Ref.TH.3595-CERN

ON THE COMPATIBILITY OF OBSERVABLE GRAND UNIFIED
MONOPOLE FLUXES AND NEUTRON STARS

Keith A. Olive *)

CERN — Geneva

and

David N. Schramm

University of Chicago

Chicago IL 60637

and

Fermilab, Chicago IL 60510

ABSTRACT

We consider the possibility that the constraints on grand unified monopole fluxes derived from limits on the X-ray background due to hot neutron stars, contain a window in the range $10^{-15} \lesssim F_{\sigma_0} \lesssim 10^{-13} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. The appearance of this window is due primarily to three effects :

- 1) neutron stars with large numbers of monopoles catalyzing baryon decay in their interiors are mainly producing neutrinos rather than photons;
- 2) the photons radiated are hard X-rays or γ -rays in which the background limits are slightly less restrictive, and
- 3) the lifetime of the neutron star is drastically reduced through disintegration (i.e., all the nucleons in the star will have been processed by monopoles).

All of the arguments are sensitive to the equation of state inside the neutron star, leading to uncertainties which should not dissuade experimenters from monopole searches.

---

*) Address after 1 July 1983 : Fermilab,
Batavia, IL 60510, USA.

There exists the possibility that two of the most distinct and exciting predictions of grand unified theories ¹⁾ (GUTs) [proton decay and magnetic monopoles ²⁾] can be related. Observational evidence of either is, however, very difficult to obtain. Present limits on proton decay ³⁾ are beginning to push towards experimental capabilities and astrophysical limits ⁴⁾⁻¹¹⁾ appear to severely restrict moderately large (observable) fluxes of grand unified monopoles (GUMs). The most stringent limits on GUM fluxes are directly related to baryon non-conserving interactions between GUMs and nucleons ¹²⁾⁻¹⁴⁾. In particular, old neutron stars which trap GUMs will become X-ray sources due to the nucleon "decay" processes occurring in their interior ^{8),9),11)}. If sufficiently abundant these neutron stars will contribute significantly to the observed X-ray background, and if one is close enough to us, it would be detectable as an X-ray source. Thus observational limits on the X-ray background can be used to place limits on the flux of GUMs.

In this letter, we would like to look in detail at some of the assumptions which go into the neutron star limit. Contrary to the previous highly restrictive flux limits ($\leq 10^{-22} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) we will show that under certain reasonable conditions, relatively large fluxes [$\sim 10^{-13} - 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, i.e., the Parker limit ^{4),7)}] of GUMs will be allowed. However, the lower fluxes ($10^{-17} - 10^{-22} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) may be still excluded, although recent arguments ¹⁵⁾ may allow fluxes (up to $10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) if monopole-anti-monopole annihilation occurs within neutron stars. There are also arguments against such annihilations ¹⁶⁾. Basically, a large GUM flux will yield a larger number of GUMs trapped in the star's interior, which leads to a higher rate of nucleon "decay" and hence a hotter neutron star. Hot neutron stars radiate primarily neutrinos not photons. In addition, hot neutron stars will produce hard X-rays rather than soft, $E \lesssim 0.2 \text{ keV}$ X-rays and there is a bump in the X-ray background spectrum at $\sim 10 \text{ keV}$ which allows up to ~ 10 times the photon flux limit. Finally, a large GUM flux can drastically affect the lifetime of the neutron star, i.e., the lifetime will be determined when the number of catalyzed decays equals the number of nucleons in the star. All of these effects lead to the possibility that relatively large GUM fluxes are allowed by neutron star arguments. Because of the many uncertainties (mainly in the equation of state for a neutron star) we do not believe that neutron stars and the X- (or γ -) ray limits are sure enough to entirely rule out the possibility of large GUM fluxes. Depending on the strength of the baryon number violating interactions, such fluxes can produce an observable amount of proton "decay" in existing detectors. Hence the lack of events yields a limit to the GUM flux, $F \lesssim 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ ¹⁷⁾.

We will begin by reviewing the arguments which lead to a flux limit based on neutron stars. The essential ingredient of course is the fact that monopoles possess baryon violating interactions. The cross-section for such a process may be parametrized by ^{12),11)}

$$\sigma = \begin{cases} \frac{1}{v} \frac{\sigma_0}{E^2} & E \gtrsim 1 \text{ GeV} \\ \frac{1}{v} \frac{\sigma_0}{1 \text{ GeV}^2} & E \lesssim 1 \text{ GeV} \end{cases} \quad (1)$$

where v is the relative velocity between the GUM and fermion with energy E . The constant σ_0 characterizes the strength of the interaction and has been estimated ¹¹⁾ to be $\sigma_0 \sim 10^{-3}$ to 10^{-5} with the possibility of large errors in either direction. We will display the dependence on σ_0 in all our results.

We will assume that each GUM striking the neutron star will be trapped. For a given flux F , the rate at which GUMs are captured is

$$\Gamma_c = 4\pi^2 R_N^2 C F \text{ s}^{-1} \quad (2)$$

where R_N is the neutron star radius

$$R_N = 1.2 \times 10^6 \left(\frac{M}{n} \right)^{1/3} \left(\frac{r}{12} \right) \text{ cm} \quad (3)$$

and M is the neutron star mass in solar mass units ($1M_\odot \simeq 2 \times 10^{33} \text{ g}$), n is the nucleon density in the star in units of nuclear density ($n_0 = 0.17 \text{ fm}^{-3}$) and r is a factor which depends on the equation of state (e.g., for a star of uniform density $r=12$, in general r may be in the range $\sim 8-25$). The factor C in Eq. (2) is a gravitational correction ⁸⁾

$$C \approx \left(4 + M^{2/3} n^{1/3} \left(\frac{r}{12} \right)^{-1} \beta^{-2} \right) / \left(4 - M^{2/3} n^{1/3} \left(\frac{r}{12} \right)^{-1} \right) \quad (4)$$

The total number of GUMs contained in a neutron star is just given by

$$N_m = \Gamma_c t_N \quad (5)$$

where t_N is the age of the star.

For a GUM inside a neutron star of density n , the cross-section (1) yields the following rate for catalyzed nucleon decay

$$\Gamma = n\sigma v = 2 \times 10^{21} n \sigma_0 \quad s^{-1} \quad (6)$$

The total number of such decays after a time t_N is given by

$$\begin{aligned} I &= \int_0^{t_N} \Gamma N_m dt = \Gamma \frac{t_N^2}{2} \\ &\approx 5.7 \times 10^{34} M^{1/3} n^{2/3} \left(\frac{r}{12}\right)^2 C t_N^2 F \sigma_0 \end{aligned} \quad (7)$$

For large enough $F \sigma_0$, I may become comparable to the total number of nucleons in the star $N_B = 1.2 \times 10^{57} M (r/12)^3$. Thus setting $I = N_B$ will determine the lifetime of the neutron star

$$t_N = 1.5 \times 10^{11} \left(\frac{M}{n}\right)^{1/3} \left(\frac{r}{12}\right)^{1/2} (C F \sigma_0)^{-1/2} \quad s \quad (8)$$

This will be useful whenever $t_N < 3 \times 10^{17}$ s, i.e., the age of the galaxy.

The final quantity of importance is energy generation rate within the neutron star due to catalyzed nucleon decay

$$Q_m = m_B \Gamma N_m = 1.7 \times 10^{32} M^{1/3} n^{2/3} \left(\frac{r}{12}\right)^2 C F \sigma_0 t_N \quad \text{erg s}^{-1} \quad (9)$$

where m_B is the nucleon mass. As the decay products will tend to thermalize, the neutron star will heat up. The temperature of the star will depend upon whether the dominant energy loss mechanism is neutrinos or photons. In general there will be two temperatures of importance, the central temperature T_c and the surface temperature $T_s = (\alpha/100) T_c$ where α depends on the equation of state and may range ¹⁸⁾ from $1/4 - 1$ (see the Table). The energy loss rate for neutrinos is given by ¹⁹⁾

$$Q_v \approx 6.6 \times 10^{39} M n^{-1/3} \left(\frac{r}{12}\right)^3 T_c^8 \quad \text{erg s}^{-1} \quad (10)$$

where T_c is in units of 10^9 °K. The energy loss rate for photons is

$$\begin{aligned} Q_\gamma &= 4\pi R_n^2 a T_s^4 \\ &= 4.1 \times 10^{37} \left(\frac{M}{n}\right)^{2/3} \left(\frac{r}{12}\right)^2 \alpha^4 T_c^4 \quad \text{erg s}^{-1} \end{aligned} \quad (11)$$

where a is the Stephen-Boltzmann constant. For $T_c > 0.28(r/12)^{-1/4} (Mn)^{-1/12} \alpha$, the dominant energy loss mechanism is neutrinos.

The flux limit on GUMs is derived by considering the effects on an old population of neutron stars. Assuming a formation rate of neutron stars of about 1 per 100 years, there will be a sea of 10^8 neutron stars in the galaxy if their lifetimes exceed 10^{10} years. The safest observational limits available come from the total isotropic background of X-rays per neutron star ²⁰⁾ and requires that

$$Q_X t_N < \frac{1.9 \times 10^{67}}{t_N} f(E_r) \text{ erg}; \quad t_N < 10^{10} \text{ yrs} \\ < 6 \times 10^{49} f(E_r) \text{ erg}; \quad t_N > 10^{10} \text{ yrs} \quad (12)$$

The factor $f(E_Y)$ takes into account the dependence of the limit on the photon energy.

The limit on the X-ray background per neutron star of 6×10^{49} ergs ²⁰⁾ can be derived from recent data assuming neutron stars radiate in the "C band", $0.15 \text{ keV} \leq E \leq 0.28 \text{ keV}$ with energy in the band equalling the observed flux of $\sim 2 \times 10^{-8} \text{ ergs cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ ^{21), 22)}. However, if E_Y is above the C band, the observed energy flux is not as restrictive since the differential photon flux spectrum roughly flattens to a power law ²⁰⁾

$$\frac{dF}{dE} \sim 12 E^{-0.5} \text{ keV}/(\text{keV cm}^2 \text{ s sr}) \quad (13)$$

for $1 \text{ keV} \lesssim E_Y \lesssim 20 \text{ keV}$, [Marshall et al. ²³⁾ actually fit their spectrum from 3-50 keV with a hot thermal plasma] which must be compared with the steeper spectrum in the C band ²¹⁾. If we now define $f(E_Y)$ as the ratio of the energy per neutron star allowed to be radiated at $E_Y \approx 2.7 \text{ kT}$ to the C band limit above, then we find that $f(E_Y)$ ranges from ~ 2 to ~ 10 as E_Y goes from 1 to 20 keV.

There has also been some discussion that the Einstein observatories serendipitous mode may set a more severe limit ^{8), 16)}. Such a limit also depends on the density of neutron stars which determines the probability that one would be close enough (and hence bright enough) to show up in a random field of view. If neutron stars are able to be eaten, then their density is lowered. In addition, it is not clear ²⁴⁾ that the serendipitous data have been scanned in an appropriate way to give any improvement over the isotropic background limit used above. Another alternative approach might be to look at known neutron stars *).

---

*) See note added in proof.

Let us now use Eqs. (9)-(12) to derive the limits on $F\sigma_0$. For $F\sigma_0 < 2 \times 10^{-13} (M/n)^{2/3} (r/12) \alpha^{-1} \approx 7 \times 10^{-13} \beta^2$ for $M=n=1$ and $r=12$, $t_N \approx 3 \times 10^{17}$ s, i.e., the lifetime of the neutron star is not affected by monopoles. For $F\sigma_0 < 2 \times 10^{-15} \beta^2$ the dominant energy loss mechanism is photons. Thus in this case, let us use the approximation $Q_\gamma = Q_m$ (valid if $Q_\gamma \ll Q_\nu$). The central temperature T_c is found from Eqs. (9) and (11)

$$T_c^4 = 4.1 \times 10^{-6} M^{-1/3} n^{4/3} \alpha^{-4} C t_N F\sigma_0 \quad (14)$$

and

$$Q_r = 1.7 \times 10^{32} M^{1/3} n^{2/3} C F\sigma_0 t_N \text{ erg s}^{-1} \quad (15)$$

Taking $t_N \approx 3 \times 10^{17}$ s and $M=n=1$ yields the limit from Eq. (12)

$$F\sigma_0 < 10^{-17} \beta^2 \quad (16)$$

comparable to the result of Kolb et al. 8).

For larger fluxes ($F\sigma_0 > 2 \times 10^{-15} \beta^2$) the dominant energy loss mechanism is no longer photons but neutrinos. In the range $2 \times 10^{-15} \beta^2 < F\sigma_0 < 7 \times 10^{-13} \beta^2$, we still have $t_N \approx 3 \times 10^{17}$ s but we use the approximation $Q_\nu = Q_m$ (valid if $Q_\gamma \ll Q_\nu$) and T_c is found using Eqs. (9) and (10)

$$T_c^4 = 1.6 \times 10^{-4} M^{-1/3} n^{1/2} \left(\frac{r}{12}\right)^{-1/2} (C F\sigma_0 t_N)^{1/2} \quad (17)$$

and Q_ν is found by inserting T_c into (11) to yield

$$Q_r = 6.6 \times 10^{33} \left(\frac{r}{12}\right)^{3/2} M^{1/3} n^{-1/6} C^{1/2} \alpha^4 (F\sigma_0 t_N)^{1/2} \text{ erg s}^{-1} \quad (18)$$

Taking $t_N \approx 3 \times 10^{17}$ s, the limit (12) implies

$$F\sigma_0 < 8 \times 10^{-21} \beta^2 \frac{f^2(E_r)}{\alpha^8} \quad (19)$$

and hence is not applicable, the limit (16) still holds.

Let us now see what happens for still larger fluxes $F\sigma_0 > 7 \times 10^{-13} \beta^2$. At such fluxes, the neutron star lifetime will be given by (8) which must then be inserted into Eq. (12) to derive the limit

$$F\sigma_0 > 4.1 \times 10^{-8} \left(\frac{r}{12}\right)^{11/3} M^{14/9} n^{-4/3} C^{-1} \left(\frac{\alpha^4}{f(E_r)}\right)^{4/3} \quad (20)$$

Notice that the limit requires $F\sigma_0$ to be larger than a given value ! For $M=n=1$, $r=12$

$$F\sigma_0 > 1.2 \times 10^{-7} \beta^2 \left(\frac{\alpha^4}{f(E_r)}\right)^{4/3} \quad (21)$$

For fluxes near this limit, $\alpha \sim \frac{1}{2}$ and hence we are allowing fluxes

$$F\sigma_0 > 2 \times 10^{-8} \beta^2 [f(E_r)]^{-4/3} \quad (22)$$

The final limit which can be placed on GUM fluxes from neutron stars is the requirement that the lifetime does not become too short ¹¹⁾. Since neutron stars are known to exist with lifetimes as long as 10^6 years (e.g., Vela), we must require $t_N \gtrsim 3 \times 10^{13}$ s. From Eq. (8), this means that

$$F\sigma_0 \lesssim 2.3 \times 10^{-5} \left(\frac{M}{n}\right)^{4/3} \left(\frac{r}{12}\right) C^{-1} \quad (23)$$

or

$$F\sigma_0 \lesssim 7.6 \times 10^{-6} \beta^2 \quad (24)$$

for $M=n=1$, $r=12$. If it should turn out that the recent observation of the rapid pulsar ²⁵⁾ is a very old neutron star, then the limits (23) and (24) will be improved possibly ruling out (20)-(22).

Equations (20)-(22) only imply that monopole induced baryon decay and neutron stars alone are not enough to rule out large GUM fluxes, they do not prove the existence of a window. We must also check that fluxes as large as (20)-(22) are consistent with other cosmological and astrophysical limits. For $\beta > 10^{-3}$, if GUMs are not clustered with the galaxy, then we have two additional limits. The first comes from looking at the total energy density of the Universe ^{5)-7), 11)} and we find that

$$F = \frac{n_m \beta}{4\pi} < 5 \times 10^{-4} \frac{\beta}{m} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (25)$$

where n_m is the number density of GUMs and m is the GUM mass in GeV. Together with (20) this implies

$$\frac{m}{\beta \sigma_0} \left(\frac{r}{12}\right)^{11/3} M^{14/9} n^{-4/3} C^{-1} \left(\frac{\alpha^4}{f(E_r)}\right)^{4/3} \lesssim 10^{12} \quad (26)$$

which for $M=n=1$, $r=12$ yields

$$m \beta \left(\frac{\alpha}{f(E_r)}\right)^{4/3} \lesssim 3 \times 10^{11} \sigma_0 \quad (27)$$

and in the most favourable case ($\beta = 10^{-3}$, $\sigma_0 = 1$, $m = 10^{16}$ GeV) requires

$$\frac{\alpha^4}{f(E_r)} \lesssim 0.07 \quad (28)$$

and is at best marginally possible.

The limit coming from the survival of galactic fields ^{4),7)} must also be checked. In this case we have

$$F \lesssim 10^{-26} m \beta^2 \quad (29)$$

which, together with (20), give

$$\left(\frac{r}{12}\right)^{11/3} M^{14/9} n^{-4/3} C^{-1} \left(\frac{\alpha^4}{f(E_r)}\right)^{4/3} \lesssim 2.5 \times 10^{-19} m \beta^2 \sigma_0 \quad (30)$$

and for the same choice of parameters as used for (25) we find a tighter constraint

$$\frac{\alpha^4}{f(E_r)} < 5 \times 10^{-3} \quad (31)$$

If GUMs are clustered with the galaxy, the limit due to the total energy density of the Universe does not apply. We may thus choose a larger GUM mass, e.g., if $m = 10^{19}$ the limit on α^4/f becomes order unity. The final limit which requires that GUMs do not add too much mass to the galaxy ^{7),11)} ($F < 10^9 \beta/m$) does not give a significant constraint. For $\beta < 10^{-3}$ the constraints due to galactic magnetic fields may not apply, depending on the GUM mass and the velocity a GUM would pick up starting at rest.

Putting these results together, one can see that the existence of a window will depend both on the equation of state of a neutron star and the limits on the X- and γ -ray background as a function of E_γ . Independent of

any other astrophysical limits allowed GUM fluxes depend only on α and f (for $M=n=1$ and $r=12$). Equations (16) and (21) give limits on $F\sigma_0$ which are strictly due to baryon non-conserving GUM interactions in neutron stars. For the most interesting case of $\beta=10^{-3}$ the results are displayed in Fig. 1. When we include also limits coming from the mass density of the Universe, galaxy and galactic magnetic fields, we see the possible appearance of an observable window for GUM fluxes. In Fig. 2, we display the allowed regions for $F\sigma_0$ as a function of the GUM mass with $\beta=10^{-3}$ for both cases where GUMs do and do not cluster with galaxies. For the unclustered case (Fig.2a), the mass density of the Universe for large m and galactic magnetic fields for small m prevent the existence of a window with large fluxes. Hence the Kolb et al.⁸⁾ limit (15) remains firm. In the clustered case (Fig.2b), we see the possible appearance of a window (shaded region) between the neutron star and galactic magnetic field limits. In Fig. 2, we have plotted the mass density and galactic magnetic field limits using $\sigma_0=1$. As they are independent of σ_0 they will scale down with σ_0 . Therefore for $\sigma_0 < 10^{-2}$ the window might disappear entirely. We have also chosen $F\sigma_0 \approx 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ to be about the lowest possible flux consistent with choices of α and f . Fluxes lower than $10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ require (for even extreme choices) higher values of α and lower values of f . At $F\sigma_0=10^{-15}$, we have used $\alpha \sim \frac{1}{2}$ and $f \sim 2$. This choice is, of course, equation of state dependent.

In summary, we have seen that if GUMs cluster with galaxies, there exists the possibility that there is a window for an observable flux between 10^{-15} and $10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. The appearance of this window was due to a softening of previous limits from neutron stars because of greatly enhanced neutrino emission for large fluxes, less constraining limits in the X- (γ -) ray background at higher energy and a shortening of neutron star lifetimes for large fluxes. Because these results are very sensitive to the equation of state of a neutron star, we feel that the existence of this window cannot as yet be ruled out. Future observations of the X- (γ -) ray background in the serendipitous mode or an observation of a neutron star with lifetime $t_N \gtrsim 2 \times 10^8$ years or even a careful calculation of the baryon number violation cross-section which has $\sigma_0 < 10^{-2}$ could rule out this window. A more definitive way to eliminate this window could come from proton decay detectors which also limit $F\sigma_0$ ^{11),17)}.

ACKNOWLEDGEMENTS

We would like to thank J. Ellis and J. Grindlay for useful discussions. One of us (D.N.S.) would like to acknowledge the hospitality of CERN and FNAL. This work was supported in part by NSF and DOE at the University of Chicago.

TABLE :   Values of $\alpha \equiv 100 T_s/T_c$ [from Ref. 15].

T_c	0.1	0.2	0.5	1	2
α	1	0.78	0.6	0.45	0.28

NOTE ADDED IN PROOF

After completion of this work, recent data on a nearby pulsar has led to a new limit on GUM fluxes. For details on obtaining limits from particular known stars, see Ref. 26).

R E F E R E N C E S

- 1) For reviews, see :
J. Ellis, CERN preprint TH.3174 (1981), to be published in Proceedings of 1981 Les Houches Summer School;
P. Langacker, Physics Reports 72C (1981) 185;
D.V. Nanopoulos, Ecole d'Eté de Physique des Particules, Gif-sur-Yvette 1980, IN2P3, Paris (1980), p. 1.
- 2) G. 't Hooft, Nuclear Phys. B79 (1974) 276;
A.M. Polyakov, Zh.Eksp.Teor.Fiz. Pis'ma Red. 20 (1974) 430; JETP Letters 20 (1974) 194.
- 3) See, e.g., M. Goldhaber and L. Sulak, Com.Nucl.Part.Phys. 10 (1981) 215.
- 4) E.N. Parker, Ap.J. 160 (1960) 383.
- 5) Ya.B. Zel'dovich and M.Yu. Khlopov, Phys.Letters 79B (1978) 239.
- 6) J.P. Preskill, Phys.Rev.Letters 43 (1979) 1365.
- 7) M.S. Turner, E.N. Parker and T.J. Bogdan, Phys.Rev. D26 (1982) 1296.
- 8) E.W. Kolb, S.A. Colgate and J.A. Harvey, Phys.Rev.Letters 49 (1982) 1373.
- 9) S. Dimopoulos, J.P. Preskill and F.A. Wilczek, Phys.Letters 119B (1982) 320.
- 10) Y. Raphaeli and M.S. Turner, Phys.Letters 121B (1983) 115.
- 11) J. Ellis, D.V. Nanopoulos and K.A. Olive, Phys.Letters 116B (1982) 127;
F.A. Bais, J. Ellis, D.V. Nanopoulos and K.A. Olive, Nuclear Phys. B in press (1983) - CERN preprint TH.3383 (1982).
- 12) V.A. Rubakov, Zh.Eksp.Teor.Fiz. Pis'ma Red. 33 (1981) 658; JETP Letters 33 (1981) 644; Nuclear Phys. B203 (1982) 311.
- 13) C.G. Callan, Phys.Rev. D25 (1982) 2141; Nuclear Phys. B212 (1983) 391.
- 14) F.A. Wilczek, Phys.Rev.Letters 48 (1982) 1146.
- 15) V.A. Kuzmin and V.A. Rubakov, ICTP preprint IC/83/17 (1983).
- 16) J. Harvey, Princeton University preprint (1983).
- 17) J. Van der Velde, to appear in the Proceedings of the XVIIIth Rencontre de Moriond (1983);
P.C. Bosetti, University of Aachen preprint PITHA 82-21 (1982).
- 18) G. Glen and P. Sutherland, Ap.J. 239 (1980) 671.
- 19) B.L. Friman and O.V. Maxwell, Ap.J. 232 (1979) 541;
O.V. Maxwell, Ap.J. 231 (1979) 201.
- 20) J. Silk, Ann.Rev.Astron.Astrophys. 11 (1973) 269.

- 21) P.M. Fried, J.A. Novsek, W.T. Sanders and W.L. Kraushaar, Ap.J. 242 (1980) 987.
- 22) R. Rosner, Y. Avni, J. Bookbinder, R. Giacconi, L. Golub, F.R. Harnden Jr., C.W. Maxson, K. Topka and G.S. Vaiana, Ap.J. 249 (1981) L5.
- 23) F. Marshall, E.A. Boldt, S.S. Holt, R.B. Miller, R.F. Mushotzky, L.A. Rose, R.E. Rothschild and P.J. Serlemitsos, Ap.J. 235 (1980) 4.
- 24) J. Grindlay, private communication.
- 25) D.C. Backer, S.R. Kulkarni, C. Heiles, M.M. Davis and W.M. Gross, Nature 300 (1982) 615.
- 26) K. Freese, M.S. Turner and D.N. Schramm, University of Chicago preprint "Monopole catalysis of nucleon decay in old pulsars" (1983).

*****

FIGURE CAPTIONS

- Figure 1 : Allowed values of $F\sigma_0$ as a function of α^4/f where $\alpha \equiv 100 T_s/T_c$ depends on the equation of state and f contains the dependence of the X-ray limits on the photon energy. The limits from top to bottom are derived from Eqs. (24), (21) and (16), respectively.
- Figure 2 : Allowed values of $F\sigma_0$ as a function of the GUM mass m . For the case when GUMs do not cluster with galaxies (a) limits are shown due to the mass density of the Universe (MDU), galactic magnetic fields (GM) and neutron stars (NS). For the clustered case (b) the MDU limit is replaced by the limit from the mass density of the galaxy (MDG). $F\sigma_0$ must lie below all solid curves. Thus in (a) the MDU limit excludes a window and $F\sigma_0$ must be below the lower NS limit as well. In (b) two regions are allowed, the shaded region and the region below the lower NS curve.

FIG.1

FIG. 2