PLANETARY HEAT FLOW LIMITS ON MONOPOLE AND AXION FLUXES

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Abstract. Recent improvements in the quantitative estimates of the observed heat flow from planetary objects of the solar system may be used to put rather stringent limits on any background monopole flux. The axion flux from the giant planets is also estimated.

The existence of magnetic monopoles is an inevitable feature of a large class of grand unified theories of the fundamental forces of nature apart from providing a natural explanation for charge quantization. In such theories the monopole is very massive, mass $> 10^{16}$ GeV. There have been several recent terrestrial searches for monopoles and only one experiment can be interpreted as detection of a monopole, that of Cabrera (1982) whose method is based on the change in the macroscopic quantum state of a superconducting ring when a magnetic charge passes through the ring. This method is independent of the monopole mass, velocity, etc. With a three loop superconducting detector continuously operated for 150 days no candidate events were seen and this enables an upper limit of $\sim 3 \times 10^{-11}$ cm^{-2} s^{-1} sr^{-1} to be put on cosmic ray monopoles of any mass and velocity passing through the Earth's surface (Cabrera *et al.*, 1983). Another astrophysical limit based on the requirement that large-scale galactic magnetic fields do not have their energy drained away by accelerated monopoles on time scales of a galactic rotation time, imposes a monopole Flux (Parker, 1971):

$$F_M \leq 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$

Another remarkable property of monopoles arising in the grand unified theories is their ability to catalyze proton or nucleon decay at rates comparable to those of strong interactions. That baryon number is not conserved in the presence of a magnetic monopole was known for some time and although nucleon decay (another feature of most grand unified theories) is typically a very slow process ($> 10^{31}$ yr) the surprising result of model calculations was that in the presence of a monopole (mass $\sim 10^{16}$ GeV), the cross-section for the nucleon decay may be as large as a typical strong interaction cross-section, i.e. $\sigma_{\Delta B} \simeq 10^{-27}$ cm$^2 \sim 1$ mb (mb is millibarn, ΔB denotes change in baryon number in the monopole induced proton decay, i.e. $PM \rightarrow e^+ \pi^\circ M$; M denotes the monopole, p the proton, e^+ the positron and π° the neutral π meson decaying spontaneously to gamma ray photons). This theoretical prediction based on a study of the peculiar properties of the S-wave

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system of a fermion with a SU(2) monopole was made by Rubakov (1981, 1982) and Callan (1982). This so-called Rubakov effect has been recently shown to also hold for SU(5) monopoles where the effect is due to the anomaly in the baryon number current due to the monopole's static magnetic field and the estimate of the cross-section for p decay catalyzed by the SU(5) M, i.e. $PM \rightarrow e^+ \pi^\circ M$ is $\sigma \simeq (2 \times 10^{-3}/\beta)$ mb which for the expected galactic monopoles with $\beta = V/C \approx 10^{-3}$ again gives a C.S. of ~ 1 mb (Bernreuther and Craigie, 1985). When these cross-sections are combined with the IMB data they imply a monopole flux of $F_M < 10^{-14}$ cm^{-2} sr^{-1} s^{-1} in the velocity range $10^{-4} < \beta < 10^{-2}$.

This large cross-section for monopole induced nucleon decay is potentially of great astrophysical interest (Kolb *et al.*, 1982) for each nucleon decay releases about a nucleon rest mass of energy (i.e. $m_N c^2$) in the form of gamma photons, muons, etc. The specific luminosity due to monopole induced nucleon decay can be written as

$$\begin{aligned} L_M &\simeq m_N c^2 n_N \sigma_{\Delta B} V \\ &\simeq 1.6 \times 10^{-3}\, n_N \cdot \sigma/(1\ \mathrm{cm}^2) \cdot V\,\mathrm{erg\ s}^{-1}\ \mathrm{monopole}^{-1}; \\ &\simeq 1.6 \times 10^{-3}\, n_N \cdot \sigma/(1\ \mathrm{cm}^2) \cdot \mathrm{erg\ s}^{-1}\ \mathrm{monopole}^{-1}; \end{aligned} \tag{1}$$

where n_N is the nucleon number density and V the relative velocity between monopole and nucleon.

The cross section can be parametrized as

$$\sigma = \pi/\Lambda^2 \simeq 10^{-27}\, \Lambda_{\mathrm{GeV}}^{-2}\ \mathrm{cm}^2; \tag{2}$$

where $\Lambda_{\mathrm{GeV}} = \Lambda/(1\ \mathrm{GeV})$. Λ_{GeV} would be of order unity if monopole induced p decay characterized by a strong C.S., so that $\sigma_{\Delta B} \simeq 10^{-27}\ \mathrm{cm}^2 \simeq 1$ mb.

It is assumed that the catalysis of nucleon decay is a statistically independent process. Equation (1) gives the energy produced per second per monopole present. To calculate the luminosity we have to multiply L_M as given by Equation (1) by the total number of monopoles present in the star or planet. If we ignore any monopoles present at the formation of the object (including them will only increase the produced energy) then the number of monopoles present is the same as the number of monopoles that have been captured by the star ever since its formation. The number captured is given by

$$N_M = (2/3\pi)\, F_M A\, t_s, \tag{3}$$

where F_M is the monopole flux, t_s is the age of the star and A is the area of the star.

When Equations (1)–(3) were applied to a neutron star the point made was the monopoles hitting the star (with $\beta \sim 0.1$) would be stopped in the surface layers itself and the energy released by the resulting catalyzed nucleon decays would emerge in the form of keV X rays. Thus with the passage of time as more and more monopoles accumulate the neutron star will become a more efficient emitter of X rays. t_s was chosen as $\simeq 10^{10}$ years. Thus with all the parameters known except F_M, one can obtain a relation between L (the luminosity) and F_M and from the observed limit on the X-ray flux from neutron stars a limit on F_M can be obtained.

In the case of ordinary stars like the Sun or planetary body, the striking monopoles would have smaller velocity ($\beta \sim 10^{-3}$ to 10^{-4}) and because of the low density of these bodies, they would not be stopped near the surface layers but because of their large mass ($\sim 10^{-8}$ g) would sink to the centre or cores of the planets. It can be shown that if the monopoles have typical velocities $\sim 10^{-3}$ C and mass less than 10^{-2} g, they will be permanently trapped in the cores of stars or planets. The monopoles trapped will then catalyze nucleon decay in these celestial objects and release energy at a rate given by Equation (1). The nucleon densities n_N at the cores of these objects being $n_N \simeq 10^{24}$ cm^{-3}, the gamma photons produced would have small mean free paths of centimetres, and would have their energy diminished to much longer wavelengths (i.e. heat) by the time they emerge out at the surface. For instance in the case of Jupiter the capture area (A) is effectively its surface area ($\sim 6 \times 10^{20}$ cm^2) and with $n_N \simeq 10^{24}$ cm^{-3}, $t_s \sim 10^{10}$ yr (3×10^{17} s), Equations (3)–(1) then give for the energy released per second, at the core due to catalyzed nucleon decay.

$$L \simeq 9 \times 10^{39} \, [F_M/(1 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1})] \text{ ergs s}^{-1}.$$

Comparing this with the observed total luminosity of Jupiter as deduced from Voyager measurements (Hanel *et al.*, 1981) i.e. $L_J \simeq 4 \times 10^{24}$ ergs s^{-1}, we get the limit on F_M as $F_M \leq 4 \times 10^{-16}$ cm^{-2} s^{-1} sr^{-1}, more stringent than the IMB data and near the Parker bound. For Saturn where the capture area (A) is comparable, the observed total luminosity is $L_{\text{sat}} \simeq 5 \times 10^{23}$ ergs s^{-1}. Hanel *et al.* (1983) giving a bound on F_M nearly a factor of 10 lower, i.e. $< 5 \times 10^{-17}$ cm^{-2} s^{-1} sr^{-1}. Similar figures hold for Uranus and Neptune. The above formulae applied to the Earth would give

$$L \approx 8 \times 10^{37} \, (F_M/1 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}) \text{ ergs s}^{-1}.$$

Recent geophysical data gives the global average intrinsic heat flux to be ~ 50 erg cm^{-2} s^{-1} corresponding to a total telluric heat flux $\sim 10^{20}$ erg s^{-1}. Considering that a substantial portion of this is due to decay of known amounts of radioactive isotopes chiefly K^{40}, this would imply a limit of $F_M < 10^{-18}$ cm^{-2} s^{-1} sr^{-1}, about two orders more stringent than the Parker bound. For the Moon, Apollo 15 and 17 data at the landing sites gave results of a heat flux ≈ 15 erg cm^{-2} s^{-1} (Keihm and Langseth, 1977) giving a total L of about a factor of 50 lower than the Earth with a corresponding limit on $F_M < 3 \times 10^{-19}$ cm^{-2} s^{-1} sr^{-1}. These limits are not that stringent as those based on the X-ray luminosity of neutron stars, but since we have much better direct data from planets, these limits are probably more reliable. For smaller bodies like asteroids, with radius ~ 10 km, the core densities being lower the mean free path of the gamma photons produced $\sim 10^2$ cm and they would emerge out of the surface in about a second and the energy would be in the form of X rays, with total luminosity $\sim 10^{30}$ (F_M/1 cm^{-2} s^{-1} sr^{-1}) erg s^{-1} which for the above bounds on F_M implies 10^{14} to 10^{11} erg s^{-1} (a few kilowatts to some megawatts) in soft- and hard-X rays. Of course no data is available on this and impacts on the asteroid surface by high energy solar flare particles is likely to produce comparable amounts of X rays. In any case this would be too low a flux to be measurable on earth or in Earth orbit; ($< 10^{-23}$ W cm^{-2} s^{-1}). In summary the best limits on F_M from planetary objects give $F_M < 10^{-19}$ cm^{-2} s^{-1} sr^{-1}.

The axion is another particle proposed some time ago (Wilczek, 1978) that is generating lot of current interest. Initially suggested to render the theory of strong interactions (i.e. quantum chromodynamics) invariant with time reversal or CP transformation, i.e. by introducing a new pseudoscalar field, the time reversal violating phases can be removed by rotating them into the complex phase of the new field. Axion mass is given by $M_a \approx \sim m_\pi f_\pi / V$; $m\pi$, $f\pi$ are the pion mass and coupling and V the (VEV) of the axion field, $\langle \phi_a \rangle = Ve^{i\theta}$. For e.g. $V < 10^{12}$ GeV, implies $m_a > 10^{-5}$ eV. Axions are a currently favoured candidates for the missing mass in the Universe and the dark matter in galactic halos. For axions to account for the dark matter in galaxy halos the axion number density is

$$n_a \simeq (10^{14} \text{ axions/cm}^3)(V/10^{12} \text{ GeV});$$

i.e. 10^{-5} eV mass axions have a number density of $\sim 10^{14}$, in our Galaxy. As axions can couple to photons and charged matter they are expected to be produced copiously in the cores of stars and especially in red giants and evolved stars. In order not to drastically alter red giant evolution the axion mass is bounded above (Dicus *et al.*, 1978) as $m_a \leq 10^{-3}$ eV. Given the axion mass and thus the coupling V, one can estimate the rate of axion production in a celestial object with a central particle density n_c as proportional to $\sim n_c^2 \sigma_a \cdot V_{\text{thermal}} \times$ volume of core; σ_a being related to the strong nuclear cross-section σ_s as $\sigma_a \sim \sigma_s \cdot f_\pi^2 / V^2$; $\sigma_s \simeq 10$ mb. Substituting for the various parameters we get for instance the axion production of the Sun as $\simeq 10^{42}$ s^{-1} $(10^8 \text{ GeV/V})^2$ giving a solar axion flux on earth of

$$\simeq 10^{14} \text{ s}^{-1} \text{ cm}^{-2} (10^8 \text{ GeV/V})^2.$$

The solar axions would have a broad spectrum of energies centred about the Sun's interior temperature, i.e. 1 keV, i.e. if converted into photons would have their energies in the soft X-ray range.

We can similarly estimate the axion flux on Earth from Jupiter and with the appropriate values for the various parameters this turns out to be $F_J \simeq 10^6$ s^{-1} cm^{-2} $(10^8 \text{ GeV/V})^2$ with an intrinsic flux of $\approx 10^{35}$ s^{-1} $(10^8 \text{ GeV/V})^2$. The energy of the axions from Jupiter would be centred about $\simeq 10$ eV. Similar fluxes from the other giant planets may be expected.

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