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HIGH ENERGY PHOTONS AND NEUTRINOS FROM COSMIC SOURCES[1]

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I. INTRODUCTION

1. Cosmic rays were first detected more than 50 years ago and after a terrestial origin was disproved they were first taken to be γ-rays. Only when they were found to be deflected in the earth's magnetic field was it realized that they are charged particles. Until a few years ago there was no direct evidence for the presence of hard radiation from the cosmos. In 1957 x-rays were first detected from the sun by the NRL group [1], but only in the last two or three years have x-ray sources which lie outside the solar system been detected and γ-ray observations been attempted.

From the theoretical standpoint it is clear that since a flux of charged particles is known to be present in the cosmos, fluxes of energetic quanta must always be present since there are many mechanisms which give rise to photons as secondary quanta. At present, many of the observations of high energy photons are very preliminary and, in some cases, contradictory. However, it is clear that the interpretation of these observations can provide significant information on a large number of astronomical problems. Of special interest are questions of cosmology, and the early observational data was soon employed as a means of testing cosmological theories. Actually, further interpretation of the data already available may provide additional answers to cosmological questions. The data itself is difficult to come by, because of the necessity of carrying photon detectors above the earth's absorbing atmosphere by means of balloons, rockets, or satellites. In this article we shall not attempt to describe the ingenious techniques developed for carrying out such observations, and shall concentrate on the problem of the interpretation of the results. However, on occasion we shall comment on the question of whether certain experimental results are suspect.[2]

[2] A number of other reviews of x-ray and γ-ray astronomy are also available:

V. L. GINZBURG and S. I. SYROVATSKY: Uspekhi Fiz. Nauk SSSR 84, 201 (1964) translation in Space Science Reviews (to be published) - S. HAYAKAWA and M. MATSUOKA: Prog. Theor. Phys. Suppl. (to be published) - S. HAYAKAWA, H. OKUDA, Y. TANAKA, and Y. YAMAMOTO: Prog. Theor. Phys. Suppl. (to be published). - Discussions of the techniques which are used to detect hard quanta are given by: G. GARMIRE and W. L. KRAUSHAAR: Space Science Reviews (to be published) - R. GIACCONI and H. GURSKY: Space Science Reviews (to be published) - G. G. FAZIO: Ann. Rev. Astronomy and Astrophysics (to be published).

There are essentially three general sources of uncertainty involved in the interpretation of the observations on energetic photons: (1) experimental uncertainties or errors, (2) uncertainties in the calculations of the basic physical processes which produce the photons, and (3) uncertainties in the astronomical parameters employed in calculating the photon flux. Usually this last source of uncertainty is the most serious; for example, the mean gas density, (low energy) stellar photon density, magnetic field, and cosmic ray (proton) intensity in the Galaxy and intergalactic medium are known only approximately and in some cases may be different by several orders of magnitude. Moreover, the photon flux received from sources at great distances depends on the detailed structure of the universe.

The basic physical processes responsible for photon production may be summarized as follows: 1) Bremsstrahlung is emitted in the interaction of charged particles with matter. It results from e-p COULOMB scattering at non-relativistic energies and from both e-p and e-e scatterings at relativistic energies. 2) The COMPTON scattering of a low energy thermal photon by a high energy electron produces a high energy scattered photon, the energy being transferred from the electron. This process was first discussed by FEENBERG and PRIMAKOFF [2]. FERMI pointed out that this was probably the mechanism by which electrons were removed from the primary cosmic ray flux. 3) Electrons moving in magnetic fields emit synchrotron radiation; this is the primary mechanism for radio emission in galaxies. Very high electron energies are required to produce high energy photons by this process; cosmic synchrotron spectra probably extend at most to photon energies in the keV-MeV range. 4) Gamma rays result from the decay of π°-mesons ($\pi^{\circ} \rightarrow 2\gamma$) following the production of mesons in collisions between primary cosmic ray particles and nuclei of the interstellar and intergalactic gas. Cosmic ray nuclear collisions are also a source of high energy electrons via charged pion production and ($\pi \rightarrow \mu \rightarrow e$) decay, as was proposed by BURBIDGE and GINZBURG in the early attempts to understand radio sources. A recent discussion applying to galactic radiation has been given by POLLACK and FAZIO [3] and by GINZBURG and SYROVATSKY [4]. π°-gammas are also produced following meson production in matter - anti-matter annihilation. Some processes which produce line radiation are: 5) Characteristic x-rays are produced following the ejection of an atomic inner shell electron by, for example, a high energy particle or photon flux. The resulting cascade transitions give rise to the emission of K, L, etc.-series x-rays. 6) Gamma rays are produced in the annihilation of electrons and positrons ($e^{+} + e^{-} \rightarrow 2\gamma$). Energetic positrons in the interstellar (but not intergalactic) medium come essentially to rest by various energy loss processes (see Sect. II) before annihilating, and the resulting γ-rays are essentially monoenergetic at about 0.51 MeV. 7) The formation of deuterium via $n + p \rightarrow d + \gamma$ (the inverse of photodisintegration) produces a photon of energy 2.23 MeV. This is the only low energy nuclear reaction we have listed here which gives rise directly to γ-radiation. There are many low energy reactions which give rise to γ-rays either directly or indirectly, but in general they will occur only in stellar interiors so that the γ-rays do not escape. However, there are some indications that nuclear reactions sometimes take place in stellar surfaces, so that these γ-rays may be observable. Both the 0.51 and 2.23 MeV lines were mentioned in an early paper by MORRISON [5] on the subject of gamma ray astronomy. 8) Finally, we mention the more general process called inner bremsstrahlung which really includes some of the processes mentioned above. If an electron is suddenly accelerated from rest to a velocity βc by *any* mechanism, the probability that in the acceleration process an additional *soft* photon of energy within $\hbar d\omega$ is emitted is given by the simple expression

$$dw = \frac{\alpha}{\pi}\left(\frac{1}{\beta}\,\ln\frac{1+\beta}{1-\beta} - 2\right)\frac{d\omega}{\omega}$$

$$\rightarrow \frac{2\alpha}{3\pi}\,\beta^2\,\frac{d\omega}{\omega}, \text{ if } \beta \ll 1, \tag{1.1}$$

where α is the fine structure constant.

Most of the photon-producing processes are treated in Part II of this article where the effects of the high energy electrons produced in cosmic ray nuclear collisions are considered. Part III is devoted to the problem of discrete sources of x-rays and the possibility of observing extragalactic sources of high energy photons . High energy neutrino astronomy is intimately related to high energy photon astronomy, since in the production of a shower of pions from a nuclear collision neutrinos result from the charged pion and muon decays and photons result directly from neutral pion decays. Neutrino sources are discussed in Part IV. As we have already emphasized, the presently available data on both the photon fluxes and astronomical parameters are very rough; for this reason, we feel that in attempting interpretation no elaborate calculations are warranted. We have tried to give as simple a treatment of the physical processes as is possible while still doing justice to the data.

II. PRODUCTION IN THE INTERSTELLAR GAS, THE GALACTIC HALO, AND THE INTERGALACTIC MEDIUM

2. In this section we consider the general background flux of cosmic photons produced in electromagnetic interactions involving non-thermal particles. A source of high energy particles is provided by the ordinary cosmic rays, in particular the cosmic ray protons, whose energy spectrum is known and extends up to $\sim 10^{20}$ ev. The protons themselves are not efficient at producing photons in direct electromagnetic interactions, due to their large mass. However, high energy electrons can result from nuclear collisions of cosmic rays in which a shower of pions is produced; the charged pions then decay into electrons via $\pi \rightarrow \mu \rightarrow e$. The energetic "secondary" electrons which result can produce high energy photons by a number of processes, and these will be considered later in this section. The photon spectrum produced by a specific process is determined (among other things) by the electron spectrum, which in turn is determined by the cosmic ray proton spectrum. We shall assume a universal cosmic ray spectrum, that is, except near local sources of cosmic rays, the cosmic ray flux at any place in the universe is assumed to be the same as that measured at the earth. There is some difference of opinion as to whether the primary cosmic rays are predominantly of galactic or extragalactic origin. For a discussion of two extreme schools of thought on this point the reader is referred to the work of GINZBURG and SYROVATSKY [6] and BURBIDGE and HOYLE [7]. However, to make the calculations described here we have made the assumption that a universal cosmic ray flux with the same energy density inside and outside galaxies is present. We take no position on the validity of this hypothesis in this article, as this has been done simply to facilitate the computations. The results are easily adjusted for other assumptions. GINZBURG and SYROVATSKY have argued against a universal cosmic ray flux and estimate that the intergalactic cosmic ray density

is smaller than the local (galactic) value by a factor $\sim 10^{-3}$. However, their reasoning is based on equipartition arguments and is, in our opinion, not convincing. Of course, it may be that there exists a "primary" cosmic ray electron component, where by primary electrons we mean those which may have been accelerated by the same process and in the same sources that produced the cosmic ray protons. This question is open. Recent experiments by DE SHONG, HILDEBRAND, and MEYER [8] measuring the electron/positron ratio in the local cosmic ray flux are certainly relevant to this problem, but the experiments still do not allow a definite conclusion regarding the primary or secondary origin of these electrons and positrons. We shall consider only the contribution from secondary electrons. It might be remarked that the acceleration of protons without an accompanying acceleration of electrons can be envisaged easily, since the electrons, with their smaller mass, lose energy by electromagnetic processes more readily.

We shall take a universal differential cosmic ray flux given by

$$dJ_p = K_p \gamma_p^{-\Gamma_p} d\gamma_p, \tag{2.1}$$

where dJ_p is the number of incident protons per cm^2 per second having LORENTZ factors γ_p ($= E_p/m_p c^2$) within $d\gamma_p$ (centered at γ_p); here K_p and Γ_p are constants. By appropriate choice of K_p and Γ_p the power law (2.1) can be used to describe the observed flux for any range of γ_p. The choice $\Gamma_p = 2.6$, $K_p = 100$ cm^{-2} sec^{-1} fits the observations [9] over many orders of magnitude of γ_p in the high energy range. At lower energies the actual flux is smaller than that described by this choice of Γ_p, K_p. The extrapolation from high energies is too large by a factor ~ 2 at $\gamma_p \sim 100$ and by a factor ~ 4 at $\gamma_p = 10$. Since we are interested in the effects of the high energy cosmic rays we shall adopt the above values for the parameters Γ_p, K_p in the calculations outlined in this section. Given the astronomical parameters (gas density, magnetic field, etc.), the cosmic photon fluxes from various processes (synchrotron radiation, bremsstrahlung, COMPTON effect, etc.) are essentially determined by the cosmic ray spectrum. However, due to uncertainties in our knowledge of the physics of certain processes, in particular that of meson production in high energy nuclear collisions, the calculated photon fluxes must be considered at best only order of magnitude estimates. Uncertainties in the astronomical parameters further complicate the interpretation of the results. In view of this, a number of simplifying assumptions and approximations are made in the calculation of the physical processes.

After discussing meson production in cosmic ray collisions (part a) the electron production spectrum is derived in (b). Electron energy losses in the galaxy and intergalactic medium are treated in (c) and (d) and the resulting electron spectra are derived in (e). The photon fluxes are calculated in (f) and a discussion and comparison with the observational results follows. Some cosmological considerations of photon production in the intergalactic medium are given in (h).

a) Meson Production in Cosmic Ray Nuclear Collisions

All of the laboratory results on meson production are for incident proton energies less than 10 Bev at which it is possible energetically to produce only a few relatively low energy pions per inelactic collision. Our knowledge of meson production by high energy protons is based primarily on theory, and the theories of meson production are very crude; of course, an accuract theoretical treatment of the problem would be extremely difficult, probably beyond our present knowledge of elementary particle interactions. The simplest theory of meson production in high energy nuclear collisions is that of FERMI[3] and is outlined briefly below. The theory predicts the correct shape for the spectrum of high energy γ-rays resulting from π^o's produced in cosmic ray collisions.

[3] See, for example, R. MARSHAK: Meson Physics (New York: McGraw-Hill Book Co., 1952).

3. FERMI Theory of Meson Production Consider the collision of a proton of (lab) energy $\gamma_p m_p c^2$ incident on a proton at rest. In the center of mass (c.m.) system the total energy of the two protons is $2\bar{\gamma}_p m_p c^2 = [2(\gamma_p + 1)]^{\frac{1}{2}} m_p c^2$, where $\bar{\gamma}_p$ is the LORENTZ factor of the protons in the c.m. system. Each proton carries a cloud of virtual pions; in the proton's rest frame the radius of this cloud is approximately $\Lambda_\pi = \hbar / m_\pi c$, where m_π is the pion mass. The interaction cross section is then $\sigma \sim \pi \Lambda_\pi^2$. In the c.m. system each cloud is contracted in the direction of motion by a factor $\bar{\gamma}_p$, and when the protons collide the maximum common volume of the meson clouds (which, presumably, is when the interaction is strongest) is

$$\Delta V = \frac{4\pi}{3} \Lambda_\pi^3 \frac{1}{\bar{\gamma}_p} . \tag{3.1}$$

For high proton energies it is possible energetically to produce many pions in an inelastic collision and FERMI made the assumption that the interaction in the volume (3.1) was strong enough to produce a distribution of pion energies corresponding to thermal equilibrium with most of the initial proton kinetic energy having been fed into the pion gas. Also, the pions are predominantly highly relativistic and thus have a PLANCKian distribution. The "temperature" for this distribution is easily shown to be $kT \approx \gamma_p^{\frac{1}{4}} m_\pi c^2$, so that in the c.m. system the mean pion energy corresponds to

$$\langle \bar{\gamma}_\pi \rangle \approx \gamma_p^{\frac{1}{4}} , \tag{3.2}$$

and in the lab system (where one of the protons is initially at rest)

$$\langle \gamma_\pi \rangle \approx \bar{\gamma}_p \ \gamma_p^{\frac{1}{4}} \approx \gamma_p^{3/4} . \tag{3.3}$$

FERMI assumed that the distribution arising when the pion clouds of the colliding protons overlap is "frozen in", so that Equation (3.3) would apply to the pions produced in the collision. Equation (3.3) also implies that the multiplicity of pions produced is proportional to (and is, in fact, roughly given by) $\gamma_p^{\frac{1}{4}}$.

A number of attempts have been made to improve the FERMI theory and some authors have taken a quite different approach to the problem. However, these alternative theories usually predict a pion production spectrum not radiacally different from that of the FERMI theory. The assumption of thermal equilibrium in the FERMI theory has been questions by LANDAU[4], who has developed his own

[4] L. LANDAU: Izv. Akad. Nauk, SSSR 17, 51 (1953)

theory of meson production. Another defect in the simple FERMI theory is that the effects of the production of other unstable particles (for example, K-mesons), which eventually decay into pions, has not been taken into account. Nevertheless, for our purposes essentially the only result which need be specified is the relation between multiplicity (and mean pion energy) and γ_p. The detailed shape of the pion energy spectrum produced by an incident proton of given energy need not concern us.

4. Pion Production Spectrum The number of pions produced per second per cm^3 within the energy range $d\gamma_\pi$ in p - p collisions would be computed from

$$q_\pi(\gamma_\pi)\ d\gamma_\pi = \int dJ_p\ n_H\ \sigma\ f(\gamma_\pi;\gamma_p)\ d\gamma_\pi, \tag{4.1}$$

where dJ_p is the differential incident cosmic ray proton flux, n_H the local density of hydrogen nuclei, σ ($\approx \pi\ \Lambda_\pi^2$) the total (excluding the multiplicity factor) cross section for the event, and $f(\gamma_\pi;\gamma_p)$ the distribution function for the pion production spectrum. We approximate the spectrum $f(\gamma_\pi;\gamma_p)$ by a product of the multiplicity ($\approx \gamma_p^{\frac{1}{4}}$) and a δ-function at the mean energy ($\approx \gamma_p^{3/4}$) of the pion spectrum for given γ_p:

$$f(\gamma_\pi;\gamma_p) \approx \gamma_p^{\frac{1}{4}}\ \delta(\gamma_\pi - \gamma_p^{3/4}). \tag{4.2}$$

With a cosmic ray spectrum given by the power law (2.1) we then obtain

$$q_\pi(\gamma_\pi) \approx (4\pi/3)\ \Lambda_\pi^2\ K_p\ n_H\ \gamma_\pi^{-\Gamma_\pi},\ \Gamma_\pi = \frac{4}{3}\ (\Gamma_p - \frac{1}{2}). \tag{4.3}$$

The δ-function approximation (4.2) does not introduce appreciable error. For example, if one computes $q_{\pi}(\gamma_{\pi};\gamma_{p})$, using the WIEN approximation to the PLANCK thermal distribution, one obtains a slowly varying function of γ_{π} times γ_{π} to the power $-\frac{4}{3}(\Gamma_p - \frac{1}{2})$, that is, essentially the same result as Equation (4.3). Moreover, the exponent in the spectrum (4.3) will be the same for the case where the mass of the incident cosmic ray particle is different from that of the "target" nucleus. In such a case the analysis follows analogously, since the LORENTZ factors in the c.m. system are still proportional to $\gamma^{\frac{1}{2}}$ (when γ is large), where γ is the LORENTZ factor of the incident particle in the rest frame of the target particle.

5. An Experimental Test for $q_{\pi}(\gamma_{\pi})$ For nuclear collisions at high energy the number of π^+, π^-, and π^o mesons produced are the same, as is their energy distribution. The π^o decays via $\pi^o \rightarrow 2\gamma$, with the mean (lab) γ-ray energy being roughly $E_{\pi}/2$. Thus, a measurement of the γ-ray spectrum from π^o-mesons produced in primary cosmic ray events would give the pion source spectrum $q_{\pi}(\gamma_{\pi})$. Recently, KIDD [10] has measured the spectrum of high energy γ's from π^o-mesons produced by cosmic rays at the top of the atmosphere. By performing the experiment at high altitudes he was able to observe γ's from π^o's produced predominantly in primary jets. KIDD found for the differential energy spectrum of the γ-ray flux a power law with exponent $\Gamma_o = 2.9^{+0.3}_{-0.2}$. The γ-ray energy range observed by KIDD was 0.7×10^{11} eV $< E_o < 10^{12}$ eV, corresponding to $10^3 < \gamma_{\pi} < 10^4$ and $10^4 < \gamma_p < 2 \times 10^5$. At these proton energies the cosmic ray spectrum is described by the high energy fit with $\Gamma_p = 2.6$. The corresponding Γ_{π} from Equation (4.3) is 2.8 and is consistent with the value (Γ_o) measured by KIDD. We should like to emphasize that KIDD's experiment confirms the results of the FERMI theory, but not the fundamentals of the theory itself.

b) The Electron Production Spectrum

6. In the charged pion decay $(\pi^{\pm} \to \mu^{\pm} + \nu)$ most of the center of mass kinetic energy released to the products μ, ν is carried away by the neutrino whose energy is small compared with $m_\pi c^2$. The resulting lab energy of the muon is then approximately $(m_\mu/m_\pi)\ E_\pi$, where E_π is the lab energy of the pion before decay. The electron resulting from the muon decay $(\mu^{\pm} \to e^{\pm} + 2\nu)$ is highly relativistic and behaves kinematically like the two neutrinos in the decay products. Thus, the mean energy in the spectrum of electron energies is about $\frac{1}{3} m_\mu c^2$ in the rest frame of the μ, and the mean lab energy $\langle E_e \rangle$ of the electron resulting from the $\pi \to \mu \to e$ decay is roughly $\frac{1}{3}\ (m_\mu/m_\pi)\ E_\pi \approx \frac{1}{4}\ E_\pi$; thus, $\langle \gamma_e \rangle \approx \frac{1}{4}(m_\pi/m_e)\ \langle \gamma_\pi \rangle$. Approximating the electron spectrum $f(\gamma_e;\gamma_\pi)$ by a δ-function at this energy we get, for the electron source spectrum,

$$\begin{aligned} q_e(\gamma_e)d\gamma_e &\approx \frac{2}{3} \int q_\pi(\gamma_\pi)\ d\gamma_\pi\ \delta\ \left(\gamma_e - \frac{m_\pi}{4m_e}\ \gamma_\pi\right)\ d\gamma_e \\ &= \frac{8m_e}{3m_\pi}\ q_\pi \left(\frac{4m_e}{m_\pi}\ \gamma_e\right) d\gamma_e ; \end{aligned} \tag{6.1}$$

a factor $\frac{2}{3}$ has been introduced because only charged pions decay into electrons.

We shall consider production and energy losses of electrons with $10^2 \le \gamma_e \le 10^{10}$ corresponding to $1 \le \gamma_\pi \le 10^8$ and to $1 \le \gamma_p \le 10^{11}$.

c) Electron Energy Losses in the Galaxy

Here we consider the various processes tending to decrease the energy of high energy electrons in the galaxy. We calculate the average rate of energy loss in the galaxy which we consider as the region within the galactic halo of radius $R_h \sim 5 \times 10^{22}$ cm. Actually, energy losses involving interactions with the galactic gas occur predominantly near the plane of the galaxy where most of the gas lies and where the gas is predominantly unionized. The volume of this disk of galactic interstellar gas is $\sim 10^{-2}$ of the volume of the galactic halo.

7. Ionization Losses The energy loss due to ionization and excitation of the interstellar gas may be computed from BETHE's formula for the stopping power. For high energy electrons this formula is

$$-\left(\frac{dE_e}{dx}\right)_I = \frac{2\pi ne^4}{m_e c^2} \ln \frac{\gamma_e^3 m_e^2 c^4}{2 I_o^2} \tag{7.1}$$

where I_o is the mean excitation energy of the stopping material (hydrogen), and n is the number density of atoms of the material. The argument of the logarithm in Equation (7.1) is very large and I_o may be set equal to the RYDBERG energy $\frac{1}{2} \alpha^2 m_e c^2$ ($\alpha^{-1} \approx 137$). We then have for the ionization loss in a hydrogen gas of mean density $\langle n \rangle$:

$$-\langle d\gamma_e/dt \rangle_I = 2\pi c r_o^2 \langle n \rangle \ln (2\gamma_e^3/\alpha^4). \tag{7.2}$$

Here r_o ($= e^2/m_e c^2$) is the classical electron radius. The energy loss computed from Equation (7.2) is shown as a function of γ_e in Figure 1 for a mean gas density $\langle n \rangle = 0.03 \text{ cm}^{-3}$. This mean galactic gas density corresponds to a mean density near the plane of the galaxy of 3 cm^{-3}. This value (3 cm^{-3}) is about three times the observed density of atomic hydrogen. The higher value may be more appropriate if there is a high abundance of interstellar modecular hydrogen[5].

[5] R. J. GOULD, T. GOLD, and E. E. SALPETER: Ap. J. 138, 408 (1963); J. DORSCHNER, J. GÜRTLER, and K.-H. SCHMIDT: Astron. Nachr. (to be published)

8. Bremsstrahlung The energy loss rate by bremsstrahlung emission would be computed from

$$-(dE/dt)_B = nc\int \hbar\omega d\sigma_B, \tag{8.1}$$

where n is the density of hydrogen nuclei and $d\sigma_B$ is the differential cross section for the emission of a bremsstrahlung photon of energy within $\hbar d\omega$; in Equation (8.1) the integral is over ω from 0 to $\gamma_e m_e c^2/\hbar$. For $d\sigma_B$ we take the approximate simplified expression [11] $d\sigma_B \approx 4\, \alpha\, r_o^2\, \omega^{-1}\, d\omega \ln 2\gamma_e$ and calculate the mean bremsstrahlung loss rate:

$$- \langle d\gamma_e/dt \rangle_B \approx 4\, c\, \alpha\, r_o^2\, \langle n \rangle\, \gamma_e\, \ell n\, \gamma_e . \qquad (8.2)$$

This is the bremsstrahlung loss rate for interaction of electrons with protons and would be appropriate for calculating the energy loss in regions of ionized hydrogen. Actually, most of the galactic bremsstrahlung is likely to be produced near the galactic plane where the gas is predominantly atomic or molecular, and a correction for the associated shielding effects of the atomic electrons must be made. In fact, for the electron energies of interest the strong shielding expression would be more appropriate. In this case the argument of the logarithm in Equation (8.2) should be replaced by ~ 137 (see HEITLER [12]). Using this corrected expression the bremsstrahlung loss rate was computed for $\langle n \rangle = 0.03\ cm^{-3}$ and is shown in Figure 1.

9. Synchrotron Losses It is well known that a highly relativistic electron of energy E_e in a magnetic field H moves in a circle with a LARMOR radius $r_L = E_e/eH$ and radiates energy by the synchrotron process at a rate

$$-\langle dE_e/dt \rangle_S = \frac{2}{3}\, c\, r_o^2\, \langle H^2 \rangle\, \gamma_e^2 . \qquad (9.1)$$

The frequency spectrum of the radiation consists of a continuum with a maximum around $\nu_L\ \gamma_e^2$, ν_L $(= eH/2\pi m_e c)$ being the LARMOR frequency. The loss rate $-\langle d\gamma_e/dt \rangle_S$ is shown in Figure 1 for a magnetic field $H = 3 \times 10^{-6}$ gauss corresponding to the galactic halo.

10. COMPTON Scattering by Stellar Photons The COMPTON process, whereby a high energy electron makes an elastic collision with a thermal stellar photon, and transfers some of its kinetic energy to the photon, has been considered in some detail by FEENBERG and PRIMAKOFF [2] and by DONAHUE [13]. More recently, FELTEN and MORRISÓN [14] have suggested this process as a mechanism for producing energetic photons. Consider the collision between an electron of energy

$\gamma_e\ m_e c^2$ and a thermal photon of the galactic radiation field of initial energy ϵ_r. Let ϵ_r' denote the photon energy after scattering; let ϵ_r^* denote the initial energy of the photon in the rest frame of the electron; $\epsilon_r^* \approx \gamma_e\ \epsilon_r$. For $\epsilon_r^* \ll m_e c^2$ the cross section for the scattering process is given by the THOMPSON limit:

$$\sigma_I \rightarrow \frac{8\pi}{3}\ r_o^2, \tag{10.1}$$

while the mean energy loss per scattering may easily be shown, by the kinematics of the problem, to be

$$(\bar{\epsilon}_r')_I \approx \gamma_e^2\ \epsilon_r. \tag{10.2}$$

For collisions with very high energy electrons in which $\epsilon_r^* \gg m_e c^2$, the KLEIN-NISHINA formula must be used to compute the scattering cross section. For high energies this formula approaches

$$\sigma_{II} \rightarrow \pi\ r_o^2\ \frac{m_e c^2}{\epsilon_r^*}\ \ln \frac{2\ \epsilon_r^*}{m_e c^2}, \tag{10.3}$$

while the mean energy loss per scattering is now comparable to the initial energy of the electron:

$$(\bar{\epsilon}_r')_{II} \approx \gamma_e\ m_e c^2. \tag{10.4}$$

The electron energy loss is computed from

$$-\langle dE_e/dt \rangle_C = c\ \langle \int \sigma n_r(\epsilon_r)\ \bar{\epsilon}_r'\ d\epsilon_r \rangle, \tag{10.5}$$

where $n_r(\epsilon_r)d\epsilon_r$ is the number density of photons of energy within $d\epsilon_r$ in the radiation field. We shall lump the stellar radiation field into one mean photon energy $\bar{\epsilon}_r$. Then $\int n_r(\epsilon_r)d\epsilon_r \equiv n_r \rightarrow \rho_r/\bar{\epsilon}_r$, where ρ_r is the radiation energy density and n_r the number density of photons. For a thermal (black body) radiation field $\bar{\epsilon}_r$ is approximately $3\ kT_o$, where T_o is the temperature of the thermal distribution. By employing the expressions for σ and $\bar{\epsilon}_r'$ for the low energy region (I) where $\gamma_e \ll m_e c^2/\bar{\epsilon}_r$ and the high energy region (II) where $\gamma_e \gg m_e c^2/\bar{\epsilon}_r$ we get for the energy loss rates:

$$-\langle\frac{d\gamma_e}{dt}\rangle_{CI} = \frac{8\pi}{3}\frac{r_o^2}{m_e c}\langle\rho_r\rangle \gamma_e^2, \qquad (10.6\ I)$$

$$-\langle\frac{d\gamma_e}{dt}\rangle_{CII} = \pi r_o^2 m_e c^3 \frac{\langle\rho_r\rangle}{\bar{\epsilon}_r^2} \ln \frac{2\gamma_e \bar{\epsilon}_r}{m_e c^2}. \qquad (10.6\ II)$$

It is interesting to note that at low energies the energy loss rate is proportional to the radiation energy density $\langle\rho_r\rangle$ while at high energies it is essentially proportional to $\langle n_r\rangle/\bar{\epsilon}_r$. Most of the contribution to the radiation field in the galactic halo comes from the relatively cool stars in the nuclear region of the galaxy. We shall take $\bar{\epsilon}_r = 3$ eV and $\langle\rho_r\rangle = 10^{-13}$ erg/cm^3 as representative values for the radiation field in the halo. The corresponding energy loss rate is shown in Figure 1. The curves for regions I and II were joined smoothly.

11. Leakage Out of the Galactic Halo Even for electron energies as high as $\gamma_e \sim 10^{10}$ the LARMOR radii are only ~ 1 pc, which, presumably is much less than the scale of "magnetic field condensations" in the halo. For this reason the high energy electrons moving in the halo are likely to penetrate only the outer edges of the magnetic field regions, and the paths of the electrons would resemble that of BROWNian motion. The mean free path would correspond to motion between magnetic field condensations and, because of the smallness of the electrons' LARMOR radii, would be independent of energy if the magnetic field between the condensations were very small. The mean leakage time τ_L for escape from the halo would be roughly

$$\tau_L \sim R_h^2/\lambda c, \qquad (11.1)$$

where R_h ($\approx 5 \times 10^{22}$ cm) is the radius of the halo and λ is the mean free path for the BROWNian motion. The appropriate value of λ to be used to calculate τ_L is very uncertain. In the galactic disk the mean distance between gas clouds is ~ 100 pc; λ for the halo is probably larger than this. Taking $\lambda = 1$ kpc we calculate $\tau_L \sim 3 \times 10^{15}$ sec.

In a leakage process the energy of the electron is not lost gradually; instead essentially the total energy of the particle is lost (to the intergalactic medium) instantaneously. The equivalent loss rate is then

$$- \langle d\gamma_e/dt \rangle_L = \gamma_e/\tau_L, \tag{11.2}$$

and this quantity is plotted in Figure 1 for $\tau_L = 3 \times 10^{15}$ sec.

d) Electron Production and Energy Losses in the Intergalactic Medium

12. The calculation of processes in the intergalactic medium is made difficult by our lack of knowledge of the astronomical parameters such as the gas density and magnetic field. Here we shall present results for assumed values of the parameters. The calculated production rates and energy losses are simply related to the parameters and can be easily revised when better astronomical data are available. Actually, it may be that some additional knowledge of these poorly known data may be gained from further interpretation of the high energy cosmic photon experiments.

As mentioned earlier, we assume a universal cosmic ray flux. The pion and electron production rates are then proportional to the intergalactic gas density and this gas is very likely to be predominantly hydrogen. Observationally, the upper limit to the intergalactic density of atomic hydrogen is[6] $\sim 10^{-5}$ cm^{-3}; the amount of ionized hydrogen is unknown. The usually assumed total density of intergalactic hydrogen is $\langle n_H \rangle \sim 10^{-5}$ cm^{-3}; this is the so-called

[6] G. FIELD: Ap. J. 135, 684 (1962); R. D. DAVIES and R. C. JENNISON: M.N. 128, 123 (1964); R.D. DAVIES: M.N. 128, 133 (1964)

cosmological[7] value and is the figure which we shall adopt. Also, we shall

7 Several cosmological theories, including HOYLE's formulation of the steady-state theory, lead to values of this order for the mean density in the universe. One can arrive at this result by simply setting $E_o + V = 0$, where E_o (= Mc^2; M is the "mass of the universe") is the rest energy of the universe, and V ($\sim -GM^2/R$; R is the "radius of the universe" or HUBBLE radius) is the gravitational energy. The resulting mean density is about two orders of magnitude greater than the observed smeared out density ($\sim 3 \times 10^{-31}$ gm/cm^3) from galaxies. The bulk of the matter in the universe is then attributed to the uncondensed intergalactic gas.

assume that the intergalactic hydrogen is fully ionized. We adopt 10^{-7} gauss for the mean intergalactic magnetic field. Certainly the intergalactic medium must have some, if only random, magnetic field. The intergalactic radiation field can be estimated with some reliability. The contribution from all galaxies in the universe results in a radiation field similar to the galactic (halo) field but diluted by about a factor of ten. Thus we take $\langle \rho_r \rangle = 10^{-14}$ erg/cm^3 and, again, $\bar{\epsilon}_r = 3$ eV.

Assuming the above values for the gas density, magnetic field, and radiation density in the intergalactic medium the various processes can be calculated readily by employing the relations given in part (c) of this section for galactic processes. However, for the bremsstrahlung contribution one must include the effects of electron-electron bremsstrahlung B_{ee} [11] as well as the contribution from B_{ep}. Since the cross section for high energy B_{ee} is approximately equal to that for B_{ep}, and since $n_e = n_p$ for the assumed fully ionized intergalactic medium, the total bremsstrahlung loss $-\langle d\gamma_e/dt \rangle_B$ is given by simply twice the expression (8.2) with $\langle n \rangle = 10^{-5}$ cm^{-3}.[8] The "ionization losses" for the fully

8 Although $B_{ee} \approx B_{ep}$ for highly relativistic electrons, for non-relativistic

electrons $B_{ee} \ll B_{ep}$. Essentially, this is because the photon emission by the non-relativistic system results from the dipole moment formed by the e-p system. ionized intergalactic medium actually correspond to production of plasma oscillations. The associated expression for the electron energy loss at high energies reduces to[9]

[9] S. HAYAKAWA and K. KITAO: Prog. Theor. Phys. 16, 139 (1956)

$$-\left\langle\frac{d\gamma_e}{dt}\right\rangle_P = 4\pi\, r_o^2\, c\, \langle n\rangle\, \ln\frac{2\, m_e c^2\, \gamma_e}{\hbar\omega_p}\ , \tag{12.1}$$

where ω_p $(= [4\pi e^2 \langle n\rangle/m_e]^{\frac{1}{2}})$ is the plasma frequency. The result is plotted in Figure 2.

For the intergalactic medium one should consider another "effective" energy loss process. The expansion of the universe results in an effective energy loss for the electrons in a given volume of

$$-\langle d\gamma_e/dt\rangle = \gamma_e/\tau_E, \tag{12.2}$$

where τ_E is the characteristic expansion time given by $\frac{1}{3}\, H^{-1} \sim 10^{17}$ sec (H = HUBBLE constant). The factor $\frac{1}{3}$ takes into account the fact that the expansion is three dimensional, that is, H^{-1} is the characteristic time for the one dimensional expansion. The effective energy loss due to expansion is plotted in Figure 2 for $\tau_E = 10^{17}$ sec, along with the energy losses due to bremsstrahlung, synchrotron radiation, and COMPTON scattering.

e) The Electron Energy Spectrum in the Halo and Intergalactic Medium

13. Here we consider the electron spectrum which results from production (via π-μ-e decay) in nuclear collisions of cosmic rays and from the various loss processes. Let $n_e(\gamma_e)\, d\gamma_e$ denote the number of electrons per cm^3 with energies within $m_e c^2\, d\gamma_e$.

The spectral electron density $n_e(\gamma_e)$ satisfies a continuity equation in γ_e (energy) space:

$$\frac{\partial n_e(\gamma_e)}{\partial t} + \frac{\partial}{\partial \gamma_e}\left(n_e(\gamma_e)\frac{d\gamma_e}{dt}\right) = \sum_i q_i(\gamma_e). \tag{13.1}$$

In Equation (13.1) the terms on the right hand side (r.h.s.) represent sources and sinks of high energy electrons corresponding to production, annihilation, and to processes leading to a sudden loss of a large fraction of the energy of the electron; terms representing leakage out of the halo or the expansion of the universe would also be included on the r.h.s. The factor $d\gamma_e/dt$ represents the total gradual energy loss from processes described earlier. We shall consider steady state conditions, so that $\partial n_e(\gamma_e)/\partial t = 0$.

14. Electron Spectrum in the Galactic Halo From Figure 1 we see that for $\gamma_e \leq 10^4$ (region I) the effective energy loss is primarily by leakage from the halo and the continuity equation reduces to

$$0 = q_e(\gamma_e) - n_e(\gamma_e)/\tau_L, \tag{14.1}$$

where $q_e(\gamma_e)$ is the production spectrum given by Equation (6.1) and is of the form $k_e\gamma_e^{-\Gamma_\pi}$, and τ_L is the leakage time. Thus, for $\gamma_e \leq 10^4$, $n_e(\gamma_e)$ is of the form

$$n_e^{(I)}(\gamma_e) = K_e^{(I)}\ \gamma_e^{-\Gamma_\pi},\ K_e^{(I)} = \tau_L\ k_e. \tag{14.2}$$

The electron spectrum in region I is essentially the same as the production spectrum, that is, the electrons escape from the galaxy without losing an appreciable amount of their origianl production energy.

For $\gamma_e \geq 10^5$ (region II) the electrons lose their energy primarily by synchrotron radiation for which $d\gamma_e/dt = -b\gamma_e^2$, and the continuity equation reduces to

$$-b\frac{\partial}{\partial \gamma_e}\left(\gamma_e^2 n_e(\gamma_e)\right) = q_e(\gamma_e) = k_e\ \gamma_e^{-\Gamma_\pi}. \tag{14.3}$$

The solution is then

$$n_e^{(II)}(\gamma_e) = K_e^{(II)}\ \gamma_e^{-(\Gamma_\pi + 1)},\ K_e^{(II)} = k_e/b(\Gamma_\pi - 1). \tag{14.4}$$

With the assumed values for the parameters and with k_e computed from

Equations (4.3) and (6.1) the calculated spectral electron density is shown in Figure 3. The solutions for $n_e(\gamma_e)$ in regions I and II were joined smoothly.

15. Electron Spectrum in the Intergalactic Medium The approximate spectrum of the intergalactic electrons is calculated by similar procedures. We approximate the effective energy loss for $\gamma_e \leq 10^5$ (region I, see Fig. 1) by the expansion loss and for $\gamma_e \geq 10^6$ (region II) by synchrotron losses. The electron spectrum in the two regions is then given by expressions similar to Equations (14.1) and (14.2) for the halo, essentially with τ_L replaced by τ_E. The calculated spectrum, **with the curves for the two regions joined smoothly, is** shown in Figure 3 for the previously stated assumed values of the astronomical parameters.

f) High Energy Photon Flux from Various Processes

16. Absorption of High Energy Photons, The absorption of cosmic photons is important in certain energy ranges. For x-ray photons traversing matter in the plane of the Galaxy absorption by the photoelectric effect in various elements is appreciable at the longer wavelengths. In Figure 4 we give the optical thickness as a function of wavelength for a path of 1 kpc in neutral atomic gaseous matter of "cosmic" composition with $n(H) = 1\ cm^{-3}$. The curve with the total contribution from all elements is given as well as that including only hydrogen and helium. The discontinuity in the total at 23 A is due to the onset of K-shell photoionization of oxygen. The curves have a slope of approximately 3 due to the (approximate) λ^3 dependence of photoelectric absorption, and are taken from the results of STROM and STROM [15].

Except for the pronounced edge due to oxygen, we have smoothed over the data which shows several other small jumps due to the onset of photoionization edged. Since the distance to the galactic center is ~ 10 kpc, and over this distance $\langle n(H) \rangle \sim 1\ cm^{-3}$, we see that $\tau > 1$ for $\lambda \geq 5$ A. For photons traversing intergalactic matter the path length is $\sim 5 \times 10^{27}$ cm, so that $\tau > 1$ for $\lambda > 10$ A if $\langle n(H) \rangle > 10^{-6}$ cm^{-3} (here a similar "cosmic" abundance has been assumed). A density of $\langle n(H) \rangle \sim 10^{-5}$ cm^{-3} is a reasonable value to assume for intergalactic space; however, this material is also likely to be composed essentially of pure hydrogen, or perhaps hydrogen and helium; material with this composition would be ionized if the temperature of intergalactic matter were $\geq 1.5 \times 10^{4}$ °K (hydrogen), and $\geq 6 \times 10^{4}$ °K (helium). The absorption by the ionized matter would be negligible.

The only other instance where absorption of high energy cosmic photons is appreciable is when very high energy photons travel distances comparable with the classical radius of the universe. As NIKISHOV [16] has shown, absorption by pair production in photon-photon collisions ($\gamma + \gamma \rightarrow e^{+} + e^{-}$) prevents us from seeing to the "outer edge" of the universe in photons of energy $\sim 10^{12}$ - 10^{13} eV. For photons of this energy the cross section for pair production in collisions with the thermal stellar photons in the intergalactic radiation field has a maximum. The intergalactic radiation field in the thermal stellar range ($\sim$ eV) is due to emission from galaxies. NIKISHOV calculated the optical thickness for a black body radiation field of temperature $kT = 0.5$ eV and total energy density 0.1 eV/cm^3 out to the distance of Cygnus A ($R_C = 6.6 \times 10^{26}$ cm). We feel that the energy density which he employed may be on the high side and shall give the results for a radiation field one-tenth as large but for a distance of $R = 5 \times 10^{27}$ cm (the "cosmological cut-off"). The associated optical thickness is shown in Figure 5 as a function of photon energy. We should like to emphasize again the uncertainty in the intergalactic radiation field and thus in the magnitude of the effect. Because of this and other uncertainties we shall ignore absorption in the remainder of this article; however, it should still be kept in mind that it could be appreciable for certain photon energies and could effect the high energy cosmic photon spectrum.

17. Photon Spectra The photon production spectrum by a given process may be computed from the electron (energy) spectrum $n_e(\gamma_e)$ and the expression for the photon emission spectrum by this process as a function of γ_e. Denote the photon energy by ϵ. The energy loss by an electron of energy E_e in time dt due to the emission of dN photons of energy within $d\epsilon$ is

$$-dE_e \equiv \epsilon\, dN = f(E_e,\epsilon)\, d\epsilon\, dt, \qquad (17.1)$$

where $f(E_e,\epsilon)$ is the emission spectrum. The number of photons emitted per cm^3 per second per interval of ϵ by an electron spectrum $n_e(\gamma_e)$ would then be

$$\frac{dn}{dt\, d\epsilon} \equiv \frac{dn(\epsilon)}{dt} = \int d\gamma_e\, n_e(\gamma_e)\, \frac{dN}{d\epsilon\, dt}\,. \qquad (17.2)$$

We now approximate the emission spectrum by a δ-function at the characteristic photon energy ϵ_c:

$$\frac{dN}{d\epsilon\, dt} = \frac{1}{\epsilon}\, f(E_e,\epsilon) \rightarrow -\frac{m_e c^2}{\epsilon}\, \frac{d\gamma_e}{dt}\, \delta(\epsilon-\epsilon_c), \qquad (17.3)$$

where $\epsilon_c = \epsilon_c(\gamma_e)$. The photon spectral flux due to emission along a line of sight of path $\int ds = R$ would be

$$j(\epsilon) = \frac{dJ}{d\epsilon} = \int \frac{dn(\epsilon)}{dt}\, ds = \left\langle\frac{dn(\epsilon)}{dt}\right\rangle R. \qquad (17.4)$$

The incident photon spectra from both the galaxy and the intergalactic medium are readily calculated from the Equations (17.2), (17.3), and (17.4) using the derived electron spectra $n_e(\gamma_e)$ and the expressions for the energy losses $-\langle d\gamma_e/dt\rangle$. For synchrotron emission $\epsilon_c \approx \hbar\omega_L\, \gamma_e^2$; for bremsstrahlung $\epsilon_c \approx m_e c^2\, \gamma_e$; for the COMPTON process from electrons with $\gamma_e \ll m_e c^2/\bar{\epsilon}_r$, $\epsilon_c \approx \bar{\epsilon}_r \gamma_e^2$; for the COMPTON process from electrons with $\gamma_e \gg m_e c^2/\bar{\epsilon}_r$, $\epsilon_c \approx m_e c^2\, \gamma_e$.

Taking a path length $R = 5 \times 10^{22}$ cm (the radius of the galactic halo) for the Galaxy and a path length $R = 5 \times 10^{27}$ cm (half the HUBBLE radius) for the intergalactic medium, the resulting photon spectra are shown in Figure 6. The photon energy η is in units of $m_e c^2$, that is, $\eta = \epsilon/m_e c^2$, $j(\eta) = dj/d\eta$. The spectra are for synchrotron radiation, bremsstrahlung, COMPTON scattering, and

π^o-decay. The spectra from π^o-decay are calculated directly from the pion production spectrum which is of the form $q_\pi(\gamma_\pi) = k_\pi \gamma_\pi^{-\Gamma_\pi}$ [Eq. (4.3)]. One-third of the pions produced are π^o's, and each π^o gives two photons of mean energy $\frac{1}{2}\gamma_\pi m_\pi c^2$. The π^o-decay photon production spectrum is then approximately

$$dn^o/d\eta dt \approx \frac{2}{3} k_\pi \ (2m_e/m_\pi)^{-(\Gamma_\pi - 1)} \ \eta^{-\Gamma_\pi}. \qquad (17.5)$$

The galactic photon fluxes plotted in Figure 6 are averaged over all directions; the average magnitude of the flux <u>per steradian</u> is $1/4\pi$ times the flux in Figure 6. Actually, the photon flux per steradian from bremsstrahlung and π^o decay would be greatest in the direction along the galactic plane where the production and interaction with the gas takes place. The synchrotron radiation and COMPTON photons would also show a moderate anisotropy due, at least, to our off-center position in the Galaxy. We have not computed the spectrum from positron annihilation. The cross section for direct positron (energy: $\gamma_e m_e c^2$) annihilation with an electron at rest is, at high energies [11],

$$\sigma_a \approx \pi r_o^2 \frac{\ell n \ 2\gamma_e}{\gamma_e} \qquad (17.6)$$

so that the bremsstrahlung spectrum dominates the annihilation spectrum by a factor $\sim \alpha\gamma_e$ for $\gamma_e \geq 10^2$. At lower positron energies ($\gamma_e < 10^2$) ionization losses are dominant (see Fig. 1) and the positron comes essentially to rest before annihilating, giving two photons each of energy $\eta \approx 1$.

To calculate the photon flux from the intergalactic medium we have taken essentially a static EUCLIDian universe cut off at $R = 5 \times 10^{27}$ cm. It is natural to inquire into the effects of the expansion (differential red shift) and detailed structure of the universe on the resulting photon spectra. It can be shown that only if the photon production spectrum is a <u>power law</u>, will the observed flux show the same shape spectrum (power law with the same index), independent of the structure (including expansion) of the universe. This results essentially because the DOPPLER-shifted photon energy is proportional to the unshifted energy. As a result, our calculated spectra, which are of the power law type in different energy regions, depend on the detailed structure of the universe only as far as the energy at which the spectra change their slope is concerned (at $\eta \sim 10^5$ for B and C, Fig. 6). However, the shift in this critical energy is likely to be less than an order of magnitude.

We should like to emphasize again that the calculated photon fluxes are only approximate, and this should be kept in mind when we attempt possible interpretations of the observations. In particular, our treatment of meson production in cosmic ray collisions is very rough, especially at low energies where the FERMI theory should be invalid. Moreover, as mentioned earlier, our assumed cosmic ray spectrum is too large at the low energy end; this effect alone would produce a bend in the calculated photon fluxes at low energies such that the low energy ends of the curves in Figure 6 should be reduced by about an order of magnitude.

g) Comparison with Observations

18. General Discussion The experimental points exhibited in Figure 6 correspond to the observed cosmic background photon fluxes as summarized in Table 1 below[10]. The observations are in essentially four energy regions and are

[10] In this discussion we have taken the observational values given in Table 1 at their face value. However, it appears now that, while the background x-ray fluxes have been detected at the levels quoted, the γ-ray results are more uncertain and should all be treated as upper limits to the fluxes which may be present. That we are, therefore, only discussing possible explanations of hypothetical γ-ray fluxes in this section is to be emphasized.

over ranges such that $\Delta\bar{\eta}/\bar{\eta} \sim 1$. There is, of course, another range of energies where cosmic photons are observed, namely, the radio range. The radio spectrum is represented fairly well by the low energy range (not included in Fig. 6) of the calculated synchrotron radiation spectrum. We shall return to this question of the radio spectrum shortly.

We now consider the possibilities of interpreting any of the observed photon fluxes in terms of the various calculated spectra represented in Figure 6. First consider the x-ray observations. The flux $j(\eta)$ for point X (Fig. 6) is five orders of magnitude above the curve S' and six orders of magnitude above S. This discrepancy is, in our opinion, sufficient to rule out the interpretation of the point X as due to synchrotron radiation, at least if the high energy electrons are of a secondary origin. The curves C and C' do not extend to lower energies because we have considered electrons with $\gamma_e \geq 10^2$, and in our approximate calculations have assumed that $\langle \epsilon \rangle_C = \gamma_e^2 \bar{\epsilon}_r$, giving $\langle \epsilon \rangle_C \geq 30$ keV. However, due to the distribution of thermal photon energies there is, of course, a distribution of photon energies which can be produced by an electron of given energy. Moreover, for a pion decaying at rest there is still an appreciable probability for a low energy (say, $\gamma_e \sim 30$) electron being produced. Therefore, the COMPTON spectra C and C' certainly do extend to the x-ray region. In spite of this, we do not believe that the x-ray point can be due to the COMPTON process, if the electrons responsible for the scattering have a secondary origin. For, as previously mentioned, the actual cosmic ray spectrum which produces the low energy pions and finally electrons is smaller by about a factor of 10 than the power law spectrum used to compute the curves in Figure 6. A realistic extrapolation of, for example, the curve C' to the x-ray region would still fall about three orders of magnitude below the observational point B.

FELTEN and MORRISON [14] suggested that not only the x-ray flux, but also the photon fluxes at ~ 1 Mev and ~ 100 Mev (see Table 1), are due to the COMPTON process in the intergalactic medium. They suggested that the sources of the high energy intergalactic electrons are the strong radio sources. We can see from the curve C' in Figure 6 that the intergalactic spectral density $n_e(\gamma_e)$ required to explain the results is about 20-30 times as large as the density which we estimated to result from secondary production in intergalactic space. The COMPTON spectrum must, of course, extrapolate to the x-ray region and this precludes a secondary origin for the electrons, unless they are produced by a cosmic ray spectrum which has a much higher intensity at low energies than that for cosmic rays observed at the earth. We cannot rule out the FELTEN-MORRISON hypothesis; in fact, elementary considerations of the necessary number of sources (radio galaxies) of high energy electrons in the universe suggest that the hypothesis is reasonable quantitatively. As we have shown, for our Galaxy this relatively low energy part of the electron spectrum, that is, the radio electrons, does escape from the galaxy into the intergalactic medium before losing an appreciable amount of its initial energy. We shall show presently that, if the FELTEN-MORRISON idea is correct, the amount of synchrotron radiation which these electrons would produce places an upper limit to the intergalactic magnetic field.

Regarding the possible interpretation of the observations at 1 Mev (A, Fig 6), we see that the observed flux is about an order of magnitude above the calculated curve C'. In view of the inaccuracies involved this "agreement" within an order of magnitude indicates that COMPTON scattering by secondary-produced intergalactic electrons provides a possible explanation for the observed photon flux at 1 Mev. Of the calculated processes represented in Figure 6 this appears to be the only possible association with the observations at 1 Mev. The spectrum from π^0 decay certainly does not extend below $\log \eta = 2$ ($E \approx 50$ Mev), and the bremsstrahlung spectra B and B' must be less steep below $\log \eta = 2$ since, although the energetic secondary electrons can emit a bremsstrahlung spectrum extending to the lower energies, the corresponding bremsstrahlung photon would then carry away only a small fraction of the electron's energy, and the photon production process would be less efficient.

It would appear from Figure 6 that the ~ 100 Mev photon flux which KRAUSHAAR and CLARK first reported could be accounted for by π^o's produced in the galaxy or in the intergalactic medium. However, our calculated π^o spectrum, based on the FERMI theory, is very unsatisfactory at the low energy end. For low energy p-p collisions it is primarily π^+ mesons that are produced and a more accurate treatment of meson production than our extrapolation of the FERMI theory must be employed. Now, in the KRAUSHAAR-CLARK observation the photon flux observed included essentially the whole spectrum from decays of π^o's of all energies, and most of the π^o's produced are of low energy. By employing the available data on meson production by incident protons of energy less than 10 Bev and the observed low energy cosmic ray spectrum, POLLACK and FAZIO [3] have computed the rate of production of pions by p-p, p-α, and α-p collisions per hydrogen nucleus as the rate of production of π^o decay and positron annihilation (after $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay) photons:

$$\pi^o\text{-decay:}\quad q^o \approx 1 \times 10^{-26} \text{ photons/sec-ster}$$

$$\text{positron annihilation:}\quad q^+ \approx 2 \times 10^{-26} \text{ photons/sec-ster.}$$

The π^o-decay photons have energies above about 70 Mev and the galactic positron annihilation photons have energies of about 0.5 Mev, since the positrons come essentially to rest before annihilating. The π^o-decay photon flux from a region of density $\langle n_H \rangle$ of extent R would then be $4\pi q^o \langle n_H \rangle R$ and in this manner we estimate fluxes of 2×10^{-4} photons/cm^2-sec and 6×10^{-3} photons/cm^2-sec from the Galaxy and intergalactic medium respectively; the galactic flux is a directional average. The KRAUSHAAR and CLARK flux is roughly the same as the calculated contribution from the intergalactic medium while the flux observed by DUTHIE _et al_. is an order of magnitude larger. The origin of the discrepancy between the KRAUSHAAR-CLARK and DUTHIE _et al_. observations may lie in the latter's extrapolation of their balloon observations to zero atmospheric depth. At any rate, it is clear that an upper limit to essentially the product of the intergalactic cosmic ray flux and gas density is established by these observations. The calculated intensity of the positron annihilation line using POLLACK and FAZIO's value of q^+ and again the "standard" intergalactic gas density (10^{-5} cm^{-3}) is 1×10^{-2} photons/cm^2-sec which is just below the upper limit of 1.5×10^{-2} photons/cm^2-sec established by ARNOLD et al. However, intergalactic relativistic positrons do not slow down before annihilating (see Fig. 2) and would not produce a 0.51 MeV line but rather an annihilation continuum extending to higher energies.

The point denoted by EAS in Figure 6 results from observations of Extensive Air Showers [22], [23] in which an abnormally low number of muons was observed, indicating possibly that the shower was initiated by electromagnetic processes rather than by a nuclear collision. If these showers result from primary photons the flux of these photons would be $\sim 10^{-3}$ times the flux of cosmic ray protons at the same energy. The results of these experiments are questionable and may only represent an upper limit to the primary cosmic photon flux at these high energies. In Figure 6 we see that the EAS point lies 2 or 3 orders of magnitude above the curve corresponding to the decay of high energy secondary-produced π^0-mesons in the intergalactic medium.

As was mentioned in the footnote at the beginning of this section, it is necessary to emphasize the preliminary nature of all of these observations of high energy photons. While the existence of cosmic x-ray sources seems well established, the existence of positive fluxes at higher energies (the $\sim$ MeV, 100 MeV, and 10^{15} eV observations) is not established. The fluxes given for these higher energy photons probably should all be taken as upper limits until the observational situation is clarified. For example, the $\sim$ MeV observations may be plagued by radioactivity induced in the crystal of the scintillation detector[11].

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[11] L. E. PETERSON: J. Geophys. Res. 65 (1965)

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19. X-rays from External Galaxies We should like to mention another possible explanation for the observed background flux of x-rays, which we proposed earlier [24]. About 10 discrete sources of x-rays have been observed, and because of their apparent concentration toward the plane of the Galaxy, are assumed to be galactic and presumably at a galactic distance $R_g \sim 10$ kpc (see Sect. III). Since our Galaxy is believed to be a normal "average" galaxy, one would expect that this is a general characteristic of galaxies, so that external galaxies have x-ray luminosities L_x not too different from that of our own Galaxy. If the average x-ray luminosity for galaxies is $\langle L_x \rangle_g$, the isotropic background flux per steradian observed at the earth would be roughly

$$f_x \approx \langle L_x \rangle_g \, n_g \, R_c / 4\pi, \qquad (19.1)$$

where n_g ($\sim 3 \times 10^{-75}$ cm^{-3}) is the number density of galaxies, and R_c ($\sim 5 \times 10^{27}$ cm) is a cosmological cut-off distance. Neglecting absorption, the total flux received from sources in our Galaxy is

$$F_x = \sum_i L_x^{(i)} / 4\pi r_i^2 \approx L_x / 4\pi R_g^2, \qquad (19.2)$$

where L_x ($= \sum_i L_x^{(i)}$) is the total x-ray luminosity of the Galaxy. Assuming $\langle L_x \rangle_g \approx L_x$, we find

$$f_x \approx F_x \, n_g \, R_g^2 \, R_c \qquad (19.3)$$

The total flux from all galactic sources is (see Sect. III) about $F_x \approx 33$ photons/cm^2-sec, so that we estimate from Eq. (19.3) $f_x \approx 0.5$ photons/cm^2-sec-ster, which is about an order of magnitude smaller than the observed flux. In view of the uncertainties and the assumptions involved, agreement within an order of magnitude must be regarded as satisfactory. Clearly, we make no assumption as to the production mechanism of these x-rays, but only that our Galaxy is "typical".

20. Radio Emission We conclude our discussion here with a few remarks about the observed cosmic radio spectrum from the galactic halo, which is undoubtedly due to synchrotron radiation by relativistic electrons. We attempt to answer the question as to whether the electron spectrum can be accounted for by secondary production by cosmic rays. This problem has been considered by a number of authors in a manner similar to our treatment. However, our view differs somewhat in that we consider leakage from the halo as the primary loss process for the radio electrons.[12]

[12] Our conclusions also differ. We conclude that the spectrum of radio electrons in the galactic halo can be accounted for by the production (via π-μ-e decay) by cosmic-ray nuclear collisions in the galactic plane and subsequent diffusion to the halo. However, GINZBURG and SYROVATSKY [25] conclude, by a similar analysis, that the halo radio electrons cannot be expalined in this manner, and that the expected secondary electron spectrum is smaller by one or two orders of magnitude than the value derived from radio observations. We feel that the astronomical data are not known sufficiently accurately to expect agreement within an order of magnitude. Moreover, we do not understand the results given in Figs. 5 and 6 of the paper by GINZBURG and SYROVATSKY; it appears to us that the electron spectra computed for the higher assumed mean galactic gas density n should be proportionally larger, offsetting the small effect of increased collisional energy loss.

If the energy radiated per second per interval of frequency by an electron of energy $\gamma_e m_e c^2$ is $P(\nu, \gamma_e)$, the spectral intensity (erg/sec-cm^2-ster-frequency interval) of radiation received from a direction $\underset{\sim}{r}$ is

$$I_\nu = dE/dt dA d\Omega d\nu = (4\pi)^{-1} \iint n_e(\gamma_e)\, P(\nu,\gamma_e)\, d\gamma_e\, d\underset{\sim}{r}, \tag{20.1}$$

where $n_e(\gamma_e)\, d\gamma_e$ is the differential electron density. For an electron spectrum $n_e(\gamma_e) = K_e \gamma_e^{-\Gamma_e}$ the intensity I_ν may be computed approximately by taking $P(\nu,\gamma_e)$ to be equal to the expression (9.1) for dE_e/dt times a δ-function $\delta(\nu-\nu_L\gamma_e^2)$ at frequency where $P(\nu,\gamma_e)$ is a maximum. Assuming a constant magnetic field H and a path length $\int dr = R_h$, the halo radius, we obtain a familiar result:

$$I_\nu \approx (12\pi)^{-1}\, c r_o^2\, K_e\, R_h\, H^2\, \nu_L^{(\Gamma_e-3)/2}\, \nu^{-(\Gamma_e-1)/2}; \tag{20.2}$$

a power law spectrum with exponent $\alpha \equiv (\Gamma_e-1)/2$ is also obtained using the exact expression for $P(\nu,\gamma_e)$. The constant K_e may be determined by the observed value (500°K) of the radio brightness temperature $T_b = I_\nu\, \lambda^2/2k$ at 100 Mc/sec in the direction of the galactic pole. Employing Equation (20.2) with $H = 3 \times 10^{-6}$ gauss, $R_h = 5 \times 10^{22}$ cm, $\Gamma_e = 2.8$ ($\alpha = 0.9$), we obtain $K_e = 1 \times 10^{-6}$ cm^{-3}. This number is to be compared with the value calculated from the production and loss processes. By Equations (4.3), (6.1), and (14.1) we get for the calculated K_e:

$$K_e \approx (8\pi/9)\, \Lambda_\pi^2\, (m_\pi/4m_e)^{\Gamma_e-1}\, K_p\, \langle n_H\rangle\, \tau_L. \tag{20.3}$$

Using the previously assumed values $K_p = 100$ cm^{-2} sec^{-1}, $\langle n_H\rangle = 0.03$ cm^{-3}, $\tau_L = 3 \times 10^{15}$ sec we calculate $K_e = 1 \times 10^{-6}$ cm^{-3}; the agreement with the radio value is fortuitous. Actually, the observed radio spectrum has an index $\alpha \approx 0.7$-0.8, and we have adopted the "theoretical" value 0.9. This discrepancy may not be serious; the observed slightly flatter spectrum could be accounted for by a slight variation with γ_e of the effective value of τ_L. For example, if τ_L were slightly shorter for the low energy electrons (caused, perhaps by another energy loss process at low energy) the smaller value of α and Γ_e could be understood. A more accurate treatment of the production spectrum could also indicate a smaller value for α and Γ_e. Further, we might mention that with our assumed values of the parameters (density, magnetic field, etc.) for the intergalactic medium, the calculated synchrotron intensity in the radio region from the intergalactic medium is comparable to that from the halo, while, as is seen from Figure 6, the calculated intergalactic synchrotron radiation is actually greater by ~ 10 at the high energy end. Admittedly, our calculations are based on many assumptions, but these assumptions may well be valid, and much of the observed non-thermal radio background radiation may be coming from the intergalactic medium.[13]

[13] Recently this view has also been expressed by some radio astronomers, for example, J. E. BALDWIN at the Second Texas Symposium on Relativistic Astrophysics (proceedings to be published by the University of Chicago Press).

It is of interest to consider the requirements on the intergalactic magnetic field if the FELTEN-MORRISON idea is correct. From Figure 6 we see that for the curve C' to pass near the points X, A, and K-C, the value of K_e must be larger by a factor ~ 30, or must be $\approx 3 \times 10^{-7}$ cm^{-3}. One can then compute the intergalactic magnetic field, by Equation (20.2) with $R_h \rightarrow 5 \times 10^{27}$ cm, $\frac{1}{2}$ the Hubble radius, necessary to produce a brightness temperature of 500°K at 100 Mc/sec. One then finds 1×10^{-8} gauss for this magnetic field. Thus, if the FELTEN-MORRISON idea is correct, the intergalactic magnetic field must be less than 1×10^{-8} gauss.

Finally, we should like to mention some further checks on the calculated spectrum of the halo electrons. Recently the French-Italian group (AGRINIER *et al.* [8]) has reported the measurement of a primary cosmic ray electron flux of 6.6×10^{-4} particles/cm^2-sec-ster for $E_e > 4.5$ BeV, corresponding also to an electron/proton cosmic ray ratio of 1×10^{-2}. This measurement of the primary electron flux at fairly high energies is probably more reliable than results of measurements at lower energies which are influenced by solar activity. The measured flux is to be compared with that from the calculated spectra above 4.5 BeV ($\gamma_e > \gamma_o = 4.5$ BeV$/m_e c^2$). One finds, with $K_e = 1 \times 10^{-6}$ cm^{-3}, $\Gamma_e = 2.8$, a flux

$$f_e = (4\pi)^{-1} \int_{\gamma_0}^{\infty} cK_e \gamma_e^{-\Gamma_e} d\gamma_e \approx 1 \times 10^{-4} \text{ particles/cm}^2\text{-sec-ster.} \qquad (20.4)$$

This flux is somewhat smaller than the observed one, but in view of the uncertainties involved in the calculations, agreement within an order of magnitude is all that one could hope for.

Another check on whether the observed cosmic ray electrons result from secondary production can be made by a measurement of the positron/electron ratio. This has been done by the group at the University of Chicago [8], who conclude that their measurements are inconsistent with the assumption that the bulk of the electron and positron spectrum is a result of secondary production. If indeed electrons and positrons of galactic origin are being observed, this would settle the question. Again, we take the conservative view that the question is still open, since the measured ratio is only off by a factor ~ 2 from the ratio expected on the basis of secondary production.

h) Tests of Cosmological Theories

21. The Hot Universe Model - Bremsstrahlung from the Intergalactic Medium

GOLD and HOYLE[14] have suggested a cosmological model in which the intergalactic

[14] T. GOLD and F. HOYLE: Paris Symposium on Radio Astronomy, ed. by R. N. BRACEWELL (Stanford: Stanford University Press 1958)

medium is at a very high temperature ($\sim 10^{9}$°K). The high temperature is supposed to arise from the ~ 1 Mev electrons which would result after the decay of spontaneously created neutrons as envisioned by the steady-state theory. Galaxy formation within the framework of this model was considered by BURBIDGE, BURBIDGE, and HOYLE[15]. An observational test of this model can be made, since such a hot

[15] E. M. BURBIDGE, G. R. BURBIDGE, and F. HOYLE: Ap. J. 138, 873 (1963)

intergalactic medium would emit thermal bremsstrahlung photons in the x-ray region where observations have been made [18]. For a mean thermal electron energy $\langle E_e \rangle = 50$ keV, and a density $n_e = n_p = 1.2 \times 10^{-5}$ cm^{-3} the rate of production of bremsstrahlung photons within the energy range of the observations is about $r_b = 1.17 \times 10^{-25}$ photons/cm^3-sec [24]. Taking a cut-off radius $R = 5 \times 10^{27}$ cm for the universe, one calculates a flux $f_b = r_b\, R/4\pi \sim 50$ photons/cm^2-sec-ster to be expected at the earth. This flux is ~ 10 times the observed x-ray background flux and is evidence against the hot universe model (and the steady-state theory with spontaneous creation of neutrons). Actually, if the appropriate intergalactic density to be used is four times the usually adopted 2×10^{-29} gm/cm^3, as suggested by SCIAMA,[16] the disagreement with observations is even more violent.

16 D. W. SCIAMA: Quart. J. R.A.S. 5, 196 (1964)

In any case it appears that the x-ray observations have established an upper limit of 10^7°K for the temperature of the intergalactic medium.

22. Matter and Anti-Matter and the Steady State Cosmological Theory The attractive feature of the steady state theory is its simplicity. The unique feature is a spontaneous creation rate of "new" matter $dn/dt \sim 3\,Hn$, where $n \sim 10^{-5}$ cm^{-3} is the mean matter density in the universe (taken to be the mean hydrogen density in the intergalactic medium) and H is the Hubble constant ($3\,H \sim 10^{-17}$ sec^{-1}). One might expect that in the spontaneous creation process, to conserve baryon and lepton number, particles and anti-particles are created. Since the expansion rate constant 3 H is about two orders of magnitude greater than the annihilation rate (see below), BURBIDGE and HOYLE[17] suggested the possibility of an appreciable abundance of anti-matter in the universe. This idea can be put to a test, since the end products of matter and anti-matter annihilation are observable high energy γ-rays.

17 G. R. BURBIDGE and F. HOYLE: Nuovo Cimento 4, 1 (1956)

Let us suppose that (p, e^-) and $(\bar{p}, e^+)$ are spontaneously produced and have a steady state mean number density $n = 10^{-5}\ cm^{-3}$ and $\bar{\alpha}n$ respectively, where $\bar{\alpha}$ denotes the mean ratio of anti-matter to matter (or vice-versa). The electron-positron annihilation cross section at non-relativistic energies is [11] $\sigma_a = \pi r_o^2/\beta$, where r_o is the classical electron radius and $\beta = v/c$. The annihilation rate is then $dn_a/dt = \bar{\alpha}\, n^2\, \pi r_o^2 c \sim \bar{\alpha} \times 10^{-24}\ cm^{-3}\ sec^{-1}$, and the expected flux of 0.51 MeV photons from the intergalactic medium out to a distance $R \sim 5 \times 10^{27}$ cm is $2R\ dn_a/dt \sim \bar{\alpha} \times 10^4$ photons/cm^2-sec. This can be reconciled with the upper limit of 10^{-2} photons/cm^2-sec suggested by ARNOLD et al. [19] only if $\bar{\alpha} < 10^{-6}$. This means that if there is appreciable anti-matter in the universe, it must be separated from matter, so that it cannot annihilate and produce observable γ-radiation.

A limit on the amount of anti-matter in the universe can also be provided from an analysis of the γ-ray experiments at higher energies which can detect π^o-decay γ's. In the proton-antiproton annihilation ~ 5 pions are produced, some of which are π^o's which produce γ-rays of energy ~ 100 MeV in their decay. In each p-$\bar{p}$ annihilation about $m_\gamma = 4$ γ-rays are produced. The cross section for p-$\bar{p}$ annihilation is $\sigma_a' = \sigma_o/\beta$, where $\sigma_o = 5 \times 10^{-26}\ cm^2$ and βc is the relative velocity.[18] Again setting $n (= 10^{-5}\ cm^{-3})$ and $\bar{\alpha}n$ equal to the matter and

[18] C. A. COMBES, B. CORK, W. GALBRAITH, G. R. LAMBERTSON, and W. A. WENZEL: Phys. Rev. 112, 1303 (1958)

anti-matter densities respectively, the mean number of γ's produced in the universe per cm^3 is $m_\gamma\, \bar{\alpha} n^2\, \sigma_o c \sim \bar{\alpha} \times 6 \times 10^{-25}\ cm^{-3}\ sec^{-1}$. If this production occurred in the universe out to a distance $R = 5 \times 10^{27}$ cm, the resulting flux of γ-rays would be consistent with the KRAUSHAAR-CLARK experiment only if $\bar{\alpha} < 10^{-6}$ - the same limit established from the observed upper limit for the intensity of the cosmic positron annihilation line. Thus, it appears that in the steady state cosmology matter and anti-matter cannot be created in comparable amounts in the same region.

Finally, regarding cosmological tests, we should like to mention the recent discussion by GOULD and SCIAMA [26]. They indicate how the measurement of the shape of an emission line, smeared into a continuum by the cosmic differential red shift, would provide information about the structure of the universe at great distances.

III. DISCRETE SOURCES OF HIGH ENERGY PHOTONS

It has now been demonstrated quite conclusively by the NRL [18], [27], [28], MIT [17], [29], [30], and Lockheed [31], [32], [33] groups that there exist discrete cources of cosmic x-rays. About 10 such sources have been found and their properties are described below. The problem of the types of astronomical object and the mechanismsof emission which give rise to these sources is as yet unsolved, although it appears that there are only a few possible explanations. While the basic mechanism by which the x-rays are produced is not known, the present indication is that the x-ray sources are galactic and, in fact, are supernova remnants. This viewpoint is advanced here where supernova remnants, as sources of x- and γ-rays, are discussed in some detail; the Crab Nebula in particular receives considerable attention. We also discuss the x-ray source at the galactic center. However, before considering these specific objects, we give a general review of possible galactic sources and then discuss the possible physical mechanismsfor high energy photon production in discrete sources.

a) General Summary of the Observations

23. The positions and intensities of the discrete x-ray sources as they are known at present are given in Table 2 which is taken from the paper by

BOWYER *et al.* [27]. Results reported by the other experimental groups (MIT and Lockheed) are in essential agreement with these in regards to both the positions[19] and intensities of the sources. The uncertainty in the positions of the sources is given as 1.5°, while the Tau XR-1 source has been localized to within 1' of the optical center of the Crab Nebula. The observational results on the Crab source will be summarized in more detail later (Sect. 29). The discrete sources appear to have a spatial distribution showing a concentration toward the plane of the Galaxy, indicating that the sources are probably galactic and at characteristic distances of ~ 1-10 kpc. The most intense of the x-ray sources is that in the constellation Scorpius (Sco XR-1) from which an x-ray flux of about $F_x \sim 10^{-7}$ erg/cm^2-sec is detected. The flux from most of the other sources is about one-tenth as large as that from Sco XR-1. With the exception of Tau XR-1, none of the sources have been identified with a reasonable degree of certainty with any radio or optical objects, although there have been some tentative identifications.

Attempts have been made [34] to identify the Scorpius x-ray source with the so-called spur of radio emission which some have argued is a comparatively nearby supernova remnant. However, it has been pointed out [35] that this positional identification is very poor since even with the uncertainties quoted for the position the center of the radio source component is some 27° away. Thus the situation here is uncertain.

Of the other x-ray sources, it is of interest to note that Oph XR-1 is 1.1° away from the position of KEPLER's 1604 supernova and that Sgr XR-1 is 2.3° from the galactic center.

[19] Recent unpublished work by the Lockheed group has given a more accurate position for the Sco XR-1 source: $\alpha = 16^h\, 14^m$, $\delta = -15°\, 36'$, with an expected error of ±20'.

The size of Sco XR-1 has been established to be less than about 0.2° by both the NRL and MIT groups. With the exception of Tau XR-1, all that is known about the sizes of the other sources is that they are less than about 10° in extent. Little is known at present about the spectra of the x-ray sources. From the change in the counting rate from Sco XR-1 as the rocket was passing through the upper atmosphere (in which absorption is wavelength dependent) the NRL group [27] has concluded that 1/3 of the observed flux from the strong Scorpius source is emitted in the 1-6 Å band and 2/3 of the flux is emitted in the 6-10 Å band. Such a spectrum is compatible with emission from a black body having a temperature of 2 or 3×10^6 degrees. However, these results on the spectra of x-ray sources are suspect; the Lockheed group [33] has found an effective black body temperature of $\sim 2 \times 10^7$ °K for the Scorpius source - an order of magnitude higher than that reported by the NRL group.

b) Possible Galactic Sources

If an x-ray source at 10 kpc is to produce an x-ray flux of 10^{-8} erg/cm^2-sec, its x-ray luminosity must be 10^{38} erg/sec. Clearly, no individual normal star could produce such a luminosity in x-rays. For, although there are stars which have a total luminosity this large, the atmospheric conditions in these stars are such that most of the radiation emitted is at much lower energies ($\sim$, say, 10 eV). The sun emits x-rays from its corona and from flares, but at a much smaller rate (10^{21} to 10^{26} erg/sec). Only the cumulative effect of very populous clusters or the integrated effect of the stars in the galactic bulge could possibly produce a significant x-ray flux. This possibility will be discussed later (Sect.33); suffice it to say for the moment that these combined effects of stellar coronae appear likely to be unimportant. However, there is an abnormal type of star which, at least for part of its evolutionary phase, emits a spectrum peaked on the x-ray region; this is the neutron star. We prefer to discuss neutron stars after first considering supernovae, which are known sources of large amounts of energy and high luminosity.

24. Supernovae Although much of the energy released in a supernova is emitted soon after the outburst, the remnants still possess a large amount of energy and could possibly maintain an x-ray luminosity of 10^{38} erg/sec for much longer times. The required characteristic loss time τ_ℓ for x-ray emission can be determined approximately as follows. Let us suppose that the $N_x \sim 10$ x-ray sources are galactic and resulted from supernova outbursts. Since the rate of supernova outbursts and formation of x-ray sources in the Galaxy is $dN_s/dt \sim 1/100$ yr, we must have

$$(dN_s/dt)\ \tau_\ell = N_x, \qquad \tau_\ell \sim 1000 \text{ yr}. \tag{24.1}$$

Clearly, this result must hold for whatever type of mechanism is to produce the x-rays, as long as the origin of the x-ray sources is to be supernovae outbursts. Moreover, if a characteristic time for x-ray emission by some process is computed to be much shorter than 1000 yr, then without regeneration that process cannot account for the x-ray sources. It is of interest to compare τ_ℓ with the expected lifetime of total emission from the Crab Nebula (see Sect. 29), for which $E_{tot.} \sim 10^{48}$ erg and $L_{tot.} \sim 10^{37}$ erg/sec. Then $E_{tot.}/L_{tot.} \sim 3000$ yr $\sim 3\ \tau_\ell$.

Supernova remnants can emit high energy photons through a variety of processes and at very different power levels. After the initial outburst, emission can occur by the synchrotron process, by bremsstrahlung in the high temperature gas produced by the expanding ejecta, and by the radioactivity produced. The initial outburst is more spectacular, however, and we shall now consider what can be expected during this very early, violent stage.

25. Early Phases of Supernova Outbursts At this phase two processes may be important. These are:

(a) Nuclear γ-rays emitted in the process of nucleosynthesis at the time of the outburst.

(b) γ-rays emitted through the early interaction of a cloud of relativistic particles with the magnetic field and material in the expanding shell.

If, in a supernova outburst, the inner part implodes and the outer part is suddenly heated so that hydrogen burning takes place very rapidly, we can suppose that the bulk of the energy released is degraded through its passage through the material, but some fraction, perhaps the energy released in burning 0.01 $M_{\odot}$ of hydrogen, will be emitted as γ-rays in the Mev range. Thus we might suppose that 10^{50} ergs is emitted in ~ 1000 seconds. For a galactic supernova at assumed distances of 1 and 10 kpc this gives fluxes at the earth of 10^3 and 10^5 erg/cm^2 sec^{-1}, fantastic rates. However, the appearance of a galactic supernova is highly improbable. From extragalactic supernovae at characteristic distances of 10 and 100 Mpc the fluxes would be 10^{-5} and 10^{-7} erg/cm^2 sec^{-1} respectively. These rates are obviously uncertain by several powers of 10. It might also be expected that some part of the flux is degraded to the energies of a few kilovolts and is emitted as x-rays. As an upper limit we might suppose that this flux is of comparable intensity for a few days with the flux at maximum light from the supernova. If we suppose that it reaches a value of $M_v = -18$ this corresponds to 10^{43} erg/sec and at distances of 1 kpc and 10 kpc (Galactic) and 10 Mpc and 100 Mpc (extragalactic) fluxes at earth of 10^{-1} and 10^{-3} erg/cm^2 sec^{-1} (Galactic) and 10^{-9} and 10^{-11} erg/cm^2 sec^{-1} (extragalactic) may be expected.

A large flux of relativistic electrons is currently present in many supernova remnants, and it is possible that this in part is the remnant of a much larger flux of relativistic particles which was produced at the time of the outburst. Let us suppose that some 10^{50} ergs of particles, largely protons, was generated in the explosion. If they are originally confined in an expanding shell containing a magnetic field (they are the relativistic plasma component), then because of the high density in the shell in the first hours they will largely be destroyed, and their energy will be dissipated in the form of neutrinos, γ-rays, and electrons and positrons which radiate in the magnetic field. A large flux of high energy ($\geq$ 100 Mev) γ-rays will thus be generated and we might expect fluxes to escape over this period at a rate of perhaps $10^{44} - 10^{45}$ erg/sec. For reasonable magnetic field values the synchrotron radiation will not lie in the x-ray or γ-range. However, it is possible that some part of the electron-positron flux will be dissipated by COMPTON collisions with thermal photons in which γ-rays are emitted. It is obvious that these suggestions are highly speculative. However, it is clear that detection of a supernova explosion by x-ray and γ-ray telescopes would give much information on the conditions at the early phases. For example, if there are no high energy γ-rays emitted this might be interpreted as meaning that there was no early generation of a large flux of relativistic protons.

26. Hard Radiation Emitted through Radioactivity. It has been suggested that in a supernova outburst considerable nucleosynthesis takes place[20]. In this

[20] E. M. BURBIDGE, G. R. BURBIDGE, W. A. FOWLER, and F. HOYLE: Rev. Mod. Phys. 29, 547 (1957)

a large flux of neutrons is added very rapidly to seed nuclei (r-process) building up to nuclei with A $\simeq$ 270 and giving rise to large numbers of neutron rich nuclei which subsequently decay. It is still not clear what fraction of the supernovae goes through this process but in connection with the possibility of checking this theory CLAYTON and CRADDOCK [36] have made calculations of the fluxes of γ-rays to be expected following such a process. The γ-ray line spectrum is calculated from the production curve for the r-process isotopes[21]. Using these

[21] D. D. CLAYTON, W. A. FOWLER, P. SEEGER: Ap. J. Suppl. (to be published)

abundances the best estimates are made of the prompt γ-ray spectrum using the nuclear energy levels. Also, an estimate has been made of the γ-ray flux which is emitted in spontaneous fission in such isotopes as Cf^{252}. The fluxes to be expected for a supernova remnant at the distance of the Crab (~ 1000 pc) are shown in Fig. 7 taken from the calculations of CLAYTON and CRADDOCK. The strongest line (390 kev line from Cf^{249}) radiates at a rate 10^{39} photon/sec at the source. The calculations have been normalized for the assumption that in a supernova remnant 1.5×10^{-4} $M_\odot$ (3×10^{29} gm) of Cf^{254} are produced. This is adequate to explain the light curve of a Type I supernova on the assumption[20] that this is due to Cf^{254}. Detection of such a flux is being attempted at the time of writing. This will give a direct observational test of this hypothesis of r-process isotope synthesis in Type I supernovae.

27. Neutron Stars It has been pointed out by CHIU [37] and FINZI [38] that, since it is possible that neutron configurations may be reached as an end phase of stellar evolution by processes which leave the star extremely hot, such configurations may, for rather a short period, be thermal x-ray emitters. However, from the theoretical standpoint it must be conceded that at the present time we cannot demonstrate conclusively that stable neutron configurations are ever formed or can exist if formed. The presumption of these authors is that the neutron configurations are formed during a supernova outburst, as was first proposed by BAADE and ZWICKY[22] many years ago. There are many theoretical uncertainties

[22] W. BAADE and F. ZWICKY: Ap. J. 88, 411 (1938); F. ZWICKY: Ap. J. 88, 522 (1938).

associated with neutron configurations which we mention breifly.

It is well known that there is a critical mass for a degenerate neutron configuration above which no stable equilibrium is possible. This result was first derived by LANDAU[23] and calculations by OPPENHEIMER and VOLKOFF[24] gave a value of

[23] L. LANDAU: Physik Zeit. Sovietunion 1, 285 (1932); [24] J. R. OPPENHEIMER and G. M. VOLKOFF: Phys. Rev. 55, 374 (1939)

about 0.7 $M_\odot$ for this observable mass limit. While in later calculations this mass limit has been slightly revised, it is clear that the mass limit lies near 1 $M_\odot$. Even the doubtful assumption of a hard-core nuclear potential, which is known to be incorrect from relativistic considerations, only extends the maximum mass to about 3 $M_\odot$. In fact it is clear from the earliest considerations[23] that the maximum mass is very insensitive to the equation of state at nuclear densities and above. For masses above the critical mass it appears that implosion must occur[25]. For a modern review see HOYLE, FOWLER, BURBIDGE, and BURBIDGE[26].

[25] B. DATT: Zeit. f. Ap. 108, 314 (1938; J. R. OPPENHEIMER and H. SNYDER: Phys. Rev. 56, 455 (1939).

[26] F. HOYLE, W. A. FOWLER, G. R. BURBIDGE, and E. M. BURBIDGE: Ap. J. 139, 909 (1964)

Thus, if neutron configurations which can exist long enough to be detected as sources of x-rays come from supernova outbursts, it is required that in the supernova outburst sufficient mass is ejected so that the resulting configuration falls below the limit for support by a degenerate neutron configuration. None of the attempts to unravel the processes of supernova outbursts have yet given any real indication that such conditions can be achieved. The attempts by the California-Cambridge group[20, 27] have not been able to answer this question.

[27] W. A. FOWLER and F. HOYLE: Ann. Phys. 10, 280 (1960); Ap. J. Suppl. 9, 201 (1964)

Even the range of masses of stars which become supernovae is in doubt, but it appears highly probable that the Type II supernovae are stars of quite large mass $\sim 30\ M_\odot$ [27]. All of the discussion of the supernova outburst as it applies to the last phases of nucleosynthesis, and neutrino emission, etc. have been carried out by neglecting the effects of rotation. However, as has been shown by HOYLE *et al.*[26] this *may* have the effect of allowing a massive star to fragment, either into white dwarf, or into neutron configurations (cf. Equation (45) of that paper[26]). In the work of CHIU [37] no conclusion as to whether a degenerate neutron configuration with a mass below the critical mass is left has been reached. The only attempt at a hydrodynamical calculation of the implosion of a supernova before relativistic effects become important is that by COLGATE and his colleagues[28].

28 S. COLGATE: Proc. of the Jaipur Conference (in press)

This calculation follows the collapse until nuclear densities are reached, but then it is supposed that a bounce occurs and the outer envelope is ejected. The calculation is not able to determine what fraction of the mass is left as a degenerate neutron configuration.

The only supernova remnant which can be studied in any detail is the Crab Nebula. While there are uncertainties in the mass of the nebula, analysis shows that it is only[29] $\sim 0.64\ M_{\odot}$ so that if the outburst originated from a star with

29 C. R. O'DELL: Ap. J. 136, 809 (1962)

a mass in excess of about $3\ M_{\odot}$ (and the type of supernova involved is still uncertain, as is the relation of type with mass) it must be concluded either that a large remnant has imploded or else that it is fragmented into a number of neutron stars.

Finally, there is some question about the stability of neutron configurations. The question of their dynamical stability has recently been considered for a range of models by MISNER and ZAPOLSKY[30] who have concluded that dynamically

30 C. W. MISNER and H. S. ZAPOLSKY: Phys. Rev. Letters 12, 635 (1964)

stable solutions exist for stars below the maximum mass for cold static equilibrium.

There is thus considerable uncertainty as to whether neutron stars are ever formed. If they are then detection of their x-rays emitted while the surfaces are still hot might provide the only direct observational test of their existence. Whether they are likely to be detected depends on the time that they may be expected to spend with their atmospheres hot enough to emit x-rays. The first calculations of the cooling rates [39], [40] suggested that such stars might emit for periods $\sim 10^3$ years. Thus if they were embedded in supernovae remnants such as the Crab which exploded in 1054 A.D. we might expect to detect them. The cooling is dominated by the neutrino production rate in the interior since the neutrinos escape from the stars with a negligible probability of being scattered or absorbed. A recent investigation by BAHCALL and WOLF [41] (see also FINZI [42]) taking into account the cooling reactions

$$n + n \rightarrow n' + p + e^- + \bar{\nu}_e$$

and

$$n + \pi^- \rightarrow n' + \mu^- + \bar{\nu}_\mu$$

and their inverses. If the first reaction alone is operating, the cooling rate is such that atmospheric temperatures only remain $\sim 2\text{-}3 \times 10^6$ degrees for about 10 years. There is still some doubt as to whether the second process operates, but if it does the cooling times are very much shorter than this. In any case, because of the argument previously given [see Eq. (24.1) and discussion], the short cooling time for neutron stars would rule them out as likely sources of x-rays.

From the observational side also there are very strong arguements against the neutron star hypothesis. The occultation observation of the NRL group [28] which shows that the source in the Crab has a diameter ~ 1 light year rules out its being a single neutron star and the existence of a cluster of such stars is improbable. Also, the observation of fluxes of 10-50 kev x-rays is not explicable in terms of a thermal source, since temperatures $\sim 10^8$ degrees are required, and these are far above that which the surface of a neutron star could attain for any significant time.

c) Mechanisms for X-ray Production in Discrete Sources

28. Apart from the mechanisms discussed earlier in this section, there are

three possible mechanisms for the x-ray production: (1) COMPTON scattering, (2) bremsstrahlung, and (3) synchrotron emission. When x-ray sources were first discovered, the possibility that they were neutron stars was discussed at length, but as was shown in the previous sub-section this explanation now appears to be untenable. It has been suggested [43] that the x-rays from the Crab are due to COMPTON scattering of the radio-optical synchrotron photons by the associated synchrotron electrons; in this manner the synchrotron photon energy is amplified by a factor γ_e^2, where $\gamma_e m_e c^2$ is the energy of the (synchrotron) electron involved in the scattering. However, as has been emphasized recently [44], the intensity of this COMPTON-synchrotron radiation can be shown to be far too small to explain the observations. The effect is small essentially because the probability that a synchrotron photon undergoes such a COMPTON scattering before escaping from the nebula is very small. The Crab is one of the most intense galactic radio emitters and if the effect is small for it, one should not expect to observe the effect in other galactic objects. One might think that COMPTON scattering might produce a large x-ray flux from quasi-stellar radio sources in which the photon density and high energy electron density are large. Again, however, simple calculations indicate a completely negligible and unobservable x-ray flux from this process. Consequently, we are led to rule out COMPTON scattering as an x-ray production mechanism in discrete sources[31]. This leaves only the synchrotron and brems-

[31] See, however, V. L. GINZBURG, L. M. OZERNOI, and S. I. SYROVATSKY: Doklady Akad. Nauk SSSR 154, 557 (1964), transl. Soviet Physics - Doklady 9, 3 (1964). They consider circumstances where one might be able to detect COMPTON-synchrotron photons of energy $\sim 10^7$-10^8 eV at a rate $\sim 10^{-5}$ photons/cm^2-sec from the quasi-stellar object 3C273-B which has a negative radio spectral index α. Because of the negative index, most of the COMPTON-synchrotron photon flux comes from the high energy end of the spectrum. The expected number of x-ray photons is

smaller and unobservable.

strahlung processes as possible x-ray sources.

First we consider the possibility that the x-rays from discrete sources are synchrotron radiation. We shall assume that an x-ray flux $F_x = 10^{-8}$ erg/cm^2-sec comes from a galactic source at a distance r = 10 kpc; the x-ray luminosity of the source is then $L_x = 4\pi r^2 F_x = 1 \times 10^{38}$ erg/sec. Further, we assume for simplicity that the x-ray flux is at an effective wavelength 3A and frequency $\nu = 10^{18}$ c/s, which is the characteristic synchrotron frequency $\nu_L \gamma_e^2$ emitted by electrons of energy $E_e = \gamma_e m_e c^2$. For a magnetic field H = 10^{-4} gauss (the assumed value in the Crab Nebula) the electron energy required is $E_e (\propto H^{-1/2})$ $= 3 \times 10^{13}$ eV. For such a high energy electron the lifetime against energy loss by synchrotron emission is only $E_e(dE_e/dt)^{-1} = \tau_e(\propto H^{-3/2}) = 30$ yr. The total energy in these electrons necessary to produce the flux F_x is E_t $(\propto F_x r^2 H^{-3/2})$ $= 1 \times 10^{47}$ erg. We note that: (1) The electron energies required to produce synchrotron x-rays are extremely high, (2) their lifetime is very short, and (3) the total energy involved is comparable to the energy released in a supernova outburst. Actually, the energy E_t quoted above is really the minimum energy of the highly relativistic electrons, since it includes only the synchrotron electrons producing x-rays. The contributions of the lower energy extension of the electron spectrum to the total energy would increase the value of the total energy by an amount depending on the index of the spectrum and the low energy cutoff. For the case of the Crab Nebula (see Sect. 29) the extension of the x-ray spectrum (which has an index of about 1.1) to the visible leads to a total electron energy which is not excessively large ($\sim 10^{48}$ erg). However, it is very significant that the lifetime of the high energy electrons required to produce synchrotron x-rays is appreciably less than the age of the Crab Nebula and other supernova remnants, because it would mean that the electrons would have to be continuously or at least periodically produced. If they are spasmodically produced or accelerated, one might expect to observe variations in the x-ray intensity over time scales ≤ 10 yr.

Because of the difficulties associated with the hypothesis that the x-rays from discrete sources are produced by the synchrotron process, it is worthwhile considering an alternative model in which it is supposed that an outburst gives rise to a small very hot cloud which continues to emit x-rays as part of the thermal bremsstrahlung. We now discuss the properties associated with such a model. Earlier, we had suggested that the source at the galactic center resulted from bremsstrahlung. At the time we envisaged bremsstrahlung production by non-thermal electrons of energy greater than the energy of the x-ray photons. However, as was first pointed out by ROSSI[32], about 10^5 times as much energy would be lost by these electrons in inelastic atomic collisions, so that if the x-ray luminosity of the source at the galactic center is 10^{38} erg/sec, about 10^{43} erg/sec must be supplied. This energy rate is excessively large on a galactic time scale (10^{10} yr), although perhaps it may be supplied during shorter times.

[32] Private communication.

In spite of this difficulty the conditions whereby x-rays are produced by non-thermal particles may still exist. If so, there will also be production of characteristic x-rays, as was pointed out by us [24] and by HAYAKAWA and MATSUOKA [45]. These x-ray lines are produced in the radiative cascade following the ejection of K-shell electrons by the incident electrons or protons. Actually, most of the K-shell vacancies produced result in the emission of an AUGER electron. The probability of x-ray emission by an element is given by the so-called K-fluorescence yield which is small for the light elements. The x-ray line emission, say of the K_α line, is approximately proportional to the product of the element abundance and K-fluorescence yield. One finds that the total intensity of the x-ray lines in the 2-8 A region should be $\sim 10\%$ of the intensity of the bremsstrahlung continuum in the same wavelength range. This result holds essentially independent of the spectrum of the incident suprathermal particles and holds whether the incident particles are protons or electrons. As HAYAKAWA and MATSUOKA have shown, the incident protons produce knock-on electrons and a radiation continuum by inner bremsstrahlung during the knock-on process. The observation of x-ray lines produced in this manner would be of great importance because, among other things (Cf. [26]), the abundances of the elements producing x-ray lines could be determined in this manner. In Table 3 we list the K_α wavelengths of the elements from carbon to iron along with their abundance and K-fluorescence yield. It appears that the most intense lines would be from Si (7.1A) and S (5.4A).

Energetically, bremsstrahlung x-ray production is more efficient in a high temperature ($T \sim 10^7$ °K) and low density gas where the bremsstrahlung is produced by thermal electrons and constitutes a major source of cooling and energy loss for the gas.

For the production of thermal bremsstrahlung the GAUNT approximation[33] to

[33] See, for example, H. A. BETHE and E. E. SALPETER: Quantum Mechanics of One- and Two-Electron Atoms (New York: Academic Press, 1957).

the bremsstrahlung cross section provides an adequate simplification. The differential cross section for the production of a bremsstrahlung photon of energy within $\hbar\, d\omega$ by an electron of velocity βc incident on a nucleus of charge Ze is

$$d\sigma_B(\beta,\omega;Z) = \frac{16\pi}{3\sqrt{3}} Z^2 \alpha r_o^2 \frac{1}{\beta^2} \frac{d\omega}{\omega}, \qquad (28.1)$$

where α is the fine structure constant and r_o the classical electron radius. The bremsstrahlung energy spectrum emitted per unit volume by encounters with ions of charge Ze is then

$$\frac{dE_B(Z)}{dt dV d\omega} = n_e n_Z \int \frac{d\sigma_B(\beta,\omega;Z)}{d\omega} \hbar\omega\, v f(v)\, dv, \qquad (28.2)$$

where $f(v)$ is the Maxwellian velocity distribution of the electrons; the integration in Equation (28.2) is over v from $(2\hbar\omega/m)^{\frac{1}{2}}$ to ∞. One obtains

$$\frac{dE_B(Z)}{dt dV d\omega} = n_e n_Z \; 2^4 \; 3^{-3/2} \; \alpha r_o^2 \hbar c^2 Z^2 (2\pi m/kT_e)^{\frac{1}{2}} e^{-\hbar\omega/kT_e}, \qquad (28.3)$$

and for the total emission between ω_1 and ω_2

$$\frac{dE_B(Z)}{dt dV} = n_e n_Z \; 2^4 \; 3^{-3/2} \; \alpha r_o^2 mc^2 Z^2 (2\pi kT_e/m)^{\frac{1}{2}} \cdot \left(e^{-\hbar\omega_1/kT_e} - e^{-\hbar\omega_2/kT_e}\right). $$

$$(\omega_1 < \omega < \omega_2) \qquad (28.4)$$

The total energy emitted per unit volume over all frequencies ($\omega_1 \rightarrow 0$, $\omega_2 \rightarrow \infty$) is

$$\Lambda_b = \sum_Z \frac{dE_B(Z)}{dt \; dV} = 1.43 \times 10^{-27} \; T_e^{\frac{1}{2}} \; n_e \sum_Z n_Z \; Z^2 \text{ c.g.s. units.} \qquad (28.5)$$

It is noteworthy that the bremsstrahlung spectrum (Eq. (28.3)) is significantly different from the spectrum of a black body, so that from measurements of the x-ray spectrum it may be possible to establish that some sources are hot optically thin gases.

In addition to bremsstrahlung, there is also cooling and x-ray emission by electron-ion radiative recombination and by inelastic electron collisions with ions followed by radiative de-excitation (line emission). The line emission is due mainly to oxygen and neon in high stages of ionization and the calculation of the cooling and x-ray production involves a calculation of the ionization equilibrium. Equilibrium is established between ionization by electron collision and radiative and dielectronic recombination. Here we give only the results; the details will be published elsewhere. Preliminary results have already been published [44]. Figure 8 gives[34] the rate of loss Λ_e (erg/cm^3-sec) of the free

34 The curve L in this figure differs from that given in [44] at lower temperatures. In our earlier work a rough estimate of the dielectronic recombination was used. More accurate calculations by W. TUCKER at UCSD give the curve in Fig. 8.

Λ_e ($erg/cm^3 sec$) of the free electron kinetic energy density by various processes in the temperature range between 10^6 and 10^8 °K. It is seen that bremsstrahlung dominates the cooling at higher temperatures. In Fig. 9 we give the rate of production of x-rays ($p_x = P_x/n_e^2$) in the 1 - 10 keV range as a function of temperature. In the calculation of these processes a general cosmic abundance of the elements has been assumed. The cooling time ($\tau_c \approx 3kT_e/n_e\Lambda_e$), density ($n_e$), and mass (M) of a volume V of gas required to produce the observed x-ray fluxes are of prime interest. We assume the source to be at a distance $r = 10$ kpc and to produce an x-ray energy flux $F_x = 10^{-8}$ erg/cm^2-sec on the range 1 - 10 keV. Further, we assume the gas to be at a temperature of 10^7 °K; parameters for other values of the temperature may be determined readily from Figs. 8 and 9. Since

$$F_x = p_x n_e^2 V/4\pi r^2, \qquad (28.6)$$

this choice of F_x, T, and r fixes the product $n_e^2 V$ at 4×10^{61} cm^{-3}. Then for a range $n_e = 0.1$ to 10^4 cm^{-3}, $\tau_c \sim 10^8$ to 10^3 yr, $V \sim 10^8$ to 10^{-2} pc^3, and $M \sim 4 \times 10^5$ to 4 solar masses. The associated optical bremsstrahlung intensity is of interest and depends only on the choice of T. One finds that this intensity corresponds to a 12th magnitude visual object which may be observable, depending on the extent of the source.

d) The Crab Nebula

29. The general observational data on the Crab are probably more extensive than for any other celestial object with the exception of the sun, although the general physical state of the Crab as derived from these observations is poorly known. Photon fluxes have been detected over a frequency range from 10^7 to 10^{19} c/s.

In this section we shall consider what can be inferred from the more recent observations in the high energy end of the spectrum.

Observations of continuum radiation emitted by the Crab have been made in essentially three frequency ranges: the radio range[35], the optical range[29], and

[35] R. G. CONWAY, K. J. KELLERMANN and R. J. LONG: M.N. 125, 261 (1963)

the x-ray range [18], [46]; Figure 10 summarizes the results. The radio spectral flux F_ν [watts/m^2- (c/s)] is of the form $C_r \nu^{-\alpha}$, where $\alpha = 0.27$, and C_r can be determined by the value[35] [1.23×10^{-23} w/m^2-(c/s)] of F_ν at $\nu = 400$ Mc/s. The synchrotron spectrum apparently retains this form up to a frequency $\nu_m = 10^{14}$ c/s at the beginning of the optical region. Designating this region $\nu < \nu_m$ as the radio range the radio luminosity L_r can then be computed from an assumed distance $d = 1030$ pc to the Crab:

$$L_r = 4\pi d^2 \int_0^{\nu_m} C_r \nu^{-\alpha} d\nu = 4\pi d^2 C_r (1-\alpha)^{-1} \nu_m^{1-\alpha} \approx 7.4 \times 10^{36} \text{ erg/sec.} \quad (29.1)$$

The luminosity in, for example, the visible range ($\nu = 4\text{-}8 \times 10^{14}$ c/s) of the optical region is

$$L_v \approx 1.7 \times 10^{36} \text{ erg/sec.}$$

Assuming a spectrum $F_\nu \propto \nu^{-\alpha'}$ with $\alpha' = 1.1$ for the low energy part of the x-ray region, the observations of the NRL group [18] in the range $3 \times 10^{17} < \nu < 10^{18}$ c/s indicate an x-ray luminosity

$$L_{x1} = 1.6 \times 10^{36} \text{ erg/sec.}$$

The observations of CLARK [45] in the higher energy x-ray region between $5 \times 10^{18} < \nu < 10^{19}$ c/s suggest an index $\alpha'' = 2$ and an x-ray luminosity in this range of

$$L_{x2} = 1.6 \times 10^{36} \text{ erg/sec.}$$

It should be noted that in the x-ray spectrum at the higher energies there is an apparent cutoff (see Fig. 10) or at least another change in slope.

When it was discovered that the Crab was an x-ray source, the suggestion was made that the x-rays were coming from a neutron star formed during the initial supernova outburst [18], [47]. An observation designed to test this hypothesis was carried out by the NRL group in July of 1964 during the lunar occultation of the Crab [28]. Since a neutron star would be essentially a point source of x-rays, as it would be occulted by the limb of the moon the observed counting rate would drop abruptly to zero. Had this effect been observed, it could have been taken as strong evidence for the existence of a neutron star. It was not observed. When the NRL group sent up a rocket during the time of the occultation (which lasted only a few minutes) with a detector system designed to look at the Crab, they found that the x-ray counting rate changed <u>continuously</u> during the occultation. This meant that the x-rays were coming from an <u>extended</u> source. The angular diameter of the x-ray source was found to be about 1', compared with an optical diameter of 2' and a radio diameter of 5'.

Assuming the radio spectrum $C_r \nu^{-\alpha}$ is due to synchrotron emission by relativistic electrons, an energy spectrum $n_e(\gamma_e) = K_e \gamma_e^{-\Gamma_e}$ with $\Gamma_e = 1 + 2\alpha = 1.54$ is implied. If the mean magnetic field in the Crab is $H = 10^{-4}$ gauss[29] the LARMOR frequency is $\nu_L = 280$ c/s, and the frequency $\nu_m = 10^{14}$ c/s would be emitted primarily by electrons with $(\gamma_e)_m = (\nu_m/\nu_L)^{\frac{1}{2}} \approx 6.0 \times 10^5$. The optical radiation from the Crab would be emitted by slightly higher energy electrons. If the radio emission originates from a volume $\int dV = V_0$, the radio flux F_ν is related to V_0, d, K_e, H by [see Eq. (20.1)].

$$F_\nu \approx (12\pi d^2)^{-1} V_0 K_e \, c r_0^2 \, H^2 \, \nu_L^{(\Gamma_e - 3)/2} \, \nu^{-(\Gamma_e - 1)/2} \; . \qquad (29.2)$$

From the value of the product $V_0 K_e$ determined from the radio brightness we can compute the total energy of the radio electrons in the Crab:

$$E_r = \int dV K_e\, m_e c^2 \int d\gamma_e\, \gamma_e^{-(\Gamma_e - 1)} = V_0 K_e\, m_e c^2 (2-\Gamma_e)^{-1}\, (\gamma_e)_m^{2-\Gamma_e} \qquad (29.3)$$

$$\approx 1.0 \times 10^{48} \text{ erg.}$$

The age τ of the Crab is 910 years and we see that $E_r/\tau = 3.5 \times 10^{37}$ erg/sec $\gg L_r, L_v, L_x$.

For the assumed magnetic field 10^{-4} gauss the electrons lose energy at a rate [Eq. (9.1)] $-\gamma_e^{-1}(d\gamma_e/dt) \approx \gamma_e \times 1.94 \times 10^{-17}$ sec^{-1}; for $\gamma_e \leq 1.8 \times 10^6$ ($\nu = \nu_L\, \gamma_e^2 \leq 9.0 \times 10^{14}$ c/s), $-\gamma_e^{-1}(d\gamma_e/dt) < \tau^{-1}$. Thus, for the radio and optical electrons the characteristic time for energy loss by synchrotron emission is greater than the age of the nebula. The rough coincidence of the critical electron energy and synchrotron emission frequency with the value (Fig. 10) above which the spectrum is apparently reduced or perhaps cut off may be interpreted as an indication that the relativistic electrons in the Crab were produced in the initial supernova outburst. The absence of any continuous production of high energy electrons would preclude any interpretation of the x-ray point in Figure 10 as being due to electron synchrotron emission, since the lifetime against energy loss through synchrotron emission by the energetic electrons necessary to produce this synchrotron frequency is about 30 years $\ll \tau$. An important parameter in this discussion is the strength of the magnetic field in which the electrons radiate. We have chosen a value of $H = 10^{-4}$ gauss, for which the lifetimes of the radio and optical electrons are longer than 10^3 years. However, if the assumed value of H is increased perhaps to 5×10^{-4} gauss, the lifetimes of the electrons emitting the same synchrotron frequencies are decreased by a factor of $(5)^{3/2}$ (= 11.2), and the optical electrons have lifetimes less than the age of the nebula so that continuous injection of such electrons is required to explain the optical radiation. Since the magnetic field strength is uncertain we shall consider the possibility of continuous injection of electrons in what follows. We also might mention that as GINZBURG, PIKELNER, and SHKLOVSKY[36]

[36] V. L. GINZBURG, S. B. PIKELNER, and I. S. SHKLOVSKY: Astr. Zhur. 32, 503 (1955)

have shown, there might exist in the Crab an energy loss by scattering by magnetic field condensations in the expanding nebula. These scatterings lead to a FERMI-type statistical deceleration of the electrons. The corresponding energy loss is approximately $-d\gamma_e/dt \approx \gamma_e V/r$, where V is the expansion velocity of the nebula and r its size; thus $r/V \approx \tau$, the age of the nebula. This energy loss process, if it is operative, dominates synchrotron losses for the radio and optical electrons but is negligible for higher energy electrons. With only this type of energy loss ($\propto \gamma_e$) the electron spectrum $n_e(\gamma_e)$ retains the power law shape of its production spectrum $q_e(\gamma_e)$.

Consider the case where the radio electrons of the Crab are produced continuously and, for simplicity, at a constant rate since the origin of the nebula. Neglecting energy losses[37] the continuity equation (13.1) reduces to

[37] A similar result would be obtained if the FERMI-type statistical deceleration were operative since the characteristic loss time for this process is approximately τ, the age of the nebula.

$$\partial n_e(\gamma_e)/\partial t = q_e(\gamma_e) = k_e \gamma_e^{-\Gamma_e}, \qquad (29.4)$$

and so the electron spectrum at the present time would have become

$$n_e(\gamma_e) = \tau\, q_e(\gamma_e) = K_e \gamma_e^{-\Gamma_e}. \qquad (29.5)$$

If the continuous production is via meson production in nuclear collisions, as was proposed[38] by one of us, there will also be continuous production of

[38] G. R. BURBIDGE: Nuovo Cimento Suppl. 8, 403 (1958)

π^o-decay photons, and it is of interest to compute the resulting π^o-photon flux. For a pion production spectrum $q_\pi(\gamma_\pi) = k_\pi\, \gamma_\pi^{-\Gamma_\pi}$ the π^o-decay photon production spectrum is approximately [Eq. (17.5)]

$$dn^{\circ}/d\eta\, dt \approx \frac{2}{3} k_{\pi} (2m_e/m_{\pi})^{-(\Gamma_{\pi} - 1)} \eta^{-\Gamma_{\pi}}. \tag{29.6}$$

The observed spectral flux of π°-photons would then be

$$j^{\circ}(\eta) = dJ/d\eta = (4\pi d^2)^{-1} \int dV(dn^{\circ}/d\eta\, dt). \tag{29.7}$$

Employing the relation (6.1) between k_{π} and k_e and Equations (29.2) and (29.5) to determine k_{π} from the radio spectrum we find

$$j^{\circ}(\eta) = 1.0 \times 10^{-4} \times \eta^{-1.54} \tag{29.8}$$

For photons of energy around $\eta = 200$ ($E \sim 100$ MeV) the integrated spectrum with $\Delta\eta/\eta \sim 1$ gives $\int j^{\circ}(\eta)\, d\eta \sim 10^{-4}\, \eta^{-0.54} \sim 5.7 \times 10^{-6}$ photons/cm^2-sec. This photon flux is almost four orders of magnitude smaller than the upper limit established by KRAUSHAAR and CLARK [20].

One can also calculate the high energy proton flux required to produce the pion production rate necessary to account for the secondary electron density and the radio spectrum. From this proton flux one can then compute the amount of K-series and inner bremsstrahlung x-rays in the wave-length range of the observations of BOWYER et al. [18]. The calculated x-ray flux, for a low energy proton cut-off $\gamma_p = 1$ is about 6 orders of magnitude smaller than the observed flux.

A more definite conclusion regarding secondary electron production in the Crab Nebula may be provided by an analysis of the observations of FRUIN et al. [48]. By employing CERENKOV light detectors to observe light pulses from showers in the atmosphere they were able to set upper limits for the high energy photon flux from the Crab Nebula and also from the quasi-stellar radio sources 3C147, 3C196, and 3C273. The threshold energy for their detection system was 5×10^{12} eV ($\eta \approx 10^7$). The established upper limits to the photon fluxes are listed in Table 4.

If photons of energy $\eta = 10^7$ result from the decay of π^0's produced in nuclear collisions, the corresponding synchrotron emission frequency in the Crab's magnetic field by electrons resulting from the decay of charged pions of the same energy is about $\nu = 10^{16}$ c/s for $H = 10^{-4}$ gauss. This frequency is about midway (on the logarithmic scale) between the optical and x-ray frequencies at which the Crab has been observed (see Fig. 10). It is of interest to compute the π^0-photon flux at $\eta = 10^7$ from the Crab on the assumption that the optical - x-ray flux (if it exists) from the Crab is due to synchrotron emission by secondary - produced electrons.

In the region around $\nu = 10^{16}$ c/s the apparent index of the synchrotron spectrum is (Fig.10) $\alpha = 1.1$, so that the electron spectrum in this region is of the form $n_e(\gamma_e) = K_e \gamma_e^{-\Gamma_e}$ with $\Gamma_e = 3.2$. Moreover, for these high energy electrons the dominant energy loss process is synchrotron emission and K_e is related to the electron production spectrum $q_e(\gamma_e) = k_e \gamma_e^{-\Gamma_\pi} (\Gamma_\pi = \Gamma_e - 1)$ by Eq. (14.4)

$$K_e = k_e / b(\Gamma_\pi - 1), \qquad (29.9)$$

with k_e related to k_π by Equation (6.1). Calculating the π^0-photon flux as in Equations (29.5) and (29.6) and again determining the parameter $(4\pi d^2)^{-1} V_0 k_\pi$ from the supposed synchrotron emission rate [$F_\nu \approx 1.4_5 \times 10^{-27}$ w/m^2 - (c/s) at $\nu = 10^{16}$ c/s] one calculates a π^0-photon spectrum given by

$$j^o(\eta) = 2.2_1 \eta^{-2.2} \; . \qquad (29.10)$$

For photons of energy $\eta = 10^7$ we find the integrated spectrum with $\Delta\eta/\eta \sim 1$ gives $\int j^o(\eta)\, d\eta \sim 2.2_1\, \eta^{-1.2} \sim 8 \times 10^{-9}$ photons/cm^2-sec. This calculated photon flux is almost two orders of magnitude <u>above</u> the observational upper limit (Table 4). Thus, the present preliminary observations are inconsistent with the interpretation of the x-ray emission from the Crab as synchrotron radiation <u>if</u> the necessary continuous production of high energy electrons is through secondary production via π-μ-e decay. If electrons are produced by secondary processes at a lower energy and then accelerated by FERMI processes to energies at which they will radiate synchrotron x-rays, it may be possible to expalin the observed x-ray flux without coming into conflict with the results of FRUIN *et al*.

In summary, regarding synchrotron radiation and the relativistic electrons in the Crab, provided that the magnetic field is as weak as 10^{-4} gauss, the view that the energetic electrons responsible for the radio and optical radiation in the Crab were produced in the initial supernova outburst is quite consistent. In fact, the apparent reduction below the extrapolated radio spectrum $F_\nu = C_r \nu^{-\alpha}$ in the optical region may possibly be interpretated as a result of energy losses by the more energetic electrons; that is, higher energy electrons would have already decayed in energy since the birth of the nebula. On the other hand, the electrons required to produce synchrotron radiation in the x-ray region would have to be continuously produced.

It should be pointed out that x-rays can also be emitted by the synchrotron process if electrons which are normally radiating in the optical range spiral into regions of much higher magnetic field. Since the critical frequency is proportional to H this means that the field must be increased by a factor of $(\nu_x/\nu_o) \sim 10^3$. Thus this would imply that there are regions in the Crab with magnetic field strengths as high as 10^{-1} gauss. There are many difficulties associated with such a model partly because it would require continuous production of particles which move into regions of high field, since the lifetimes are proportional to $(H)^{-2}$. Also, the mechanism by which such concentrations of magnetic flux can be maintained is difficult to understand.

Regarding the possibility that the x-rays from the Crab are from the bremsstrahlung process, we must emphasize again the difficulties of the energy requirement if the bremsstrahlung is by non-thermal electrons. On the other hand, as CLARK [45] has emphasized, to explain his observations at 50 keV a temperature of about 2 x 10^8 °K would be required to produce such energetic thermal bremsstrahlung. This temperature is about an order of magnitude larger than the values predicted from theories of the heating of the gas by the shock front resulting from the expanding ejecta. In view of these difficulties, which seem very great, it would seem that the "least objectionable" explanation for the x-ray production in the Crab is that the synchrotron process is responsible. Such an explanation has also been suggested by SHKLOVSKY and WOLTJER [68]. This problem of the Crab x-ray source has not as yet received a thorough theoretical treatment, and present conclusions must be regarded as tentative.

e) The Galactic Center

30. The x-ray source Sgr XR-1 at (or near) the galactic center is of special interest if it is indeed connected with processes in the nucleus of the galaxy. The first discrete x-ray source discovered [17] was identified with the galactic enter, although apparently most of the observed counting rate was actually due to the stronger Scorpius source which, with the poor resolution, could not be distinguished from the galactic center. On the assumption that the x-ray source was the galactic center, we attempted to connect the effect with phenomena observed in the nuclei of external galaxies and with the radio observations of the galactic center [24]. As we mentioned earlier (Sect. 28), our initial hypothesis of production by bremsstrahlung by non-thermal electrons meets with difficulties of energy requirements. A more plausible explanation is that the x-rays are due to thermal bremsstrahlung, in which case the characteristics (density, mass, etc.) of the source would correspond to those enumerated at the end of Sect. 28.

Alternatively, the x-rays from the galactic center could be explained as synchrotron radiation. The energies of the synchrotron electrons would then have to be very large and their lifetime very short. However, it is interesting to plot [44] the x-ray observations of the galactic center along with the radio observations[39] of the non-thermal source, as in Figure 11. The lines are the

[39] A. MAXWELL and B. DOWNS: Nature 204, 865 (1964).

extensions of the power low spectra derived for indices within limits (-0.72 ±0.05) such as to fit the radio data. It is seen that the x-ray point lies within the limits defined by the extrapolated curves, although the extrapolation is over a factor 10^{10} in frequency. While this might be taken to mean that a single mechanism is responsible for both the radio and x-radiation, it must be remembered that the ratio of the lifetimes τ_r/τ_x of the electrons giving rise to synchrotron radiation in the two spectral regions ν_r and ν_x is $(\nu_r/\nu_x)^{\frac{1}{2}}$. Since the lifetimes of the x-ray synchrotron electrons must be very short (~ 30 yr, see Sect. 28), and there is apparently no change in spectral index over the radio to x-ray frequency range, this would mean that the radio synchrotron source was also formed recently.

f) Solar System Sources

31. The Sun. The solar corona is well known to be a source of x-rays. A detailed review of solar x-ray astronomy has been given by FRIEDMAN [49] and our discussion will be extremely brief. Since the corona has a temperature $\sim 10^6$ degrees, the x-ray spectrum will consist of lines and continuum emitted in a variety of atomic processes; the first detailed computations of the spectrum which is emitted were made by ELWERT [50]. Early observations were made by the NRL group and since then there have been many observations from rockets and satellites. References are given by FRIEDMAN. At times of solar activity the x-ray emission is very greatly increased. The quiet sun is emitting in the kev range about 10^{21} erg/sec while at the time of a class 3 flare the emission can increase to $\sim 10^{26}$ erg/sec.

PETERSON and WINCKLER [51], using balloon techniques, detected hard radiation in a short burst lasting only a few seconds during a 2^+ flare. They deduced that the quanta had energies near 0.5 Mev. Later other observers [52] also detected radiation in short bursts at the times of flares; these have energies in the range 20 - 80 kev and 20 - 150 kev. A theoretical discussion of the γ-rays which may be emitted from the sun has been given by DOLAN and FAZIO [53]. It is well known that a burst of high energy charged particles is accelerated in a solar flare, and thus a flux of hard radiation is to be expected along with radio emission and enhancement of the visible light. SHKLOVSKY [54] proposed that these hard photons are produced by the COMPTON effect. However, it has been shown by ACTON [55] that the flux of electrons required in SHKLOVSKY's model ($\sim 10^{30}$ ergs of ~ 50 Mev electrons) will produce bremmstrahlung fluxes greater than those detected by ANDERSON and WINCKLER [52]. His computations show that a similar situation to that described for the Crab (Sect. 29) exists, i.e., a flux of relativistic electrons moving in any other than an exceedingly intense radiation field will emit far more quanta by bremmstrahlung than through the COMPTON effect. Thus the hard photons emitted in flares are most likely of bremmstrahlung or synchrotron origin. The latter mechanism is entirely probable since the magnetic fields are high and high energy electrons are known to be present.

32. The Planets and the Interplanetary Medium Fluxes of hard quanta may be produced whenever charged particles are present. Thus Jupiter and the Earth both of which contain trapped fluxes of charged particles must emit some x-rays and γ-rays. Discussion of the hard photons associated with the VAN ALLEN belts lies outside the scope of this article. In the case of Jupiter the total flux of radio emission which is believed to be of synchrotron origin is $\sim 10^{16}$ erg/sec. We may suppose that some fraction of the electron energy is dissipated in the upper atmosphere of Jupiter by bremmstrahlung processes which give rise to some

hard photons. An attempt to measure x-rays from Jupiter in the 4 - 8 kev range by FISHER et al. [56] set a limit of < 2.4 photons/cm^2 sec. This corresponds to setting a limit to the energy emitted in x-rays of $< 10^{19}$ erg/sec. This is far from being a meaningful limit, since the flux of x-rays is likely to be $\leq 10^{16}$ erg/sec.

HAYAKAWA and MATSUOKA [57] have attempted to estimate the amounts of hard radiation which are produced through the collision of cosmic-ray primaries with the surfaces of the moon and planets and the interplanetary medium. Information can be obtained on the compositions of lunar and planetary material by detecting the characteristic x-rays which may be emitted from some elements.

g) Hard Radiation from Stellar Coronae

33. Since the sun is the only star whose corona is directly detectible, all theories concerning the origin and conditions in a corona have stemmed from it. The first question that arises is therefore whether it is plausible to suppose that other stars have coronae similar to that of the sun. To answer that question it is necessary to consider the probable origin and source of heating of the solar corona. The theory of the expanding solar corona[40] is based on the concept that the convection below the photosphere generates wave motions (both acoustic and hydromagnetic waves have been discussed) which propagate upward and dissipate, and it is the dissipative heating which leads to coronal expansion. It therefore may be supposed that all stars which have extensive outer convection zones will maintain expanding coronae. This would imply that all main sequence stars below about F2 ($M \leq 1.5\ M_{\odot}$) would have extensive coronae and these stars comprise a considerable fraction of the mass of a galaxy. Also, all stars in the giant stage of their evolution would have coronae. The critical question next is to estimate the average temperature of such hypothetical coronae.

[40] E. N. PARKER: Interplanetary Dynamical Processes (New York: Interscience, 1963).

PARKER has pointed out that coronae heated at their bases will have temperatures given approximately by the relation $GMm_H/RkT \geq 4$, or $T \leq 5.8 \times 10^6 (M/R)^\circ K$ with (M/R) measured in solar units. For stars on the main sequence M/R is of the order of unity so that coronal temperatures in the range $10^6 - 10^7$ degrees are to be expected. For giant stars M/R is ≤ 0.1 and for supergiants it is ≤ 0.01. Thus the temperatures of the hypothetical coronae of giants are expected to be $\leq 10^6$ degrees, while for supergiants they are $\leq 10^5$ degrees, and it would appear that only main sequence stars are likely to have hot enough coronae to emit x-rays. PARKER has given various arguments for supposing that more massive main-sequence stars also may have coronae. However, the spectroscopic evidence for extended atmospheres in those stars suggests that the gas has temperatures only $\sim 10^4$ degrees (the heating is by dilute stellar radiation). Thus it is highly improbable that they have hot coronae.

In a previous discussion [58] we attempted to estimate the x-ray flux from the coronae of all of the stars in the galactic disk. There are a large number of uncertainties involved in making this estimate since many assumptions have to be made about the luminosity function of the stars, etc. However, from the early work of TUCKER [58] we estimated that the background flux from stars in the galactic bulge with "quiet" coronae would amount to about 4×10^{-11} erg/cm^2-sec in the 2 - 8 A region at the earth with an uncertainty of about an order of magnitude. More detailed work on this aspect of the problem is being carried out by TUCKER but the possible flux levels still appear likely to lie in the range $10^{-10} - 10^{-12}$ erg/cm^2-sec. Though many stars may be continuously flaring, their integrated contribution is not likely to affect this estimate appreciably.

h) Extragalactic Discrete Sources

34. There is still the possibility that some of the sources are extragalactic, and we consider in particular the Scorpius source from which an energy

flux of $J_E \sim 10^{-7}$ erg/cm^2-sec is observed in the x-ray region. If the Scorpius source were at a typical galactic distance (that is, within our own Galaxy) $d_g \sim 10$ kpc, its x-ray luminosity would be $L_g = 4\pi d_g^2 J_E \sim 10^{39}$ erg/sec. If it were at a typical inter-galactic distance (the distance to a nearby galaxy) $d_{i-g} \sim 1$ Mpc, its luminosity would be $L_{i-g} \sim 10^{43}$ erg/sec, while if it were at a cosmological distance (to a distant galaxy) $d_c \sim 1000$ Mpc, its luminosity would be $L_c \sim 10^{49}$ erg/sec. We now make several observations concerning the energetics of the problem of establishing the distance to and nature of the Scorpius source. On a cosmic time scale[41] $\tau_c \sim 10^{10}$ yr. the energy $L_{i-g}\ \tau \sim 3 \times 10^{60}$ erg is small compared with the optical energy radiated by a normal galaxy ($\sim 10^{62}$ erg), but a normal galaxy would be expected to radiate a very much smaller amount of energy in x-rays. No unusual external galaxies are observed in the direction of the Scorpius source which is about 20° off the galactic center, although interstellar extinction of our own Galaxy prevents observations at lower galactic latitudes (say $\leq 10°$). However, there are no strong radio sources in the direction of Scorpius. Regarding the possibility that the Scorpius source is a distant galaxy, we note that $L_c\ \tau_c \sim 3 \times 10^{66}$ erg, much greater even than the rest mass energy $M_g c^2$ of a galaxy. Moreover, in the matter-anti-matter annihilation of a galactic mass which we might conceive took place in a time $\ll \tau_c$, the photon energies would be ≥ 0.5 MeV, not x-ray (keV) energies. On the other hand, the size of a small radio source, for example a quasi-stellar object, is $s \sim 10$ kpc, and the time τ_s for a light signal to propagate this distance is $s/c \sim 10^{12}$ sec. The product $L_c\ \tau_s$ is then $\sim 10^{61}$ erg, roughly the energy E_r of strong radio sources which may be stored in the relativistic particles.

[41] This time is also roughly the characteristic time for the evolution of a galaxy.

In summary, it appears that normal distant galaxies (including radio galaxies) are incapable of producing the observed energy flux J_E corresponding to the Scorpius source over evolutionary time scales $\sim 10^{10}$ yr. However, an outburst over a shorter time might be capable energetically of producing the required x-ray luminosity. Let us consider further such a hypothetical outburst in a galaxy at a distance d involving the release of an amount E of energy, of which a fraction f_γ is emitted in high energy photons of mean energy $\bar{E}_\gamma$. If the outburst occurs during a time τ, the observed resulting photon flux would be

$$J_\gamma = \frac{f_\gamma E/\bar{E}_\gamma}{4\pi d^2 \tau} . \qquad (34.1)$$

For $E = 10^{60}$ erg, d = 1000 Mpc, and with $\bar{E}_\gamma$ in MeV and τ in years we have

$$J_\gamma \approx 170\ f_\gamma/\bar{E}_\gamma \tau \text{ photons/cm}^2\text{-sec},$$

and for $\bar{E}_\gamma \sim 100$ MeV (mean energy from π^o-decay) and $\tau \sim 1000$ yr (time scale for outburst), $J_\gamma \sim 10^{-3} f_\gamma$ photons/cm^2-sec. Unless f_γ is very small, a flux of this magnitude could be observable. The detection of such a discrete source of γ-rays (or x-rays) might then possibly be interpreted as the observation of the birth of a strong radio source. Finally, we might mention that DUTHIE et al.[21] report a possible (~ 100 MeV) γ-ray flux of ~ 0.002 photons/cm^2-sec from Cygnus A which is at a distance ~ 100 Mpc.

IV. NEUTRINO SOURCES

35. Any review of the fluxes of hard radiation which may be present in the universe would not be complete without mention of neutrinos. In principle detection of neutrino fluxes would give valuable direct evidence concerning conditions in stellar interiors, and also if high energy neutrinos could be observed

information on the high energy particle flux could be obtained. Moreover, evidence of the energy density of neutrinos in the universe may have cosmological significance. The subject of neutrino astronomy has been discussed and reviewed ad nauseam in the last two or three years following developments in the theory of weak interactions and the realization that neutrino emission processes will become the dominant energy loss mechanism in the final stages of stellar evolution. There are a number of recent papers and reviews which have given some account of these processes and their repercussions on stellar evolution, nucleosynthesis, supernovae and cosmology; full references can be obtained in papers by PONTECORVO [59], FOWLER and HOYLE [60], BURBIDGE [61], WEINBERG [62], FODOR, KÖRVESSY, and MARX [63], CHIU [37], and BAHCALL [64]. We only give a very brief summary here.

While the energy density in the flux of neutrinos is very considerable, so that, for example, for a normal galaxy it will be some 4% of the total luminous flux or about 4 x 10^{42} erg/sec, the very small interaction cross-sections $\left(\sim 10^{-44}\, \eta_{\nu}^{2}\ \mathrm{cm}^{2}\right)$, (unless resonances are present, cf. below) obviously make the fluxes very difficult of detection. Moreover, no method of detecting low energy neutrinos with energies below those necessary to induce inverse beta decays is known. We illustrate the problems by discussing the work on solar neutrinos and then consider fluxes from more distant stars and galaxies.

Neutrinos (ν_e) are emitted in the normal hydrogen burning processes in stars. About 2% of the energy released in the p-p chain and about 6% in the CNO cycle is emitted as neutrinos.

Undoubtedly the sun is likely to be the strongest apparent source of neutrinos and direct detection of them is of the greatest importance. Following an early suggestion of PONTECORVO, BAHCALL [65] and DAVIS [66] have considered in detail the possibility of the detection of neutrinos emitted in $Be^7(e^-,\nu)\ Li^7$

and $B^8(e^-,\nu)$ Be^8 through their absorption $C\ell^{37}$ (ν,e^-) Ar^{37}; the activity of Ar^{37} is then measured. On the basis of the best solar models[42] BAHCALL [65]

[42] R. L. SEARS: Ap. J. 140, 477 (1964).

has estimated that the fluxes at the earth's surface will be 1.2×10^{10} neutrinos/cm^2/sec and 2.5×10^7/cm^2 sec from the decay of Be^7 and B^8 respectively. From BAHCALL's analysis of the cross-sections for $C\ell^{37}$ (ν,e^-) Ar^{37} DAVIS has concluded that the expected neutrino captures in 10^5 gallons of $C_2C\ell_4$ in a mine would be about 4 - 11 a day which would be an order of magnitude above the background produced by the production of Ar^{37} by cosmic rays underground through $C\ell^{37}$ (p,n) Ar^{37}. The flux of detectable neutrinos from the central bulge of the galaxy will be less than that from the sun by a factor $10^7 - 10^8$ while the flux to be expected from a nearby galaxy such as M 31 would be less than the sun by a factor $\sim 10^{11}$. While neutrinos are emitted in the normal energy producing cycles in the stars, neutrinos and anti-neutrinos are emitted with positrons and electrons respectively by beta unstable nuclei in the processes of energy generation and element synthesis beyond hydrogen. However, for a galaxy in a steady state it is easily shown that the fluxes to be expected are small compared with those emitted in hydrogen burning.

In the high temperature phases of stellar evolution (for core temperatures $\geq 5 \times 10^8$ degrees) neutrino pair emission becomes the dominant mechanism of energy loss. They arise by a variety of reactions in all of which they replace photon emission. An important process is

$$e^+ + e^- \rightarrow \nu + \bar{\nu} \; . \qquad (35.1)$$

While this mechanism of energy loss is important from the point of view of the evolutionary process, an individual object (perhaps the immediate forewarning of a supernova) would be very difficult to detect even if a mechanism of detecting low energy neutrinos were found, because of the very short time scale associated with such evolutionary phases. Thus, for example, FOWLER and HOYLE [60] have calculated that if one solar mass in the center of a massive star reaches a temperature of 3.5×10^9 degrees the neutrino flux will amount to $\sim 10^{47}$ erg/sec. However, this phase will only last a few seconds. At a later stage, after a star has exploded and if a neutron configuration remains, the initial neutrino flux for a core temperature of 10^9 degrees will be much less (see [39], [41], and [42]).

We turn finally from the low energy neutrinos emitted in stellar evolution to consider the possibility as to whether high energy neutrinos ($E_\nu \geq 100$ MeV) are emitted in supernova outbursts and from radio sources in which large fluxes of high energy particles are present. Neutrinos are produced whenever a flux of high energy nuclei interacts with the nuclei of the local gas atoms to produce pions. In the $\pi \to \mu \to e$ decay of the charged pions both neutrinos and antineutrinos of the electron and muon type result. That is, in the pion decay

$$\pi^+ \to \mu^+ + \nu_\mu, \qquad \pi^- \to \mu^- + \bar{\nu}_\mu, \tag{35.2}$$

while in the muon decay

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu, \qquad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu . \tag{35.3}$$

Thus, a single charged pion pair π^+, π^- results in $2(\nu_\mu + \bar{\nu}_\mu) + (\nu_e + \bar{\nu}_e)$; twice as many μ-neutrinos as e-neutrinos are produced. In the pion decay the muon is essentially non-relativistic in the rest frame of the pion and most of the energy is carried away by the neutrino; here $E_\nu \approx (m_\pi - m_\mu)c^2 \approx \frac{1}{4} m_\pi c^2$. In the muon decay the mean neutrino energy is about $\frac{1}{3} m_\mu c^2 \approx \frac{1}{4} m_\pi c^2$ in the rest frame of the muon and pion (see Sect. IIb). Thus, the mean lab energy of the neutrinos in both decays is about $\frac{1}{4} \gamma_\pi m_\pi c^2 = \frac{1}{4} E_\pi$.

The (anti)neutrino production spectrum is readily computed from the pion production spectrum and is of the form similar to that for the production spectrum of π^o-decay photons [see Eq. (17.5)], that is, $dn_\nu/d\eta_\nu dt \propto \eta_\nu^{-\Gamma_\pi}$, where Γ_π is the index of the pion production spectrum. The ratio of the (anti)neutrino production spectrum (or of the spectral flux) to the π^o-decay photon spectrum at the same η is, assuming equal number of π^+, π^-, π^o produced, roughly

$$\left(\nu_\mu/\gamma\right)_{\text{same }\eta} \approx 2^{-(\Gamma_\pi - 2)}$$
$$\left(\nu_e/\gamma\right)_{\text{same }\eta} \approx 2^{-(\Gamma_\pi - 1)} \qquad (35.4)$$

BAHCALL and FRAUTSCHI [67] have discussed the detection of high energy neutrinos and have considered the possibility of observing a neutrino flux from the Crab Nebula and other radio sources. They assume neutrino production via $\pi - \mu$ decay, which implies also continuous production of pions and π^o-decay photons. Assuming a continuous constant production of high energy radio electrons through π-μ decay in the Crab since its birth, the associated π^o-decay photon flux was calculated in Section III [Eq. (29.8)]. The corresponding neutrino flux is of the same form

$$j_\nu(\eta_\nu) = k\eta_\nu^{-\Gamma_\pi}, \qquad (35.5)$$

with $\Gamma_\pi = 1.54$. For μ-neutrinos $k_\mu \approx 2^{0.46} \times 1.0 \times 10^{-4}$ cm^{-2} sec^{-1}, while for e-neutrinos $k_e \approx \frac{1}{2} k_\mu$. This neutrino spectrum and also the π^o-decay photon spectrum is associated with (if there is continuous production) the radio synchrotron spectrum for 10^7 c/s $< \nu < 10^{14}$ c/s and with electron energies $200 < \gamma_e < 6 \times 10^5$. The range of η_ν over which Equation (35.5) should represent the neutrino spectrum is the same as the range of γ_e, that is for 100 MeV $\le E_\nu \le$ 300 BeV. A neutrino spectrum similar to Equation (35.5) was derived by BAHCALL and FRAUTSCHI. However, we doubt that such a neutrino flux will ever be observed from the Crab. In Section III we showed that there is evidence against continuous production via π-μ decay of very high energy electrons which would produce synchrotron radiation in the optical - x-ray range; moreover, the lifetime against synchrotron losses for the radio and optical electrons in the Crab is longer than the age of the nebula. We therefore feel that probably there is little or no continuous production of radio electrons in the Crab and no associated neutrino or π^0-decay photon production.

Regarding possible neutrino production in other radio sources, in particular in extragalactic objects, similar considerations apply. If there does exist continuous production of radio electrons via π-μ decay, and a steady state exists, then the energy radiated in neutrinos would be comparable to the total energy emitted in synchrotron radiation by the relativistic electrons produced with the neutrinos. For "normal" radio galaxies with steep spectra (index $\alpha \approx 0.8$) most of the neutrinos produced would have fairly low energies ($E_\nu \sim 100$ MeV), while sources with flat radio spectra (e.g., Crab Nebula, M 82) might be expected to emit predominantly higher energy neutrinos (say, $E_\nu \sim 100$ BeV). The strong extragalactic radio sources and quasi-stellar objects would be emitting lower energy neutrinos with $E_\nu \sim 1$ BeV at power levels of 10^{44} - 10^{45} erg/sec.

However, it appears probable now that such steady state conditions are not present in these sources, so that even if large proton fluxes are present, the neutrino fluxes will be much lower than this[43]. On the other hand it is possible that at an early phase when a violent outburst in a galaxy gives rise to some 10^{60} ergs of high energy particles (perhaps over a period of 1000 years), a large fraction of which may be protons, the collisions of some part of these with the interstellar gas before they escape into regions of very low density might give rise to a flux of high energy neutrinos several orders of magnitude greater

[43] G. R. BURBIDGE, E. M. BURBIDGE, A. R. SANDAGE: Rev. Mod. Phys. 35, 947 (1963).

than the values corresponding to steady state conditions. Thus one might expect to observe both neutrinos and π^0-decay photons from a violent outburst in a galaxy (see Sect. III).

The possibility of detecting such fluxes of high energy neutrinos has been considered by BAHCALL and FRAUTSCHI [67]. They have pointed out that the very small cross sections for the interaction of neutrinos with matter mean that from very strong radio sources with a dominant proton flux only one neutrino-induced event per day would be experienced in a 10^5 ton absorber. However, as BAHCALL and FRAUTSCHI have proposed, the possibility exists that resonances in neutrino interaction processes are present. As they suggest, the reaction

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^+ \qquad (35.6)$$

may have a resonance and may be detected by neutrino interactions with material in the earth's crust. Clearly a great deal of information might be gained from observations of neutrinos from extragalactic objects. Thus the most pressing requirement is to devise a neutrino telescope which has good angular resolution. BAHCALL and FRAUTSCHI have suggested that the muons ejected in (35.6) may enable this to be achieved.

V. CONCLUSION

36. We have tried to summarize those mechanisms which may give rise to hard radiation in the universe. At present, apart from observations of the sun, there is little observational evidence which can be used in conjunction with the theoretical estimates. The brilliant work of the NRL, MIT, and Lockheed groups has shown that there are sources of x-rays at flux levels which are detectable with present techniques. Moreover, the absence of a large isotropic flux of x-rays has enabled us to set limits on the temperature of the intergalactic medium.

As far as γ-rays are concerned it is not yet clear whether high energy γ-rays are present at the flux levels calculated in Section II. The detection of high energy neutrino fluxes would be very exciting but the preliminary results must be viewed with caution.

What are the possibilities for further investigations in this field? To us the parallel of this field of research with that of the early days in radio astronomy is strong. There is one major difference, however, and this concerns the theoretical expectations in the field.

The discovery of significant fluxes of radio emission from the cosmos was totally unexpected, and in the first decade after the war theoreticians only gradually came to understand that the process by which the non-thermal sources radiate is the synchrotron mechanism. Of course the process of thermal emission was well understood but could not explain the strength or the spectral characteristics of the bulk of the radiation. During this period there was much confusion because of the unexpected nature of the discoveries and it was the interplay between the theory and optical observation which led to the elucidation of the mechanism by which the sources radiate. The theoretical problem then devolved into that of understanding how the vast fluxes of relativistic particles and magnetic field originate.

As far as the hard radiation is concerned, the physical mechanisms by which such radiation can be emitted are well known and the level at which fluxes have been detected (or not detected) suggests that no objects with the unexpected character of the radio sources are likely to be found by observational techniques in this energy range. If hard radiation is emitted by hot bodies such as neutron stars, then they must have very hot surfaces and they will cool very rapidly and soon cease to emit hard radiation. If very hot low density regions are generated in supernova outbursts they may well have much longer lifetimes so that it is possible that they can be detected (cf. Section III). Otherwise the mechanisms by which hard quanta are emitted all stem from the interaction of fast charged particles with matter, radiation, or magnetic fields. Knowledge gained through cosmic-ray and radio astronomical discoveries enables predictions to be made of the fluxes of hard radiation to be expected with a range of parameters associated with the present uncertainties in these quantities. Thus detection and even non-detection of hard radiation will be most valuable in determining the state of matter and radiation in the universe.

The parallel between the developments in radio astronomy and x-ray, γ-ray, and neutrino astronomy is very close when we consider the problem of the discrete sources. In the early days in radio astronomy resolution was very poor and at least one of the strongest sources was put in the wrong constellation by one notable group of investigators. All of the major developments in the study of discrete radio sources have come in step with the increase in precision with which positions of sources could be determined. This has enabled the objects to be observed optically with large telescopes. With optical identification has come measurement of distance and with this a beginning of quantitative study of the physical conditions in the sources. It is the absence of a method of determining the distance of an extragalactic source which has required the cooperation of optical and radio telescopes[44]. The same situation appears to apply in γ-ray and x-ray astronomy, since the flux emitted in lines will in general be small. A considerable improvement in resolution is required in order to determine better positions for the x-ray sources so far detected. The lunar occultation observation of the Crab by the NRL group is a first step in this

[44] In principle the 21 cm line is a powerful tool for determining distance by redshift measurements, but in practice it cannot be used since to detect the feature in galaxies at only very modest distances (≥ 20 Mpc) is beyond the capability of present day radio telescopes.

direction and at the time of writing a more accurate position for the Scorpius source is being obtained. Already the combination of observational arguments concerning the angular diameter and spectral characteristics of the Crab source together with theoretical discussions of the cooling rate for neutron stars leads to the conclusion that this source is almost certainly not a neutron star, and it is very doubtful whether any of the sources discovered so far are neutron configurations.

It is clear that the various theoretical estimates of fluxes which we have given in this paper suggest that a great increase in sensitivity of detectors as well as good resolution will be needed to exploit this field to the utmost. Finally, it is not out of place to remark that the x-ray observations have already shown that the universe is not very hot, and it may in fact be rather cool. In this case, apart from the neutrino flux which is part of the general cosmological thermal radiation field, the flux of hard radiation may be rather weak.

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TABLE 1

THE OBSERVED HIGH ENERGY COSMIC PHOTON SPECTRUM

Author	Designation in Fig. 6	Energy	$\bar{\eta}$	$j(\bar{\eta})$ (cm^{-2} sec^{-1})
GIACCONI *et al.* [17]	G	$\sim$ 2-3 kev	5×10^{-3}	4×10^{3}
BOWYER *et al.* [18]	B	$\sim$ 2-3 kev	5×10^{-3}	2×10^{4}
ARNOLD *et al.* [19]	A	$\sim$ 1 Mev	2	$\lesssim 0.08$
KRAUSHAAR and CLARK [20]	K-C	$\sim$ 100 Mev	200	$\lesssim 4 \times 10^{-5}$
DUTHIE *et al.* [21]	D	$\sim$ 100 Mev	200	$\lesssim 3 \times 10^{-4}$
FIRKOWSKI *et al.* [22] SUGA *et al.* [23]	EAS	$\sim 10^{15}$ ev	2×10^{9}	$\lesssim 10^{-20}$

TABLE 2

X-RAY SOURCES

(after BOWYER *et al.* [27])

Source	R. A.	(1950) Dec.	Flux (a) (counts/cm^2-sec)	(10^{-8} ergs/cm^2-sec) (b)	(c)
Tau XR-1	05^h 31.5^m	22.0°	2.7	5.5	1.1
Sco XR-1	16^h 15^m	-15.2°	18.7	38	7.9
Sco XR-2	17^h 8^m	-36.4°	1.4	2.9	0.6
Sco XR-3	17^h 23^m	-44.3°	1.1	2.3	0.5
Oph XR-1	17^h 32^m	-20.7°	1.3	2.7	0.6
Sgr XR-1	17^h 55^m	-29.2°	1.6	3.3	0.7
Sgr XR-2	18^h 10^m	-17.1°	1.5	3.0	0.6
Ser XR-1	18^h 45^m	5.3°	0.7	1.5	0.3
Cyg XR-1	19^h 53^m	34.6°	3.6	7.3	1.5
Cyg XR-2	21^h 43^m	38.8°	0.8	1.7	0.4

(a) Uncorrected for atmospheric absorption. Measured 1/4-mil Mylar window

(b) Computed for 2 x 10^7 deg K black body, 1.5 - 8 A

(c) Computed for 5 x 10^6 deg K black body, 1.5 - 8 A

TABLE 3

CHARACTERISTIC X-RAY DATA

(after GOULD and BURBIDGE [24])

Element	Logarithmic Abundance	K-Fluorescence Yield	K_α Wavelength (A)
C	8.60	0.00126	45
N	8.05	.00223	31
O	8.95	.00397	24
F	6.0	.00634	18
Ne	8.70	.00963	15
Na	6.30	.0140	12
Mg	7.40	.0197	9.9
Al	6.22	.0269	8.3
Si	7.50	.0360	7.1
P	5.40	.0468	6.1
S	7.35	.0597	5.4
Cl	6.25	.0748	4.7
Ar	6.88	.0923	4.2
K	4.82	.112	3.7
Ca	6.19	.134	3.4
Sc	2.85	.158	3.0
Ti	4.89	.184	2.7
V	3.82	.212	2.5
Cr	5.38	.241	2.3
Mn	5.12	.272	2.1
Fe	6.57	0.304	1.9

TABLE 4

UPPER LIMITS TO THE HIGH ENERGY PHOTON FLUX FROM VARIOUS SOURCES
(after FRUIN *et al.* [48])

Source	Photon Flux (photons/cm^2-sec)
Crab Nebula	1×10^{-10}
3C147	1×10^{-10}
3C196	5×10^{-11}
3C273	3×10^{-10}

FIGURE CAPTIONS

Fig. 1 Electron energy loss rate in the Galaxy by synchrotron emission (S), leakage out of the halo (L), bremsstrahlung (B), COMPTON scattering (C), and ionization (I).

Fig. 2 Electron energy loss rate in the intergalactic medium by synchrotron emission (S), cosmic expansion (E), COMTPON scattering (C), bremsstrahlung (B), and excitation of plasma oscillations (P).

Fig. 3 Calculated energy spectrum of relativistic electrons in the galactic halo and in the intergalactic medium.

Fig. 4 Optical thickness τ as a function of wavelength λ in the x-ray range for photons traversing a distance of 1 kpc in which the matter is gaseous and atomic at a cosmic abundance with $n(H) = 1\ cm^{-3}$.

Fig. 5 Optical thickness τ as a function of photon energy E at very high energies for photons traversing 5×10^{27} cm of intergalactic matter in which the radiation field is PLANCKian with kT = 0.5 eV with a total energy density of 0.01 eV/cm^3.

Fig. 6 Calculated high energy photon background fluxes from synchrotron radiation, COMPTON scattering, bremsstrahlung, and π^o-decay. The unprimed-designated spectra represent the galactic contributions and the primed denote the spectra from the intergalactic medium. Observational points are denoted by circles and arrows (limits). The letters next to the points refer to the observers (see Table 1).

Fig. 7 The spectrum of the line fluxes anticipated from the Crab Nebula as calculated by CLAYTON and CRADDOCK [36].

Fig. 8 Cooling rate as a function of temperature. Λ_e denotes the rate of change of the free electron kinetic energy density. Cooling by bremsstrahlung (B), line emission following inelastic electron collisions (L), and recombination (R) is shown. The ions of the following elements have been included: (B) H + He, (L) He + C + N + O + Ne + Mg, and (R) H + He + O + Ne.

Fig. 9 X-ray production rates in the 1 - 10 keV range by bremsstrahlung (B_1), recombination radiation (R) and the line emission (L). The bremsstrahlung rate (B_{10}) in the 10 - 20 keV range is also shown. Ions of the following elements have been included: (B_1, B_{10}) H + He, (L) Ne, and (R) H + He + H + O + Ne. The line emission is due to the 1s - 2p transition in Ne^{+9} (E = 1.02 keV). This is the strongest line emitted in 1 - 10 keV range.

Fig. 10 The observed emission continuum of the Crab Nebula in the radio (R), optical (O) and x-ray regions (X1, X2). The observational data is shown somewhat schematically, the rectangles showing errors in the observed fluxes. The point at the highest energy represents an upper limit [46].

Fig. 11 The observed radiation spectrum from the galactic center. Dots denote the radio observations; an x denotes the x-ray point, determined from an energy flux 10^{-8} erg/cm^2-sec and bandwidth $\Delta\nu/\nu = 1$ at $\nu = 10^{18}$ c/s.

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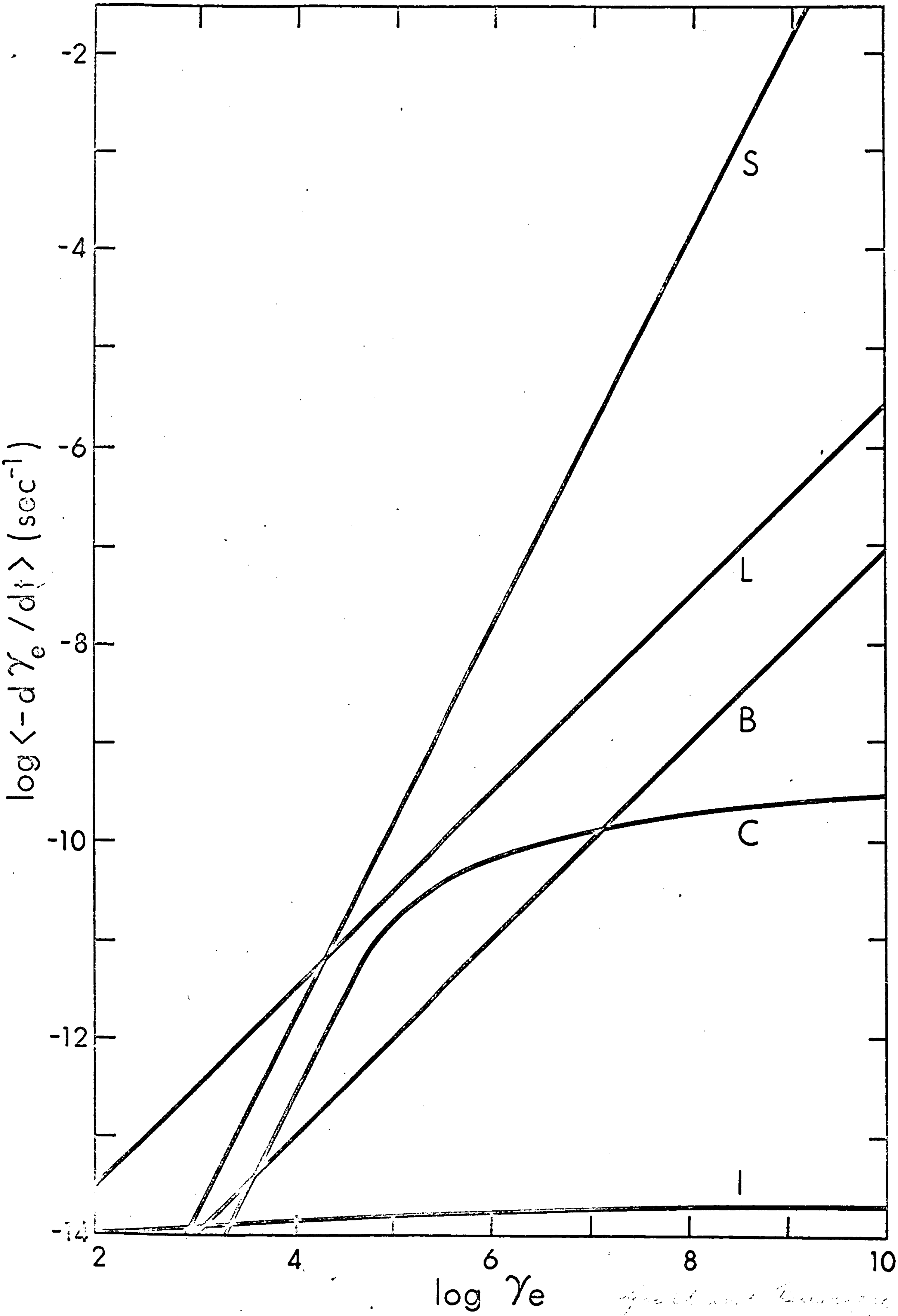
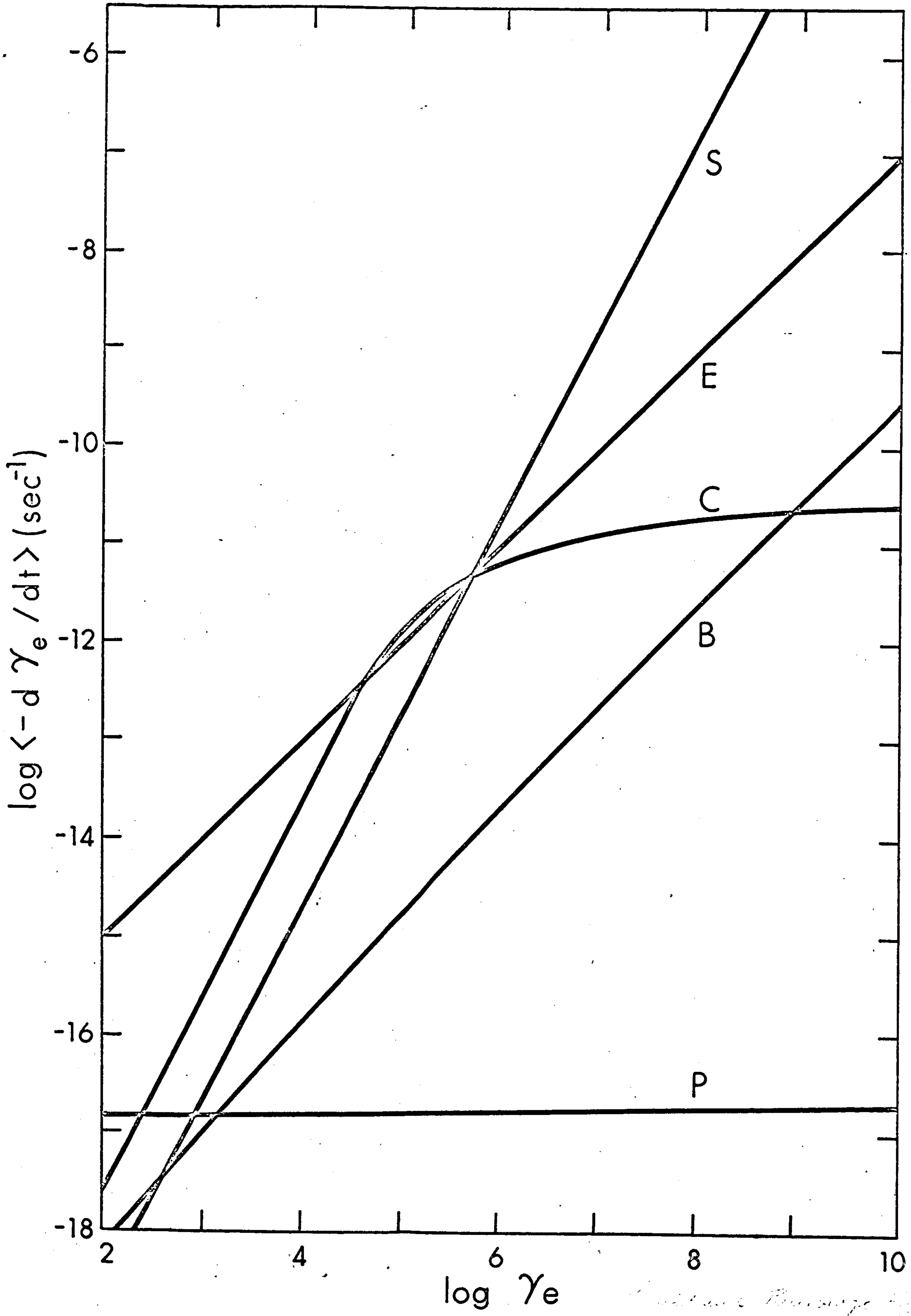


-2
-4
-6
-8
-10
-12
-14
2
4
6
8
10
log ⟨−dγe /dt⟩ (sec⁻¹)
log γe
S
L
B
C
I



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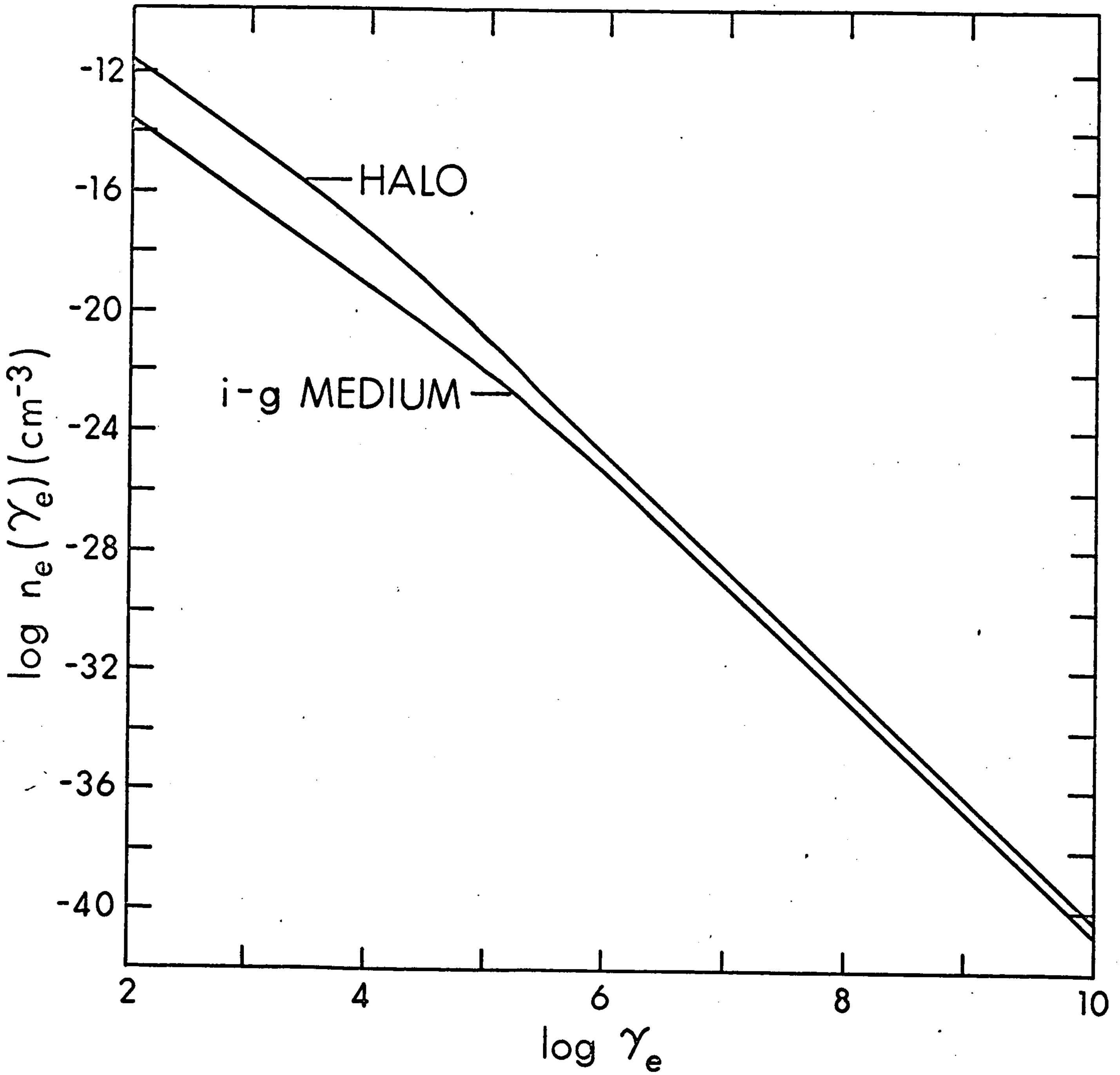
log γe



HALO
i-g MEDIUM
log $n_e(\gamma_e)$ (cm^{-3})
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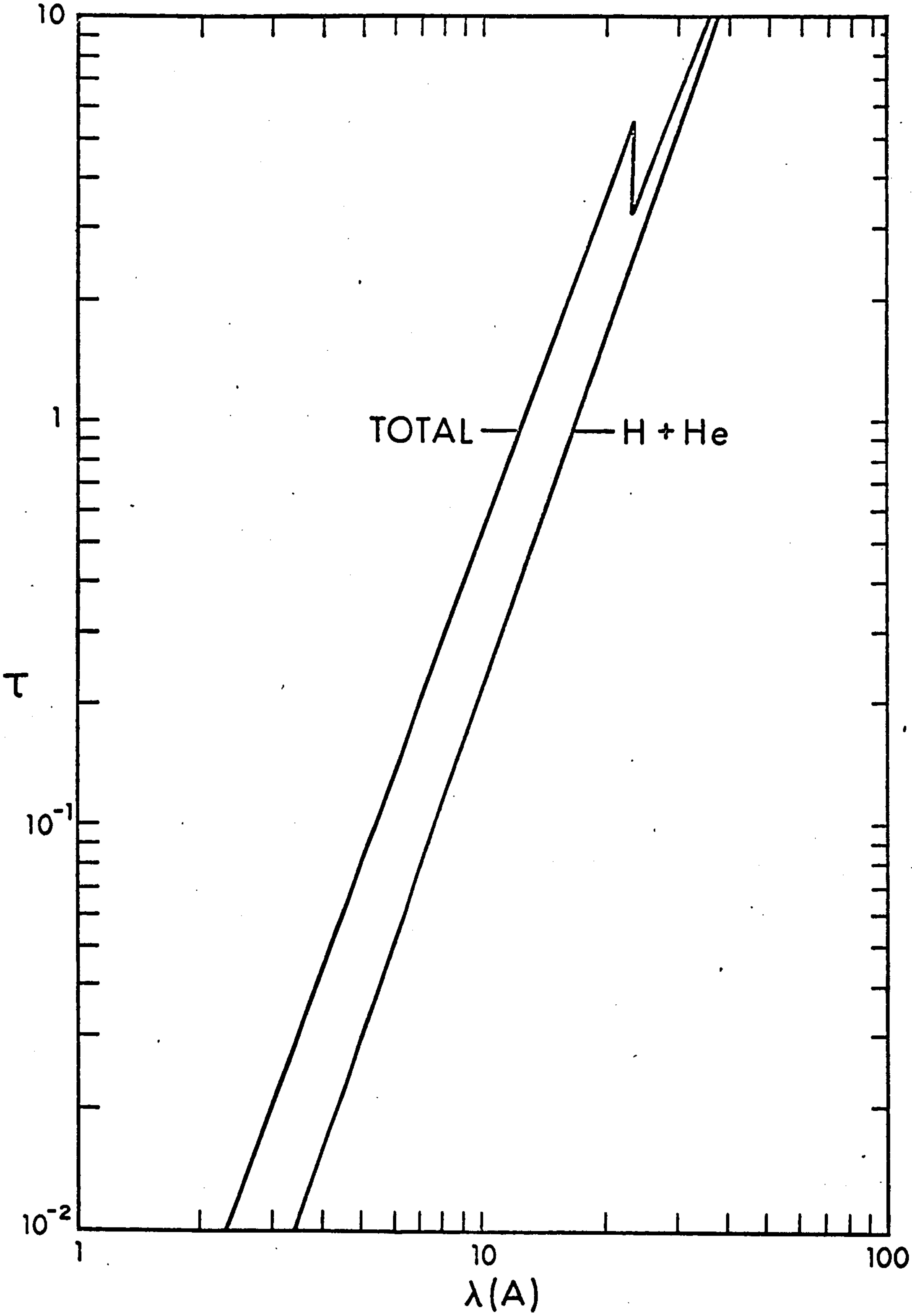
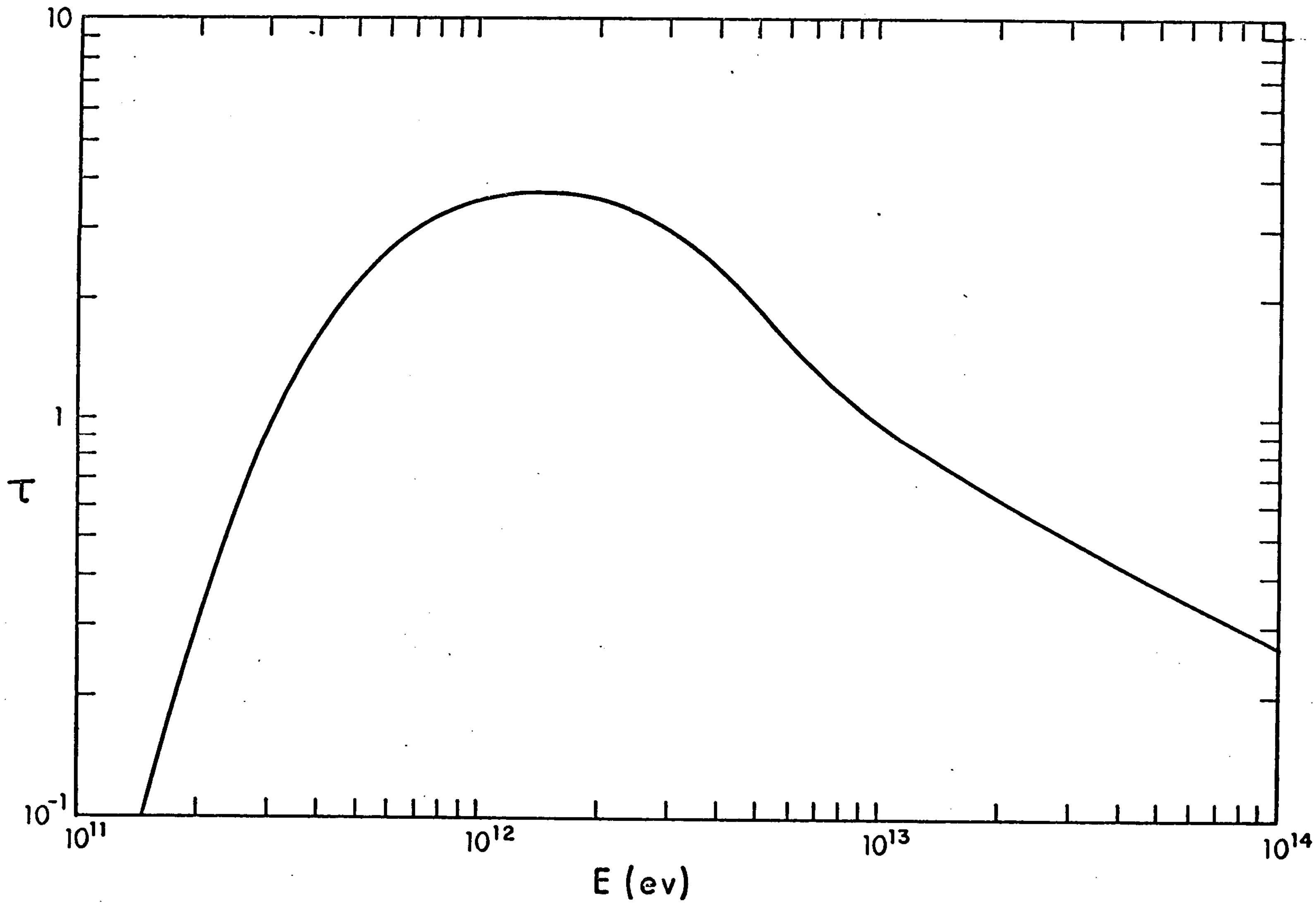
-20
-24
-28
-32
-36
-40
2
4
6
8
10
log γ_e



Gould and Burbidge, Fig. 7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τ
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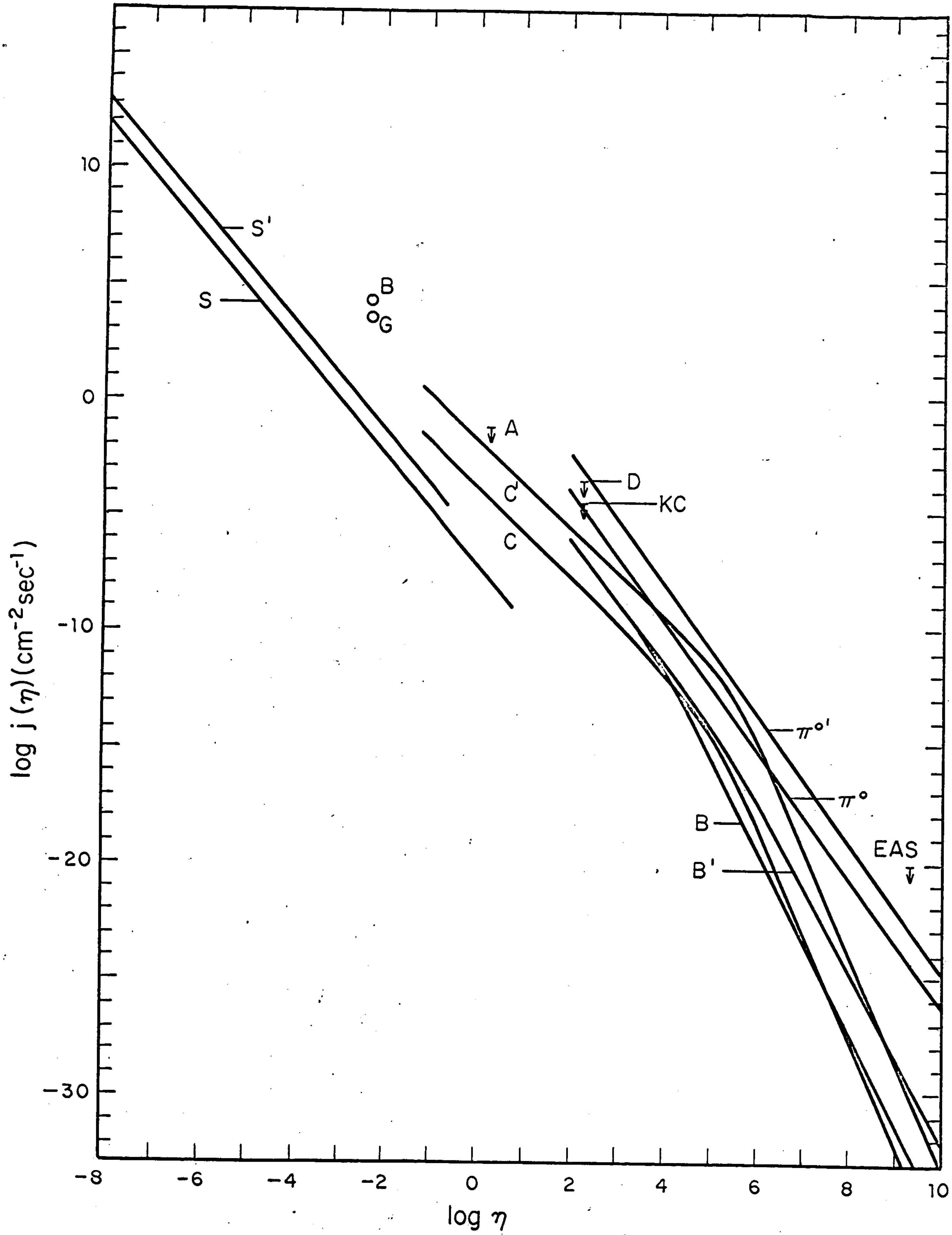
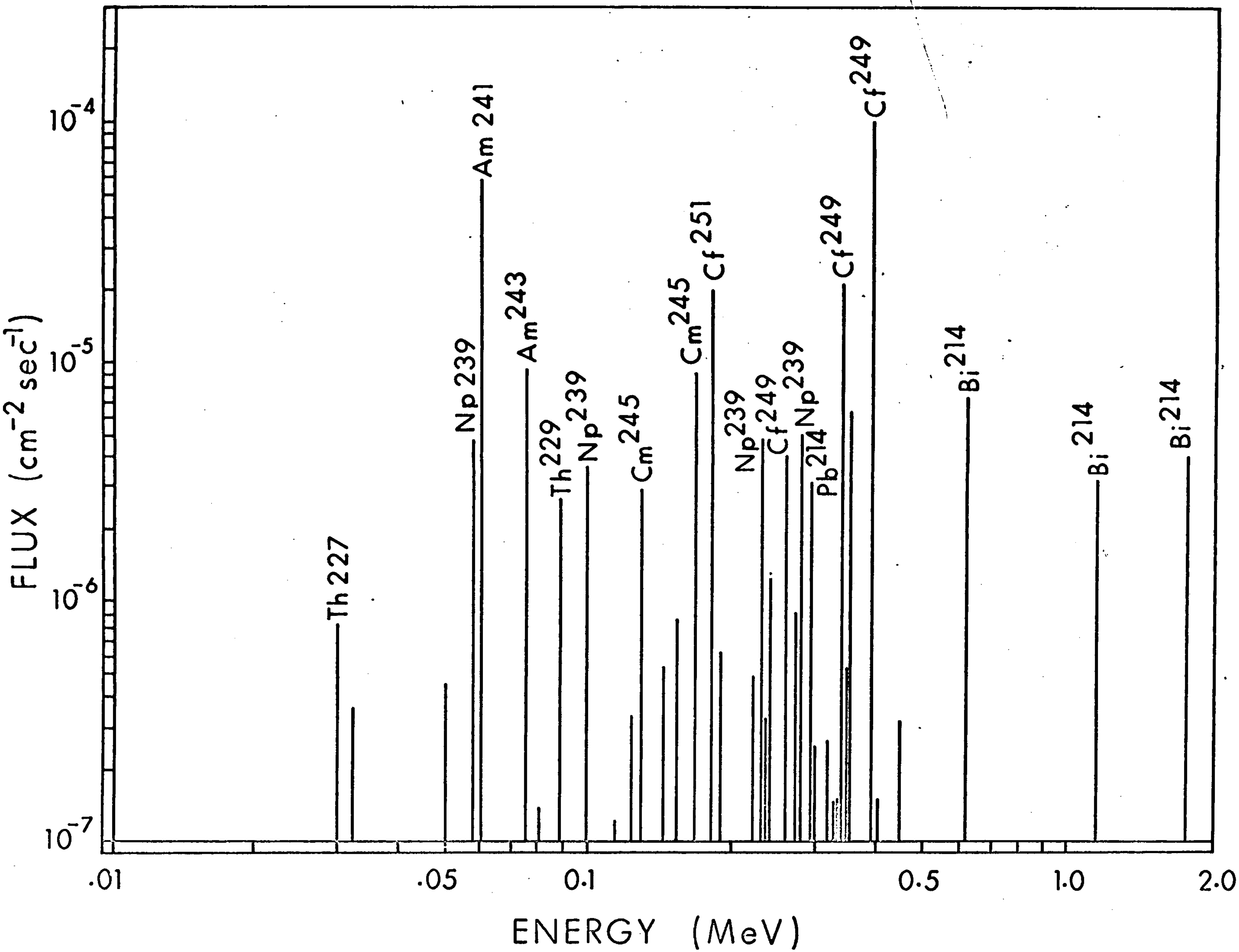
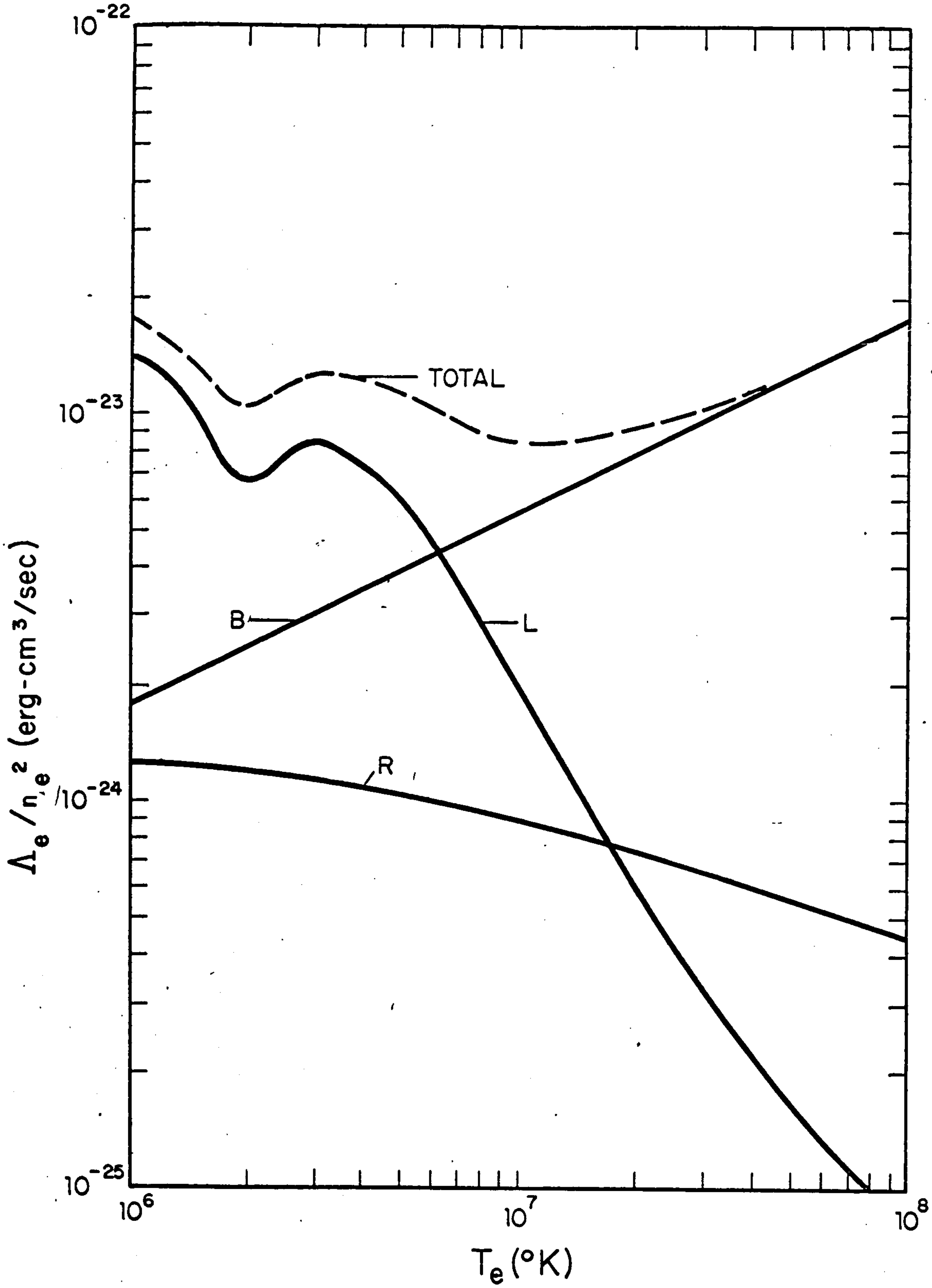
E (ev)

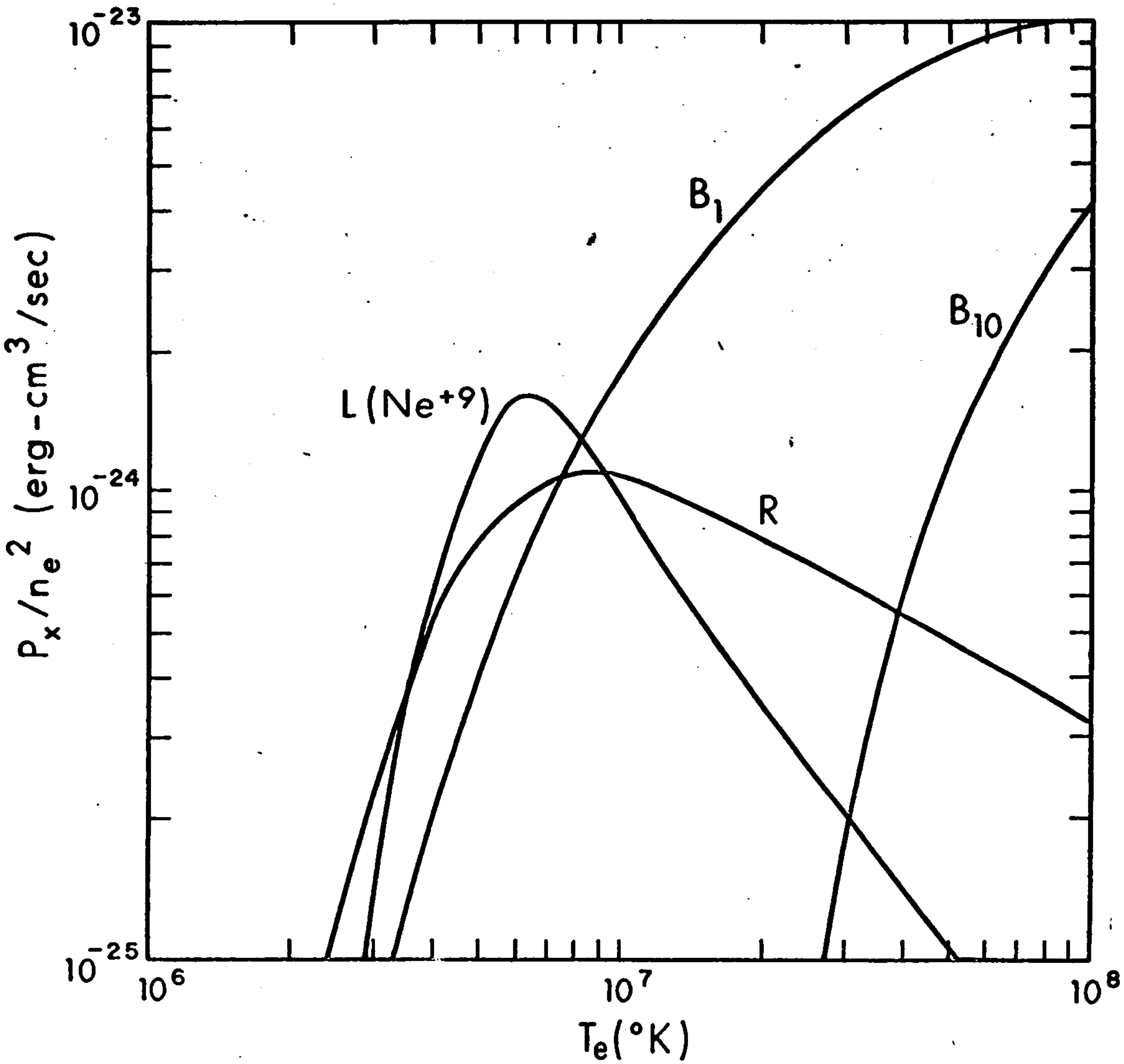


Gould and Burbidge Fig 6


FLUX (cm^{-2} sec^{-1})
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Th 227
Np 239
Am 241
Am^{243}
Th^{229}
Np^{239}
Cm^{245}
Cm^{245}
Cf 251
Np^{239}
Cf^{249}
Np^{239}
Pb^{214}
Cf^{249}
Cf^{249}
Bi^{214}
Bi^{214}
Bi^{214}
.01
.05
0.1
0.5
1.0
2.0
ENERGY (MeV)



Gould and Burbidge Fig. 8



Gould and Burbidge Fig 9

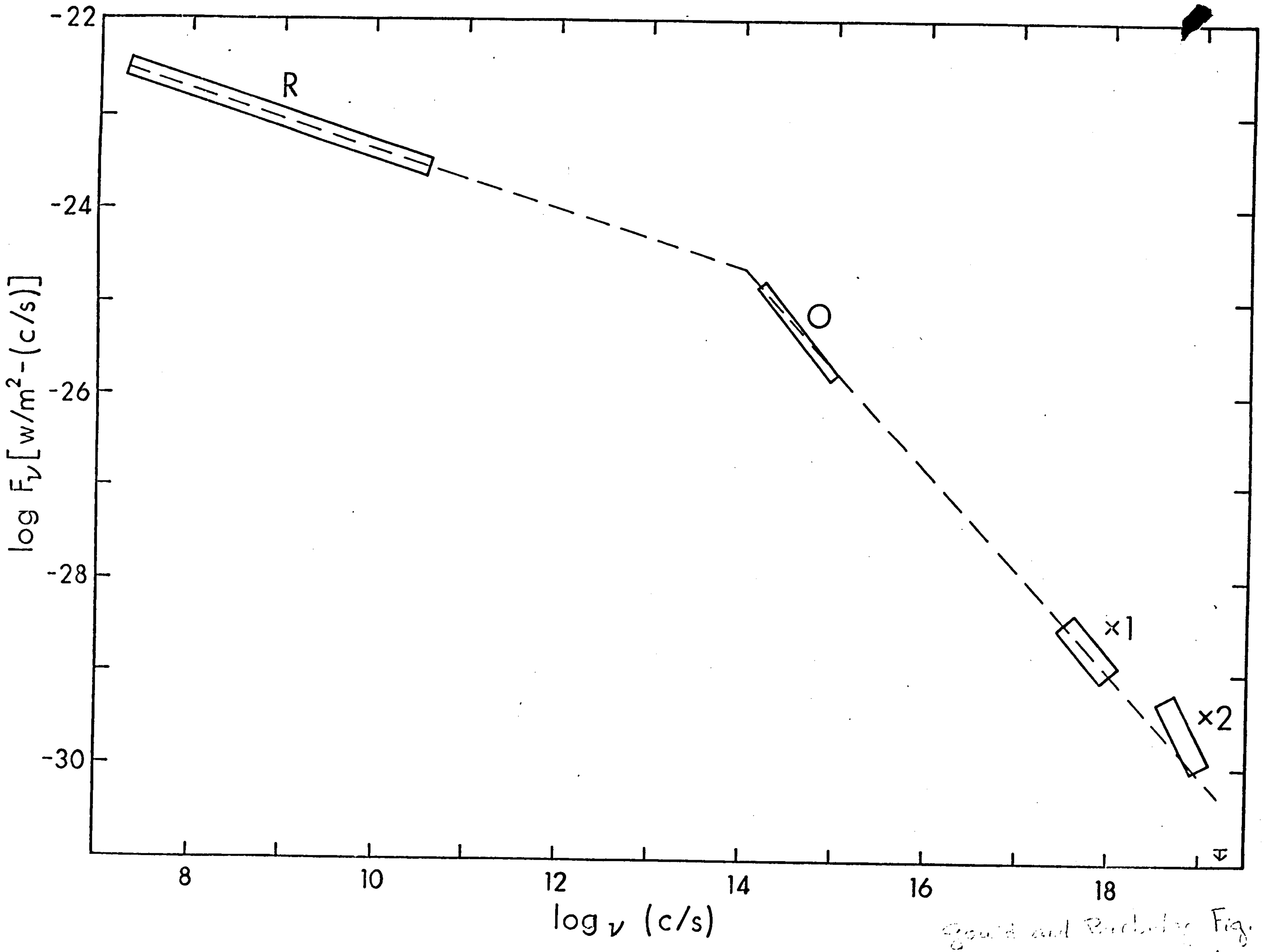
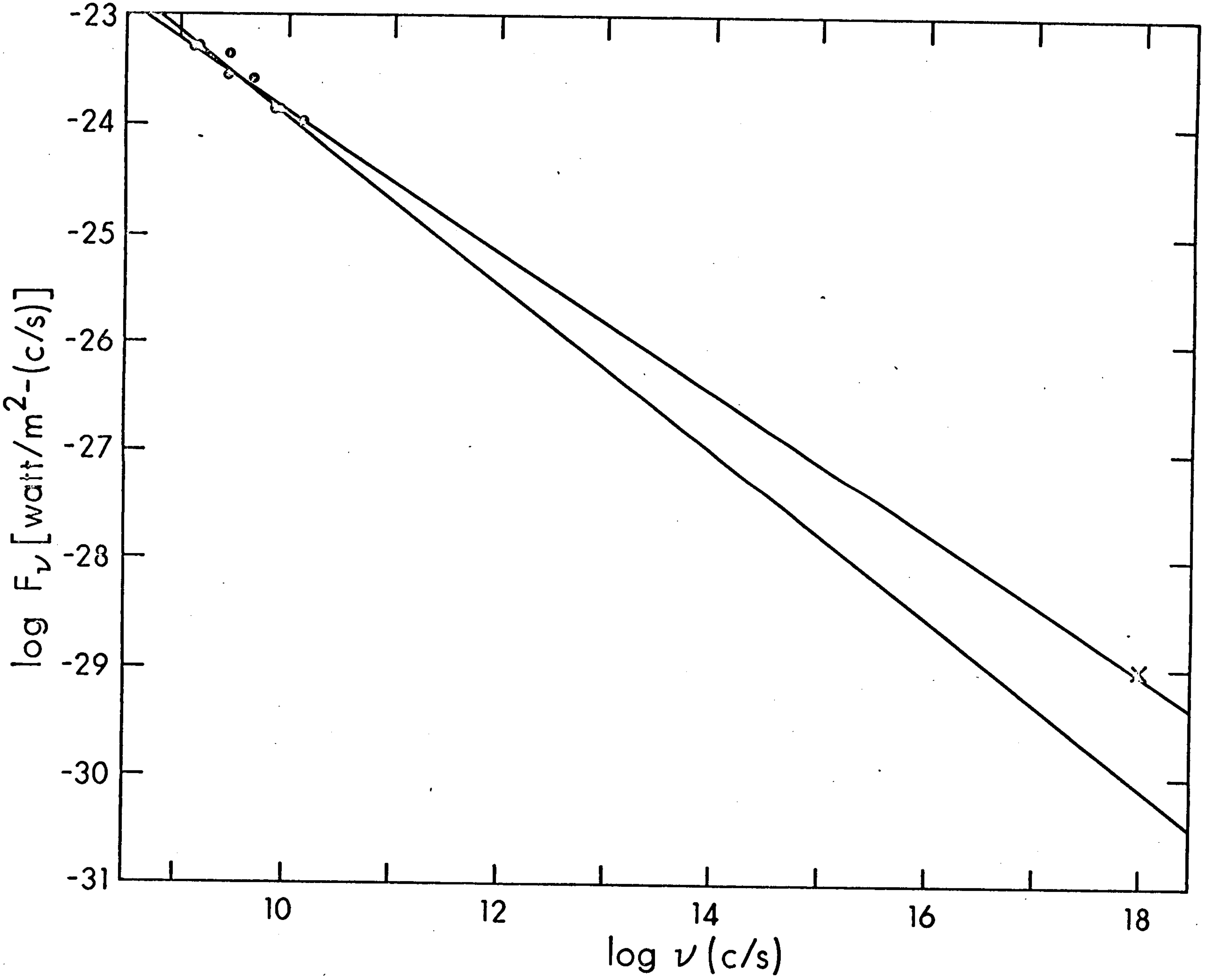


Fig. 10



-23
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-28
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log F_ν [watt/m²-(c/s)]
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12
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16
18
log ν (c/s)