming. In this model the amount of interstellar gas always is a fairly small fraction of the total.

This picture is quite different from previous pictures of galactic evolution (Schmidt 1959; Salpeter 1959; Reddish 1961; Truran, Hansen, and Cameron 1965), where it has been assumed that stellar formation proceeds in a much more leisurely way, the stellar formation rate being some fairly slowly varying function of the interstellar gas density. The decisive question is whether a relatively small number of stars in the young galaxies can keep the remaining gas turbulent enough to prevent the system from collapsing. We have assumed that it cannot, that most of the gas must have been disposed of in short order.

Some check of the model is provided by a calculation of the expected present stellar abundances. In this calculation the stellar luminosity function $\phi(M_v,t)$ is taken to be a measure of the total number of stars present in the Galaxy at time t,

$$dN = \phi(M_v,t)dM_v\,. \tag{13}$$

We shall normalize this function and the stellar creation function (11) to unit solar mass of the model galaxy, so that the functions satisfy

$$\int \psi(M_v)\mathfrak{M}(M_v)dM_v = 1\,,$$
$$\int \phi(M_v,t)\mathfrak{M}(M_v)dM_v = 1\,. \tag{14}$$

Here $\mathfrak{M}(M_v)$ is the mass of a star with absolute magnitude M_v on the main sequence, and the second integral includes the white dwarfs.

The assumed stellar lifetimes and masses were taken from the article of Truran *et al.* (1965). We have supposed that the luminosity of a star remains constant while it is on the main sequence, and that once the star evolves off the main sequence it returns to the interstellar medium all but a remnant amounting to 0.5 $\mathfrak{M}_\odot$. Within the accuracy we can hope to attain, we can neglect the effect of varying element abundances on the stellar evolution.

We let $S(t)$ be the rate at which mass is going into new stars, computed per unit mass of the galaxy. Then the stellar luminosity function (equation 13) satisfies

$$\frac{\partial\phi(M_v,t)}{\partial t} = \psi(M_v)\{S(t) - S[t - \tau(M_v)]\}\,, \tag{15}$$

where $\tau(M_v)$ is the lifetime of a star with absolute magnitude M_v. Except for the relatively brief period of the initial stellar formation we have assumed that the rate of star formation $S(t)$ is equal to the rate at which material is coming from old stars. With adequate accuracy this situation is represented by the equation (valid if $t > 0$)

$$S(t) = \int_{-\infty}^{\infty} dM_v S[t - \tau(M_v)]\psi(M_v)[\mathfrak{M}(M_v) - 0.5] \tag{16}$$

with the condition

$$S(t) = 0 \qquad \text{if} \qquad t < 0\,, \tag{17}$$

and, to take account of the initial production, that $S(t) = \delta(t)$ in the neighborhood of $t = 0$. In these equations we have measured time from the formation of the galaxy.

The results of a numerical integration of equation (16) are shown in Figure 2. The sharp initial peak in $S(t)$ is due to the oversimplified initial conditions. In a more realistic model this peak would be smoothed over a time interval of perhaps 3×10^7 years (Partridge and Peebles 1967). This would have little effect on the subsequent development of the model.

The stellar luminosity function was obtained by integrating equation (15), with the initial condition that there be no stars when $t < 0$. The variation of the luminosity function with time is indicated in Figure 3 for the stellar creation function $\psi_1(M_v)$ of Limber (1960). The present luminosity functions (evaluated at 10^{10} years) for the two creation functions ψ_1 and ψ_2 are shown in Figure 4. The sharp drop in the luminosity function occurs at that magnitude for which the first generation of stars has just completed its evolution. Thus in Figure 4, there is a shoulder where the stellar life time is just equal to the age of the galaxy. In Figure 4 we have converted the luminosity function to total numbers of stars in the model for the Galaxy by multiplying the luminosity function $\phi(M_v)$ by the mass of the Galaxy, $1.2 \times 10^{11}\, \mathfrak{M}_\odot$ (Innanen 1966).

In our own Galaxy the Population II stars may provide a shoulder in the total stellar luminosity function like the one shown in Figure 4. Dixon (1965) has given evidence that roughly two-thirds of the low-mass main-sequence field stars in the solar neighborhood are Population II. In our model, for Limber's creation function ψ_1, 62 per cent of the stars with absolute magnitude $M_v = 5$ were formed in the initial production, and the remainder were formed later. For the function ψ_2, 70 per cent were formed in the initial production. This result is consistent with the idea that the Population II stars are the remnants of an early generation of stars, formed with a stellar creation function not very dissimilar from the present one, during the collapse of the proto-galaxy.

Also shown on Figure 4 are observational estimates of the total numbers of the brighter stars in the Galaxy. For stars with $M_v < 5.0$, the total number of stars was obtained by multiplying the stellar luminosity function for the number of stars per unit volume in the solar neighborhood (Schmidt 1959) by an effective area of the disk, $\pi \times (12\ \text{kpc})^2$, and an effective thickness of the stellar disk for each magnitude interval (von Hoerner 1960). For stars with $M_v > 5.0$, some account was taken of the Population II stars of the halo. Following Dixon (1965), we assumed that two-thirds of these faint stars per unit volume

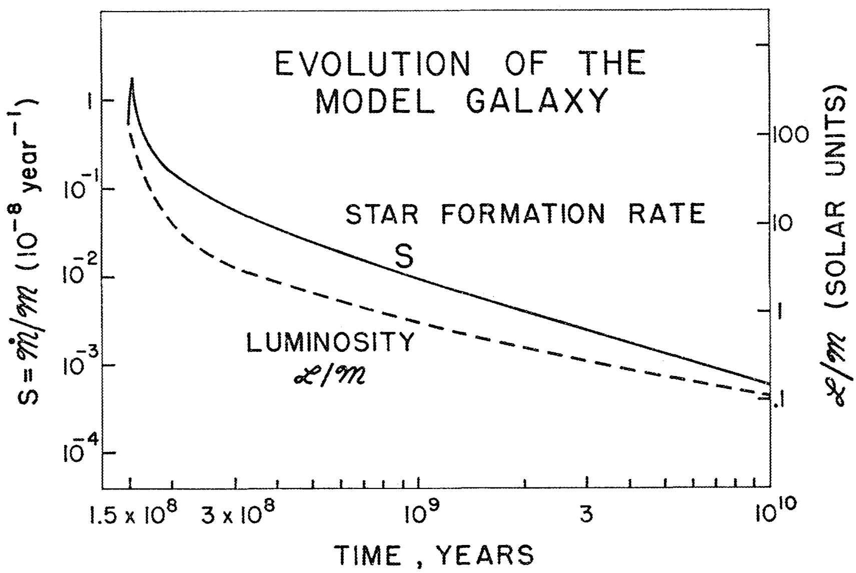

FIG. 2.—Evolution of the model galaxy. The solid curve is the total rate of star production, expressed as the rate at which mass is going into new stars per unit mass of the galaxy. The broken curve is the bolometric luminosity per unit mass of the galaxy, expressed in solar units. The creation function is ψ_1.

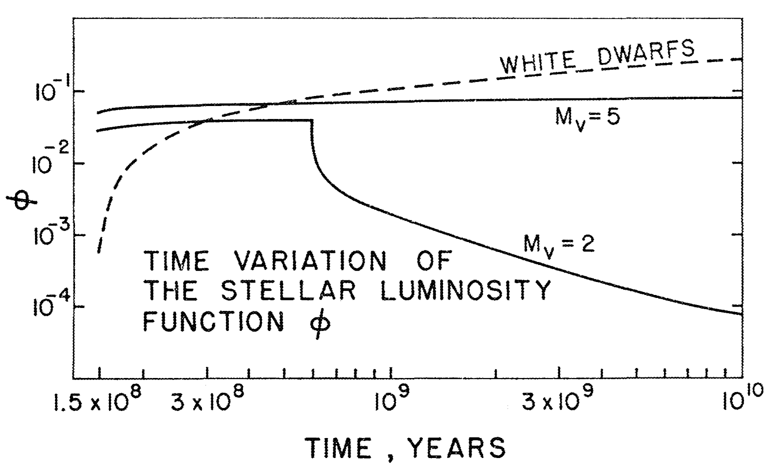

FIG. 3.—Time variation of the stellar luminosity function. The solid lines indicate the time variation of the luminosity function for stars of two different magnitudes for the stellar creation function ψ_1. The break in the lower curve occurs when the initial stars of the second magnitude have completed their evolution. The broken curve shows the time variation of the fraction of the total mass of the model galaxy in white dwarfs.

in the solar neighborhood were Population II stars. We then assumed an effective Galactic thickness of 10000 pc for this fraction of these stars, corresponding approximately to the effective thickness of the RR Lyrae population of the halo (Kinman, Wirtanen, and Janes 1966). These observational estimates agree with the model within a factor of 3 for Limber's creation function ψ_1, while the discrepancy is at most a factor of 10 for the creation function ψ_2. The effect of this discrepancy on the computed background is slight, however, so we shall not pursue this discrepancy here.

Within the framework of the adopted model the only parameter we were free to adjust was the mass of the remnant left behind by each evolved star. The stellar abundances were found to be independent of this quantity unless it was taken to be as large as 1.0 $\mathfrak{M}_\odot$. In this case the number of bright stars is substantially reduced because little

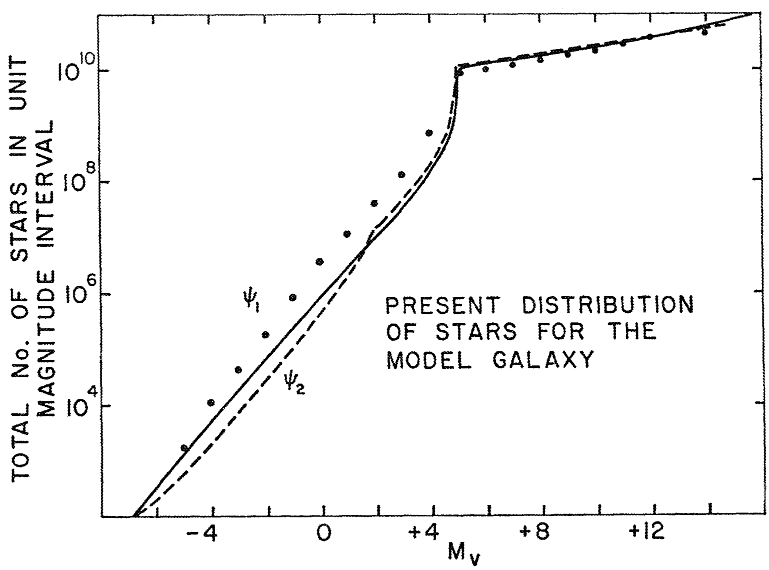

FIG. 4.—Present stellar abundances in the model galaxy. Plotted are the total number of stars in a model galaxy with total mass equal to 1.2 × 10^{11} solar masses. Curves are shown for two stellar creation functions, and the dots are estimates of the actual stellar abundances in our Galaxy, including halo Population II stars.

material is being returned to the interstellar medium. The total luminosity is, however, only slightly reduced (15 per cent on going from 0.5 to 1.0 $\mathfrak{M}_\odot$ for the average size of the remnant).

Since the bright stars are much younger than the Galaxy, the abundance of bright stars is a measure of the total present rate of stellar formation. The rough agreement of the observed stellar abundances with our model results thus appears to indicate that matter is being released from old stars at about the rate that matter is going into new stars, consistent with our basic assumption.

The total luminosity of the model galaxy has been computed using the bolometric corrections listed by Allen (1963). The luminosity plotted in Figure 2 is based on Limber's luminosity function $\psi_1(M_v)$. The luminosity of the model when it is 10^{10} years old depends on the creation function for the numerous small stars, so the present luminosity is almost the same for the creation function ψ_2 as it is for ψ_1. The present value of the mass to luminosity ratio of the model is about 10, consistent with the estimated value for the Galaxy. According to the model the bolometric luminosity of the Galaxy is increasing the rate of 0.07 mag per billion years. Making a somewhat different assumption about galactic evolution (essentially that no new stars are formed from the ashes of old ones), Wielen (1964) finds for elliptical galaxies a rate about 30 per cent above this value.

Next, we consider the spectrum of radiation from the model galaxy. We have supposed that the spectrum of each star is a black-body curve cut off shortward of 912 Å (the Lyman limit). For the characteristic temperature of the black-body curve we have adopted the values of the effective temperature T_e listed by Allen (1963). These have the virtue that they reproduce with modest accuracy the observed ratios of stellar brightnesses at 1400 and 5500 Å (Chubb and Byram 1963). The resulting spectrum of the model galaxy is shown in Figure 5 for the model with the creation function ψ_1. We find that at $t = 1 \times 10^{10}$ years the color index is $B - V = 0.77$. No account has been taken of absorption in the source in deriving the spectrum and the color index.

The amount of hydrogen consumed is obtained by integrating under the dashed curve in Figure 2. We will be discussing the helium abundance only, considering the heavy element abundance as an unimportant addition. In the model with creation function ψ_1,

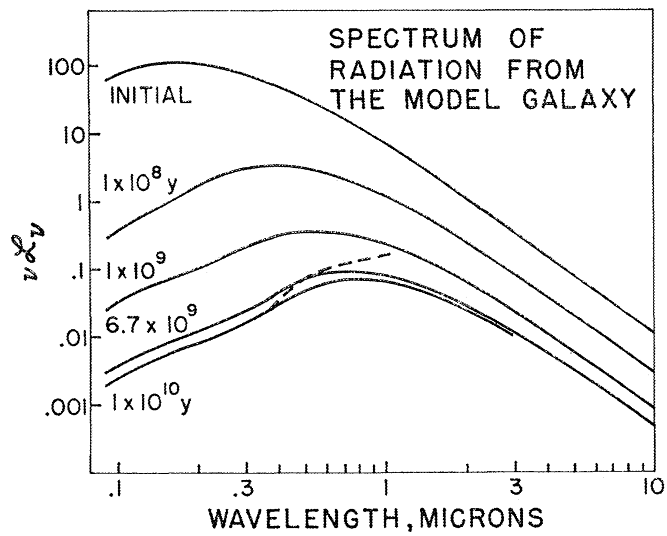

FIG. 5.—Spectrum of the model galaxy. The labels refer to time after the formation of the galaxy. The luminosity $\nu\mathfrak{L}_\nu$ is given in units of solar luminosities per solar mass of the galaxy. The dashed curve is a typical reddened curve for a spiral galaxy. If the dashed curve were corrected for $1/\lambda$ interstellar reddening, it would coincide almost exactly with the computed spectrum of the model galaxy.

5.9 per cent of the mass is converted to helium in 10^{10} years. This should not be compared directly with observed interstellar abundances because the elements are not uniformly distributed: the white dwarfs contain little hydrogen and the extreme Population II stars little helium (if we may presume that the primordial helium abundance was small). An upper limit to the present interstellar helium abundance in the model is obtained in the following way. We suppose that as each star completes its evolution it thoroughly mixes its contents before returning material to the interstellar medium. This is an upper limit to the helium abundance in ejected material because the remnant surely was not less enriched than the envelope. Next, we suppose that there is negligible mass in the interstellar gas. (Again, any interstellar gas would dilute the stellar debris and presumably reduce the helium abundance.) With these two assumptions, the helium abundance in interstellar gas and in newly formed stars is determined by the helium abundance coming out of evolved stars, and this in turn is the sum of the fractional helium production in the stars and the interstellar helium abundance at the times of formation of the stars. We find that in this picture the present helium abundance in newly formed stars is at most 13 per cent by mass (with the luminosity function ψ_1). The total amount of material ejected from evolved stars is about 60 per cent of the mass of the galaxy. Of this rejected material two-thirds came from the first generation (Population II stars), and one-third from younger stars.

The upper limit on helium abundance in this model is a factor more than 2 smaller than the observed value. The discrepancy could be due to several uncertain approximations in the model. We have neglected nuclear burning off the main sequence. If the massive early stars managed to mix fresh hydrogen into the core, they would have burned a larger fraction of the hydrogen. Also, we have supposed that the stellar creation function is a constant. This seems particularly uncertain for the very first stars to form because the hydrogen would have been clean, and so could only have radiated once it was ionized.

The model takes no account of the characteristic difference among the elliptical, spiral, and irregular types of galaxies. There remains the puzzle of the lack of young stars in elliptical galaxies. It may be significant that in a system with low angular momentum the debris from old stars would not be supported by rotational kinetic energy. It

TABLE 2*

FIVE POSSIBLE MODELS FOR THE EVOLUTION OF THE GALAXIES

Model	Mass-to-Light-Ratio		ΔX (10^9 years)	ΔX (10^{10} years)	Y_{max}
	Bolometric Luminosity	Photographic Luminosity			
(1) Constant luminosity. ...	. . ....	... .	0 0005	0.005	. . ..
(2) Ψ_1	9	16	.039	059	0.13
(3) Ψ_2.	9	15	.024	044	.12
(4) Ψ_1+Pop. III...	9	16	.24	.26	33
(5) Ψ_3 (eq. [18]).	10.5	20	0 18	0 24	0.35

* The model numbers correspond to the models described in the text. The mass-to-light ratio is evaluated at $t = 1 \times 10^{10}$ years, and it is given in solar units. The fractional amount of hydrogen burned at $t = 1 \times 10^9$ years is given in the third column, and the amount burned at $t = 10^{10}$ years is given in the fourth column. The final column is the maximum helium abundance in young stars at $t = 1 \times 10^{10}$ years.

would collapse not to a disk but rather to the center of the system where, whatever became of it, the debris would be fairly well shielded from our view. The dwarf and irregular galaxies are a second enigma from our point of view. The irregularity of the Magellanic Clouds gives the impression that these systems have evolved little, although the high helium and heavy element abundances in these systems bear witness to an active past. In any case, spiral galaxies provide most of the light in the present state of the Universe, and it appears that our model provides a reasonable phenomenological description of spiral galaxies. We conclude that, if the general assumptions of § II are valid, the model should provide a reasonably sound basis for a discussion of the integrated background radiation from the galaxies.

IV. TEN MODELS FOR THE INTEGRATED BACKGROUND

To show how the expected background depends on the assumed model for galactic evolution, we have considered five different models. For each of these five models we have computed the background using two cosmological models, one which is just closed and one which is open. These models correspond to the two density extremes in equation (2).

The five models for the evolution of the galaxies are described below, some relevant properties of the models are listed in Table 2, and the integrated background for each model is plotted in Figures 6 and 7.

a) Model (1): Constant Luminosity

For comparison with later results, we have computed the background to be expected assuming that the luminosity and spectrum of the galaxies have been constant since the galaxies turned on at a cosmic time $t = 1.5 \times 10^8$ years. We have taken the spectral distribution of the radiation from the galaxies to be the same as for our Galaxy as given by Allen (1963, p. 255). The integrated background is then determined by the cosmological model and the quantity (7) which fixes the total luminous emission per unit volume at 4300 Å.

b) Model (2): Creation Function $\psi_1(M_v)$

The model described in the previous section, with the conventional stellar creation function given by Limber (1960), is taken over as a model for the average evolution of

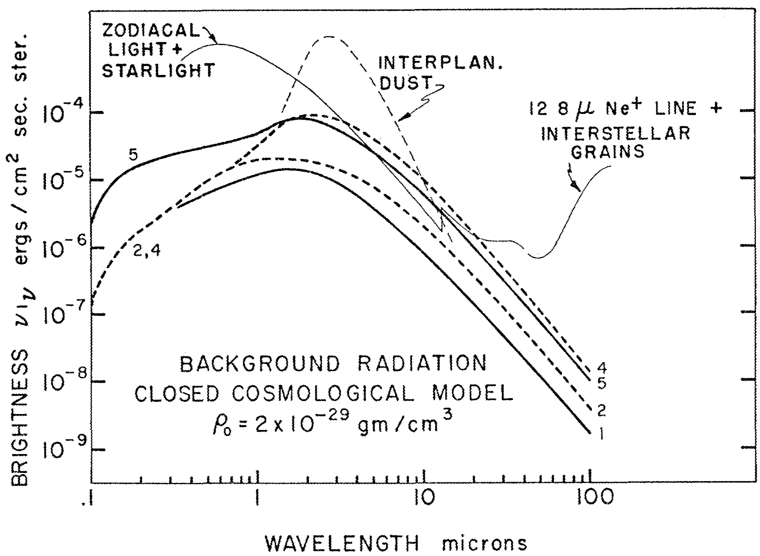

FIG. 6.—Integrated background radiation from the galaxies for the closed cosmological model. The numbers associated with the heavy curves refer to the model numbers of § IV. The light lines are estimates of the background contributed by other sources.

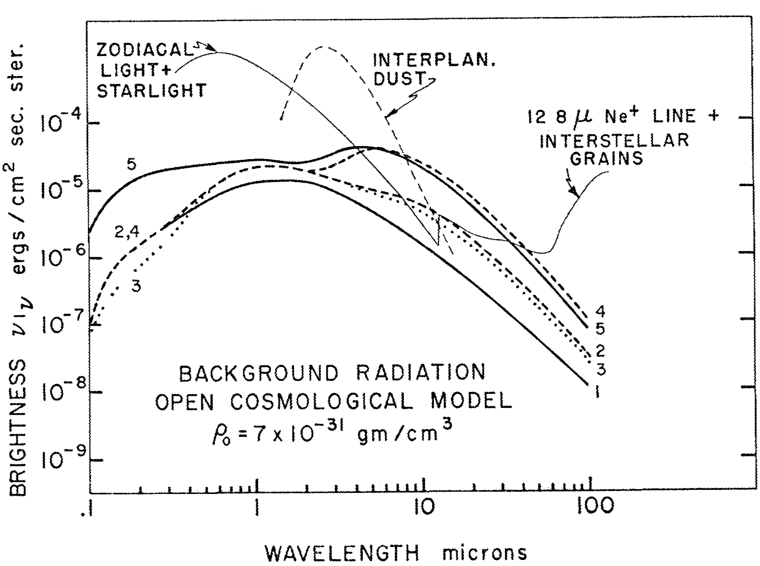

FIG. 7.—Integrated background radiation from the galaxies for the open cosmological model

galaxies. Again, the spectrum of the present galaxies is normalized at 4300 Å wavelength using the quantity (7).

c) *Model (3): Creation Function* $\psi_2(M_v)$

The alternate creation function $\psi_2(M_v)$, was used to derive a model for the evolution of the galaxies, and this was used to compute the integrated background as for the previous model.

d) *Model (4): Creation Function* $\psi_1(M_v)$ *and Population III*

A possible remedy for the inadequate helium production in the two preceeding models is to introduce a new kind of first-generation stars. One could speculate, for example, that until the hydrogen has been polluted with a trace of heavy elements the stellar formation process was quite different from the present one, and the stellar creation function was correspondingly different. An interesting possibility is that the first stars to have formed during the initial collapse of the proto-galaxy were a collection of massive stars (the Population III) which produced the pollution necessary if stars were to be created according to the present stellar creation function. These stars also might have manufactured the missing helium, which is about 20 per cent by mass. This idea has some basis in the following consideration: We know that by the time the first disk stars formed, the heavy-element abundance had risen to nearly the present value, perhaps 2 per cent by mass. Although model (2) above starts out very bright, it manages only to convert 4 per cent of its mass to helium and heavy elements in the first 10^9 years. Thus, if the actual helium production paralleled the rapid production of heavy elements, the young Galaxy must have been even brighter than the model allows. As a simple model for this we have assumed that 20 per cent of the hydrogen was converted to helium in a time short compared to 10^8 years, the radiation energy spectrum being assumed to be a black-body shape characterized by a temperature of 20000° K. We have used the luminous emission per unit volume (7) and the mass-to-luminosity ratio (9) to find the amount of radiation energy released per unit volume.

e) *Model (5): Modified Creation Function* ψ_3

Another way to obtain better agreement with the adopted helium abundance and the mass-to-light ratio is to suppose that the stellar creation function ψ_1 we have been using is not a very representative function for the whole of the evolution of the Galaxy. We have considered a model with the stellar creation function modified according to the formula

$$\psi_3(M_v) = \psi_1(M_v)\ e^{(A - BM_v + CM_v^2)} . \qquad (18)$$

One of the three constants in this equation is needed to fix the normalization. The other two constants were adjusted so that the present value of the ratio of mass to photographic luminosity, measured in solar units, be equal to 20, and the maximum helium abundance in young stars be 35 per cent by mass. The modified stellar creation function $\psi_3(M_v)$ is shown in Figure 1 (see above). At $t = 1 \times 10^{10}$ years the spectrum of the model galaxy agrees with that of models (2) and (3) longward of 4000 Å wavelength, and rises well above the previous model at shorter wavelengths. Again, in computing the integrated background the spectrum has been normalized at 4300 Å to the value given in equation (7). This creation function makes too many bright stars in the present galaxy, so the resulting integrated background is too high shortward of 1 μ. According to available criteria it should yield a reasonable value for the background at longer wavelengths.

The ten curves of the integrated background, obtained from these five models and the two cosmological models, are plotted in Figures 6 and 7. The reader is free according to his own prejudices to adopt any admixture of these models along with any models of his own invention. We prefer model (1) or (2) shortward of 1 μ and model (4) or (5) longward of 1 μ, and will use this conclusion in the discussion of a possible observational test. Although a large number of assumptions have been used in this calculation, a relatively few major factors determine the integrated background. In the next section we have attempted to set the assumptions in proper perspective, to make clear the important assumptions in the calculation.

V. THE INTEGRATED BACKGROUND, AND HOW UNCERTAIN IS IT?

The basic formula (3) for the integrated background follows simply from the assumption of homogeneity and isotropy and the condition that in a local sense the conventional laws of physics should be valid. The primordial fireball (Dicke, Peebles, Roll, and Wilkinson 1965), if it exists, provides us with an excellent confirmation of the over-all isotropy of the visible universe (D. T. Wilkinson and R. B. Partridge, to be published) and, indirectly, of the homogeneity of the visible universe.

The appropriate choice of gravity theory must be considered much less sure. The gravity theory fixes the connection between the redshift and time. If we take account of time-scale restrictions it appears that the two adopted models cover the range of reasonable possibilities in the connection between redshift and time. Thus we believe that despite the primitive state of present-day cosmology the uncertainty due to the cosmology is justly reflected in the difference between Figures 6 and 7.

An important normalization is provided by the present mean luminosity per unit volume. Barring untoward difficulties such as excessive numbers of dwarf galaxies or large-scale density irregularities this quantity appears to be established within a factor of 2. This leads to a like uncertainty in our estimate of the integrated background at wavelengths shorter than 1 μ.

In our original model for the evolution of the Galaxy we used the present stellar creation function $\psi_1(M_v)$ back to the earliest times. This model was fairly successful in predicting absolute stellar abundances in the present Galaxy. In this model the mass-to-light ratio is 25 per cent smaller than the value assumed above (eq. [9]) and the maximum helium abundance is a factor of 2 smaller than the adopted value (§ II). The effect of choosing a new model consistent with both of these values would be to increase the computed background by a factor of about 3. The models obtained by adjusting the stellar creation function, or by introducing a new Population III, raised the background the expected amount. These are not the only possible remedies. There may have been substantial burning off the main sequence at some point, or possibly massive stars in the young galaxies managed to burn convectively. However, the amount of burning is fixed by the helium abundance, and it is only of secondary importance whether the burning occurred for the most part on or off the main sequence.

Finally, in computing the infrared background it is important to know when the galaxies formed. If the helium were produced in stars at a very early epoch, the redshift would have moved the radiation to uninteresting wavelengths. We have argued for an instability picture, according to which the stars turned on at a modest redshift, the total radiation energy released in the production of the elements being reduced by a factor of 30 at most. If this basic assumption is valid it appears that once the cosmological model is chosen the uncertainty in the far infrared background is something like a factor of 3. However, if the galaxies have been particularly remiss in converting hydrogen to helium the infrared background could be a factor of 10 lower than our estimate.

The final estimates of the integrated background are listed in Table 3 for the two possible cosmological models.

VI. OBSERVATIONAL CONSIDERATIONS

Since the predicted integrated brightness of the distant galaxies is rather small, it is worthwhile to consider in some detail other sources of background radiation in the infrared.

a) Atmospheric Emission

Observation of a faint infrared continuum below the atmosphere is made impossible by the intense OH emission bands of the upper atmosphere (Harrison and Vallance Jones 1957), and by thermal emission from the atmosphere at wavelengths longer than a few microns (Bell, Eisner, Young and Oetjen 1960), as well as by atmospheric absorption. Even at balloon altitudes, the night-sky brightness is orders of magnitude greater than the brightness of the integrated light of galaxies. A rocket or satellite experiment would almost certainly be called for.

b) Local Background

Above the atmosphere a major source of undesired background radiation is the zodiacal light (see Fig. 8). The absolute intensity of the zodiacal light in the visible region of the spectrum has been rather accurately determined. At the ecliptic north pole, Beggs, Blackwell, Dewhirst, and Wolstencroft (1964) found νi_ν for the zodiacal light to be about

TABLE 3

FINAL ESTIMATES OF THE INTEGRATED BACKGROUND

ρ_0 (gm/cm^3)	BRIGHTNESS, $\nu\, i_\nu$ (ergs cm^{-2} sec^{-1} sterad^{-1})		
	$\lambda = 2\ \mu$	$\lambda = 5\ \mu$	$\lambda = 15\ \mu$
2×10^{-29}	1×10^{-4}	3×10^{-5}	3×10^{-6}
7×10^{-31}	2×10^{-5}	4×10^{-5}	1×10^{-5}

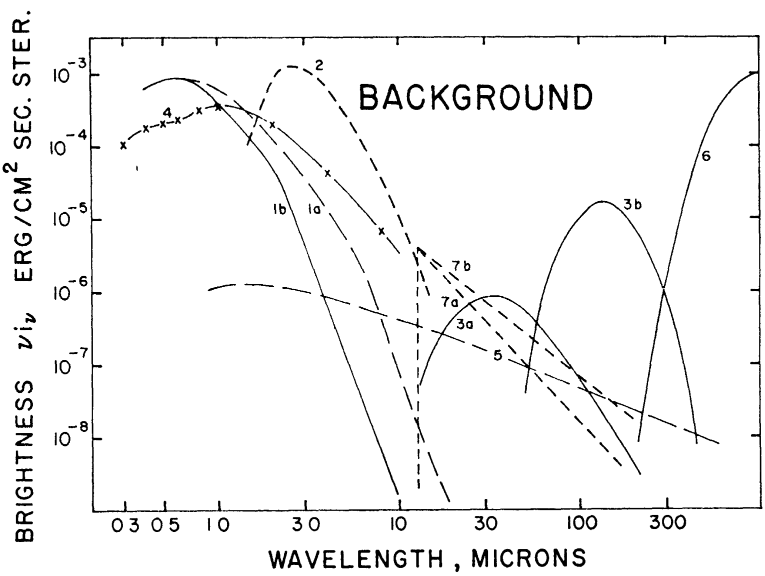

FIG. 8.—Other sources of background radiation. The contribution of local, galactic, and extragalactic sources is plotted as a function of wavelength. The various curves are defined as follows: *1a*, zodiacal light perpendicular to the ecliptic with characteristic particle radius 1.8 μ; *1b*, zodiacal light perpendicular to the ecliptic with characteristic particle radius 0.7 μ; *2*, interplanetary dust (small particles); *3a*, interstellar grains (metallic); *3b*, interstellar grains (dielectric, or "dirty-ice"); *4*, integrated starlight from the Galaxy, perpendicular to the galactic plane; *5*, galactic free-free emission, perpendicular to the plane; *6*, 3° K cosmic background radiation; *7a*, 12.8 μ Ne^+ emission from all galaxies (closed model); *7b*, 12.8 μ Ne^+ emission from all galaxies (open model).

9×10^{-4} ergs/cm^2 sec sterad at $\lambda = 5500$ Å ($\sim$130 tenth-mag stars per square degree), in agreement with measurements by Schmidt and Elsässer (1962). Ingham (1962) reports values of νi_ν rising from 5×10^{-4} to 9×10^{-4} ergs/cm^2 sec sterad in the spectral range 3700–4650 Å.

The intensity of the zodiacal light in the infrared is not known with any accuracy. To extrapolate the spectrum of the zodiacal light beyond the visible we have made the following assumptions:

1. Zodiacal light is sunlight scattered by interplanetary dust.

2. The scattering cross-section can be represented by a Mie curve (see, e.g., p. 278 of van de Hulst 1957). Specifically, we assume that the particles are approximately spherical with radius a and that the imaginary part of the refractive index of the dust material is very small ($n' < 0.05$). In this case, the Mie curve may conveniently be divided into three segments, in each of which the scattering has a different wavelength dependence:

for $0 \leq \lambda \leq \frac{2}{7}\pi a$, scattering cross-section approximately constant,
for $\frac{2}{7}\pi a \leq \lambda \leq \pi a$, scattering cross-section $\propto \lambda^{-1}$,
for $\lambda \geq \pi a$, scattering cross-section $\propto \lambda^{-4}$ (Rayleigh scattering).

3. The solar spectrum itself is black body for $\lambda \leq 20\ \mu$, with a color temperature of about 5900° K.

These assumptions allow us to continue the zodiacal-light spectrum once a characteristic radius for the dust particles has been determined. Little, O'Mara, and Aller (1965) found that the wavelength dependence and polarization properties of the zodiacal light could be reproduced by assuming a mixture of particles with radii ranging from 0.07 to 1.8 μ. The number of particles with radius a was taken to be $n(a) \propto (a/a_0)^{-4}$ where a_0 is a constant. Thus the smaller particles dominate the scattering. It is therefore a quite conservative assumption to select 1.8 μ as the characteristic radius of the dust particles. With this radius, the scattering becomes proportional to λ^{-4} for λ just less than 6 μ. A more realistic assumption is to adopt a smaller value for a, such as 0.7 μ, which is still sufficiently large to ensure that the scattering is wavelength-independent throughout the visible region of the spectrum. For both these assumptions, computed infrared intensities of the zodiacal light are plotted in Figure 8 (curves 1a and 1b). If we had adopted a still smaller value for the characteristic radius, the infrared background would have been lower. It should be emphasized that our estimates of the infrared brightness of the zodiacal light are only approximate. However, they represent a reasonable upper limit to the brightness in the infrared unless the scattering particles are much larger than 1 μ in radius (in which case the partial polarization of the zodiacal light would be difficult to explain).

These particles will also radiate in the infrared at their own characteristic temperature. Peterson (1963) assumed that the absorption and re-emission of radiation by the interplanetary dust were wavelength independent, and found an equilibrium temperature of approximately 250° K for the dust. If this estimate of the temperature is correct, the thermal emission of the interplanetary dust will reach a maximum at $\lambda \sim 12\ \mu$, and may mask the integrated light from the galaxies in this spectral region.

However, if the radiating particles are very small, as is suggested by the polarization of the zodiacal light, they will be inefficient radiators at long wavelengths. The result is to increase the temperature of the particles and to decrease the wavelength of maximum emission. To estimate the equilibrium temperature of the particles, we assume that they have a characteristic radius $a = 0.7\ \mu$ (see § (b) above), and that they absorb all the solar energy incident upon them. The equilibrium temperature may be found from the equation

$$\pi a^2 S_c = 4\pi a^2 \int B_\lambda(T) Q(\lambda) d\lambda\ , \tag{19}$$

where S_c is the solar constant (1.4×10^6 ergs sec^{-1} cm^{-2}: Allen 1963), $B_\lambda(T)$ is the Planck function for the energy radiated per unit area, and $Q(\lambda)$ is a measure of the re-emission efficiency, taken to be equal to unity at short wavelengths. $Q(\lambda)$ is assumed to have the same functional dependence on λ as the scattering cross-section described in section (*b*). By numerical integration of this equation, the equilibrium temperature was found to be 700° K for particles at 1 a.u. from the Sun. At this temperature, the intensity νi_ν of the emitted radiation is expected to reach a maximum at about 2.5 μ. The spectrum was normalized by assuming that the total energy radiated by the dust perpendicular to the plane of the ecliptic is equal to energy of the zodiacal light in the same direction.

The resulting curve appears in Figure 8. We emphasize that both the spectrum and the total intensity of the thermal radiation from the interplanetary dust are highly uncertain: it would probably be necessary to study this source of background in some detail before any quantitative estimate could be made of the integrated light from distant galaxies.

Thomson scattering from the electrons of the solar wind has been computed, assuming an electron density of 15 cm^{-3} at 1 a.u. (Neugebauer and Snyder 1962). It is at least two orders of magnitude smaller than other sources such as the zodiacal light and integrated starlight in the entire spectral region under consideration.

c) Galactic Background

The interstellar grains will produce considerable thermal radiation in the far-infrared (Stein 1966). The brightness of the thermal radiation in a direction perpendicular to the galactic plane may be estimated from Stein's paper using as a path length, L, the approximate semi-thickness of the galactic disk, about 100 pc (at a radius of 10 kpc). The brightness calculated in this fashion is shown in Figure 8 for both metallic and "dirty-ice" (dielectric) grains. The radius of the grains is taken to be 0.2 μ, following Stein. For "dirty-ice" grains, a number density of 2×10^{-13} cm^{-3} has been adopted for the calculation. For metal grains, a smaller value, 1.5×10^{-14} cm^{-3} was used: this is the number density to be expected if *all* interstellar metal atoms (Mg, Fe, etc.) are locked in grains of 0.2-μ radius. Graphite grains would produce an emission peak lying between the two shown.

The integrated flux from all the stars in the Galaxy will also contribute to the background, although the brightness can be considerably reduced by observing perpendicular to the galactic plane. The spectral distribution of this background has been taken from Allen (1963, p. 255), which, as we have seen, is in general agreement with our own computed spectrum. The curve is normalized at 5500 Å, at which wavelength the night-sky brightness due to integrated starlight is equal to about 30 tenth-mag stars per square degree at the galactic pole (Allen 1963). This gives $\nu i_\nu = 2.2 \times 10^{-4}$ erg cm^{-2} sec^{-1} $sterad^{-1}$ at 5500 Å.

This source of background might be reduced by employing a detector with modest angular resolution, which would permit observations to be made in regions "between" most of the brightest stars which contribute largely to the galactic background. An angular resolution of 1° would thus be sufficient to reduce the integrated starlight background to about one-half its total value. An angular resolution of 0°.1 would permit observations to be made in region free of stars with $M_{pg} \leq 13$ (see Allen 1963, p. 235): in this case, 85–90 per cent of the starlight could be avoided.

Two other sources of continuous emission may be mentioned, galactic synchrotron radiation and free-free emission from galactic H II. An extrapolation from measurements at longer wavelengths (Turtle, Pugh, Kenderdine, and Pauliny-Toth 1962) indicates that the former is a negligible source of background radiation for all wavelengths less than a few centimeters, provided that observations are made away from the galactic plane. Free-free emission may be estimated using Kramer's formula (see Allen 1963, p. 100), and a path length of 100 pc, which is appropriate for observations perpendicular to the galactic plane. The resulting curve (No. 5 of Fig. 8) represents a probable upper limit, since it was assumed *all* the interstellar hydrogen above the galactic plane is ionized, at a temperature of 10^4 ° K.

Finally, strong line emission in the infrared is expected from galactic ions and molecules, such as H_2 (Gould and Harwit 1963; Takayanagi and Nishimura 1961; Field 1966) and Ne^+ (Gould 1963, 1966). Information about the origin and intensity of some infrared emission lines is collected in Table 4. Note that many of the lines originate from sources that in general will have small angular diameters. Thus a detector with modest angular resolution would enable one to discriminate against local hot spots. Furthermore, in all cases, the emission is expected to be strongly concentrated in the galactic plane and so may be avoided by observing perpendicular to the plane. Spectral resolution in the detector could also be used to discriminate against this unwanted source of infrared background.

TABLE 4

INFRARED LINE EMISSION

Molecule or Ion*	Emission Wave-length (μ)	Intensity (ergs $cm^{-2}sec^{-1}ster^{-1}$	Place of Origin	Reference
H_2	2.12	$\sim 8\times10^{-7}$†	Near hot stars	Gould and Harwit (1963)
H_2	2 22	$\sim 8\times10^{-7}$†	Near hot stars	
H_2	28 2	$8\times10^{-5}n(H_2)$ $\approx 8\times10^{-5}$	Galactic plane	Takayanagi and Nishimura (1961)
Ne^+	12 8	$5\text{–}6\times10^{-5}$‡	H II regions	Gould (1963)
Ne^{++}	15 4	$<10^{-5}(?)$	H II regions	
Ne^{++++}	14 3	$<10^{-5}(?)$	H II regions	
Mg^{+++}	4 5	$<10^{-5}(?)$	H II regions	
H_2	4.4	$<10^{-7}$	Mach 15§ shock front in H I regions	Field (1966)
H_2	5 0	$<10^{-7}$		
H_2	6 1	$<3\times10^{-7}$		
H_2	8 0	$<3\times10^{-7}$		
H_2	12.0	$<3\times10^{-7}$		
H_2	28 2	$<3\times10^{-7}$		
Fe^+	26	$<10^{-7}$		
Fe^+	35	$<10^{-7}$		
Si^+	35	$<5\times10^{-7}$		

* Most of these sources of infrared background are strongly concentrated in the galactic plane

† Intensity expected from a large H II region like Orion Nebula

‡ Assuming that the entire Galaxy emits 4×10^{42} ergs/sec (Gould and Sciama 1964)

§ The intensities will be lower for shock fronts with lower Mach numbers

d) Extragalactic, Isotropic Background

In addition to the integrated light from distant galaxies, there are several other extragalactic sources of background radiation in the infrared. At very long wavelengths, there is the cosmic black-body radiation (see, e.g., Roll and Wilkinson 1966). This source is negligible for $\lambda \lesssim 300\ \mu$ (Fig. 8).

Also, there might be free-free and line emission from ionized intergalactic hydrogen, if it is present (Gould and Burbidge 1963; Field and Henry 1964). Most recently, Weymann (1966) has calculated the extragalactic background from this source for an intergalactic number density of $2\times10^{-5}/cm^3$. His results show that intergalactic free-free and line emission should reach a maximum at about 7000 Å, where $\nu i_\nu \simeq 10^{-5}$ erg cm^{-2} sec^{-1} $sterad^{-1}$. For longer wavelengths, νi_ν should decrease rapidly, reaching 5×10^{-8} at 3 μ. These values are at least two orders of magnitude lower than the contribution from other galactic and local sources.

Radiation emitted in the 12.8-μ line of Ne^+ by distant galaxies may also be a source of background in the infrared. Gould and Sciama (1964) point out that if all galaxies emitted radiation in the Ne^+ line a continuum should be present at wavelengths greater than 12.8 μ. The frequency dependence of this background is determined by the cosmological model assumed. If we assume that galaxies are not created or destroyed, and that their rate of emission in the Ne^+ line is independent of epoch, then for a closed universe $\nu i_\nu \propto \nu^{5/2}$ and for an open universe νi_ν is nearly proportional to ν^2. Adopting Gould and Sciama's value of 4×10^{42} ergs/sec for the luminosity in the Ne^+ line for a galaxy like our own, and Allen's (1963) value of 0.03/Mpc^3 for the space density of galaxies, we obtain the curves *7a* and *7b* of Figure 8. The area under these curves is less by a factor of about $2\frac{1}{2}$ than the total emission predicted by Gould and Sciama: this discrepancy arose because we employed a smaller number for the space density of galaxies. Even this assumption leads to a value of $\nu \mathfrak{E}_\nu = 4 \times 10^{-33}$ ergs/cm^3 sec for the mean emission per unit volume in this line, a value about one-sixth of the total given by (7). As Gould and Sciama point out, the intensity of Ne^+ line emission is quite uncertain, but we would not expect it to rise much above the curves of Figure 8, and it might fall considerably lower.

VII. CAN THE LIGHT FROM DISTANT GALAXIES BE DETECTED?

The various sources of infrared background discussed above have been added to give the total background in the spectral region 0.3–100 μ, which may be compared with the predicted brightness of the integrated light from distant galaxies. Figure 6 exhibits the expected background for a closed cosmological model with $q_0 = \frac{1}{2}$. The unwanted background from 0.3 to 10 μ is contributed by the zodiacal light and integrated starlight (curves *1b* and *4* of Fig. 8). We have kept separate the thermal radiation from interplanetary dust (curve *2* of Fig. 8), since it is so uncertain. The longer wavelength background is contributed by thermal emission from the interstellar grains (curves *3a* and *3b* of Fig. 8) and by Ne^+ (curve *7a*). From Figure 6, it appears that the spectral region 5–12 μ offers the best hope of detecting the integrated light from distant galaxies. Observations at wavelengths up to about 30 μ might be possible if the background contributed by Ne^+ line emission from the galaxies was smaller than estimated.

The largest uncertainty in the background is the radiation by the interplanetary dust. Measurements of the integrated background at a few microns as a function of ecliptic angle would be useful in distinguishing this source of background.

For an open universe the outlook is somewhat brighter. According to the model the light from distant galaxies should be directly detectable above the background starlight longward of 5 μ wavelength.

To test the model of the evolution of the galaxies, we would like to have a measure of, or improved upper limit to, the background in the range 5–15 μ and also a measure of the spectral character of the radiation. If the sensitivity could be pushed to the general level of the background starlight, perhaps 5×10^{-6} ergs cm^{-2} sec^{-1} sterad^{-1} at 10 μ, it would test or eliminate the model in an open cosmology. If the sensitivity could be improved a further factor of perhaps 5, either by a subtraction technique or by making use of angular resolution, it would put the model to the test for any reasonably acceptable cosmology.

Are present infrared detectors sensitive enough to measure brightnesses as small as 5×10^{-6} ergs cm^{-2} sec^{-1} sterad^{-1}? Bolometers of approximately 0.15 cm^2 area with a noise-equivalent power rating of less than 10^{-13} watts are available (Low 1961; Johnson 1966). With such a detector and a lens or concave mirror subtending 1 sterad at the detector, an integrating time of less than 1 min should be sufficient to make the signal-to-noise ratio greater than unity for the computed extragalactic background in a 5-μ band centered at 10 μ. A mirror with a radius of about 50 cm would allow an angular resolution of 1°.

Some experimental evidence is already available on the integrated background. The rocket experiment of Harwit, McNutt, Shivanandan, and Zajac (1966) has fixed an upper limit $\nu i_\nu \lesssim 3 \times 10^{-3}$ ergs cm^{-2} sec^{-1} sterad^{-1} in 1–3 μ region. This is within two orders of magnitude of the expected brightness.

There is also one recent ground-based experiment which bears on the question of the integrated extragalactic background. By subtracting the contributions of integrated starlight, zodiacal light, and atmospheric emission, Roach and Smith (1966) were able to fix an upper limit to the brightness of extragalactic radiation at 5300 Å. The upper limit at this wavelength is $\nu i_\nu \lesssim 3 \times 10^{-5}$ ergs cm^{-2} sec^{-1} sterad^{-1}. This limit is a factor of 5 above the computed brightness, which is nearly independent of the assumed model for the evolution of the galaxies and of the Universe. This fixes a similar limit on the possible contribution to the mean luminosity per unit volume (eq. [7]) by dwarf galaxies or by stars well outside the observed limits of galaxies. This upper limit would confirm the discrepancy of a factor of thirty between the mass density required to close the Universe and the mass available in luminous matter. The missing mass necessary to close the Universe could not be provided by dwarf galaxies or extragalactic stars with a mass to light ratio less than or of the order of equation (9).

It is a pleasure to acknowledge a number of very helpful discussions of this work with Professor R. H. Dicke. The research was supported in part by the National Science Foundation and by the Office of Naval Research of the U.S. Navy, and made use of computer facilities supported in part by National Science Foundation grant NSF-GP-579.

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