# FREE-FREE EMISSION BY INTERGALACTIC HYDROGEN

George B. Field and Richard C. Henry
Princeton University Observatory
*Received April 3, 1964*


## ABSTRACT

The amount of free-free emission by intergalactic hydrogen is calculated and compared with observation. The calculations are carried out for the steady-state model and for closed evolving models with $q_0 = \frac{1}{2}$ and 1. It is shown that the temperature of the intergalactic medium must be less than $4 \times 10^{6}$ ° K (steady-state model) or $3 \times 10^{6}$ ° K ($q_0 = \frac{1}{2}$ or 1), judging by recent X-ray results.

A simple analytic expression is derived for the emission in a steady-state model, which is finite for all assumed values of the temperature. The emission in evolving models depends critically on the behavior of temperature with density at distant points; for effective ratios of specific heat between $\frac{4}{3}$ and 2, the results indicate unbounded intensities at the Earth. Calculations of the intensities emitted by material out to limited values of the redshift indicate that future observations, particularly just shortward of 20 Å, may provide decisive information on the state of the universe at earlier times.


## I. OBSERVATIONAL EVIDENCE

There are a number of reasons for believing that a significant amount of matter lies outside of galaxies. Sandage (1961*a*) notes that the amount of matter within galaxies is only 2 per cent of the value required in an evolving model with a deceleration parameter $q_0 \approx 1$, as indicated by the magnitude-redshift relation. A steady-state model requires a comparable amount of matter. Not only is intergalactic matter needed if the universe is to have negative energy, but also such matter may be needed to stabilize the clusters of galaxies (*Astronomical Journal*, Vol. **66**, 1961).

Several observations are relevant to the problem. Dufay (1957) considers that there is less than $10^{-3}$ mag. per megaparsec extinction in general intergalactic space, although Zwicky (1962) has put forward evidence for intergalactic extinction within clusters.

Intergalactic neutral hydrogen has been studied through its 21-cm absorption by Field (1962) and through its emission by Goldstein (1963). Field concluded that $n_H < 5 \times 10^{-6}$ cm$^{-3}$ if the medium is predominantly neutral, while Goldstein obtained $n_H < 2 \times 10^{-5}$ cm$^{-3}$, the latter observation being much more secure because it is independent of the very uncertain excitation temperature. (Both data are based on $H_0 = 100$ km sec$^{-1}$ mpc$^{-1}$, the value adopted throughout this paper.) Unfortunately, even the lower value is still only slightly less than the value expected on cosmological grounds, so that the problem as to whether intergalactic neutral hydrogen makes a significant contribution to the mass remains open. Definite evidence that there is at least some intergalactic neutral hydrogen, however, has been discovered by Robinson, van Damme, and Koehler (1963), who found a 21-cm absorption feature having the velocity of the Virgo cluster in the radio spectrum of M87. The data suggest that $M < 10^{12} M_{\odot}$, which is insufficient to stabilize the cluster, however.

Field (1959) suggested techniques for observing ionized intergalactic matter, based on electron scattering, free-free absorption of long radio waves, Lyman-$\alpha$ emission, and calcium absorption. None of these tests appears sensitive enough to detect the expected amount of material with present techniques.

Recently, Hoyle (1963) and Gould and Burbidge (1963) have pointed out that free-free emission by the intergalactic gas may be detectable in the X-ray region if the temperature is high enough. The latter authors showed that recent observations of X-rays gave only 1 per cent of the flux expected if the intergalactic gas were as hot as $10^{9}$ ° K, as proposed by Gold and Hoyle (1959). In this paper we extend their calculations to include evolving models and a variety of assumptions concerning the temperature. Before doing so, however, we shall discuss those observations which might provide upper limits on the free-free emission.

McVittie and Wyatt (1959) argue for an upper limit of (3–8) $\times 10^{-18}$ erg cm$^{-2}$ sec$^{-1}$ ster$^{-1}$ (c/s)$^{-1}$ (called "units" hereafter), on the extragalactic component of intensity at $10^8$ c/s—the other 50–80 per cent of the observed 100 Mc/s intensity being attributed to the Galaxy.

At optical frequencies ($7 \times 10^{14}$ c/s or 4500 Å), we adopt the upper limit of $10^{-17}$ units, based on the assumption that not more than half the brightness of the mean night sky at the zenith (200 tenth-magnitude stars per square degree according to Allen [1963], p. 134) is due to an extragalactic component.

In the X-ray region we have three relevant observations. Byram, Chubb, and Friedman (1961) give an upper limit of $3 \times 10^{-24}$ units for the mean intensity in the interval 8–18 Å, and $9 \times 10^{-23}$ units for the interval 44–60 Å. According to Strom and Strom (1961), the latter radiation would not be expected to penetrate the galactic disk in any case, because of helium absorption, so this upper limit cannot be used. Because of absorption by helium and heavier elements, the former upper limit must be revised upward by 15 per cent (see Fig. 5). Giacconi, Gursky, Paolini, and Rossi (1962) obtained a positive result of $1 \times 10^{-27}$ units for an isotropic component in the interval 2–8 Å. Bowyer, Byram, Chubb, and Friedman (1963) obtained $4 \times 10^{-27}$ units for the interval 3–8 Å; we

TABLE 1

OBSERVATIONS OF $\gamma$-RAYS BY ARNOLD *et al.* (1962)

| Energy (MeV) | log $\nu$ (c/s) | log $I_\nu$ (erg cm$^{-2}$ sec$^{-1}$ ster$^{-1}$ [c/s]$^{-1}$) |
|---|---|---|
| 0 4 | 20 0 | −27 8 |
| 0 8 | 20 3 | −28 1 |
| 1 2 | 20 5 | −28 1 |
| 1 6 | 20 6 | −28 0 |
| 2 0 | 20 7 | −27 9 |

have adopted the latter result in view of the indication that the result of Giacconi *et al.* was apparently based on an overestimate of their detector efficiency. It is the positive results of Giacconi *et al.* which led Hoyle to consider possible cosmological implications.

In the $\gamma$-ray range, Arnold, Metzger, Anderson, and van Dilla (1962) have performed a space-probe experiment which is probably the most free of atmospheric cosmic-ray effects among several $\gamma$-ray experiments. They obtained the data in Table 1.

Duthie, Hafner, Kaplon, and Fazio (1963) obtained $5 \pm 0.7 \times 10^{-3}$ photons cm$^{-2}$ sec$^{-1}$ ster$^{-1}$ above 60 MeV, while Kraushaar and Clark (1962) obtained 0.4 to $1.1 \times 10^{-3}$ (in the same units) above 50 MeV. We have averaged the results and assumed them to apply to the range 55–100 MeV; the result is $I_\nu = 1.5 \times 10^{-29}$ intensity units.

The data given above are plotted in Figure 1, together with an infrared intensity computed by Law (1963) from the superposition of the redshifted emission by distant galaxies.

## II. THEORY

We require the intensity arriving at the Earth which originates in free-free emission at points along a typical line of sight in an expanding universe. As it is important to consider the relativistic effects with care, we shall proceed from the basic equations.

Consider a volume element $dV_1$ containing pure ionized hydrogen of density $n_1$ and temperature $T_1$, and emitting toward the Earth at cosmic time $t_1$. According to Robertson (1938),

$$dF = \frac{R_1^2}{R_0^4 \sigma^2} j_{\nu 1} d V_1 d\nu_1 \qquad (1)$$

is the flux which leaves in the frequency interval $d\nu_1$ and is measured on the Earth at time $t_0$. In this equation, $j_{\nu 1}$ is the free-free emission coefficient evaluated in terms of $n_1$ and $T_1$, and $R$ and $\sigma$ are defined by the line element,

$$ds^2 = dt^2 - \frac{R^2(t)}{c^2}\,[d\eta^2 + \sigma^2(\eta)(d\theta^2 + \sin^2\theta\, d\varphi^2)]. \tag{2}$$

$R_0$ and $R_1$ are the values of the radius of curvature at times $t_0$ and $t_1$. Now

$$dV_1 = R_1{}^3\sigma^2(\eta)\sin\theta\, d\eta d\theta d\varphi\,, \tag{3}$$

$$\nu_1 = \frac{\nu_0}{w(\eta)}, \tag{4}$$

and

$$R_1 = w(\eta)R_0\,, \tag{5}$$

where

$$\begin{aligned} \sigma(\eta) &= \sin\eta\,, & (k=-1) \\ &= \eta\,, & (k=0) \\ &= \sinh\eta\,, & (k=+1) \end{aligned} \tag{6}$$

and

$$w(\eta) \equiv \frac{1}{1+z(\eta)} \tag{7}$$

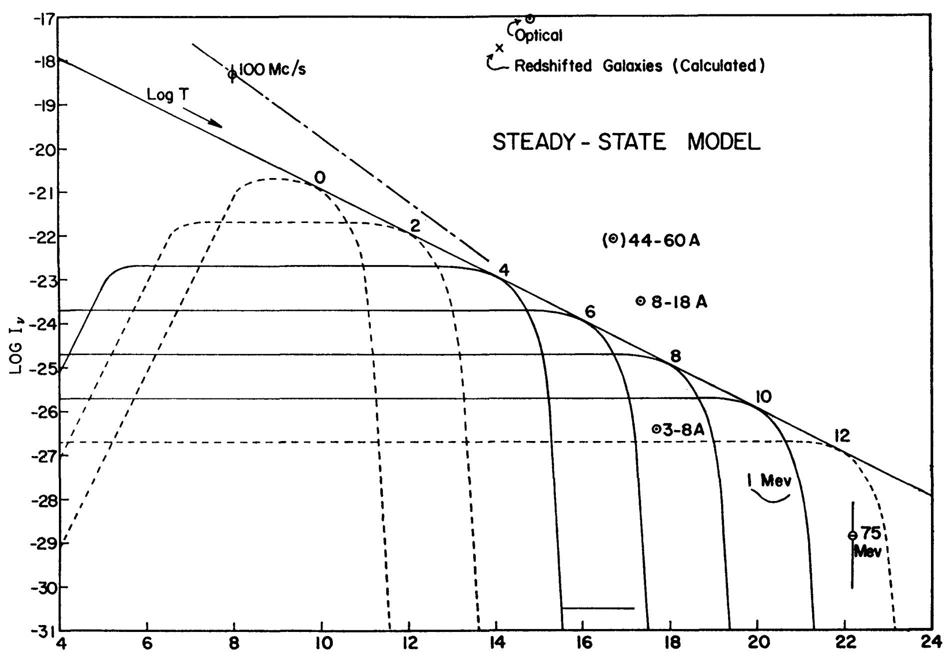


FIG. 1.—Free-free emission spectra for the steady-state model, computed for a range of temperatures, indicated by the value of log $T$. The spectra for log $T$ = 0, 2, and 12 have gaunt factors that are uncertain and are therefore dotted. The units of intensity are ergs cm$^{-2}$ sec$^{-1}$ ster$^{-1}$ (c/s)$^{-1}$. Observed upper limits to the free-free intensity at various frequencies are indicated; the observation at 44–60 Å occurs in a frequency region of heavy interstellar obscuration (indicated by the short horizontal line). The upper limit at 100 Mc/s is extended to higher frequencies on the basis of a spectral index of 0.7.

are known functions of the co-moving space-coordinate, $\eta$, for any given model. Substituting equations (3)–(5) into equation (1), we have

$$dF = [R_0 j_{\nu 1} w^4 d\eta(w)] \sin\theta d\theta d\varphi d\nu_0 , \tag{8}$$

the $\sigma$'s cancelling. Since the factors outside the brackets constitute $d\Omega_0 d\nu_0$, the specific intensity at the Earth is

$$I_\nu = R_0 \int_{\eta=0}^{\eta_{\max}} j_{\nu 1} w^4 d\eta(w) , \tag{9}$$

where $\eta_{\max}$ refers to the most distant matter considered. Equation (9) shows how the naïve expression for the intensity, $R_0 j_{\nu 0}$, is changed by the varying density and temperature along the line of sight ($j_{\nu 1}$), and redshift and curvature effects ($w^4$).

Free-free emission at non-relativistic temperatures obeys the law,

$$j_{\nu 1} = K g n_1^2 T_1^{-1/2} \exp\left(-\frac{h\nu_1}{kT_1}\right), \tag{10}$$

where $K = 5.44 \times 10^{-39}$ cgs units (Allen [1963], p. 100), and $g$ is the gaunt factor representing deviations from elementary theory. According to Karzas and Latter (1961), $g$ is between 0.8 and 10 for all temperatures between $10^4$ and $10^{10}$ ° K. Although calculations of the velocity-averaged gaunt factor for relativistic conditions ($T > 10^{10}$ ° K) do not seem to be available, estimates based on the formulae for a single electron velocity given by Koch and Motz (1959) indicate that $g$ will be of order $(kT/mc^2)^{1/2}$, which exceeds unity by hypothesis. The reason for this is that the product of the cross-section for photon production and the electron velocity is independent of electron energy in the relativistic range, while the non-relativistic formula would have predicted a decrease like $E^{-1/2}$. It follows from these arguments that if we use equation (10) with $g = 1$, we may underestimate the true emission, but we will never overestimate it by more than 25 per cent.

We obtain the density in terms of the local value from

$$\begin{aligned} n_1 &= n_0 , && \text{(steady-state model)} \\ &= n_0 w^{-3} . && \text{(evolving models)} \end{aligned} \tag{11}$$

We represent $T$ in the form

$$\begin{aligned} T_1 &= T_0 \left(\frac{n_1}{n_0}\right)^{\gamma-1} = T_0 , && \text{(steady-state model)} \\ &= T_0 w^{3-3\gamma} , && \text{(evolving models)} \end{aligned} \tag{12}$$

where $\gamma = \frac{5}{3}$ represents an adiabatic expansion unaffected by radiation pressure. To calculate the integral in equation (9), we need $d\eta/dw$. From Mattig (1958) and Sandage (1961*a*) we find that

$$\begin{aligned} \frac{d\eta}{dw} &= -\frac{c}{H_0 R_0}\frac{1}{w^2}, && \text{(steady-state model)} \\ &= -\frac{c}{H_0 R_0}\frac{1}{w^{1/2}}, && (k=0,\ q_0=\tfrac{1}{2}) \\ &= -\frac{c}{H_0 R_0}\frac{1}{w^{1/2}(2-w)^{1/2}} . && (k=-1,\ q_0=1) \end{aligned} \tag{13}$$

Substituting equations (11) through (13) into equation (9), we find that

$$I_\nu = I_0 \int_{w_0}^{1} \exp(aw^{-1}) w^2 dw \, ; \qquad \text{(steady state)} \quad (14)$$

$$I_\nu = I_0 \int_{w_0}^{1} \exp(-aw^{3\gamma-4}) w^{(3\gamma-8)/2} dw \, ; \qquad (k=0,\ q_0 = \tfrac{1}{2}) \quad (15)$$

and

$$I_\nu = I_0 \int_{w_0}^{1} \exp(-aw^{3\gamma-4}) w^{(3\gamma-8)/2} (2-w)^{-1/2} dw \, ; \quad (k=-1,\ q_0=1) \quad (16)$$

where

$$a = \frac{h\nu_0}{kT_0}, \quad (17)$$

$$I_0 = K n_0^2 T_0^{-1/2} c H_0^{-1} \, , \quad (18)$$

and $w_0$ corresponds to $\eta_{\max}$. The dimensionless integrals (14)–(16) are functions of $a$, $\gamma$, $w_0$, and $q_0$. Since $T_0$ is not specified by theory or by observation, we shall consider a range of values from 1° to $10^{12}$ ° K. If the intergalactic matter is losing energy, the effective value of $\gamma > \frac{5}{3}$, while if it is heating up, the effective value is $< \frac{5}{3}$; we shall consider four values from $\frac{4}{3}$ to $\frac{7}{3}$. As shown below, it is often necessary to consider a minimum value of $w$, $w_0$, to secure a finite result; we shall consider $w_0 = 0.1$ and 0.5 in particular; these correspond to redshifts of 9 and 1, respectively. The values of $q_0$ indicated in equation (13), $\frac{1}{2}$ and 1, represent parabolic and elliptic universes, respectively. They are in the range indicated by observation of the magnitude-redshift relation (Sandage 1961*b;* Baum 1962).

$I_0$ follows from the adopted value of $H_0$, the assumed value of $T_0$, and from the value of $n_0$ given by

$$n_0 = \frac{3H_0^2}{4\pi G m_H} q_0 = 2.2 \times 10^{-5} q_0 \text{ cm}^{-3} \quad (19)$$

for the evolving models. The value adopted for the steady-state model is

$$n_0 = \frac{3H_0^2}{8\pi G m_H} = 1.1 \times 10^{-5} \text{ cm}^{-3} \, , \quad (20)$$

following the version of the theory proposed by Hoyle (1948). An alternative version of the theory by Hoyle and Narlikar (1962) gives twice this value and would therefore yield four times the free-free emission we calculated on the basis of equation (20). Note that $I_0$ is the intensity at frequencies $\ll kT_0/h$ which would be emitted by an optically thin slab of material whose thickness is $c/H_0$.

We may take $w_0 = 0$ in equation (14) to obtain the finite result

$$I_\nu = I_0 E_4(a) \, , \qquad \text{(steady state)} \quad (21)$$

where $E$ is an exponential integral. This shows that the effect of integration along the line of sight is to replace $e^{-a}$ by $E_4(a)$.

In many cases of evolving models the results diverge as $w_0 \to 0$, however. If $\gamma < \frac{4}{3}$, the power of $w$ in the integrand diverges as $w_0 \to 0$, but the exponential decreases even more rapidly and gives a finite result. On the other hand, if $\gamma$ is larger than 2, the exponential remains close to unity as $w_0 \to 0$, but the power of $w$ becomes integrable. Hence one obtains a finite result from equations (15) and (16) if and only if $\gamma < \frac{4}{3}$ or $\gamma > 2$. The value of $\gamma$ which seems most reasonable, $\frac{5}{3}$, is in the center of the domain of divergence.

Let us examine this more closely for the case $q_0 = \frac{1}{2}$, $\gamma = \frac{5}{3}$.

$$I_\nu = I_0 \int_{w_0}^{1} \exp(-aw) w^{-3/2} dw\,, \qquad (q_0 = \tfrac{1}{2},\ \gamma = \tfrac{5}{3})\,. \tag{22}$$

The interpretation of equation (22) is as follows: $\nu_1$ increases like $w^{-1}$, but $T_1$ increases like $w^{-2}$, so that $\nu_1/T_1$ in fact decreases like $w$; there are more and more electrons energetic enough to radiate at any given frequency. On the other hand, the $w^{-6}$ dependence of $n_1^2$ dominates the $w^4$ dependence of relativistic effects, as well as the $w$ dependence of $T_1^{-1/2}$; the quadratic dependence on the density dominates all other terms and leads to a singularity. The $w^{-1/2}$ dependence of $d\eta$ adds to the divergence. For this reason we have evaluated $I_\nu$ for evolving models for finite values of $w_0$ only, 0.5 and 0.1.

In the limit $a \rightarrow 0$ a number of simplifications can be made. If the calculated intensity exceeds the Planck function (which behaves like $\nu^2$ as $\nu \rightarrow 0$) at any frequency, it must be replaced by $B_\nu(T_0)$, since one may infer a large optical depth in such circumstances. Otherwise, one may drop the exponential factor with the result that

$$I_\nu = \frac{2}{3(\gamma - 2)} I_0 [1 - w_0^{3(\gamma-2)/2}]\,. \qquad (q_0 = \tfrac{1}{2},\ a \ll 1) \tag{23}$$

This diverges like

$$w_0^{-3(2-\gamma)/2} \tag{24}$$

for $\gamma < 2$, and has a finite value

$$I_0 \frac{2}{3(\gamma - 2)} \tag{25}$$

for $\gamma > 2$ if $w_0 = 0$. The case $q_0 = 1$ cannot be discussed generally. We find for $\gamma = \frac{5}{3}$

$$I_\nu = I_0 \left[ \left( \frac{2}{w_0} - 1 \right)^{1/2} - 1 \right], \qquad (q_0 = 1,\ \gamma = \tfrac{5}{3},\ a \ll 1) \tag{26}$$

a function which behaves like $w_0^{-1/2}$ as $w_0 \rightarrow 0$ as is also the case for $q_0 = \frac{1}{2}$ (eq. [24]).

The case $\gamma = \frac{4}{3}$ is simple for all values of $a$. We find

$$I_\nu = I_0 \left( \frac{1}{w_0} - 1 \right) e^{-a}\,, \qquad (q_0 = \tfrac{1}{2},\ \gamma = \tfrac{4}{3}) \tag{27}$$

which diverges like $w_0^{-1}$ as $w_0 \rightarrow 0$. Evidently the behavior of $I_\nu$ as $w_0 \rightarrow 0$ depends on $\gamma$ and on $q_0$.

### III. NUMERICAL RESULTS

Equation (21) for the intensity of free-free emission in a steady-state universe was evaluated on an IBM 7090 computer for $\nu_0 = 10^{14}$ to $10^{24}$ c/s and $T_0 = 1$ to $10^{12}$ ° K; the results are plotted along with the data of Section I in Figure 1. (The results for $T < 10^4$ ° K and for $T > 10^{10}$ ° K are unreliable because $g$ differs from unity.)

Equations (15) and (16) were evaluated for the same frequencies and temperatures for the cases $\gamma = \frac{4}{3}, \frac{5}{3}, \frac{6}{3}$, and $\frac{7}{3}$, and $w_0 = 0.5$ and 0.1. The emission out to a redshift of unity ($w_0 = 0.5$) from a parabolic universe ($q = \frac{1}{2}$) expanding adiabatically ($\gamma = \frac{5}{3}$) is plotted in Figure 2, for the same temperatures as in Figure 1. Note that the steady-state curves are virtually identical in shape, and that they can be obtained by shifting the curves for the parabolic universe an amount $\Delta \log I = -0.43$ (downward) and $\Delta \log \nu = -0.12$ (to the left). It was found that the same statement can be made about the results for the other evolving models. Accordingly, instead of reproducing all the curves, we simply give in Table 2 the logarithmic increments by which one must shift the curves for the standard case in Figure 1 ($q_0 = \frac{1}{2}$, $\gamma = \frac{5}{3}$, $w_0 = 0.5$) to obtain the curves in question.

Another approach is illustrated for the steady-state case in Figure 3, where we have shown combinations of density and temperature (both considered as free parameters) which would entirely account for the various observed intensities (or upper limits) by free-free emission. Evidently the actual density and temperature must lie below and to the left of all the curves if the observations are not to be violated. Similar diagrams would obtain for the evolving models, with somewhat lower densities and temperatures.

Finally, Figure 4 shows the optical, X-ray, and $\gamma$-ray regions in more detail, with curves for $\gamma = \frac{5}{3}$ in the two evolving models, with $w_0 = 0.5$ and 0.1.

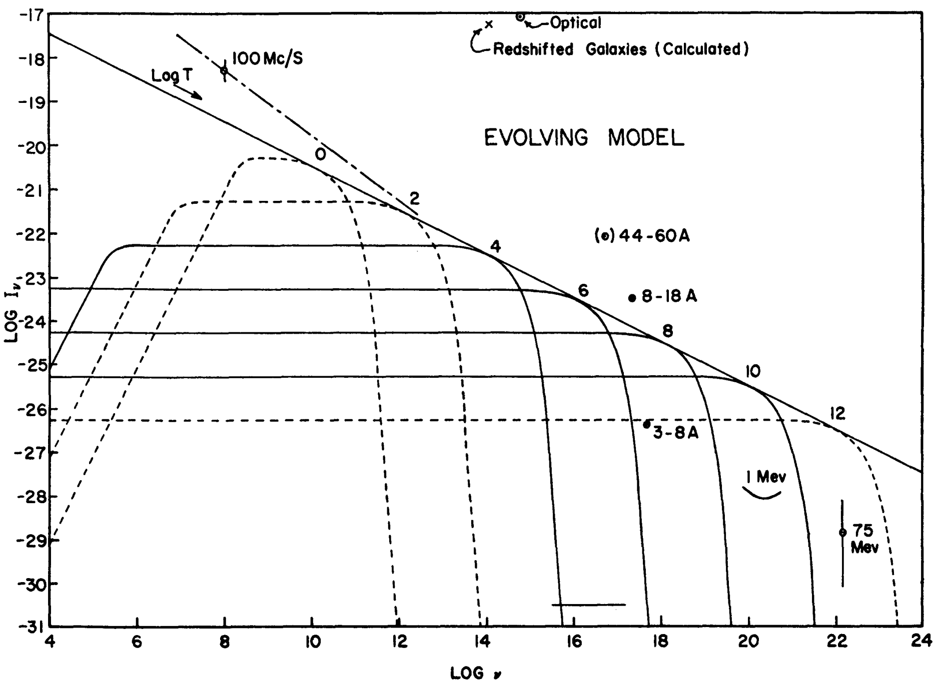


FIG. 2 —Free-free emission spectra computed for the evolving model having deceleration parameter $q_0 = \frac{1}{2}$, ratio of specific heats $\gamma = \frac{5}{3}$, and $w_0 = 0.5$, corresponding to a redshift of unity. Other evolving models give similar results if the curves are shifted according to Table 2.

TABLE 2

LOGARITHMIC INCREMENTS FROM STANDARD CASE

| $q_0$ | $w_0$ | $\gamma$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 4/3 | | 5/3 | | 6/3 | | 7/3 | |
| | | Δ log $I$ | Δ log $\nu$ | Δ log $I$ | Δ log $\nu$ | Δ log $I$ | Δ log $\nu$ | Δ log $I$ | Δ log $\nu$ |
| ½ | 0 5 | 0 08 | −0 27 | 0 00 | 0 00 | −0 08 | 0 32 | −0 15 | 0 59 |
| ½ | 1 | 1 04 | − 10 | 0.72 | 70 | + 44 | 1 65 | + 22 | 2 60 |
| 1 | 5 | 0 63 | − 12 | 0 55 | 14 | + .47 | 0 34 | + 40 | 0 59 |
| 1 | 0 1 | 1 52 | −0 19 | 1 21 | 0 70 | +0.95 | 1 60 | +0 73 | 2 51 |

## IV. DISCUSSION

Our results for the steady-state universe (see Fig. 1) are in qualitative agreement with those of Gould and Burbidge (1963), who found that a steady-state model with $T = 10^9$ ° K and $n = 10^{-5}$ cm$^{-3}$, as proposed by Gold and Hoyle (1959), would have a free-free emission intensity seventy times the observed value at 3–8 Å; our value is 20 for the same quantity, largely because our observational point is based on the higher fluxes observed by Bowyer *et al.* (1963). We therefore agree that the hot universe model of Gold and Hoyle is ruled out in the form they proposed it. We can put an upper limit on the temperature of such a steady-state model from Figure 1. Interpolation shows that $T < 4 \times 10^6$ ° K (compared to the rough estimate of $10^7$ ° K by Gould and Burbidge).

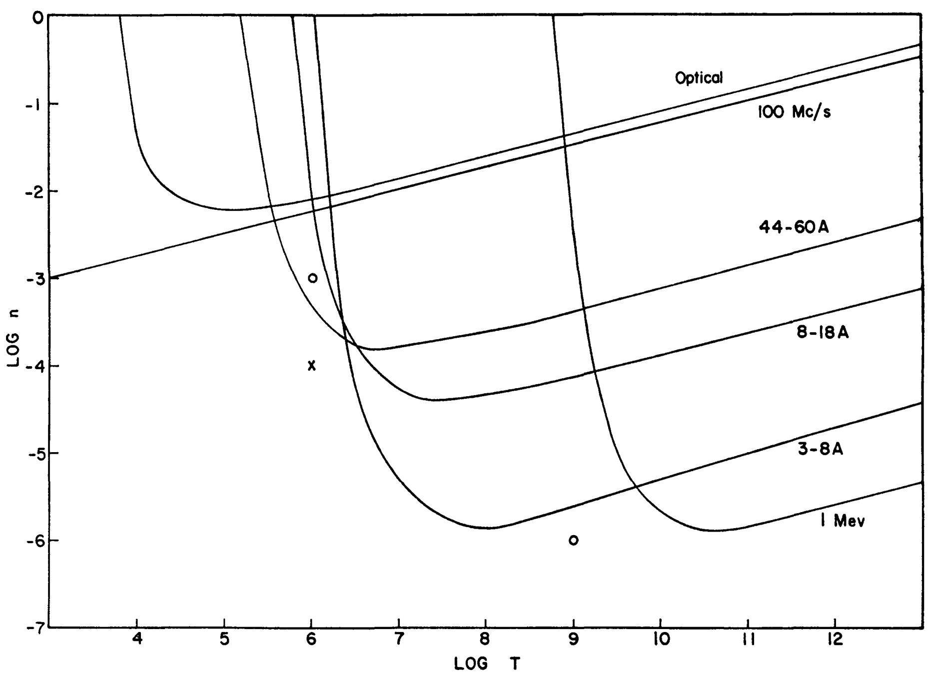


FIG. 3.—The combinations of density and temperature which for the steady-state model would give rise to the observed upper limit intensities at each frequency for which observations are available. The ratio and 1-MeV observations have uncertain gaunt factors, and the 44–60 Å observation is in a region of the spectrum where there is considerable interstellar extinction. The meaning of the cross and the circles is explained in the text.

We believe our limit is more precise because we have used the detailed frequency dependence of the free-free emission (eq. [21]) in arriving at it.

One way that Gold and Hoyle's "hot universe" can be made compatible with the data is to divide the intergalactic gas into two components in pressure equilibrium. The general intergalactic component could have $n = 10^{-6}$ cm$^{-3}$ and $T = 10^9$ ° K, while within clusters of galaxies, there could be a gas with $n = 10^{-3}$ cm$^{-3}$ and $T = 10^6$ ° K. Since the clusters fill about 1 per cent of space, the average density would be $10^{-5}$ cm$^{-3}$ as required. In Figure 3 we indicate these two components by circles. The effective smoothed-out density for free-free emission of the intracluster gas is the square root of the volume-filling factor, times the intracluster density, or $10^{-4}$ cm$^{-3}$; this point is indicated by a cross in Figure 3, and shows that the intracluster component is still below the limits of detection. Indeed, this picture is essentially that sketched by Gold and Hoyle, with the modification that the constant value of $nT$ is $10^3$ rather than $10^4$. This reduction of the "cosmological pressure" permits a combination of densities and temperatures which is marginally detectable. Indeed, the 3–8-Å observations include a significant contribution by the intercluster component on this basis (see Fig. 3). One attractive feature of this picture is that the intracluster gas would have a mass of about $3 \times 10^{14}$ suns per cluster, enough to make the clusters stable.

The evolving models yield higher intensities than the steady-state model (see Fig. 2).

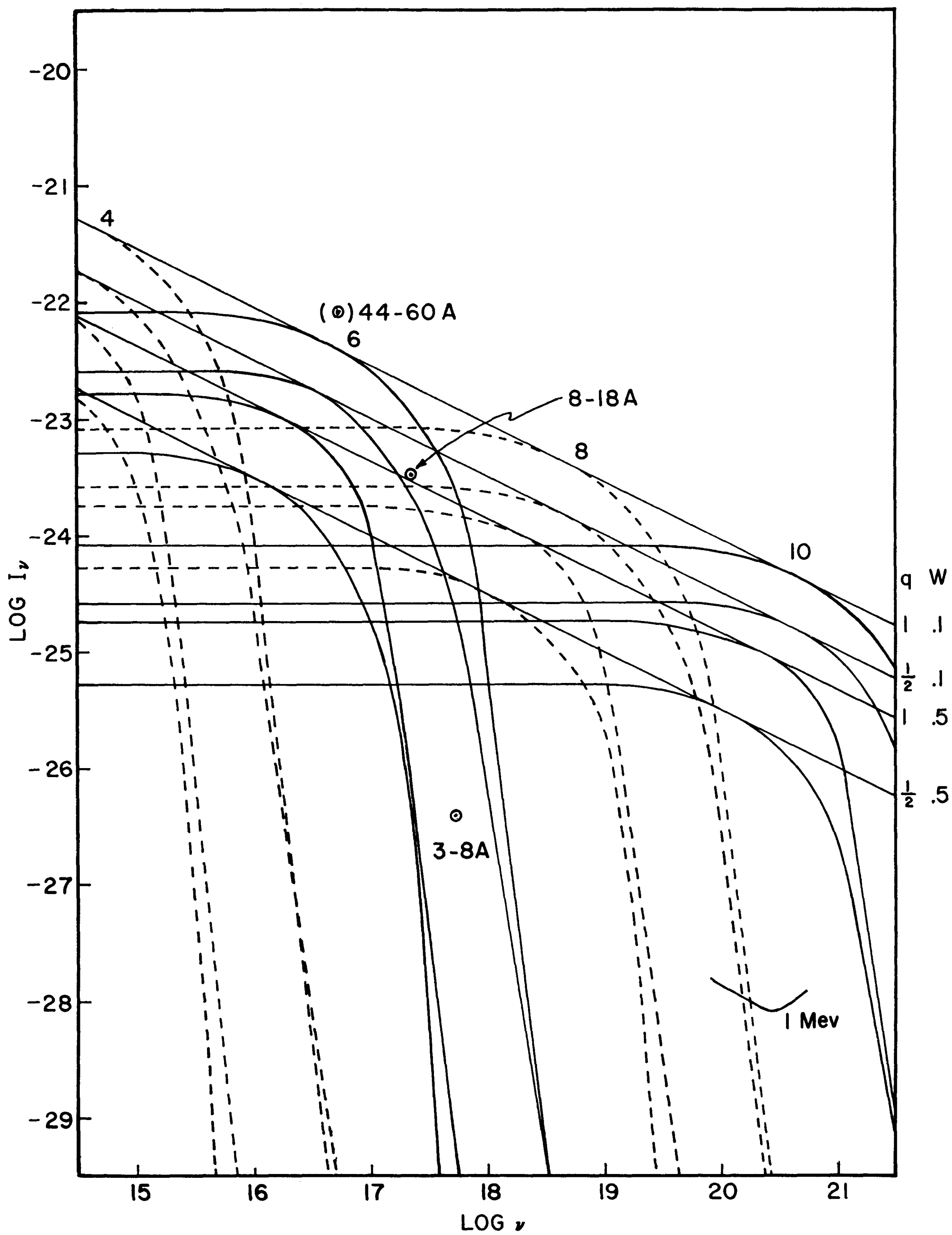


FIG. 4 —An expanded view of the spectra of evolving models for two values of $q_0$ and $w_0$, showing the critical observations Note the decisive results which would follow from an improvement in sensitivity at 8–18 Å.

The detailed situation in the X-ray region (Fig. 4) indicates that not only does the 3–8-Å point provide even smaller upper limits on the temperature for redshifts as small as 1 ($T_0 < 3 \times 10^6$ ° K for both $q_0 = \frac{1}{2}$ and 1), but also it rules out contributions by material having a redshift greater than 9, if $T_0$ is even as much as $4 \times 10^5$ ° K.

Figure 2 indicates that one of the most favorable wavelength regions for investigation of the free-free emission by intergalactic hydrogen is just shortward of 20 Å. Figure 5, based on data in Strom and Strom (1961), shows that longward of 20 Å one encounters

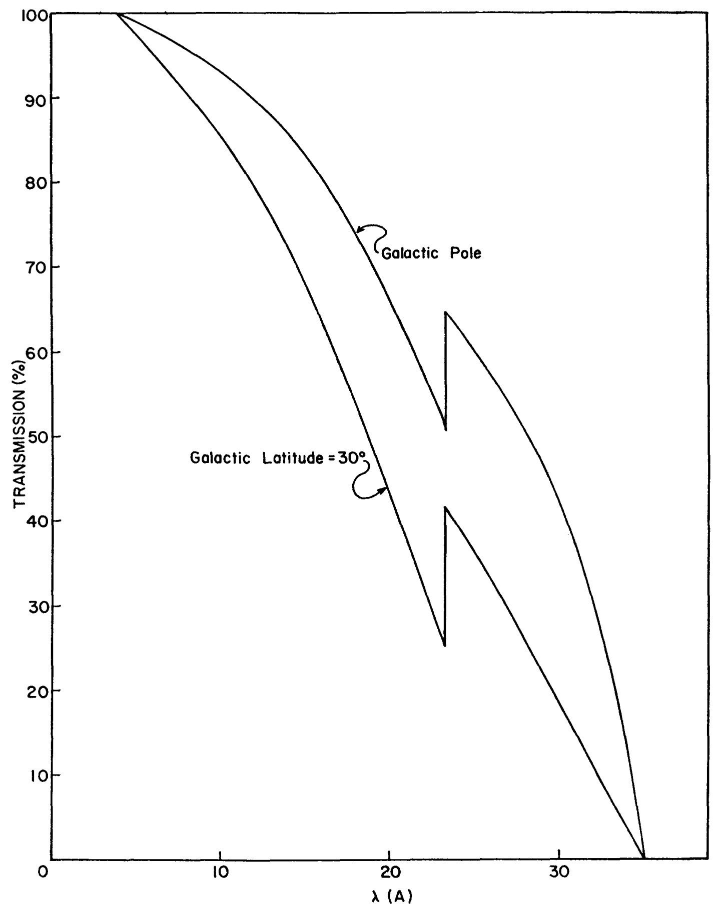


FIG. 5.—The transmission through the interstellar medium in the direction of the galactic pole and at galactic latitude 30° for the X-ray region. Experiments longward of 20 Å will be hindered greatly by interstellar extinction.

transmission factors less than 40 per cent at galactic latitudes less than 30°, while longward of 30 Å, the transmission factor even at the pole drops below 40 per cent. In the entire range from 20 to 912 Å (the Lyman limit), interstellar extinction precludes any very meaningful observations.

From 912 Å to the near infrared, on the other hand, Figure 2 indicates that ordinary starlight will swamp any intergalactic component, while the redshifted light of extragalactic nebulae will dominate at wavelengths up to 3 $\mu$, according to the calculations of Law (1963). Also, non-thermal radiation from unresolved radio galaxies may dominate at radio wavelengths and down to wavelengths as short as 30 $\mu$, if one extrapolates the results at 100 Mc/s using a spectral index of 0.7. Hence in the entire range from

20-Å to 300-m wavelengths, only the rather narrow range between 3 and 30 $\mu$ offers any real hope for observing the intergalactic free-free emission component; as yet there are no significant observational data in this region.

On the other hand, Figure 5 shows that interstellar extinction should be only moderate at wavelengths shorter than 20 Å. Since Figure 4 indicates that the emission is stronger at long wavelengths, it is advisable to carry out observations as near to about 20 Å as possible. One may even hope to establish the extragalactic nature of any emission detected by studying its distribution on the sky, as it should be strongly attenuated in the galactic plane.

The early observations of Byram, Chubb, and Friedman (1961) at 8–18 Å are relevant in this connection. Figure 4 shows that if the sensitivity of these observations had been comparable with that of the 3–8-Å observations of Bowyer *et al.*, matter out to a redshift of unity would have been detected if its temperature exceeded $10^6$ ° K, while matter out to a redshift of 9 would have been detected even if its temperature had been as low as $2 \times 10^5$ ° K. Since these values of the temperature do not seem at all extreme, we conclude that efforts to refine this earlier experiment may be rewarded with data that have very interesting implications for the temperature of the intergalactic medium and the state of the universe at earlier times.

This work was partially supported by the National Aeronautics and Space Administration under research grant NsG-414.

## REFERENCES

Allen, C. W. 1963, *Astrophysical Quantities* (2d ed.; London: Athlone Press).
Arnold, J. R., Metzger, A. E., Anderson, E. C., and Dilla, M. A. van. 1962, *J. Geophys. Res.*, **67**, 4878.
Baum, W. A. 1962, *Problems of Extra-galactic Research* (New York: Macmillan Co.), p. 390.
Bowyer, S., Byram, E. T., Chubb, T. A., and Friedman, H. 1963, Paper No. 11a, 115th meeting A.A.S., Washington, D.C.
Byram, E. T., Chubb, T. A., and Friedman, H. 1961, *Mém. Soc. R. Sci. Liège*, Ser. 5, **4**, 469.
Dufay, J. 1957, *Galactic Nebulae and Interstellar Matter* (New York: Philosophical Library), chap. xix.
Duthie, J. G., Hafner, E. M., Kaplon, M. F., and Fazio, G. G. 1963, *Phys Rev. Letters*, **10**, 364.
Field, G. B. 1959, *Ap. J.*, **129**, 536
———. 1962, *ibid.*, **135**, 684.
Giacconi, R., Gursky, H., Paolini, F. R , and Rossi, B. B. 1962, *Phys. Rev. Letters*, **9**, 439.
Gold, T., and Hoyle, F. 1959, *Paris Symposium on Radio Astronomy* (Stanford, Calif.: Stanford University Press), p. 583.
Goldstein, S. J. 1963, *Ap. J.*, **138**, 978.
Gould, R. J., and Burbidge, G. R. 1963, *Ap. J.*, **138**, 969
Gursky, H., Giacconi, R., Paolini, F. R., and Rossi, B. B. 1963, *Phys. Rev Letters*, **11**, 530.
Hoyle, F. 1948, *M.N.*, **108**, 372.
———. 1963, *Ap. J.*, **137**, 993.
Hoyle, F., and Narlikar, J. V. 1962, *Proc. R. Soc. London, A*, **270**, 334.
Karzas, W. J., and Latter, R. 1961, *Ap. J. Suppl* , **6**, 167.
Koch, H. W., and Motz, J. W. 1959, *Rev. Mod. Phys* , **31**, 920.
Kraushaar, W. L., and Clark, G. W. 1962, *Phys Rev Letters*, **8**, 106.
Law, R. R. 1963, *Proc. I.E.E.E.*, **51**, 1180.
McVittie, G. C., and Wyatt, S. P. 1959, *Ap. J* , **130**, 1
Mattig, W. 1958, *A.N.*, **284**, 109.
Robertson, H. P. 1938, *Zs. f. Ap.*, **15**, 69.
Robinson, B. J , Damme, K. J. van, and Koehler, J. A. 1963, *Nature*, **199**, 1176.
Sandage, A. 1961*a*, *Ap. J.*, **133**, 355.
———. 1961*b*, *ibid.*, **134**, 916.
Strom, S. E., and Strom, K. M. 1961, *Pub. A S.P.*, **73**, 43.
Zwicky, F. 1962, *Problems of Extra-galactic Research* (New York: Macmillan Co.), p. 349