Limits on the Neutrino Magnetic Moment from SN1987A

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A neutrino magnetic moment greater than $10^{-12}\mu_B$, the Bohr magneton, would have important implications for gravitational-collapse supernovae. Also, it has been suggested that $\mu/\mu_B \sim 10^{-10}$ might solve the solar neutrino problem. However, we show that the neutrino observations of SN1987A and general optical observations of supernovae set a firm upper limit of $\mu/\mu_B < 5\times10^{-13}$. This limit is about 100 times better than the best experimental determination and previous astrophysical limits, and 10–20 times better than a previous limit based on big-bang nucleosynthesis.

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There have been attempts[1,2] to explain the solar neutrino problem by introducing a large neutrino magnetic moment μ. With μ/μ_B in the range $(0.3\text{–}1.0)\times10^{-10}$, where $\mu_B = e/2m_ec^2$ is the Bohr magneton, normal, left-handed electron neutrinos leaving the sun's center might change their helicity upon passing through hundred-kilogauss fields that might be present in the solar interior. Right-handed neutrinos will not interact with normal matter and would not be detected on the Earth. Helicity flip would then explain the low solar neutrino counting rates first observed by Davis, Harmer, and Hoffman.[3] While these values for μ are orders of magnitude larger than the standard electroweak prediction,[1] $\mu \sim 3\times10^{-19}[m_\nu/(1\text{ eV})]\mu_B$, they are consistent with present experimental limits[4] from $\bar{\nu}_e$, $4\times10^{-10}\mu_B$, and with bounds[5] derived from astrophysical arguments, $8.5\times10^{-11}\mu_B$. They are marginally greater than a limit, $(1\text{–}2)\times10^{-11}\mu_B$, obtained from ^{4}He synthesis in the big bang.[6] However, such values would have dramatic effects in gravitational-collapse supernovae, as first pointed out by Dar.[7] In this Letter, we examine the consequences of helicity flip due to neutrino scattering during the creation of a neutron star. If this had occurred, the time scale of $\bar{\nu}$ emission and the total energy emitted in $\bar{\nu}$'s would both have been much less than what was observed from SN1987A. This sets an upper limit to μ of $5\times10^{-13}\mu_B$, larger than a previously derived[8] upper limit ($\sim10^{-14}\mu_B$) which we show to be erroneous. Our bound rules out a neutrino magnetic moment as an explanation of the low solar neutrino flux. We also conclude that helicity flips induced by magnetic fields within the supernova or between it and the Earth did not occur.

In the standard gravitational-collapse supernova scenario,[9] the stellar core ($M \lesssim 1.5M_\odot$) undergoes catastrophic collapse at the end of a massive star's life. The collapse is halted when densities a few times nuclear density ($\rho_0 \simeq 2.7\times10^{14}$ g cm^{-3}) are reached. A protoneutron star is born, and a shock wave, formed at its outer boundary, moves out through the still infalling outer stellar layers, reverses their infall, and ejects them. Whether or not neutrino radiation from the protoneutron star assists in the explosion is a point of current debate, but does not much affect the following discussion. The protoneutron star is, at first, a highly degenerate, lepton-rich, and almost unbound star, which cools and deleptonizes through neutrino radiation. The neutrino flux has basically two components[10]: a short-term ($\frac{1}{2}$–1 s) emission from the neutronization and collapse of the hot matter behind the outgoing shock, and a longer-term (several seconds) emission of the star's lepton degeneracy energy. (The total initial thermal energy of the protoneutron star is $\lesssim 10\%$ of the lepton degeneracy energy.) Both emission times scales are set by the fact that neutrinos cannot freely escape but must diffuse, from varying depths, out of the protoneutron star. About $\frac{1}{2}$ of the total binding energy of the cold, catalyzed neutron star is contained in each component. The mean energy of the emitted neutrinos is $\simeq$10–20 MeV, and neutrinos of all species are present in roughly equal proportions in the emergent flux because of the nearly complete conversion of lepton degeneracy and gravitational energy to ν-$\bar{\nu}$ pairs during diffusive cooling.[10,11] These are general consequences of neutrino diffusion and emission from a neutrinosphere near the protoneutron star's surface.

A finite neutrino magnetic moment would provide an additional path for the long-term emission by allowing the existence of right-handed ν's (ν^R) and left-handed $\bar{\nu}$'s ($\bar{\nu}^L$) which are unable to interact with matter and hence freely stream (travel time $\lesssim 1$ ms) out of the protoneutron star. If the magnetic moment, and hence the production rate of flipped helicity ν's, is large enough, this path will dominate the cooling. Neutrinos with magnetic moments can flip helicity via electron, proton, and neutron scattering. Neutrinos of both helicities are also created via electron-pair annihilation, but this process is suppressed by electron degeneracy. The rate of the flipping is[12]

$$\tau_{\rm flip}^{-1} \simeq 4\times10^4(10^{10}\mu/\mu_{\rm B})^2 Y_e(1+B_F)\rho/\rho_0\,{\rm s}^{-1}, \quad (1)$$

where Y_e is the electron/baryon ratio. In the factor $1+B_F$, the 1 is due to proton scattering, neutron scattering is ignorable, and electron scattering gives the B_F, which is a Pauli blocking factor ($\sim\frac{1}{2}$) due to electron final-state degeneracy. The relevant density to use in Eq. (1) depends on the type of emission considered. In the long term, it is the average density in the protoneutron star, which is nearly the central density, $(2-4)\rho_0$, since the matter is relatively incompressible. If $\mu \gtrsim 10^{-10}\mu_{\rm B}$, the helicity-flip rate would be important in the short-term cooling phase and during the collapse phase preceding the birth of the protoneutron star as well, since the gravitational collapse time scale is about 1 ms. The loss of leptons in this latter phase would undoubtedly be detrimental to the bounce-shock mechanism. The flipped ν's would be able to stream out of the star freely, however, only if the mean free path, $c\tau_{\rm flip}$, is less than the radius ($\lesssim 50$ km), i.e., if $\mu \lesssim 3\times10^{-11}\mu_{\rm B}$.

Equation (1) shows that if $\mu \gtrsim 5\times10^{-13}\mu_{\rm B}$ the flip time scale is less than $\frac{1}{2}$ s (using $Y_e=\frac{1}{3}$, $B_F=\frac{1}{2}$, $\rho=4\rho_0$). Given the average energy of flipped neutrinos, $E_\nu = 3\mu_\nu/(\simeq 200)$ MeV, their initial luminosity after bounce is at least 8×10^{52} erg/s. Within a second or two, the bulk of the thermal and lepton degeneracy energy from the interior would be radiated. Because neutrinos represent about $\frac{1}{5}$ of the leptons, the time needed to radiate most of the leptons is about $5\tau_{\rm flip}\simeq 2.5$ s, but this is much shorter than the diffusion time. Although the short-term flux from the collapse of the periphery might not be greatly altered, there would be virtually no long-term emission of ν's. Burrows[13] has shown that eliminating the diffusive replenishment of neutrinos to the neutrinosphere strongly suppresses their emissions after 1 s. In fact, there will be a net diffusive flow of both energy *and* lepton number into the interior, where they are radiated. The ν_e's in the star's center are very degenerate, $\eta_\nu = \mu_\nu/T \simeq 15$, and so there are almost no $\bar\nu_e$'s present [the ratio of ν_e's to $\bar\nu_e$'s is $\sim\eta_\nu^3\exp(-\eta_\nu)$]. The escaping ν_e^R's would dominate freely escaping flipped ν_e^{-L}'s and ordinary neutrinos escaping via diffusion.

It is easy to show that this situation is in disagreement with the observations of neutrinos from SN1987A. Except for at most two events, the 19 neutrinos observed[14] were $\bar\nu_e^R$'s. Their low energies ($\sim$10–40 MeV) and the multisecond time scale of the burst are what is expected from a diffusively cooling protoneutron star.[13] If $\mu \gtrsim 5\times10^{-13}\mu_{\rm B}$, the long-term emission would have been greatly diminished; the thermal signal of $\bar\nu_e^R$ from the neutrinosphere would have ceased after 2 s. The total number of $\bar\nu_e^R$'s would have been $\frac{1}{2}$ or less of what the standard model predicts. In other words, the energy from SN1987A would have to be scaled upwards, by a factor of 2 or more, from the values already inferred from conventional models, $(2-7)\times10^{53}$ ergs.[13,14] The revised energy significantly exceeds the binding energy of a $(1-1.5)M_\odot$ neutron star, expected from the explosion of SN1987A's progenitor.[9] We may conclude from the SN1987A $\bar\nu_e$ time scale and energies that $\mu < 5\times10^{-13}\mu_{\rm B}$.

We now consider the possibility that, in the presence of magnetic fields, the neutrinos might undergo helicity flips either as they leave the supernova or en route to the Earth.[8] Dar[7] has suggested that the former would be an efficient way to transport energy from the protoneutron to the matter outside, perhaps even ejecting it if the shock had failed to do so. The probability of a flip occurring within a distance z in a constant field is the same for neutrinos and antineutrinos of both helicities and is[2,7]

$$P \simeq B_\perp^2[B_\perp^2+(B_z+B_c)^2]^{-1} \times \sin^2\{\mu z[B_\perp^2+(B_z+B_c)^2]^{1/2}\}. \quad (2)$$

$B_\perp$ (B_z) is the transverse (parallel) magnetic field strength and B_c is a critical field strength given by

$$B_c \simeq G_{\rm F} n_e/\mu\sqrt{2} \simeq 3.3\times10^6\rho(\mu_{\rm B}/10^{12}\mu)\ {\rm G}. \quad (3)$$

$G_{\rm F}$ is the weak interaction coupling constant and n_e is the number density of electrons. Equation (3) assumes charge neutrality and $Y_e \simeq \frac{1}{2}$. [The numerical factor in Eq. (3) is insensitive to Y_e.] From Eq. (2) we see that the necessary conditions for helicity flip to occur are

$$B_\perp^2 \gtrsim (B_z+B_c)^2, \quad (4a)$$

$$\int \mu B\,dz \gtrsim 1. \quad (4b)$$

Although Eq. (2) applies to the case in which ρ and B are constant, it is straightforward to show that these conditions are, in fact, more general.

We note here that the authors of Ref. 8 employed only condition (4b) in their derivation of an upper limit, $\sim10^{-14}\mu_{\rm B}$, to μ. This limit is invalid because condition (4a) was assumed to hold everywhere in the star. In fact, it is unlikely that $B \gtrsim B_c$ near the protoneutron star or even in the bulk of the stellar envelope. Although field strengths of $(1-5)\times10^{12}$ G are found on the surfaces of neutron stars,[15] it is not certain if these fields are primordial or generated at a later time. At the instant when the protoneutron star is born, $\rho > 10^8$ g cm^{-3} and $B_c \gtrsim 3\times10^{14}(\mu_{\rm B}/10^{12}\mu)$ G within at least 1000 km of the core.[9] As the shock moves away from the protoneutron star, the density, and the critical field strength, behind it will decrease. Only in the case of a successful, delayed, explosion,[16] which takes $\sim\frac{1}{2}$ s, will densities lower than 10^8 g cm^{-3} and critical field strengths lower than B obtain close to the protoneutron star's surface. But a delayed explosion requires a high thermal flux of unflipped ν's, which will be depleted because of energy losses from helicity flip. Thus, it seems unlikely that helicity flip could contribute to an explosion.

Inside the outer stellar envelope, which is nearly static until the shock wave passes through seconds to hours after the neutrinos, an optimistic estimate of the magnetic field strength comes from the assumption of flux freezing, i.e., $B \propto r^{-2}$. Presupernova models[9] indicate that ρ, and hence B_c, are roughly proportional to r^{-3}. In the interstellar medium, where $B \sim 10^{-6}$ G, and $\rho \sim 10^{-24}$ g cm^{-3}, $B \gg B_c$. Thus, in general, there is some distance, R, from the protoneutron star at which $B = B_c$. For definiteness, we assume the following profiles in the outer stellar envelope (r in centimeters):

$$B = 10^{24}/r^2 \text{ G}, \quad \rho = 10^{32}/r^3 \text{ g cm}^{-3}. \tag{5}$$

These profiles imply $B > B_c$ beyond the point $R = 3.3 \times 10^{14}(10^{-12}\mu_B/\mu)$ cm. This is outside the surface of the presupernova star, at least in the case of SN1987A. The necessary condition for helicity flip as a neutrino leaves a star is then given by Eq. (4):

$$\int_R^\infty \mu B \, dr = \mu B(R) R = 10^{-6}(10^{12}\mu/\mu_B)^2 \geq 1, \tag{6}$$

which is satisfied only if $\mu > 10^{-9}\mu_B$. Thus we do not expect the magnetic field of a protoneutron star, or that in or outside the presupernova stellar envelope, to be nearly large enough to cause helicity flip.

Even if it were possible to arrange the field (neutron-star fields as large as 10^{15} G have been proposed[17]) and density structures so that reflipping did occur at early times and deep inside the star, the energy deposited in the outer layers would have been enormous. This is ruled out by optical observations of supernovae. In the usual neutrino energy-deposition model, the deposited energy is proportional to the integrated luminosity times the average neutrino energy squared.[18] Since the average ν energy would be about 10 times the value in the standard, helicity-nonflip scenario, and the integrated luminosity would likely double, an estimated energy deposition by flipped neutrinos of nearly 10^{53} ergs follows. Of course, much of this energy would be lost as the ejecta cool and neutrinos of all types are reradiated. Nevertheless, the visible light output and envelope expansion of the supernova would reflect the enhanced energy deposition. In reality, the total kinetic plus optical energy of the envelope in a gravitational collapse supernova is observed to be about 10^{51} ergs,[19] in agreement with the standard picture.[16] An intermediate case, in which μ and the ρ and B profiles were exactly that needed to give a reasonable energy deposition, requires an unbelievable degree of fine tuning—not just in SN1987A, but in all such supernovae. It appears that flipping induced by magnetic fields could not occur in a supernova.

On the other hand, helicity flip might have taken place in the interstellar and intergalactic medium which to neutrinos traverse en route to the Earth.[20] A less reliable, but slightly more stringent, limit on on μ may be obtained by arguing that had this occurred, only part of the $\bar{\nu}$'s emitted by the supernova would have been observable, and estimates of the total ν energy from the observed $\bar{\nu}$'s would have to be increased. We may assume $B \sim 1 - 0^{-6}$ G$\gg B_c$ everywhere, and evaluating Eq. (4b) we find a precession angle, which will be common to all neutrinos,

$$\alpha = \int \mu B \, dz = \mu B D \simeq 45(10^{12}\mu/\mu_B), \tag{7}$$

where $D \simeq 50$ kpc is the distance to SN1987A. Equation (7) indicates that $\alpha \geq \pi$ for $\mu/\mu_B \geq 7 \times 10^{-14}$, in which case the observed helicity state of the neutrinos would not necessarily be the same as what emerged from the supernova's core. If $\mu/\mu_B \sim 10^{-13}$, we have already seen the fraction of emitted ν_e^R's is small, but the ν_e^R fraction at Earth, $\simeq \sin^2\alpha$, would range from 0 to 1, and the total energy would be $\cos^{-2}\alpha$ times that inferred from the $\bar{\nu}$'s (a factor of 1 to ∞). Although the odds of this factor being 2 or greater is 50%, such a limit is nevertheless indefinite, and is only suggestive that our previous limit is conservative. In addition, we note that even if the mechanism proposed in Ref. 7 were to result in a large fraction of emitted ν_e^R's, their consequent reflipping to ν_e^L's in the interstellar medium would result in neutrino energies and a burst time scale substantially different from what was observed from SN1987A.

Nussinov and Rephaeli[8] have pointed out that models which predict large electron-neutrino magnetic moments generally have as large or larger μ-μ and nondiagonal e-μ terms as well (here μ refers to both μ and τ neutrinos). These terms would lead to $\nu_\mu^L \rightarrow \nu_\mu^R$ and $\nu_e \Longleftrightarrow \nu_\mu$ conversions. We can set no limit on the μ-μ terms in the absence of large e-μ terms, but a limit to the e-μ terms of the order of $10^{-12}\mu_B$ can be obtained by arguments similar to those given above. e-μ moments larger than $10^{-10}\mu_B$ would lead, during the collapse, to the production of trapped and degenerate seas of neutrinos other than ν_e^L. The readjustment of the β equilibrium between neutrinos, electrons, and baryons lowers the total pressure, and converts some degeneracy energy into heat, with catastrophic effects for supernovae. The decrease in the homologous-core mass itself will doom prompt explosion mechanisms.[21] In the range $(10^{-12}$-$10^{-10})\mu_B$, the principal effects will be similar to the "e-e only" case, since the right-handed species will escape rather than reflip. This is ruled out observationally in the case of SN1987A, even if they were to precess back into left-handed ones in the interstellar-medium.

In conclusion, the neutrino observations from SN1987A, and optical observations of supernovae in general, constrain the magnetic moment of the electron neutrino to be less than $5 \times 10^{-13}\mu_B$. This limit is better than present experimental and other theoretical limits. It rules out, by a wide margin, a magnetic moment explanation of the solar neutrino problem. We have shown that a smaller limit derived in Ref. 8 cannot be justified. Finally, the neutrino magnetic moment is too small to play an important role in supernova explosions.

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