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LIMITS FROM THE SOFT X-RAY BACKGROUND ON THE TEMPERATURE OF OLD NEUTRON STARS AND ON THE FLUX OF SUPERHEAVY MAGNETIC MONOPOLES

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Abstract

Using recent observations of the diffuse, soft x-ray background we obtain upper limits of 49 eV to the average surface temperature and 10^{32} erg s^{-1} to the total photon luminosity of old ($\simeq 10^{10}$ yrs) neutron stars in the galaxy. If neutron stars are kept hot through monopole-induced nucleon decay, this limit corresponds to a monopole flux limit of $F_M(\sigma_o\beta) \leq 3r \times 10^{-23}$ cm^{-2} sr^{-1} s^{-1}, where the cross section for catalyzed nucleon decay times the monopole-nucleon relative velocity is $\sigma v = 10^{-28}(\sigma_o\beta c)$ cm^2 ($\beta = v/c$), and $r = L_{TOT}/L_\gamma$ is the ratio of the total luminosity to the photon luminosity of a neutron star whose surface temperature $T = 50$ eV. For conventional neutron star equations of state $r \simeq 1$, while for the more exotic ones r can be $O(10^3 - 10^4)$. Although our temperature limit places a very stringent limit on the monopole flux, it does not significantly constrain other mechanisms for heating old neutron stars.

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I. Introduction

Based upon the local pulsar birthrate alone, old (≈ age of the galaxy ≈ 10^{10} yrs) neutron stars should have a local density of at least 10^{-4} pc^{-3} (see, e.g., Manchester and Taylor 1977; Lyne 1982). If these relic neutron stars are still hot ($T \geq$ few x 10^5 K), they will make a significant contribution to the diffuse background of soft x rays. In this paper we use the recent measurements of the soft x-ray background in the B, C, M1, and M2 bands made by McCammon, Burrows, Sanders, and Kraushaar (1983; hereafter MBSK) to place a limit on the average photon luminosity and surface temperature of old neutron stars.

In the standard picture, neutron stars are born very hot ($T \geq 10^{11}$ K), in the cores of supernova explosions, and cool within a few 1000 years to temperatures $\lesssim 10^6$ K by neutrino and photon emission. In the absence of any internal heat sources, one expects old (≈ 10^{10} yrs) neutron stars to be quite cold (< 10^5 K); see, e.g., Van Riper and Lamb (1981), Tsurata (1979), or Richardson etal. (1982).

However, recently it has been suggested that neutron stars could be heated by 'monopole-catalyzed' nucleon decay (Kolb, Colgate, and Harvey 1982; Dimopoulos, Preskill, and Wilczek 1982; Walsh 1982). The idea is simple. Superheavy magnetic monopoles less massive than about 10^{21} GeV which strike the surface of a neutron star lose sufficient energy (through electronic interactions) to be captured and so accumulate inside neutron stars at a rate proportional to the monopole flux. Once inside, grand unified monopoles catalyze nucleon decay through the 'Callan-Rubakov' process (Callan 1982 a,b; Rubakov 1981, 1982), e.g., $M + n \rightarrow M + e^+ + \pi^-$ (M = monopole, n = neutron). According to Callan and Rubakov, the cross section for this process is of order a 'typical strong interaction cross section' ~ 10^{-28} cm^2, and so monopoles will produce of the order of 10^{18} erg s^{-1} per monopole due to the catalysis process. Thus 10^{14} monopoles will produce ~ 10^{32} erg s^{-1}, which, if all radiated in photons, would correspond to a neutron star surface temperature of about 50 eV ≈ $0(6x10^5$ K).

Since the number of monopoles in a neutron star is proportional to the monopole flux, a limit to the total luminosity of a neutron star can be used to obtain a bound on the average flux of monopoles in the galaxy. In previous work (Kolb, Colgate and Harvey 1982; Dimopoulos, Preskill, and Wilczek 1982; Walsh, 1982; Bais etal. 1983; Freese, Turner, and Schramm 1983) limits to neutron star luminosities based upon observations of the diffuse photon background, observations of individual neutron stars, and serendipitous searches for nearby x-ray point sources have been used to derive upper limits on the monopole flux ranging from 10^{-21} cm^{-2} sr^{-1} s^{-1} to 10^{-27} cm^{-2} sr^{-1} s^{-1}. Since these limits are the most stringent-- at least 6 orders-of-magnitude more restrictive than the Parker bound

(Parker 1970; Turner, Bogdan, and Parker 1982), they are of great importance to monopole hunters, and should be subjected to the greatest scrutiny.

The primary aim of this paper is to use measurements of the diffuse background flux of soft x rays to constrain the flux of superheavy magnetic monopoles, paying careful attention to all the input parameters and astrophysics involved -- local number density of old neutron stars, absorption by the ISM, and the ratio of the total luminosity of the neutron star to its photon luminosity ($r \equiv L_{TOT}/L_\gamma$). The limit we obtain,

$$F_M(\sigma_0\beta) \lesssim 3r \times 10^{-23}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1} \quad , \qquad (1)$$

is several orders-of-magnitude less stringent than the bound derived by Dimopoulos, Preskill, and Wilczek (1982), which is also based on observations of the diffuse, soft x-ray background. [Here, $10^{-28}(\sigma_0\beta c)\mathrm{cm}^2$ = catalysis cross section times nucleon-monopole relative velocity.] The discrepancy is due to the fact that they did not take into account absorption of the soft x-rays by the ISM. The bound derived here, while similar in magnitude to the bounds derived by Kolb, Colgate, and Harvey (1982), based on serendipitous searches for soft x-ray point sources, and by Freese, Turner, and Schramm (1983), based on the measured luminosities of old radio pulsars, involves different

assumptions and hence different uncertainties and vulnerabilities. The fact that the three different methods result in similar bounds gives one some added confidence in the validity of these very stringent monopole flux limits.

In obtaining our flux limit, we used the soft x-ray background observations of MBSK to constrain the temperature and luminosity of old neutron stars. These limits,

$$T \lesssim 49\ \mathrm{eV} \qquad (R = 10\ \mathrm{km})$$
$$42\ \mathrm{eV} \qquad (R = 15\ \mathrm{km})$$
$$L_\gamma \lesssim 10^{32}\ \mathrm{erg\ s}^{-1} \quad (R=10 \text{ or } 15\ \mathrm{km}),$$

are interesting in their own right (R = radius of the neutron star). Our luminosity limit is about a factor of 4 better than the limit inferred by Silk (1973), and is more directly linked to observational data. Unfortunately, even our bound does not constrain in a significant way the more conventional mechanisms suggested for keeping old neutron stars hot.

The paper is organized as follows. In Sec. II we derive the integrated flux from old neutron stars as a function of their average surface temperature, carefully illustrating the dependence upon the input assumptions and astrophysics involved. By using the detector response functions given by MBSK we convert our calculated differential energy flux into counting rates for the B, C, M1, and M2 bands. Then we compare these predicted counting rates with the observations of MBSK to obtain our limits to the average surface temperature and photon luminosity of old neutron stars. In Sec. III we use these results to place a limit on the flux of monopoles. In this section we also discuss how our limits depend upon the various uncertainties in the problem (e.g., number density of old neutron stars, modeling of the ISM, and the neutron star equation of state). In Sec. IV we compare our monopole flux limit to the other limits which are also based upon monopole catalysis of nucleon decay in neutron stars, and address the question of the reliability of these catalysis limits. In Sec. V we finish with some concluding remarks, and also briefly mention the relevance of our limits to other mechanisms for keeping old neutron stars hot.

II. The Energy Flux From Old Neutron Stars

In this section we compute the contribution of hot ($\approx$ few x 10^5 K), old ($\approx 10^{10}$ yrs) neutron stars in the galaxy to the diffuse soft x-ray background. The total differential energy flux at earth is calculated by assuming a number density of old neutron stars ($\approx 10^{-4}$ pc^{-3}, which is based upon the local pulsar birth rate), assuming that these neutron stars radiate like blackbodys at temperature T($\approx$ few x 10^5 K), and taking into account absorption by the interstellar medium (ISM).

The total photon luminosity of a neutron star of radius R_{10} 10 km which radiates like a blackbody at a temperature T is: $L_\gamma = 1.05 \times 10^{31}$ (T/30 eV)^4 R_{10}^2 erg s^{-1}. The differential luminosity of this neutron star is

$$dL/dE = L_\gamma(15/\pi^4)(E^3/T^4)[\exp(E/T)-1]^{-1}, \qquad (2)$$
$$= 2.0 \times 10^{36}\, R_{10}^2 E^3[\exp(E/T)-1]^{-1} \text{ erg keV}^{-4}\text{s}^{-1}.$$

For a neutron star at a distance ℓ, the differential energy flux measured by a detector is

$$dF/dE = (dL/dE)\exp[-\tau(\ell,E)]/4\pi\ell^2, \qquad (3)$$

where the number of absorption lengths τ is related to the absorption cross section $\sigma(E)$ and the number density of absorbers n by

$$\tau(\ell,E) = \int_0^\ell n(r)\sigma(E)\, dr. \qquad (4)$$

Interstellar absorption of soft x rays (E $\lesssim$ O(1 keV)) is primarily due to photoionization of H, He, C, N, and O. The cross section per hydrogen atom is: $\sigma(E) \approx 6 \times 10^{-23}(E/\text{keV})^{-3}$ cm^2 (Brown and Gould 1970; Ride and Walker 1977), and n is then the number density of hydrogen atoms, n_H. At these low energies, the effect of photoionization by heavier elements is not important, although it does become important at higher energies (Ride and Walker 1977; Morrison and M^{c}Cammon 1983). If n_H were constant along the line-of-sight, then

$$\tau = \ell/\ell_{abs}, \qquad (5a)$$

$$\ell_{abs} = (n_H\sigma)^{-1} \qquad (5b)$$

$$\approx 5.4\ (n_H/1\ cm^3)^{-1}(E/0.1\ keV)^3\ pc;$$

it is clear that absorption of soft x-rays by the ISM is potentially a very important effect. If we assume that old neutron stars are distributed uniformly about us out to a distance R_* with a number density n_*, then their total contribution to the differential energy flux is

$$dF/dE = (n_*/4\pi)\int_0^{R_*} (dL/dE)\exp[-\tau(\ell,E)]d\ell. \qquad (6)$$

We will now estimate n_* and R_*. The largest <u>known</u> contribution to the neutron star birthrate comes from pulsars. A recent estimate (Lyne 1982) suggests that the local pulsar birthrate is 40 ± 15 My^{-1} kpc^{-2}, projected onto the plane and assuming a beaming factor of 0.2 (*i.e.*, due to their finite beam width we see only 20% of all pulsars). This is about a factor of 2 smaller than earlier estimates (Manchester and Taylor 1977). To convert this birthrate into a number density we need to know the scale height of

old pulsars. As a population pulsars have large velocities out of the galactic plane, $\langle v_z\rangle \approx 150$ kms^{-1}; although Helfand and Tademaru (1977) and Helfand (1983) have suggested that there may also be a population of pulsars, with small $\langle v_z\rangle$, which could include 10-20% of the pulsar population. A $\langle v_z\rangle \approx 150$ kms^{-1} translates into a present scale height of O(few kpc) (Gunn and Ostriker 1970; Oort 1965) for old ($\approx 10^{10}$ yrs) pulsars; note that this is about a factor of 10 larger than the observed scale height for young ($\lesssim$ few 10^6 yrs) pulsars. Assuming a constant birthrate throughout the past 10^{10} yrs and this scale height, we estimate the contribution of old pulsars to n_* to be $\approx 10^{-4}$ pc^{-3}. Throughout we will use $n_* \approx 10^{-4}$ pc^{-3} and $R_* \approx$ few kpc; at the end of this section we will discuss the sensitivity of our limits to these estimates for n_* and R_*.

We will now calculate the effect of interstellar absorption for two different models of the ISM: (1) a simple model where n_H = constant ≈ 1 cm^{-3}; and (2) the three-phase model of M^{c}Kee and Ostriker (1977). Although the average density of interstellar hydrogen is about 1 cm^{-3}, the ISM is very inhomogeneous (see *e.g.*, Spitzer and Jenkins 1975; Frisch and York 1983), and so the simple model should overestimate the effect of absorption by the ISM. With $n_H \approx$ 1 cm^{-3}, equation (6) is straightforward to integrate,

$$dF/dE = 9.0 \times 10^{-3}\ R_{10}^{2} n_{-4}$$
$$\times\ E^{6}[\exp(E/T)-1]^{-1} B(E)\ \mathrm{erg\ s^{-1} keV^{-7} cm^{-2} sr^{-1}}, \quad (7)$$

$$B(E) = n_o\sigma \int_0^{R_*} \exp[-\tau(\ell,E)]d\ell, \quad (8)$$
$$= (n_o/n_H)[1-\exp(-n_H\sigma R_*)],$$
$$\approx 1,$$

where $n_{-4} = n_*/10^{-4}$ pc^{-3}, and $n_o = 1$ cm^{-3}.

Although the simple model provides a good global (scales $\geq$ 100 pc) description of the ISM, it does not provide a very accurate picture on smaller scales. Within 100 pc of the sun n_H is much less than 1 cm^{-3}, being closer to a few x 10^{-2} cm^{-3} (Frisch and York 1983; Spitzer and Jenkins 1975). A more detailed picture of the ISM which takes the 'patchiness' of the ISM into account has been developed by McKee and Ostriker (1977). Their three-phase model consists of a hot component (T $\approx 10^6$ K, $n_H \approx 2 \times 10^{-3}$ cm^{-3}, volume filling factor f $\approx$ 0.8); a warm component (T $\approx 10^4$ K, $n_H \approx 0.3$ cm^{-3}, volume filling factor f $\approx$ 0.2); and a cold component (T $\approx$ 100 K, $n_H \approx 30$ cm^{-3}, volume filling factor f $\approx$ 0.025). A typical observer will find him/herself in a hot region where $n_H \approx 2 \times 10^{-3}$ cm^{-3}, and on average his/her line-of-sight will intersect a warm cloud (radius $\approx$ few pc) every 10 pc ($\simeq R_1$) or so, and a cold cloud (radius $\approx$ few pc) every 100 pc ($\simeq R_2$) or so. Statistically, this leads to an average hydrogen density along the line-of-sight

of: $n_1 \approx 2 \times 10^{-3}$ cm^{-3} for $\ell \leq R_1$; $n_2 \approx 3 \times 10^{-2}$ cm^{-3} for $R_1 \leq \ell \leq R_2$; and $n_3 \approx 1$ cm^{-3} for $\ell \geq R_2$. This picture is consistent with UV absorption studies (Spitzer and Jenkins 1975; Frisch and York 1983). Using the three-phase model, the total differential energy flux expected at the earth is given by equation (7), with

$$B(E)=(n_o/n_1)[1-\exp(-n_1\sigma R_1)] +$$
$$(n_o/n_2)\exp(-n_1\sigma R_1)[1-\exp(-n_2\sigma(R_2-R_1))] +$$
$$(n_o/n_3)\exp(-n_1\sigma R_1+n_2\sigma(R_2-R_1))[1-\exp(-n_3\sigma(R_*-R_2))]. \quad (9)$$

For E $\geq$ 0(0.3 keV) B(E) $\approx$ 1, implying that the effect of ISM absorption is about the same in both models, as one would have expected since $\ell_{abs} \approx (n_o\sigma)^{-1} \geq 150$ pc for E $\geq$ 0.3 keV. However for E $\leq$ 0(0.3 keV) B(E) >> 1, implying that the effect of ISM absorption is very different in the two models, again as expected since $\ell_{abs} \approx (n_o\sigma)^{-1} \leq 150$ pc for E $\leq$ 0.3 keV. Physically, this is because in the three-phase model we can see further out at low energies since in our neighborhood ($\lesssim$ 100 pc) $n_H \approx n_2 \approx 3\times10^{-2}$ cm^{-3} and $(n_2\sigma)^{-1} \approx$ 180 pc (E/0.1 keV)^3. Thus the counting rates for the M1($\approx$ 0.4 - 1.0 keV) and M2 ($\approx$ 0.5 - 1.2 keV) bands should be about the same for both models of the ISM, while the counting rates for the B ($\approx$ 0.11 - 0.19 keV) and C ($\approx$ 0.13 - 0.28 keV) bands should be very different for the two models of the ISM. This indeed turns out to be the case, as can be easily seen in Fig. 1.

The differential energy flux, given in model (1) by equations (7-8) and in model (2) by equations (8-9), when integrated over the detector response function A(E) gives the counting rate Γ:

$$\Gamma_{BAND} = \int (dF/dE) A_{BAND}(E)\, dE. \qquad (10)$$

Our simple analytic fits to the detector response functions given in MBSK are displayed in Table I for the B (= 0.11 - 0.19 keV), C (= 0.13 - 0.28 keV), M1 (= 0.4 - 1.0 keV), and M2 (= 0.5 - 1.2 keV) bands. The predicted counting rates for the B, C, M1, and M2 bands are shown in Fig. 1 as a function of the neutron star surface temperature for both models of the ISM.

The observations of MBSK in the B, C, M1, and M2 bands are four separate and independent measurements in the sense that 'no photon is counted twice.' The all sky average counting rates for the different bands are given in Table I. In all four bands there are large regions of the sky where the counting rate is 1/3 the all-sky average (or less). Therefore we choose to use 1/3 the all-sky average to limit the contribution to counting rate from old neutron stars. Arrows indicating 1/3 the all-sky average count rate are shown in Fig. 1, and the resulting limits to the photon luminosity and surface temperature are summarized in Table

I, for R_{10} = 1 and 1.5 and both models of the ISM.

Using either model of the ISM the C-band measurements give the best limits. With the simple model of the ISM and R_{10} = 1(1.5), we find T $\lesssim$ 60 eV (50 eV) and $L_\gamma \lesssim 1.7(1.8) \times 10^{32}$ erg s^{-1}. With the three-phase model of the ISM and R_{10} = 1(1.5), we find T $\lesssim$ 49 eV (42 eV) and $L_\gamma \lesssim 7.5(9.1) \times 10^{31}$ erg s^{-1}. For either model of the ISM L_γ is constrained to be less than about 10^{32} erg s^{-1}; this is the limit to L_γ we shall use throughout the rest of the paper.

The biggest uncertainty in deriving these limits is the <u>assumed</u> number density of old neutron stars -- a quantity which unfortunately is not an observable. We believe that we have been very conservative in estimating n_*. For example, if there exists a population of pulsars with small velocities out of the plane, say 30% of the population as a whole, then the scale height of this population would be considerably less than the few kpc we estimated for the pulsar population as a whole, and the nearby ($\ell \lesssim$ few 100 pc) number density of old neutron stars due to this subpopulation alone could be a factor of 3 or so times our estimate for n_*. This would not affect the M1 and M2 band counting rates significantly, since at these energies the ISM is transparent out to a few kpc (= R_*). However, the counting rates for the B and C bands would increase by about the same factor that the value of n_* nearby does. Increasing n_* by a factor of O(3) would tighten the C band limits on L_γ by about a factor of 2. Note that in this example we have kept the total number of old neutron stars fixed, and just varied their radial distribution.

In addition to the uncertainty in the scale height of old neutron stars, there is the uncertainty in the birthrate itself. To estimate the number density of old neutron stars we have used the present pulsar birthrate for the neutron star birthrate and assumed that this birthrate has been constant for the past 10^{10} yrs. By no means is it certain that the majority of neutron stars are born as pulsars, or that the neutron star birthrate has been constant throughout the history of the galaxy. [Neutron stars which rotate slowly or have weak magnetic fields will not pulse; roughly speaking the criteria for pulsing seems to be: $(B/10^{12}G)/(P/\mathrm{sec})^2 \geq O(1)$ (Sturrock 1971; Ruderman and Sutherland 1975).] Previous estimates of the number density of old neutron stars have been up to 100 times larger than the value we have adopted here (e.g., Lamb, Lamb, and Pines 1973; Hills 1978; Ostriker, Rees, and Silk 1970). Increasing n_* by a factor of 10 would increase all of calculated counting rates by the same factor and improve our limit to L_γ by about a factor of 10: $L_\gamma \lesssim O(10^{31}\ \mathrm{erg\ s^{-1}})$, cf., Fig. 1.

III. Limits to the Monopole Flux

In order to convert our limit on the average photon luminosity of old neutron stars to a limit on the flux of superheavy magnetic monopoles, we need to: (i) relate the monopole flux F_M to the rate of energy release due to monopole-catalyzed nucleon decay; (ii) relate the photon luminosity to the total luminosity of the neutron star (hot neutron stars also radiate neutrinos); and finally (iii) use the bound on the total luminosity to bound the energy release due to monopole catalysis (and in turn the monopole flux F_M). The rate of energy release from catalyzed nucleon decay per monopole is

$$L_o = \rho c^2(\sigma\beta c) \quad , \tag{11}$$
$$= 8.1 \times 10^{17}\ \mathrm{erg\ s^{-1}}\ (\rho/3\mathrm{x}10^{14}\ \mathrm{g\ cm^{-3}})(\sigma_o\beta),$$

where as before we have parameterized the cross section for catalysis times the monopole-nucleon relative velocity ($v = \beta c$) by

$$(\sigma\beta) = (\sigma_o\beta)10^{-28}\mathrm{cm}^2. \tag{12}$$

For the moment let us assume that a neutron star is born monopole free; later we will also take into account the monopoles captured by its main sequence (MS) progenitor. The number of monopoles captured by a neutron star is just

$$N_M \simeq (4\pi R^2)(\pi\text{-sr})\tau\varepsilon(1+2GM/Rv_M^2)F_M \quad . \tag{13}$$
$$\simeq 3.7 \times 10^{20}\varepsilon(\tau/10^{10}\text{yrs})M_1 R_{10} v_{-3}^{-2} F_{-16} \quad ,$$

where $M = M_1 M_\odot$, $R = R_{10}$ 10 km, and τ are the mass, radius and age of the neutron star, ε is the efficiency with which the neutron star captures the monopoles that strike its surface, and $F_M = F_{-16}\ 10^{-16}\ \text{cm}^{-2}\ \text{sr}^{-1}\ \text{s}^{-1}$ is the average monopole flux (over the time period τ). The factor $(1 + 2GM/Rv_M{}^2) \simeq 3 \times 10^5\ M_1\ R_{10}^{-1}\ v_{-3}^{-2}$ is just the ratio of the gravitational capture cross section to the geometric cross section. Kolb, Colgate, and Harvey (1982) and Dimopoulos, Preskill, and Wilczek (1982) have argued that monopoles less massive than about 10^{21} GeV which strike the surface will lose sufficient energy through electronic interactions to be captured, and so for monopole masses $\lesssim 10^{21}$ GeV we expect $\varepsilon \simeq 1$. In Sec. IV we will discuss the possibility that neutron star magnetic fields may eject the monopoles (or prevent their capture in the first place), and also briefly discuss the possibility that the monopole abundance in a neutron star is lower than our estimate (13) due to monopole-antimonopole annihilations. Combining the luminosity per monopole, eqn. (11), with the number of monopoles expected to be in an old neutron star, eqn. (13), we obtain the total luminosity due to monopoles,

$$L_M \simeq 3.0 \times 10^{38}\ \text{erg s}^{-1}\ (\sigma_0\beta)(\rho/3 \times 10^{14}\text{g cm}^{-3})$$
$$\times\ M_1 R_{10} v_{-3}^{-2} F_{-16} . \tag{14}$$

One is tempted to compare this luminosity with the limit we obtained in Sec. II on the average <u>photon</u> luminosity of an old neutron star, thereby deriving the monopole flux limit: $F_M(\sigma_0\beta) \lesssim 3 \times 10^{-23}\ \text{cm}^{-2}\ \text{sr}^{-1}\ \text{s}^{-1}$. Unfortunately this cannot be done quite so directly because a hot neutron star radiates not only photons, but also neutrinos, and to obtain a bound on F_M based upon L_M one must compare L_M with the bound on the <u>total</u> luminosity of an old neutron star. In order to obtain a limit to F_M we need to know $r(\equiv L_{TOT}/L_\gamma)$, then the limit to F_M which follows is

$$F_M(\sigma_0\beta) \lesssim 3r \times 10^{-23}\ \text{cm}^{-2}\ \text{sr}^{-1}\ \text{s}^{-1}. \tag{15}$$

The ratio r we require can be obtained from neutron star cooling calculations. In Fig. 2 we show L_{TOT}/L_γ as a function of L_γ for a variety of neutron star equations of states, based upon the neutron star cooling calculations of Tsurata (1979), Van Riper and Lamb (1981), and Richardson <u>etal.</u> (1982). Except for the more exotic equations of state (pion condensate or quark matter core), $L_{TOT}/L_\gamma \simeq 1$ for $L_\gamma \lesssim 10^{32}$ erg s^{-1}. If we exclude these more exotic possibilities, then $r \approx 1$ and the limit we obtain is just

$$F_M(\sigma_o\beta) \lesssim 3 \times 10^{-23} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}. \tag{16}$$

(no π-condensate or quark matter core)

If we allow for the possibility of a pion condensate or quark matter core, then for $L_\gamma = 10^{32}$ erg s^{-1} r could be as large as $O(10^3-10^4)$, and so a more conservative (and less stringent) limit follows

$$F_M(\sigma_o\beta) \lesssim 10^{-19} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}. \tag{17}$$

These limits are the main result of this paper. If the catalysis cross section is as large as the calculations of Callan (1982a,b) and Rubakov (1981, 1982) suggest: $\sigma_o\beta \approx O(1)$, then the flux of relic monopoles must be tiny (≈ 1 large city^{-1} yr^{-1}!), and probably too small to detect terrestrially. On the other hand, if the monopole flux is large enough to detect terrestrially ($F_M \gtrsim 10^{-16}$ cm^{-2} sr^{-1} s^{-1} $\approx$ football field^{-1} yr^{-1}), then the catalysis cross section must be small: $(\sigma_o\beta) \lesssim 10^{-6} - 10^{-3}$. This 'Catch-22' virtually precludes the possibility of using large proton decay detectors as 'monopole telescopes'.

Finally, let us turn to the initial monopole abundance in a neutron star. Freese, Frieman and Turner (1984) have shown that MS stars with masses in the range $(1-30)M_\odot$ can capture large numbers of monopoles which are less massive than 10^{17} GeV during their MS lifetime:

$$N_M(MS) \approx (10^{24} - 10^{25})F_{-16}. \tag{18}$$

[Note that the mass range $(1-30)M_\odot$ comfortably brackets the masses of typical neutron star progenitors.] This is some 3-4 orders-of-magnitude more monopoles than the neutron star captures in 10^{10} yr, *cf.* eqn. (13). Assuming that a substantial fraction of these monopoles find their way from the progenitor MS star into the neutron star (for discussion of this point see, Freese, Frieman and Turner 1984, and Harvey, Ruderman and Shaham 1984), our monopole flux limit improves by a factor of $10^3 - 10^4$,

$$F_M(\sigma_o\beta) \lesssim 10^{-26} r \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \quad , \tag{19}$$

where as before $r = L_{TOT}/L_\gamma$ and is ≈ 1 if we exclude exotic equations of state, and perhaps as large as $10^3 - 10^4$ if we allow for the possibility of a pion condensate or quark matter core. Note also that limit (19) is only applicable for monopoles less massive than about 10^{17} GeV; MS stars do not capture significant numbers of monopoles more massive than this.

IV. Comparisons to Other Monopole Flux Limits Based Upon Catalysis of Nucleon Decay in Neutron Stars and Possible 'Loopholes'

In this section we will compare and contrast the limit on the monopole flux obtained in this paper with the other limits on the monopole flux based on monopole catalyzed nucleon decay in neutron stars. Although the methods used are very different and involve different assumptions (and hence weaknesses), the limits which follow are very similar, giving one confidence that the very stringent limit on the monopole flux based upon monopole catalysis is a reliable one. We will also briefly discuss the possibility of evading the catalysis limit.

The limit which can be most readily compared to ours is that of Dimopoulos etal. (1982). They also used the diffuse x-ray (and UV) background to bound the luminosity of old neutron stars and in turn the monopole flux. Their limit, $F_M(\sigma_o\beta) \lesssim 10^{-24}$ cm^{-2} sr^{-1} s^{-1}, is a factor of $30r$ more stringent than ours. However, they did not take into account absorption of the emitted UV/soft x-rays by the ISM, which as we saw in Sec. II is a very significant effect.

Kolb etal. (1982) used a limit to the total energy emitted by a neutron star in photons more energetic than 0.2 keV ($E \lesssim 6 \times 10^{49}$ ergs; Silk 1973) to bound the average

photon luminosity of an old neutron star ($L_\gamma \lesssim 4 \times 10^{32}$ erg s^{-1}), to derive the bound, $F_M(\sigma_o\beta) \lesssim 5 \times 10^{-19}$ cm^{-2} sr^{-1} s^{-1}. When we allow for the possibility of copious neutrino emission ($r \approx 10^3 - 10^4$), as they did, the limits are numerically very similar. The advantage of our technique is that our bound to L_γ ($\lesssim 10^{32}$ erg s^{-1}) is related to observational data in a very straightforward way, while the 'Silk bound', which is based upon the contribution of all old neutron stars in the Universe to the isotropic x-ray background, depends upon quantities like the average supernova rate per galaxy, and has not been corrected for absorption by the ISM.

The limits discussed so far are based upon the integrated contribution of many old neutron stars ($\approx 10^{10}$) to the diffuse photon background. The advantage of this technique is that it 'averages' over many old neutron stars (recall $L_M \propto N_M \propto F_M\tau$). However, one needs to assume a number density of old neutron stars, and the photon luminosity limit ($L_\gamma \lesssim 10^{32}$ erg s^{-1}) upon which the flux limit is based is just getting into the range where the neutrino luminosity can dominate the total luminosity ($r \gg 1$), making the bound very sensitive to the neutron star equation of state assumed. The bounds which we will now discuss are based upon the observations of individual neutron stars.

Kolb etal. (1982) have used the dearth of 'blank-field' x-ray point sources in Einstein serendipitious surveys to obtain the bound $L_\gamma \lesssim 10^{31}$ erg s^{-1} and the resulting monopole flux limit, $F_M(\sigma_o\beta) \lesssim 5 \times 10^{-22}$ cm^{-2} sr^{-1} s^{-1}. Their more stringent bound on L_γ makes neutrino emission less of a worry, cf. Fig. 2. The weakness of this technique is that it depends crucially upon the local number density of old neutron stars and absorption by the ISM. The average number of neutron stars expected in a given field out to a distance d is: $N_{ns} \approx 10^{-2}\, n_{-4}(d/100\ pc)^3\ deg^{-2}$. If due to absorption by the ISM only sources closer than say 100 pc can be detected, then a field of > 100 n_{-4}^{-1} deg^2 is needed. Note that the number of neutron stars in the 'cone of detectability' depends linearly upon n_* and the cube of d. This sensitivity to n_* and d makes the interpretation of negative blank-field serendipitious searches difficult. As larger blank-field surveys are completed (e.g., Stocke etal. 1983) the reliability of this method will improve, and as with the previous technique there is the advantage that old neutron stars which have been accumulating monopoles for 10^{10} yrs are being used.

Finally, Freese etal. (1983) have used Einstein observations of nearby ($\lesssim$ few 100 pc), old ($\approx 10^6$ yrs) radio pulsars to derive a bound based upon the measured x-ray fluxes (or upper limits) of these objects. The pulsar PSR 1929 + 10 provides the most stringent limit, $F_M(\sigma_o\beta) \lesssim 7 \times 10^{-22}$ cm^{-2} sr^{-1} s^{-1} -- comparable to the limit obtained from serendipitous searches. The stringent bound on L_γ ($\lesssim 3 \times 10^{30}$ erg s^{-1}) for this object decreases the uncertainty in L_{TOT}/L_γ due to the equation of state--for all but one of the equations of state represented in Fig. 2, $r = L_{TOT}/L_\gamma \approx 1$. In addition PSR 1929 + 10 has a strong magnetic field ($B \approx$ few 10^{12} G), and strong magnetic fields tend to systematically decrease r (note most of the calculations represented in Fig. 2 were done assuming $B = 0$). The precise size of this effect is still uncertain because of the additional uncertainties introduced when strong magnetic fields are taken into account; see e.g. Van Riper and Lamb (1981). This technique also is not without weaknesses; first since the neutron stars are relatively young, the number of monopoles captured is smaller, cf., eqn. (13) (although if one includes the monopoles captured by the MS progenitor this is a moot point, since the number captured on the MS is greater than that captured by even a 10^{10} yr old neutron star). Second, there are uncertainties due to the fact that the distances to the old radio pulsars used (and pulsars in general) are not accurately determined; the distance is needed to convert the Einstein flux measurements into a total photon luminosity.

We have summarized our comparison of the different methods for obtaining a bound to F_M based upon monopole catalysis in neutron stars in Table II. Perhaps the most striking conclusion that one can draw is that while each method involves uncertainties and has its weaknesses, the uncertainties are different while the limits tend to be comparable, giving one confidence in the validity of the neutron star catalysis bound.

Finally, we will briefly discuss possible 'loopholes' in the very stringent catalysis bound. First, monopoles may not catalyze nucleon decay with a large cross section. The cross section for catalysis could be significantly smaller than the calculations of Callan (1982a,b) and Rubakov (1981, 1982) indicate; in fact the monopoles predicted by some grand unified theories are not expected to catalyze nucleon decay with a strong interaction cross section, i.e., $(\sigma_0\beta) << 1$ (see, e.g., Dawson and Schellekens 1983; Weinberg, London, and Rosner 1983). The possibility that $(\sigma_0\beta) << 1$ is not really a loophole, since all the limits discussed constrain $F_M(\sigma_0\beta)$ -- as we have been very careful to indicate.

The ratio of the gravitational force to the magnetic force on a monopole (with Dirac charge) near the surface of a neutron star is

$$F_{grav}/F_{mag} \approx 100(m_M/10^{16}\ \mathrm{GeV})(10^{12}\mathrm{G}/B); \qquad (20)$$

thus the magnetic fields of neutron stars with $B \gtrsim 10^{12}$ G may deflect monopoles less massive than about 10^{14} GeV and

such monopoles may never reach the surfaces of neutron stars. In this case our estimate for the number of monopoles in a neutron star would not be applicable [eqn. (13)], nor would the flux bounds we discussed. However, it seems likely that some neutron stars are born with weak magnetic fields ($B << 10^{12}$ G). The fact that old ($\gtrsim 10^7$ yrs) pulsars 'turn off' indicates that the surface fields of old neutron stars become weak. Therefore flux limits which involve averages over many old neutron stars (e.g., this paper, or the limits discussed by Kolb etal. 1982) are probably not affected unless monopoles are very light ($<< 10^{14}$ GeV). This example illustrates how the strengths and weaknesses of the various techniques serve to complement each other and strengthen the reliability of the limit.

Harvey, Ruderman, and Shaham (1984) have discussed the possibility that neutron stars with a pion condensate at the center may 'slingshot' monopoles out of the star once they are captured. Although a possibility, the many uncertainties involved -- whether or not neutron stars have pion condensates at their cores, the size of the flux tubes in the pion condensate, and whether or not electronic interactions dissipate the energy the monopoles gain by the 'pion slingshot' mechanism -- seem to make the slingshot a longshot.

Monopole-antimonopole annihilations can potentially reduce the number of monopoles significantly, and so deserve consideration. This issue has recently been thoroughly addressed by Harvey (1984) and Harvey, Ruderman, and Shaham (1984), and here we will just briefly summarize their conclusions. It is generally accepted that interiors of neutron stars are type II superconductors (regardless of the equation of state) (see, e.g., Baym and Pethick 1979). Magnetic flux in a type II superconductor is confined to flux tubes which carry a single flux quantum; the number of flux tubes is $\approx 10^{31}(B/10^{12}G)$. Once they penetrate the superconducting core, monopoles will be confined to flux tubes; so long as the number of monopoles is much less than the number of flux tubes [which is the case for $F_{-16} \lesssim 10^{10}(B/10^{12}G)$], monopoles and antimonopoles will not annihilate. [Note, Harvey etal. (1984) have shown that for the fluxes of interest here, $F_{-16} \lesssim 10^{-3}$, monopoles will not destroy the internal magnetic field of a neutron star in 10^{10} yrs.] In the very unlikely case that the interiors of neutron stars are not superconducting, the internal magnetic field of a neutron star will tend to separate monopoles and antimonopoles. Harvey (1984) has argued that a field of $O(10^8$ G) is sufficient to prevent a significant number of monopole-antimonopole annihilations. If the interiors of neutron stars are not superconducting, and the internal magnetic fields are weaker than 10^8 G, then the size of the

monopole cloud is determined by their thermal motions ($T \approx 100$ MeV, $r_{cloud} \approx 200$ cm), and monopole-antimonopole annihilations will be significant. In this case the equilibrium monopole abundance is determined by balancing the annihilation rate against the rate at which monopoles are being captured. Harvey (1984) derives an equilibrium monopole number of

$$N_{eq} \approx 10^{15} F_{-16}^{1/2}; \tag{21}$$

in calculating the predicted luminosity due to monopoles, it is this number which should be used in place of the total number captured [which is given by eqn. (13)]. When this is done, a much less stringent limit on the monopole flux follows,

$$F_M(\sigma_o\beta) \lesssim 10^{-17}\ r\ \text{cm}^{-2}\ \text{sr}^{-1}\ \text{s}^{-1} \quad , \tag{22}$$

where as always $r = L_{TOT}/L_\gamma$. We mention in passing that the limit derived by Freese etal. (1983) is not affected by monopole-antimonopole annihilations (even if one ignores the fact that these old radio pulsars have large surface magnetic fields and supposes that the internal magnetic fields are less than 10^8 G). That is because these neutron stars haven't had sufficient time to capture the equilibrium number of monopoles, and so annihilations are not yet important.

The different methods used to obtain limits to the monopole flux involve different assumptions (and hence vulnerabilities), but result in similar bounds. This gives one confidence in the reliability of this, the most stringent constraint on the flux of superheavy magnetic monopoles. None of the suggestions for evading the bound seem very likely. If the neutron star catalysis bound could be evaded, there is still the very stringent bound, $F_M(\sigma_o\beta) \lesssim 2 \times 10^{-18}$ cm^{-2} sr^{-1} s^{-1}, based upon catalysis of nucleon decay in white dwarfs (Freese 1984), which involves very different astrophysics. The only case in which the catalysis limits become uninteresting is if the cross section for monopole catalyzed nucleon decay is small, say $(\sigma_o\beta) < 10^{-6}$.

IV. Conclusions

We have used the diffuse, soft x-ray observations made by MBSK to obtain upper limits to the average surface temperature and photon luminosity of old neutron stars: T $\lesssim$ 49 eV and $L_\gamma \lesssim 10^{32}$ erg s^{-1}. Our luminosity limit is about a factor of 4 more stringent than the limit derived by Silk (1973) based upon the integrated contribution of neutron stars to the isotropic x-ray background at energies $\gtrsim$ 0.2 keV, and is more directly tied to observational data.

Using this bound we obtain a limit to the flux of monopoles, $F_M(\sigma_o\beta) \lesssim 3r \times 10^{-23}$ cm^{-2} sr^{-1} s^{-1}, based upon monopole catalyzed nucleon decay in neutron stars. The ratio $r = L_{TOT}/L_\gamma$ depends upon the neutron star equation of state; only for the more exotic equations of state (pion condensate or quark matter interior) is r significantly greater than unity (possibly as large as 10^3 or 10^4). This limit is comparable to the other limits based upon monopole catalysis; the various limits are summarized and compared in Table II.

Although the surface temperature and photon luminosity limits we have obtained result in a very stringent limit on the flux of superheavy magnetic monopoles, they do not constrain in a significant way the more conventional mechanisms for keeping old neutron stars hot. Starquakes in the outer crust, dynamical friction between the superfluid interior and the non-superfluid outer layers, and polar cap heating caused by the bombardment of the polar cap region by photons and relativistic particles (associated with the pulsar radio emission) all provide a means of heating the neutron star by tapping its rotational and gravitational energy reserves. While these mechanisms can keep young ($\lesssim 10^7$ yrs) neutron stars which are still rotating relatively rapidly (P $\lesssim$ few sec) and which still have sizeable magnetic fields at temperatures of 20-100 eV, they cannot keep old ($\approx 10^{10}$ yrs) neutron stars anywhere near this hot. Probably the most important mechanism for heating an old neutron star is by accretion as it moves through the ISM, but even accretion is only likely to result in a photon luminosity of O(few x 10^{29} erg s^{-1}). [Helfand, Chanan, and Novick (1980) have recently discussed neutron star heating mechanisms, and we refer the reader to their review for more details.]

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TABLE I - Summary of Soft X-ray Observations and Neutron Star Temperature and Luminosity Limits

	B	C	M1	M2
Energy Range[a] (keV)	0.11 - 0.19	0.13 - 0.28	0.4 - 1.0	0.5 - 1.2
Detector Response Function[b] (count-erg^{-1}-cm^{2}-sr-keV^{-1})	1.29×10^{11}(E-0.11 keV)	1.33×10^{11}(E-0.13 keV)	5.28×10^{9}(E-.4 keV) (0.4-0.7 keV) 5.28×10^{9}(1.0 keV-E) (0.7-1.0 keV)	7.37×10^{9}(E-0.5 keV) (0.5-0.85 keV) 7.37×10^{9}(1.2 keV-E) (0.85-1.2 keV)
All Sky Average[a] (counts s-1)	49	133	25	39
SIMPLE ISM MODEL[c]				
T_{max}(eV) R_{10}=1.0	95	60	62	68
R_{10}=1.5	68	50	58	63
L^{γ}_{max} (erg s^{-1})	1.1×10^{33} 6.2×10^{32}	1.7×10^{32} 1.8×10^{32}	1.9×10^{32} 3.3×10^{32}	2.8×10^{32} 4.6×10^{32}
3 PHASE ISM MODEL[c]				
T_{max}(eV) R_{10}=1.0	52	49	62	68
R_{10}=1.5	42	42	58	63
L^{γ}_{max} (erg s^{-1})	9.5×10^{31} 9.1×10^{31}	7.5×10^{31} 9.1×10^{31}	1.9×10^{32} 3.3×10^{32}	2.8×10^{32} 4.6×10^{32}

[a] Taken from McCammon etal. (1983).

[b] Our analytic fits to the detector response curves published by McCammon etal. (1983).

[c] All limits are based upon using 1/3 the all-sky average counting rates.

TABLE 2 - Comparison of Monopole Flux Bounds Based Upon Monopole Catalysis of Nucleon Decay in Neutron Stars

Technique used to Limit L_M	Published Flux Limit, $F_M(\sigma_o\beta) \lesssim$	Advantages	Disadvantages
Contribution to diffuse x-ray background		-Averages over a very large number of old objects ($\simeq 10^{10}$ yrs)	-Sensitive to equation of state
This paper	$3r \times 10^{-23} cm^{-2} sr^{-1} s^{-1}$	-4 band limit to L_γ -relatively insensitive to model of ISM, n_*	
Dimopoulos <u>etal</u>. (1982)	$r \times 10^{-24} cm^{-2} sr^{-1} s^{-1}$ (authors used $r \simeq 1$)		-uncorrected for absorption by the ISM
Total x-ray emission per neutron star: $E(> 200$ eV) $\lesssim 6 \times 10^{49}$ ergs Kolb <u>etal</u>. (1982)	$r \times 10^{-22} cm^{-2} sr^{-1} s^{-1}$ (authors used $r \simeq 5 \times 10^3$)	-Averages over a very large number of old objects ($\simeq 10^{10}$ yrs)	-Limit to L_γ is somewhat indirect -Sensitivity to ISM absorption not obvious -Sensitive to equation of state
Negative results of serendipitous Einstein searches for nearby x-ray point sources Kolb <u>etal</u>. (1982)	$5r \times 10^{-24} cm^{-2} sr^{-1} s^{-1}$ (authors used $r \simeq 10^2$)	-Uses old objects ($\simeq 10^{10}$ yrs) -reliability of bound can be improved by analyzing more Einstein fields	-Very sensitive to n_* and absorption by ISM -Sensitive to equation of state
Einstein observations of individual old radio pulsars Freese <u>etal</u>. (1983)	$7r \times 10^{-22} cm^{-2} sr^{-1} s^{-1}$ (authors used $r \simeq 1$)	-Most stringent limit to L_γ, and so less sensitivity to equation of state -Independent of n_* -Less sensitive to monopole annihilations	-Uses relatively young objects ($\simeq 10^6$ yrs) -Some uncertainty in distances to the radio pulsars
Taking into account monopoles captured by the MS progenitor Freese <u>etal</u>. (1983,1984)	-Limits involving old neutron stars improve by $O(10^3)$ -Limits involving young neutron stars improve by $O(10^7)$	-Improves limits by a very significant factor	-Only applicable if monopole mass $\lesssim 10^{17}$ GeV -Do the monopoles captured on the MS end up in the neutron star?

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Figure Captions

Figure 1 - The predicted counting rates for the B, C, M1, and M2 bands as a function of the assumed average surface temperature of an old neutron star. The counting rates Γ scale $\propto n_{-4}R_{10}^2$, while the total photon luminosity scales $\propto R_{10}^2$. The broken curves are for the simple model of the ISM; the solid curves are for the 3-phase model of McKee and Ostriker (1977); and the arrows indicate 1/3 the all-sky average counting rates. The counting rates predicted for the M1 and M2 bands are insensitive to modelling of the ISM (the broken and solid curves are indistinguishable).

Figure 2 - The ratio of total luminosity to photon luminosity ($= r = L_{TOT}/L_{\gamma}$) as a function of photon luminosity, as calculated for various neutron star equations of state. The curves labeled π^a and π^b are pion condensate models and the curve labeled q^a is for a neutron star model with a quark matter core. The more conventional neutron star equations of state are represented by the curves labeled BPS, PS, I, II, IIB, III, A, and B. Note that if the pion condensate and quark matter equations of state are excluded $L_{TOT}/L_{\gamma} \approx 1$ for $L_{\gamma} \lesssim 10^{32}$ erg s^{-1}. Curves π^a, q^a, BPS, and PS are from the calculations of Van Riper and Lamb (1981); curves π^b, I, II, IIB, and III are from the calculations of Richardson etal. (1982); and curves A and B are from the calculations of Tsurata (1979). For all the

calculations except those represented by curves A and B, the magnetic field was assumed to be zero. Although including the effects of magnetic fields increases the uncertainties in the cooling calculations, strong magnetic fields ($B \geq 10^{12}$G) tend to systematically <u>decrease</u> L_{TOT}/L_{γ}.

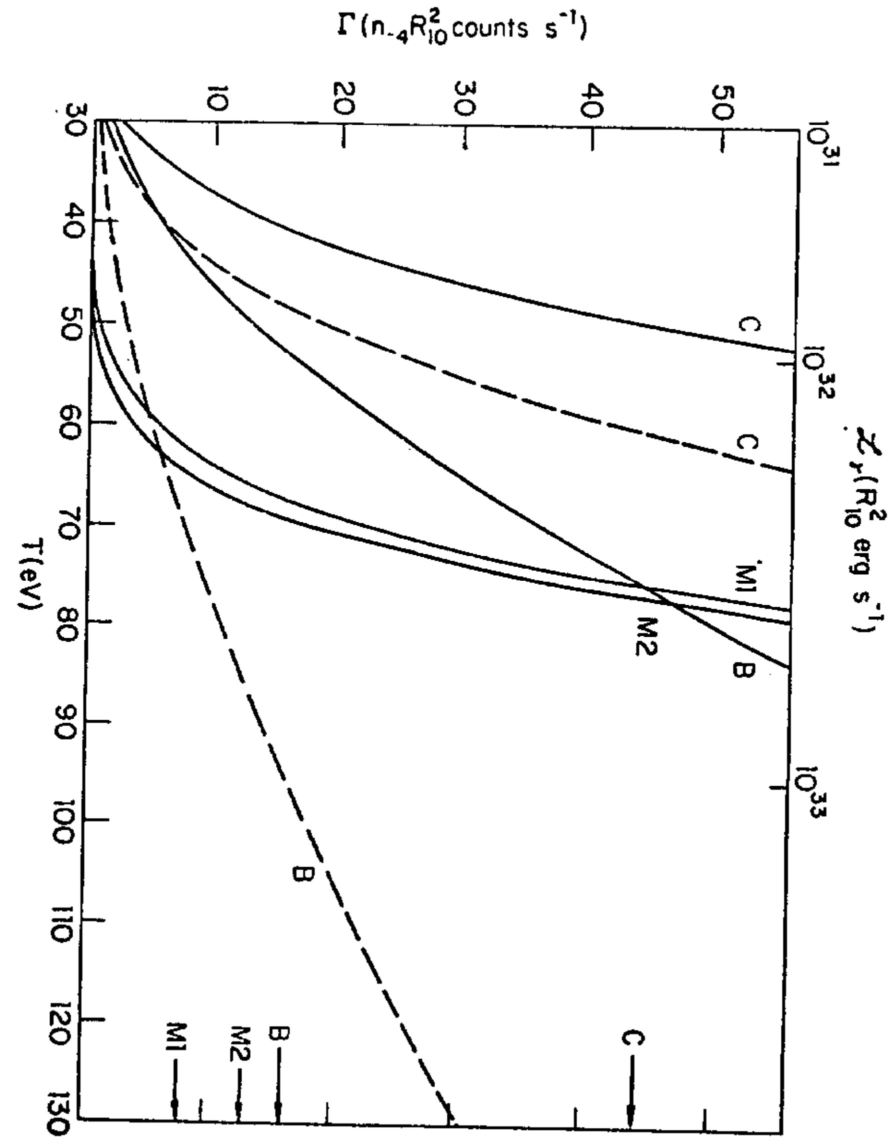
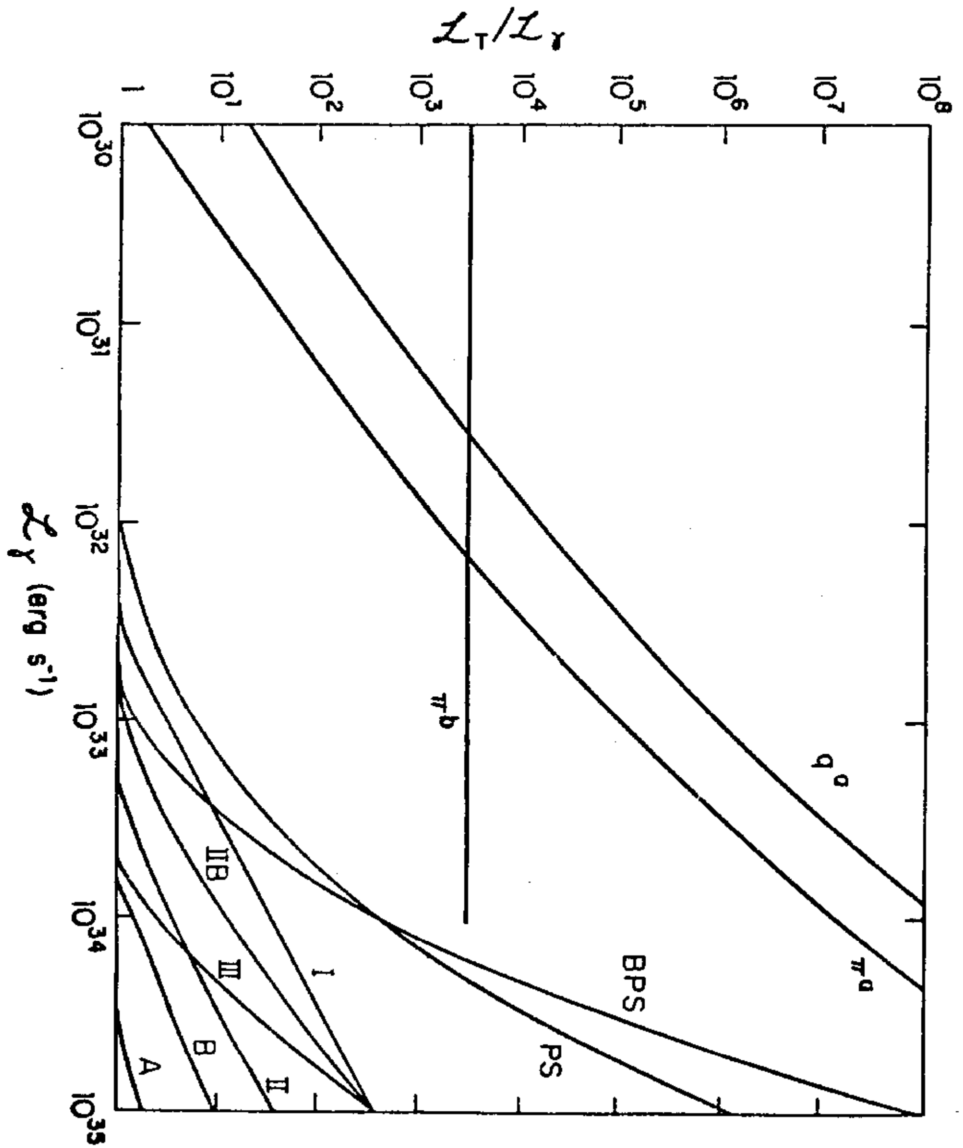


FIGURE 1



$\mathcal{L}_T/\mathcal{L}_\gamma$
1
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
$\mathcal{L}_\gamma$ (erg s^{-1})
10^{30}
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
q^a
π^a
π^b
BPS
PS
I
II
IIB
III
A
B

FIGURE 2