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# NEUTRINO REACTIONS IN STRONG MAGNETIC FIELD

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**Abstract.** We present the energy losses due to several neutrinos processes: (1) synchrotron neutrinos, (2) pair annihilation neutrinos, (3) plasmon neutrinos, and (4) photoneutrinos in the presence of a superstrong magnetic field. Numerical results are tabulated and illustrated for several values of densities and temperatures. In the low density regime ($\varrho \lesssim 10^7$ g cm$^{-3}$) the presence of a magnetic field decreases the luminosity, whereas the opposite is true at higher densities. This last effect is however almost entirely due to the existence of a new process, the synchrotron neutrinos that disappear when $H \to 0$. Even though the overall effect can only be quantitatively ascertain after a complete cooling computation is performed, one should however expect a much lower temperature for neutron star surface than the one computed in the $H = 0$ case.

## 1. Introduction

In recent years neutrino reactions in superstrong magnetic fields have been a subject of increasing interest in astrophysics. This is primarily motivated by the fact that enormously intense magnetic fields seem to be characteristic of collapsed stellar objects. Almost all models which attempt to depict pulsar observations to rotating neutron stars must ascribe to the neutron star a surface magnetic field in excess of $10^{12}$ G (Gunn and Ostriker, 1969; Chiu and Canuto, 1971; Tsuruta *et al*, 1972). The discovery of polarized light from white dwarfs suggests that such stars possess exterior fields of $\approx 10^7$ G (Kemp *et al.*, 1970). The observational evidence delineated hereinbefore lend further support to the general belief that gravitational collapse of stellar objects may give rise to strong magnetic fields of at least $10^8$ G (Woltjer, 1964).

The importance of neutrino reactions during late stage stellar evolution is now quite well established (Chin *et al.*, 1966). In the presence of a strong magnetic field, it is expected that the neutrino reactions will be modified. Weak interactions in strong magnetic fields have been emphasized by many authors (see for instance Canuto

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*et al.*, 1970; Canuto *et al.*, 1970a, b; Canuto and Chou, 1971; Chou, 1971; and McFee, 1971).

The purpose of this communication is to summarize the results for the following reactions: namely,

(1) Synchrotron neutrinos

$$e^- \to e^- + \nu + \tilde{\nu}\,;$$

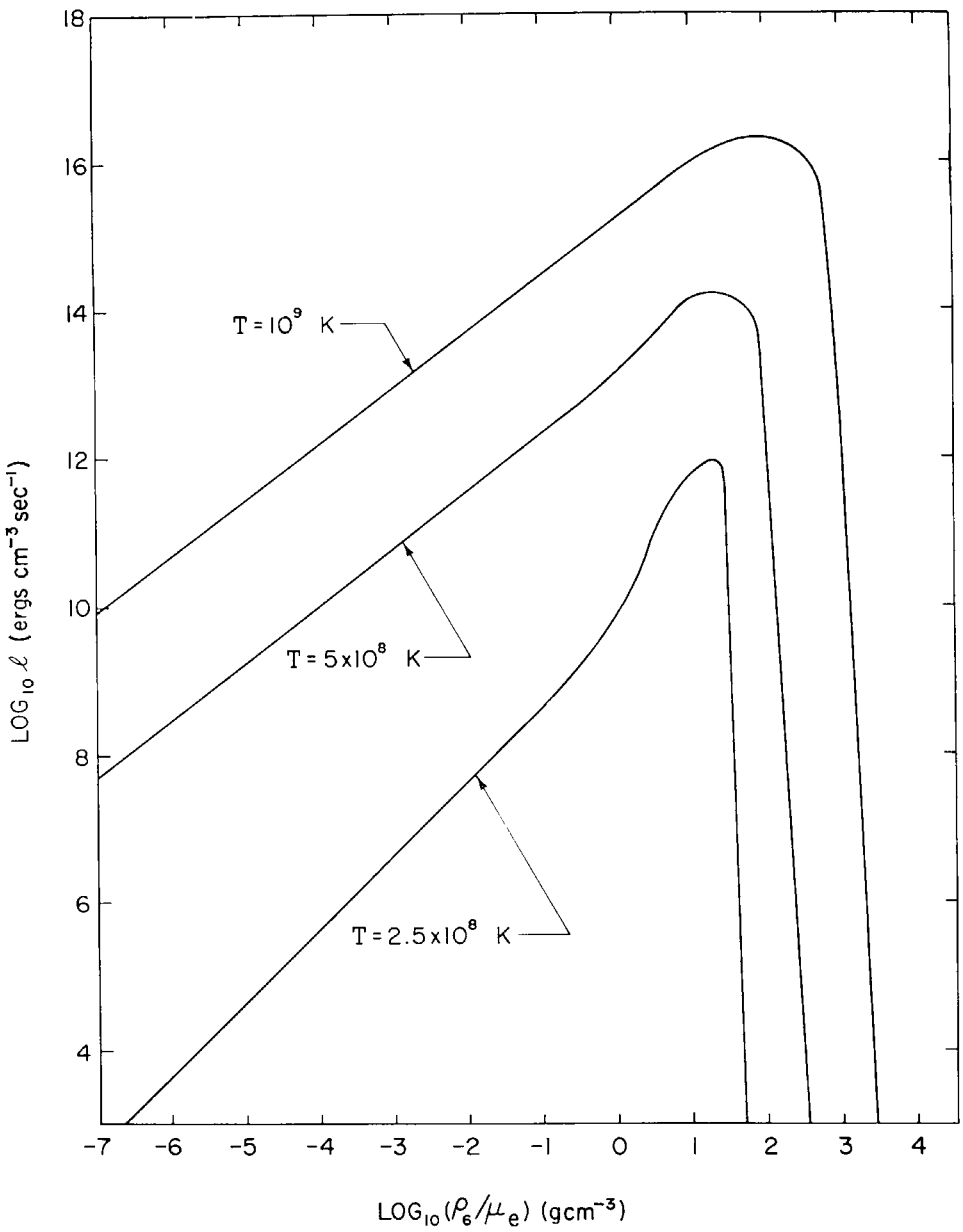


Fig. 1. Neutrino luminosities for synchrotron process $\log_{10} l(\mathrm{erg\,cm^{-3}\,s^{-1}})$ as a function of $\varrho_6/\mu_e$ ($\mathrm{g\,cm^{-3}}$) for temperatures $2.5 \times 10^8$, $5 \times 10^8$, and $10^9$K at $H = H_q (H_q \equiv m^2c^3/e\hbar = 4.414 \times 10^{13}\,\mathrm{G})$.

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(2) Pair annihilation neutrinos

$$e^+ + e^- \rightarrow \nu + \tilde{\nu}\,;$$

(3) Plasma neutrinos

$$\gamma \rightarrow \nu + \tilde{\nu}\,;$$

(4) Photoneutrinos

$$e^- + \gamma \rightarrow e^- + \nu + \tilde{\nu}\,.$$

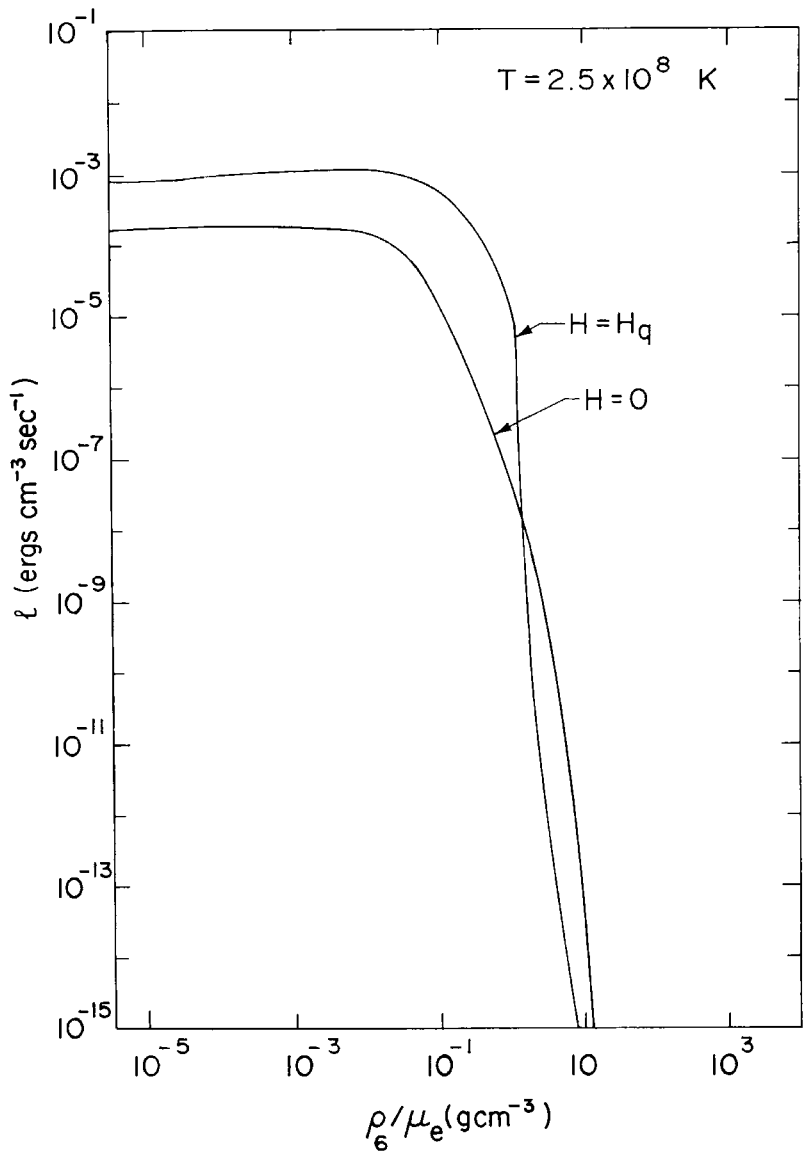


Fig. 2. Neutrino luminosity for pair annihilation $l$ (erg cm$^{-3}$ s$^{-1}$) as a function of $\varrho_6/\mu_e$(g cm$^{-3}$) for $2.5 \times 10^8$K at $H = H_q$. The corresponding field free case is included for comparison.

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Whereas process (1) can operate only in a magnetic field the rest are allowed in the absence of magnetic fields. The neutrino luminosity due to the synchroton process and the pair annihilation process are described in Section 2. The energy loss rates for the plasma neutrino and that for the photoneutrino processess are presented in Section 3. Some rival neutrino reactions such as the URCA process and the proton-proton reaction in strong magnetic fields have been reported elsewhere (Canuto and Chou, 1971; Chou, 1971).

## 2. Neutrino Synchrotron and Pair Annihilation Processes

Among the direct electron neutrino interactions suggested by the conserved vector

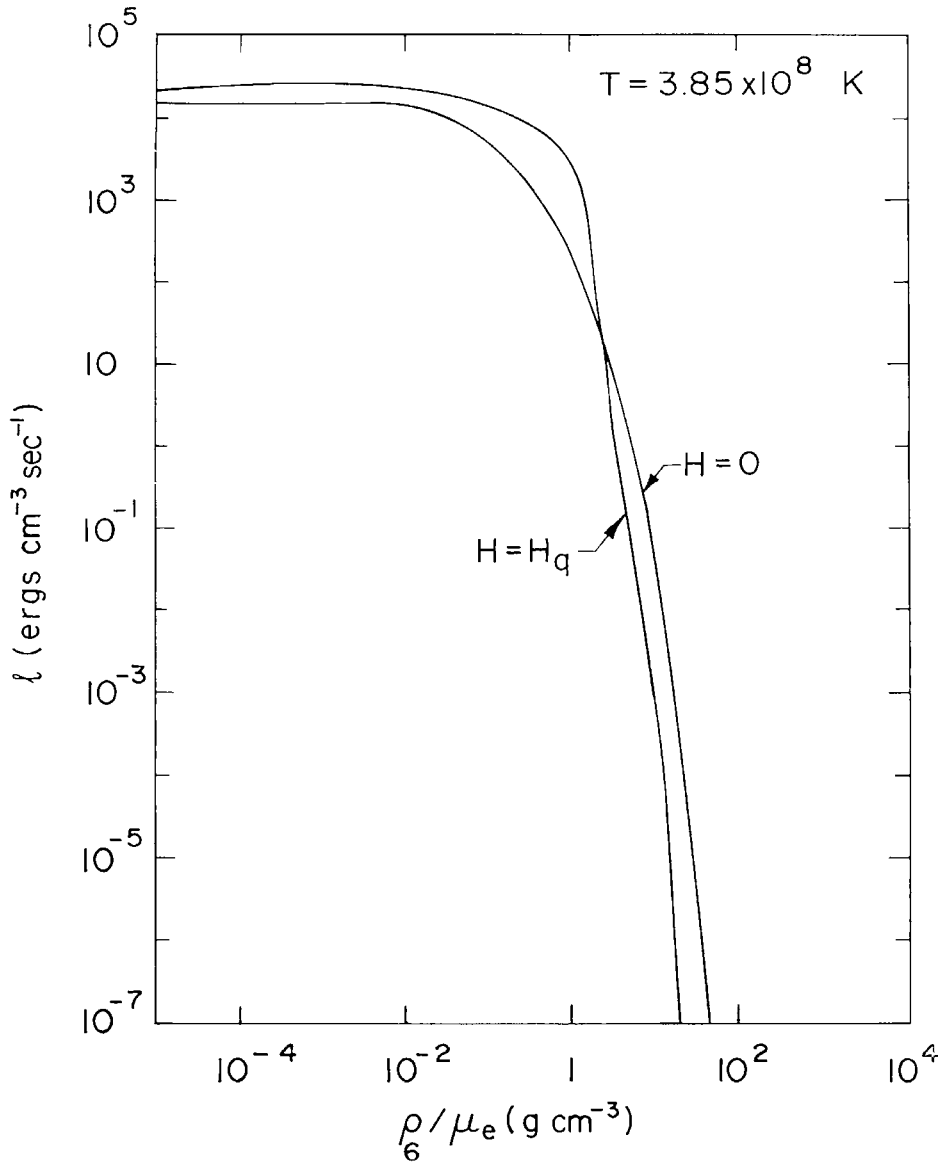


Fig. 3. Same as Figure 2 for $T = 3.85 \times 10^8$ K.

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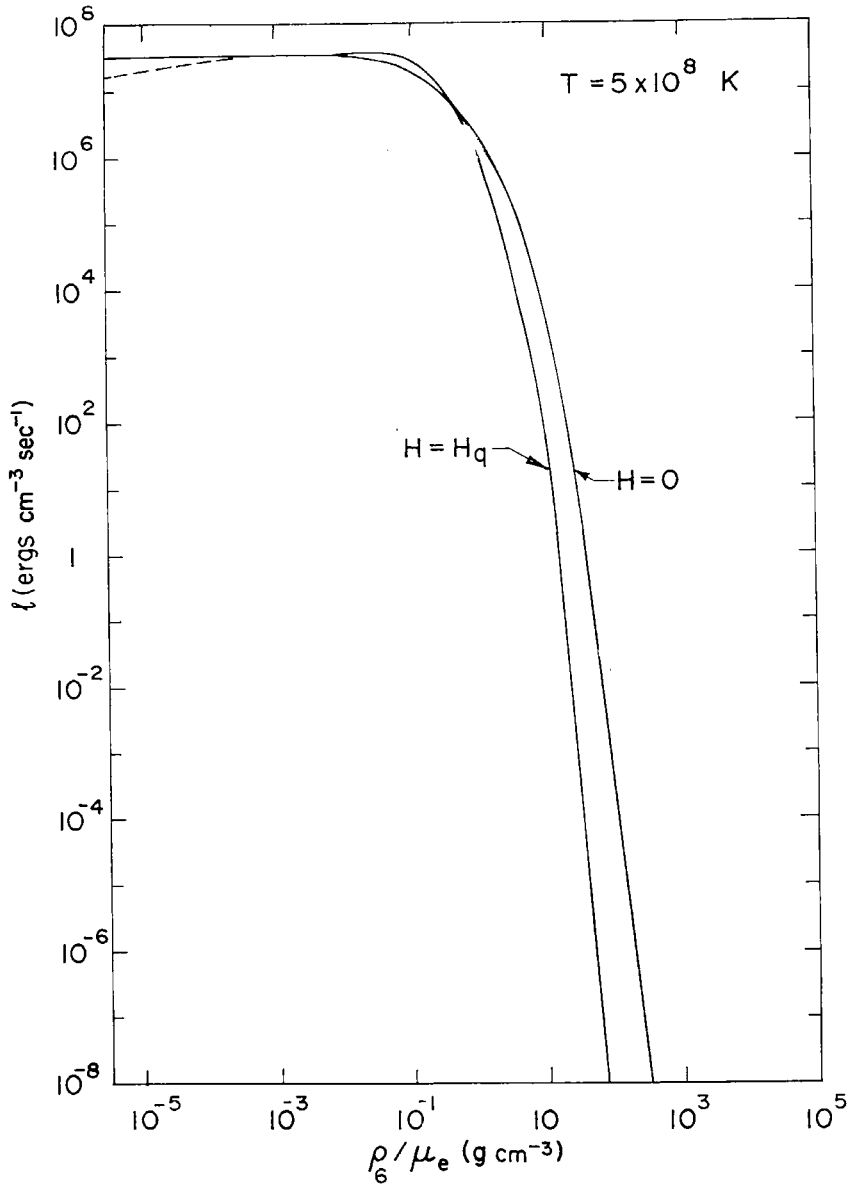


Fig. 4. Same as Figure 2 for $T = 5 \times 10^8$K.

current hypothesis, the simplest (and perhaps the most important) reactions are the neutrino synchroton process and the pair annihilation process. The energy losses for both processes were computed by Canuto *et al.* (1970) and by Canuto and Fassio-Canuto (1973a), and the results are presented in Figure 1, Table I and Figure 2–5, Tables II–V, respectively.

### 3. Plasma Neutrino and Photoneutrino Processes

The plasma neutrino process in a strong magnetic field has been investigated by

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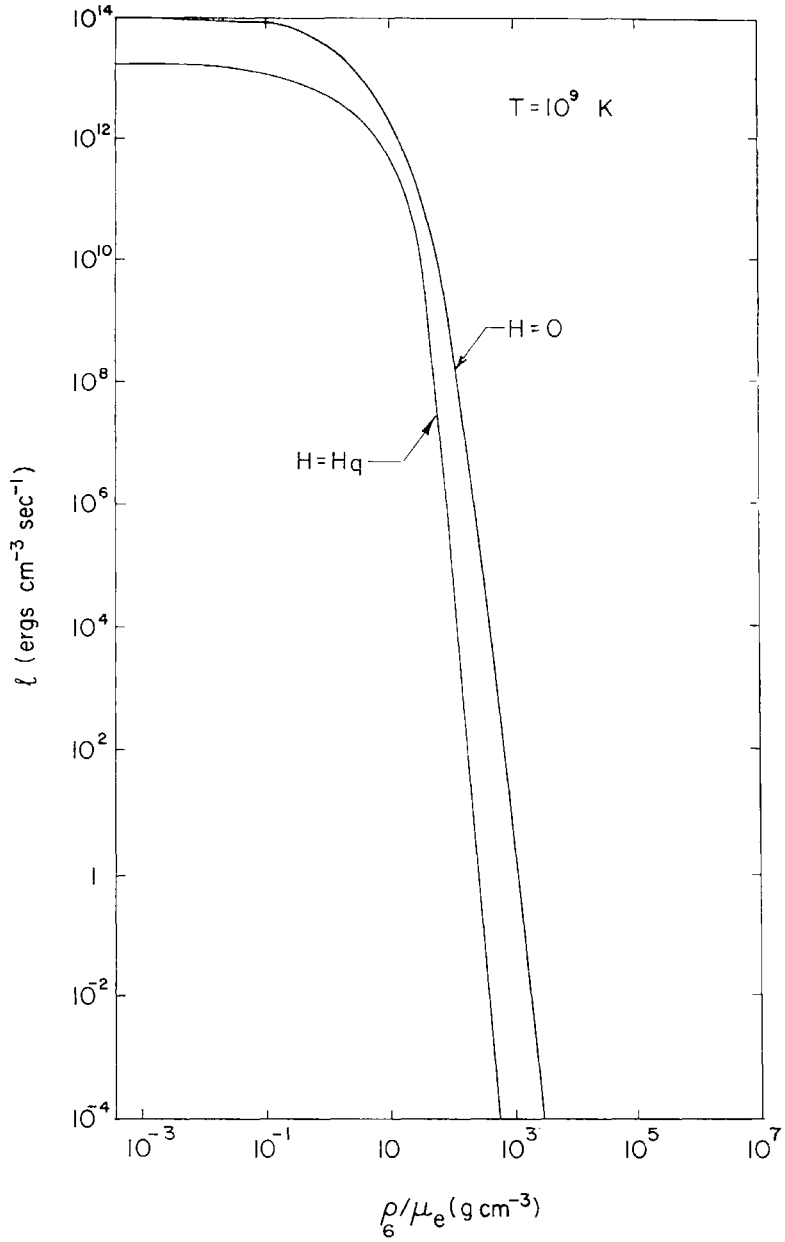


Fig. 5. Same as Figure 2 for $T = 10^9$ K.

Canuto *et al.* (1970a, b). Only two special cases were considered i.e. propagation along and perpendicular to the magnetic field axis. For $\theta = 0$, one still has to distinguish between ordinary ($O$) and extraordinary ($X$) modes, since they have a different dispersion relation. The results for $\theta = 0$ are shown in Table VI and VII. The general conclusion is that sizable effects can be obtained only for low densities and very strong fields. A different situation is encountered when one consideres the longitudinal plasmon. An interesting case is that of propagation perpendicular to the field. For propagation parallel to the field the dispersion relation yields $\omega = \omega_p$, and $\omega = \omega_c$.

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The energy loss rate for the first mode is field independent and no change is therefore expected from the results of Adams *et al.* (1963). The second mode ($\omega = \omega_c$) is unphysical so that no energy loss can be derived from it.

TABLE I

Neutrino luminosities $l$(erg cm$^{-3}$ s$^{-1}$) for the synchrotron process as a function of the degeneracy parameter $\eta$ and density $\varrho_6/\mu_e$ (g cm$^{-3}$) for temperatures $2.5 \times 10^8$, $5 \times 10^8$, and $10^9$ K at $H = H_q = 4.414 \times 10^{13}$ G

| $\eta$ | $T = 2.5 \times 10^8$ | | $T = 5 \times 10^8$ | | $T = 10^9$ | |
|---|---|---|---|---|---|---|
| | $\log_{10}(\varrho_6/\mu_e)$ | $\log_{10} l$ | $\log_{10}(\varrho_6/\mu_e)$ | $\log_{10} l$ | $\log_{10}(\varrho_6/\mu_e)$ | $\log_{10} l$ |
| 5 | | | | | | |
| 10 | −0.3772 | 3.2498 | −1.11297 | 12.2498 | 0.4898 | 15.5710 |
| 15 | −4.2057 | 5.4189 | +0.03894 | 13.118 | 1.1145 | 16.055 |
| 20 | −2.0415 | 7.5808 | +0.41086 | 13.556 | 1.5256 | 16.256 |
| 25 | −0.3528 | 9.3589 | +0.8098 | 13.9689 | 1.8332 | 16.270 |
| 30 | +0.0493 | 10.0068 | 1.096 | 14.175 | 2.0799 | 16.255 |
| 35 | 0.1997 | 10.2700 | 1.3243 | 14.256 | 2.2863 | 16.246 |
| 40 | 0.3533 | 10.6519 | 1.5166 | 14.225 | 2.4638 | 16.134 |
| 45 | 0.6578 | 11.3255 | 1.6819 | 14.124 | 2.6197 | 15.952 |
| 50 | 0.7960 | 11.4839 | 1.8277 | 13.9689 | 2.7588 | 15.5296 |
| 55 | 0.9640 | 11.7057 | 1.9581 | 13.0737 | 2.8842 | 14.3589 |
| 60 | 1.0891 | 11.8307 | 2.0762 | 11.0068 | 2.9986 | 12.3255 |
| 65 | 1.2170 | 11.9277 | 2.1841 | 9.3589 | 3.1036 | 10.4716 |
| 70 | 1.3177 | 12.0737 | 2.2836 | 7.3899 | 3.2008 | 8.2286 |
| 75 | 1.4239 | 11.6351 | 2.3758 | 5.8466 | 3.2912 | 6.0415 |

TABLE II

Neutrino luminosities $l$(erg cm$^{-3}$ s$^{-1}$) for the pair annihilation process as a function of the degeneracy parameter $\eta$ and density $\varrho_6/\mu_e$(g cm$^{-3}$) for $T = 2.5 \times 10^8$ K, at $H = H_q$. The corresponding field free case is included for comparison

| $\eta$ | $\varrho_6/\mu_e$(g cm$^{-3}$) | $T = 2.5 \times 10^8$ K | |
|---|---|---|---|
| | | $H = H_q$ $l$ (erg cm$^{-3}$ s$^{-1}$) | $H = 0$ $l$ (erg cm$^{-3}$ s$^{-1}$) |
| 10 | $4.19 \times 10^{-7}$ | $0.922 \times 10^{-3}$ | $0.2498 \times 10^{-3}$ |
| 15 | $6.22 \times 10^{-5}$ | $0.859 \times 10^{-3}$ | $0.2439 \times 10^{-3}$ |
| 20 | $9.08 \times 10^{-3}$ | $1.033 \times 10^{-3}$ | $0.1676 \times 10^{-3}$ |
| 25 | $4.44 \times 10^{-1}$ | $3.23 \times 10^{-4}$ | $1.1386 \times 10^{-6}$ |
| 30 | 1.12 | $0.796 \times 10^{-5}$ | $5.3546 \times 10^{-8}$ |
| 35 | 1.58 | $1.028 \times 10^{-7}$ | $1.2564 \times 10^{-8}$ |
| 40 | 2.26 | $1.159 \times 10^{-9}$ | $2.2421 \times 10^{-9}$ |
| 45 | 4.55 | $3.872 \times 10^{-11}$ | $3.6698 \times 10^{-11}$ |
| 50 | 6.26 | $4.126 \times 10^{-13}$ | $3.8464 \times 10^{-12}$ |
| 55 | 9.20 | $0.609 \times 10^{-14}$ | $1.7456 \times 10^{-13}$ |
| 60 | 12.3 | $0.597 \times 10^{-16}$ | $1.2556 \times 10^{-14}$ |
| 65 | 16.5 | $0.656 \times 10^{-18}$ | $6.5432 \times 10^{-16}$ |
| 70 | 20.8 | $0.469 \times 10^{-20}$ | $5.0801 \times 10^{-17}$ |

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TABLE III

Same as Table II for $T = 3.85 \times 10^8$ K

| $\eta$ | $\varrho_6/\mu_e$(g cm$^{-3}$) | $T = 3.85 \times 10^8$ K | |
|---|---|---|---|
| | | $H = H_q$ $l$ (erg cm$^{-3}$ s$^{-1}$) | $H = 0$ $l$ (erg cm$^{-3}$ s$^{-1}$) |
| 10 | $2.14 \times 10^{-3}$ | $3.906 \times 10^4$ | $1.7679 \times 10^4$ |
| 20 | 1.19 | $1.007 \times 10^3$ | $1.7976 \times 10^2$ |
| 30 | 4.96 | 0.794 | 1.7387 |
| 40 | 13.5 | $1.629 \times 10^{-4}$ | $9.9519 \times 10^{-3}$ |
| 50 | 28.8 | $1.709 \times 10^{-8}$ | $4.5322 \times 10^{-5}$ |
| 60 | 52.1 | $1.925 \times 10^{-12}$ | $2.1009 \times 10^{-7}$ |
| 70 | 85.0 | $1.033 \times 10^{-16}$ | $9.732 \times 10^{-10}$ |

TABLE IV

Same as Table II for $T = 5 \times 10^8$ K

| $\eta$ | $\varrho_6/\mu_e$(g cm$^{-3}$) | $T = 5 \times 10^8$ K | |
|---|---|---|---|
| | | $H = H_q$ $l$ (erg cm$^{-3}$ s$^{-1}$) | $H = 0$ $l$ (erg cm$^{-3}$ s$^{-1}$) |
| 2.2 | $3.45 \times 10^{-5}$ | $0.436 \times 10^8$ | $0.5197 \times 10^8$ |
| 10 | $7.71 \times 10^{-2}$ | $0.512 \times 10^8$ | $0.3476 \times 10^8$ |
| 25 | 6.45 | $0.744 \times 10^4$ | $0.3835 \times 10^5$ |
| 34 | $1.90 \times 10$ | 3.449 | $3.68 \times 10^2$ |
| 43 | $4.14 \times 10$ | $0.897 \times 10^{-3}$ | 3.239 |
| 50 | $6.71 \times 10$ | $1.298 \times 10^{-6}$ | $8.111 \times 10^{-2}$ |
| 55 | $9.07 \times 10$ | $0.689 \times 10^{-8}$ | $5.743 \times 10^{-3}$ |
| 60 | $1.19 \times 10^2$ | $1.536 \times 10^{-10}$ | $4.089 \times 10^{-4}$ |
| 65 | $1.52 \times 10^2$ | $0.469 \times 10^{-12}$ | $3.007 \times 10^{-5}$ |
| 70 | $1.92 \times 10^2$ | $0.668 \times 10^{-14}$ | $2.001 \times 10^{-6}$ |
| 75 | $2.37 \times 10^2$ | $0.927 \times 10^{-16}$ | $1.426 \times 10^{-7}$ |

TABLE V

Same as Table II for $T = 10^9$ K

| $\eta$ | $\varrho_6/\mu_e$(g cm$^{-3}$) | $T = 10^9$ K | |
|---|---|---|---|
| | | $H = H_q$ $l$ (erg cm$^{-3}$ s$^{-1}$) | $H = 0$ $l$ (erg cm$^{-3}$ s$^{-1}$) |
| 2.2 | $1.92 \times 10^{-2}$ | $2.77 \times 10^{13}$ | $9.9624 \times 10^{13}$ |
| 10 | 2.91 | $0.529 \times 10^{13}$ | $2.3962 \times 10^{13}$ |
| 15 | $1.29 \times 10$ | $3.017 \times 10^{11}$ | $2.8798 \times 10^{12}$ |
| 25 | $6.80 \times 10$ | $1.527 \times 10^8$ | $2.6493 \times 10^{10}$ |
| 50 | $5.73 \times 10^2$ | $1.049 \times 10^{-2}$ | $8.8926 \times 10^4$ |
| 55 | $7.66 \times 10^2$ | $2.238 \times 10^{-4}$ | $6.5702 \times 10^3$ |
| 60 | $9.96 \times 10^2$ | $3.314 \times 10^{-5}$ | $4.8793 \times 10^2$ |
| 65 | $1.26 \times 10^3$ | $1.726 \times 10^{-8}$ | $3.8375 \times 10^1$ |
| 70 | $1.58 \times 10^3$ | $0.961 \times 10^{-10}$ | 2.6978 |
| 75 | $1.95 \times 10^3$ | $2.479 \times 10^{-12}$ | $1.8777 \times 10^{-1}$ |

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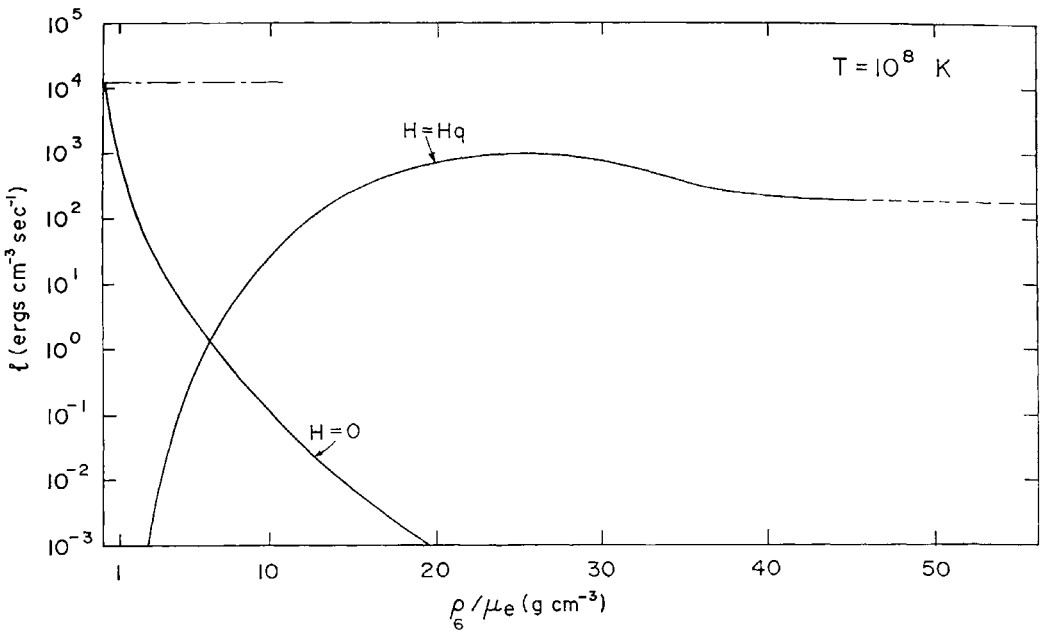


Fig. 6. Neutrino luminosity for photoneutrino reaction $l$ (erg cm$^{-3}$ s$^{-1}$) as a function of $\varrho_6/\mu_e$(g cm$^{-3}$) for $T = 10^8$K and $H = H_q = 4.414 \times 10^{13}$ G. The corresponding field free case is included for comparison.

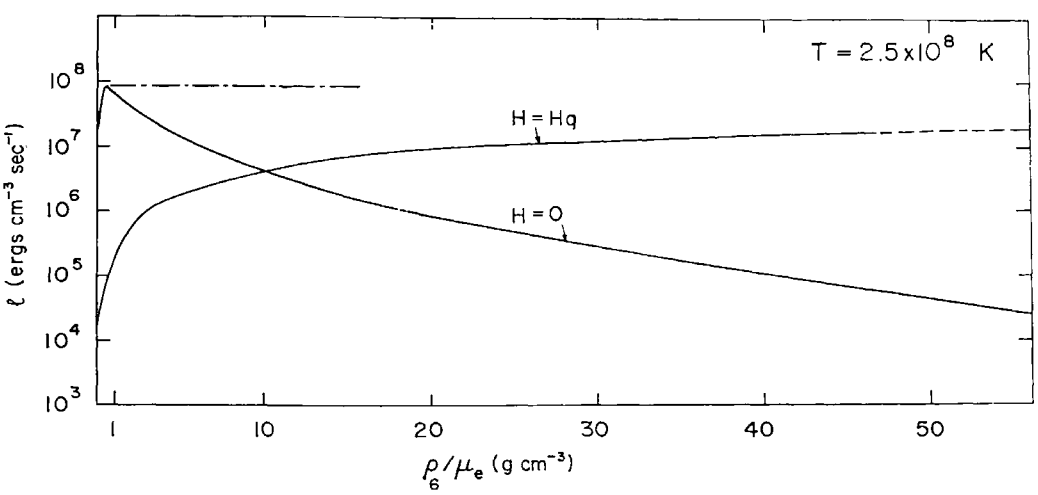


Fig. 7. Same as Figure 6 for $T = 2.5 \times 10^8$K.

Recently Canuto and Fassio-Canuto (1973b) computed the energy loss rate due to the photoneutrino reaction. They investigated the special case of a photon traveling along the field and they worked the non-relativistic limit. Their results are given in Table VIII and in Figures 6, 7, 8 and 9 where the corresponding field free results are included for purpose of comparison.

In order to assess the relative importance of the various neutrino reactions in a

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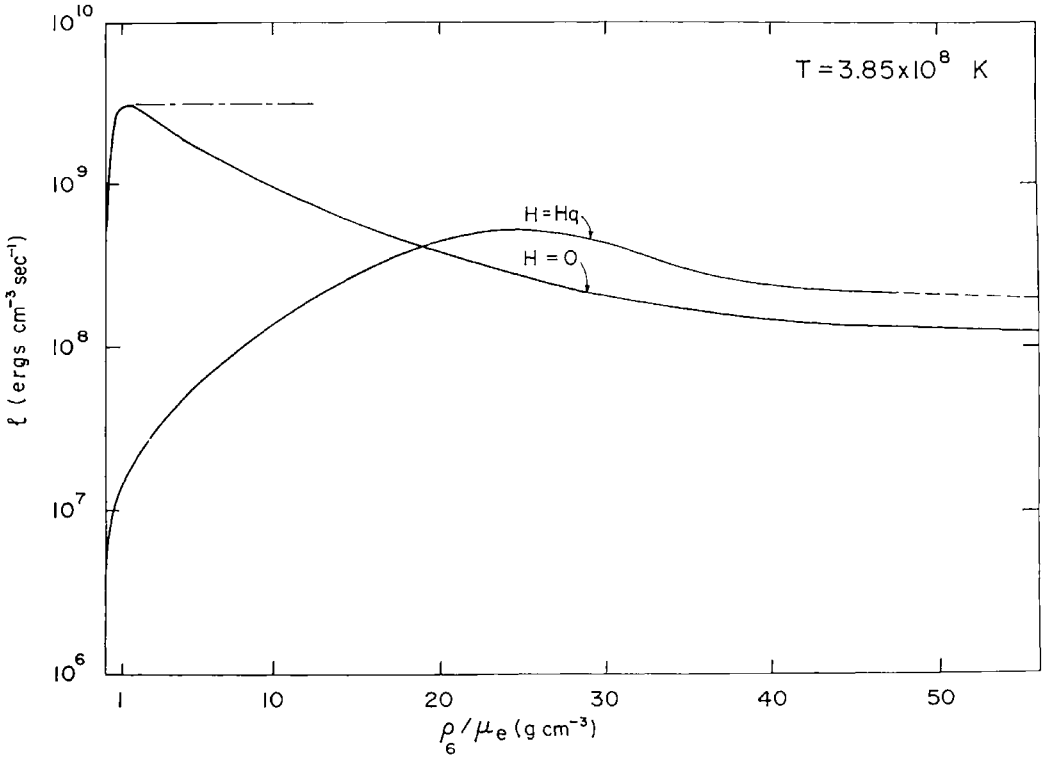


Fig. 8. Same as Figure 6 for $T = 3.85 \times 10^8$ K.

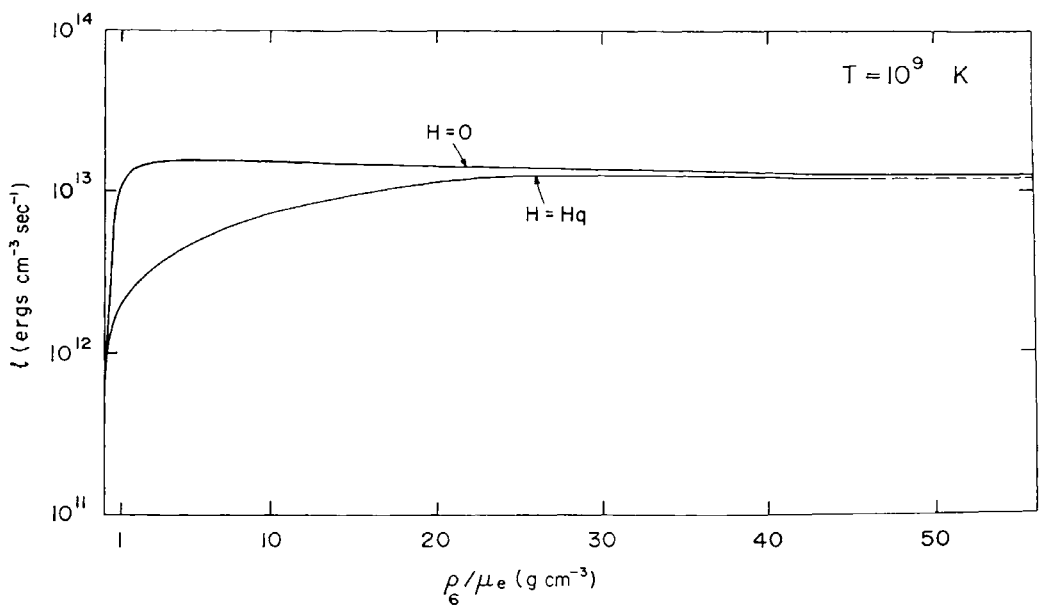


Fig. 9. Same as Figure 6 for $T = 10^9$ K.

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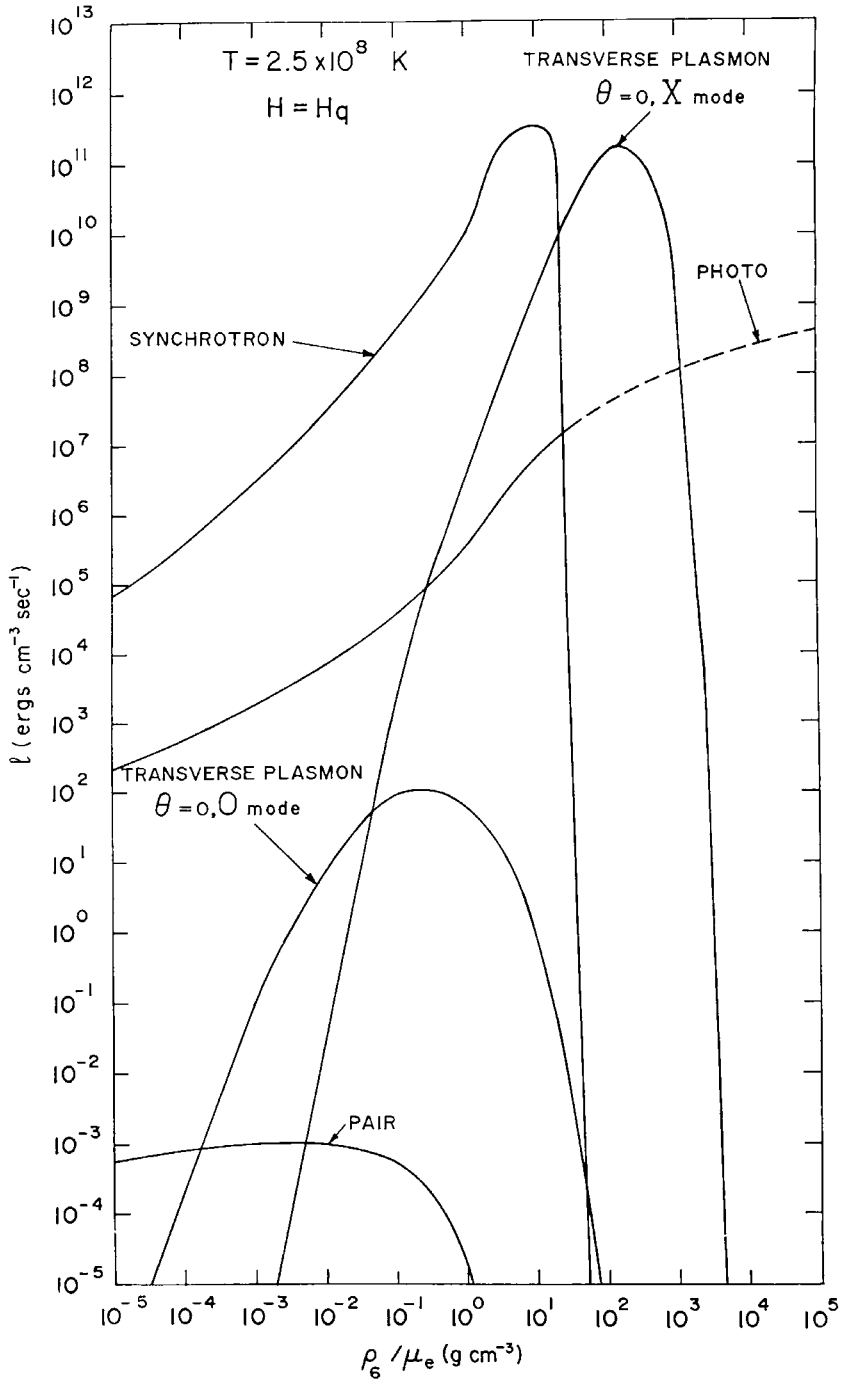


Fig. 10. Neutrino luminosities $l$ (erg cm$^{-3}$ s$^{-1}$) for: pair, photoneutrino, plasma neutrino, and synchrotron process as a function of $\varrho_6/\mu_e$ for $T = 2.5 \times 10^8$ K and $H = H_q = 4.414 \times 10^{13}$ G.

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strong magnetic field we present in Figures 10, 11, and 12 the neutrino luminosities as a function of density $\varrho_6/\mu_e$ for the four main reactions at each of three temperatures ($T=2.5\times10^8$, $3.85\times10^8$, $10^9$ K). It can clearly be seen that the plasmon process and the synchrotron process dominate the other two processes near their respective peaks, whereas the pair annihilation process is important only for high temperatures and at relatively lower densities below the synchrotron and plasmon peaks. On the other hand the photoneutrino process is significant at medium and high densities at relatively

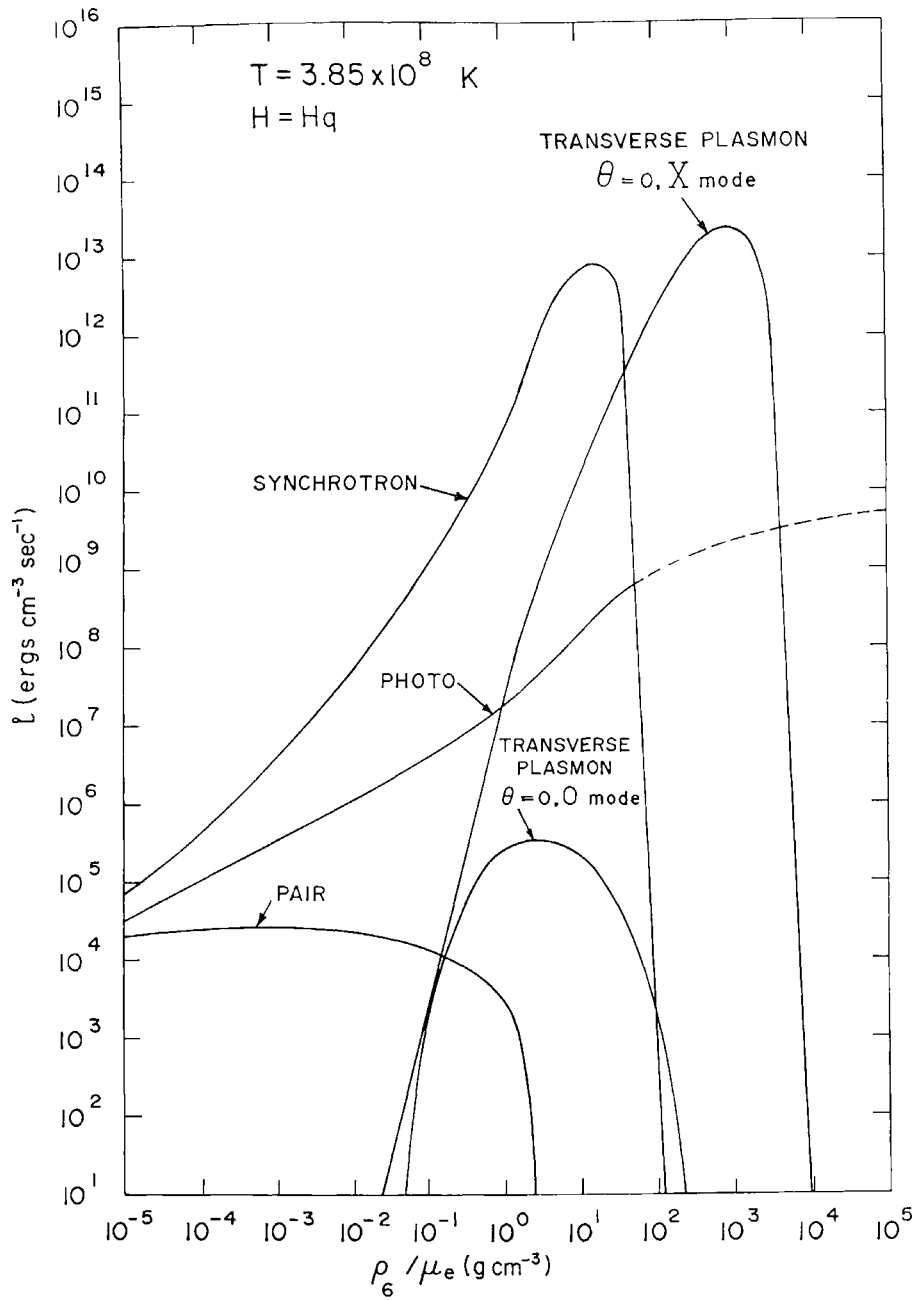


Fig. 11. Same as Figure 10 for $T=3.85\times10^8$K.

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low temperatures. In particular, the photoneutrino luminosity remains roughly constant toward high densities. This is because the effect of the plasma on the photons was neglected. We note that the photoneutrino reaction is sensitive to the presence of a background plasma even in the absence of a magnetic field (Beaudet *et al.*, 1967). It is thus to be expected that in the presence of an anisotropic magnetoactive plasma the neutrino luminosity will further be modified in significant ways. Generalizations to include plasma effects are now in progress.

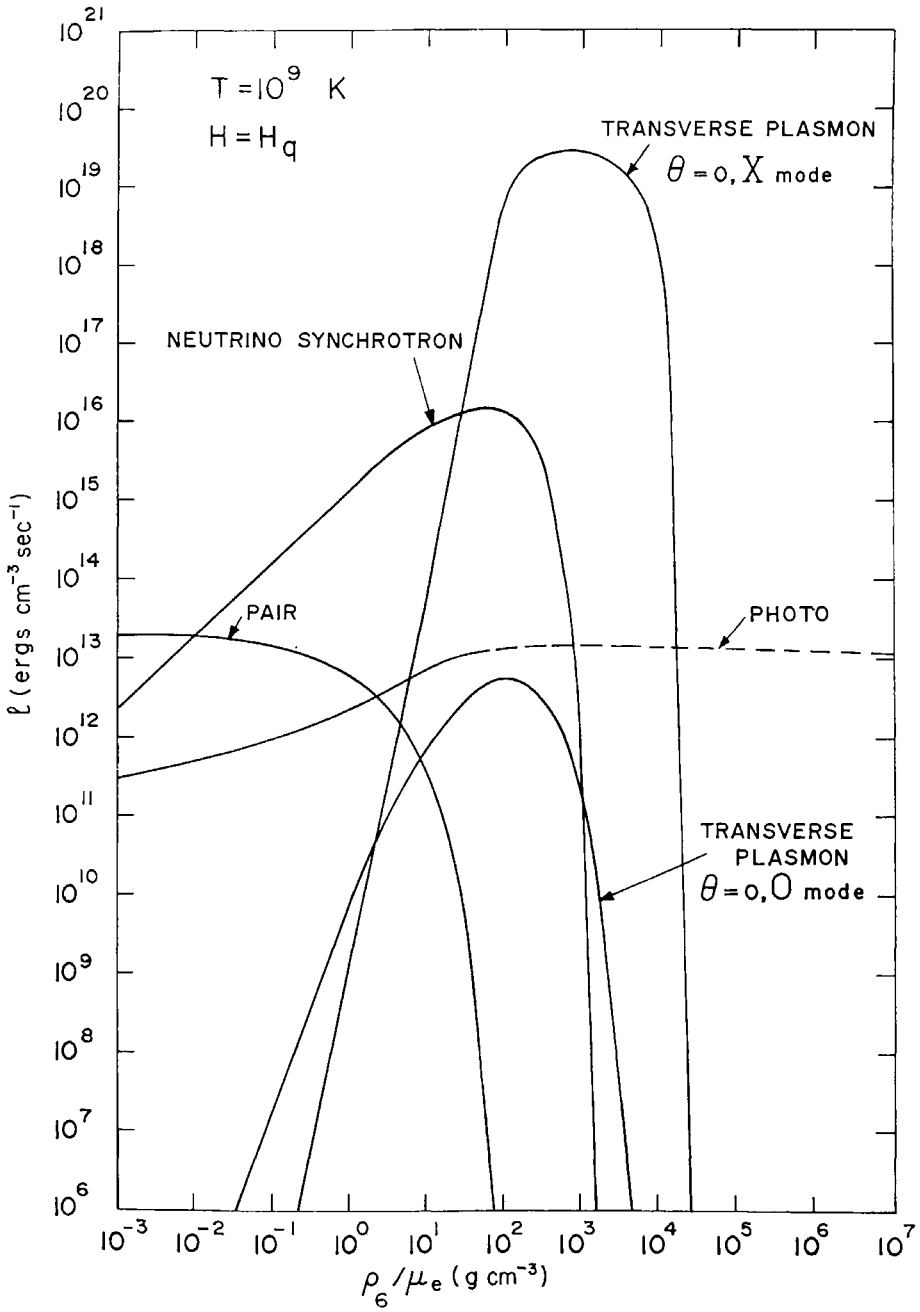


Fig. 12. Same as Figure 10 for $T = 10^9$ K.

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TABLE VI

Neutrino luminosities $l_0$(erg cm$^{-3}$ s$^{-1}$) for transverse plasmons propagating along the magnetic field as a function of density $\varrho_6/\mu_e$ for temperatures $10^8$, $2.5 \times 10^8$, $3.85 \times 10^8$, $5 \times 10^8$, $10^9$, $10^{10}$ K at $H = H_q$. The subscript $o$ indicates the ordinary mode

| $l_0$(erg cm$^{-3}$ s$^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|
| $\varrho_6/\mu_e$ | $T = 10^8$ | $T = 2.5 \times 10^8$ | $T = 3.85 \times 10^8$ | $T = 5 \times 10^8$ | $T = 10^9$ | $T = 10^{10}$ |
| $10^{-7}$ | $4.78 \times 10^{-14}$ | $6.63 \times 10^{-13}$ | $1.44 \times 10^{-12}$ | $2.15 \times 10^{-12}$ | $5.37 \times 10^{-12}$ | $6.48 \times 10^{-11}$ |
| $10^{-6}$ | $2.12 \times 10^{-11}$ | $8.22 \times 10^{-10}$ | $2.18 \times 10^{-9}$ | $3.51 \times 10^{-9}$ | $9.87 \times 10^{-9}$ | $1.31 \times 10^{-7}$ |
| $10^{-5}$ | $3.85 \times 10^{-9}$ | $7.42 \times 10^{-7}$ | $2.73 \times 10^{-6}$ | $4.98 \times 10^{-6}$ | $1.69 \times 10^{-5}$ | $2.58 \times 10^{-4}$ |
| $10^{-4}$ | $1.86 \times 10^{-7}$ | $4.08 \times 10^{-4}$ | $2.54 \times 10^{-3}$ | $5.69 \times 10^{-3}$ | $2.62 \times 10^{-2}$ | $4.98 \times 10^{-1}$ |
| $10^{-3}$ | $1.26 \times 10^{-6}$ | $1.03 \times 10^{-1}$ | 1.47 | 4.61 | $3.51 \times 10$ | $9.47 \times 10^{2}$ |
| $10^{-2}$ | $4.52 \times 10^{-7}$ | 7.99 | $4.01 \times 10^{2}$ | $2.14 \times 10^{3}$ | $3.71 \times 10^{4}$ | $1.78 \times 10^{6}$ |
| $10^{-1}$ | $2.12 \times 10^{-9}$ | $9.96 \times 10$ | $3.28 \times 10^{4}$ | $3.93 \times 10^{5}$ | $2.61 \times 10^{7}$ | $3.33 \times 10^{9}$ |
| 1 | $1.52 \times 10^{-14}$ | $8.01 \times 10$ | $4.17 \times 10^{5}$ | $1.65 \times 10^{7}$ | $8.67 \times 10^{9}$ | $6.45 \times 10^{12}$ |
| 10 | $3.69 \times 10^{-24}$ | $8.61 \times 10^{-1}$ | $2.9 \times 10^{5}$ | $6.9 \times 10^{7}$ | $7.79 \times 10^{11}$ | $1.34 \times 10^{16}$ |
| $10^{2}$ | $\sim 0$ | $2.98 \times 10^{-6}$ | $9.53 \times 10^{2}$ | $4.32 \times 10^{6}$ | $7.37 \times 10^{12}$ | $2.38 \times 10^{19}$ |
| $10^{3}$ | | $1.27 \times 10^{-20}$ | $4.78 \times 10^{-6}$ | 8.58 | $3.6 \times 10^{11}$ | $1.68 \times 10^{22}$ |
| $10^{4}$ | | $\sim 0$ | $\sim 0$ | $1.74 \times 10^{-19}$ | $2.13 \times 10^{3}$ | $2.36 \times 10^{24}$ |
| $10^{5}$ | | | | $\sim 0$ | $1.29 \times 10^{-27}$ | $3.09 \times 10^{24}$ |
| $10^{6}$ | | | | | $\sim 0$ | $7.18 \times 10^{17}$ |
| $10^{7}$ | | | | | | $5 \times 10^{-11}$ |

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TABLE VII

Same as Table VI for the extraordinary mode

| $l_X$ (erg cm$^{-3}$ s$^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|
| $\varrho_6/\mu_e$ | $T=10^8$ | $T=2.5\times10^8$ | $T=3.85\times10^8$ | $T=5\times10^8$ | $T=10^9$ | $T=10^{10}$ |
| $10^{-5}$ | $2.2\times10^{-17}$ | $5.613\times10^{-17}$ | $8.687\times10^{-17}$ | $1.131\times10^{-16}$ | $2.269\times10^{-16}$ | $2.276\times10^{-15}$ |
| $10^{-4}$ | $2.055\times10^{-12}$ | $5.5\times10^{-12}$ | $8.608\times10^{-12}$ | $1.125\times10^{-11}$ | $2.276\times10^{-11}$ | $2.298\times10^{-10}$ |
| $10^{-3}$ | $1.626\times10^{-7}$ | $5.1\times10^{-7}$ | $8.267\times10^{-7}$ | $1.097\times10^{-6}$ | $2.274\times10^{-6}$ | $2.347\times10^{-5}$ |
| $10^{-2}$ | $6.874\times10^{-3}$ | $3.865\times10^{-2}$ | $7.081\times10^{-2}$ | $9.88\times10^{-2}$ | $2.222\times10^{-1}$ | 2.462 |
| $10^{-1}$ | $3.217\times10$ | $1.331\times10^{3}$ | $3.9\times10^{3}$ | $6.546\times10^{3}$ | $1.973\times10^{4}$ | $2.768\times10^{5}$ |
| 1 | $1.035\times10^{4}$ | $3.416\times10^{6}$ | $3.81\times10^{7}$ | $1.255\times10^{8}$ | $1.18\times10^{9}$ | $3.966\times10^{10}$ |
| 10 | $3.03\times10^{6}$ | $9.548\times10^{8}$ | $1.61\times10^{10}$ | $1.147\times10^{11}$ | $7.082\times10^{13}$ | $1.952\times10^{17}$ |
| $10^{2}$ | $7.468\times10^{7}$ | $1.702\times10^{11}$ | $3.33\times10^{12}$ | $4.652\times10^{13}$ | $9.565\times10^{18}$ | $1.307\times10^{24}$ |
| $10^{3}$ | $4.341\times10^{-4}$ | $4.664\times10^{9}$ | $8.71\times10^{13}$ | $2.736\times10^{14}$ | $4.234\times10^{19}$ | $1.061\times10^{27}$ |
| $10^{4}$ | 0 | $4.833\times10^{-15}$ | $5.57\times10^{-1}$ | $2.436\times10^{6}$ | $1.795\times10^{18}$ | $1.093\times10^{29}$ |
| $10^{5}$ | | 0 | 0 | 0 | $5.869\times10^{-10}$ | $2.104\times10^{26}$ |
| $10^{6}$ | | | | | 0 | $2.758\times10^{20}$ |
| $10^{7}$ | | | | | | $3.02\times10^{-7}$ |

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TABLE VIII

Neutrino luminosities $l$ (erg cm$^{-3}$ s$^{-1}$) for the photoneutrino process as a function of density $\varrho_6/\mu_e$ for temperatures $10^8$, $2.5 \times 10^8$, $3.85 \times 10^8$, and $10^9$ K

| $\varrho_6/\mu_e$ | $T = 10^8$ | | $T = 2.5 \times 10^8$ | | $T = 3.85 \times 10^8$ | | $T = 10^9$ | |
|---|---|---|---|---|---|---|---|---|
| | $l\ (H=0)$ | $l\ (H=H_q)$ | $l\ (H=0)$ | $l\ (H=H_q)$ | $l\ (H=0)$ | $l\ (H=H_q)$ | $l\ (H=0)$ | $l\ (H=H_q)$ |
| $4.67 \times 10^{-2}$ | | | $2.84 \times 10^7$ | $1.48 \times 10^4$ | $7.82 \times 10^8$ | $3.13 \times 10^6$ | $8.26 \times 10^{11}$ | $\sim 8.26 \times 10^{11}$ |
| $4.69 \times 10^{-1}$ | | | $9.33 \times 10^7$ | $8.4 \times 10^4$ | $3.98 \times 10^9$ | $1.25 \times 10^7$ | $6.49 \times 10^{12}$ | $\sim 2.72 \times 10^{12}$ |
| 1.44 | $4.61 \times 10^2$ | $1.26 \times 10^{-7}$ | $7.17 \times 10^7$ | $4.49 \times 10^5$ | $4.81 \times 10^9$ | $2.55 \times 10^7$ | $1.31 \times 10^{13}$ | $\sim 4.13 \times 10^{12}$ |
| 2.76 | $6.13 \times 10^1$ | $7.45 \times 10^{-4}$ | $4.32 \times 10^7$ | $1.09 \times 10^6$ | $4.09 \times 10^9$ | $4.08 \times 10^7$ | $1.67 \times 10^{13}$ | $4.44 \times 10^{12}$ |
| 4.66 | 7.47 | $2.11 \times 10^{-1}$ | $2.31 \times 10^7$ | $1.82 \times 10^6$ | $3.08 \times 10^9$ | $8.6 \times 10^7$ | $1.85 \times 10^{13}$ | $4.93 \times 10^{12}$ |
| 12.9 | $2.85 \times 10^{-2}$ | $1.17 \times 10^2$ | $3.68 \times 10^6$ | $4.57 \times 10^6$ | $1.15 \times 10^9$ | $3.36 \times 10^8$ | $1.77 \times 10^{13}$ | $9.5 \times 10^{12}$ |
| 23.7 | $3.20 \times 10^{-4}$ | $1.01 \times 10^3$ | $7.65 \times 10^5$ | $1.02 \times 10^7$ | $4.70 \times 10^8$ | $7.3 \times 10^8$ | $1.50 \times 10^{13}$ | $1.09 \times 10^{12}$ |
| 36.5 | $6.88 \times 10^{-6}$ | $4.3 \times 10^2$ | $1.93 \times 10^5$ | $1.65 \times 10^7$ | $2.09 \times 10^8$ | $4.38 \times 10^8$ | $1.24 \times 10^{13}$ | $1.09 \times 10^{13}$ |
| 46.7 | $5.79 \times 10^{-7}$ | $2.58 \times 10^2$ | $7.85 \times 10^4$ | $2.03 \times 10^7$ | $1.22 \times 10^8$ | $3.3 \times 10^8$ | $1.08 \times 10^{13}$ | $1.1 \times 10^{13}$ |

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## References

Adams, J. B., Ruderman, M. A., and Woo, C. H.: 1963, *Phys. Rev.* **129**, 1383.
Beaudet, G., Petrosian, V., and Salpeter, E. E.: 1967, *Astrophys. J.* **150**, 979.
Canuto, V. and Chiu, H. Y.: 1968, *Phys. Rev.* **173**, 1210, 1220, 1229.
Canuto, V., Chiu, H. Y., Chou, C. K., and Fassio-Canuto, L.: 1970, *Phys. Rev.* **D2**, 2, 281.
Canuto, V., Chiuderi, C., and Chou, C. K.: 1970a, *Astrophys. Space Sci.* **7**, 407.
Canuto, V., Chiuderi, C., and Chou, C. K.: 1970b, *Astrophys. Space Sci.* **9**, 453.
Canuto, V. and Chou, C. K.: 1971, *Astrophys. Space Sci.* **10**, 246.
Canuto, V. and Fassio-Canuto, L.: 1973a, *Phys. Rev.* **D 7**, 1593.
Canuto, V. and Fassio-Canuto, L.: 1973b, *Phys. Rev.* **D 7**, 1601.
Chin, C. W., Chiu, H. Y., and Stothers, R.: 1966, *Ann. Phys.* **39**, 280.
Chiu, H. Y. and Canuto, V.: 1971, *Astrophys. J.* **163**, 577.
Chou, C. K.: 1971, *Astrophys. Space Sci.* **10**, 291.
Gunn, J. E. and Ostriker, J. P.: 1969, *Nature* **221**, 454.
Kemp, J. C., Smedlund, J. B., Landstreet, J. D., and Angel, J. R. P.: 1970, *Phys. Letters* **161**, L77.
McFee, R. W.: 1971, *Astrophys. Space Sci.* **14**, 446.
Tsuruta, S., Canuto, V., Lodenquai, J., and Ruderman, M. A.: 1972, *Astrophys. J.* **176**, 739.
Woltjer, L.: 1964, *Astrophys. J.* **140**, 1309.

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