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Research Article

Pulsars: Cosmic Permanent "Neutromagnets"?

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We argue that pulsars may be spin-polarized neutron stars, that is, cosmic permanent magnets. This would simply explain several observational facts about pulsars, including the "beacon effect" itself, that is, the static/stable misalignment of rotational and magnetic axes, the extreme temporal stability of the pulses, and the existence of an upper limit for the magnetic field strength, coinciding with the one observed in "magnetars." Although our model admittedly is speculative, this latter fact seems to us unlikely to be pure coincidence.

1. Introduction

We will assume that the simple model of a pulsar [1] as a rotating neutron star (NS) with a dipole magnetic field at an angle with respect to its orbital axis [2] is basically correct. The radiated power from the magnetic dipole is proportional to $\sin^2\theta$ [3], where θ is the angle between the dipole axis and the rotational axis.

In order to make our point as simply as possible, we further assume the following:

(i) The NS is composed solely out of neutrons [4]. (Nearly true assuming that quark stars do not exist. There are observational indications [5] that NS indeed are composed out of normal nuclear matter.)

(ii) The density is constant throughout the NS and roughly the same as the density of normal nuclear matter. (In reality, the density is a few times higher in the NS core and much less in its thin crust.)

(iii) The magnetic field is due to spin alignment of the neutrons in the NS. This is motivated by the fact that aligned spins are energetically favored by the nuclear force, as evidenced, for example, by the deuteron, the more strongly so for the unusually small internucleon separation present in neutron stars [6]. We, thus, assume that the NS is a "neutromagnetic" material (in direct analogy to ferromagnetic materials). The orbital angular momentum does not contribute to the magnetic field as the neutrons are electrically neutral (no currents). We understand that this is far from the orthodox view; however, the extreme conditions inside neutron stars are not accessible to direct experimental tests, so some leeway seems reasonable. The Pauli principle, naively prohibiting parallel spin states for $n-n$ (or $p-p$), may well be partially lifted by the extreme gravitational and magnetic interactions, so that some quantum numbers may differ. Also, isotopic triplet ($I=1$) states allow spin triplet ($S=1$) states for $n-n$ (and $p-p$). There are also experimental observations of ferromagnet-like nuclear spin ordering phenomena in controlled laboratory experiments [7] (first example of "nuclear spin Ising system").

2. Origin of Magnetic Field

Magnetic fields generally can have two origins: (i) charged particles in motion and (ii) alignment of magnetic moments of the constituents.

The observationally inferred magnetic field of neutron stars range from 10^4 T for millisecond radio pulsars to a few times 10^{11} T for magnetars.

There is no general consensus about the microscopic origin of the magnetic field of a neutron star. If the "lighthouse"/"beacon" effect which produces the observed pulses in the assumed model [2] is correct, the magnetic field must be very strong and at the same time very *stable* to account for the fact that pulsars are extremely accurate "clocks." Any "wobbling" or dynamical behavior of the magnetic field would destroy the accurate pulsing. The magnetic field must also be oriented in a direction different from the rotational axis for any pulsar to exist.

In our model, we automatically get all these characteristics, as the neutron magnetic moments are "frozen" in the same direction by the requirement of lowest nuclear energy. In the orthodox model, it is hard to see how a coupled (superfluid neutron—superfluid and superconducting proton) liquid can produce a simple and misaligned, dipole field, as a superconductor will constrain the B-field into quantized vortex lines (and not give rise to them). The electrons (expected to be "normal") should be electromagnetically coupled to the proton "fluid," and; hence, all charged currents should co-rotate giving a magnetic field collinear with the angular momentum. It is also known that several dynamic magnetic instabilities may endanger the field itself. All in all it seems that a more orthodox model of neutron star interiors should give B-fields (i) collinear with L ($\theta = 0$) and (ii) of highly dynamical complex nondipole form.

In empirical nuclear potentials, for example, [6], it can be seen that the spincontribution becomes increasingly attractive the smaller the separation. As the neutrons in a neutron star are more highly packed than in normal nuclei, due to gravitation, aligned spins are energetically favored configurations.

Also, in the presence of gravity, bound neutrons are stable. It adds an additional, attractive background potential to the nuclear one, lowering the potential below the level required for bound states.

We take the attractive potential for aligned spins to be $\simeq$ 10 percent of the total nuclear binding energy Δmc^2, as corroborated by calculations in various models. (Roughly $0.1 \times 10\,\text{MeV} = 1\,\text{MeV}$ or 10^{10} K.) The NS temperature, originally also roughly 10^{10} K at birth in a supernova, rapidly cools via the neutrinos produced in (gravity driven) inverse beta decay. When it falls below the neutron star "Curie-temperature" 10^{10} K, the neutron star suddenly becomes magnetized, the mechanism being analogous to the case in a normal ferromagnetic material. If the temperature at creation happens to be less than 10^{10} K the NS will be polarized from the outset; the global energy minimum of the NS will correspond to aligned neutron spins. In an NS the process is connected to the strong nuclear force (instead of the electromagnetic force in a ferromagnet). The NS can thus be labelled a "neutromagnetic" material.

An independent way to motivate the numbers given above is to make a calculation of the classical dipole-dipole interaction. Their magnetic interaction energy is

$$E = \frac{\mu_0 \mu^2}{2\pi x^3}, \tag{1}$$

where, for neutrons, $\mu = -1.91\,\mu_N$ (the nuclear magneton), $x \simeq 10^{-15}$ m (1 fm), giving $E \simeq 0.1$ MeV, corresponding to a critical ("Curie") temperature of $T \simeq 10^9$ K. However, it is known that the above classical dipole-dipole calculation underestimates the real value for iron by almost four orders of magnitude, allowing for the Curie temperatures, and interaction energies, for "neutromagnets" to be substantially higher. As NSs are expected to form at $\sim 10^{10}$ K, this could indicate that they become magnetized already at birth, which may help explain the supernova explosion itself.

As all neutron stars seem to have very similar masses (That this value coincides with the Chandrasekhar limit, the maximum stable mass of a white dwarf, is a mystery in itself.) $M_{\text{NS}} = 1.4 \pm 0.08 M_{\odot}$ [8], where $M_{\odot} = 1.99 \times 10^{30}$ kg is the solar mass (and from general theoretical stability reasons cannot exceed $M_{\text{NS}} \sim 4M_{\odot}$), we get for the maximum attainable permanent magnetic field, corresponding to total, uniform polarization of the neutron magnetic moments:

$$B_{\text{neutromagn.}} \leq 10^{12}\ T. \tag{2}$$

This coincides nicely with the largest measured magnetic fields of pulsars, in some so-called "magnetars" [9]. It seems strange that such a close match should be pure coincidence.

3. Origin of the "Beacon" Effect

The magnetic field of the massive progenitor star, especially in its core, at the moment of collapse will tend to align the spins of the nuclei, breaking the spherical symmetry. As they come sufficiently close, the strong, spin-dependent, nuclear force suddenly becomes active, aligning the spins of the produced neutrons in the same direction. The original magnetic field of the star, thus, acts as a "seed" for the final NS magnetic field (like the magnetizing field in normal ferromagnetism). However, the ("fossil") B-field of the original star is not conserved, and boosted through contraction of the field lines, as most of the star envelope is blown off. This is a problem in more orthodox models especially in trying to reproduce the extreme B-fields of magnetars [10], but not in our case as it is known that the magnetizing field can be a very small fraction (many orders of magnitude) of the resulting permanent magnetic field. (The other standard scenario, dynamo mechanism due to differential rotation during collapse, seems destined to produce magnetic fields collinear with the rotational axis, removing the "beacon" altogether.) We know from the sun that the magnetic field is not a simple dipole but has a more chaotic behavior (solar cycle, etc.) and does generally not coincide with the rotational axis. The misalignment of the NS magnetic field will then be statistically distributed with respect to its orbital axis, according to the configuration at collapse. Also, the magnitude of the B-field will be dependent on how complete the spin polarization will be. (Unless it always saturates, see Section 5 below.) This, in turn, will depend on the deviation from simple dipole at the time of star collapse, differently polarized domains, and so forth.

In other models of neutron stars, where the interior is assumed to consist of superfluid neutrons and superconducting protons (roughly 1 percent of NS), it seems that the NS magnetic field must lie along the orbital axis, which would preclude pulsars. The superfluid neutron angular momentum vortices are strongly coupled to the protons, creating strong magnetic fields parallel to the orbital axis. If so, there would be no observable pulsars, as no "beacon effect" results. In such models, the magnetic field is believed to somehow arise in the highly (normal-) conducting crust, but it is hard to see how it could reach the strength [10], stability, and misalignment needed.

4. Magnetic Field-Period Relation and Glitches?

Very fast, millisecond, pulsars generically seem to have the weakest magnetic fields. In the orthodox view, millisecond pulsars are supposed to be old pulsars that have been spun up by accretion from a binary companion star. In our model one could imagine a different scenario. The magnetic field is proportional to the total spin of the neutrons and only weakly dependent on other variables

$$B \propto S. \tag{3}$$

However, the orbital angular momentum is strongly dependent on other variables, especially on the frequency of rotation, as the mass and composition of the NS can be assumed to be fairly generic,

$$L = L(\omega). \tag{4}$$

The maximum angular momentum of a NS arising from spin polarization is

$$|\mathbf{S}| = N|\mathbf{s}_n| = N\frac{\hbar}{2} \simeq 10^{23} Js, \tag{5}$$

whereas the orbital angular momentum is a function of the rotational angular frequency (or rotational period, P):

$$\mathbf{L} = I\vec{\omega} = \frac{2\pi\hat{\omega}I}{P}. \tag{6}$$

The total angular momentum of the NS is then

$$\mathbf{J} = \mathbf{L} + \mathbf{S}. \tag{7}$$

For a solitary (radio) pulsar, as there is no outside torque,

$$\frac{d\mathbf{J}}{dt} = 0. \tag{8}$$

One could then speculate that pulsar glitches, sudden speedups of $\Delta P/P \sim 10^{-8}$, may be due to rearrangement of $\mathbf{L}$ and $\mathbf{S}$ through L-S coupling, tensor coupling, or relaxation (small amount of $\mathbf{S} \leftrightarrow \mathbf{L}$). However, as pulsars exhibiting glitches are very rare, the dataset at present may be too small to test such a hypothesis, and we will refrain from further analysis here.

5. Universal NS-"Magnet"?

Magnetic (dipole) field strengths of pulsars are *indirectly inferred* from observed spin-down rates:

$$B_{\text{inferred}} = \left(\frac{3c^3 I}{8\pi^2 R^6}\right)^{1/2} \left(P\dot{P}\right)^{1/2}, \tag{9}$$

or, in Tesla,

$$B_{\text{inferred}} \simeq 10^{15} \left(P\dot{P}\right)^{1/2}, \tag{10}$$

where P is measured in seconds and $\dot{P} = dP/dt$ is dimensionless.

In a normal ferromagnet below the Curie temperature the spin alignment is near 100 percent. In a neutron star the process should be at least equally efficient and most likely also faster, as it is driven by the strong nuclear force instead of electromagnetism.

If we assume that the same (but with much higher effective binding forces) applies for neutron stars, they will all be almost identical permanent magnets. NS will then be extremely simple, all having almost the same mass ($1.4 \pm 0.08 M_\odot$ from observations [8]) and the same magnetic field ($\sim 10^{12}$ T). This loss of individuality is well in line with the next step on the cosmic compact object ladder, the black hole, which is very simple and is totally described by only three numbers (its mass M, angular momentum L, and charge Q).

If now B is *constant*, the power of dipole radiation dE/dt depends on angle and period only:

$$\frac{dE}{dt} = \text{const}\frac{\sin^2\theta}{P^4}, \tag{11}$$

where const $= 32\pi^4 R^6 B^2/3c^3$.

In cases where B is parallel to L ($\theta = 0$), no pulsar appears if they are almost aligned ($\theta \sim 0$), a "weak" B is inferred, and for large misalignment ($\theta \sim \pi/2$) a huge "magnetar" B is inferred.

6. Conclusions

Even though the presented model of a neutron star being a "giant polarized nucleus" is overly simplified, it nevertheless has an attractive simplicity—in the vein of Zwicky, who together with Baade originally introduced the very concepts of NS, supernova, and their interconnections [4]—and explains several unresolved properties of pulsars.

(i) The origin of the magnetic field is simple and unavoidable. In other models it is a complication which has to be addressed separately. That a completely polarized neutron star automatically gets a magnetic field comparable to that of magnetars seems, to us, too compelling to be pure coincidence.

(ii) The nonzero angle of the magnetic field to the rotational axis is explained. The direction is triggered by the original magnetic field of the massive star at time of collapse and then "frozen in" by the nuclear force.

(iii) We get a natural maximum limit for the magnetic field, $B \simeq 10^{12}$ T, corresponding to the field in "magnetars." The model also predicts that no pulsars (or neutron stars) will have a B-field greater than this, as all measured neutron star masses are highly peaked around 1.4 solar masses, and, from general stability arguments, their maximum masses cannot be more than a few times higher than this. In that sense our model is directly falsifiable; if any neutron star with $B > 10^{12}$ T is detected, some other mechanism for generating the magnetic field must apply.

(iv) The fact that pulsars are extremely exact "clocks" means that their magnetic fields must be very stable. As the neutrons align their spin akin to the atoms in a normal ferromagnet, we get this property for free.

(v) Glitches may possibly be caused by relaxation, due to *L*-*S* coupling, to a state with lower energy. This should then be accompanied by a (minute) decrease in the *B*-field, which in principle could be measured.

(vi) If only the small proton admixture, of order 1 percent in the orthodox scenario, contributes to permanent magnetization through quantum mechanical $(n - p)$ pairing, $B_{\max} \sim 10^{10}$ T, with only marginal alteration in the Curie temperature.

One should remember that the nuclear physics at these extreme circumstances and densities is not known *a priori*, so several unexpected properties (such as "neutromagnetism") might apply. The fact that there also exists a huge "seeding" external magnetizing field from the collapsing star at the moment of neutron star creation makes neutromagnetization plausible.

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