LEAKAGE ELECTRONS FROM NORMAL GALAXIES: THE DIFFUSE COSMIC X-RAY SOURCE*

K. Brecher† and P. Morrison
Department of Physics and Center for Space Research,
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 11 July 1969)

Diffuse cosmic x rays arise from Compton collisions between galactic leakage electrons and the 2.7°K thermal background photons in extragalactic space. Assuming that the break seen in the electron spectra within normal galaxies is intrinsic to the cosmic-ray sources, we obtain detailed agreement with the observed x-ray spectral shape and intensity using only parameters obtained from radio observations. This serves to verify most of the properties of the microwave blackbody radiation.

To calculate the x-ray emission of intergalactic space, we must know both the low-energy-photon scattering "medium" and the high-energy cosmic-ray electron flux present there. We shall assume that the universe is described in the large by an expanding, homogeneous and isotropic, relativistic cosmological model in which there is at present a primordial blackbody radiation with $T \approx 2.7°\mathrm{K}$.[1] Such microwave radiation represents by far the largest pool of photons throughout intergalactic space, so that to first approximation we may neglect all other scattering radiation. The main uncertainty facing us is the density of relativistic electrons residing in the large volume of space outside the regions of galactic magnetic fields, within which only are they detectable by radio means. If cosmic-ray electrons are of galactic origin, we may estimate the extragalactic cosmic-ray electron density from a knowledge of the electron flux seen within galaxies, once we know the rate of leakage of galactic electrons out of the magnetic trapping regions.

The flux of cosmic-ray electrons observed directly at Earth has a power-law spectrum $I(E_e) \propto E_e^{-2.6}$, for 3 GeV $\lesssim E_e \lesssim$ 300 GeV. Below 3 GeV the spectrum appears to flatten, with $I(E_e) \propto E_e^{-1.6}$ down[2] to about 0.3 GeV. We may roughly represent the spectrum by two simple power-law segments joining at the break point in electron energy, E_{eb}. These electrons are observed indirectly in our galaxy and in other galaxies by the synchrotron rf radiation they produce in magnetic fields. Radio observations of our galaxy[3] and of other normal galaxies[4] indicate that the majority of normal galaxies have similarly bent radio spectra. From the theory of synchrotron radiation we know that if $I(E_e) \propto E_e^{-m}$, then $I(\nu_s) \propto \nu_s^{-\alpha}$, where $2\alpha + 1 = m$. Therefore an increase in the radio index α by $\frac{1}{2}$ represents a steepening in the electron spectrum by 1 power.

Lang and Terzian[4] find a steepening to occur between 500 and 1500 MHz in most of the normal galaxies they observed. Taking the magnetic field strength in normal galaxies to be about 4 μG (the value derived in various ways, including equipartition, for many normal galaxies[5,6]), we find 2 GeV $\lesssim E_{eb} \lesssim$ 5 GeV. Compton scattering of electrons with energy $E_e = \gamma m_e c^2$ on the photons of a blackbody distribution of radiation at temperature T gives x rays of energy E_x, where $E_x \approx (3.1 \times 10^{-4}\ \mathrm{eV/°K})\gamma^2 T$. Taking $E_{eb} = 3.5$ GeV, and $T = 2.7°\mathrm{K}$, we find $E_x(E_{eb}) \equiv E_\mathrm{B} \approx 40$ keV.

If electrons were injected into normal galaxies with a power-law spectrum $I(E_e) \propto E_e^{-1.6}$, and the steepening observed or inferred at E_{eb} were due to radiative losses in the starlight flux and the magnetic fields within the galactic disk, there would follow the familiar result that the mean trapping time for galactic electrons is $(1-2) \times 10^8$ yr.[5] But with the slow leakage rate which that interpretation implies, one cannot account for the diffuse x-ray observations.

We shall here take the opposite point of view, and assume that the observed break at E_{eb} is intrinsic to the electron sources in galaxies (e.g., supernovae, or even the galactic nucleus). But no other break is seen in the distribution of electrons in our own galaxy up to some 300 GeV, and no second break is observed in the radio spectra of this or other normal galaxies. We therefore place an upper limit on the galactic lifetime of the trapped electrons, and conclude that they diffuse out of normal galaxies in a time not longer than a few million years. Since the electron flux inside of galaxies is fixed observationally, we find then a rate of supply of electrons to the extragalactic volume which is two orders of magnitude greater than that derived from the usual long trapping time.

Such a short cosmic-ray trapping time is indicated by several independent observations. In particular, it receives support from (i) studies[5] of spallation of cosmic-ray nuclei with $A \sim 10$-20; (ii) direct (though rough) measurement[7] of the cosmic-ray storage time with Be^{10}; (iii) determination of the local cosmic-ray positron energy spectrum[8]; and (iv) the lack of a radio halo for most normal galaxies.[4]

We calculate anew the isotropic x-ray spectral intensity, making use of the measured distributions of radio sources in power P (W Hz^{-1} sr^{-1}), in spectral indices above and below the break $\overline{\alpha}_1$ and $\overline{\alpha}_2$, and in cosmic time (or redshift z).

The radio luminosity function for all extragalactic radio sources (normal galaxies, strong radio galaxies, and quasars) has been constructed by several authors[9] and been found to be of the form $n(P)dP = aP^{-\eta}dP$, where P is the radio power at 178 MHz for an individual source, and $n(P)dP$ is the source number density in Mpc^{-3}. Estimates of the index η vary from 2.15 to 2.35. We use Sholomitskii's value $\eta = 2.18$ (for which $a = 1.3\times10^{23}$). Since the 178-MHz radio power of bright normal galaxies is in the range $P \sim 10^{20.5-22}$, and that for strong radio galaxies and quasars is in the range 10^{25-29}, we find that the normal galaxies contribute more than 90% of the total radio luminosity of the universe. Normal galaxies will be the dominant source of fast electrons as well, provided only that the characteristic escape time of electrons from radio galaxies is not an order of magnitude less than a million years. {In fact, if one extrapolates $n(P)$ down to the reported density of weak normal galaxies[10] [$\int n(P)dP \approx 0.45$ Mpc^{-3}], strong radio sources are even less important.}

Radio astronomical observations of the spectra of both the normal and the radio galaxies show a fairly wide dispersion in their radio spectral indices, which fit approximately a Gaussian distribution in α. In addition Lang and Terzian[4] have found a wide spread for the slope change in the spectra of normal galaxies, with $\langle\Delta\alpha\rangle \simeq 0.8 \pm 0.4$, which they consider to be consistent with a general change in radio index of $\frac{1}{2}$. We therefore take the distribution of indices of normal galaxies to be $n(\alpha) = (2\pi\mu^2)^{-1/2}\exp\{-(\alpha-\overline{\alpha})^2/2\mu\}$, where $\overline{\alpha}_1 = 0.8$ above the break, $\overline{\alpha}_2 = 0.3$ below the break, and the dispersion in indices is $\mu = 0.3$.

X-ray background spectrum. – The Compton-scattered x-ray spectrum produced in intergalactic space is calculated by integrating the electron-photon collisions over cosmic time and over the distribution of cosmic-ray electron source power and spectral index. The time integration has been previously carried out.[11] Integrating again over the electron spectral index m we find $I(E_x)$ (without absorption) to be[6,12]

$$I(E_x)dE_x = cH_0^{-1}J_0(E_x/E_B)^{-\beta}\exp\{\tfrac{1}{2}[\mu\ln(E_x/E_B)]^2\}Q(z_{max})dE_x \tag{1}$$

with

$$Q(z_{max}) = \int_0^{z_{max}} \frac{(1+z)^{p-1}dz}{[1+2(q_0+1)z+(q_0+1+3\sigma_0)z^2+2\sigma_0 z^3]^{1/2}},$$

$$\beta = \tfrac{1}{2}(\overline{m}_1+2) = \overline{\alpha}_1+\tfrac{3}{2} = 1.8, \quad \tfrac{1}{4}\text{ keV} \lesssim E_x \lesssim E_B \text{ keV};$$

$$\beta = \tfrac{1}{2}(\overline{m}_2+2) = \overline{\alpha}_2+\tfrac{3}{2} = 2.3, \quad E_B\text{ keV} \lesssim E_x \lesssim 10^4\text{ keV},$$

where E_x is in keV, $I(E_x)$ is in photons (cm^2 sec sr keV)$^{-1}$, J_0 is the local extragalactic volume x-ray emissivity in photons (cm^3 sec sr keV)$^{-1}$, $Q(z_{max})$ is a cosmological-model-dependent function of the density and deceleration parameters σ_0 and q_0, and H_0 is the Hubble constant $\approx 2.5\times10^{-18}$ sec^{-1}. Here a factor $(1+z)^p$ has been introduced to allow crudely for the possibility of a density evolution of normal galaxies with respect to the comoving coordinates. In particular, for the simplest choice which fits the observations, an open Friedman universe, $\sigma_0 = q_0 = 0$, and assuming no density evolution, $p = 0$, one finds $Q(z_{max} = 2) = \frac{2}{3}$. Unless there is a very rapid galaxy evolution in the past, $Q(z_{max})$ will remain of order 1 for all other Robertson-Walker cosmological models.

J_0 is found by integrating (1) over E_x and setting the result equal to the time-integrated cosmic-ray electron leakage power from normal galaxies. This procedure is accurate for the entire cosmic-ray electron energy range for which the microwave background mediates the conversion of fast electrons into x rays. We estimate the electron energy for normal galaxies by assuming rough equipartition between the energy densities of magnetic fields and cosmic rays, and setting the electron energy density equal to 10^{-2} that of all cosmic rays, as in our galaxy. Using an electron leakage time of 1×10^6 yr, and the known number density of galaxies, we arrive at a local cosmic-ray electron source power density of approximately 3×10^{-22} eV/cm^3 sec. We then find that $J_0 \approx 2\times10^{-30}$ (cm^3 sec sr keV)$^{-1}$. In Fig. 1 we have plotted our final calculated x-

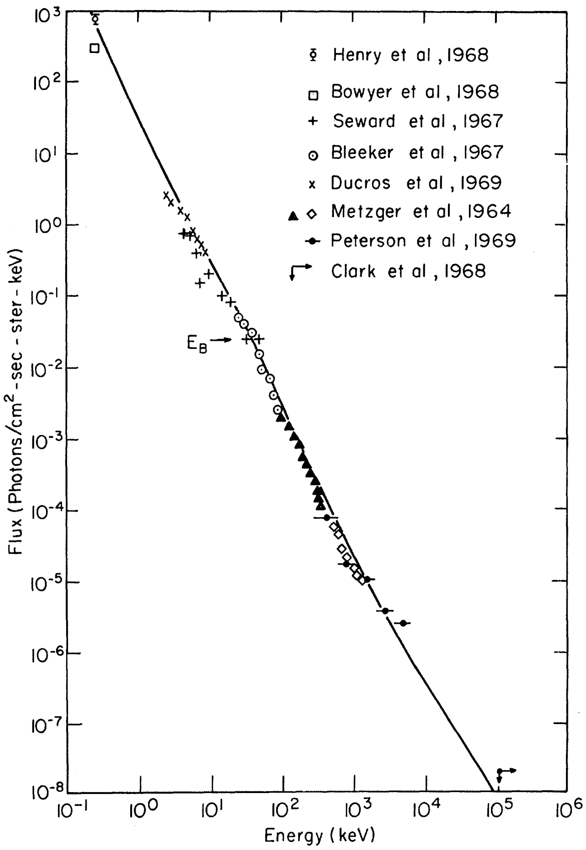

FIG. 1. Representative measurements of the diffuse x rays from 1/4 keV to 10^5 keV [R. C. Henry et al., Astrophys. J. 153, L11 (1968); C. S. Bowyer, G. B. Field, and J. E. Mack, Nature 217, 32 (1968); F. Seward et al., Astrophys. J. 150, 845 (1967); J. A. M. Bleeker et al., Can. J. Phys. Suppl. 46, S461 (1968); G. Ducros, R. Ducros, R. Rocchia, and A. Tarrius, to be published; A. E. Metzger et al., Nature 204, 766 (1964); L. E. Peterson, in Proceedings of the International Astronomical Union Symposium on Non-Solar X- and Gamma-Ray Astronomy, Rome, Italy (to be published), No. 37, and private communication; G. W. Clark, G. P. Garmire, and W. L. Kraushaar, Astrophys. J. 153, L203 (1968)]. The point at 10^5 keV represents an integral upper limit, and was plotted for $I(E_x \gtrsim 10^5 \text{ keV}) \propto E_x^{-2.3}$. The solid curve is the theoretical spectrum, plotted with the values $E_B = 40$ keV, $\mu = 0.3$, $\bar{\alpha}_1 = 0.8$, and $J_0 = 2\times 10^{-30}$ (cm^3 sec sr keV)$^{-1}$. (Since the volume emissivity J_0 can be determined only within a factor of about three, the particular curve plotted has been adjusted to that extent to the observed flux at 40 keV.)

ray spectrum (1), fully determined by the parameters E_B, J_0, μ, and β, which are all four inferred directly from radio observations of other normal galaxies. (Our own galaxy—if we assume no halo—is a rather weak radio source, $\sim\frac{1}{10}$ the mean.[5])

Above 10-50 MeV, however, there are two reasons why the x-ray spectrum should no longer be of the form (1). First, we note that no normal radio sources are observed to have spectral indices flatter than $\alpha \approx 0.3$. Taking the logarithmic derivative of (1) we find that the slope $s = -\beta + \mu^2 \times \ln(E_x/E_B)$ reaches 1.8 (equivalent to a galactic radio index of 0.3) at $E_x \approx 10^4$ keV, corresponding to an electron energy of about 50 GeV. The x-ray spectrum would therefore continue with a slope of −1.8, if it were not for the fact that at $E_e \approx 2 \times 10^2$ GeV the electron radiation losses to optical photons and magnetic fields during the short residence time inside the galaxy becomes important, depressing the electron spectrum above this energy even before leaving the galaxy. Then for $E_x \gtrsim 10^8$ eV, $I(E_x) \propto E_x^{-2.3}$. For $E_x \lesssim 10^2$ eV, we expect another turnover in the Compton x-ray spectrum, because electrons corresponding to this x-ray energy would suffer severe attenuation by ionization before leaving the galaxy.[5]

Implications.—The price of this excellent fit is a large cosmic-ray electron and proton source strength in normal galaxies (unless there is an unlikely preferential trapping of cosmic-ray protons). The energetics of normal galaxies are placed in context by Table I.[13]

In the present picture, the cosmic-ray electrons injected into intergalactic space rapidly lose most of their energy to produce the observed x-ray background. Protons, on the other hand, are not subject to rapid radiation losses, and would constitute an intergalactic cosmic-ray density of some $\frac{1}{2}$-1×10^{-2} eV/cm^3 at present. Such a flux may be indicated by the observed spectral slope increase in the locally observed cosmic-ray proton spectrum above about 10^{15} eV, and flattening beyond 10^{18} eV. Since cosmic-ray protons with large gyroradii ($R \simeq 10$ pc for $E_p \approx 10^{16}$ eV and $H \simeq 1$ μG) diffuse rapidly out of normal galaxies, depressing the galactic spectrum, at energies above 10^{18} eV we expect to see the universal leakage cosmic-ray flux originating in normal galaxies, and filling all space with an intensity 10^{-2} of the stored lower energy component. At still higher energies unusual galaxies may contribute.

The π^0 gamma-ray flux produced by these protons colliding against even the critical gas density required for a closed universe is not inconsistent with observations of high-energy gamma rays. The presence of such a proton flux in intergalactic space would maintain the ionization

Table I. Various forms of energy available in a normal galaxy. For a typical normal galaxy, age $=10^{10}$ yr, mass $=10^{11}M_{\odot}$, radio power $=10^{38}$ erg/sec ($10\times$ that of our galaxy), total relativistic electron energy stored $=3\times 10^{54}$ erg.

Source	Estimated Energy (ergs)
Rest energy	2×10^{65}
Nuclear energy released (starlight, etc.)	10^{63}
Supernova outbursts: maximum total energy release,	
10^{-2} SN/yr, 0.1 to 1.0 $M_{\odot}c^2$ each	10^{61} to 10^{62}
prompt photon energy release	10^{60}
Pulsar energy (10^8/galaxy; lifetime, 10^4 yr)	10^{58} to 10^{60}
Required by present theory:	
Cosmic-ray electrons	3×10^{58}
Cosmic-ray protons	3×10^{60}

of any gas existing between galaxies. Bremsstrahlung x rays from the subsequently heated residual gas electrons can be more important than Compton recoil photons only below about $\frac{1}{2}$ keV.

Further consequences are as follows: (a) Even if there exists a physical halo to our galaxy, it does not trap cosmic rays for more than 10^6 yr. The isotropic background usually attributed to our own radio halo must be of extragalactic origin. In fact, the very distribution of normal galaxies we have used here predicts an isotropic meter-band background in good agreement with present data.[6] (b) The x-ray background spectrum serves as a test of the extragalactic existence of the microwave background radiation. From the position of the x-ray break E_B between 20 and 60 keV, we can set limits on the mean local background temperature (if it is a blackbody distribution) at $2°\mathrm{K} \lesssim T \lesssim 4°\mathrm{K}$. The absence of any electron break between 3 and 3000 GeV implies that the microwave energy density in the disk of the galaxy is less than about 1 eV/cm^3, or $T \lesssim 4°\mathrm{K}$ for $\rho = aT^4$. The low-energy fit to our curve at about $\frac{1}{4}$ keV requires that the present extragalactic microwave-photon energy density be greater than 0.1 eV/cm^3, so that $T \gtrsim 2°\mathrm{K}$. The very presence of a break in the x-ray spectrum implies a cosmological evolution of the microwave photon temperature of $T = T_0(1+z)$, at least out to $z \simeq 1$ to 2. In particular, the existence of an x-ray break seems to be incompatible with the steady-state cosmological model, in which the blackbody radiation temperature T and the normal galaxy electron spectral break E_{eb} are both independent of z.

We thank for their helpful discussions Professor J. Shklovskii, Sternberg Astronomical Institute, and Dr. R. McCray, Harvard College Observatory.

---

*Research supported in part by National Aeronautics and Space Administration Grant No. NGL 22-009-019.

†Present address: Department of Physics, University of California, La Jolla, Calif.

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

[2]J. A. M. Bleeker, J. J. Burger, A. J. M. Deerenberg, A. Scheepmaker, B. N. Swanenburg, and Y. Tanaka, Can. J. Phys. Suppl. 46, S522 (1968).

[3]C. R. Purton, Monthly Notices Roy. Astron. Soc. 133, 463 (1966).

[4]K. R. Lang and Y. Terzian, Astrophys. Letters 3, 29 (1969).

[5]V. L. Ginzburg and S. I. Syrovatskii, Origin of Cosmic Rays (Pergamon Press, Inc., New York, 1964); J. E. Baldwin, in Radio Astronomy and the Galactic System, edited by H. van Woerden (Academic Press, Inc., New York, 1967), p. 353.

[6]K. Brecher, thesis, Massachusetts Institute of Technology, 1969 (unpublished).

[7]M. M. Shapiro and R. Silberberg, Bull. Am. Phys. Soc. 14, 596 (1969).

[8]J. L. Fanselow, R. C. Hartman, R. H. Hildebrand, and P. Meyer, to be published; cf. K. C. Anand, R. R. Daniel, and S. A. Stephens, Phys. Rev. Letters 20, 764 (1968).

[9]G. B. Sholomitsky, Astron. Zh. (USSR) 44, 939 (1967) [translation: Soviet Astron. AJ, 11, 756 (1968); V. Petrosian, Astrophys. J. 155, 1029 (1969).]

[10]T. Kiang, Monthly Notices Roy. Astron. Soc. 122, 263 (1961).

[11]K. Brecher and P. Morrison, Astrophys. J. Letters 150, L61 (1967); J. E. Felten and P. Morrison, Astrophys. J. 146, 686 (1966).

[12]K. Brecher and P. Morrison, to be published.

[13]T. Gold, Nature 221, 27 (1969).

EVIDENCE FOR A $\Lambda\pi^+$ RESONANCE AT 1480 MeV*

Yu-Li Pan and Fred L. Forman†
University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 22 April 1969)

An enhancement in the $\Lambda\pi^+$ mass spectrum has been observed at 1480 MeV in the reaction $\pi^+p \rightarrow K^+\pi^+\Lambda$ at 1.7 GeV/c. In addition, the Λ polarization undergoes a sharp oscillation in the same $\Lambda\pi$ mass region. The best fit values for this resonance are $M = 1480 \pm 15$ MeV and $\Gamma = 35 \pm 20$ MeV.

We have examined the reaction

$$\pi^+p \rightarrow K^+\pi^+\Lambda \tag{1}$$

produced by 1.7-GeV/c π^+ mesons in the Princeton-Pennsylvania Accelerator 15-in. hydrogen bubble chamber. The data presented represent approximately 90% of the sample found in our 1.4×10^6 pictures. Each picture contained, on the average, about seven beam tracks.

The distribution of the mass squared for the $\Lambda\pi^+$ system is shown in Fig. 1. The mass resolution is approximately ±5 MeV. $Y_1^*(1385)$ production dominates the reaction. The analysis of the two-step process $\pi^+p \rightarrow K^+Y_1^*(1385)$, $Y_1^*(1385) \rightarrow \pi^+\Lambda$ will be presented elsewhere. The existence of a $\Lambda\pi$ resonance as reported by Cline, Laumann, and Mapp[1] at 1440 MeV is not needed to explain our data. Upon examination of the Dalitz plot we do not find statistically significant evidence for resonances in the ΛK^+ or $K^+\pi^+$ channels.

We have tried to fit Reaction (1) with a $Y_1^*(1385)$ resonance and nonresonant background (i.e., making the interaction matrix element a constant) assuming a Breit-Wigner form for the resonance.[2] We found that the confidence level of the best fit for this hypothesis is less than 0.5%. The major reason for this unsatisfactory fit is the $\Lambda\pi$ enhancement around 2.19 GeV^2. Cline, Laumann, and Mapp,[1] in addition to the 1440-MeV peak, also observed an enhancement in the $\Lambda\pi$ system in this mass region. However, their peak can be explained by the kinematics of the K^-d interaction and do not require the introduction of another resonance.

We have also fitted Reaction (1) in terms of two $\Lambda\pi$ resonances with the same type of nonresonant background assuming Breit-Wigner forms for both resonances.[2] The best fit found for this hypothesis gives a confidence level of 50% for these data.

If an anomaly in the mass distribution is due to a resonance, one may expect that the angular distributions will show a related anomaly. Such an anomaly is shown, in the present case, by the Λ polarization. We show the $\alpha\overline{P}$ distribution of the Λ as a function of mass$^2(\Lambda\pi^+)$ in Fig. 2. The maximum-likelihood technique was used to

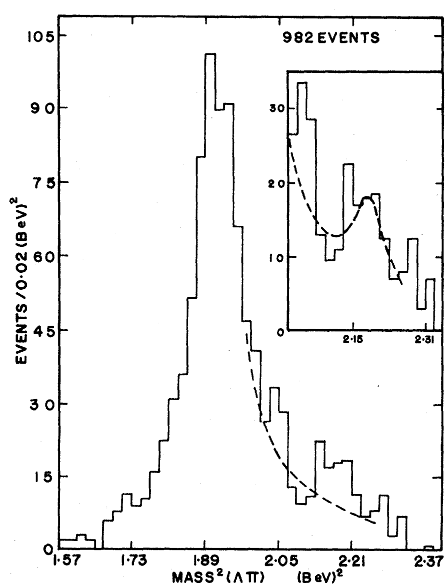

FIG. 1. Distribution of the $\Lambda\pi^+$ mass for all $\pi^+p \rightarrow K^+\pi^+\Lambda$ events. The dashed line represents the best fit obtained for $Y_1^*(1385)$ plus nonresonant background. The insert is an enlargement of the same mass distribution in the 2.17-GeV^2 region. The dashed line in the insert represents the two-resonance fit.