PRAMANA
—journal of
physics

© Indian Academy of Sciences

Vol. 51, Nos 1 & 2,
July/August 1998
pp. 229–237

Astrophysical constraints on particle properties

SUBHENDRA MOHANTY
Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India

Abstract. I summarize some astrophysical phenomenon like gamma ray bursters, astrophysical proof of the existence of blackholes, Active galactic nuclei – as high energy neutrino sources, and some unsolved issues in supernova. I touch on the aspects where novel particle properties (like neutrino mass and magnetic moment) are invoked to understand the astronomical observations.

Keywords. Black-hole; gamma ray bursts; supernova; neutrino properties.

PACS Nos 14.60; 97.60; 98.70

1. Introduction

Astrophysical processes are increasingly used as testing grounds for particle physics [1]. This is not because of higher energies available in astrophyical processes (the energy scale of astrophysical processes is MeV as primary source of energy in stars is nuclear fusion and fission) but because of higher densities which enable elementary particles of small cross section to have observable consequences. The standard paradigm has been to use astrophysical observations to put bounds on particle properties. However there are some novel astrophysical processes like black-hole accretion and gamma ray bursts which are not understood. It will be a useful endeavour to employ the standard particle properties and see if some of the puzzling features of these astrophysical processes can be resolved.

I begin with those astrophysical processes which have so far not been used extensively for studying particle properties. These are accretion discs of black-hole candidates. I summarize what is known and list the unsolved problems (with a particle physics angle) associated with them in § 2.

There is a large number of high energy neutrinos detectors being built with the aim of detecting neutrinos from AGN's and supernovae. I discuss the expected neutrino spectrum from AGN's and what can be learnt about neutrino masses from them in § 3.

One of the most intriguing astrophysical phenomenon of recent times is the phenomenon of gamma ray bursts. Due to the large number of observations of these bursts and their optical after-glows these make good candidates for tests of particle properties. I summarize what is known about GRB's in § 4 and make some predictions based on some novel properties of a dense neutrino gas.

The standard testing ground for particle properties (like neutrino mass and magnetic moment) has been the supernova 1987a. I summarize the neutrino bounds obtained from SN87a in § 5.

2. Astrophysical 'proof' of the existence of blackholes

There are two types of astronomical objects which are candidates for being blackholes: (a) active galactic nuclei (AGN) of galaxies and (b) X-ray binaries of compact stars. The two classes of object differ in mass – AGN have a mass between $10^6 M_\odot$ to $10^{10} M_\odot$ whereas X-ray binaries which are considered candidates for being blackholes have masses in the range of (5–20) $M_\odot$ (well above the Chandrashekhar limit of $\sim 1.4 M_\odot$). The reason for considering these objects as blackholes is that these huge masses are seen to be confined within their respective Schwarzschild radii $R = 2MG$. The measurement of the radii of these objects cannot be done as accurately as their masses. The masses of these objects are determined by measuring the Kepler velocity (which can be done by measuring the Doppler shift of known spectral lines) of the matter which accretes into them. An accurate determination of the inner radii of these accretion discs cannot be done with the same accuracy. Therefore it is not possible to give a direct proof that the observed masses and radii obey the relation $R < 2GM$ (which can only be true in blackholes) and indirect proofs for the existence of black-hole are called for.

The black-hole accretes mass from its binary companion in the form of an accretion disc. The mass in the disc sheds its energy and angular momenta either radiatively or by viscosity. The proof of black-hole is arrived at by comparing the luminosity of the disc with a one way horizon at the inner radius versus re-scattering of radiation by a hard surface. As the gas falls into the gravitational potential of the accreting body its temperature increases. The maximum steady state luminosity is (called the Eddington luminosity $L_{\rm Edd}$) attained when the in-falling gas is balanced by the radiation pressure,

$$\frac{L_{\rm Edd}\sigma_T}{4\pi R^2} = \frac{GMm_p}{R^2}, \tag{1}$$

where M, is the mass of the accreting body and m_p is the proton mass and σ_T is the scattering cross section between electrons and protons. For a typical AGN like SGA*, the mass is $10^6 M_\odot$ and therefore its maximum luminosity at steady state is

$$L_{\rm Edd} = \frac{4\pi GMm_p}{\sigma_T} = 1.3 \times 10^{44}\left(\frac{M}{10^6 M_\odot}\right) \text{erg s}^{-1} \tag{2}$$

The observed luminosity of the galactic source SGA* is 10^{38} ergs s^{-1}. The puzzle which has not been solved satisfactorily is why some AGN's are under-luminous by such a large factor.

The radiative cooling of a proton–electron plasma is mainly accomplished by the electrons. The main radiative processes are (a) Bremstrahlung $e + p \rightarrow e + p + \gamma$, (b) synchrotron radiation from a 'frozen-in' magnetic field $e + B \rightarrow e + \gamma$ and (c) comptonization of low energy photons $e + \gamma(\text{IR}) \rightarrow e + \gamma$ (X-ray). These processes are inversely proportional to the mass. Hence the contribution of protons to these radiate is comparatively smaller. One way to get around the problem of unexplained low luminosity is to assume that the electron temperature is a factor 10^{-3} smaller in what are called the two temperature models. It is assumed that protons have an average temperature of $T_p = 1$ GeV and electrons have an average temperature of $T_e = 1$ MeV. It

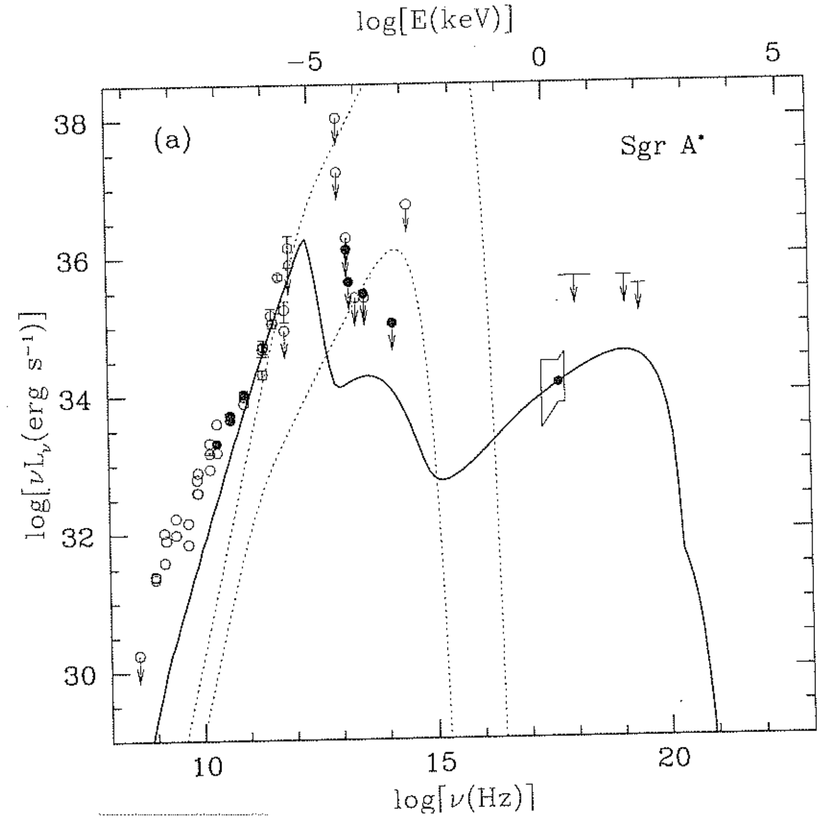

Figure 1. Spectrum of the AGN SGA* (from ref. [1]). Solid lines are the predictions of the two-temperature model, dotted lines are predictions of a typical one-temperature model.

is an open problem to show why a plasma (of average density $10^{10}\,\mathrm{cm}^{-3}$) evolves in such a way during accretion in a way that the electrons and protons have such widely different temperatures. With the electrons assumed at low temperatures, the problem of low luminosity is solved by *fiat*. In the two temperature models the energy and the angular momentum is assumed to be advected into the membrane of the black-hole [2]. In this model with one adjustable parameter (the rate of mass accretion) it is possible to explain both the broadband non-thermal spectrum and the low luminosity of the AGN's (figure 1). In such a model if the inner one way horizon is replaced with a hard surface which can re-scatter the x-ray photons, the luminosity spectrum does not fit the observations for any value of the adjustable parameter. This constitutes the astrophysical proof that the AGN's host a black-hole at their centers. This argument is not complete as there is a possibility that a fraction of the energy re-scattered from the star may be in the form of neutrinos. A detailed calculation of the neutrino luminosity from gas accreting on to a hard surface (like a neutron star) could make the black-hole proof more watertight or make it invalid.

3. High energy neutrinos from AGN's

Not all AGN's are under-luminous. There are some galaxies whose luminosities are close to the Eddington limit of 10^{44} ergs s$^{-1}(M/10^6 M_\odot)$. These objects (like blazers, quasars, Seyfert galaxies) are expected to have a large luminosity in high energy neutrinos [3]. When protons encounter a region of frozen in magnetic field traveling at a large velocity, they gain energy by multiple scattering (this mechanism is called Fermi acceleration). A 1 GeV proton can, after repeated scatterings, acquire an energy $E_P = 10^7$ GeV which is the threshold for producing a $\Delta(1232)$ particle by inelastic scattering of UV photons, $p(10^7\,\mathrm{GeV}) + \gamma\,(50\,\mathrm{eV}) \rightarrow \Delta(1232)$. The $\Delta(1232)$ initiates the following series of decays,

$$\Delta^+(1232) \rightarrow n + \pi^+, \tag{3}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \tag{4}$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu. \tag{5}$$

It is clear from (5) that for every ν_e there is one ν_μ and one $\bar{\nu}_\mu$ produced. This implies that the following prediction can be made about the relative neutrino fluxes from AGN's;

$$\frac{L_{\nu_\mu} + L_{\bar{\nu}_\mu}}{L_{\nu_e} + L_{\bar{\nu}_e}} = 2, \tag{6}$$

$$L_{\nu_\tau} = 0. \tag{7}$$

The reasoning is identical to that of atmospheric neutrinos since the primary source of neutrinos there are also pions produced by hadronic reactions. In the experiments which measure high energy neutrino fluxes any deviation from the predicted flux ratios would be a signal of neutrino oscillations. The energy spectrum of the neutrinos is expected to be the same as the primary proton energy spectrum. A characteristic feature of Fermi acceleration is that the spectrum $n(E) \sim E^{-2}$. The maximum neutrino energy is expected to be $E_\nu = 0.05,\ E_p = 5 \times 10^5$ GeV. In the high energy neutrino detectors appearance of an upward going ν_τ or a deviation of the $\nu_\mu - \nu_e$ flux ratio from 2 would be a signal of neutrino oscillations and would put a bound on neutrino mass $\Delta m^2 \sim (2E_\nu/L) = 10^{-16}\,\mathrm{eV}^2$. The bound is smaller than other oscillation experiments owing to the cosmological distance of the oscillation length.

4. Gamma ray bursts

Gamma ray bursts occur for a duration of 1–10 sec and they have an average fluence $F = 10^{-6}\,\mathrm{erg/cm}^2$, per burst. Recent observation of the x-ray, optical and radio after-glows prove that they are at cosmological distances ($z \sim 0.8$). If they are at cosmological distances [4] $D = 3000$ Mpc then the total energy output per burst $E = 4\pi D^2 F = 10^{52}$ ergs. Since this is equal to the gravitational binding energy of a typical neutron star, they are thought to arise from the merger of neutron stars. The gravitational energy of the neutron stars gets converted into kinetic energy in the form of relativistically expanding fireball [5]. The basic idea here is that neutron stars collide and their gravitational binding energy ($\sim 10^{52}$ ergs) gets converted to the kinetic energy of relativistically expanding high temperature plasma. Then the expanding ball of gas must have a bulk Lorentz factor of about 10^3. This can be understood by realising that for pair production by photons colliding with matter through this gas the photon rest frame energy must be $\gamma \cdot 2m_e \sim \gamma$ MeV. Since GRB bursts have been observed even in the GeV range it means that photons of up to a GeV energy must be able to propagate through the plasma without losing energy in pair production. Therefore a fireball expansion with $\gamma \sim 10^3$ is needed to prevent the photon degradation by pair production. In a stationary plasma photons can propagate without attenuation as long as its frequency is larger than the plasma frequency $\omega_P = (e^2 n_e/m)^{1/2}$. In a relativistically moving plasma the photons are scattered in the forward direction (called relativistic beaming) and they are transported with the motion of the plasma. A relativistically expanding plasma is therefore optically thin compared to a static plasma with the same density. The predictions of the relativistic fireball model [5] have been confirmed by observations of the optical afterglow of GRB 970508 [6] and other such GRBs [7].

Assuming that the basic ingredients of the neutron star collision and the subsequent relativistic fireball model are correct, we can make some more fine-tuned predictions. The main constituent of the neutron star collisions are expected to be neutrinos – as in the case of supernovae. It has been predicted [8] that when photons propagate through a gas of neutrinos the left and the right circular polarisations experience different refractive indices. This is due to parity violation of the weak interactions and the charge asymmetry of the medium. Their is a differential time delay between the two polarisation states given by

$$\Delta t = \frac{\sqrt{2}\, G_F \alpha}{3\pi m_e^2} (n_{\nu_e} - n_{\bar{\nu}_e}) \frac{\omega_P^4}{K^3} \ell, \tag{8}$$

where ℓ is the distance propagated through the neutrino gas. This formula can be applied to make new predictions about signals from gamma ray bursts and their optical afterglows.

Assuming that the neutrinos are produced by a shift in the beta equilibrium of the neutron star, there will be a larger number of ν_e produced compared to $\bar{\nu}_e$ which would give rise to a C asymmetric neutrino medium. Assuming that the energy carried away by the neutrino gas is $E_\nu \sim 10^{51}$ ergs $= 6 \times 10^{56}$ MeV, similar to what is observed in supernovae, we can estimate the ν_e density as a function of time – or the fireball radius R as follows. The temperature of the neutrino gas can be obtained from the relation $E_\nu = (4/3)\pi R^3 (7/8)(\pi^2/30) T_\nu^4$. From this relation we find that the neutrino temperature and number density as a function of the fireball radius R are given by $T_\nu = ((7/180)\pi^3)^{-1/4} (E_\nu/R^3)^{1/4}$ and $n_\nu = (3\xi(3)/4\pi^2)((7/180)\pi^3)^{-3/4}(E_\nu/R^3)^{3/4}$. The differential time delay (8) is a function of the neutrino density $(n_{\nu_e} - n_{\bar{\nu}_e}) \sim n_\nu$, the distance $\ell \sim R$ the fireball radius and the plasma frequency $\omega_P = (e^2 n_e/m_e)^{1/2}$. Taking the electron density $n_e \simeq N/(4/3)\pi R^3$ where N is the total number of electrons in the fireball ($N \simeq 10^{57}$) we have $\omega_P = (3\alpha N/m_e R^3)^{1/2}$. Substituting for ω_P and n_ν in (8) we obtain the expression for the differential time delay of the GRB signals as a function of the fireball radius R as

$$\delta t(R) = 0.1 \frac{G_F \alpha^3}{m_e^4} N^2 E_\nu^{3/4} \frac{1}{R^{29/4}} \frac{1}{K^3}. \tag{9}$$

The differential time falls off rapidly with the fireball radius R. Consider a GRB signal of a millisecond duration which corresponds to a fireball of radius $R = ct \simeq 300$ km. The differential time delay between the right and the left polarized components of a millisecond duration signal in the x-ray band ($K \sim 1$ KeV) turns out to be $\Delta t \sim 2.5 \times 10^{-5}$ s, which may be observable.

5. Particle processes in a medium

In particle interactions in astrophysical contexts the medium plays a crucial role in determining whether the processes are kinematicaly allowed, and determining the cross sections of the interactions. As an example consider the neutrino photon interaction vertex which can exist if for example neutrinos have a non-zero magnetic dipole moment. There are two processes which can occur: (1) Plasmon decay of a photon into two neutrinos and (2) Cerenkov radiation of a photon form a neutrino. Both these processes are forbidden in vacuum . Which of these processes is kinematicaly allowed is determined by the refractive index of the photons in the medium. (In principle the refractive index of neutrinos is also relevant but it has smaller effect $o(G_F n_e)$ compared to the photon which is of $O(\alpha n_e)$).

In red-giants and helium burning stars (with density $\sim 10^4$ gm cm^{-3} and temperatures $\sim 10^8$ K) photons have a large diffusion time due to large scatterings. In these stars photons can decay into $\nu\bar{\nu}$ and the neutrinos can free stream out of the stars. Such a process is kinematicaly allowed as the photons have a time-like dispersion $w^2 - k^2 = (\alpha N_e/m^2)$. In other words a photon in a medium can decay into a real particle-antiparticle pair if the refractive index $n(w) \equiv (k/w) < 1$. The photons have an effective mass equal to the plasma frequency $(\alpha N_e/m^2)^{1/2}$. The luminosity of the neutrino pairs from photon (plasmon) decay is

$$Q = \frac{\mu_\nu^2}{2} \frac{8\xi_3}{3\pi} T^3 \left(\frac{\omega_P}{4\pi}\right)^2 \tag{10}$$

The neutrino luminosity must be smaller than the photon luminosity in order that the lifetime of the helium burning stars confirm with observations. This enables one to put a bound $\mu_\nu < 10^{-11}\mu_B$, on the neutrino magnetic moment [1].

At higher densities such as in the core of a supernova (where $\rho = 3 \times 10^{14}$ gm cm^{-3}) even the neutrinos which are produced during core collapse are trapped for an initial period for about 1 sec. The mean free path of the left handed neutrinos is $\lambda = ((G_F^2 E_\nu^2/\pi)N)^{-1} = 300$ cm. If the neutrino flips its helicity by scattering with the neucleons ($\nu_{\rm L} n \rightarrow \nu_{\rm R} n$) then the resulting right handed neutrinos being sterile under weak interactions can free-stream out of the supernova core. In order that the core-collapse lifetime is not shortened below the observed 1 sec the right handed neutrino luminosity should be less than 10^{51} ergs. This constraint enables one to put bounds on the magnetic moment and the mass of the neutrino.

If the neutrino has a Dirac mass then the helicity flipping process $\nu_{\rm L} n \rightarrow \nu_{\rm R} n$ is suppressed by a factor $(m_\nu/2E_\nu)^2$ compared to the non-helicity flip scattering from a nucleon $\nu_{\rm L} n \rightarrow \nu_{\rm L} n$. The cross section of the helicity flipping scattering from a nucleon is $\sigma = G_F^2 m_\nu^2/4\pi$. The constraint that the total luminosity of right handed neutrinos thus produced $(G_F^2 m_\nu^2/4\pi) N_{\nu_{\rm L}} N_n E_\nu < 10^{53}$ ergs puts a bound on the neutrino mass, $m_\nu < 30$ KeV [9].

Similar reasoning is also employed for establishing a bound on the magnetic moment of neutrinos. Since the magnetic moment operator $\mu_\nu \bar{\psi}\sigma_{\mu\nu}k_\mu\psi\epsilon_\nu$, is a helicity flipping operator left handed neutrinos can flip their helicity by scattering with background protons mediated by a photon ($\nu_{\rm L}p \to \nu_{\rm R}p$) and the sterile right-handed neutrinos can escape the supernova. The rate of this process is $\alpha\mu_\nu^2 n_p n_{\nu_{\rm L}} E_\nu$ should be smaller than the supernova luminosity 10^{53} ergs. This puts an upper bound on the neutrino magnetic moment $\mu_\nu < 4 \times 10^{-12}\mu_B$ [10].

In the examples of helicity flipping by scattering the medium does not play any role except for providing a large number of target particles for the scattering. There is one helicity flipping process which is forbidden in vacuum and which takes place in a medium, namely the Cerenkov radiation of a photon by a neutrino, $\nu_{\rm L} \to \nu_{\rm R}\gamma$ [11]. This process is kinematicaly allowed if the refractive index of the medium $n(w) > 1$. In the application in supernova cooling it is not the emitted photon which is important as the photon is trapped in the core, but the helicity flipping which takes place with the subsequent free streaming of the right-handed neutrino can efficiently cool the supernova core [11, 13].

Consider for example the longitudinal part of the photon (which can be gauged away in vacuum but not in a medium), whose dispersion relation in at high temperature and density is given by [12]

$$\Pi_{\rm L}(k,w) = \frac{\tilde{\mu}_e^2 e^2}{\pi^2}\left(1 - \frac{w^2}{k^2}\right)\left[1 - \frac{w}{2k}\ln\left(\frac{w+k}{w-k}\right)\right] \tag{11}$$

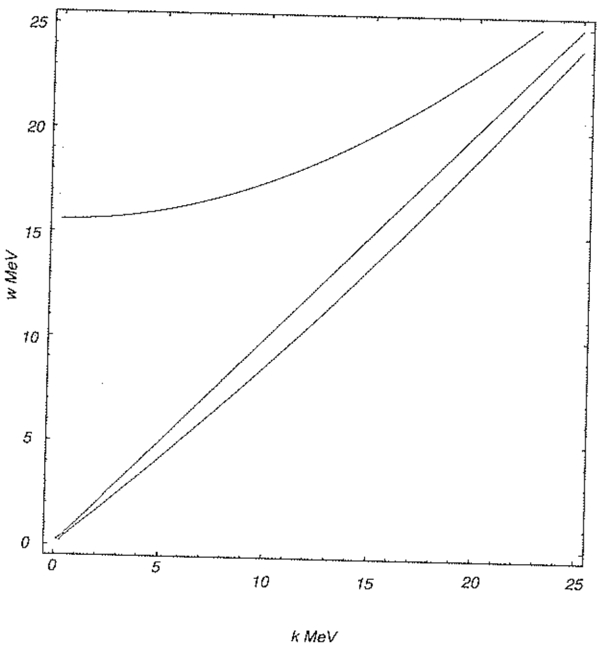

Figure 2. The dispersion relations of longitudinal photons in a supernova core. There is one space-like and one time-like branch. The space-like branch is responsible for Cerenkov processes.

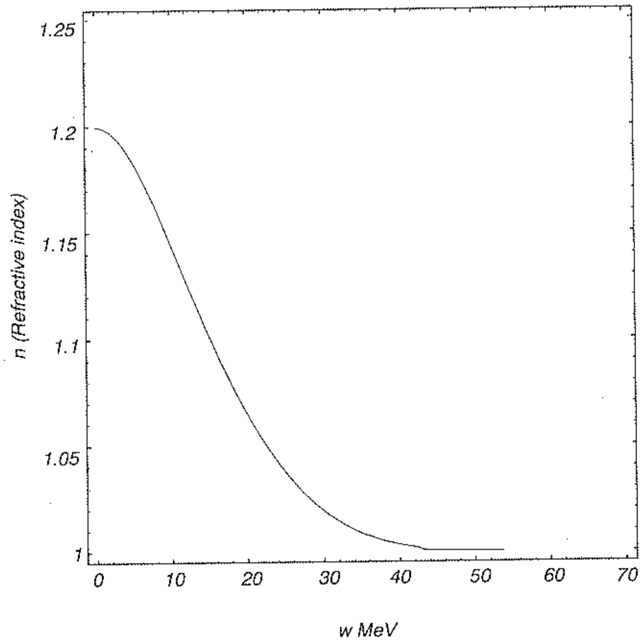

Figure 3. The refractive index of the space-like longitudinal photon showing that there is a range of frequencies where $n(w) > 1$ (and the Cerenkov process is allowed).

where $\tilde{\mu}_e$ is the electron chemical potential which we have assumed to be larger than m_e and T. The dispersion relation for the longitudinal propagating mode $w^2 - k^2 = \mathrm{Re}\Pi_{\mathrm{L}}(k, w)$ is plotted in figure 2. There is a lower branch which is space-like. Using this dispersion relation we find that in a supernova core there is a range of frequencies $(0.3 - 50)$ MeV for which the refractive index $n = k/w > 1$ as shown in figure 3 and therefore plasmon emission or absorption by the Cerenkov process is kinematicaly allowed in this range of plasmon frequencies.

At high temperature the rate of Cerenkov absorption process $\nu_{\mathrm{L}}(p_1) + \gamma(k) \rightarrow \nu_{\mathrm{R}}(p_2)$ is much larger than the Cerenkov emission. The cross section for the Cerenkov absorption is given by

$$\sigma(p_1, k) = \frac{\pi}{2E_1 w} \, \delta((p_1 + k)^2 - m_\nu^2)|\mathcal{M}|^2, \tag{12}$$

where

$$|\mathcal{M}|^2 = \mu^2 \frac{(n^2 - 1)^2}{n^2} Z_l w^2 (2E_1 + w)^2. \tag{13}$$

The rate of energy carried away by ν_{R} is given by

$$Q_{\nu_{\mathrm{R}}} = \mu_\nu^2 (1.1 \times 10^{64}\,\mathrm{MeV}^4) \tag{14}$$

in terms of the neutrino magnetic moment. Using the same constraint viz. $Q_{\nu_{\mathrm{R}}} < 10^{52}$ erg/sec we obtain from eq. (14) the upper bound on neutrino magnetic moment [13]

$$\mu_\nu < 0.7 \times 10^{-13} \mu_{\rm B}. \tag{15}$$

This is two orders of magnitude lower than the earlier bounds [12]. This shows that if the neutrino has a non-zero magnetic moment then helicity flipping of the neutrinos by the Cerenkov absorption of plasmons is the most efficient cooling mechanism in a supernova.

References

[1] G G Raffelt, *Stars as laboratories for fundamental physics* (University of Chicago Press, 1996)

[2] Kristen Menou, Eliot Quataert, Ramesh Narayan, *Astrophysical evidence for black hole event horizons*, astro-ph/9712015

[3] F W Stecker, C Done, M H Salamon and P Sommers, *Phys. Rev. Lett.* **66**, 2697–2700 (1991) Erratum *Phys. Rev. Lett.* **69**, 2738 (1992)

[4] B Paczynski, *Ap. J. Lett.* **317**, L51 (1987)

[5] P Meszaros and M Rees, *Ap. J.* **476**, 232 (1997)
M Rees and P Meszaros, *MNRAS* **258**, L41 (1992)

[6] L Piro *et al*, IAU circ 6617 (1997)

[7] J van Paradjis *et al*, *Nature* **386**, 686 (1997)

[8] S Mohanty, J Nieves and P B Pal, *Optical properties of a neutrino gas*, hep-ph 9712414

[9] G G Raffelt and D Seckel, *Phys. Rev. Lett.* **60**, 1793 (1988)
K Gaemer, R Gandhi and J Lattimer, *Phys. Rev.* **D40**, 309 (1989)
J A Grifolls and E Masso, *Phys. Lett.* **B242**, 77 (1990)

[10] R Barbieri and R N Mohapatra, *Phys. Rev. Lett.* **61**, 27 (1988)
J Lattimer and J Cooperstein, *Phys. Rev. Lett.* **61**, 23 (1988)
A Goyal, S Dutta and S R Choudhary, *Phys. Lett.* **B346**, 312 (1995)

[11] S Mohanty and M K Samal, *Phys. Rev. Lett.* **77**, 806 (1996)
S Sahu, *Phys. Rev.* **D56**, 1688 (1997)
W Grimus and H Neufeld, *Phys. Lett.* **B315** 129–133 (1993)

[12] E Bratten, *Phys. Rev. Lett.* **66**, 1655 (1991)
H A Weldon, *Phys. Rev.* **D26**, 1394 (1982)
J C D'Olivo and J F Nieves, *Nucleon effects on the photon dispersion relations in matter*, hep-ph/9710305

[13] S Mohanty and S Sahu, *Neutrino helicity flip by the Cerenkov emission and absorption in a supernova*, hep-ph/9710404