Monopole abundance in the Solar System and the intrinsic heat in the Jovian planets

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The intrinsic-heat generation has long been known in the Jovian planets. The current view ascribes its origin to the gradual release of primordial heat produced at the birth of these planets. This scenario, however, fails to explain coherently the magnitude of the excess heat in each planet, other than Jupiter, and must invoke some additional sources. We point out the possibility that this heat, or at least a part of it, could be attributed to proton decay which is catalyzed by grand-unified magnetic monopoles (Rubakov effect) captured in the planets. The monopole flux required for this is of order $\sim 1\times 10^{-23}$ cm^{-2} sr^{-1} sec^{-1}, which is smaller than the limit on the cosmic monopole flux so far obtained. We also show that if the monopole flux is of this order the monopole captured in the Sun gives rise to the neutrino flux ($\langle E_\nu \rangle \simeq 35$ MeV) which should be detectable in the underground experiment searching for nucleon decays currently in progress.

I. INTRODUCTION

A recent observation made by Rubakov and also by Callan that the grand-unified monopole catalyzes nucleon decay with a cross section typical of strong interactions[1] (we call this the Rubakov effect, hereafter) leads us to various significant consequences not only in particle physics, but also in the astrophysical context. In stars the Rubakov effect would cause heat generation. By requiring that such a heat be smaller than that observed, one obtains a bound on the monopole abundance.[2] This consideration has also been made for Earth and Jupiter to give a constraint on the local monopole flux.[3] The naive application of the Rubakov effect to Earth led to an apparently strong constraint on the monopole abundance in the earth. It was so much stronger than that obtained for Jupiter that further attention has not been paid to monopoles in Jupiter.

We have noticed, however, that the constraint on the monopole abundance in the earth from the Rubakov effect disappears when we take account of strong repulsive forces between a monopole and matter.[4] The Rubakov effect is likely to happen only in stars rich in hydrogen, such as the Sun and the Jovian planets, or in neutron stars. We then point out that we would be tempted to ascribe the intrinsic heat of the Jovian planets[5–8] to the Rubakov heat. This possibility arises when we observe that the required monopole density is two orders of magnitude smaller than the strongest bound on the monopole density in the Solar System,[9] which is derived from the present solar neutrino experiment.[10] We also show that if the monopole density in the Sun is of the order of that it is enough to account for the Jovian heat, the neutrino flux from μ^+ decay ($\langle E \rangle \sim 35$ MeV) through

$$p \rightarrow (\rho^0,\omega,\eta,K^+,\ldots)+e^+ \ (\text{or } \mu^+)\ ,$$

$$(\rho^0,\omega,\eta,K^+,\ldots)\rightarrow \pi^+,\pi^+\rightarrow\mu^+\nu$$

should be detectable in the underground experiment searching for nucleon decay currently in progress. We finally comment that the search for this neutrino flux down to this level could explore the monopole flux as small as that constrained by the excess luminosity of neutron stars.[2]

Let us briefly recapitulate our argument on the behavior of the monopole in matter. We expect the Rubakov process to happen when a grand-unification monopole comes sufficiently close to the nucleus. In matter, however, this probability is greatly suppressed for a slowly moving monopole by two factors. The first is due to the fact that a monopole-nucleus system carries an extra angular momentum $q=egZ/4\pi$ (Z=charge of the nucleus), which leads to a suppression factor $\approx(\beta/\beta_0)^{2\nu}$ with $\nu=-\frac{1}{2}+(\frac{1}{4}+|q|)^{1/2}$ for spinless nuclei ($\beta_0=10^{-3}$–10^{-4} depending on the nucleus). A similar suppression factor is also expected for nuclei with spin when the anomalous magnetic moment (as defined in Ref. 4) is negative.[4] For the abundant elements in the earth, therefore, the Rubakov process is strongly suppressed for slowly moving monopoles with $v/c=\beta\lesssim 10^{-3}$–$10^{-4}$. The exception is the case for nuclei with a positive anomalous magnetic moment. Examples are H, ^{27}Al, ^{19}F, ^{55}Mn, etc., which are rather rare in the earth. In these elements we expect an attractive force between a monopole and a nucleus (Re$\nu=-\frac{1}{2}$). Even in this case, however, there is yet another suppression for slowly moving monopoles approaching the atom from infinity: The effect of the monopole magnetic field on atomic electrons induces a repulsive force between a monopole and an atom.[11,12] This repulsive potential ΔE is $\sim \eta Z^2 \mathscr{R}$ with $\mathscr{R}$ the Rydberg constant and η a fractional number that depends on the atom.[11] For instance, $\Delta E \sim 16$ eV for the helium atom[12] and hence the monopole with $\beta \lesssim 10^{-4}$ can hardly approach the helium nucleus. For heavier atoms such repulsive force is stronger by the factor Z^2,[11] and the threshold velocity increases as $\sim Z/A^{1/2}$. Thus, once a monopole is captured in the material, the above repulsive forces prohibit the monopole from overlapping with nuclei and the monopole hardly contributes to the heat generation. An application of this argument to monopoles in the earth evades the strong limit on the monopole abundance in the earth previously obtained[3] from the heat flow.

An exception which escapes from both suppression factors is the case of hydrogen. In the hydrogen atom there exists a ground state[12] which does not receive any repulsive force when a monopole approaches the atom (such a state does not exist with an atom with more than two electrons). For hydrogen $\mathrm{Re}\nu = -\frac{1}{2}$ and the cross section for the Rubakov process reads

$$\sigma \sim \sigma_0 \beta^{-2} \tag{1}$$

(this β dependence agrees with that in Ref. 13) with σ_0 the high-energy cross section of an order typical of strong interactions (our following argument will hold even if σ_0 is suppressed to the order of $m_W{}^{-2}$). This form of the cross section may apply until it grows up for a small β to $\sigma \sim \pi d^2$ (d = mean distance of atoms in the matter), beyond which many-body effects will be important and cutoff effects may start to work. Thus in stars rich in hydrogen we expect the Rubakov process to take place efficiently, generating a monopole heat.

The prime candidate of the stars that concerns us is the Sun. We have shown[9] that the strongest constraint is derived from the neutrino flux from the decay of μ^+ that would arise in catalyzed proton decay. Most of the muons decay after they are stopped in the Sun and hence the average energy of ν_e is about 35 MeV. This ν_e should be captured in $\nu_e + {}^{37}\mathrm{Cl} \to e^- + {}^{37}\mathrm{Ar}$. Allowing for an excess capture rate corresponding to 1 SNU (solar neutrino unit), we have obtained the bound

$$n_M \lesssim [(4\text{--}8)\times 10^{12}\ \mathrm{g}]^{-1}(10^{27}\ \mathrm{cm}^2/\sigma_0)(0.5/B_\pi)\ , \tag{2}$$

with[14] $B_\pi \simeq 0.3$–0.7 the branching ratio for $p \to \pi^+ + \text{anything}$. This bound may be compared with that obtained from the restriction against the decay of the solar magnetic field: $n_M \lesssim 1/(2\times 10^7\ \mathrm{g})$.[15,16]

II. MONOPOLES IN THE JOVIAN PLANETS

The presence of intrinsic heat in the Jovian planets (except Uranus) has long been known from infrared spectroscopy and the measurement of their Bond albedo.[5,6] The magnitude of this heat for Jupiter and Saturn, which is now measured more precisely through the nearby flight of Pioneer 10/11 (Ref. 7) and Voyager I,[8] is quite large and is about two orders of magnitude larger than that of Earth on average per unit mass.

The current view ascribes the source of this excess heat to gradual release of the primordial heat that is generated by gravitational energy at the birth of these planets.[6] This scenario, however, fails to explain coherently the magnitude of each planet other than Jupiter and must invoke some additional stories,[6,17] e.g., the downward migration of helium in Saturn and upward convective transport of heavy elements in Neptune, etc. We consider here the possibility that this intrinsic heat, or at least a part of it, could be attributed to the proton decay catalyzed by monopoles.

In Jupiter and Saturn the largest part of the interiors consists of H and He. The catalyzed proton decay rate is given by

$$f = \int n_M n_{\mathrm{H}} \sigma v_{\mathrm{rel}} d^3x\ , \tag{3}$$

where n_M and n_{H} are monopole and hydrogen number densities, respectively, and v_{rel} is the relative velocity between the monopole and proton, which is of the order of $c\beta_{\mathrm{th}} \sim c(2kT/m_N c^2)^{1/2} \sim (3\text{--}5)\times 10^{-5}c$ for a typical interior temperature of the Jovian planets.[17] For $\rho \sim 4$ g/cm^3, the velocity corresponding to the cutoff is about $\beta \sim 3\times 10^{-6}$ which lies well below the thermal velocity β_{th}, and the cross section (1) applies. Since the thermal momentum in Jupiter is still larger than the Fermi momentum or zero-point oscillation momentum of the lattice, we put $\beta = \beta_{\mathrm{th}}$ and evaluate $n_{\mathrm{H}}/\beta_{\mathrm{th}} = N_A \rho_{\mathrm{H}}/\beta_{\mathrm{th}}$ (N_A = Avogadro number) using a typical calculation of the interior structure of the Jovian planets.[17]

In order to evaluate (3), we have to know the distribution of monopoles in the planets. We consider two typical cases: (i) Monopoles are distributed rather uniformly, or at least a considerable amount is present outside the core ($R_c \sim 0.2R$); (ii) monopoles are sunk in the core. We here notice that monopole-antimonopole annihilations are negligible in the presence of the planetary magnetic field.[18] Naively, case (ii) seems more plausible. However, with the strong Jovian magnetic field which could be as strong as ~ 1000 G,[19] a considerable portion of monopoles would be brought out of the core (for the mass of monopoles $m_M \sim 10^{16}$ GeV). Therefore, the heat production would well be in the middle between these two typical cases.

In case (i) we evaluate (3) using $\langle \rho/\beta_{\mathrm{th}} \rangle \sim (3\text{--}7)\times 10^4$ g/cm^3 [the value is slightly larger, $(5\text{--}10)\times 10^4$ g/cm^3 for Uranus and Neptune], since the quantity ρ/β outside the core does not depend much on the position of the planet. We then multiply $X_{\mathrm{H}} \sim 0.7$ for Jupiter and Saturn. If we equate the total amount of the observed intrinsic heat (summarized in Table I) to the monopole heat, we see that the average monopole density

$$n_M \approx [(3\text{--}8)\times 10^{14}\ \mathrm{g}]^{-1}(10^{-27}\ \mathrm{cm}^2/\sigma_0) \tag{4}$$

is enough to explain the heat of Jupiter and Saturn. For Uranus and Neptune, the intrinsic heat per unit mass is an order of magnitude smaller than that for Jupiter and Saturn. This may be, however, understood by considering the fact that a principal part of the Uranus and Neptune interiors consists of an ionic ocean of $\mathrm{H_3O^+OH^-}$ (with dissolved $\mathrm{NH_3}$),[17] and that its hydrogen component ($X_{\mathrm{H}} \sim \frac{4}{36}$) is effective to the Rubakov process. Therefore, we obtain the monopole abundance for those stars of the

TABLE I. Intrinsic heat of the Jovian planets (Refs. 6 and 8) and possible monopole abundance deduced therefrom.

	Jupiter	Saturn	Uranus	Neptune
Intrinsic heat (erg/g sec)	$(1.76\pm0.14)\times10^{-6}$	$(1.52\pm0.11)\times10^{-6}$	$<0.2\times10^{-6}$	$\sim0.2\times10^{-6}$
Monopole density $[g^{-1}(10^{-27}\ cm^2/\sigma_0)]$	$1/[(1-8)\times10^{14}]$	$1/[(1-5)\times10^{14}]$	$<1/[(1-2)\times10^{15}]$	$\sim1/(2\times10^{15})$

same order of magnitude as that for Jupiter and Saturn (Table I).

We now consider case (ii) for Jupiter, where we have the best knowledge of the interior structure among the Jovian planets. The core is supposed to consist of ice (mainly H_2O, CH_4, and NH_3) and rock.[6] Accepting the ratio of rock to ice $\sim\frac{1}{3}$,[20] we estimate that the hydrogen composition is $\sim10\%$ in the core. The density of the core is 10–20 g/cm^3 and hence $\langle\rho_H/\beta_{th}\rangle_{core}\approx(1-2)\times10^4$ g/cm^3 is only four times less than the value outside the core. Then the average monopole density (average over the whole planet) required to give the whole intrinsic heat is only four times more than (4),

$$n_M\approx[(1-2)\times10^{14}\ g]^{-1}(10^{-27}\ cm^2/\sigma_0)\ . \tag{5}$$

We may give a similar argument also for Saturn, Neptune, and Uranus, though our knowledge of their cores is much poorer.

So far we have made an argument, assuming that the whole intrinsic heat is ascribed to the monopole, for simplicity. We now show that if the monopole density is slightly less (by a factor, say) than the value which accounts for the whole intrinsic-heat generation, the monopole heat does not cause a significant effect on the thermal evolution of the Jovian planets. This is easily seen by employing the adiabatic-convective cooling model.[6,21] The thermal evolution equation for the effective surface temperature T_e in the presence of the monopole heat is given by

$$4\pi R^2\sigma(T_e{}^4-T_s{}^4-T_m{}^4)=-\int dm\left[\frac{dE}{dt}-\frac{P}{\rho^2}\frac{d\rho}{dt}\right]\ , \tag{6}$$

where $4\pi R^2\sigma T_s{}^4=(1-\text{Bond albedo})\times(\text{solar energy flux})$ is the solar heat absorbed in Jupiter and $4\pi R^2\sigma T_m{}^4=L_m$ is the monopole heat (σ is the Stefan-Boltzmann constant). Using the equation of state for Jupiter, the evolution equation reads approximately[22]

$$dt=-\alpha T^{-3.757}[1-(T_s{}^4+T_m{}^4)/T^4]^{-1}dT \tag{7}$$

with $\alpha=2.79\times10^{23}$ in cgs units for Jupiter. After integration we see that the cooling time of Jupiter with inclusion of the monopole heat is longer only by 10% than that without the monopole heat, if the monopole density is by a factor of 3 less than the value (4) or (5). This shows that the presence of the monopole heat of the order that we obtained could well explain the discrepancy in the heat generation among the Jovian planets in the thermal evolution model. Of course, this seems to be an exotic possibility and one may take the more conservative view,[6,17] i.e., take the number (4) as an upper limit on the monopole abundance. We note, however, that the presence of a monopole with this amount does not conflict with any observations so far made, but will rather lead to observable consequences in future experiments, as we discuss in the following section.

III. LOCAL MONOPOLE FLUX

Let us now discuss the constraint on the local monopole flux that is derived from the monopole abundance in the Sun and the Jovian planets. Whether a monopole which hits the star stops or not depends on the velocity and mass of the monopole, as well as the interior structure of the stars. The energy loss caused by the free electrons in the Sun is

$$\frac{dE}{dx}=-(10-100)\ \text{GeV}\,cm^2\,g^{-1}\beta\rho \tag{8}$$

depending on the position in the Sun.[23] A monopole with the velocity $\beta\lesssim10^{-3}$ that particularly concerns us will stop in the Sun within a distance $l\approx0.1R_\odot$. [A calculation for the deceleration of monopoles in a plasma[24] shows that a monopole will stop in the Sun in a distance $l\approx0.01R_\odot\ (m_M/10^{16}\ \text{GeV})(\beta/10^{-3})$.] Energy loss due to the hadronic process of the Rubakov effect is at least an order of magnitude smaller than (8) for $\beta\approx10^{-3}$. The total number of monopoles accumulated in the Sun in the period $\tau\simeq4.6\times10^9$ yr is given by

$$N_M\approx4\pi F_m\pi R_\odot{}^2\left[1+\left[\frac{\beta_{esc}}{\beta}\right]^2\right]\tau \tag{9}$$

with F_m the local monopole flux, $R_\odot\simeq7\times10^{10}$ cm the geometrical radius of the Sun, and $\beta_{esc}\simeq2\times10^{-3}$ the escape velocity.

In Jupiter most electrons are bound electrons and the most important mechanism of energy loss is the excitation of the hydrogen and helium atoms.[12] For 2×10^{-4} $(\simeq\beta_{esc})\lesssim\beta$,

$$\frac{dE}{dx}=-(190-340)\ \text{GeV}\,cm^2\,g^{-1}\beta\rho\ . \tag{10}$$

The average distance which is necessary to decrease the velocity of monopoles ($\beta\approx10^{-3}$) to that below the escape velocity is $l\approx R_J$. A considerable portion of monopoles moving more slowly than $\beta\approx2\times10^{-3}\ (m_M/10^{16}\ \text{GeV})^{-1}$ will eventually stop in Jupiter. We calculate N_M using (9) with R the geometrical radius of Jupiter for $\beta\lesssim10^{-3}$, but for $10^{-3}\lesssim\beta\lesssim2\times10^{-3}$, R is replaced by an effective radius $R_{eff}\ (<R_J)$. Monopoles with $\beta\gg2\times10^{-3}$ will not be captured in Jupiter. For $m_N\simeq10^{16}$ GeV and $10^{-4}\lesssim\beta\lesssim2\times10^{-3}$ we find the ratio of monopole density ($n_M=N_M/M_{star}$) captured in the Sun and Jupiter as

$$\frac{n_M(J)}{n_M(\odot)}\approx0.13-1.6\ . \tag{11}$$

We, therefore, expect that the monopole densities for these stars are not very much different. For Saturn we obtain a similar value for $\beta \lesssim 1\times 10^{-3}$.

Using (2) and (9) we obtain a limit on the local monopole flux,

$$F_m \lesssim 1.2\times 10^{-21}\ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1}(\sigma_0/10^{-27}\ \mathrm{cm}^2)^{-1} \times (B_\pi/0.5)^{-1} . \quad (12)$$

On the other hand, the monopole flux which provides the monopole abundance required to account for the heat in Jupiter is of the order of

$$F_m \sim 1\times 10^{-23}(\sigma_0/10^{-27}\ \mathrm{cm}^2)^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{sec}^{-1} , \quad (13)$$

or less when there are some additional monopoles in rocks which would have been captured in Jupiter. We conclude that the hypothesis that the presence of monopoles can heat the Jovian planets does not conflict with any other constraints obtained for the local monopole flux. We also remark here that we cannot calculate the actual magnitude of σ_0 in (1), and we left it as a scale. Our argument, however, will not be modified unless σ_0 is smaller than 0.2 nb which would increase the values (4) or (5) to the level at which the solar magnetic field is disturbed[15] by the presence of monopoles.

The values (12) and (13) may be compared with the limit on the galactic monopole flux from the excess x-ray luminosity of neutron stars,[2]

$$F_m \lesssim 10^{-20}\text{--}10^{-23}(\sigma_0/10^{-27}\ \mathrm{cm}^2)^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1} , \quad (14)$$

using cross section (1). There is, however, a critique that this is not regarded as a safe bound.[25] The limit very much depends on the assumed birth rate of the neutron stars, when the significant absorption for soft x rays in the interstellar matter is considered. For example, if the uncertainties allow the x-ray luminosity $L_\gamma \sim 10^{33}$ erg sec^{-1}, which is five times larger than the value used in Ref. 2 for the diffuse x-ray luminosity, the bound is loosened to be

$$F_m \lesssim 10^{-18}(\sigma_0/10^{-27}\ \mathrm{cm}^2)^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1} , \quad (15)$$

because of the possible rapid increase in the neutrino luminosity.[26] The authors in Ref. 25 proposed to consider the known (visible) pulsar (e.g., PSR 1929 + 10) and obtained the limit similar to (14). This limit, however, depends on the parameters used. If we accept the distance to PSR 1929 + 10, ~250 pc, suggested by the more recent parallax measurement[27] rather than the 60 pc they used,[28] the bound will largely be loosened, and it is again a value similar to (15).[29] Therefore, the limit (12) obtained for the local monopole flux may well be stronger than that for the galactic monopole flux from the excess x-ray limit of neutron stars.

IV. HIGH-ENERGY SOLAR NEUTRINOS IN UNDERGROUND LABORATORIES

Finally, we discuss the possibility of improving the bound on the monopole abundance in the Sun (2), and hence that on the local monopole flux (12), using the underground experiment designed for the nucleon-decay search as a solar neutrino detector. Let us notice that the Rubakov process in the Sun corresponding to the limit (2) gives rise to the neutrino flux from μ^+ decay that is weaker than $I_\nu = 1.2\times 10^4/\mathrm{cm}^2\,\mathrm{sec}$ on Earth, which gives in a water detector 120 events/1000 ton yr [40 $\nu_e e^- \to \nu_e e^-$ events, 70 $^{16}\mathrm{O}(\nu_e,e^-)^{16}\mathrm{F}$ events,[30] 10 $\overset{(-)}{\nu}_\mu e^- \to \overset{(-)}{\nu}_\mu e^-$ events; $\bar{\nu}_e$ flux is absent because of nuclear effects in the Sun] or 1000–2000 events/1000 ton yr (Ref. 30) in a detector with iron. On the other hand, the atmospheric neutrino with $E < 50$ MeV does not exceed $\lesssim 0.2\text{--}2/\mathrm{cm}^2\,\mathrm{sec}$ depending on the geomagnetic latitude[31] and hence gives at most 0.5 events/1000 ton yr in a water detector. Therefore, we could search the monopole in the Sun down to the level

$$n_M \approx (1.5\times 10^{15}\ \mathrm{g})^{-1}(10^{-27}\ \mathrm{cm}^2/\sigma_0)(0.5/B_\pi) \quad (16)$$

by detecting the neutrino flux with an average energy 35 MeV from the Sun using, say, a 3000-ton water detector. This value will give a limit on the local monopole flux,

$$F_m \lesssim 6\times 10^{-24}(\sigma_0/10^{-27}\ \mathrm{cm}^2)^{-1}(0.5/B_\pi)\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{sec}^{-1} \quad (17)$$

which is comparable to or smaller than (13) required for the Jovian heat.

It has been thought that any direct search for monopoles on Earth is by no means possible if the monopole flux is as small as that originally derived from neutron stars. Searching for the neutrino flux from the Sun, albeit not direct, will provide us with a unique method, by using the Sun as a collector, to search for monopoles at a prohibitively small flux.

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[14]To estimate B_π we used the effective Lagrangian,

$$L \propto \epsilon^{ijk} u_R^{ci} \gamma_\mu u_L^j (e_L^c \gamma_\mu d_R^k + e_R^c \gamma_\mu d_L^k + \mu_L^c \gamma_\mu s_R^k + \mu_R^c \gamma_\mu s_L^k) \ .$$

We note that the terms with antineutrinos are absent and those with muons are enhanced relative to electrons by a factor $\frac{5}{2}$ compared with the case of spontaneous proton decays. Using partial conservation of axial-vector current, $B(\pi^0 e^+)/B(e^+)$ is estimated to be 10—0.25 depending on the extrapolation procedure [e.g., C. Schmid, Phys. Rev. D **28**, 1802 (1983); J. Arafune and M. Fukugita (unpublished)]. For hadronization into mesons we use the standard estimate for the spontaneous proton decay [e.g., P. Langacker, Phys. Rep. **72**, 185 (1981)].

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