Bound on the flux of magnetic monopoles from catalysis of nucleon decay in white dwarfs

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Catalysis of nucleon decay in white dwarfs is used to constrain the abundance of magnetic monopoles arising from grand unified theories. Recent discoveries of the dimmest white dwarf ever observed, WD 1136-286 with $L=10^{-4.94}L_\odot$, place limits on the monopole flux that are two orders of magnitude stronger than previous bounds from white dwarfs. An abundance of monopoles greater than the new bound would heat this star to a luminosity higher than what is observed. The new bound is $(F/\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1})\,(\sigma v/10^{-28}\,\mathrm{cm}^2)$ $<1.3\times10^{-20}(v_M/10^{-3}c)^2$, where v_M is the monopole velocity in the Galaxy. The limit is improved by including the monopoles captured by the main-sequence progenitor of the white dwarf: $(F/\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1})$ $(\sigma v/10^{-28}\,\mathrm{cm}^2)<3.5(26)\times10^{-21}$ for 10^{17} (10^{16}) GeV monopoles. We also note that the dependence on monopole mass of flux bounds due to catalysis in neutron stars with main sequence accretion has previously been calculated incorrectly [previously the bound has been stated as $F(\sigma v/10^{-28}\,\mathrm{cm}^2)<10^{-28}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$]. We show that the correct bounds are somewhat weaker for monopole mass other than 10^{17} GeV. [S0556-2821(99)05404-1]

I. INTRODUCTION

The question of whether or not magnetic monopoles exist has intrigued theorists and experimentalists for a long time [1]. In 1974, 't Hooft [2] and Polyakov [3] independently showed that magnetic monopoles always appear as stable topological entities in any grand unified theory (GUT) that breaks down to electromagnetism. Hence, if grand unified theories are shown to be correct, monopoles of mass in the range 10^{15}–10^{19} GeV should exist. Rubakov [4] and Callan [5] calculated that these monopoles catalyze nucleon decay with a cross section characteristic of strong interactions, $\sigma v \approx 10^{-28}\,\mathrm{cm}^2$. (Throughout, we take $\hbar=k_B=c=1$.)

The abundance of these monopoles is an open question. The Kibble mechanism predicts roughly one monopole per horizon volume at the time of the grand unified phase transition. However, this estimate provides a severe overabundance of the number of monopoles: monopoles overclose the Universe by many orders of magnitude. Instead an inflationary epoch [6] may reduce their density in the Universe. Then the present abundance is difficult to estimate. A clue for experimentalists about what monopole flux to expect can be provided by astrophysics.

The Parker bound [7] on the flux of monopoles was obtained by requiring survival of μG magnetic fields observed in our Galaxy and gave $F\lesssim10^{-16}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{sec}^{-1}$. Subsequent improvements on this work include consideration of the monopole velocities [8] due to acceleration by the galactic magnetic field. Another improvement is the extended Parker bound, which required survival of a smaller seed magnetic field in the early period of the Galaxy [9]: $F\lesssim1.2\times10^{-16}(m/10^{17}\,\mathrm{GeV})\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$.

Another class of methods for determination of the monopole flux is based on the hypothesis that GUT monopoles give rise to the catalysis of nucleon decay. The basic idea is that monopoles traveling through the Galaxy lose enough energy to be captured in an object (e.g. white dwarfs, neutron stars, etc.) where they subsequently catalyze nucleon decay.

The energy produced by the nucleon decay heats up the object and results in a flux of photons from the surface of the object. One can then compare this predicted luminosity with what is actually observed. One must ensure that the monopoles would not make the object brighter than what is seen. The coolest star (or other object) seen provides the tightest limit on the monopole flux. If there were more monopoles than allowed by the bound, then the dimmest star observed could not exist.

Several authors have carried out this kind of analysis in neutron stars [10], nearby pulsar and white dwarfs. The strongest bound was obtained from consideration of the catalysis process in PSR 1929+10, an old pulsar [11]. From this pulsar, the bound on the product of monopole flux times cross section for catalysis is $(F/\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{sec}^{-1})(\sigma v/10^{-28}\,\mathrm{cm}^2)\lesssim7\times10^{-22}$. If one includes the monopoles captured by the main sequence progenitor of the white dwarf, this bound becomes even tighter [12], $(F/\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{sec}^{-1})\times(\sigma v/10^{-28}\,\mathrm{cm}^2)\lesssim7\times10^{-28}$. In Sec. IV we will indicate corrections to this work. We will show that the correct bounds are somewhat weaker for monopole mass other than 10^{17} GeV. The consideration of monopole dynamics inside superconducting neutron-star cores leads to a bound $5\times10^{-24}\tau_{10}^{-2}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$ [13], where τ_{10} is the age (in 10^{10} years) of the pulsar's present magnetic field.

As neutron stars are the densest astrophysical objects observed, they give rise to the tightest catalysis bounds. However, there is a certain amount of uncertainty due to the fact that the interiors of neutron stars are not well understood. For example, neutron stars can have very large magnetic fields $\sim10^{12}$ G of unknown topology, and the motion of magnetic monopoles inside the neutron star would undoubtedly be affected by these magnetic fields. In addition neutron star interiors may contain pion condensates, again with uncertain effects on the monopoles. Because of the uncertainties with neutron star interiors, we turn to the next densest astrophysical objects in the Universe, white dwarfs. These stellar remnants are far better understood. The flux limits obtained from

consideration of the catalysis process in white dwarfs are therefore important. Previously Freese [14] considered monopole catalyzed nucleon decay in white dwarfs. By comparing with the lowest luminosity white dwarf that had been seen at that time, she obtained a limit

$$(F/\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1})(\sigma v/10^{-28}\ \text{cm}^2) \lesssim 2\times 10^{-18}. \quad (1)$$

The present work is motivated by new observational data of cool white dwarfs [15]. In particular, Bergeron, Ruiz, and Leggett found a white dwarf 1136-286 (ESO 439-26) with luminosity $10^{-4.94}L_\odot$; this is the dimmest white dwarf observed to date. We use the measured luminosities of old white dwarfs to constrain the radiation due to monopole-catalyzed nucleon decay and thus to obtain an upper limit to the average flux of monopoles in the Galaxy. Since a white dwarf with luminosity $10^{-4.94}L_\odot$ is observed today, we know that the monopole-induced contribution to the white dwarf luminosity cannot exceed this value. These new data improve the limit on the monopole abundance due to catalysis in white dwarfs [14] by roughly two orders of magnitude.

A monopole flux saturating this bound would keep the white dwarfs at luminosities at least this great and would lead to the prediction that no cooler white dwarfs will be found. As we will discuss, if it were indeed true that monopoles are keeping dwarfs hot, one would expect a different dependence of white dwarf luminosity on mass than expected in the standard model.

We shall explicitly indicate the dependence of our results on various parameters. We will parametrize the properties of the white dwarf in terms of typical values from observations: for the mass, $M = M_{0.6}0.6M_\odot$, for the radius $R = R_9 9 \times 10^8$ cm, and for the average density $\bar\rho = 4 \times 10^5\,\text{g cm}^{-3}M_{0.6}R_9^{-3}$. The central density is about an order of magnitude higher, $\rho_c = 3\times 10^6\,\text{g cm}^{-3}M_{0.6}R_9^{-3}$. Rubakov [4] estimated the product of cross section for catalysis and relative velocity v of the monopole and nucleon to be constant: $\sigma v = \sigma_0 = 10^{-28}(\sigma v_{-28})$ cm^2. For the thermal nucleon velocities expected inside carbon and oxygen white dwarfs, the relative velocity is $v \approx 10^{-3}c$, suppression effects may reduce the cross section by a factor of $10^{-2}s_{-2}$ [16], and so we include this factor. In white dwarfs made of helium the suppression effects would be less effective ($s_{-2} = 10$), and all the monopole flux bounds would be an order of magnitude stronger. Note the three different velocities used in the calculations: v is the relative velocity of the monopole and nucleon inside the white dwarf, v_M is the velocity of the monopole far from the white dwarf, and β is the velocity of the monopole as it passes through the white dwarf.

II. ESTIMATION OF THE MONOPOLE FLUX

As we noted in the Introduction, monopole-catalyzed nucleon decay caused by the monopoles captured in white dwarfs can provide an additional internal heat source for the star. Our evaluation of the monopole flux is based on the observed luminosity of the white dwarfs and estimation of the number of monopoles trapped inside the stars. As a monopole passes through a white dwarf, it loses energy and

is captured. Electronic interactions are considered to be the primary source of energy loss for the monopoles, with [17,18]

$$\frac{dE}{dx} = \frac{2\pi n_e(eg)^2\beta}{k_F}\left(\ln\frac{1}{Z_{min}} - \frac{1}{2}\right) \approx 100\rho\beta\ \ \text{GeV/cm},$$
$$(2)$$

where n_e is the electron density, the Fermi momentum of the electrons $k_F \approx 0.1$ MeV, $Z_{min} = 2k_F\lambda/h$, λ is the mean free path of the electron, ρ is the density of the white dwarf (in gcm^{-3}), and β is the velocity of the monopole as it passes through the white dwarf. At the surface of the star, $\beta = (v_M^2 + 2GM/R)^{1/2} \sim (2GM/R)^{1/2} \sim 3\times 10^{-2}$.

As was shown in [14], a white dwarf accumulates almost all the monopoles with $m \lesssim 10^{20}$ GeV incident upon it. The number of monopoles captured by a white dwarf exposed to a monopole flux $F(\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1})$ for a time $\tau = \tau_{10}10^{10}$ yr is given by

$$N_M \approx FA\tau(\pi sr) \approx 2.0\times 10^{39}a_1 F \quad (3)$$

where $A = 4\pi R^2[1 + (2GM/Rv_M^2)]$ is the capture area, $v_M = v_{-3}10^{-3}c$ is the velocity of the monopole far from the white dwarf, $a_1 = \tau_{10}R_9 M_{0.6}v_{-3}^{-2}$.

Once captured, the monopoles sink to the center of the white dwarf. In calculating the luminosity from catalyzed nucleon decay, we use the central density of the white dwarf. We are justified in doing this since the time for the monopole to fall (from rest) into the center is $\approx 1000s$, as has been calculated [14] by treating the motion of the monopoles as a harmonic oscillator with a dE/dx damping term. We find the luminosity from catalyzed nucleon decay per monopole:

$$L_1 = \rho_c\sigma v = 8.1\times 10^7\ \ \text{ergs}^{-1}(\sigma v)_{-28}s_{-2}M_{0.6}R_9^{-3}. \quad (4)$$

Then the total luminosity of a white dwarf due to a monopole-catalyzed nucleon decay is

$$L_{mon} = N_M L_1 = 1.6\times 10^{47}a_2 F\ \ \text{ergs}^{-1}, \quad (5)$$

where $a_2 = \tau_{10}R_9^{-2}M_{0.6}^2(\sigma v)_{-28}s_{-2}v_{-3}^{-2}$.

From the Stefan-Boltzmann law, $L_{mon} = \sigma_{BB}4\pi R^2T_{eff}^4$, where σ_{BB} is the Stefan-Boltzmann constant, we can find the blackbody temperature corresponding to this luminosity,

$$T_{eff} = 1.3\times 10^8\ \ \text{K}(Fa_2R_9^{-2})^{1/4}. \quad (6)$$

White dwarfs cool as they age. The cooling time is a function of the white dwarf mass and composition. For white dwarf 1136-286, we use the mass and composition provided by the observers [15]. The observed energy distributions are obtained from a combination of both optical BVRI and infrared JHK photometric data and used to derive both the effective temperature and the atmospheric composition of the star. This white dwarf is seen to have a helium atmosphere. Stellar masses were also obtained with trigonometric parallax. Bergeron, Ruiz, and Leggett [15] derive $M = 1.2M_\odot$ for

WD 1136-286. Then from measurements of the luminosity and T_{eff}, Eq. (6) implies that the radius is $R \approx 3.9 \times 10^8$ cm.

We also use two different cooling models. First we use the white dwarf cooling theory from the calculations of Segretain et al. [19], as communicated by Chabrier. The Segretain et al. [19] model accounts for gravitational energy release due to carbon-oxygen differentiation at crystallization. This treatment of crystallization yields significantly longer white dwarf cooling times, which in turn imply an older age for any particular white dwarf. These white dwarf models correspond to a mass sequence of initially unstratified white dwarfs composed of equal parts carbon and oxygen, with helium atmospheres. With these models, the age of white dwarf 1136-286 is 9.63 Gyr. For comparison we also use the cooling curves of Wood [20] which do not include chemical fractionation. Chemical fractionation provides an additional source of energy to be radiated away; thus models that lack it cool faster. With the Wood cooling models, the ages of white dwarfs are somewhat younger. Hence these models give younger white dwarfs that accumulate somewhat fewer monopoles and provide somewhat less restrictive bounds. With the Wood cooling curve, the age of white dwarf 1136-286 is 6.47 Gyr. To illustrate the uncertainty we provide flux bounds using both possible ages, but note that the discrepancy is not very great.

The cooling models discussed above do not yet have an additional heat source due to monopoles. If white dwarfs have indeed been accumulating monopoles, then the monopole contribution to the luminosity increases linearly in time, and monopole catalyzed nucleon decay will eventually become the dominant source of luminosity. Since white dwarf WD 1136-286 with luminosity $10^{-4.94}L_\odot$ has been observed to exist, we know that the monopole-induced contribution to the white dwarf luminosity cannot exceed this value, i.e., $L_{mon} < 10^{-4.94}L_\odot$. Using the mass and radius discussed previously for this white dwarf, we then find from Eqs. (3)–(5) that

$$N_M \leq 2.2 \times 10^{19} (\sigma v)_{-28}^{-1} s_{-2}^{-1}. \qquad (7)$$

With the cooling curves of Segretain et al., which include the effects of chemical fractionation, the age for this particular white dwarf WD 1136-286 is given to be 9.63 Gyr as mentioned above. We find a flux bound

$$F \leq 1.3 \times 10^{-20} (\sigma v)_{-28}^{-1} s_{-2}^{-1} v_{-3}^2 \quad \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}. \qquad (8)$$

The factor of 160 improvement over previous white dwarf bounds comes from the following: a factor of ten comes from the fact that the white dwarf is an order of magnitude dimmer, a factor of four comes from the bigger white dwarf mass, and a factor of four from the smaller radius than the white dwarfs used in [14].

With the Wood [20] cooling curves, the age of the white dwarf is 6.47 Gyr as mentioned above. Then Eq. (6) corresponds to a flux bound

$$F \leq 1.9 \times 10^{-20} (\sigma v)_{-28}^{-1} s_{-2}^{-1} v_{-3}^2 \quad \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}. \qquad (9)$$
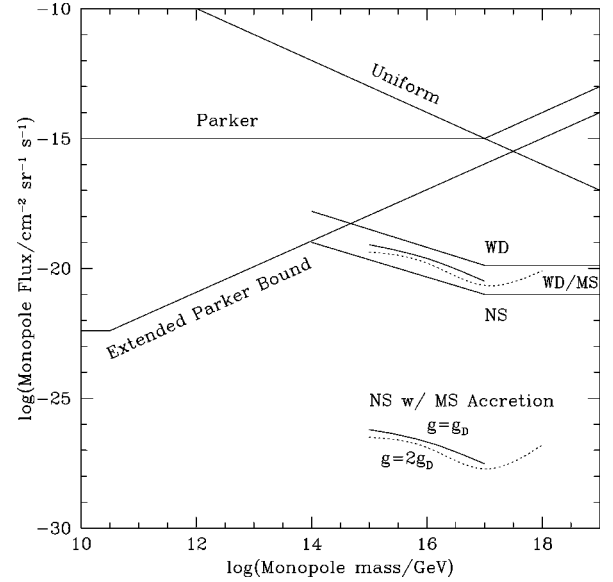

FIG. 1. Bounds on the monopole flux as a function of monopole mass. The Parker bound [7] due to survival of the galactic magnetic field is plotted, as is the extended Parker bound [9] due to survival of the magnetic field early in the history of the Galaxy. Mass density limits ($\Omega h^2 < 1$) are plotted for a uniform density of monopoles in the universe. Note that h is the Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The bounds due to catalysis in white dwarf WD1136-286 as discussed in this paper are plotted; the plots assume the cooling curves of Wood [20], and are very similar to those obtained using cooling curves of Segretain et al. In addition, the bounds from this white dwarf with main sequence accretion (WD/MS) are plotted for $g = g_D$ (solid line) and for $g = 2g_D$ (dotted line). The bounds due to calaysis in neutron star PSR 1929+10 are plotted, as are bounds due to this neutron star with main sequence accretion. Again the solid line is for $g = g_D$ and the dotted line is for $g = 2g_D$. Note that the neutron star bounds with main sequence accretion have dependence on the monopole mass.

This bound using the Wood cooling curves is less restrictive than the one obtained using the Segretain et al. cooling curves. Hence, to be conservative, in Fig. 1 we plot the flux bound of Eq. (9). Note that the monopole velocities far from the white dwarf have been determined as a function of monopole mass by the following equation: $v_M \approx 3 \times 10^{-3} c (10^{16} \text{ GeV/m})^{1/2}$ for monopole mass $m < 10^{17}$ GeV and $v_M \approx 10^{-3} c$ for monopoles with mass greater or equal to 10^{17} GeV [8]. Thus the flux bound is flat for monopole masses greater than 10^{17} GeV and drops as m^{-1} for smaller masses. This behavior can be seen in Fig. 1.

If the monopole flux saturates the bound in Eqs. (8) and (9), the heat release due to monopole-catalyzed nucleon decay would explain the dearth of white dwarfs with luminosity $\leq 10^{-5} L_\odot$. That is, monopoles may be keeping white dwarfs hot. Note that the white dwarf luminosity due to monopole catalyzed nucleon decay scales as $L_{mon} \propto \tau_{10} M_{0.6}^2$. If the luminosity of the coolest objects we see today is in fact due primarily to the contribution from monopoles, then one would in principle be able to see this dependence on white dwarf mass (this idea arose in conversations with Nahm). However, one would need to be able to inde-

TABLE I. Bounds on the flux F of magnetic monopoles in cm^{-2} s^{-1} sr^{-1}. Monopoles captured by white dwarfs (WD) or neutron stars (NS) and their main sequence (MS) progenitors are included. The white dwarf cooling time is taken to be $\tau = 9.63$ Gyr. M_m is the monopole mass in GeV, β is the monopole velocity, b_{crit}/R is the ratio of the critical impact parameter for a monopole in units of the radius of the main sequence star, and the monopole charge is $g = 69e(g/g_D)$ in units of the Dirac charge g_D. The number of monopoles captured by the MS progenitor and by the white dwarf are N_{MS} and N_{WD} respectively. The second to last column is the flux bound due to catalysis in WD 1136-286 (with MS monopoles included). The last column is the (corrected) flux bound due to catalysis in neutron star PSR 1929+10 (with MS monopoles included).

M_m (GeV)	β	$\dfrac{b_{crit}}{R}$	g/g_D	$N_{MS}/10^{38}F$	$N_{WD}/10^{38}F$	WD with MS $F(\sigma v)_{-28}$	NS with MS $F(\sigma v)_{-28}$
10^{15}	10^{-2}	0.4	1	2.5	0.17	8.2×10^{-20}	6.2×10^{-27}
		0.56	2	4.9		4.3×10^{-20}	3.2×10^{-27}
10^{16}	3×10^{-3}	0.48	1	7.4	1.8	2.4×10^{-20}	2.1×10^{-27}
		0.62	2	12.3		1.6×10^{-20}	1.3×10^{-27}
10^{17}	10^{-3}	0.54	1	52	17	3.2×10^{-21}	3.0×10^{-28}
		0.68	2	82		2.2×10^{-21}	1.9×10^{-28}
10^{18}	10^{-3}	-	1	-	17	-	-
		0.24	2	10		8.1×10^{-21}	1.6×10^{-27}

pendently measure the white dwarf luminosity, mass, and age in order to test this hypothesis.

In an earlier paper Freese [14] checked that the presence of monopoles did not drastically affect the properties of the white dwarf in any way. A usual white dwarf is an isothermal, electron degenerate object surrounded by a very thin radiative envelope. The primary mechanism of heat transfer through the body of the star is conduction. In the presence of monopoles the white dwarf remains essentially isothermal, with a radiative envelope, conductive main body, and convective core so that one may conclude that monopoles have a negligible effect on the overall structure of white dwarfs (for more details see [14]).

Monopole/antimonopole annihilation: As discussed in Freese [14], monopole-antimonopole annihilation has no effect on the flux bound obtained in Eqs. (8) and (9). There it was shown that, if the above flux bounds are satisfied, the number of monopoles accumulating inside the white dwarf never reaches a sufficient abundance for annihilation to become significant.

III. TIGHTER BOUNDS OBTAINED IF MONOPOLES CAPTURED BY THE MAIN SEQUENCE PROGENITOR ARE INCLUDED

During its main sequence period the progenitor of the white dwarf may also have captured a significant number of monopoles. These additional monopoles will lead to an even tighter bound on the monopole flux. In order to estimate the number of monopoles captured by the main sequence progenitor, we must determine its mass. Unfortunately, the transformation from main sequence mass to white dwarf mass is somewhat uncertain, as discussed by Wood [20]. Here we use $M_{WD} = A_x \exp(B_x M)$, where $A_x = 0.49$ and $B_x = 0.095$. For white dwarf 1136-286 with mass $M_{WD} = 1.2 M_\odot$, we find progenitor mass $M = 9.4 M_\odot$.

As a monopole passes through a main sequence (MS) star,

it loses energy. If it loses all its initial kinetic energy (i.e. its energy infinitely far from the star), it is captured by the star. Since the energy loss increases with decreasing impact parameter, the number of monopoles captured by a MS star exposed to a monopole flux F for a time $\tau = \tau_{MS}$ is just the number incident upon the star with surface impact parameter less than some critical value, b_{crit}:

$$N_M = (4\pi b_{crit}^2)(\pi s r)\left[1 + \left(\frac{v_{esc}}{v_\infty}\right)^2\right]F\tau_{MS}, \quad (10)$$

where v_∞ is the monopole velocity far from the star and $v_{esc} = (2GM/R)^{1/2}$ is the escape velocity from the star. Frieman, Freese, and Turner [12] previously calculated numerically the critical impact parameter for capture. We use those results here.[1] Given the value of b_{crit}, we can substitute it into the previous equation (10) to obtain the number of monopoles captured by the main sequence progenitor. The sum of monopoles captured by the progenitor plus those captured by the white dwarf cannot exceed the maximum number allowed in Eq. (7), so that we obtain a new flux bound. Again, we have taken monopole velocities to be $v_M \approx 3 \times 10^{-3} c (10^{16}\,\text{GeV}/m)^{1/2}$ for monopole mass $m < 10^{17}$ GeV and $v_M \approx 10^{-3} c$ for monopoles with mass greater or equal to

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[1]Recent calculations of Ahlen and Tarle [21] indicate that estimation of the energy loss of monopoles in main sequence stars used in [12] must be increased by a factor of 2. Thus b_{crit} should be somewhat larger than what was calculated by Frieman, Freese, and Turner [12]. For example, for the case where $\beta = \beta_{esc} = 3.3 \times 10^{-3}$ (for a 9 $M_\odot$ star), rough analytic estimates indicate that the modified value of b_{crit} is roughly given by $(b_{crit}/R)_{new} = 0.058 + (b_{crit}/R)_{old}^2$. As the calculations of [12] are numerical and the difference is very small, we will continue to use the prior results of [12]. In fact, if one were to use the newer value of b_{crit}, the flux bounds would be somewhat tighter.

TABLE II. Same as Table I for white dwarfs, but for cooling time $\tau = 6.47$ Gyr.

M_m (GeV)	β	$\dfrac{b_{crit}}{R}$	g/g_D	$N_{MS}/10^{38}F$	$N_{WD}/10^{38}F$	$F(\sigma v)_{-28}/\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$
10^{15}	10^{-2}	0.4	1	2.5	0.11	8.4×10^{-20}
		0.56	2	4.9		4.4×10^{-20}
10^{16}	3×10^{-3}	0.48	1	7.4	1.2	2.6×10^{-20}
		0.62	2	12.3		1.6×10^{-20}
10^{17}	10^{-3}	0.54	1	52	11	3.5×10^{-21}
		0.68	2	82		2.4×10^{-21}
10^{18}	10^{-3}	—	1	—	11	—
		0.24	2	10		1.0×10^{-20}

10^{17} GeV [8]. The inclusion of monopoles captured by the progenitor of the white dwarf results in a bound on monopole flux that is another order of magnitude lower. We have evaluated the new bound for both white dwarf cooling models. In Table I, we have recorded, as a function of monopole mass, the value of b_{crit}/R, the number of monopoles captured by the progenitor and white dwarf, and the resultant flux bound. The flux bound is plotted in Fig. 1.

The flux bound is most restrictive for $m \sim 10^{17}$ GeV. One can understand the reason for the weaker flux bounds for masses greater and less than 10^{17} GeV as follows: For masses less than this, it is the increasing monopole velocity as a function of decreasing monopole mass that drives the flux bound to become weaker for smaller mass. For masses $m > 10^{16}$ GeV, the factor $[1 + (v_{esc}/v_\infty)^2]$ in Eq. (10) is dominated by the second term $(v_{esc}/v_\infty)^2$. As the monopole mass decreases below 10^{17} GeV, the monopole velocity increases, the term $(v_{esc}/v_\infty)^2$ decreases, so that in Eq. (10) the monopole flux can increase and still maintain the same number of monopoles in the star and hence the same luminosity. Eventually, when the mass drops to $m \lesssim 10^{16}$ GeV, the first term, 1, starts to dominate in the factor $[1 + (v_{esc}/v_\infty)^2]$, so that the monopole velocity becomes unimportant and the curve becomes more and more flat with decreasing monopole mass. This behavior can be seen in Fig. 1. For monopole masses greater than 10^{17} GeV, the flux bound also becomes weaker, this time as a function of increasing mass. The reason for this is as follows. These monopoles all move with the virial velocity of the Galaxy $\sim 10^{-3}c$. The heavier the monopole, the harder it is to stop. Hence b_{crit} becomes smaller for heavier masses. Thus a larger monopole flux can be accommodated in Eq. (10) to still obtain the same number of monopoles in the star.

IV. NEUTRON STARS WITH MAIN SEQUENCE ACCRETION

We also note that the dependence on monopole mass of flux bounds due to catalysis in neutron stars with main sequence accretion has previously been calculated incorrectly. In the past the bound due to catalysis in PSR 1929+10 with main sequence accretion has been stated as [11] $F(\sigma v/10^{-28}\,\mathrm{cm}^2) < 10^{-28}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. As discussed in the previous paragraph, the velocity dependence of monopoles

of different masses determines the shape of the curve of flux bounds as a function of monopole mass. As can be seen in Table I and Fig. 1, the correct bounds are somewhat weaker for monopole mass other than 10^{17} GeV because of the faster velocities of monopoles with smaller masses and the lower critical impact parameter for monopoles with larger masses. In obtaining the numbers, we have assumed a main sequence progenitor of 9 $M_\odot$. Then the number of monopoles captured by the main sequence progenitor of the neutron star is the same as the number of monopoles captured by the white dwarf considered in this paper.

V. CONCLUSION

Figure 1 shows a plot of several monopole bounds: the Parker bound, the extended Parker bound, neutron star bounds, and the new white dwarf bound with and without main sequence capture. In the plots we have used the Wood cooling curves to be conservative. We have found that consideration of newly observed white dwarf 1136-286 with luminosity $10^{-4.94}L_\odot$ and with new calculations of white dwarf cooling curves leads to a bound on the monopole flux that is two orders of magnitude lower than previous bounds due to catalysis in white dwarfs. The new bound is $F(\sigma v/10^{-28}\,\mathrm{cm}^2) < 1.3(1.9) \times 10^{-20}(v/10^{-3}c)^2\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ for the Segretain [19] (Wood [20]) cooling curves respectively, where v is the monopole velocity. The limit is improved by including the monopoles captured by the main-sequence progenitor of the white dwarf: $F(\sigma v/10^{-28}\,\mathrm{cm}^2) < 3.5(26) \times 10^{-21}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ for 10^{17} (10^{16}) GeV monopoles with $g = g_D$. Flux bounds for other monopole masses and parameters are given in Tables I and II. If cooler white dwarfs are discovered, a stricter bound on the monopole flux will result.

Here we discuss future prospects for improved monopole flux bounds due to catalysis in white dwarfs. If cooler white dwarfs are discovered, a stricter bound on the monopole flux will result. However, the white dwarf discussed in this paper is already very old, close to the age of the universe, so that much further improvement on monopole flux bounds is unlikely. Technologically it should be possible to find white dwarfs that are several orders of magnitude fainter, in principle down to $10^{-9}\,L_\odot$ [J. Allyn Smith (personal communication)]. However, such faint white dwarfs would undoubt-

edly have to be older than the age of the universe and hence cannot exist. Although cooling models have not been perfected down to such low luminosities, one can still attempt to estimate the coolest white dwarfs that could exist by extrapolating the models of Segretain *et al.* The heaviest white dwarfs cool the most rapidly and would provide the best limit. For example, a 1.2 $M_\odot$ white dwarf of $10^{-6}L_\odot$ would be 11 Gyr old while a $10^{-7}L_\odot$ white dwarf would be 13 Gyr old. Cooler white dwarfs cannot exist. Hence the flux bound due to catalysis in white dwarfs could improve by at most two further orders of magnitude if such cool white dwarfs do exist and are seen.

We also showed that the dependence on monopole mass of flux bounds due to catalysis in neutron stars with main sequence accretion has previously been calculated incorrectly. Previously the bound due to catalysis in PSR 1929 $+10$ with main sequence accretion has been stated as [11] $F(\sigma v/10^{-28}\,\mathrm{cm}^2)<10^{-28}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. Instead, as can be seen in Table I and Fig. 1, the correct bounds are somewhat weaker for monopole mass other than $10^{17}\,\mathrm{GeV}$.

ACKNOWLEDGMENTS

[1] P. A. M. Dirac, Phys. Rev. **74**, 817 (1948).

[2] G. 't Hooft, Nucl. Phys. **B79**, 276 (1974).

[3] A. Polyakov, Pis'ma Zh Éksp. Teor. Fiz. **20**, 430 (1974) [JETP Lett. **20**, 194 (1974)].

[4] V. A. Rubakov, Pis'ma Zh Éksp. Teor. Fiz. **33**, 658 (1981) [JETP Lett. **33**, 644 (1981)]; Nucl. Phys. **B203**, 311 (1982).

[5] C. G. Callan, Phys. Rev. D **25**, 2141 (1982); **26**, 2058 (1982).

[6] A. H. Guth, Phys. Rev. D **23**, 347 (1981).

[7] E. N. Parker, Astrophys. J. **160**, 383 (1970).

[8] M. S. Turner, E. N. Parker, and T. Bogdan, Phys. Rev. D **26**, 1296 (1982).

[9] F. C. Adams, M. Fatuzzo, K. Freese, G. Tarle, and R. Watkins, Phys. Rev. Lett. **70**, 2511 (1993).

[10] E. W. Kolb, S. A. Colgate, and J. A. Harvey, Phys. Rev. Lett. **49**, 1373 (1982); S. Dimopoulos, J. Preskill, and F. Wilczek, Phys. Lett. **119B**, 320 (1982); F. A. Bais, J. Ellis, D. V. Nanopoulos, and K. A. Olive, Nucl. Phys. **B219**, 189 (1983).

[11] K. Freese, M. S. Turner, and D. N. Schramm, Phys. Rev. Lett. **51**, 1625 (1983).

[12] J. A. Frieman, K. Freese, and M. S. Turner, Astrophys. J. **335**, 844 (1988).

[13] J. A. Harvey, M. A. Ruderman, and J. Shaham, Phys. Rev. D **33**, 2084 (1986).

[14] K. Freese, Astrophys. J. **286**, 216 (1984).

[15] M. T. Ruiz, P. Bergeron, S. K. Leggett, and C. Anguita, Astrophys. J. Lett. **455**, 159 (1995); Astrophys. J., Suppl. Ser. **108**, 339 (1997).

[16] J. Arafune and M. Fukugita, Phys. Rev. Lett. **50**, 1901 (1983).

[17] V. Martem'yanov and S. Kakimov, Sov. Phys. JETP **35**, 20 (1972).

[18] S. Ahlen and K. Kinoshita, Phys. Rev. D **26**, 2347 (1982).

[19] L. Segretain *et al.*, Astrophys. J. **434**, 641 (1994).

[20] M. A. Wood, Astrophys. J. **386**, 539 (1992); in *9th European Workshop on White Dwarfs*, edited by D. Koester and K. Werner (Springer-Verlag, Berlin, 1995), p. 41.

[21] S. P. Ahlen, I. DeMitri, J. T. Hong, and G. Tarle, Phys. Rev. D **55**, 6584 (1997).