SOVIET PHYSICS USPEKHI VOLUME 14, NUMBER 5 MARCH-APRIL 1972

523.038

THE UNIVERSAL ELECTROMAGNETIC BACKGROUND RADIATION

M. S. LONGAIR* and R. A. SUNYAEV†

Usp. Fiz. Nauk 105, 41-96 (September, 1971)

CONTENTS

INTRODUCTION

ELECTROMAGNETIC radiation is our principal source of information about the universe and about the processes which are taking place in stars, galaxies, quasars and other cosmical objects. Until recently astronomers were primarily concerned with the study of the radiation from discrete objects but during the last ten years the importance of analyzing the radiation which is not associated with discrete sources has been realized and has been intensively studied. The brightness of the sky—or the electromagnetic background radiation—gives us information about the radiation which fills the universe, and so gives us general information about the universe as a whole. It is thus obvious why the analysis of this radiation is particularly important for cosmologists.

The question of the darkness of the night sky has played a central role in cosmological speculation since the origins of modern cosmology when it constituted the only fact concerning the large scale structure of the universe. Interest in this problem is particularly lively at the present time since the most recent studies relate the background radiation to specific physical processes taking place at different stages in the evolution of the universe.

The paradox which is normally associated with the name of Olbers was known to astronomers and philosophers of earlier times (for an interesting historical review see [2]). The paradox can be simply stated "Why is the sky dark at night"? In an infinite stationary universe filled with stars the line of sight from any observer must eventually encounter the disc of a star and it is therefore expected that the brightness of the sky should be similar to that of the surface temperature of stars, i.e., $T \sim 5000°K$. This is clearly in contradiction with our experience.

The resolution of the paradox had to await the discovery of the recession of the nebula in the 1920's. The answer is that the universe is not at all stationary but is in a state of expansion in which the relative velocity of recession of any two points is locally proportional to the distance between them (Hubble's Law). At very large distances the form of Hubble's Law depends upon the exact choice of cosmological model but independent of the model the important effect is that the light from stars (or as we now know, galaxies) at very great distances is received at a redshifted wavelength, i.e., photons emitted by a distant star are observed with much smaller energy than that with which they were emitted and this effect can entirely explain why the sky is dark at night.

Thus Olber's paradox is resolved but the question of how dark (or light) the sky actually is is a question of great interest for classical cosmology. If we know the principal sources of radiation in a particular wavelength region we can, in principle, distinguish which cosmological model is the best description of the large scale structure of the Universe. In practice this test is of little use since there is little difference between the predictions of different cosmological models and generally it is not known what the principal contributors to the background radiation are at large redshifts.

This is the first aspect of the discussion of the background radiation—the integrated background intensity due to discrete sources.

During the 1920's observations were restricted to the optical region of the spectrum but within the last twenty years the wavelength range available for observation has greatly expanded as a result of the development of radio astronomy and of observations above the earth's atmosphere. Most recently the infrared, ultraviolet, x-ray and γ-ray regions have been opened up.

What is the background radiation or the brightness of the sky in these wavebands? Below we will discuss the universal electromagnetic radiation which is observed once the effect of nearby interfering sources such as the atmosphere or the radiation from our own galaxy has been eliminated—the radiation we will discuss is present in every cubic centimeter of intergalactic space.

As a result of the great prowess of the observers the background radiation spectrum is more or less known from long radio waves ($\lambda \gtrsim 300$ m; $\nu \lesssim 10^6$ Hz) to γ-ray wavelengths ($\mathcal{E} > 100$ MeV; $\nu > 10^{22}$ Hz). Un-

---

*P. N. Lebedev Institute of Physics, USSR Academy of Sciences and Mullard Radio Astronomy Observatory, Cavendish Laboratory, Cambridge, England.

†Institute of Applied Mathematics, USSR Academy of Sciences, Moscow, USSR.

fortunately there are still gaps in the background spectrum which are either a) due to the fact that in principle it is impossible to make observations from within our galaxy because of strong absorption (e.g., the unobservable ultraviolet) or b) because the extragalactic component is weaker than the emission from the atmosphere, from the interplanetary and interstellar medium and from discrete galactic sources (optical and ultraviolet wavelengths) or c) because it is difficult at the present day to achieve sufficient sensitivity and angular resolution with the existing techniques (sub-millimeter, infrared and γ-ray wavelengths). However we can make estimates of the objects and the types of physical process which are likely to be important in these wavebands. These analyses are important in planning future experiments.

The other aspect of the problem of the background radiation is not associated with discrete sources. Its importance is either concerned with the properties of the universe as a whole (the microwave background) or with the existence of different forms of matter in intergalactic space (gas or cosmic rays).

Background observations in the centimeter and millimeter wavelength regions since 1965 have shown that there exists an isotropic component with a spectrum in excellent agreement with that of blackbody radiation at a temperature 2.7°K. This discovery appears to be the most important for cosmology since the discovery of Hubble's Law. It lends powerful support to the theory of the hot model of the universe first described in detail by Gamow and his co-workers in 1948. In the hot model of the universe it is supposed that the universe is characterized by a high specific entropy. The ratio of the number of quanta to each atom is very large (10^7–10^9). At the present day these quanta are of very low energy ($h\bar{\nu} \approx 10^{-3}$ eV) but (since in an expanding universe the energy of each photon decreases with time) extrapolation into the past leads to gigantic radiation temperatures and a thermodynamic equilibrium between matter and radiation is set up at a high temperature. In the early stages of the expansion the fundamental parameters of the universe such as its density, pressure, speed of expansion, etc. are determined by this radiation. In the USSR this blackbody radiation which contains information about the early stages of expansion of the universe is called the relict radiation but in order not to prejudice the issue we will prefer to refer to this radiation as the isotropic microwave background radiation.

There is no positive evidence at all for the existence of a diffuse gas in the space between galaxies but the existing observations do not contradict the hypothesis that there is a diffuse gas in intergalactic space. The lines of reasoning which lead to this hypothsis are indirect. Firstly it is known that the mean density of matter in the universe as determined by its deceleration is much greater than the mean density of visible matter contained in galaxies. The difference between the two estimates corresponds to a factor of about 40. Secondly it is difficult to imagine that the process of galaxy formation was so effective that all the matter in the universe condensed into discrete objects from a more or less uniform medium.

This discrepancy could be ascribed to the existence of an intergalactic gas or to other forms of invisible matter such as collapsed objects, dead galaxies, weakly interacting particles with zero rest mass, etc. This is again directly related to the question of the choice of cosmological model. If the mean density of matter in the universe is greater than the critical value $\rho_c \sim 10^{-29}$ g-cm^{-3} then according to the Friedman models the universe is closed and its present expansion will eventually be reversed in the future. If $\rho \leq \rho_c$ the universe is open and the expansion will continue indefinitely. An intergalactic gas could be discovered by its emission and therefore it is very important for cosmology to measure the background radiation at radio, ultraviolet and x-ray wavelengths where there is relatively little emission from other objects and there is a real possibility of determining the characteristic spectrum of the radiation of a hot plasma of low density.

From observations of extragalactic radio sources it is well known that clouds of relativistic electrons and possibly protons and the nuclear components of cosmic rays are ejected into intergalactic space. Therefore, in the space between galaxies there co-exists non-relativistic matter, cosmic ray protons and electrons and photons of a wide range of energy. There is a very wide range of possible interactions between these components which can lead to changes in the spectrum of the background radiation. It is evident that their influence upon the background spectrum depends strongly upon the present state of the universe and its past history which can in principle be deduced from such observations.

Background components due to discrete sources and to the radiation of intergalactic space can in principle be distinguished by studying the angular fluctuations of the background intensity. In the first case it is expected that significant fluctuations should be observed if the angular resolution and sensitivity of the telescopes enable angular scales of the order of minutes or degrees to be studied whereas in the second case there should be no fluctuations. This is a useful general criterion for those regions of the spectrum where the origin of the background radiation is unknown.

In this survey we will discuss the existing observations, the problems of accounting for the background emission and the properties of the principal sources of radiation for each spectral region in turn. The over-all spectrum of the background is shown in Fig. 1; regions for which there exist definite measurements of an isotropic background component are shown with a continuous line whereas those for which only theoretical estimates or observational upper limits are available are shown with a dashed line. Figure 2 shows the difficulty of accounting for the background in different wavelength regions. In Table I we give the energy density and the photon number density at the present epoch for different regions of the spectrum. Below we will discuss the various regions indicated in Fig. 1 and their importance for cosmology. We emphasize that many aspects of the problems discussed in this survey are far from being properly understood and many questions are still unclear. Naturally the exposition of these problems has somewhat of a subjective character and to an extent reflects the point of view of the authors.

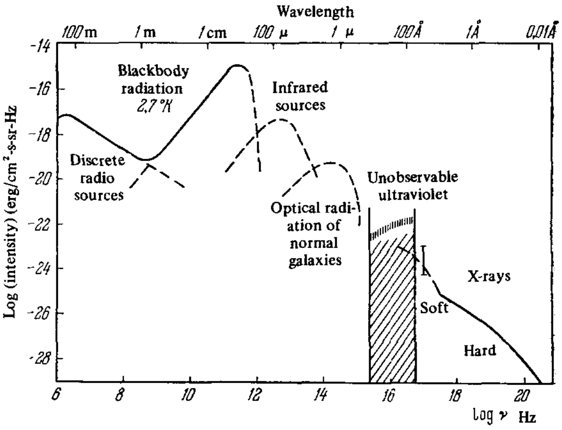

FIG. 1. Spectrum of background radiation of universe. The continuous line shows the observation results, and the dashed line the theoretical estimates.

Notation

Before we begin our review we give a number of useful cosmological formulae and the form of the expressions which we will use for intensities. Below we will use the concepts of intensity of the background radiation J_ν (erg $cm^{-2}s^{-1}sr^{-1}Hz^{-1}$) related to which we can define a brightness temperature T_b according to the Rayleigh-Jeans Law

$$J_\nu = \frac{2kT_b}{\lambda^2},$$

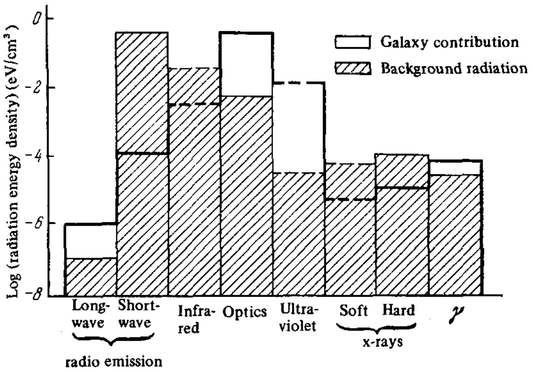

FIG. 2. Energy density of diffuse radiation in the galaxy, which is the sum of the isotropic component of the background radiation and the radiation of galactic origin. This method of representing the data [2] demonstrates the difficulty of separating the isotropic component of the diffuse scattering in various spectral bands.

The spectral power of sources will be denoted by P_ν [$erg\text{-}s^{-1}Hz^{-1}$] and the flux density received by an observer of such a source by S_ν [$erg\text{-}cm^{-2}s^{-1}Hz^{-1}$]. If J_ν (or S_ν) is to be described by a power law spectrum in some range of frequency we can define the spectral index α by the relation

$$\alpha = -\nu \frac{d\ln J_\nu}{d\nu}$$

For a continuous power law spectrum this becomes $J_\nu \propto \nu^{-\alpha}$.

It is useful to introduce the dimensionless density of a particular constituent of the universe by the relations $\Omega = 2q_0 = \rho/\rho_c$ where $\rho_c = 3H_0^2/8\pi G = 2\times10^{-29}$ $g\text{-}cm^{-3}$ taking the Hubble constant to be $H_0 = 100$ $km\text{-}s^{-1}Mpc^{-1}$ $= 3\times10^{-18}s^{-1}$ and Λ the cosmological constant to be zero. ρ_c is often referred to as the critical density in that it separates open from closed world models.

It is often useful to have a relationship between cosmic time and redshift rather than distance and time. The redshift is defined to be $z = (\lambda_{obs} - \lambda_0)/\lambda_0$, which describes the change in wavelength of a particular spectral line which was emitted with wavelength λ_0 which is received by the observer with wavelength λ_{obs}. For world models in which the cosmological constant Λ is equal to zero the relationship between the increment of cosmic time is related to the increment in redshift by

$$\frac{dt}{dz} = -\frac{H_0^{-1}}{(1+z)^2(1+\Omega z)^{1/2}},$$

The density of matter in matter-conserving cosmologies changes with redshift as

$$n = n_0(1+z)^3,$$

whereas the energy density of radiation (assuming the total number of quanta to be conserved) changes as

$$W_r = W_0(1+z)^4,$$

On the other hand the spectral density of energy of radiation varies with redshift as

Table I. Energy density and number of background-radiation quanta at different wavelengths

Wavelength	Radiation energy density, eV/cm³	Photon-number density, cm⁻³
1a. Long wave radio emission 1b. Residual radio emission	$\sim 10^{-7}$ 0.25	~ 1 400
2. Infrared	$\sim 10^{-2}$	~ 1
3. Optical	$\sim 3\cdot10^{-3}$	$\sim 10^{-3}$
4a. Soft x-rays ($\mathcal{E} < 1$ keV) 4b. Hard x-rays ($\mathcal{E} > 1$ keV)	$10^{-4} \div 10^{-5}$ 10^{-4}	$3(10^{-7} \div 10^{-8})$ $3\cdot10^{-9}$
5a. Soft γ radiation ($\mathcal{E} \sim 1$–6 MeV) 6b. Hard γ radiation ($\mathcal{E} > 10$ MeV)	$\sim 3\cdot10^{-5}$ $< 10^{-5}$	$\sim 10^{-11}$ $< 10^{-12}$

$$\mathscr{E}_\nu = 4\pi \frac{J_\nu}{c} = \mathscr{E}_\nu(0)\,(1+z)^{3+\alpha}.$$

In the above formulae n_0, W_0, $\mathscr{E}_\nu(0)$ all refer to the present epoch. Finally the observed background due to sources having proper space density N(z) is equal to

$$J_\nu = -\frac{c}{4\pi}\int_0^\infty \frac{P_\nu(z)}{(1+z)^{3+\alpha}} N(z)\frac{dt}{dz}\,dz = \frac{cH_0^{-1}}{4\pi}\int_0^\infty \frac{P_\nu(z)\,N(z)}{(1+z)^{5+\alpha}\sqrt{1+\Omega z}}\,dz$$

In terms of comoving coordinate density $N_0(z)$ we have $N(z) = N_0(z)(1+z)^3$ so that for a source conserving cosmology in which $N_0(z)$ = constant and the luminosities of the sources are unchanged with time

$$J_\nu = \frac{cH_0^{-1}}{4\pi} P_\nu(0) N_0(0) \int_0^\infty \frac{dz}{(1+z)^{2+\alpha}\sqrt{1+\Omega z}}$$

The formal justification for these formulae can be found in the review article "Observational Cosmology" by one of us[219] (M.S.L.).

I. RADIO WAVELENGTHS

Our review begins with the one wavelength region in which there exist measurements of the background radiation and there is sufficient information that their interpretation is reasonably certain. It is convenient to consider separately the long wavelength region in which the background emission results from the superposition of discrete radio sources and the short wavelength region in which the microwave background radiation is dominant.

1. Long Wavelength Radio Emission ($\nu < 600$ MHz; $\lambda > 50$ cm)

In this wavelength region the determination of the isotropic background radiation is difficult because radio telescopes detect not only the isotropic component but also the synchrotron radiation of our own Galaxy. The extragalactic component can be distinguished from the emission of our own Galaxy at meter wavelengths because their spectra are different. Careful measurements at different wavelengths in different directions about the galactic poles where the radiation from the Galaxy is small enable the intensity of the background radio emission to be determined.

The extragalactic background found from such analyses can be simply explained as the integrated emission of distant discrete radio sources having spectra similar to those of radio galaxies and quasars in the wavelength range under consideration. The space density of galaxies and radio galaxies and their known radio luminosities seem insufficient however to explain the observed intensity of the background emission. This problem is resolved by the counts of weak (and therefore distant) radio sources. It turns out that the number of faint radio sources increases more rapidly with decreasing flux density than would be expected in all uniform cosmological models. When their number over all the sky exceeds a million the rate of growth decreases. We can interpret these facts in the following way. The majority of sources included in the counts are radio galaxies or quasars and have very high radio luminosities. The more distant the source the smaller its flux density. In the expanding universe distant sources are observed at epochs earlier than the present so that weak distant sources emitted their radio waves at much earlier epochs than the brightest ones. The source counts indicate that the number density of radio sources has changed with time in such a way that there were many more powerful radio sources in the past than there are at the present time (a more detailed discussion will be given below).

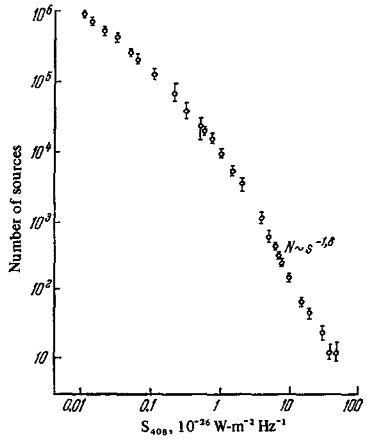

FIG. 3. Count of radio sources at frequency ν = 408 MHz [13].

The following simple picture might be constructed. At some stage in the expansion of the universe radio sources were first formed. These sources have lifetimes much shorter than the timescale of the universe so that the observed space density of sources is determined by the product of their rate of formation and their lifetimes. If the source lifetimes remain constant whilst the rate of formation decreases continuously with time, we will observe more sources at large distances then we would expect for a uniform model. This type of model can explain the excess number of faint sources found in surveys of faint radio sources. The discovery of the evolution of the number of radio sources with time resolves the problem of the origin of the background. It is due to the large number of powerful sources at great distances and can entirely explain the observed background.

a) Observations. At meter wavelengths the sky is very bright but the distribution of radio brightness is highly anisotropic and concentrated towards the galactic plane. The problem consists in separating out of this anisotropic distribution an isotropic component which could be associated with the integrated emission of extragalactic radio sources or with the radiation from matter in intergalactic space. An upper limit to the intensity of the isotropic component can obviously be found from the minimum brightness of the sky. According to surveys of the northern sky the minimum sky temperature in roughly but not exactly the direction of the galactic pole is $T_b < 80$°K at a frequency of 178 MHz.[3]

The procedure for determining the isotropic component of the background consists of studying the sky at different frequencies with scaled aerials, i.e., aerials which have exactly the same polar diagrams at different frequencies. In analyzing the observations it is assumed that the extragalactic component is isotropic and that the anisotropic component which is associated with our

Galaxy has a spectrum which is independent of direction. We may write

$$T(\nu;\alpha,\delta)=T_0(\nu)+T_{\text{gal}}(\nu;\alpha,\delta),$$

where α and δ are coordinates on the celestial scale. From observations of the sky at different frequencies it is possible to determine from the relationship

$$T_0(\nu_1)+T_{\text{gal}}(\nu_1;\alpha_i,\delta_i)=a\left(\frac{\nu_1}{\nu_2}\right)T_0(\nu_2)+b\left(\frac{\nu_1}{\nu_2}\right)T_{\text{gal}}(\nu_2;\alpha_i,\delta_i)$$

the value of $b = T_{\text{gal}}(\nu_1;\ \alpha,\ \delta)/T_{\text{gal}}(\nu_2;\ \alpha,\ \delta)$ for different pairs of frequencies and hence to construct the spectrum of the radio emission from our Galaxy. This spectrum in the wavelength range 13–178 MHz can be described by a power law spectrum $J_\nu \propto \nu^{-\alpha}$ having spectral index $\alpha = 0.4$.[4] Several independent experiments have obtained this result although some groups find a slightly different value (see e.g., [4,5]). At higher frequencies the Galactic radio spectrum steepens and is in good agreement with the spectrum of relativistic electrons observed within the solar system; the latter is well known in the energy range $E_e > 1$ GeV. It is now possible to determine the extragalactic background emission but the errors involved in each step in the separation of this component accumulate to such an extent that it is impossible to obtain both the slope of the extragalactic spectrum and its absolute intensity. The observations only exclude an isotropic component having spectral index α smaller than 0.6.

What is done in practice is the following. It is assumed that the principal contribution to the background is due to extragalactic radio sources and their mean spectral index can be used. Various analyses (6) have found $\alpha = 0.75$ corresponding to a value of the brightness temperature of the isotropic background of 30 ± 7°K at a frequency 178 MHz.[7] If an increased value of α is assumed the intensity of the background decreases. For example, if $\alpha = 0.9$, $T_b = 15 \pm 3$°K.[7] We note that the integrated background from sources detected in deep surveys amounts to $T_b \approx 15$°K (see below) which suggests that α must be less than 0.9.

Another method of determining the intensity of the background emission has been described by Shane.[8] The nebula 30 Doradus in the Large Magellanic Cloud is optically thick at meter wavelengths and its thermal emission at 85 MHz can be shown to be insignificant. Comparison of the brightness of the sky in the direction of the Cloud and in its vicinity enables an estimate of the background of $T_b = 250$°K at 85 MHz to be found. This corresponds to roughly 30°K at 178 MHz if $\alpha = 0.75$. However because of inhomogeneities in the electron density (and therefore fluctuations in brightness and optical depth) there are considerable errors on this estimate. Thus this method is basically of technical interest.

There has been considerable work on the separation of the isotropic component at frequencies below 10 MHz where the observations are strongly affected by the ionosphere. Because of the difference in spectra of the radio emission of the Galaxy and of the extragalactic background the latter should be dominant in directions away from the galactic plane at low frequencies (less than 3 MHz) but unfortunately absorption by ionized hydrogen in our Galaxy becomes important at these frequencies. Measurements from the surface of the earth at 2 MHz[9] and satellite observations in the range 0.4 to 2 MHz[10] have however given important information on the spectrum in this region. The spectrum of the observed radiation flattens and at very low frequencies cuts off abruptly. Bridle[11] has shown that it is likely that the intensity of the isotropic background radio emission decreases at about 2 MHz. This follows from the fact that there is no absorption of the background at 2 MHz in the direction of the Large Magellanic Cloud which would be expected because of absorption by ionized hydrogen. Analysis of the satellite observations support this conclusion.[12]

b) Sources and their evolution. The long wavelength radio background is the one region of the background spectrum which can be explained with reasonable certainty in terms of observed objects, viz., extragalactic radio sources. In directions away from the galactic plane practically all radio sources are extragalactic. A great deal of effort has been expended in determining their space distribution, the ultimate aim being to use these sources in cosmological tests. Observations of the numbers of sources in different directions can give information about the degree of isotropy of the universe and the change in the numbers of sources with distance from our Galaxy can give information about the evolution of the universe with time. Unfortunately there are no characteristic lines in radio spectra from which redshifts and hence distances can be found. Therefore the change in numbers of sources with distance must be studied indirectly and it is possible to do this using the counts of radio sources, N(S), meaning the function which describes the numbers of sources brighter than different limiting flux densities $s = F_\nu$.

The most recent observations[13] have determined the function N(S) at 408 MHz to very low flux densities $S_{408} \geq 0.01 \times 10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}} = 10^{-25}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}}$. On the celestial sphere the sources contributing to the counts exhibit a high degree of isotropy.[14] However at the lowest flux densities optical information is only available on a very small fraction of their number (roughly 5% and a number of these are quasars, i.e., objects with very large radio and optical luminosities). This implies that the majority of objects included in the counts are at very great cosmological distances. For these sources, their radio luminosities must exceed by a large factor those of normal galaxies. Galaxies such as our own would only be observable at the lowest flux densities to about 50 Mpc which is negligible in comparison with cosmological distance scales $cH_0^{-1} \approx 10^{28}$ cm ≈ 3000 Mpc. In the range R < Mpc the number of such galaxies is small, certainly no more than thousands whereas the source counts to the present limits of flux density require more than millions sources. Also, such galaxies are readily identified optically.

Knowing the density and luminosity function* of radio sources at the present epoch it is simple to work out the number of sources as a function of flux density for any model of the universe. The result of these calculations leads to the following surprising results. The ob-

---

*The luminosity function N(P) is the function which describes the space density of objects having radio luminosity P.

served numbers of weak sources greatly exceed the predictions of all simple world models.[15,16] This observation contradicts the predictions of steady state cosmology but can easily be explained in evolutionary cosmological models in which the number of powerful radio sources can be much greater in the past than it is at the present day. Detailed analyses of the counts show that these evolutionary effects must be very strong and associated mainly with the most powerful radio sources having radio luminosities $P_{178} > 10^{27}$ WHz^{-1} = 10^{34} erg s^{-1}Hz^{-1}. The radio luminosity of our galaxy is about 5 or 6 orders of magnitude smaller than this value. The space density of radio sources in co-moving co-ordinates changes with epoch and can be written $N_0(z) \propto (1+z)^{5-6}$, i.e., the proper space density of sources taking account of the expansion of the universe changes as $N \propto (1+z)^{8-9}$. This strong evolution only takes place at relatively small redshifts ($z \lesssim 3$–4) and is only connected with the most powerful sources. These constraints result from the known background due to sources and from the abrupt decrease in the counts of radio sources at small flux densities. The existence of evolution has been now confirmed by observations at optical wavelengths where the existence of spectral lines enables redshifts to be determined. The space density of quasars also evolves with epoch as $N_0(z) \propto (1+z)^6$ (in comoving coordinates) out to redshift $z_{max} \sim 2.3$[17] beyond which there is not yet any evidence of evolution. Evidently the rate of formation of quasars and radio sources was greatest at about this epoch. It is possible that this activity is related to the epoch of formation of galaxies. The integrated emission from sources included in the source counts to the lowest flux densities which have yet been investigated give a brightness temperature $T_b \approx 15$°K which is roughly half of the background radiation of $T_b = 30$°K at 178 MHz. Thus a significant contribution to the background comes from powerful radio sources having redshifts in the range $z \sim 2$–4.

The observed counts of sources can be extrapolated to much smaller flux densities and the total background due to all radio sources estimated. Such estimates lead to a figure of the order 20–24°K at 178 MHz.[19] Thus virtually all the background can be accounted for as the radiation of discrete sources. In view of the uncertainty in the value of the brightness temperature of the radio background and in the extrapolation of the counts the discrepancy between these figures is of little significance. It is interesting that cosmological evolution plays an essential role in this argument. Without it the integrated emission of all radio sources would only be 5°K at 178 MHz (Table II). The excess over this figure is explained entirely by the existence of large numbers of powerful radio sources at earlier stages in the expansion of the universe. Sholomitskiĭ[20] has estimated that non-evolving objects such as weak radio galaxies and galaxies might make a significant contribution to the background. The supposition of Brecher and Morrison[21] that normal galaxies contribute 90% is in contradiction with the results of the integrated flux from sources which are included in the source counts and also their spectra do not correspond to the radio spectra necessary to explain the background ($\overline{\alpha} = 0.3$ for normal galaxies whereas the background spectrum must have α in the range 0.6 to 0.9—see above).

c) The background radio emission and the intergalactic gas. The decrease in the background intensity at frequencies below 2 MHz could be attributed to intergalactic absorption or to the intrinsic properties of the radio sources themselves. The first possibility might be associated with bremsstrahlung absorption by the intergalactic gas;[11,22] it is difficult however to find a suitable temperature history of the gas which would not contradict other pieces of experimental evidence on the parameters of the gas and yet produce the necessary absorption. Induced Compton scattering of the background radiation by the electrons of the intergalactic gas cannot distort the intrinsic spectra of sources in this spectral region.[23] It is most likely that the spectrum in this region corresponds to the spectra of the sources themselves.

Observations have discovered no evidence for any neutral hydrogen in intergalactic space out to a redshift $z = 2.8$. At the same time these observations would be consistent with the existence of a hot ionized intergalactic gas. The spectrum of the thermal emission of an optically thin gas has the following characteristic spectrum; for frequencies $h\nu \ll kT_e$ the spectral intensity does not depend on frequency, i.e., $\alpha = 0$ whereas at frequencies $h\nu \sim kT_e$ the spectrum is $J_\nu = (\text{const}/T_e^{1/2}) \exp\{-h\nu/kT_e\}$. Therefore it can be seen that in the decimetric range where there is a minimum in the radio background intensity due to our galaxy, to extragalactic sources having spectrum $J_\nu \propto \nu^{-0.75}$ and to the microwave background radiation having $J_\nu \propto \nu^2$ (see Figs. 1 and 4) is the optimum for seeking a thermal component of the background emission. From measurements in the frequency range 400 to 2000 MHz[24,25] an upper limit on the thermal radio emission of the intergalactic plasma can be set $J_\nu < 10^{-19}$ erg cm^{-2} s^{-1} sr^{-1} Hz^{-1} corresponding to $T_b < 10$°K at 178 MHz or 1°K at 600 MHz. This figure is of the order of that due to radio sources at 178 MHz. In spite of this generous upper limit these measurements are very useful. It is known that, if the ionization is due to electron collisions, then below a temperature of 10^4°K a hydrogen plasma is practically neutral and emits only weak thermal radiation but at higher temperatures the degree of ionization and radiation rate increase rapidly. This fact together with the present upper limit to the brightness temperature of hot radiating gas implies a small optical depth for the bremsstrahlung process back to the period corresponding to a redshift $z \sim 10^4$. This upper limit on the radio emission of the intergalactic gas leads to important limits to the epoch of the re-heating of any intergalactic matter in the universe.[26,27]

2. The Microwave Background Radio Emission (600 MHz $< \nu < 10^{12}$ Hz; $300\mu < \lambda < 50$ cm)

In 1965 Penzias and Wilson[28] discovered that the background radiation at 7 cm was at least two orders of magnitude greater than that expected by extrapolation from the long wavelength region and corresponded to a brightness temperature of about 3°K.* Since that time all ground based experiments in the wavelength

---

*Poroshkevich and Novikov [29] emphasised the importance of making observations in the centimeter waveband as a possible test of the hot model of the universe.

Table II. Background radio emission at 178 MHz

Nature of radiation	Brightness temperature
Observations	
Observed minimal brightness of sky	80 °K
Isotropic background if the spectral index is: $\alpha = 0.75$ $\alpha = 0.9$	30±7 °K 15±3 °K
Central background connected with sources entering in the calculations of the discrete radio sources with s (ν = 408 MHz) $>$ 0.01 × 10^{-26} W/m² Hz	~ 14° K
Predicted background	
Without cosmological evolution contribution: of normal galaxies of powerful extragalactic radio sources of all galactic sources	 ~ 4 °K ~ 1 °K ~ 5 °K
With cosmological evolution contribution: of normal galaxies (non-evolving part) of powerful extragalactic radio sources of all extragalactic sources	 ~ 4 °K ~ 16—19 °K ~ 20—23 °K

range 75 cm to 3 mm have confirmed the existence of a background component having a blackbody spectrum with radiation temperature 2.7°K. Most of these experiments refer to Rayleigh-Jeans region of the spectrum which can be approximated by the law $J_\nu \propto \nu^2$ but recent observations[30,31,220] are of sufficient accuracy that the departure of the Planck curve from the Rayleigh-Jeans Law close to the maximum of the blackbody curve have been detected.

a) Interstellar molecules as a thermometer. Other evidence on the existence of the cut-off at millimeter wavelengths is obtained from observations of molecular absorption lines in stellar spectra. Observations of the optical abosrption line of CN enable the populations of the fine structure levels of the ground state, the difference in energies of which correspond to a wavelength of 2.6 mm to be determined. The observed intensities correspond to the level populations which would be expected if the molecules were situated in a radiation field at a temperature of 2.83 ± 0.15°K. This figure is found in observations of the absorption lines in the spectrum of the star ζ Oph,[35] Similar values of temperature were found in observations of ten other stars but the accuracy of the measurements was much poorer because the stars are much fainter.[32-35] Studies of other optical absorption lines of the interstellar molecules CN, CH, CH⁺ can be used to derive upper limits to the radiation temperature.[35] These limits are important because they give information about even shorter wavelengths and support the view that there exists a Planck cut-off in the spectrum (at λ = 1.32 mm, $T_b < 4.74$°K corresponding to $J_\nu < 1.9 \times 10^{-14}$ erg cm^{-2} s^{-1} sr^{-1} Hz^{-1}; at λ = 0.56 mm $T_b < 5.43$°K, corresponding to $J_\nu < 2 \times 10^{-14}$ erg cm^{-2} s^{-1} sr^{-1} Hz^{-1}; at λ = 0.36 mm $T_b < 8.1$°K, corresponding to $J_\nu < 6.2 \times 10^{-14}$ erg cm^{-2} s^{-1} sr^{-1} Hz^{-1}).

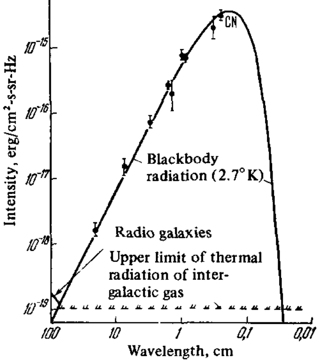

FIG. 4. Spectrum of microwave radiation.

The interpretation of some of the molecular data is very complicated. For example, direct radio observations[36] of the absorption lines of interstellar formaldehyde at a wavelength of 6 cm have shown that the populations of the levels between which the transitions take place correspond to an effective temperature less than 1.8°K (the absorption lines are observed against the microwave background radiation). Such a low effective temperature can be attributed to the net effect of molecular transitions, electron collisions and infrared radiation all of which influence the populations of the four lowest levels of this molecule and each of which has a different lifetime relative to that of radiation decay. In the case of the molecules CN and CH the radiation lifetimes are very short and it appears that electron collisions do not play a significant role.

b) Measurements in the submillimeter region. Direct rocket and balloon observations appear to be in contradiction with the molecular data. The Cornell group[37,38] have confirmed in a number of rocket flights that in the range 0.4 to 3 mm the background radiation is about 25 times more intense than that expected if the radiation were of blackbody character at a temperature of 2.7°K and corresponds to $T_r = 8.3^{+2.4}_{-1.3}$ °K.* A similar result has been found by the Massachusetts group[41] who performed measurements from a balloon in three spectral regions between 0.5 and 1.5 mm which they attributed to a spectral feature between 1 and 1.25 mm superimposed upon the 2.7°K Planck curve. Muehlner and Weiss [41] emphasize that the result is preliminary and that because of the large uncertainties in taking account of the contribution of the atmosphere and the instrumental parameters it is probably best to regard their results as an upper limit to the intensity of the background in the submillimeter region.

More recent ground based observations by Blair et al.[221] have failed to detect the millimeter excess background emission in the range 6 to 0.8 mm, their results being consistent with black body radiation background radiation having temperature $T_b = 3.1^{+0.5}_{-2.0}$ °K. These results are thus inconsistent with the observations of Muehlner and Weiss and the observational situation in this wavelength region remains confused.

Measurements in this region are made with broadband semiconductor radiometers at liquid helium temperatures. Since the earth's atmosphere is opaque to sub-millimeter radiation the detector and cooling system must be taken to very great altitudes which entails other experimental difficulties. The techniques of submillimeter astronomy have been recently reviewed by Salomonovich[42] and Kislyakov[43] and therefore we will give no further discussion of these problems.

These observations would be consistent with the molecular line data if the background radiation in the submillimeter region is confined to narrow lines, the wavelengths of which do not coincide with the wavelengths of interstellar molecules; alternatively the radiation may originate in some nearby source such as, for example, the atmosphere.[44,45] Severe limitations can be set to the first of these possibilities. If the lines originated in galaxies or other extragalactic objects then the cosmological redshift would broaden the lines to a greater extent than is permissible from the interstellar molecular line observations. In addition, it is difficult to envisage such powerful sources of line radiation which can produce an energy density in background radiation on the order of 6 eV-cm^3, i.e., at least a thousand times greater than that in the optical, radio and x-ray regions. This can be seen from Table I since for a given background the ratios of the energy density in different spectral regions must be the same as in the sources themselves.

The results of the rocket and balloon measurements also contradict the data on the spectra of cosmic rays of very high energy and the generally accepted ideas concerning the lifetime of relativistic electrons in the Galaxy. These data and the inferences which can be made from them cannot however be used as definitive arguments against the validity of the direct measurements. The resolution of these questions can only come from future experiments.

In spite of these uncertainties in the millimeter waveband we consider that with a high degree of accuracy (better than 10%) there exists a Planck curve between 75 cm and 3 mm. The Rayleigh-Jeans character of the background at centimeter wavelengths and the discovery of the cut-off in the millimeter region ($\lambda \geq 3$ mm) are powerful evidence for the existence of blackbody radiation with temperature 2.7°K. If the powerful emission in the submillimeter region in fact exists then it is most likely that it is not in any way related to the microwave background radiation and should be attributed to some process unrelated to that which produces the Planck spectrum.

c) The hot model of the universe. The high degree of isotropy of the microwave background radiation and its blackbody spectrum are normally considered powerful evidence for the fact that the universe passed through a stage at which it was at a high temperature and a high density. The blackbody radiation which we observe at the present day is normally considered the result of physical processes which took place at a much earlier stage in the expansion and is the fossilized remnant of these energetic days. This is why in the USSR it is referred to as the "relict radiation." Many questions relating to the hot model of the universe such as the equilibrium between different types of elementary particles, nuclear reactions, recombination of hydrogen at a redshift $z \sim 1500$ and so on have been described in detail by many workers (e.g., [1,46]) and we will not go into these questions in detail. In Friedmann universes consideration of the physical processes[47,48] shows that the observed Rayleigh-Jeans spectrum could not have formed later than a redshift $z \sim 10^5$, $t \sim 3 \times 10^9$ s (at this time the radiation temperature was 3×10^5 °K). This defines the earliest epoch to which the hot model is supported by the observations. For example, if sufficient energy were injected into a cold universe at redshifts greater than 10^5 then we would also obtain the observed blackbody spectrum but if the energy release took place at a later stage then observable distortions to the equilibrium spectrum would occur.

It is natural to ask whether the spectrum of the microwave background must be exactly Planckian? Apparently, no. A perfect Planck spectrum arises naturally in a uniform universe but the observed universe is distinctly inhomogeneous on a small scale. We have much evidence of violent events taking place in discrete objects which can result in large releases of energy. Any injection of energy at an early stage in the expansion of the universe leads to distortions from a Planck spectrum. Only if the energy release takes place in the redshift range $10^4 < z < 10^5$ are distortions in the Rayleigh-Jeans region expected[47,48] and at later epochs such injections of energy lead to distortions in the Wein region.[27,49] On the other hand, the presence or absence of specific distortions of the spectrum of the microwave background enable us to discuss quantitatively possible sources of energy, such as the annihilation of antimatter or the dissipation of primeval turbulence.

d) Isotropy of the microwave background. As opposed to the situation at meter wavelengths there is no difficulty in detecting the isotropic component of the micro-

---

*In these observations, measurements were made in several wavelength intervals between 5μ and 1.3 mm; it seems that in other wavebands high estimates of the background have been made. In a recent rocket flight [39] measurements were made at 100μ and an upper limit to the background intensity 25 times smaller than the background intensity reported by Houck and Harwit [40] has been derived for the same spectral region (see discussion below).

wave background radiation. The galaxy and discrete radio sources do not contribute significantly to large scale observations at short wavelengths (wavelengths less than 3 cm). The observed background radiation is highly isotropic and on no angular scale have any departures from isotropy been detected. The existing upper limits correspond to temperature fluctuations $\Delta T/T < 10^{-3}$ on all scales from a 24-hour period to about 3′ arc.[49-51,222]

Although the majority of astronomers consider the microwave background radiation strong evidence in favor of the hot model of the universe attempts have been made to explain this radiation as the integrated effect of discrete sources with inverted radio spectra at centimeter wavelengths.[52,53] In order to produce spectrum similar to a Rayleigh-Jeans curve at centimeter wavelengths it is necessary to adjust carefully the many parameters which describe these sources and their space distribution. Without supposing a rather exotic distribution of such sources, for example, supposing their number to be much greater than that of galaxies, such sources should lead to angular fluctuations in intensity of the microwave background radiation exceeding the existing upper limits.[54-56] In addition, the most recent counts of discrete radio sources at 1407 MHz are in excellent agreement with those at lower frequencies assuming the mean spectral index to be $\alpha = 0.75$. In this case discrete sources cannot explain more than 3% of the background radiation at this frequency. Not more than 2% of the sources detected at this frequency could conceivably have spectra sufficiently steep to produce a Rayleigh-Jeans curve.

The high degree of isotropy of the microwave background radiation has a number of other important consequences. On the largest angular scales much interest is attached to the possibility of detecting a 24- or 12-hour period in the background intensity. The first of these could be associated with the peculiar motion of the earth relative to the inertial frame of reference associated with the microwave background radiation. This motion is the vector sum of our motion about the sun, the velocity of the sun relative to the center of the galaxy, and the motion of our galaxy in the local group and supercluster. Estimates of the magnitude of this velocity[57] give $v \approx 250$ km-s^{-1} which is just at the limit of sensitivity of present-day techniques. There, of course, remains the possibility that these vectors could add up by chance to a small value but with an order of magnitude increase in sensitivity it should be possible to measure the 24-hour period associated with the motion of the earth about the sun.[58] Conklin[59] has estimated that the projected velocity of the motion of the earth relative to the microwave background in the plane in which he makes his observations to be 400 km-s^{-1} (this velocity does not exceed significantly the experimental errors of the measurements). The theoretical estimate which Conklin gives for the relative velocity of the Galaxy relative to the microwave background radiation is $v \approx 160$ km-s^{-1}. Although the third component of velocity is unknown* this figure is surprisingly small suggesting that the galaxy is practically at rest in a system of coordinates attached to the microwave background radiation. X-ray measurements give limits to all three components of this velocity (see below).

The absence of any observed anisotropy with 12-hour periodicity sets limits to the anisotropic expansion of the universe at the epoch when the last scattering of the photons of the microwave background took place. This method is about two orders of magnitude more sensitive than direct observations of the distribution of galaxies and radio sources.

It is normally supposed that galaxies, clusters of galaxies and other extragalactic systems condensed from a more or less uniform primaeval distribution of matter which contained small imperfections which grow as the universe expands.[1] The interaction of these fluctuations of density with radiation at the epoch of recombination of hydrogen[60,61] ought to give rise to small scale angular fluctuations ($\theta < 1°$) in the temperature of the microwave background.[62,63] It might be possible to determine from the amplitude of such temperature fluctuations which relate to the epoch of recombination the epoch of formation of galaxies since the law of growth of such fluctuations is well known.

Small-scale fluctuations could also arise due to the gravitational deflection of light in massive large-scale systems in the process of formation,[64] due to the interaction of radiation with gravitational waves[65] and due to irregular reheating of the intergalactic gas.[63] Thus, observations of the fluctuations in the microwave background can give information about the epoch of galaxy formation, about gravitational waves in the universe, etc. In fact, it turns out that the most likely source of fluctuations is discrete radio and infrared sources.[56] At long wavelengths ordinary radio sources make a large contribution and at millimeter wavelengths infrared sources dominate. At 11 cm Stankevich[66] has found fluctuations on an angular scale of about 1° of $\Delta T/T \approx 3 \times 10^{-4}$. This is exactly what one would expect from discrete radio sources. Thus although discrete sources cannot contribute to the total intensity of the microwave background they are likely to be the principal source of fluctuations.

e) X-rays and cosmic rays. It is clear from Table I that the microwave background provides the dominant contribution to the energy density of radiation in intergalactic space. As a result it is the principal source of photons for interactions with cosmic ray protons and electrons. These interactions give rise to x- and γ-rays and therefore we will defer discussion to the appropriate sections.

II. INFRARED WAVELENGTHS ($10^{12} < \nu < 3 \times 10^{14}$ Hz; $1 < \lambda < 300\mu$)

In this spectral region there are only upper limits to the intensity of the background radiation (excluding of course the submillimeter background discussed above). In general there are far fewer observations in the infrared region because of absorption and emission by molecules in the upper atmosphere. Observations from the surface of the earth are only possible in a window at wavelengths less than 25μ. Observations of celestial objects in the range $25 < \lambda < 300\mu$ must be made from rockets, balloons and high flying aircraft.

---

*The measurements are only made in one plane. The radiotelescope remains fixed with respect to the Earth and thus the beam sweeps out a circle on the celestial sphere.

The development of techniques in infrared observations has led to the discovery of an excess in the infrared spectral power of discrete sources. A significant number of galactic objects including certain types of stars as well as a number of planetary and infrared nebulae[67] appear to be anomalously bright in the far infrared wavelength range ($\lambda < 25\mu$). In the majority of these cases the objects are either cold stars (e.g., condensing protostars or giant stars) having temperatures less than 3000°K or dusty systems involving the re-radiation of ultraviolet and optical radiation in the vicinity of hot stars.[68] The luminosities of these objects however are not particularly great and they do not give an important contribution to the background radiation. Recently observations of extragalactic sources have given an unexpected result. The nuclei of many galaxies and quasars radiate a great deal of energy in the infrared waveband, in many cases more than in all other wavebands.

1. The Infrared Radiation from the Nuclei of Galaxies and Quasars

a) Observations. The most interesting galactic source is the center of the Galaxy which is at a distance from the Sun of 10 kpc. According to measurements made from the surface of the earth in the range 10 to 20μ there is a nuclear component which has diameter about 1 pc and luminosity $L \sim 10^6 L_\odot \sim 3 \times 10^{39}$ ergs^{-1}.[69] But an even more surprising result has come from observations (of the galactic center) made from above the atmosphere at about $\lambda \sim 100\mu$. According to the balloon observations[70] in the range 80 to 120μ it consists of an extended line source (about 6°) and has luminosity $L \sim 10^9 L_\odot \sim 10^{42}$ erg-s^{-1}. Recent observations from high flying aircraft[71] have discovered a powerful point source (radius less than 5 pc) coincident with the nucleus in the 10 to 20μ region. This source is also observed at radio wavelengths. In addition to this a number of weak sources have been discovered apparently lying in the galactic plane in the direction of the center. The luminosity of the nucleus of our galaxy in the range 40 to 350μ seems to be about $L \sim 10^8 L_\odot \sim 3 \times 10^{41}$erg-s^{-1}, i.e., about 1% of the total luminosity of the galaxy. The peak of the radiation occurs at a frequency of about $\nu_0 = 4.2 \pm 0.2 \times 10^{12}$ Hz; $\lambda = 70\mu$ (see Fig. 5).

A similar maximum at 70μ has been discovered in the spectrum of the Seyfert galaxy* NGC 1068[72] (see Fig. 5) but in this case infrared luminosity is $L \sim 2 \times 10^{12} L_\odot \sim 10^{46}$ erg-s^{-1} implying that its integrated emission is 5 orders of magnitude greater than the nucleus of our galaxy.

Kleinmann and Low[72] have observed 28 galaxies in the range 5 to 25μ. In 14 cases intense infrared emission from the nuclei was discovered and in the majority of these 14 galaxies the maximum emission must occur in infrared range peaking about 100μ. This conclusion follows from the rapid increase in spectral power between the optical and infrared regions and the necessity of a sharp drop from the latter to the radio waveband. In some objects this sharp rise has been observed experimentally (see Fig. 5). Among the extragalactic infrared sources are the nuclei of normal galaxies (The Milky Way, M31), irregular galaxies (such as the exploding galaxy M82), Seyfert galaxies (NGC 1068), N-galaxies (3C 120) and quasars (3C 273), the luminosities of which span a range of at least 6 orders of magnitude. In Table III we give estimates of the luminosities of these objects in different wavebands. In the case of the infrared wavebands it is assumed, following Kleinmann and Low,[72] that all the spectra of infrared sources are sharply peaked in this waveband. It can be seen from the table that a maximum emissivity in the infrared waveband is a general property of the nuclei of galaxies and quasars but there is a wide range of spectral powers among different objects.

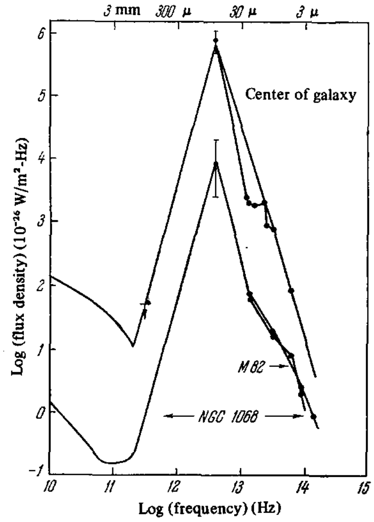

FIG. 5. Spectrum of infrared radiation of the center of the galaxy, the core of the Seyfert galaxy NGC 1068, and the core of the galaxy M 82 [72,75].

b) Models of infrared sources. The origin of the maximum in the infrared region is not yet understood. It is important to note that a wide class of different extragalactic objects peak in exactly the same wavelength region. This suggests that the same type of physical mechanism is occurring in all these cases, perhaps having a character similar to that of a resonance frequency. In many cases the radiation in this peak is equal to the total luminosity of the object and therefore a highly efficient radiation mechanism is required.

Until the discovery of the infrared peak at 70μ the intense radiation from the nuclei of Seyfert galaxies in the range 1 to 25μ was attributed to the emission of dust. In this type of model[73] it is supposed that there exists a compact central source of optical emission having luminosity 10^{44}–10^{47} erg-s^{-1} surrounded by a cloud of dust. The optical radiation is absorbed and reradiated by the hot dust at infrared wavelengths. In this model the spectrum in the infrared region is the integrated radiation from dust at different temperatures and densities. As a result it is possible to obtain, for example, a power law spectrum in the range 2 to 22μ by assuming particular distributions of density and

---

*Seyfert galaxies are characterized by very active nuclei in which the emission lines in the spectra are very broad. Often the compact nucleus contributes a significant fraction of the luminosity of the galaxy.

Table III. Luminosities of extragalactic sources in different wavebands* (erg/sec)

	Type of source	Waveband							Distance to source	Spatial density of sources (N = 0.03 Mpc^{-3})
		radio		infrared		optical	x-ray	γ-rays		
		$0{,}5\,m < \lambda < 300\,m$	$3\,mm < \lambda < 0{,}5\,m$	$25\,\mu < \lambda < 3\,mm$	$1\,\mu < \lambda < 25\,\mu$	$3\cdot 10^3 < \lambda < 10^4\,Å$	$1\,keV < \mathscr{E} < 10\,keV$	$\mathscr{E} > 100\,MeV$		
Normal galaxies	Our galaxy	$\sim 3\cdot 10^{38}$ (e)	$\sim 5\cdot 10^{38}$ (e)	10^{42} (c)	—	$5\cdot 10^{43}$	10^{39}—10^{40} (e)	10^{38}—10^{39}	—	N
	Large Magellanic Cloud	$\sim 3\cdot 10^{35}$	$\sim 5\cdot 10^{35}$	—	—	$5\cdot 10^{42}$	$4\cdot 10^{38}$	—	0.05	$\sim 10N$
Radio galaxies	M 87 (NGC 4486) Virgo A	$2\cdot 10^{41}$	$3\cdot 10^{41}$ (c), (j)	—	$< 2\cdot 10^{43}$	10^{44}	$3\cdot 10^{43}$ (v)	$< 4\cdot 10^{44}$	15	$\sim 10^{-3}N$
	Cen A (NGC 5128)	10^{41}	—	—	—	$8\cdot 10^{43}$	$5\cdot 10^{41}$ (c)	—	5	$\sim 10^{-3}N$
	Cyg A	$3\cdot 10^{44}$	—	—	—	$7\cdot 10^{44}$	$< 10^{43}$	$< 10^{47}$	220	$\sim 10^{-6}N$
Seyfert galaxies	NGC 1275 (3C 84)	$2\cdot 10^{41}$	10^{45} (c), (v)	10^{46} (e?)	$3\cdot 10^{44}$ (c), (v)	$6\cdot 10^{43}$	$4\cdot 10^{45}$ (c?)	$< 4\cdot 10^{46}$	70	$\sim 10^{-4}N$?
	NGC 1068	10^{39}	$3\cdot 10^{41}$ (c)	10^{46}	$3\cdot 10^{44}$ (c), (v)	$8\cdot 10^{43}$	$< 4\cdot 10^{42}$	—	13	$\sim 10^{-2}N$
	NGC 4151	10^{38}	$< 10^{40}$	10^{45} (e?)	$2\cdot 10^{43}$ (c), (v)	$2\cdot 10^{43}$	$3\cdot 10^{42}$ (c?)	$7\cdot 10^{44}$	13	$\sim 10^{-2}N$
Quasars	3C 273	$2\cdot 10^{43}$	$3\cdot 10^{45}$ (v)	$7\cdot 10^{47}$ (e?)	$2\cdot 10^{47}$ (v)	10^{46} (v)	10^{46}	$< 7\cdot 10^{47}$	630	$\sim 10^{-6}N$

*In this table the letters e, v, c, and j denote the following: "e"—estimates, and not measurements; "v"—variability of source (energy flux from the source varies with time); "c"—the main contribution to the galaxy luminosity is made by a compact source in the region of the core; "j"—the same for the jet from the core. The question mark denotes uncertainty of the estimate (e?) or of the identification (c?).

temperature for the interstellar dust. The biggest difficulty with this type of model is that the dust is expected to expand from the nucleus because of the high radiation pressure. In addition because of the large dimensions of the region containing the dust it is difficult to explain the rapid variations of these objects. There is one attractive feature, however,—in this model it is simple to explain why the maximum often occurs in the infrared wavelength region. If the dust were hotter than 1500°K it would evaporate. As a result we have a reasonably good explanation for the spectrum in the region 2 to 22μ. The discovery of rapid variations of infrared nuclei (for references, see [68]) and the sharp infrared peak at 70μ are not explicable in this model which requires an extended dust-filled region. Detailed discussions of these difficulties have been given by [68,71,74].

Pacholczyk[74] has shown that the rapid variability ($t < 3\times 10^4$ s; $R < ct = 10^{15}$ cm) of the nucleus of the galaxy NGC 1068 at 2.2μ cannot be reconciled with the hypothesis that the infrared peak is due to either a uniform cource of synchrotron radiation or to synchrotron radiation from many compact sources (IRtrons).[75] In the first case the small dimensions of the source at a frequency of 4×10^{12} Hz leads to an energy density in the magnetic field which is much less than the energy density in radiation. In this case the relativistic electrons lose their energy principally by inverse Compton scattering and not by synchrotron radiation. In the second case, it is not possible to obtain rapid variability.* Pacholoczyk has described an inhomogeneous spherically symmetric synchrotron source in which the magnetic field, the flux of radiation and the maximum frequency vary with radius and in which the source is optically thick.

All models designed to explain the infrared peak as the synchrotron emission of relativistic electrons[68,75 74,77] encounter the following difficulties (i) the peak emission occurs at the same frequency although the luminosities range over many orders of magnitude; (ii) the steep slope of the spectrum to the low frequency side of the maximum (synchrotron self-absorption gives $\alpha = -5/2$ but the observations require $\alpha = -7/2$). If the magnetic field were directed radially outward from the source the spectrum could be steeper than $\alpha = -5/2$;[78] (iii) the anomalously steep spectrum of relativistic electrons necessary to explain the observed spectral index $\alpha = 3.5$ to the high frequency side of the maximum, as a result of which most of the energy is concentrated in relativistic electrons having minimum energy which practically do not radiate synchrotron emission because of self-absorption. They lose their energy in other spectral regions and therefore would produce large contributions to the luminosity of the source outside the infrared region (an example of such a mechanism is the inverse Compton effect). But this is in contradiction with the observed properties of different nuclei and also the data on the background radiation (see Tables I and III). The requirement that most of the energy of the nucleus be lost in the infrared waveband is probably the most difficult requirement for the majority of non-thermal mechanisms; (iv) if the brightness temperature at the peak frequency is greater than $kT_b > m_ec^2/\tau_T(1+\tau_T)$ then induced Compton scattering by thermal electrons leads to significant distortions of the spectrum of the peak and results in a cut-off at low frequencies.[23] Here $\tau_T = \sigma_T N_e R$ is the optical depth of the radiating region to Thomson scattering and $kT_b = Lc^2/8\pi R^2\nu_0^3$ which in many models exceeds m_ec^2. This condition

---

*See the discussion below of the possibility of obtaining rapid variations from a large number of objects. [76]

sets a significant limit to the quantity and distribution of gas in the source no matter what the origin of the radiation (i.e., this result refers not only to synchrotron emission). If the nucleus is gaseous, then the infrared radiation must originate in an optically thin region at its surface.

Bisnovatyĭ-Kogan and Sunyaev[78] have attempted to explain the infrared peak as the result of the supercritical accretion* of gas onto neutron stars. This comes about because in the case of supercritical accretion the electron density in the region at the surface of the star N_e is practically independent of the density of gas far from the star. For the parameters appropriate to neutron stars, the plasma frequency $\nu = \sqrt{e^2 N_e / \pi m_e}$ for electrons in the flow of material close to the surface of the neutron star is close to the frequency of the observed infrared peak. The formation of collisionless shock waves and the consequent excitation of plasma waves in the envelope can in principle result in the radiation of a major part of the kinetic energy of the incident gas at the plasma frequency.

If the nuclei of galaxies and quasars consist of compact clusters of stars then there will be frequent supernova explosions[79] and many neutron stars. Accretion onto neutron stars is a particularly efficient source of energy in that the infalling gas can liberate 0.2 of its rest mass energy and therefore there is no energy problem. By choosing an appropriate number of neutron stars it is possible to obtain any luminosity from the nucleus and yet the spectral properties will remain unchanged. The spectrum of the near infrared ($\lambda < 25\mu$) and millimeter region can be ascribed to Compton interactions of the radiation at the peak with the thermal electrons in the space between neutron stars. Any chang in the density of interstellar gas will lead to intensity variations from the object at these wavelengths. Because the flux of radiation in the peak is 4 orders of magnitude greater than that in the other regions (see Fig. 5) changing the physical conditions in only a small fraction of gas in the nucleus can lead to large changes in the flux from the object in the near infrared and millimeter region whilst the amplitude of the peak remains constant. It is therefore possible in this model to explain the rapid variability of NGC 1068 at 2.2μ.[74]

In studying such models the principal difficulty is the means by which radiation leaves a zone having radius $r < 10^8$ cm around the neutron star. The density of energy in radiation is very large so that the motions of electrons in the varying electromagnetic field become relativistic. They must therefore radiate at harmonics of the fundamental frequency and the spectrum will be distorted. Calculations show that the plasma frequency remains more or less constant in the region $10^6 < r < 10^8$ cm. It is possible that the whole zone containing relativistic electrons behaves like a single generator of plasma waves radiating at the plasma frequency. Many other possibilities are opened up if account is taken of the existence of a strong magnetic field which can lead to a decrease in the cross section for scattering and in the opacity of the gas. This problem needs further clarification.

2. The Background Radiation

a) Calculations. It is impossible to determine with any accuracy the expected background due to infrared sources since their luminosity function and source counts are unknown. The problem has been discussed by Low and Tucker[80] who have evaluated the background using the meager experimental data available and making different assumptions about the choice of cosmological model and about the importance of cosmological evolution. According to their estimates[80] the background in the infrared region is primarily determined by Seyfert galaxies. Although there is no direct evidence for the cosmological evolution of the radio properties of Seyfert galaxies, the situation could be quite different in the infrared wavebands. We have indicated their estimates in Fig. 1, Fig. 6, and in Table I, the last of which includes a typical model without cosmological evolution. We note that these results were obtained prior to the discovery of the maximum at about 100μ[75] so that the estimates under favorable conditions might be an order of magnitude greater. It is evident that these values are only order-of-magnitude estimates.

Other sources of infrared radiation such as the radiation due to hyperfine transitions of ions and molecules in interstellar gas in galaxies have been discussed in [44,45]. The most important contributions are expected to arise from the lines of C II (λ 156μ), Si II (λ 34.8μ) and Ne II (λ 12.8μ), but these are likely to give only a small contribution in comparison with that of the nuclei of galaxies because the total energy balance in the interstellar gas is small in comparison with the luminosity of a galaxy. It would however be interesting if such radiation were to be discovered in our own or in other galaxies. If galaxies originate at large redshifts ($z \gg 2$)

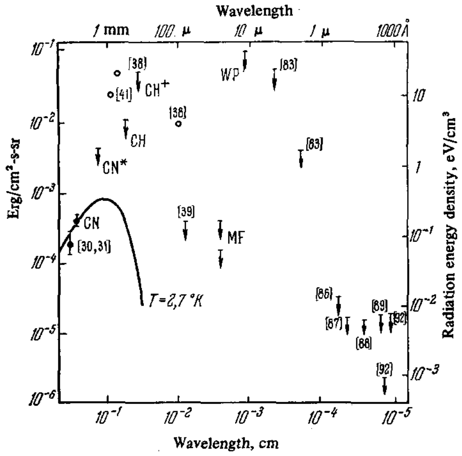

FIG. 6. Summary of experimental data on the background in the millimeter, infrared, optical and ultraviolet regions of the spectrum (details in text).

---

*The equilibrium between the force of gravitational attraction and the repulsion due to radiation pressure determines the critical luminosity of a neutron star by accretion which is $L_c \approx 10^{38}$ erg-s^{-1}. For the known gravitational potential of a neutron star ($M = M_\odot$, $r_0 = 10^6$ cm, $\varphi = 0.2c^2$, the velocity of infall = 0.4c), the critical luminosity of the neutron star corresponds to $dM/dt = L/\varphi = 5 \times 10^{17}$ g/s^{-1} and $N_e = (dM/dt)(4\pi r_0^2 u)^{-1} = 10^{18}$ cm^{-3}. Further increase in the gas density far from the neutron star (the supercritical condition) cannot lead to an increase in L, dM/dt or N_e. For details see [1].

and young galaxies were much brighter than they are at the present time then their optical emission would be redshifted into the infrared band and could give a significant contribution to the near infrared background emission.[81,82]

b) Observations. In Fig. 6 we have collected together the experimental data on the background at millimeter, infrared, optical and ultraviolet regions of the spectrum. In this graph the measurements are presented in terms of the brightness multiplied by frequency, i.e., νJ_ν [$\mathrm{erg\text{-}cm^{-2}s^{-1}sr^{-1}}$], which characterizes the energy density radiated in the frequency interval $\Delta\nu \sim \nu$ whereas in Fig. 1 the intensity of the background J_ν is given, which characterizes the number density of quanta in the range $\Delta\nu \sim \nu$. The upper limits and measurements in Fig. 6 are taken from the following references: [30,31] – observations of the microwave background measured from the surface of the Earth; [38,83,84] – rocket observations by the Cornell group; [41] – balloon observations; [39,85] – rocket observations by McNutt and Feldman; [86] – optical observations from the surface of the Earth; [87] – American, [88] British, [89] Japanese rocket observations in the ultra-violet; [90–92] measurements from the Soviet space probe "Venus"; unpublished rocket data by Walker and Price (WP) and McNutt and Feldman (MF) presented in a recent survey;[82] the symbols CN, CH, CN* and CH$^+$ indicate the results obtained from observations of interstellar molecules.[35]

Figure 6 illustrates the uncertainties in the present situation, in particular the complications in the submillimeter and infrared regions of the spectrum as a result of the contradictory results of measurements by different groups. Particularly striking is the difference of 1.5 orders of magnitude between the rocket data of McNutt and Feldman[39] and the Cornell group[40] in the same spectral region at $\lambda \sim 100\mu$ (see discussion in [93]). In the former experiments luminescence due to atmospheric oxygen was observed. The intensity and distribution of the radiation from the atmosphere was in full agreement with theoretical estimates.

The upper limits to the intensity of the background at 100μ is about an order of magnitude greater than estimates of the background due to extragalactic sources of Low and Tucker. All the other points in the infrared region are too high to provide useful limits.

III. OPTICAL WAVELENGTHS. $3 \times 10^{14} < \nu < 10^{15}$ Hz; $3000\,\text{Å} < \lambda < 1\mu$

To determine the extragalactic component of the background optical radiation it is necessary to eliminate contributions from relatively nearby sources such as the emission of the atmosphere, zodiacal light (solar light scattered by interplanetary dust) and the integrated emission of stars in our Galaxy. The first of these difficulties can be eliminated by making observations from above the earth's atmosphere. If observations are made on the surface of the earth theoretical corrections must be made from studies of the luminescence of the atmosphere as a function of zenith angle. The second could in principle be eliminated by making observations from a space station at a distance of about one astronomical unit in a direction perpendicular to the ecliptic where there is little dust. Alternatively, as can only be done at the present day, it is necessary to eliminate this component using a model for the scattering due to zodiacal dust. It is also possible to make observations within the Fraunhofer lines in which the sum emits relatively little radiation and therefore the zodiacal light is weak. The third component must be evaluated from a knowledge of the luminosity function and space distribution of stars in our Galaxy. This last remains the main uncertainty in determining the extragalactic component of the sky brightness. A recent detailed study has been made by Roach and Smith[86] who have made observations from the surface of the earth. Many months' observations of the sky were averaged and the data compared with models of the distribution of zodiacal light and the light from stars in the galaxy. No evidence was found for an isotropic component and they give an upper limit of 5 tenth-magnitude stars per square degree corresponding to $J_\nu < 10^{-19}$ $\mathrm{erg\text{-}cm^{-2}\,sr^{-1}\,Hz^{-1}}$ at a wavelength $\lambda = 5500$Å. This figure is about a hundred times smaller than the total sky brightness which can all be attributed to the above causes. Until it is possible to construct better models for the zodiacal light and the distribution of stars in the Galaxy it will be difficult to improve this estimate at 5500 Å. At the present time the zodiacal light is being intensively studied with rockets and satellites. Recently Lillie[87] has described rocket measurements of the background at a wavelength $\lambda = 4100$ Å with a result corresponding to 2 blue stars per square degree or $J_\nu < 2 \times 10^{-20}$ $\mathrm{erg\text{-}cm^{-2}s^{-1}Hz^{-1}}$.

Knowing the spectrum of individual galaxies and their space densities it is possible to evaluate the integrated emission of normal galaxies from the universe as a whole. It is found that the principal contribution to the background comes from normal galaxies, i.e., the radiation is basically starlight. The accuracy of these calculations is not very great since they require an exact knowledge of the luminosity function of galaxies which is not precisely known at the present time. There remain some differences between the different functions proposed to describe space density of galaxies of different luminosities, particularly in the high luminosity region.[94]

Calculations of the predicted intensity of background radiation[95] amount to about half of the experimental upper limits.[87] This implies that at small redshifts ($z < 1$) the optical luminosities of normal galaxies cannot have exhibited strong evolution. This, of course, does not exclude the possibility that particular classes of galaxies and quasars exhibit strong cosmological evolution. The latter are known to evolve at optical wavelengths just as powerful radio sources evolve at radio wavelengths.[17,96] If the evolution of galaxies took place at large redshifts then the contribution of distant galaxies would appear not in the optical region but in the infrared which is difficult to observe.[81]

Thus the situation is reasonably well defined at optical wavelengths. In Fig. 1 we have included a typical model of Peebles and Partridge.[95] It should be remembered that this prediction may have been significantly underestimated in the infrared region.

If intergalactic space contains stars, star clusters or dwarf galaxies then they are practically impossible to detect at the present day using conventional techniques of observation. It is not known how much such luminous objects contribute to the mean density of matter in the universe. An upper limit to such matter can be found from the upper limit on the background intensity at optical wavelengths if it is assumed that these objects have similar mass to light ratios to those found in galaxies. Using the data of [87] it is found that $\rho_{\text{lum}} < 0.1\rho_{\text{crit}}$ as an upper limit to the density of "luminous" material in the universe. Thus luminous material is insufficient to close the universe.[95]

IV. ULTRAVIOLET WAVELENGTHS

It is possible to consider this region of the spectrum in two parts, the first being accessible to observation from rockets and satellites, the second not being observable in experiments made within the solar system.

1. The Wavelength Range Accessible to Observation ($912\,\text{Å} < \lambda < 3000\,\text{Å}$; $10^{15} < \nu < 3.3 \times 10^{15}$ Hz)

The brightness of the sky in the ultraviolet region of the spectrum is determined by the radiation of hot stars in our Galaxy. The higher the surface temperature of the star the greater its radiation of ultraviolet quanta. The number of stars of a given temperature falls rapidly with increasing absolute magnitude. The radiation also falls off rapidly with decreasing wavelength and hence the total background radiation from stars in the Galaxy also decreases. For example, according to the measurements of V. G. Kurt from the Space Observatories in the "Venus" series, the integrated luminosity of our galaxy (excluding the unknown contribution of its nucleus) in the range 1225 to 1340 Å is 10^{40}–10^{41} erg-s^{-1} which corresponds to only 10^{-4}–10^{-3} of its optical luminosity.[97] It is therefore expected that the separation of the extragalactic component in the ultraviolet region will be simpler than at optical wavelengths and that it will contain information about the origin and nature of non-stellar sources such as the nuclei of galaxies, quasars and the intergalactic gas.[91] However, in spite of all expectations no extragalactic component has been isolated from the observations which have detected an anisotropic galactic component. An upper limit is all that has been found and this is either given by the minimum sky brightness or by the background of cosmic rays or by the sensitivities of the receivers.

a) Observations. The most important experimental points are given in Fig. 6. These points are taken from observations with the "Venus" space station: $J_\nu < 10^{-21}$ erg-cm^{-2}s^{-1}sr^{-1}Hz^{-1} in the range $1225 < \lambda < 1340$ Å [91] and $J_\nu < 7 \times 10^{-21}$ erg-cm^{-2}s^{-1}sr^{-1}Hz^{-1} in the range $1050 < \lambda < 1180$ Å.[92,98] The observations were made with gas filled counters sensitive to radiation in the range $1050 < \lambda < 1340$ Å with a filter to eliminate the resonance line radiation of Lyman α ($\lambda = 1216$ Å). The sky is very bright in this waveband because of re-radiated solar Lyman α by interplanetary hydrogen. The Japanese rocket measurements[89] have also used photon counters and give an upper limit $J_\nu < 10^{-20}$ erg-cm^{-2}s^{-1}sr^{-1}Hz^{-1} in the range $1350 < \lambda < 1480$ Å. British photometric observations made from a rocket[80] give an upper limit of $J_\nu < 1$–2×10^{-20} erg-cm^{-2}s^{-1}sr^{-1}Hz^{-1} in the range $2020 < \lambda < 2790$ Å with an effective wavelength $\lambda = 2425$ Å. The experiments on board the "Mariner" spacecraft[99] ($1250 < \lambda < 2200$ Å) and the satellites in the "Cosmos" series[100] ($2450 < \lambda < 3150$ Å) have not found an extragalactic component but the minimum observed signal in these cases is somewhat greater than the upper limits found by the British group.

The most important contribution to the brightness of the Galaxy at about 1300 Å comes from AO stars and those of earlier spectral types which constitute only a small fraction of the total number of stars in the Galaxy and which are concentrated towards the galactic plane. If the field of view of the apparatus is decreased it is possible to make observations in the directions of the galactic poles so that no hot stars fall within the field of view. In this case the signal will fluctuate violently but its minimum level will determine the extragalactic component of the background and the radiation of hot stars scattered by interstellar dust. The best results can be achieved by making observations with angular resolution better than 0.01 square degrees.[101,91] If the field of view is further decreased the contribution of cold stars begins to become important. In optical region this does not happen because the important contribution to the luminosity of the Galaxy is due to the large number of stars of late spectral type. The discrepancies between the results of the Japanese[89] and Soviet[97] groups are due to the different fields of view of the apparatus.[101] We note that the British observations[88] also imply that the Japanese data are an overestimate.

Absorption by interstellar dust has little effect on the passage of ultraviolet background radiation through the disc of the galaxy ($d \sim 100$ pc). There is little radiation from the interplanetary medium and at 1000 Å scattering of the light of hot stars by dust is small. It is therefore to be hoped that future measurements will give a significant improvement in the existing upper limits to the background.

By analogy with our Galaxy it is natural to suppose that all normal galaxies are weak emitters in the ultraviolet waveband and that the background due to them will be small. However, recent observations with the American Orbiting Astronomical observatory (OAO) have discovered unexpectedly large ultraviolet fluxes in the range 1200–2500 Å from the nuclei of M 31 (the Andromeda nebula) and from a number of other galaxies and therefore the magnitude of the background again becomes a question of interest. Even the existing data enable us to draw the following conclusion: on average the nuclei of normal galaxies radiating in the ultraviolet wavelength band cannot liberate more than 10% of the total luminosity of the galaxy.

b) Other aspects of the results. Observations of the ultraviolet background are important in studies of the properties of the hot intergalactic gas which, as we have already noted, may be the principal contributor to the mean density of matter in the universe. In particular, in the waveband 1225–1340 Å, redshifted Lyman α from redshifts less than 0.1 is expected from the most common element in the universe, hydrogen. The upper limits to the intensity of the background in this range set significant limits to the temperature and density of the gas[90]. In the spectra of distant quasars with redshifts $z > 2$ the absence of absorption bands due to redshifted Lyman α sets a very low limit to the density of neutral hydrogen at these redshifts. Photons emitted to the short wavelength side of the line are redshifted at some epoch to the Lyman α frequency at which they can be rapidly scattered because of the large scattering cross-section for Lyman α resonance scattering. The absence of such absorption implies that there is negligible neutral hydrogen in intergalactic space $n_H < 10^{-11}\ \mathrm{cm}^{-3}$, i.e., if there is any intergalactic gas at all, it must be very highly ionized, $n_H/n_p \lesssim 3\times10^{-8}$ at $z \sim 2$.[104,105] The possibility of ionizing the intergalactic gas as a result of photo-ionization by the ultraviolet radiation from quasars is related to this problem.[106,107] The ultraviolet flux must be estimated knowing the luminosities and luminosity functions of quasars. It is also necessary to suppose strong evolution to obtain significant numbers of ionizing photons. The upper limits to the intensity of the ultraviolet background at 2500 Å can help resolve this question.

An observed wavelength of 2500 Å corresponds to an emitted wavelength of 830 Å at a redshift of 2, i.e., these observations give information about the intensity of the background close to the Lyman limit at 912 Å and hence about the role of photo-ionization in the thermal balance of the intergalactic gas at this stage in the expanding universe. Simple calculations show that in the absence of other heating mechanisms* photo-ionization maintains the temperature of the gas in the range $7\times10^3 < T_e < 3\times10^4$ K and cannot explain the observed degree of ionization of intergalactic gas[105] at $z = 2$ if the density parameter of the gas Ω is greater than 0.3. This process can only be important for small values of Ω. Conversely it is possible to set limits to the cosmological evolution of the ultraviolet luminosity of quasars and galaxies.

Ultraviolet measurements of the integrated background from the Galaxy are important for determining the luminosity function of hot stars[97] and the energy density of galactic sub-cosmic rays with energy 100 keV,[108] but these topics lie outside the scope of this review.

2. The Wavelength Range Inaccessible to Direct Observations. ($100 < \lambda < 912$ Å; $3.3\times10^{15} < \nu < 3\times10^{16}$ Hz)

Quanta having wavelengths less than 912 Å ($h\nu > 13.6$ eV) ionize hydrogen atoms which are the principal constituent of interstellar gas in galaxies. It immediately follows that the background radiation at wavelengths less than 912 Å cannot be observed directly from within the solar system since the radiation is completely absorbed by the interstellar gas. However, the cross section for photo-ionization decreases rapidly with increasing energy of the photons and at wavelengths less than 50 Å the disc of the galaxy is optically thin to the background radiation. To study the background in the range 100 to 912 Å indirect methods must be used.[109,110]

The existence of ionizing background radiation must lead to the appearance of ionization zones around galaxies analogous to the Stromgren spheres around hot stars. In the central regions of spiral galaxies (R <10 kpc) where there is much gas of high density these ionization zones are small. But as we go away from the center, the total number of particles along any line of sight through the disc decreases whilst the thickness of the disc increases, i.e., the density of the gas falls rapidly and at some distance from the center of the galaxy all the gas will be ionized by the background radiation. To put it another way, if we observe neutral hydrogen in the peripheries of galaxies and we know its depth and density, we can find an upper limit to the intensity of the ionizing background radiation. We note a limiting case. An intensity of $J_\nu \sim 10^{-18}\ \mathrm{erg\text{-}cm^{-2}\,s^{-1}\,sr^{-1}\,Hz^{-1}}$ would be sufficient to ionize all the gas in our Galaxy, including clouds. In this case all the characteristic times are smaller by a large factor than the time scale of the Galaxy. It is important in these calculations to solve the problem of the ionization and dissociation of high density clouds.[111] A similarity solution for the motion of the ionization front has been found for the case in which the outflowing gas has large optical depth.

At the present time the distribution of neutral hydrogen as determined by its 21-cm radio emission has been studied in considerable number of external galaxies. In Fig. 7 we show the distribution in the galaxy M 31 (the Andromeda nebula).[112] It can be seen that the gas is observed at great distances from the center of the galaxy where there is negligible density of stars (R ~ 30 kpc ~ 10^{23} cm). The thickness l of the disc must be greater than 2 kpc[113-115,110] and the density of gas very small. In addition, an extended bridge having dimension greater than 10 kpc has been observed joining together two associated galaxies.[116,117]

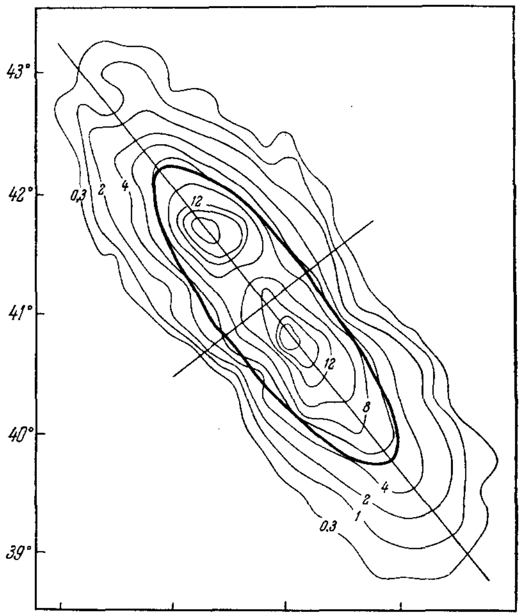

FIG. 7. Distribution of neutral hydrogen in the M31 galaxy (Andromeda nebula). The numbers correspond to the number of atoms of neutral hydrogen along the line of sight in units of 10^{20} atoms/cm^2. The heavy ellipse corresponds to the optical boundaries of the galaxy—isophot of 25th visible magnitude from a square second.

---

*In cases in which the gas is heated to a high temperature by other mechanisms, the role of photoionization becomes much more important because with increasing temperature the recombination coefficient decreases.

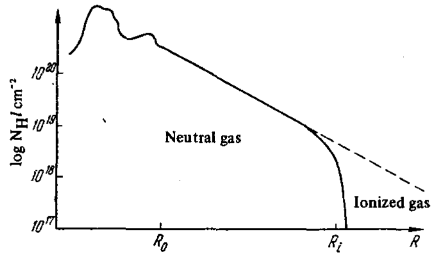

FIG. 8. Expected cutoff in the distribution of the neutral hydrogen on the periphery of galaxies.

Felten and Bergeron[118] have argued that the disc of neutral hydrogen can be protected by a thick layer of ionized gas which would absorb all the background radiation. Undoubtedly if neutral hydrogen is observed in the peripheries of galaxies, then it has not been exposed to the effect of ionizing radiation. But the question of the thickness or emission-measure ($N_e^2 l_e$) of the ionized region and that of the intensity of the ionizing background radiation can only be decided by observation but not necessarily those of the ionized gas. The decisive answer comes from 21-cm observations. Theory predicts a diffuse distribution of gas (except for clouds of neutral hydrogen) at the distant peripheries of galaxies and a rapid cut-off to the distribution of neutral hydrogen connected with the existence of ionizing background radiation.

a) The cut-off in the distribution of neutral hydrogen. Observations show that beyond some radius the emission from the gaseous disc decreases with distance from the center of the galaxy according to an exponential law (see Figs. 7 and 8). It is natural to suppose that such a dependence of $N_H l(R)$ continues to the extreme periphery of the galaxy, even beyond the region which has been observed. This postulate is important in the ensuing discussion.

Suppose the column density of gas along the line of sight at distances greater than some value R_0 decreases according to the law $Nl = N_0 l_0 e^{-aR}$ and that $aR > 1$. We will suppose that the gas is homogeneous. Within the disc the gas is neutral ($N_1 l_1$) and outside it, it is ionized so that $Nl = N_1 l_1 + N_e l_e$; $l = l_1 + l_2$. The flux of quanta which causes the ionization is

$$Nl = N_1 l_1 + N_e l_e; \quad l = l_1 + l_e.$$

$$I = \pi \int_{\nu_c}^{3\nu_c} \frac{J_\nu}{h\nu}\, d\nu \ \frac{\text{quanta}}{\text{cm}^{-2}\ \text{s}^{-1}}$$

where wavelengths $\lambda < \lambda_c = 912$ Å will be completely absorbed in the ionized region if $\alpha N_e^2 l_e = I$ i.e., the number of recombinations in a column of gas per second is equal to the number of incoming quanta. Here α is the recombination coefficient to all excited levels. Therefore

$$N_1 l = Nl - N_e l_e = Nl - I/\alpha N_e = Nl\left(1 - \frac{I}{\alpha N^2 l}\frac{N}{N_e}\right)$$
$$= N_0 l_0 e^{-aR}\left(1 - \frac{I}{\alpha N_0^2 l_0} e^{2aR}\frac{N}{N_e}\frac{l}{l_0}\right) \leqslant N_0 l_0 e^{-aR}\left(1 - Ae^{2aR}\right),$$

i.e., at the edge of the galaxy we expect to observe a sharp cut-off in the distribution of neutral hydrogen. Here the constant $A \approx I/\alpha N_0^2 l_0 \ll 1$ characterizes the weakness of the influence of the background radiation on the gas at a distance R_0. A power law dependence of $l(R)$ and the essential condition $N_e < N$ leads to a more powerful result. From Fig. 8 it can be seen that the thickness of the cut-off layer is small by comparison with the sizes of the ionized and neutral regions $\Delta R \ll R_i$. If $R < R_i$ we have $Nl \approx N_1 l_1 \gg N_e l_e$ and if $R > R_i$ the opposite inequality applies $Nl \approx N_e l_e \gg N_1 l_1$.

b) Diffuse gas or clouds? A column of gas at a great enough distance from the center of a galaxy is optically thin to radiation having wavelength less than 150 Å and therefore heating by soft x-rays or hard ultraviolet radiation must have a strong influence upon its physical parameters.[110,119] Because of the large interaction cross-section for neutral atoms of hydrogen and helium with radiation at wavelengths of 100 to 200 Å the heating of the gas in the outer regions of galaxies by such hard radiation may well exceed the heating due to ionization losses by sub-cosmic rays in the inner regions ($R < 10$ kpc) of the galaxy.*

Pikelner[120] has studied (in detail) this question of the ionization and heating of the interstellar gas by sub-cosmic rays and has shown that to explain the observed properties of the interstellar gas an energy flux of the order of $q \approx 3 \times 10^{-26}$ erg-s^{-1} per hydrogen atom is necessary (more recent computations have confirmed this conclusion[121]). As a result of such heating, thermal instabilities in the interstellar gas give rise to the existence of two phases in dynamical equilibrium; dense clouds having $N_H > 1$ cm^{-3} and with a temperature $T_e \leq 100$°K and diffuse intercloud gas with $N_H \lesssim 0.1$ cm^{-3} and $T_e \lesssim 1000$°K. In gas having mean density less than 0.1 cm^{-3} it is impossible to form new clouds in the presence of such heating.[120,121] If the density is less than 10^{-2} cm^{-3} then there is only one stable phase and any fluctuations in density will disperse because their internal pressure cannot be balanced by that of the intercloud gas so that only diffuse gas is possible.† But such a density $N_H \sim 1$–3×10^{-3} cm^{-3} seems to be the mean density of gas in the outer regions of the Andromeda nebula assuming $N_H l \sim 10^{19}$ cm^{-2} [122] and the thickness of the disc $l \gtrsim 2$ kpc. The last figure comes from an analysis of the distribution of neutral hydrogen in the Milky Way[113] and also from estimates of the thickness of a homogeneous gas disc under the influence of the gravitational field of the central regions of the galaxy.[110]

* * *

If observations confirm the absence of clouds at the peripheries of galaxies then one could conclude that out to the cut-off in the distribution of neutral hydrogen the column density in the ionized region is smaller than the neutral one. On this basis an upper limit to the intensity of the background ionizing radiation of $J_\nu < 10^{-23}$ erg-

---

*Heating by the background radiation is small if the gas is distributed in massive clouds having $N_H l > 10^{20}$ cm^{-2}. It is noted below that under typical conditions found in the outer regions of galaxies ($\bar{N}_H < 10^{-2}$ cm^{-3}), there is little likelihood of new clouds forming from the diffuse gas. It is even less likely that clouds can reach the outer regions of the galaxy from the central regions.

†We also note that a small abundance of heavy elements in the gas in the outer regions of galaxies leads to a sharp decrease in the energy losses of dense clouds and thus to the existence of only diffuse gas.

cm^{-2}s^{-1}sr^{-1}Hz^{-1} can be found.[109] This limit refers to the wavelength region $300 < \lambda < 912$ Å. With decreasing wavelength the cross section for photo-ionization falls as $\sigma \propto (\nu_c/\nu)^3$. Calculations of the secondary effect (ionization of atoms by photo-electrons) leads to a limit $J_\nu < 10^{-23}(\nu/\nu_c)^2$ erg-cm^{-2}s^{-1}sr^{-1} Hz^{-1}. These limits are important in studies of the properties of the intergalactic gas and in estimating its density. They are also important in analyzing the spectra of relativistic electrons as sources of the X-ray background (see next section).

The limits which we have obtained are two orders of magnitude smaller than those found experimentally in the neighboring "observable" ultraviolet waveband. Hydrogen in the outer regions of galaxies turns out to be potentially a hundred times more sensitive a detector than counters on board rockets and satellites. But even this limit is not particularly low since it corresponds to ten thousands of ionizing quanta falling every second on each square centimeter of the surface of the galaxy. The total energy falling on a galaxy such as the Andromeda nebula having dimensions $R \sim 30$ kpc is $L \sim 4\pi R^2 \int_{\nu_c}^{3\nu_c} \pi J_\nu d\nu \approx 10^{40}$–$10^{41}$erg-s^{-1}which is of the order of the total power of sources of cosmic rays in the Galaxy.[123] Therefore if galactic sources of energy can ionize the gas in the disc by internal heating then in the outer regions the dominant role may well be played by the background radiation.

To confirm the above limits requires careful analysis of the existing experimental data and new observations of our own Galaxy and external galaxies at 21 cm with high resolution. It is clear that the method we have described can give important information about the ionizing background radiation which is impossible to find in any other way and which is very important for understanding physical processes in the intergalactic medium.

V. X-RAY WAVELENGTHS ($0.01 < \lambda < 100$ Å; $3 \times 10^{16} < \nu < 3 \times 10^{20}$ Hz; 100 eV $< \mathcal{E} < 1$ MeV)

X-ray astronomy began in the late 1940's when x-ray emission from the Sun was discovered. In 1962 the first galactic sources were discovered and since that time systematic studies of sources and the x-ray background have continued.

1. Observations

Observations with rockets, balloons and satellites have shown that there exists a highly isotropic x-ray background in the classical x-ray region, 1 to 10 Å, implying that it is of extragalactic origin. Its spectrum has also been determined and a number of measurements made in recent years is shown in Fig. 9 which is taken from the survey of Silk.[2] It can be seen that the spectrum of the x-ray background is not particularly well determined but some features seem to be appearing.

a) The hard x-ray region ($\mathcal{E} > 1$ keV). In the range 40 keV $< h\nu = \mathcal{E} < 0.5$ MeV the spectrum is of power-law form having spectral index $\alpha \approx 1.2$ (i.e., $J(\mathcal{E}) \propto \mathcal{E}^{-1.2}$; $N(\mathcal{E}) = J(\mathcal{E})/\mathcal{E} = 100\,\mathcal{E}^{-2.2}$ quanta-cm^{-2}s^{-1}keV^{-1}sr^{-1}). It is possible that this law extends to energies greater than 100 MeV. In any case such a spectrum does not contradict γ-ray observations in the range 30 MeV $< \mathcal{E} < 1$ GeV which have been made from the space platforms "Proton-2" "Cosmos-208"[144] and OSO-III.[132] The excess background intensity in the range 1 to 6 MeV[143] can be considered a contribution of soft γ-rays superimposed on a single power law spectrum (see Fig. 12 and the subsequent discussion).

There seems to be a break in the background spectrum at about 30 to 40 keV and in the range 10 to 40 keV the spectral index is most likely to be $\alpha \approx 0.7$. It is possible that in the range 1 to 10 keV the spectrum is even flatter and values as low as 0.3 have been reported. However there is no single opinion as to the exact value as is evident from Fig. 9. It is not known whether the radiation in this region is truly a power law spectrum. It is only clear that in the range 1 to 40 keV the slope of the spectrum is significantly smaller than that for $\mathcal{E} > 40$ keV. Figure 9 should also include the background measurements at 1 keV from the space station "Luna-12"[145] which were among the first observations to find a break about 10 keV.

The determination of the exact spectrum for energies greater than 300 keV are extremely difficult because in this region the Compton losses of the quanta in the counters are not unambiguously related to the initial spectrum of the radiation[147] which is why Vette et al.[143] could not give an exact estimate of the spectrum in the range 0.25 to 6 MeV. The parameters of the spectrum can only be obtained from the spectrum of energy losses on the basis of certain assumptions (see the following section). These remarks,[147] however, are not important in the region of the break of the spectrum at $\mathcal{E} \sim 40$ keV.[2]

b) The soft x-ray region (250 eV $< \mathcal{E} < 1$ keV). From Fig. 9 it can be seen that at energies less than 1 keV the spectrum again steepens. The exact value of

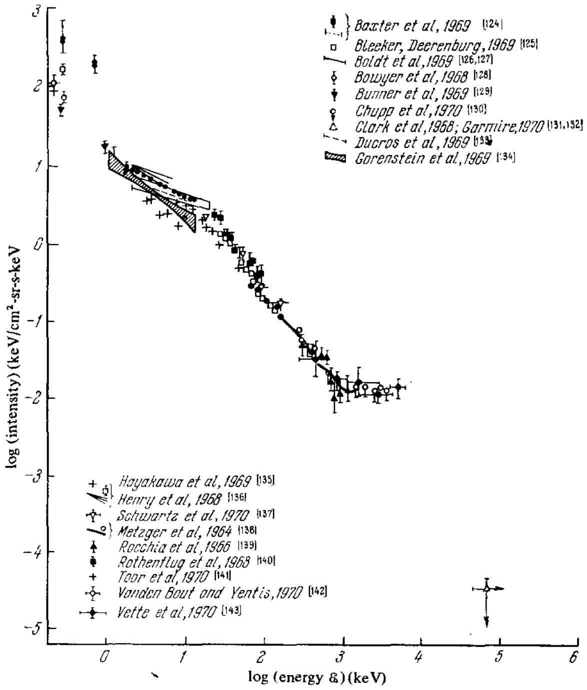

FIG. 9. Spectrum of x-ray background radiation of universe.

intensity of the background in this region is not known because of uncertainties in the corrections for absorption by interstellar gas in the galaxy. But even if no account is taken of these corrections the measurements indicate the existence of excess soft x-ray emission in comparison with that expected from extrapolation from the region having energy $\mathcal{E} > 1$ keV.[129] It is found that the intensity of the background at $\mathcal{E} \sim 250$ eV has a strong dependence upon galactic coordinates.[128,129,135,142] Other measurements[148] have shown that the excess background and dependence upon galactic coordinates are still present at 680 eV. The intensity has a maximum in directions perpendicular to the galactic plane which is readily explained if the absorption of the background radiation takes place in the interstellar gas and is evidence for the extragalactic nature of the soft x-ray background emission. Only one set of measurements[124] has not found this dependence on galactic coordinates and they have found an anomalously high background intensity contradicting all the other data. These results could be explained if the background which they observed originates in the atmosphere.[149] The discrepancies between the results of different groups are not great and are mostly connected with differences in the direction of observation which of course corresponds to different amounts of absorption. In addition some groups[136] have attempted to make corrections for the absorption for observations in the direction of the galactic poles (basing their corrections on 21-cm emission measurements which would suggest a factor of 3 should be applied to their results). Other groups[128] do not include these corrections since they consider the interstellar gas to be concentrated in clouds which would make the interstellar medium optically thin for soft x-ray radiation.[150] In any case as we have already noted the measurements indicate that there exists an excess background in the soft x-ray region and that it is extragalactic in nature. There remains the possibility that this radiation could originate in the halo of our galaxy. However such an interpretation encounters energetic difficulties. On the other hand it is impossible to reject this possibility completely in view of the many difficulties which will be encountered in constructing satisfactory models for the soft x-ray background. For example Shklovsky and Sheffer[151] have proposed that if the galactic spurs—extended arc-like features of the radio sky are the remnants of nearby old supernovae ($\sim$30–100 pc distant, ages $\sim 10^5$–10^6 years) then their thermal emission could explain the observed excess soft x-ray emission.

Recent observations of the background with high spectral resolution[148,152] have found evidence for the existence of a narrow spectral feature in the background spectrum close to 7 keV ($\Delta\lambda/\lambda < 0.15$) which they interpret as the K_α line of iron. There is independent evidence for the existence in the background spectrum for the K_α line of carbon.[153] These data have not been substantiated but if they are, then the small spectral width of the lines imply that the source of the radiation is nearby.* The sources of the radiation cannot be at cosmological distances because the redshift would smear out the line to a broader bandwidth. The well-known mechanism for producing effective K_α line emission from heavy ions is charge exchange non-resonance transitions due to sub-cosmic rays (E $\sim$ 10–30 MeV), by interstellar hydrogen.[154] If supernova remnants accelerate a large quantity of enriched heavy elements to sub-cosmic ray energies then their charge transfer radiation in x-ray lines could be associated with nearby supernova remnants, such as might explain the galactic spurs.

2. The Origin of the X-ray Background

The question of the origin of the x-ray background radiation and what the principal sources are is not yet settled. There exists a large number of theories of varying degrees of credibility. This is connected with the fact that information is almost completely lacking both about discrete extragalactic x-ray sources and also about physical conditions in intergalactic space. More than 50 x-ray sources are now known and of these 6 are extragalactic. These include—the nearest galaxy to us, the large Magellanic Cloud,[155] the radio galaxy Centaurus A (NGC 5128),[156,157] the powerful radio galaxy with an active nucleus M 87 (Virgo A)[158,159] in which the observed explosion contributes a significant fraction of the radio and optical luminosity of the galaxy, the quasar 3C 273[156,157] and the Seyfert galaxies NGC 1275[160,161] and NGC 4151.[161] In addition there exist upper limits to the x-ray luminosity of the powerful radio sources Cygnus A,[163] the Seyfert galaxy NGC 1068[161] and a number of other objects. The x-ray emission from the radio galaxy Centaurus A comes from the region of the compact nucleus and not from the extended radio structure[156,157] whereas in the case of the radio galaxy M 87 an extended region of x-ray emission is observed which was at one time thought to be the integrated x-ray emission from galaxies in the Virgo cluster.[162] The extended region of x-ray emission in the Virgo cluster was first discovered in observations with the satellite "Cosmos."[164] The radio galaxy M 87 has been found to be variable at x-ray wavelengths—over a period of two years the hard x-ray emission ($\mathcal{E} > 10$ keV) has changed by a factor of about 10.[157] X-ray emission has also been observed from the Milky Way having intensity about 10% that of the isotropic background in the range $\mathcal{E} \sim 1$–10 keV.[165] In fact it is difficult to estimate the total x-ray luminosity of our Galaxy from these data. The most reliable estimates of the luminosity of the Galaxy due to discrete x-ray sources is $L_X \sim 10^{39}$–10^{40} erg-s^{-1}.[166] The luminosities of the objects described above are included in Table III.

It is a straightforward calculation to estimate the contribution of discrete sources such as our Galaxy to the total energy density of the x-ray background and it amounts to $w_X \approx L_X N t \sim 3\times10^{-7}$–$3\times10^{-6}$ eV-cm^{-3} which is 30 to 300 times smaller than the observed background of $w_X \approx 10^{-4}$ eV-cm^{-3}. The spectral character of such radiation is not known although it is clear that there are other difficulties with this model. It is not known, for example, how a population of sources such as the Crab Nebula, ScoXRI and so on can explain the observed spectrum of the background and in particular

---

*More recent observations [152a] designed to search for line radiation have failed to detect any line on the background spectrum at about 7 keV.

the break at $\mathcal{E} \sim 40$ keV. If it is supposed that the x-ray sources evolve with cosmological epoch then the energy problem can be solved but not the problem of the spectrum. By the same type of argument sources such as Cen A, Cyg A, M 87, and 3C 273 also cannot explain the observed intensity of the x-ray background and the only possibility seems to be Seyfert galaxies (see Table III). If on average the latter have x-ray luminosities of the order of that found in NGC 1275 then the background would be about 10 times greater than that observed. However NGC 4151 and 1068 are much weaker x-ray sources than NGC 1275.

The observed spectrum and intensity lead to severe restrictions upon models of the origin of the background and upon possible sources such as the intergalactic medium or discrete sources—quasars, normal galaxies, radio galaxies, Seyfert galaxies or some other type of galaxy. Any theoretical model must explain the following facts—

a) a power law spectrum with $\alpha \approx 1.25$ in the energy range $40 < \mathcal{E} < 500$ keV;

b) the spectral break at $\mathcal{E} \approx 40$ keV;

c) the excess of soft x-ray emission at $\mathcal{E} \sim 250$ eV;

d) the high energy density of the x-ray background radiation which corresponds to a factor of 1000 greater than the energy density of the non-thermal radio background (see Table I).

Condition a) can be explained by some non-thermal mechanism of radiation. It is often supposed that this is the inverse Compton scattering process of low energy (relict?) radiation by relativistic electrons having power law spectrum $dN_e = K_e E_e^{-\gamma} dE_e$. The existence of such electrons in cosmic objects is without doubt. They are observed as a constituent of the primary cosmic rays in our Galaxy and in addition their radiation in the galactic magnetic field gives rise to the radio emission from our Galaxy and from radio galaxies. In spite of the fact that this radiation mechanism is well known it is not clear what the sources of the relativistic electrons are nor the region in which the x-ray emission is generated (discrete sources or intergalactic space). The simplest models cannot explain conditions b), c), and d).

The high intensity of the soft x-ray background is usually explained by another mechanism—the bremsstrahlung emission of hot gas in intergalactic space or in discrete sources or as the radiation of supernovae in other galaxies. An interesting model of the latter type has been proposed by Shklovskiĭ[167] in which the excess radiation at $\mathcal{E} \sim 250$ eV is attributed to the remmants of supernovae radiating in the resonance lines of oxygen, O VII and O VIII, at a wavelength $\lambda \sim 20$ Å. A significant fraction of the kinetic energy of the cloud ejected from the star would have to be radiated in these lines. The redshift of this radiation from distant galaxies will be observed at $\mathcal{E} \sim 250$ eV ($\lambda \sim 50$ Å) if they have a redshift $z \sim 1$. The model predicts that there should be sharp x-ray lines in the spectra of the remnants of supernovae in our Galaxy (we note that at higher energies continuous radiation has already been observed from such objects) and a sharp cutoff to the spectrum of the background at wavelengths $\lambda < 20$ Å.

It is important to note the importance of precise spectral measurements of the background. In particular observations of absorption features in the background spectrum could be related to photo-ionizing K electrons of atoms and ions of heavy elements and make it possible to determine the abundances of heavy elements (C, N, O etc.) in the interstellar gas of our Galaxy.

Below we will describe particular mechanisms of radiation as the source of the x-ray background. We will find limits to the parameters of the intergalactic gas and to the energy density of relativistic electrons in intergalactic space as well as other information which can be found from analysis of the intensity and spectrum of the observed background radiation.

3. The Bremsstrahlung Mechanism

a) The radiation from the intergalactic gas. The observed soft x-ray background together with the ultraviolet observations described above set important limits to the present state and past history of the intergalactic gas. A hot intergalactic gas[168] radiates high energy quanta principally by free-free transitions in the field of the nuclei of atoms. The spectrum of this emission by electrons at temperature T_e is roughly flat ($\alpha = 0$) up to a frequency $\nu \sim kT_e/h$ above which the emission decreases exponentially. The exact predicted spectrum of the x-ray background depends upon the thermal history of the gas but an exponential cutoff is characteristic for all reasonable models.[169,170] In Fig. 10 we show the radiation spectrum of the intergalactic gas for a number of different models of its temperature history and making different assumptions about its density as discussed by Doroshkevich and Sunyaev.[171]

It is impossible to explain the overall x-ray background spectrum as bremsstrahlung emission of the intergalactic gas. In the hard x-ray region ($\mathcal{E} > 1$ keV) it is impossible to explain the power law spectrum up to energies $\mathcal{E} \sim 500$ keV.[146] The excess soft x-ray emission was immediately interpreted as evidence for the existence of a hot intergalactic gas of roughly critical density at a temperature $T_e \sim 3 \times 10^5 - 10^6$ °K.[136,172] In this case, however, it is difficult to find a satisfactory exponential law in the soft x-ray region which does not exceed the upper limits to the intensity of the ultraviolet background which were found in the preceding section from observations of neutral hydrogen in the peripheries of galaxies, provided, of course, these limits are confirmed by future studies. These arguments apply not only

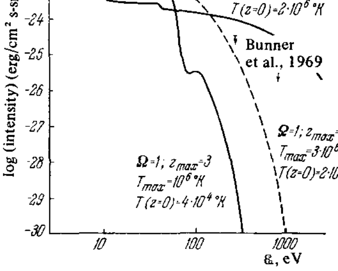

FIG. 10. Radiation spectrum of intergalactic gas, calculated under various assumptions concerning its density and thermal history.

to the radiation of the intergalactic gas but also to any model which involves large quantities of high temperature gas ($T_e \sim 10^5$–10^6 °K) along the line of sight, e.g., gas in the halos of galaxies, discrete thermal sources or intergalactic gas in clusters of galaxies.[174]

Bunner et al.[129] have made observations in two spectral bands at 250 eV and 900 eV. From the relative intensities in these two bands they have found that their observations are best represented by bremsstrahlung emission of an intergalactic gas with density $\Omega \sim 0.2$ ($n_e \sim 2 \times 10^{-6}$ cm^{-3}) and $T_e \sim 2.5 \times 10^6$ °K. This involves a correction for the hard x-ray emission which is found from extrapolation from the range 1 to 10 keV. This model does not contradict the limits in the ultraviolet because at such a high temperature the intensity of the radiation $J_\nu \propto \exp(-h\nu/kT_e)$ practically does not increase with decreasing energy of the quanta ($h\nu/kT_e < 1$ for $h\nu > 250$ eV).

We digress from particular models of the evolution of the intergalactic gas since knowing only the total intensity of radiation at $\mathscr{E} \sim 250$ eV upper limits can be found for the intergalactic gas at any redshift.[173] If $\Omega = 1$ we find $T_e < 1.5 \times 10^6 (1 + z)$ °K. Because the expression for the intensity of bremsstrahlung radiation has the form $j_\nu \propto n_e^2 T_e^{-1/2} \exp\{-h\nu/kT_e\}$ then for $h\nu/kT_e \gg 1$ the limits to the temperature depend logarithmically upon Ω. The dependence of the limiting temperature on redshift is connected with the fact that for a constant exponent in the above expression T_e must change in the expansion as ν, i.e., $T_e \propto (1 + z)$. Because of the many ways in which n_e and T could depend upon redshift the above limit is useful since it must be true for any redshift provided there exists hot gas for periods of time of the order of the cosmological time scale at that epoch.

The intergalactic gas is optically thin for soft x-ray radiation. It therefore follows that the abundances of heavy elements are small (about $100/\Omega$ times smaller than in the Galaxy) and also that helium is highly ionized which requires $T_e > 10^5$ °K if $\Omega \sim 1$.[174] A 10% helium abundance in the primaeval matter is predicted by the hot model of the universe. For small values of Ω photo-ionization can lead to the ionization of the gas even at low temperatures.[171]

b) The bremsstrahlung emission of subcosmic rays. It has been proposed as an alternative that in the intergalactic medium besides a Maxwellian plasma there also exist large fluxes of sub-cosmic rays, both electrons[175] and protons.[176,177] The spectrum of their bremsstrahlung emission will not be exponential but will depend upon that of the injected particles. We note that non-thermal protons radiate x-ray quanta in collisions with the Maxwellian electrons of the intergalactic gas—in a sense, this is "inverse" bremsstrahlung radiation—and the non-thermal electrons interact with protons of the intergalactic gas. By an appropriate choice of the initial spectrum of particles and the epoch of injection, it is possible to obtain a spectrum of the x-ray emission similar to that observed. The break at 40 keV can be explained in such a model as a distortion of the spectrum of the non-thermal particles in the low energy region because of ionization losses (to be more exact, because of Coulomb scattering) in the intergalactic gas. In order that the break occur at 40 keV in the case of electrons, the density must be less than $\Omega \lesssim 1/40$ and in the proton case all the particles will be thermalized by electrons within cosmological time scales if their energies are greater than 60 keV (E ~ 800 keV if $\Omega = 1$) and the spectrum of the radiation will not be power-law in nature.

This model can only be tenable in the case when the intergalactic gas contains (or contained in the past) a very high density of sub-cosmic rays because the non-thermal bremsstrahlung mechanism is a very ineffective way of converting the kinetic energy of particles into radiation. A major fraction of their energy goes into heating the surrounding plasma and this energy is lost adiabatically in the expanding universe. In the case of x-ray radiation, only about 10^{-4} of the energy loss of the sub-cosmic rays goes into x-ray emission. To explain the observed intensity of the x-ray background it is necessary to suppose unacceptably large injections of energy a significant fraction of which goes into ionizing and heating the gas. The re-radiation of even a small fraction of this energy of the intergalactic gas (or the gas in the sources of cosmic rays themselves) at radio, optical, ultraviolet and x-ray wavelengths would contradict the observations.

There is a further difficulty; it is not known how the particles can escape from their sources which are supposed to be radio galaxies or quasars. They must escape through regions of high density cold plasma where they must be rapidly thermalized (detailed criticisms of this hypothesis are given in [178,179,2].

4. The Inverse Compton Scattering Mechanism

The theory of the origin of the x-ray background for energies $\mathscr{E} > 1$ keV which has received most attention is the following. Photons of the microwave background radiation which have mean energy $h\bar{\nu}_{ph} \approx 2.8 kT_r = 7 \times 10^{-4}$ eV are scattered by relativistic electrons originating in extragalactic radio sources or normal galaxies. These photons are elevated to X-ray energies with

$$\mathscr{E} = \frac{4}{3} h\bar{\nu}_{ph} \left(\frac{E_e}{m_e c^2}\right)^2. \qquad (1)$$

If the spectrum of electrons is of power-law form

$$N_e d\left(\frac{E_e}{m_e c^2}\right) = K_e \left(\frac{E_e}{m_e c^2}\right)^{-\gamma} d\left(\frac{E_e}{m_e c^2}\right).$$

then the x-ray emission also obeys a power law. In fact, to first approximation it follows from (1) that

$$J_{\mathscr{E}} \sim N_e [E_e(\mathscr{E})] \frac{dE_e}{d\mathscr{E}} \mathscr{E} \sim \mathscr{E}^{-\frac{\gamma-1}{2}},$$

i.e., the spectral index of x-ray emission is $(\gamma - 1)/2$.

It is well known that there is a strong similarity between the synchrotron and inverse Compton mechanisms of energy loss by relativistic electrons[180] For our further discussion it is sufficient to use the simple formulae describing the radiation of relativistic electrons located in a magnetic field of intensity B and in an isotropic radiation field of energy density w_{ph}. The spectral coefficient of the radiation (per unit volume if K_e is given in units of cm^{-3} or for any number of electrons provided the dimensions are correct) is equal to the following at radio and x-ray wavelengths

$$\left.\begin{aligned} j_\nu(\nu_R) &= 0{,}69\,\frac{K_e\sigma_T c}{\nu_m}\left(\frac{B^2}{8\pi}\right)\left(\frac{\nu_R}{\nu_m}\right)^{-\frac{\gamma-1}{2}}, \\ j_\nu(\nu_x) &= 0{,}47\,\frac{K_e\sigma_T c}{\nu_{ph}}(w_{ph})\left(\frac{\nu_x}{\nu_{ph}}\right)^{-\frac{\gamma-1}{2}}, \end{aligned}\right\} \qquad (2)$$

where $\sigma_T = (8\pi/3)(e^2/m_ec^2)^2$ is the Thompson scattering cross section, $\nu_m = 0.4\,eB/2\pi m_ec = 1.2\times10^{-6}\,B$ (where B is given in Gauss) and the mean frequency of the photons is ν_{ph}, which in the case of the microwave background radiation is $\nu_{ph} = 1.5\times10^{11}(1+z)$ Hz, assuming it to be Planckian. Since the energy losses of relativistic electrons by inverse Compton scattering is

$$\frac{dE_e}{dt} = -\frac{4}{3}\sigma_T w_{ph} c\left(\frac{E_e}{m_ec^2}\right)^2, \qquad (3)$$

and by synchrotron radiation

$$\frac{dE_e}{dt} = -\frac{2e^4B_\perp^2}{3m_e^2c^3}\left(\frac{E_e}{m_ec^2}\right)^2 = -\frac{4}{3}\sigma_T\left(\frac{B^2}{8\pi}\right)c\left(\frac{E_e}{m_ec^2}\right)^2, \qquad (4)$$

it can easily be shown that the lifetime of relativistic electrons is

$$t \approx \frac{m_ec}{\sigma_T\left(w_{ph}+\frac{B^2}{8\pi}\right)}\frac{m_ec^2}{E_e} \approx 7\cdot10^{11}\left(\frac{1\ \text{эв/см}^3}{w_{ph}+\frac{B^2}{8\pi}}\right)\frac{m_ec^2}{E_e}\ \text{years} \qquad (5)$$

a) The microwave background radiation and the x-ray background. Relativistic electrons originating in extragalactic radio sources lose energy both by the synchrotron and inverse Compton mechanisms. Synchrotron losses become negligible when the relativistic electrons leak out of radio sources but the inverse Compton losses due to the microwave background radiation are always present because the electrons cannot escape from this omnipresent radiation. The electrons therefore continue radiating x-rays until they have lost all their energy. Because ν_{ph} and ν_x change during the expansion of the universe according to the general law $\nu = \nu_0(1+z)$ and there is a linear relation between them, $\nu_x = \frac{4}{3}\nu_{ph} \times (E_e/m_ec^2)^2$ a given observed x-ray wavelength always corresponds to low frequency photons being scattered by relativistic electrons of the same energy independent of redshift. The lifetime of electrons against inverse Compton scattering losses is

$$t_c(E_e, z) = \frac{3}{4}\frac{m_ec}{\sigma_T w_{ph}}\left(\frac{m_ec^2}{E_e}\right) = \frac{t_c(E_e, z=0)}{(1+z)^4}$$

so that it decreases rapidly with redshift because of the increasing radiation energy density. The lifetime of electrons having energies $E_e < 100$ MeV exceeds cosmological time scales at the present epoch $t \sim H_0^{-1} \sim 10^{10}$ years and therefore for $\mathscr{E} < 100$ eV the spectrum of the radiation is determined by the above formula and $\alpha = (\gamma-1)/2$.[181] Electrons having energies $E_e > 500$ MeV correspond to x-ray photons of energy $\mathscr{E} > 100$ eV and their half-lives are $t_c \lesssim 2\times10^9$ years, i.e., their lifetime is significantly smaller than cosmological time scales. Since $t_c \propto E_e^{-1} \propto \mathscr{E}^{-1/2}$, it follows that for $\mathscr{E} > 100$ eV the spectral index of photons of the x-ray radiation changes by a half, i.e., $\alpha = \gamma/2$ for an injection spectral index of electrons into the intergalactic space of γ. This result is independent of the time dependence of the injection of particles. It is only important that the particles lose all their energy.

There is another way of seeing how this comes about. If we have a continuous injection of electrons per unit volume and their lifetimes are small then

$$\frac{\partial N_e}{\partial t} + \frac{\partial}{\partial E_e}[b(E_e)N_e] = q(E_e, t),$$

where $b(E) \propto E_e^{-2}$ describes the Compton losses (Eq. (3)) and $q(E_e, t) = Ak_eE_e^{-\gamma}$ characterizes the rate of injection.[182] In the stationary situation $\partial N_e/\partial t = 0$ and the solution of the above transfer equation is $N_e \propto E_e^{-\gamma-1}$, i.e., the spectrum of electrons has steepened.* The steady-state x-ray emission of the electrons then corresponds to $J_\nu(\mathscr{E}) \propto \mathscr{E}^{-\gamma/2}$. Taking account of the expansion of the universe does not change this conclusion. Thus the spectrum of the x-ray emission must be steeper than the spectrum of the radiation from the sources of relativistic electrons in the radio waveband.

The observed integrated energy density of x-rays can be used to find an upper limit to the density of cosmic rays in intergalactic space

$$w_{cr} \leqslant 1.8\cdot10^{-4}(1+K)\ \text{eV cm}^{-3} \qquad (6)$$

independent of the source of the particles, their cosmological evolution and the epoch of injection of cosmic rays.[183] The only hypothesis is that the ratio of protons to electrons remains the same as generated in sources ($L_p = KL_e$). It immediately follows from (6) that the energy density of relativistic electrons at the present epoch in intergalactic space is $w_e \leq 1.8\times10^{-4}$ eV-cm^{-3}. But the limit given by (6) is much more powerful. Electrons rapidly lose all their energy but the lifetime of protons having energies in the range $10^8 < E_p < 10^{18}$ eV are significantly greater than cosmological time scales. This is why the x-ray background radiation, which gives directly the energy in relativistic electrons ejected into intergalactic space, contains important information about the present day density of cosmic rays in the universe.† In our own galaxy $K \approx 100$ and therefore if the cosmic rays observed in the Galaxy having energy density $w_{cr} \sim 1$ eV-cm^{-3} were extragalactic in origin, then an x-ray background 60 times greater than that observed should be observed. This is an important piece of evidence in relation to the theory of the galactic origin of cosmic rays (see discussions in [184,185]).

b) Discrete source models. The nearby extragalactic objects which have extended regions of radio emission such as normal galaxies and radio galaxies are certainly sources of x-ray emission because of the existence of the microwave background radiation. However such objects cannot explain the observed x-ray background, because in radio galaxies (Cyg A, Cen A) $L_x/L_R \lesssim 3$ (see Table III) in comparison with that necessary to explain the background $L_x/L_R \sim w_x/w_R \sim 10^3$ (see Table I). In the case of our Galaxy the losses due to inverse Compton scattering are of the same order as those due to synchrotron radiation because $L_x/L_R \sim w_{ph}/(B^2/8\pi) \sim 1$ (see [123]). This means that if we neglect the effects of cosmological evolution the inverse Compton scattering of the microwave background radiation by relativistic electrons in galaxies and radio

---

*If the characteristic lifetime for low energy electrons exceeds the characteristic time of the system t_s, then the electron spectrum (and the corresponding x-ray spectrum) will have a break in the energy range for which $t_c \sim t_s$.

†This refers, of course, to redshifts $z \ll 100$, at which distortions of the x-ray background may be expected (see next section).

sources cannot give much more than 10^{-3} of the observed background unless we suppose the magnetic fields in radio galaxies are less than 10^{-8} Gauss (since $B^2/8\pi < 10^{-3}\, w_{ph}$) which is implausibly low.

The necessary ratio of w_X/w_R can be found if:

1) The escape time of relativistic electrons from galaxies and radio galaxies is 1000 times less than the characteristic time for synchrotron losses. Then the electrons can lose all their energy by inverse Compton scattering in intergalactic space where undoubtedly $B^2/8\pi \ll 10^{-3}\, w_{ph}$.

2) The principal contribution to the background originates at large redshifts ($z \sim 5$–10). This hypothesis enables us to use the observed cosmological evolution of powerful radio sources so that the injection of relativistic electrons in the past was much greater than at the present day. More important is the change in the energy density of the microwave background which changes as $w_{ph} = w_{ph}(z=0)(1+z)^4$. If the magnetic field in sources remains the same with epoch then the ratio $8\pi w_{ph}/B^2$ and hence L_X/L_R increases.[186,187]

3) The x-ray emission originates in the nuclear regions of Seyfert or other galaxies or even quasi-stellar galaxies in which objects the energy density of infrared radiation $w_{ph} \sim L_{ir}/4\pi r^2 c$ in the small region $r < 1$–100 pc can greatly exceed the value of $B^2/8\pi$.[188] We note that this model can explain the excess soft x-ray background radiation (see below). The majority of models of the first and second type cannot account for the spectral difficulties a) and b) described above and do not explain the excess soft x-ray emission c).

In the most popular form of the theory[181,189-192] it is supposed that the electrons lose a small fraction of their energy in radio sources and therefore their radio spectra are of the form $J_\nu \propto \nu^{-\alpha}$ where α is related to the spectrum of electrons by $\alpha = (\gamma - 1)/2$. The electrons are then injected into intergalactic space where they lose all their energy to photons of the microwave background converting them into x-rays with spectrum $J(\mathcal{E}) \propto \mathcal{E}^{-(\alpha+1/2)}$. The mean spectral index of radio sources is $\alpha = 0.75$[6] and therefore the predicted x-ray spectrum has $\alpha = 1.25$ which is in excellent agreement with the observed value for energies greater than 40 keV. With an appropriate choice of parameters of radio sources namely weak magnetic fields and lifetimes of the electrons within radio sources of 10^6 years (i.e., their diffusion time from the region have $B \approx 10^{-6}$ Gauss and $R \sim 10$ kpc), it is possible to construct models of radio sources which include cosmological evolution and which can explain the observed ratio of energy densities at x-ray and radio wavelengths.

However, in this simple model it is very difficult to explain the existence of the break in the x-ray spectrum at about 40 keV, as has been discussed in detail by [191,188,183]. The only break in the injection spectrum of the electrons of the correct from to produce the observed break in the spectrum of the x-ray background is the break in the radio background emission at 2 MHz (see Sec. 1). However only if the magnetic field in all radio sources is less than 10^{-7} Gauss could these breaks be related, which seems an unreasonably small value of the magnetic field. In any other variant it is necessary to suppose the existence of further loss mechanisms for the electrons as they are injected into intergalactic space, e.g., adiabatic losses.[191] In this case the parameters of radio sources must be carefully adjusted at large redshifts or else the distant radio sources would have spectra $J_\nu \propto \nu^{-1.25}$ which would contradict the observations.[13] According to these observations the mean spectral index of very faint radio sources are the same as those of bright radio sources and have $\alpha = 0.75$. Furthermore it has recently been found that the spectra of a significant fraction (about 40%) of radio sources in the revised 3C catalogue (the standard catalogue of bright sources in the northern sky) have a spectral break at high frequencies.[193] This fact is difficult to reconcile with this theory because it implies the existence of a further break within the observed hard x-ray region. If the break were connected with synchrotron losses in radio sources then the theory would be completely untenable because in this case the electrons would have already lost a large fraction of their energy in radio waves and could not supply a further factor of 1000 to produce the x-ray emission.

Brecher and Morrison[21] have considered the first of the above possibilities for obtaining $w_X/w_R \sim 10^3$—the rapid ejection of electrons from normal galaxies (with escape times of $\sim 10^5$ years for galaxies such as ours). The radio spectra of normal galaxies appear to have a break with $\Delta\alpha \sim 1/2$ in the frequency range $\nu_b \approx 500$–1500 MHz ($\alpha \approx 0.8$ for $\nu > \nu_b$ and $\alpha \approx 0.3$ for $\nu < \nu_b$).[194] Normally this break is attributed to the fact that electrons radiating in a magnetic field will have a break in their spectrum at a frequency corresponding to the energy of electrons for which the diffusion escape time from the galaxy is equal to their lifetime against synchrotron losses. The electrons from the high energy region lose all their energy as radio emission and therefore for $\nu > \nu_b$ the spectral index is $\alpha = \gamma/2$. Electrons with small energies lose only a small fraction of their energy as synchrotron emission and therefore $\alpha = (\gamma - 1)/2$. Thus, for injection with $\gamma = 1.6$, most of the total energy of electrons $\int N_e(E_e) E_e \, dE_e$ is radiated in the radio region.

For this reason Brecher and Morrison must suppose that the break in the spectrum of electrons at $E_e \sim 3$ GeV from $\gamma \sim 2.6$ to $\gamma \sim 1.6$ is formed in the sources of cosmic rays themselves, i.e., the break is primeval. Compton scattering of photons of the microwave background from such electrons when they diffuse into the intergalactic medium result in the observed break, namely $\alpha = \gamma/2$ changes from 1.3 to 0.8 at $\mathcal{E} \sim 40$ keV.* Even allowing for a range in spectral indices it is difficult to obtain good agreement with the soft x-ray background and the γ-ray background at energies greater than 1 MeV. In the energy region $\mathcal{E} > 30$ MeV the predictions of this model contradict the experimental data (see Fig. 12).

In fact, normal galaxies can only contribute about 10% of the total radio background (see Table III) whereas Brecher and Morrison suppose that they provide the

---

*A similar model [185,192] has been proposed utilizing radio galaxies in which the break in the radio spectra at high radio frequencies [196], from $\alpha_R = 0.75$ to $\alpha_R = 1.25$, i.e. the spectra are steeper than in the case of normal galaxies. The break in the x-ray background, from $\alpha_X = 1.25$ to $\alpha_X = 1.75$, contradicts the observed x-ray background spectrum.

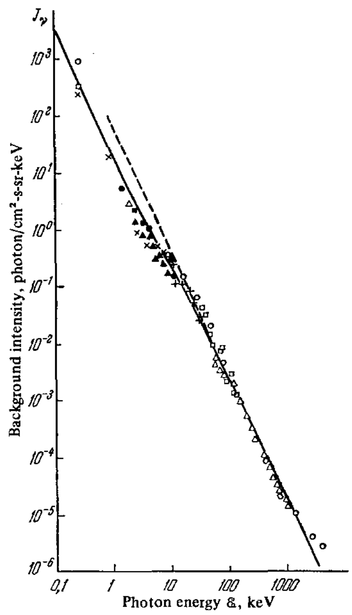

FIG. 11. Comparison of spectrum predicted by the model of [188] with the observed spectrum of the background x-radiation—solid line; the dashed line corresponds to extrapolation of the power-law spectrum from the hard region: $J_{\mathcal{E}} \sim \mathcal{E}^{-1,2}$.

dominant contribution, about 90%. This means that to obtain the observed ratio $w_X/w_R \sim 10^3$ it is necessary that the escape time of electrons from galaxies is less than 10^{-4} of the characteristic time for losses by synchrotron emission for electrons having $E_e \sim 3$ GeV in a field of a few microgauss, $t \sim 10^8$ years, i.e., $t_{diff} \sim 10^4$ years. Cosmic-ray protons have lifetimes in the galaxy greater than 10^7 years because of their high degree of isotropy. It seems unnatural to suppose that the escape time of electrons should be 2 to 4 orders of magnitude different from that of relativistic protons of the same energy.

The model of Brecher and Morrison predicts the existence of a second break in the spectrum of relativistic electrons in galaxies. No matter how rapid the escape of the electrons from galaxies there exists some lower energy such that electrons of greater energy have lifetimes against synchrotron losses less than the escape time. We also note that if the primary source of relativistic electrons in the galaxy is the nucleus then the break at $E_e \sim 3$ GeV could be explained by inverse Compton losses of electrons close to the nucleus and the secondary break could be the result of synchrotron losses in interstellar medium. Such a model has been considered by the authors[197] to explain the relationship between the observed infrared and gamma ray activity of the nucleus of our Galaxy.

c) Are the nuclei of galaxies the principal source of the x-ray background? A way of avoiding all of the above difficulties whilst retaining the attractive features of the inverse Compton models was proposed by the authors[188] in which it was possible to explain not only the hard region of the spectrum but also the complete background at energies greater than 100 eV. In this model we used the fact that the spectrum of the background for $\mathcal{E} > 40$ keV is in good agreement with the mean spectrum of the radio emission of discrete powerful radio sources if the electrons lose a large part of their energy by inverse Compton scattering. Possible sources of the low energy quanta for scattering by relativistic electrons are the compact infrared sources discussed above in Sec. 2. The energy density of infrared radiation within a distance of 1 to 100 kpc greatly exceeds the energy density of the microwave background and the magnetic field energy $B^2/8\pi$. We suppose that compact infrared nuclei, in which it is well known violent explosions take place releasing colossal energies, are the sources not only of intense infrared emission but also of relativistic electrons with spectra similar to those found in powerful extragalactic radio sources. As the electrons escape from the nucleus the most energetic of them lose a large fraction of their energy by inverse Compton scattering of the infrared quanta in the nucleus which leads to a hard x-ray spectrum with a break similar to that observed at $\mathcal{E} > 40$ keV. The electrons then escape into intergalactic space where they lose all their remaining energy by scattering photons of the microwave background radiation converting them into soft x-ray quanta.

Since the mean energy of quanta in the infrared peak ($\lambda \approx 70\mu$) is 25 to 30 times greater than the mean energy of quanta of the microwave background, the break in the electron spectrum must take place about $E_e \approx 600$ to 700 MeV. In this case we will obtain a break in the x-ray spectrum at 40 keV. The energy of the x-ray quanta originating in intergalactic space have energy $\nu_{ir}/\nu_{ph} \sim 25$–30 times smaller than quanta resulting from the scattering by the same electrons of the infrared radiation close to the nucleus, i.e., the soft x-ray radiation in this model originates in intergalactic space. As a result it is possible to explain the complete spectrum of the x-ray background as arising from a population of infrared sources. Detailed calculations are shown in Fig. 11 and it can be seen that the results are in good agreement with the observations throughout the range 250 eV to 1 MeV and for $\mathcal{E} > 30$ MeV.

This model has a number of attractive features. For example, it can explain why the total energy of radiation in the soft and hard regions of the x-ray spectrum are of the same order of magnitude. Secondly, there is no energy difficulty since to obtain the observed x-ray background it is only necessary that about 0.1 to 1% of the energy in the infrared quanta go into relativistic electrons.

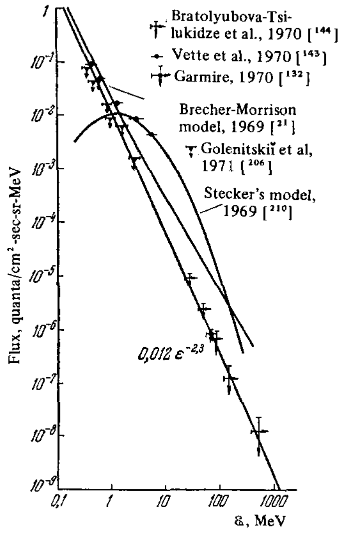

FIG. 12. Experimental data on background γ radiation. It is seen that the model of [210], whereby the γ radiation comes from π^0-meson decay at $z \sim 100$, contradicts the background measurements at $\mathcal{E} > 30$ MeV.

The x-ray quanta having energy $\mathcal{E} \sim 1$ to 3 keV correspond to electrons having energy 100 to 200 MeV. At such energies the injection spectrum of electrons may be distorted because of ionization losses in the interstellar gas close to the nucleus which could explain the flattening of the x-ray spectrum in the low energy region and also for $\mathcal{E} < 250$ eV. In the latter case the increase in intensity also diminishes because the lifetime of electrons having $E_e < 100$ MeV exceeds cosmological time scales (see formula (5)).

The principal difficulty with this model is the requirement that the principal sources of the x-ray background have similar physical properties or else the spectral features of the background spectrum will be washed out. This problem is, of course, present in all models in which the detailed features of the x-ray background are to be explained as the superposition of the spectra of discrete sources. It is also important that the sources which contribute to the background lie within a relatively narrow range of redshift.

In the proposed model powerful infrared sources must be among the most powerful and common class of x-ray sources. The mean x-ray luminosity of the nuclei of Seyfert galaxies would have to be $L_X \sim 10^{43}$ erg-s^{-1}, i.e., of the order of that observed in the radio galaxy M 87. The existence of large numbers of randomly distributed powerful sources of hard x-ray emission must lead to fluctuations of the background radiation of the order $\Delta J_{\mathcal{E}}/J_{\mathcal{E}} \sim 5 \times 10^{-2}$ on angular scales of about 1°.

The nuclei of galaxies of small infrared luminosity must also be sources of x-ray emission. In the case of our galaxy the energy density in infrared radiation exceeds that of the microwave background within a radius of 500 pc and part of the gamma-ray emission from the region of the center[131] could be explained on the basis of such a model.[197]

Recently unexpectedly large x-ray fluxes have been detected from the Seyfert galaxies NGC 1275.[160,161] NGC 4151[161] and the quasar 3C 273[161] which are also powerful sources of infrared emission. As we have already noted above, observations of the radio galaxy Cen A and the variability of M 87 at x-ray wavelengths indicate that the x-ray emission originates in the compact nuclear regions of these galaxies. The fact that we expect the nucleus of NGC 1275 and the quasar 3C 273 to be x-ray sources has already been discussed. It appears that the synchrotron spectrum of the radio source associated with NGC 1275 could lie on the extrapolation of the x-ray spectrum[198] and Shklovskiĭ noted that it might be thermal emission from hot plasma close to the nucleus. He also noted at that time the possibility of converting radio quanta into x-ray quanta by scattering by relativistic electrons.[198] At the same time the existence of the powerful infrared peak in the spectrum of the radiation from the nucleus and relativistic electrons in the observed compact radio source must inevitably lead to x-ray emission by inverse Compton scattering. Simple calculations show that in the cases of NGC 1275 and 3C 273 the x-ray radiation of the electrons inferred to be present from the radio emission from the compact source and radiating in the field of the infrared radiation is of the order of that observed.* The solution of the problem of the mechanism of generation of the x-ray emission can only be resolved by detailed spectral observations of individual sources. Preliminary data on the spectrum of the radiation suggest $1 < \alpha < 2$. Much further research is needed.

5. The Isotropy of the X-ray Background

The most convincing evidence for the extragalactic origin of the x-ray background is the high degree of its isotropy. Measurements from the satellite OSO-III[165] have set an upper limit to large scale fluctuations in the background in the range $10 < \mathcal{E} < 100$ keV of $\Delta J_X/J_X \leq 5\%$ on angular scales $\theta \sim 10°$ and $\Delta J_X/J_X \leq 3\%$ on scales $\theta \sim 20°$. In the latter case the solid angle subtended by the detector on the celestial sphere is $\Omega = 0.1$ sr. These data decisively rule out the hypothesis that the hard x-ray background originates in the halo of our galaxy and suggest that the contribution of the halo to the background cannot exceed a few percent.

The observed upper limits to the large scale fluctuations enable lower limits to be set to the number of extragalactic x-ray sources in the universe—i.e., $\Delta J_X/J_X \approx \Delta N/N \approx (\Delta\Omega)^{-1/2}$ assuming a random distribution of sources of the same observed brightness on the celestial sphere or $\Delta J_X/J_X \approx \Delta N/N \approx (N\Omega)^{-1/3}$ assuming them to be randomly distributed in space. The first assumption corresponds to the picture of strong cosmological evolution in which the maximum number of sources occurs at some redshift z_{max} and the second to that in which sources within a Hubble radius ($R < cH_0^{-1}$) are randomly distributed in space. In the latter case the measurements[165] set a lower limit $4\pi N > 3 \times 10^6$ to the number of sources on the celestial scale. This limit is about 10 times smaller than the observed number of clusters of galaxies[199] and much less than the number of Seyfert galaxies. At the same time this limit sets interesting restrictions on the existence of super clusters of galaxies assuming, of course, that x-ray sources tend to be concentrated in them. It is clear that if sources are concentrated in clusters and superclusters much larger fluctuations in the background are expected.

Thus the observations[165] do not contradict the majority of models for the origin of the x-ray background. There is the further possibility that observations of fluctuations of the background can be used to distinguish between different models. These models give different predictions for the dependence of the amplitude of the fluctuations upon the energy of the quanta. If the x-ray background originates due to inverse Compton scattering of low energy radiation by relativistic electrons in discrete objects then there should be no such dependence. In models in which electrons escape into intergalactic space the amplitude of the fluctuations should increase with increasing energy of the quanta because the high energy electrons do not have time to diffuse far from

---

*The spectrum of the radio emission from the compact source will be distorted because of induced compton interactions between the radiation and thermal electrons, [23] and so the radio spectrum may differ from the x-ray spectrum and have $\alpha \approx 0$.

their sources. In the case of non-thermal bremsstrahlung radiation in intergalactic space the opposite picture is found—particles with low energies are most easily thermalized—and fluctuations are expected to decrease with increasing energy.

In the model in which the principal sources of relativistic electrons are the nuclei of infrared objects fluctuations in the background at hard x-ray energies do not depend on frequency but the soft x-rays which originate in intergalactic space must be almost absent because the lifetimes of the electrons radiating in this region are comparable with cosmological time scales and greatly exceed the travel time of electrons over the mean distance between sources. At the same time other models of the origin of the soft x-ray background (e.g., supernovae and their remnants, thermal emission of hot gas in clusters of galaxies and discrete sources, and also the intergalactic medium because of possible fluctuations in the density of matter) predict significant fluctuations in the background. Indeed observations of fluctuations in the soft x-ray region are very difficult because of the presence of irregularities in the interstellar gas which lead to nonuniform absorption of the x-ray background.

Measurements of the isotropy of the background also give information about the large scale properties of the universe, any anisotropy in its expansion, its rotation, etc. The existing upper limit to the 12- and 24-hour period of the anisotropy is $\Delta J_X/J_X \leq 3\%$. These limits [165] in the range $10 < \mathcal{E} < 30$ keV have been determined from a survey of roughly half the celestial sphere which, of course, differs from the isotropy measurements of the microwave background radiation which are made in a single plane. The x-ray radiation is much more sensitive to large scale anisotropies in the universe (and of course for other sources of angular variations of intensity) because of the power law character of its spectrum, i.e., it has positive spectral index.[200] The existing limits are three times weaker than those of the microwave background radiation so that, for example, the upper limit to the velocity of the earth with respect to the x-ray background is 800 km-s^{-1} in comparison with $\sim$250 km-s^{-1}, see Sec. 1. In practice, it is very difficult to improve the observations in the centimeter region whereas observations at x-ray wavelengths are just beginning to be made.

VI. γ-RAY WAVELENGTHS ($\nu > 10^{20}$ Hz; $\mathcal{E} > 0.5$ MeV)

Just as at x-ray wavelengths, γ-ray emission is produced by the inverse Compton scattering of low frequency radiation by relativistic electrons

$$e + h\nu \rightarrow e' + \gamma$$

and by the bremsstrahlung radiation of non-thermal particles interacting with thermal gas

$$e^- + p \rightarrow e^- + p + \gamma.$$

However, there are now new processes. Among these are the production of π mesons in proton collisions and in the annihilation of antimatter followed by the decay of neutral pions

$$p + p \rightarrow p + p + N\pi,$$
$$p + \bar{p} \rightarrow N\pi,$$
$$\pi^0 \rightarrow 2\gamma,$$

The excitation of nuclei by non-thermal particles can also result in γ-ray quanta

$$p + Z \rightarrow p + z^*,$$
$$Z^* \rightarrow Z + \gamma,$$

and the annihilation of positrons

$$e^- + e^+ \rightarrow 2\gamma$$

and so on. Since the cross sections and probabilities of all these processes are well known, theoretical estimates of the expected fluxes of γ rays from discrete sources and the plane of our Galaxy can be made as well as the intensity of the background. Even the first detailed observations have given interesting and unexpected results.

1. OBSERVATIONS

The discovery of powerful of γ-ray emission from the plane of our galaxy was as unexpected for the observers as it was for the theoreticians. The telescopes on board the orbiting solar observatory (OSO-III) discovered an extended line source lying in the plane of the galaxy in the direction of the galactic center, the flux of quanta having energies greater than 100 MeV being $F \sim 5 \times 10^{-4}$ cm^{-2} rad^{-1} s^{-1}.[131] This flux was 25 times greater than that expected from a knowledge of the density of cosmic rays in the galaxy which was assumed to be constant and equal to that observed at the surface of the earth. The results of the calculations, of course, were strongly dependent upon the model taken for the distribution of the galactic magnetic field, the density of cosmic rays and of interstellar gas but they could not account for this discrepancy. The intensity of the background according to these observations was also several times greater than that expected from extrapolation from the x-ray region. These observations resulted in much theoretical speculation. Among these was the possibility that the excess was related to the intense background radiation observed in the sub-millimeter region which has already been described in Sec. 1. In this hypothesis it is supposed that the γ rays were the result of inverse Compton scattering of the millimeter background radiation by galactic relativistic electrons. However, more recent balloon experiments have not only verified the existence of a flux of γ rays from the disc of the galaxy but also have shown that the intensity of the background was overestimated by a factor of 4 (this was connected with uncertainties in the calibration of the telescopes on board OSO III[132,204]. They also showed that the mechanism of production of the γ rays in the plane of the galaxy is most likely to be the decay of π_0 mesons which are produced in p-p collisions.[204] This follows from a comparison of the fluxes having energies $\mathcal{E} \sim 50$ MeV and those having $\mathcal{E} \gtrsim 100$ MeV which indicate that the spectrum of the radiation must be practically flat, in contradiction to the production spectrum of most other possible mechanisms of γ-ray production. The corrected value of the flux $F \approx 10^4$ cm^{-2} rad^{-1} s^{-1} can be explained on the basis of reasonable models of the distribution of cosmic rays and interstellar gas.[205]

The value of the intensity of the γ-ray background[131] was also revised. Garmire[132] on re-investigating the old data from OSO III gives only an upper limit to the background for $\mathscr{E} \geq 100$ MeV which is shown in Figs. 9 and 12. The background γ emission has also been studied from the satellite "Cosmos 208"[144] and their overall data are in good agreement with an extrapolation from the hard x-ray region 40 keV $< \mathscr{E} <$ 500 keV using a spectral index $\alpha = 1.2$ (often the spectra are given in numbers of photons per unit bandwidth for which the spectral index is $\alpha + 1 = 2.2$).

The soft γ-ray region has also not been without surprises. Observations from the satellite ERS-18 in a very distant orbit from the earth have discovered an excess background intensity in the range $1 < \mathscr{E} < 6$ MeV. The intensity of the background is significantly greater than the value expected by extrapolation from the hard x-ray region.[143] Investigations of the soft γ-ray background have also been made in the range $0.3 < \mathscr{E} < 3.7$ MeV by the low-flying satellites "Cosmos 135" and "Cosmos 163".[206] In these experiments only upper limits have been found to the intensity of the background but these upper limits in the range 1 to 3.7 MeV are about an order of magnitude smaller than the data of Vette's group[143] but do not contradict the values expected by extrapolation from the x-ray region.

The bulk of the γ rays observed near the Earth and detected by the "Cosmos" satellites[206] are generated in the atmosphere due to the interaction of primary cosmic rays and their intensity depends upon geomagnetic coordinates and the rigidity of the geomagnetic cutoff. To separate the isotropic component from the observed emission of γ rays it is necessary to know exactly the above dependences which are not very well known. Using additional evidence on the form of these relations it is possible to make an extrapolation of the experimental data to infinite threshold rigidity and to obtain a value for the intensity of the γ-ray background. In fact only an upper limit is found.[206]

In interplanetary space the flux of γ-ray radiation evidently gives only a limit to the γ-ray background. The authors of [206] believe that a possible cause of the discrepancy between the results of the measurements of the background radiation close to the earth and beyond the magnetosphere is connected with differences in the levels of activity in the material of the detector for primary cosmic rays, the density of which is much greater in interplanetary space than within the magnetosphere. We note that measurements of soft γ-ray background in the atmosphere made from balloons[121 121a] seem to be in agreement with the results of Vette's group.[143] The situation in this interesting spectral range is not yet clear. If the results of Vette's group are confirmed, they are evidence for the existence of some other mechanism besides inverse Compton scattering which is no less important in determining the spectrum of the γ-ray background.

Discrete sources were not discovered in these experiments nor in any of the earlier experiments. Kniffen and Fichtel[204] found no evidence for the source of γ rays having energies greater than 100 MeV which was discovered by Frye et al.[207] There exist only upper limits to the fluxes of γ rays from a number of extragalactic objects some of the most interesting of which are given in Table III.[218]

Antimatter in the universe. It is often supposed that the universe is symmetrical with respect to baryon number. It is clear that the existence of intermixed matter and antimatter is most easily detected by its γ-ray emission. Despite special investigations, the γ-ray line at 0.511 MeV due to positron annihilation has not yet been discovered. Of course it will be broadened by the effects of cosmological redshift.

The universe is optically thin for annihilation γ rays having energy $\mathscr{E} \sim 100$ MeV out to a redshift $z \approx 100$ (see below). This fact and the observed background make many hypotheses about the existence of matter and antimatter in the universe unattractive because the total energy density in γ-rays is negligible in comparison with that contained in matter, $w_\gamma / w_{\text{matter}} \sim (10^{-8}/\Omega)(1 + z_{\text{ann}})$. Here z_{ann} is the redshift at which the annihilation takes place and Ω is the density parameter of the intergalactic gas. It follows that in the case $\Omega = 1$ throughout the period $0 < z < 100$ during which the mean density of matter in the universe changes by 6 orders of magnitude only one-millionth part of the matter could have annihilated. If the annihilation took place earlier it would lead to distortions of the spectrum of the microwave background radiation.[47]

2. Theoretical Models of the Origin of the γ-ray Background

a) The inverse Compton mechanism. In our interpretation (see also [89]) the spectrum of the γ-ray background must be the continuation of the hard x-ray spectrum and results from inverse Compton scattering (of low frequency radiation) by relativistic electrons—the microwave background radiation in intergalactic space or infrared quanta in discrete sources. Such an extrapolation is not particularly remarkable. In our Galaxy the spectrum of relativistic electrons detected at the earth is a power law up to about 100 GeV. Therefore, if the break in the x-ray spectrum at 40 keV corresponds to electrons of energy 3 GeV (supposing them to scatter photons of the microwave background) or having energy 700 MeV (if they scatter infrared quanta—see above) then the γ rays having energy 100 MeV correspond to electrons having energy $E'_e = (\mathscr{E}'/\mathscr{E})^{1/2} E_e$ corresponding to 150 GeV in the first case and 30 GeV in the second.

We note that the model of Brecher and Morrison[21] to explain the γ-ray background runs into difficulties because of the dispersion in the spectral indices of normal galaxies which implies that the slope of the background will become less steep with increasing energy and the predicted intensity of γ-rays in the range 50 to 100 MeV would considerably exceed the experimental upper limits.

The excess background radiation at 1 to 6 MeV cannot be explained in such a model but can be interpreted as some additional source of radiation superimposed upon a single power law spectrum.

b) p-p collisions. The decay of neutral π mesons originating in collisions between cosmic ray protons and intergalactic protons leads to the characteristic broad γ-ray spectrum with a maximum close to $\mathscr{E} = 70/(1 + z)$ MeV.[180,201,208,209] If the injection of cosmic rays into intergalactic space and the decay of π^0 mesons takes place at small redshifts then to explain the intensity of the γ-ray background in the range 50 to 100 MeV the intergalactic density of cosmic rays must be only 5 to 10 times smaller than that observed in the galaxy if $\Omega_{\text{iyg}} \sim 1$. If the density of intergalactic gas is less than the critical value much higher densities of intergalactic cosmic rays are needed.

Taking account of the integrated effect of p-p collisions in normal galaxies does not change this picture much. Silk's calculations[2] using figures similar to the observed radiation from the plane of our Galaxy have shown that normal galaxies could not contribute more than 10% of the present upper limits to the intensity of the background at 100 MeV.

To explain the excess radiation in the range 1 to 6 MeV Stecker[210] proposed that cosmic rays are injected into intergalactic space at a redshift $z \sim 70$. In this case the maximum γ-ray emission from the decay of π^0 mesons is observed at about 1 MeV. This model encounters the following difficulties:

1) The predicted intensity of the background in the range 30 to 100 MeV is much greater than that observed (see Fig. 12).

2) The spectrum of the radiation will be strongly distorted because of interactions with the intergalactic gas (see below in Sec. 3).

3) Such an early injection of protons requires 100 times greater energy input per gram of matter than at the present day because the energy of each quantum decreases due the effect of redshift whereas the rest mass energy of matter does not change.

4) The observed evolution of quasars and powerful radio galaxies is restricted to small redshifts ($z < 2$–4). At earlier epochs the growth in the number density cannot have continued or the number of quasars having redshifts greater than 2 would be much greater than that observed. It is also likely that such objecys would make a significant contribution to the radio, optical and ultraviolet background radiation. It is still not impossible, however, that discrete objects existed at redshifts ~ 100 but we recall that at the present time there is only one object known with redshift greater than 2.5, the quasar 4C 0534 having a redshift 2.877.

c) The origin of the soft γ-ray background. Clayton and Silk[211] have proposed that the excess background radiation in the soft γ-ray region is the result of β and subsequent γ-ray activity of the nuclei Ni^{56} and Co^{56}, these elements being synthesized in large quantities in supernova explosions. This model predicts a cut-off in the spectrum at 3.26 MeV which has not been observed.[143]

The soft γ-ray emission discovered by Vette's group can be ascribed to the integrated emission of discrete γ-ray sources.[212] There are a number of reasons for this hypothesis. Firstly, heating by induced Compton scattering of low frequency radiation heats all the electrons close to powerful sources of infrared and radio emission to relativistic temperatures.[213] It is possible that other sources of heating such as shock waves, varying magnetic fields, etc. can also lead to relativistic temperatures. Secondly, calculations of the equilibrium concentration of positrons in a stationary, optically thick, relativistic plasma have shown that for temperatures (or in the absence of a Maxwellian distribution, if the mean energy of electrons) $\mathscr{E} \geq 20$ MeV, catastrophic formation of pairs takes place[214] and energy losses by bremsstrahlung and synchrotron radiation are greatly enhance. The density of electron-positron pairs is then determined by the rate of energy injection from the source and the temperature stabilizes at 20 MeV.

This conclusion can be readily understood. The concentration of positrons under stationary conditions is determined by the equilibrium between two processes—pair formation—

$$e^- + p,\ e^-,\ e^+ \rightarrow e^- + p,\ e^-,\ e^+ + e^- + e^+$$

and pair annihilation

$$e^+ + e^- \rightarrow 2\gamma.$$

The cross section of the first of these processes for energies greater than threshold is practically independent of energy but the second falls rapidly, $\sigma \propto E_e^{-2}$. At an energy $E_e \approx 20$ MeV the cross section for the first process is greater than that for the second, the concentration of positrons becomes similar to that of electrons and these in turn become further sources of pairs due to interactions with protons, etc. In this way, the number of pairs rapidly increases. In this argument, the supposition of a Maxwellian electron distribution is not important—it is only important that the mean energy is high.

The existence of a relativistic plasma within and surrounding quasars, the nuclei of galaxies and other sources of low frequency radiation means that they must be sources of γ rays with a characteristic spectrum. In astrophysics, high energy radiation often has a nonthermal spectrum which is normally explained by the inverse Compton scattering of low energy radiation or by the synchrotron emission of relativistic electrons having a power law spectrum and the "thermal" electrons in the object play a negligible role. In the present case, all the electrons in the object are heated to relativistic temperatures and have a Maxwellian distribution radiating thermal γ rays with a spectrum $J_\nu = \text{const} \times e^{-h\nu/kT_e}$. The existence of an upper limit to the temperature $kT_e = 20$ MeV for the stationary relativistic plasma determines the conditions in the object and the spectrum of the γ-ray emission which must cut off exponentially at energies greater than 20 MeV (by stationary we mean that the time during which the region exists exceeds the time for positron formation and the density must be sufficiently high that bremsstrahlung losses are greater than Compton losses). Because of their high energy, annihilation of positrons and electrons does not lead to radiation in the γ-ray line at 0.511 MeV because the rate of formation of positrons is 137 times less than the probability of bremsstrahlung emission.

Quasars and powerful radio galaxies exhibit strong cosmological evolution and it is therefore expected that the most important contribution to the background will come from sources having redshifts $z \sim 2$. In this case the exponential cutoff is expected about 6 MeV. We note that the total energy density of the background in the range 1 to 6 MeV is only $w_\gamma \sim 3 \times 10^{-5}$ eV-cm^{-3} which is 3 or 4 orders of magnitude less than the energy density of the background radiation in the infrared region. It follows that even if only a small fraction of the total luminosity of infrared sources goes into heating electrons to relativistic temperatures, it is possible to explain the excess soft γ-ray background.

3. The Interaction of the X- and γ-ray Backgrounds with the Intergalactic Gas

The observed spectrum of the x- and γ-ray background gives information not only about the properties of the sources but also about the epoch of their maximum activity, i.e., the epoch of formation of the hard background radiation. This arises because Compton scattering of hard radiation by electrons of the intergalactic gas (or pre-galactic gas) with temperature $kT_e \ll h\nu$ is accompanied by a decrease in the energy of the quanta ($\Delta\nu/\nu \sim h\nu/m_ec^2$ if $h\nu/m_ec^2 \ll 1$) and by distortions of the spectrum of the background radiation.[214,187] In the case $h\nu/m_ec^2 \ll 1$ the spectrum of the background will be significantly distorted if the optical depth for Compton scattering exceeds $\tau_T \sim m_ec^2/h\nu$ and, under the condition, $h\nu_0(1 + z_{max})/m_ec^2 \ll 1$, if

$$\int\limits_0^{z_{\max}} \frac{h\nu_0(1+z)}{m_ec^2}\,d\tau_T(z) = \frac{h\nu_0}{m_ec^2}\,\Omega n_c\sigma_T cH_0^{-1}\int\limits_0^{z_{\max}} \frac{(1+z)^2}{\sqrt{1+\Omega z}}\,dz \gtrsim 1;$$

Here z_{max} corresponds to the epoch of maximum activity of the sources of the x-ray emission. An analytic solution for the distortions of the x-ray spectrum of discrete sources and the background is given in [215].

This effect is most important for energies $h\nu \sim m_ec^2$ because for $h\nu/m_ec^2 \gtrsim 1$ the Compton scattering cross-section decreases according to the Klein-Nishina formula. For quanta having energies $\mathscr{E} \gtrsim 50$ MeV the principal loss mechanism is photo-pair production involving electrons and protons of the intergalactic gas. The cross section for this process has only a weak dependence on the energy of the photons. For quanta with energy greater than $10^6(1 + z)^{-2}$ GeV electron-positron pair formation due to interaction with photons of the microwave background leads to a cutoff in the spectrum of γ-rays at very high energies.[216,217]

In Fig. 13 we show the dependence of the maximum range of redshifts accessible to observations in the x- and γ-ray region in terms of the energy of the quanta observed at the present day. This dependence is shown for two extreme values of the density of the intergalactic gas, $\Omega = 1$ and $\Omega = 0.01$ and these curves show that it is likely that the observed background x-ray emission originates at redshifts less than 30. If the background originated at earlier epochs, the spectrum would no longer be of power law form. If $\Omega = 1$, the background probably arises from redshifts less than 10.[214a] This can be seen from the fact that the universe has optical depth greater than 1 for Compton scattering to a redshift $z \approx 10$ if $\Omega = 1$ and that a photon observed with $\mathscr{E} = 40$ keV at $z = 0$ would have energy $\mathscr{E} \sim m_ec^2$ at a redshift of 10 so that significant spectral distortions would take place in a single scattering.

Only in the soft x-ray region and in the hard γ-ray region can redshifts of the order 100 play an important role in forming the background spectrum. For energies less than 10 keV, Thomson scattering makes it impossible to observe sources at redshifts greater than 10 and only for $\mathscr{E} > 100$ keV are discrete sources observable out to redshifts $z \sim 60$–100. This is because the Compton scattering cross-section decreases with increasing energy of the quanta. The universe is thus optically thin to γ-ray quanta to a redshift $z \sim 100$ which indicates the importance of γ-ray astronomy as a tool for studying the evolution of the universe.

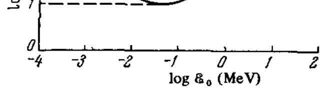

FIG. 13. Maximum red shift accessible to observation vs. the present-day quantum energy $\mathscr{E}_0$. The solid curve corresponds to the background radiation, and the dashed one to the discrete source.

---

[1] Ya. B. Zel'dovich and I. D. Novikov, Relyativistskaya astrofizika (Relativistic Astrophysics), Nauka, 1967.

[2] J. Silk, Space Sci. Rev. **11**, 671 (1970).

[3] A. J. Turtle, J. F. Pugh, S. Kenderdine, and I. I. K. Pauliny-Toth, Mont. Not. RAS **124**, 297 (1962).

[4] J. E. Baldwin, in: Collected Papers of IAU Symposium No. 31 on Radioastronomy and the Galaxy, Academic Press, 1967.

[5] G. G. Getmantsev, E. D. Pyatova, Yu. V. Tokarev, and V. A. Shibaev, Radiofizika **14**, 1480 (1970).

[6] P. J. S. Williams, R. A. Collins, J. L. Caswell, and D. J. Holden, Mon. Not. RAS **139**, 289 (1968).

[7] A. H. Bridle, Mon. Not. RAS **136**, 219 (1967).

[8] C. A. Shain, Radioastronomy, Paris Symposium 1958 (Russ. transl.) IL, 1961, p. 322.

[9] G. Reber, J. Franklin Institute **285**, 1 (1968).

[10] J. K. Alexander, L. W. Brown, T. A. Clark, R. G. Stone, and R. R. Weber, Ap. J. **157**, L163 (1969).

[11] A. H. Bridle, Nature **219**, 1136 (1968).

[12] T. A. Clark, L. W. Brown, and J. K. Alexander, Nature **226**, 847 (1970).

[13] G. G. Pooly and M. Ryle, Mon. Not. RAS **139**, 515 (1968).

[14] G. G. Pooly, Mon. Not RAS **144**, 101 (1969).

[15] M. Ryle, Ann. Rev. Astron. Aph. **6**, 249 (1968).

[16] M. S. Longair, Usp. Fiz. Nauk **99**, 229 (1969) [Sov. Phys.-Usp. **12**, 673 (1970)].

[17] M. Schmidt, Ap. J. **162**, 371 (1970).

[18] R. A. Sunyaev, Astron. and Aph. **12**, 190 (1971).

[19] A. G. Doroshkevich, M. S. Longair, and Ya. B. Zeldovich, Mon. Not. RAS **156**, 139 (1970).

[20] G. B. Sholomitskiĭ, Astron. zh. **45**, 478 (1968) [Sov. Astron.-AJ **12**, 381 (1968)].

[21] K. Brecher and P. Morrison, Phys. Rev. Lett. **23**, 802 (1969).

[22] P. D. Noerdlinger, Ap. J. **157**, 495 (1969).

[23] R. A. Syunyaev, Astron. zh. **48**, 244 (1971) [Sov. Astron-AJ **15**, 190 (1971)].

[24] T. Howell and J. R. Shakeshaft, Nature **216**, 753 (1967).

[25] S. A. Pelyushenko and K. S. Stankevich, Astron. zh. **46**, 283 (1969) [Sov. Astron.-AJ **13**, 223 (1969)].

[26] R. A. Syunyaev, Dokl. Akad. Nauk SSSR **179**, 45 (1968) [Sov. Phys.-Dokl. **13**, 183 (1968)].

[27] Ya. B. Zel'dovich and P. A. Syunyaev, Astrophys. Sp. Sci. **4**, 302 (1969).

[28] A. A. Penzias and R. W. Wilson, Ap. J. **142**, 419 (1965).

[29] A. G. Doroshkevich and I. D. Novikov, Dokl. Akad. Nauk SSSR **154**, 809 (1964) [Sov. Phys.-Dokl. **9**, 111 (1964)].

[30] P. E. Boynton, R. A. Stokes, and D. T. Wilkinson, Phys. Rev. Lett. **21**, 462 (1968).

[31] A. G. Kislyakov, V. I. Chernyshev, Yu. V. Lebskiĭ, V. A. Mal'tsev, and N. V. Sedov, Astron. zh. **48**, 39 (1971) [Sov. Astron.-AJ **15**, 29 (1971)].

[32] P. Thaddeus and J. E. Clauser, Phys. Rev. Lett. **16**, 819 (1966).

[33] G. B. Field and J. E. Hitchcock, Phys. Rev. Lett. **16**, 817 (1966).

[34] I. S. Shklovskii, Astron. tsirk. No. 364 (1966).

[35] V. J. Bortolot, J. F. Clauser, and P. Thaddeus, Phys. Rev. Lett. **22**, 307 (1969).

[36] P. Palmer, B. Zuckerman, D. Buhl, and L. E. Snyder, Ap. J. **156**, L147 (1969).

[37] K. Shivanandan, J. R. Houck, and M. O. Harwit, Phys. Rev. Lett. **21**, 1460 (1968).

[38] J. R. Houck and M. O. Harwit, Ap. J. **157**, L45 (1969).

[39] D. P. McNutt and P. D. Feldman, Science **167**, 1277 (1970).

[40] J. R. Harwit and M. O. Houck, Science **164**, 1271 (1969).

[41] D. Muehlner and R. Weiss, Phys. Rev. Lett. **24**, 742 (1970).

[42] A. E. Salomonovich, Usp. Fiz. Nauk **99**, 417 (1969) [Sov. Phys.-Usp. **12**, 731 (1970)].

[43] A. G. Kislyakov, ibid. **101**, 607 (1970) [**13**, 495 (1971)].

[44] V. Petrosian, J. N. Bahcall, and E. E. Salpeter, Ap. J. **155**, L57 (1969).

[45] R. V. Wagoner, Nature **224**, 481 (1969).

[46] Ya. B. Zel'dovich, Usp. Fiz. Nauk **89**, 647 (1966) [Sov. Phys.-Usp. **9**, 602 (1967)].

[47] R. A. Sunyaev and Ya. B. Zeldovich, Ap. Sp. Sci. **7**, 20 (1970).

[48] R. A. Sunyaev and Ya. B. Zeldovich, Comments Ap. Sp. Ph. **2**, 66 (1970).

[49] D. T. Wilkinson and R. B. Partridge, Nature **215**, 719 (1967).

[50] E. K. Conclin and R. N. Bracewell, Nature **216**, 777 (1967).

[51] Yu. N. Pariiskiĭ and T. B. Pyatunina, Astron. zh. **47**, 1337 (1970) [Sov. Astron.-AJ **14**, 1067 (1971)].

[52] A. M. Wolfe and G. R. Burbidge, Ap. J. **156**, 345 (1969).

[53] Yu. N. Pariiskiĭ, Astron. zh. **45**, 279 (1968) [Sov. Astron.-AJ **12**, 219 (1968)].

[54] C. Hazard and E. E. Salpeter, Ap. J. **157**, L87 (1969).

[55] S. A. Penzias, J. Schraml, and R. W. Wilson, Ap. J. **157**, L49 (1969).

[56] M. S. Longair and R. A. Sunyaev, Nature **223**, 719 (1969).

[57] J. M. Stewart and D. W. Sciama, Nature **216**, 748 (1967).

[58] R. N. Bracewell and E. K. Conclin, Nature **219**, 1343 (1968).

[59] E. C. Conclin, Nature **222**, 971 (1969).

[60] Ya. B. Zel'dovich, V. G. Kurt, and R. A. Syunyaev, Zh. Eksp. Teor. Fiz. **55**, 278 (1968) [Sov. Phys.-JETP **28**, 146 (1969)].

[61] P. J. E. Peebles, Ap. J. **153**, 1 (1968).

[62] J. Silk, Nature **216**, 453 (1968).

[63] R. A. Sunyaev and Ya. B. Zeldovich, Aph. Sp. Sci. **7**, 3 (1970).

[64] R. K. Sachs and A. M. Wolfe, Ap. J. **147**, 73 (1967).

[65] G. Dacourt, Mon. Not. RAS **144**, 255 (1969).

[66] K. S. Stankevich, Australian J. Phys. (1971).

[67] P. A. Feldman, M. J. Rees, and M. W. Werner, Nature **224**, 752 (1969).

[68] G. Burbidge and W. A. Stein, Ap. J. **160**, 573 (1970).

[69] E. E. Becklin and G. Neugebauer, Ap. J. **151**, 145 (1968).

[70] W. F. Hoffmann and C. L. Frederick, Ap. J. **155**, L9 (1969).

[71] H. H. Aumann and F. J. Low, Ap. J. **159**, L159 (1970).

[72] D. E. Kleinmann and F. J. Low, Ap. J. **159**, L165 (1970).

[73] M. J. Rees, J. Silk, M. W. Werner, and N. C. Wickramasinge, Nature **223**, 788 (1969).

[74] A. G. Pacholzyk, Ap. J. **161**, L207 (1970).

[75] F. J. Low, Ap. J. **159**, L173 (1970).

[76] G. S. Bisnovatyĭ-Kogan and R. A. Syunyaev, Astron. zh. **48**, (1971) [Sov. Astron.-AJ **15**, (1972)]; Ap. Lett. **7**, 237 (1971).

[77] I. S. Shklovskiĭ, Astron zh. **47**, 742 (1970) [Sov. Astron.-AJ **14**, 594 (1971)].

[78] L. M. Ozernoi and V. Sazonov, Ap. Lett. (1971)

[79] S. Colgate, Ap. J. **150**, 163 (1967).

[80] F. J. Low and W. H. Tucker, Phys. Rev. Lett. **21**, 1538 (1968).

[81] R. B. Partridge and P. J. E. Peebles, Ap. J. **148**, 377 (1967).

[82] P. J. E. Peebles, Comments Ap. Sp. Ph. **3**, 20 (1971).

[83] M. Harwit, D. P. McNutt, K. Shivanandan, and B. J. Zajac, Astron. J. **71**, 1026 (1966).

[84] R. Wagoner, Paper at Texas Symposium on Relativistic Astrophysics, 1970.

[85] D. P. McNutt and P. D. Feldman, J. Geophys. Res. **74**, 4791 (1970).

[86] F. E. Roach and L. L. Smith, Geophys. J. **15**, 227 (1968).

[87] C. F. Lillie, Bull. Amer. Astron. Soc. **1**, 132 (1969).

[88] G. C. Sudbury and M. F. Ingham, Nature **226**, 526 (1970).

[89] S. Hayakawa, K. Yamashito, and S. Yoshioka, Ap. Sp. Sci. **5**, 493 (1969).

[90] V. G. Kurt and R. A. Syunyaev, ZhETF Pis. Red. **5**, 299 (1967) [JETP Lett. **5**, 246 (1967)].

[91] V. G. Kurt and R. A. Syunyaev, Kosm. issledovaniya **5**, 573 (1967).

[92] V. G. Kurt and R. A. Syunyaev, IAU Symposium No. 36, Ultraviolet Stellar Spectra, Rediel, Dordrecht, 1970.

[93] J. R. Houck and M. O. Harwit, Science **167**, 1277 (1970).

[94] F. Zwicky, Ap. J. **140**, 1626 (1964).

[95] P. J. Peebles and R. B. Partridge, Ap. J. **148**, 713 (1967).

[96] M. Schmidt, Ap. J. **161**, 393 (1968).

[97] V. G. Kurt and R. A. Syunyaev, Astron zh. **44**, 1157 (1967) [Sov. Astron.-AJ **11**, 928 (1968)].

[98] V. L. Belyaev, V. G. Kurt, A. S. Melioranskiĭ, A. S. Smirnova, L. S. Sorokina, and V. M. Tiĭt, Kosm. issledovaniya **8**, 740 (1970) [sic!].

[99] Ch. Barth, op. cit. in [92].

[100] N. A. Dimov, A. B. Severnyĭ, and A. Zvereva, op. cit. in [92].

[101] A. S. Smirnov, Kosm. issledovaniya **8**, 740 (1970) [sic!].

[102] A. D. Code, Publ. Astron. Soc. Pacific **81**, 475 (1969).

[103] R. C. Bless, op. cit. in [92].

[104] J. E. Gunn and B. A. Peterson, Ap. J. 142, 1633 (1965).

[105] G. Burbidge and M. Burbidge, Quasistellar Objects, Freeman, 1968.

[106] J. Arons and R. McCray, Ap. Lett. 5, 123 (1970).

[107] V. Petrosian, Ap. Lett. 6, 71 (1970).

[108] V. G. Kurt and R. A. Syunyaev, ZhETF Pis. Red. 7, 215 (1968) [JETP Lett. 7, 164 (1968).

[109] R. A. Sunyaev, Ap. Lett. 3, 33 (1969).

[110] R. A. Syunyaev, Astron zh. 46, 929 (1969) [Sov. Astron.-AJ 13, 729 (1970)].

[111] Ya. B. Zel'dovich and R. A. Syunyaev, Zh. Eksp. Teor. Fiz. 56, 2078 (1969) [Sov. Phys.-JETP 29, 1118 (1969)].

[112] E. Argyle, Ap. J. 141, 750 (1965).

[113] T. Lozinskaya and N. S. Kardashev, Astron zh. 40, 209 (1963) [Sov. Astron.-AJ 7, 161 (1963)].

[114] F. J. Kerr, Ann. Rev. Astron. Aph. 7, 39 (1969).

[115] S. B. Pikelner, Ann. Rev. Astron. Aph. 6, 165 (1968).

[116] M. Roberts, Ap. J. 151, 117 (1968).

[117] J. V. Hindman, F. J. Kerr, and R. X. McGee, Australian J. Phys. 16, 570 (1963).

[118] J. E. Felten and J. Bergeron, Ap. Lett. 4, 155 (1969).

[119] J. Silk and M. Werner, Ap. J. 158, 185 (1969).

[120] S. B. Pikel'ner, Astron zh. 44, 1915 (1967) [Sov. Astron.-AJ 11, 737 (1968)].

[121] G. B. Field, IAU Symposium No. 39, Interstellar Gasdynamics, Reidel, Dordrecht, 1970.

[122] R. D. Davies and S. T. Gottesman, Mon. Not. RAS 149, 237 (1970).

[123] V. L. Ginzburg and S. I. Syrovatskiĭ, Proiskhozdenie kosmicheskikh luchei (Origin of Cosmic Rays), AN SSSR, 1963 [Pergamon, 1964].

[124] A. J. Baxter, B. G. Wilson, and D. W. Green, Canad. J. Phys. 47, 2651 (1969).

[125] J. A. M. Bleeker and A. J. M. Deerenburg, Ap. J. 159, 215 (1970).

[126] E. A. Boldt, U. D. Desai, and S. S. Holt, Ap. J. 156, 427 (1969).

[127] E. A. Boldt, U. D. Desai, S. S. Holt, and P. Serlemitsos, Nature 224, 677 (1969).

[128] C. S. Bowyer, G. B. Field, and J. Mack, Nature 217, 32 (1968).

[129] A. N. Bunner, P. C. Coleman, W. L. Kraushaar, D. McCammon, T. M. Palmieri, A. Shilepsky, and T. M. Ulmer, Nature 223, 1222 (1969).

[130] E. L. Shupp, D. J. Forrest, A. A. Sarkady, P. J. Lavakare, Preprint, 1970.

[131] G. W. Clark, G. P. Garmire, and W. L. Kraushaar, Ap. J. 153, L203 (1968).

[132] G. P. Garmire, Bull. Am. Phys. Soc. 15, 564 (1970).

[133] G. Ducros, R. Ducros, R. Rocchia, and A. Tarrius, Preprint, 1969.

[134] P. Gorenstein, E. M. Kellog, and H. Gursky, Ap. J. 156, 315 (1969).

[135] S. Hayakawa, T. Kato, F. Makino, H. Ogawa, Y. Tanaka, K. Yamashito, M. Matsuoka, M. Oda, Y. Ogawara, and S. Miyamoto, IAU Symposium No. 37, Nonsolar X-ray and γ-ray Astronomy), Reidel, Dordrecht, 1970, p. 121.

[136] R. C. Henry, G. Frtiz, J. F. Meekins, H. Friedman, and E. T. Byram, Ap. J. 153, L11 (1968).

[137] D. A. Schwartz, H. S. Hudson, and L. E. Peterson, Ap. J. 162, 431 (1970).

[138] A. E. Metzger, E. C. Anderson, M. A. Van Dilla, and J. R. Arnold, Nature 204, 766 (1964).

[139] R. Rocchia, R. Rothenflug, D. Bociet, G. Ducros, and J. Labeyrie, Space Research, v. 7, North-Holland, Amsterdam, 1966, p. 1328.

[140] R. Rothenflug, R. Rocchia, D. Boclet, and P. Durouchoux, Space Research, v. 8, North-Holland, Amsterdam, 1968, p. 423.

[141] A. Toor, F. D. Seward, L. R. Cathey, and W. E. Kunkel, Ap. J. 160, 209 (1970).

[142] P. Vanden Bout and D. Yentis, Bull. Am. Phys. Soc. 15, 614 (1970).

[143] J. Vette, J. L. Matteson, D. Gruber, and L. E. Peterson, Ap. J. 160, L61 (1970).

[144] L. S. Bratolyubova-Tsulukidze, N. L. Grigorov, L. F. Kalinkin, A. S. Melioranskii, E. A. Pryakhin, I. A. Savenko, and V. N. Yufarkin, Paper at 13th COSPAR Assembly, Leningrad, 1970.

[145] S. L. Mandel'shtam and I. P. Tindo, ZhETF Pis. Red. 6, 796 (1967) [JETP Lett. 6, 251 (1967)].

[146] L. A. Vaĭnshtein, V. G. Kurt, S. L. Mandel'shtam, A. L. Presnyakov, S. I. Syrovatskiĭ, V. A. Syunyaev, and I. P. Tindo, Kosm. issledovaniya 6, 242 (1968).

[147] J. I. Trombka, Nature 226, 887 (1970).

[148] R. C. Henry, G. Fritz, J. E. Meekins, T. Chubb, and H. Friedman, Ap. J. 163, L73 (1971).

[149] O. F. Prilutskiĭ, I. L. Rozental', and I. B. Shukalov, Astron. zh. 47, 832 (1970) [Sov. Astron.-AJ 14, 669 (1971)].

[150] C. S. Bowyer and G. B. Field, Nature 223, 573 (1969).

[151] I. S. Shklovsky and E. K. Scheffer, Nature 231, 173 (1971).

[152] S. Shulman, G. Fritz, J. Meekins, T. A. Chubb, H. Friedman, and R. C. Henry, Ap. J. 166, L9 (1971).

[152a] E. A. Boldt, U. D. Desai, S. S. Holt, and P. J. Serlemitsos, Ap. J. 167, L1 (1971).

[153] M. Lampton, D. W. Green, and G. S. Bowyer, Nature 230, 448 (1971).

[154] J. Silk and G. Steigman, Phys. Rev. Lett. 23, 597 (1969).

[155] H. Mark, R. E. Price, R. Rodrigues, F. D. Seward, and C. D. Swift, Ap. J. 155, L143 (1969).

[156] C. S. Bowyer, M. Lampton, J. Mack, and F. de Mendonca, Ap. J. 161, L2 (1970).

[157] H. Friedman, Paper at 13th COSPAR Assembly, Leningrad, 1970.

[158] H. Friedman and E. T. Byram, Science 158, 257 (1967).

[159] H. Bradt, W. Hayer, S. Naranan, S. Rappoport, and G. Spaga, Ap. J. 150, L192 (1967).

[160] G. Fritz, A. Davidsen, J. Meekins, and H. Friedman, Ap. J. 164, L81 (1971).

[161] H. Gursky, E. Kellogg, C. Leong, H. Tananbaum, and R. Giacconi, Ap. J. 165, L43 (1971); E. Kellogg, H. Gursky, C. Leong, E. Schreier, H. Tananbaum, and R. Giacconi, Ap. J. 165, L49 (1971).

[162] E. T. Byram, T. A. Chubb, and H. Friedman, Nature 229, 544 (1971).

[163] R. Giacconi, P. Gorenstein, H. Gursky, and J. R. Waters, Ap. J. 148, L119 (1967).

[164] M. M. Anisimov, N. L. Grigorov, N. V. Ilarionova, L. F. Kalinkin, A. S. Melioranskii, I. A. Savenko, and R. M. Tul'skiĭ, Proc. 11th Internat. Conf. on Cosmic Rays, Budapest, 1969, vol. 1, p. 309.

[165] D. A. Schwartz, Ap. J. **162**, 439 (1970).

[166] H. Friedman, E. T. Byram, and T. A. Chubb, Science **158**, 257 (1967).

[167] I. S. Shklovsky, Ap. Lett. **3**, 1 (1969).

[168] V. L. Ginzburg and L. M. Ozernoĭ, Astron zh. **42**, 943 (1965) [Sov. Astron.-AJ **9**, 726 (1966)].

[169] R. Weymann, Ap. J. **147**, 887 (1967).

[170] J. E. Bergeron, Astron. Aph. **4**, 335 (1970).

[171] A. G. Doroshkevich and R. A. Syunyaev, Astron zh. (1971) [Sov. Astron.-AJ], in press.

[172] L. A. Vaĭnshtein and R. A. Syunyaev, Kosm. issledovaniya **6**, 635 (1968).

[173] G. B. Field and R. C. Henry, Ap. J. **140**, 1002 (1964).

[174] M. J. Rees, D. W. Sciama, and G. Setti, Nature **217**, 326 (1968).

[175] J. Silk and R. McCray, Ap. Lett. **3**, 59 (1969).

[176] S. Hayakawa, Prog. Theor. Phys. **41**, 1592 (1969).

[177] R. Brown, Ap. J. **159**, L187 (1970).

[178] G. Setti and M. Rees, op. cit. in [135].

[179] O. F. Prilutskiĭ and I. L. Rozental', Astron zh. **48**, 489 (1971) [Sov. Astron.-AJ **15**, 385 (1971)].

[180] V. L. Ginzburg and S. I. Syrovatskiĭ, Usp. Fiz. Nauk **84**, 201 (1964) [Sov. Phys.-Usp. **7**, 696 (1965)].

[181] J. E. Felten and P. Morrison, Ap. J. **146**, 686 (1966).

[182] N. S. Kardashev, Astron zh. **39**, 393 (1962) [Sov. Astron.-AJ **6**, 317 (1962)].

[183] M. S. Longair, Mont. Not. RAS **150**, 155 (1970).

[184] V. L. Ginzburg, High Energy Astrophysics, v. 11 (DeWitt, Schatzman, Ceron. Eds), 1969, p. 291.

[185] V. L. Ginzburg, Ap. Sp. Sci. **1**, 125 (1968).

[186] R. Bergamini, P. Londrillo, and G. Setti, Nuovo Cimento **52B**, 495 (1967).

[187] M. Rees, Ap. Lett. **4**, 113 (1969).

[188] M. S. Longair and R. A. Syunaev, a) ZhETF Pis. Red. 10, 56 (1969) [JETP Lett. **10**, 38 (1969)]; b) Ap. Lett. **4**, 65 (1969); A. S. Webster and M. S. Longair, Mon. Not. RAS **151**, 261 (1971).

[189] K. Brecher and P. Morrison, Ap. J. **150**, L61 (1967).

[190] I. L. Rosental and I. Shukalov, Canad. J. Phys. **46**, 5620 (1968).

[191] J. E. Felten and M. Rees, Nature **221**, 924 (1969).

[192] Yu. N. Gnedin and A. Z. Dolginov, ZhETF Pis. Red. **12**, 383 (1970) [JETP Lett. **12**, 271 (1970)].

[193] P. W. Horton, R. G. Conway, and E. J. Daintree, Mon. Not. RAS **143**, 245 (1969).

[194] K. R. Lang and Y. Terzian, Ap. Lett. **3**, 29 (1969).

[195] I. L. Rozental' and I. B. Shukalov, ZhETF Pis. Red. **9**, 312 (1969) [JETP Lett. **9**, 183 (1969)].

[196] V. N. Kuril'chik, Astron. zh. **47**, 787 (1970) [Sov. Astron.-AJ 14, 000 (1970)].

[197] M. S. Longair and R. A. Sunyaev, Ap. Lett. **4**, 195 (1969).

[198] I. S. Shklovskiĭ, Astron. zh. **42**, 893 (1965) [Sov. Astron.-AJ **9**, 683 (1965)].

[199] C. W. Allen, Astrophys. Quantities, Athlone, Press, London, 1963.

[200] A. M. Wolfe, Ap. J. **159**, 161 (1970).

[201] G. P. Garmire and W. L. Kraushaar, Space Sci. Rev. **4**, 123 (1965).

[202] G. G. Fazio, Ann. Rev. Astron. Aph. **5**, 481 (1967).

[203] C. E. Fichtel, D. A. Kniffen, and H. B. Ogelman, Ap. J. **158**, 193 (1969).

[204] D. A. Kniffen and C. E. Fichtel, Ap. J. **161**, L157 (1970).

[205] T. P. Stecher and F. W. Stecker, Nature **226**, 1234 (1970).

[206] B. P. Konstantinov, S. V. Golenetskiĭ, E. P. Mazets, V. N. Il'inskiĭ, R. A. Aptekar', M. M. Bredov, Yu. A. Gur'yan, and V. N. Panov, Kosm. issledovaniya **6**, 927 (1970); S. V. Kolenetskiĭ, E. P. Mazets, V. N. Il'inskiĭ, R. L. Aptekar', M. M. Bredov, Yu. A. Gur'yan, and V. N. Panov, FTI Preprint No. 350, 1971.

[207] G. M. Frye, J. A. Staib, A. P. Zych, V. D. Hopper, W. R. Rawlinson, and J. A. Thomas, Nature **223**, 1320 (1969).

[208] R. J. Gould and G. R. Burbidge, Ann. d'Ap. **26**, 171 (1965).

[209] I. L. Rozental' and O. F. Prilutskiĭ, Astron zh. **46**, 481 (1969).[Sov. Astron -AJ **13**, 381 (1969)].

[210] F. W. Stecker, Nature **224**, 870 (1969).

[211] D. Clayton and J. Silk, Ap. J. **156**, L43 (1969).

[212] R. A. Syunyaev, ZhETF Pis. Red. **12**, 381 (1970) [JETP Lett. **12**, 262 (1970).

[213] E. V. Levich and R. A. Syunyaev, Radiofizika **13**, 1874 (1970); Ap. Lett. **7**, 69 (1970).

[214] J. Arons and R. McCray, Ap. J. **156**, L91 (1969).

[214a] J. Arons, Ap. J. **164**, 457 (1971).

[215] A. F. Illarionov and R. A. Syunyaev, IPM Preprint 1971. Astron. zh. [Sov. Astron.-AJ], in press.

[216] G. Fazio and F. Stecker, Nature **226**, 135 (1970).

[217] V. S. Berezinskiĭ. Yad. Fiz. **11**, 399 (1970) [Sov. J. Nuc. Phys. **11**, 222 (1970)].

[218] L. S. Bratolyubova-Tsulukidze, L. F. Kalinkin, A. S. Melioranskii, O. F. Prilutskiĭ, E. A. Pryakhin, I. A. Savenko, and V. Ya. Yufarkin, ZhETF Pis. Red. **13**, 566 (1971) [JETP Lett. **13**, 404 (1971)].

[219] M. S. Longair, "Observational Cosmology"—review article for Rep. Prog. Phys., 1972 (in press).

[220] M. F. Millea, M. McCall, R. J. Pederson, and F. L. Vernon, Phys. Rev. Letters **26**, 919 (1971).

[221] A. G. Blair, J. G. Beery, F. Edeskuty, R. D. Hiebert, J. P. Shipley, and K. D. Williamson, Jr., Phys. Rev. Letters **27**, 1154 (1971).

[222] S. P. Boughn, D. M. Fram, and R. B. Partridge, Astrophys. J. **165**, 439–444 (1971).

Translated by J. G. Adashko