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GALACTIC X-RAY SOURCES*

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During the past three years the existence of discrete x-ray sources outside the solar system has been demonstrated quite conclusively by the NRL group[1], the MIT group[2], and by Fisher and Meyerott[3]. About ten such sources have been discovered so far and a general isotropic background x-ray flux has also been reported. 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 $\sim 1 - 10$ kpc. One of the sources appears to be in the direction of the galactic center. The most intense of the x-ray sources is that in the constellation Scorpius, from which a flux at the earth of about $F_x \simeq 10^{-7}$ erg/cm^2-sec is detected; the Scorpius source has not been identified with any optical or radio emitter. The one x-ray source which has been identified with any certainty is the Crab Nebula for which $F_x \simeq 10^{-8}$ erg/cm^2-sec; the fluxes from most of the other x-ray sources are roughly the same as that from the Crab. Although the nature of all of these x-ray sources is not known, we feel that recent theoretical work on the interpretation of the observations allows one to reject many of the mechanisms proposed for the x-ray production. There are still problems connected with the mechanisms thought to be acceptable and these will be discussed briefly here. A more complete discussion of these problems, along with the details of some associated calculations, will be published elsewhere.

There are essentially four possible origins or mechanisms for the x-ray production: (1) neutron stars, (2) Compton scattering, (3) bremsstrahlung, and (4) synchrotron emission. When x-ray sources were first discovered the possibility that they were neutron stars was discussed at length, but it appears that the recent work of Bahcall and Wolf[4] and others on the cooling

[redacted]

(now thought to be very rapid) of neutron stars has shown that they are unlikely to be emitting sufficient x-rays to explain the observations. Compton scattering of high energy electrons by low energy ($\sim$ eV) photons, producing high energy photons, has not been discussed extensively as a mechanism for x-ray production in discrete sources. It has been suggested[5] that the x-rays from the Crab are due to Compton scattering of the (radio to optical) synchrotron electrons by the associated synchrotron photons. However, the intensity of this Compton-synchrotron radiation can be shown to be far too small (by a factor $\sim 10^{-6}$) to account for the observed x-ray flux[6]. This effect can easily be worked out in some detail but its unimportance can be seen readily if one estimates the probability of a Compton scattering of a photon before escaping from the nebula. One might think that Compton scattering might produce a large x-ray flux from quasi-stellar radio sources in which the photon density and the 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. This leaves only the synchrotron and bremmstrahlung processes as possible x-ray sources.

First we consider the possibility that the x-rays are synchrotron radiation[7]. We assume for the moment that the x-ray energy flux $F_x = 10^{-8}$ erg/cm^2-sec comes from a source at a galactic distance r = 10 kpc, the x-ray luminosity of the source is then $L_x (\propto r^2) = 1 \times 10^{38}$ erg/sec. Further, we assume for simplicity that the x-ray flux is at an effective wavelength 3Å and frequency $\nu = 10^{18}$ c/s, which is the characteristic synchrotron frequency $\nu_L \gamma_e^2$ emitted by electrons of energy $E_e = \gamma_e mc^2$; ν_L is the Larmor frequency. For a magnetic field $H = 10^{-4}$ gauss (the assumed value in the Crab Nebula) the electron energy required is $E_e (\propto H^{-\frac{1}{2}}) = 3 \times 10^{13}$ 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 luminosity L_x is E_t $(\propto r^2H^{-3/2}) = 1 \times 10^{47}$ 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 electron 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 contribution 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[8] of the Crab Nebula 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 is appreciably less than the age of the Crab Nebula and other supernova remnants, because it would mean that the high energy 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. It is also significant that for the Crab there can at present be no continuous production via nuclear collisions and π-μ decay, since the associated flux of high energy photons from the decay of π^o-mesons would be too high[8].

In the case of the Crab it is well known that it is emitting optical and radio synchrotron radiation as well as x-rays. We shall now compare the x-ray and radio observations[9] of the galactic center region. In Figure 1 these observations are plotted together with the extensions of power law spectra derived for indices within limits (- 0.72 ±0.05) such as to fit the radio data. The fact that the x-ray point lies so close to this extrapolation over a factor of 10^{10} in frequency of the radio data is remarkable. While it suggests that a single mechanism is operating, the ratio of the halflives (τ_r/τ_x) of the electrons giving rise to radiation in the two different spectral regions is $(\nu_r/\nu_x)^{-\frac{1}{2}}$. It should be added that if there is a continuous synchrotron spectrum over this range, detection of radiation in the optical and infra-red regions will not be possible because of obscuration by interstellar matter on the one hand and thermal radiation from stars on the other.

It is easily shown that for reasonable values of the spectral index ($\alpha \geq 0.5$) of the x-ray sources, the extension of the spectra to lower frequencies would mean that they would be easily detectable as radio sources and might also be seen as faint optical nebulae. If such identifications cannot be made, and if the synchrotron mechanism is responsible, there must be a sharp cutoff in the energy spectrum of the electrons, and this low energy cutoff must be at energies greater than about 10^{12} ev for assumed magnetic fields of order 10^{-4} gauss. It is very difficult to see how fluxes of electrons with energies $\geq 10^{12}$ ev can be produced without giving rise to large low energy fluxes, either in an acceleration process, or by deceleration by the synchrotron process itself. The only model which would seem to be possible would be direct injection already at the highest energies from a source in the remnant and then direct escape. The source must be continuously active if the flux is to be maintained. It can also be deduced that the x-ray flux would then arise in a very small volume with an upper limit of perhaps one parsec in extent.

Because of the difficulties associated with such models, we believe that 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 hard radiation as part of the thermal bremmstrahlung. We discuss now the properties associated with such a model. Two of us suggested[10] earlier that the x-rays from the source at the galactic center resulted from bremsstrahlung. At the time we envisaged bremsstrahlung production by <u>non-thermal</u> electrons. However, as was first pointed out by Rossi[11], 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. One is led to consider conditions where bremsstrahlung x-ray production is more efficient; these are realized in a high temperature ($T \sim 10^{7\circ}$ K) and low density gas where the bremsstrahlung is produced by <u>thermal</u> electrons and constitutes a major source of cooling or energy loss for the gas. An associated problem is that of the cooling rate of such a high temperature gas; we have considered this question and present here the essential results, the discussion and details to be given elsewhere. In Fig. 2 we give the rate of loss Λ_e (erg/cm^3-sec) of the kinetic energy of the electron gas of density n_e by various processes in the temperature range between 10^6 and $10^{8\circ}$K[11]. It is seen that bremsstrahlung dominates the cooling at higher temperatures. In Fig. 2 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 by various processes. The cooling time ($\tau_c \approx 3\, k\, T_e/n_e \Lambda_e$), 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 of r = 10 kpc and to produce an x-ray energy flux $F_x = 10^{-8}$ erg/cm^2-sec in the range 1 - 10 keV. Further, we assume the gas to be at a temperature of $10^{7\circ}$K; parameters for other values of the temperature

Λ = cap lambda

may be determined readily from Figs. 2 and 3. Since $F_x = p_x n_e^2 V/4\pi r^2$, 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.

As yet it is difficult to express a preference for either the synchrotron or bremsstrahlung hypothesis for the x-ray production mechanism. As we have emphasized, the energy loss time scales for the high energy synchrotron electrons are very short, while very high temperatures are required to produce bremsstrahlung x-rays. Although the basic mechanism remains uncertain, we feel that the likely origins of the x-ray sources are supernova outbursts. For it is known that supernova remnants are synchrotron emitters in the radio range (and in the case of the Crab in the optical), and it is believed that temperatures $\sim 10^7$°K are produced by the shock front associated with the expanding ejecta. We might remark, however, that the very high energy ($\sim$ 50 keV) radiation detected from the Crab by Clark[12] requires a temperature of 2×10^8°K, which is about an order of magnitude higher than theoretical estimates of the expected temperature. This would seem to suggest that the x-rays from the Crab result from the synchrotron process.

FOOTNOTES

1. S. Bowyer, E. T. Byram, T. A. Chubb, and H. Friedman, "Cosmic X-ray Sources" (to be published in Science, gives references to previous work).
2. R. Giacconi, H. Gursky, F. R. Paolini, and B. B. Rossi, "Observations of Two Sources of Cosmic X-rays in Scorpius and Sagittarius" (to be published in Nature, gives references to previous work).
3. P. C. Fisher, A. G. Meyerott, Astrophys. J. 139, 123; 140, 821, (1964), and unpublished work.
4. J. N. Bahcall and R. A. Wolf, "Neutron Stars" (preprint).
5. P. Morrison, Second Texas Symposium on Relativistic Astrophysics, Austin, 1964.
6. One of us (RJG) stated this result at the Austin Symposium and also at the Liège Symposium in August, 1964.
7. See also L. Woltjer, Astrophys. J. 140, 1309, (1964).
8. R. J. Gould, G. R. Burbidge, Ann. d'Astrophysique 28 (1965) (in press).
9. A. Maxwell and D. Downs, Nature 204, 865 (1964).
10. R. J. Gould and G. R. Burbidge, Astrophys. J. 138, 969 (1963).
11. The results disagree quantitatively with C. Heiles, Astrophys. J. 140, 470 (1964)
12. G. W. Clark, Phys. Rev. Letters 14, 91 (1965).

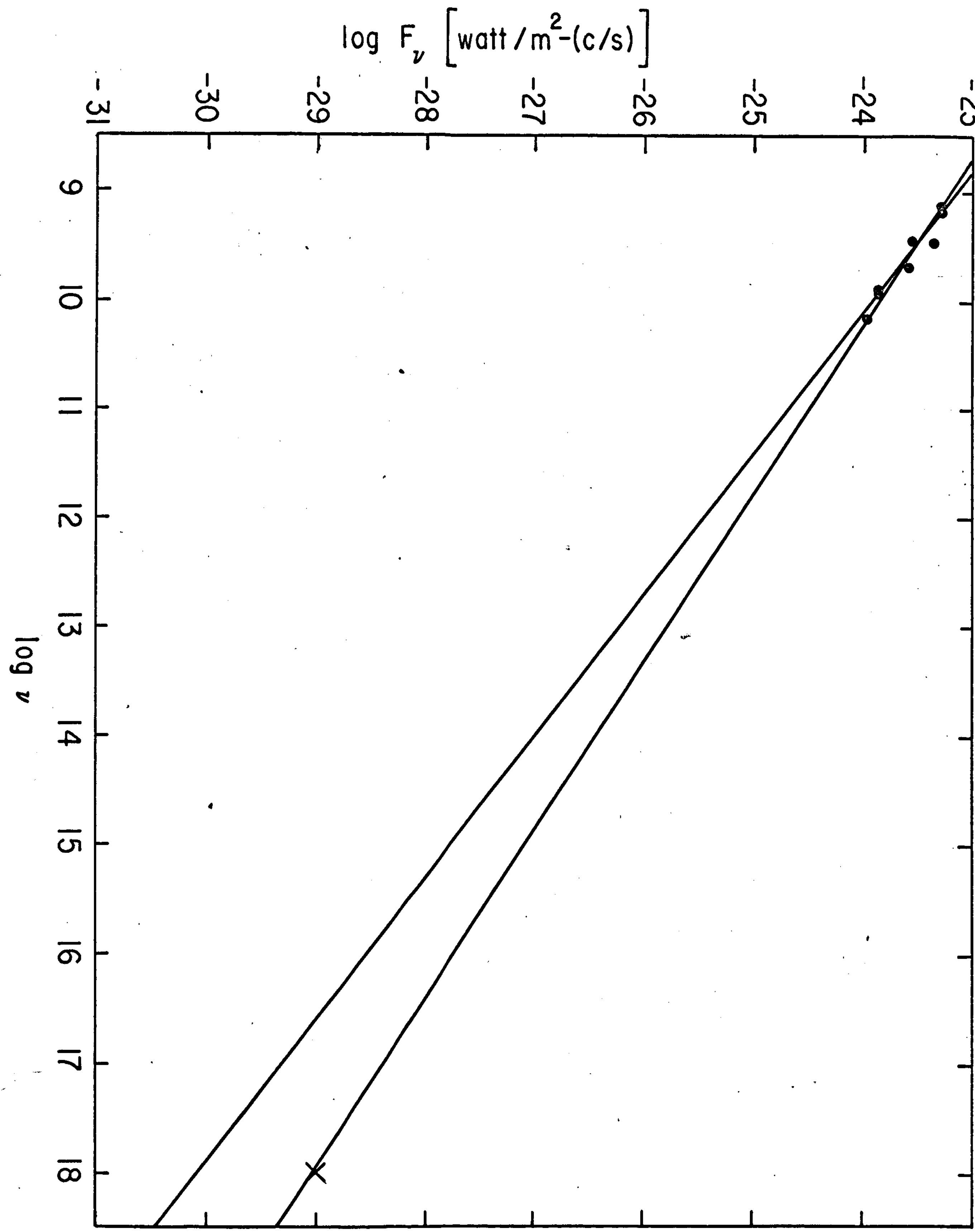
FIGURE CAPTIONS

Fig. 1 - 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.

Fig. 2 - 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) O + Ne, and (R) H + He + O + Ne.

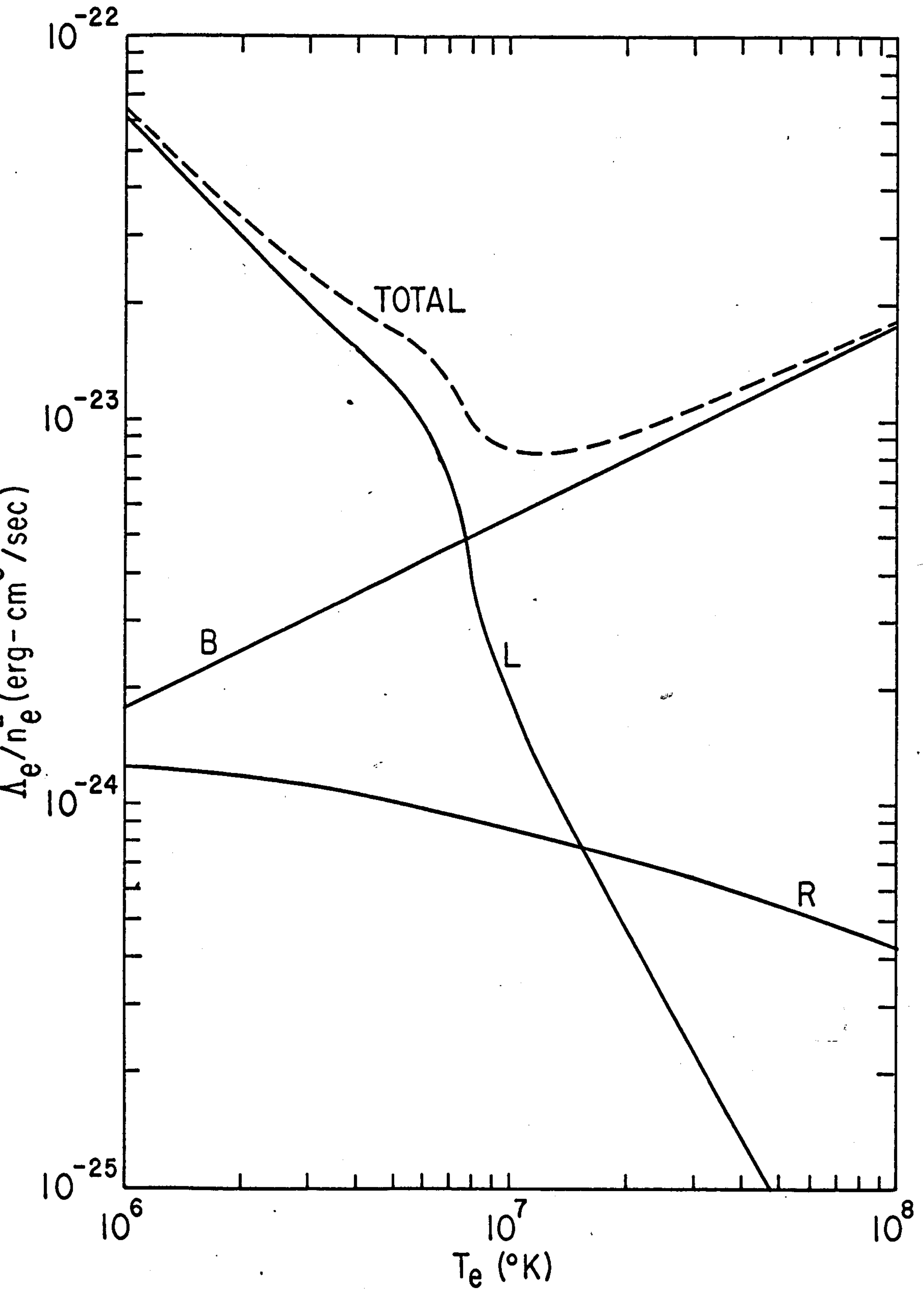
Fig. 3 - X-ray production rates in the 1 - 10 keV range by bremsstrahlung (B_1) and recombination radiation (R) and line emission (L) (essentially only the ion Ne^{+9} contributes). The bremsstrahlung production rate (B_{10}) in the 10 - 20 keV range is also shown. The ions of the following elements have been included: (B_1, B_{10}) H + He, (L) Ne, and (R) H + He + N + O + Ne.

Fig. 1



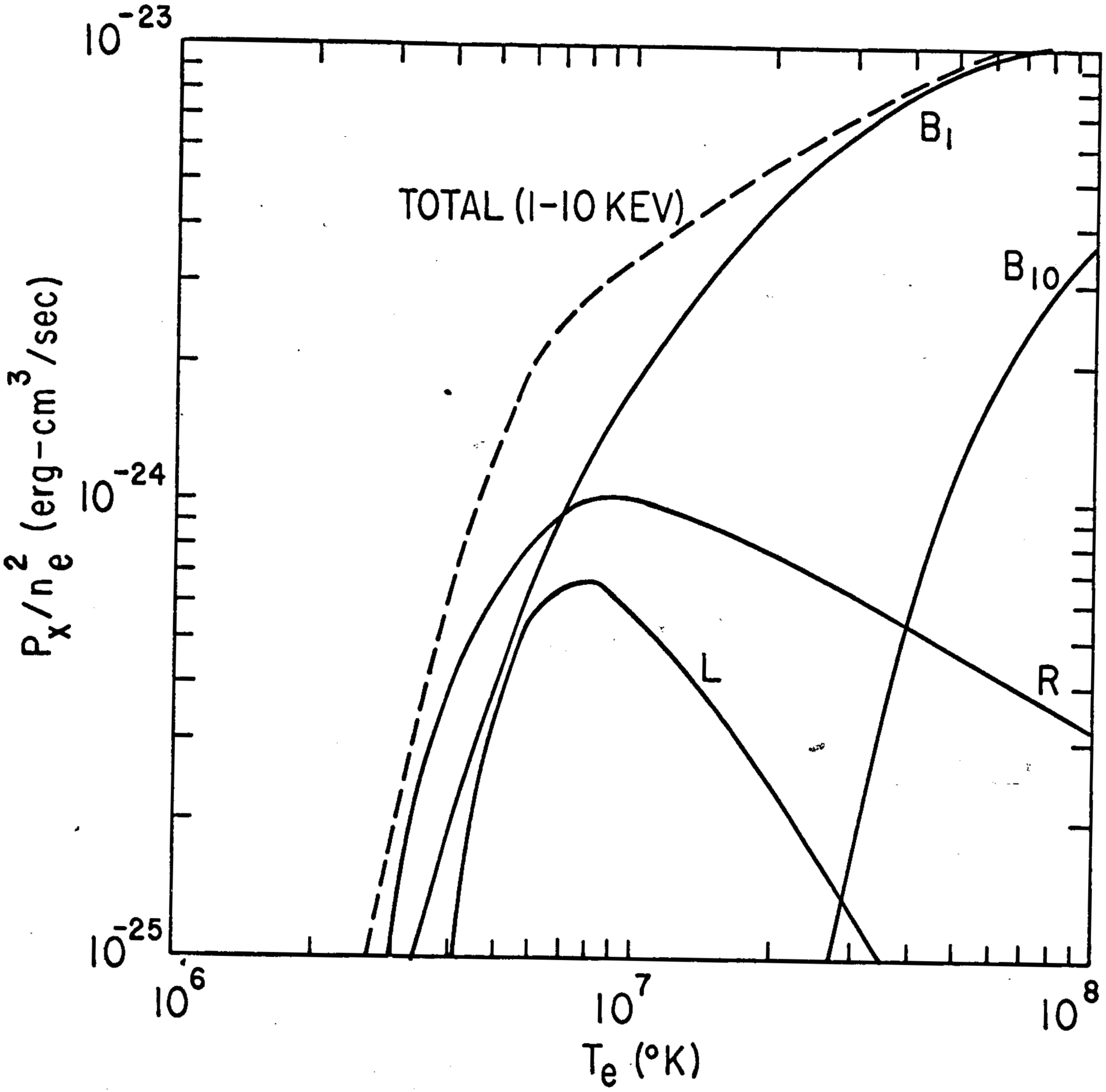
log F_ν [watt/m²-(c/s)]
-31
-30
-29
-28
-27
-26
-25
-24
-23
log ν
9
10
11
12
13
14
15
16
17
18

Fig. 2



10^{-22}
10^{-23}
10^{-24}
10^{-25}
Λ_e/n_e^2 (erg-cm^3/sec)
TOTAL
B
L
R
10^6
10^7
10^8
T_e (°K)

Fig. 3



10^{-23}
10^{-24}
10^{-25}
P_x/n_e^2 (erg-cm^3/sec)
TOTAL (1-10 KEV)
B_1
B_{10}
L
R
10^6
10^7
10^8
T_e (°K)