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Submitted to:
Dr. Donald West, Code 684.1
Lab for Astronomy and Solar Physics
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

Submitted by:
The Trustees of Columbia University
in the City of New York
351 Eng. Terrace
New York, New York 10027

Prepared by:
Columbia Astrophysics Laboratory
Departments of Astronomy and Physics
Columbia University
550 West 120th Street, MC-5247
New York, New York 10027

Principal Investigator:
Malvin Ruderman

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Neutron Star Phenomena

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Final Technical Report for NAG 5-2841

Malvin Ruderman

The main completed work supported by this grant is on various phenomena involving neutron stars.

1. *Electron-positron production in the near magnetosphere of gamma-ray pulsars* [1,7]. A model was prepared for the observed combination of power-law and thermal emission of keV X-rays from rotationally powered puslars. For γ-ray pulsars with accelerators very many stellar radii above the neutron star surface, 100 MeV curvature γ-rays from e^- or e^+ flowing starward out of such accelerators are converted to $e^\pm$ pairs on closed field lines all around the star. These pairs strongly affect X-ray emission from near the star in two ways. (1) The pairs are a source of synchrotron emission immediately following their creation in regions where $B \sim 10^{10}$G. This emission, in the photon energy range 0.1 keV $\lesssim E_X \lesssim$ 5 MeV, has a power-law spectrum with energy index 0.5 and X-ray luminosity that depends on the backflow current, and is typically $\sim 10^{33}$ egs s^{-1}. (2) The pairs ultimately form a cyclotron resonance "blanket" surrounding the star except for two holes along the open field line bundles which pass through it. In such a blanket the gravitational pull on $e^\pm$ pairs toward the star is balanced by the hugely amplified push of outflowing surface emitted X-rays wherever cyclotron resonance occurs. Because of it, the neutron star is surrounded by a leaky "hohlraum" of hot blackbody radiation with two small ones, which prevents direct X-ray observation of a heated polar cap of a γ-ray pulsar. Weakly spin-modulated radiation from the holes through it would then dominate observed low energy (0.1–10 keV) emission. For non-γ-ray pulsars, in which no such accelerators with their accompanying extreme relativistic backflow toward the star are expected, optically thick $e^\pm$ resonance blankets should not form (except in special cases very close to the open field line bundle). From such pulsars blackbody radiation from both the warm stellar surface and the heated polar caps should be directly observable. In these pulsars, details of the surface magnetic field evolution, especially of polar cap areas, become relevant to observations. This model was compared to X-ray data from Geminga, PSR 1055-52, PSR 0656+14, PSR 1929+10, and PSR 0950+08. The expected power law and index is found for 0.7–5.0 keV X-rays from the known γ-ray pulsars Geminga ($n = 0.47 \pm 0.2$) and PSR 1055-52 ($n = 0.5 \pm 0.3$) but no power law was found from PSR 1929+10 and 0950+08 with similar spin-periods but which are not γ-ray pulsars.

2. *Magnetic Field Evolution in Spun-Up and Spinning-Down Pulsars* [5,6,9,10]. Spinning superfluid neutrons in the core of a neutron star interact strongly with co-existing superconducting protons. One consequence is that the outward (inward) motion of core superfluid neutron vortices during spin-down(up) of a neutron star may alter the core's magnetic field. Such core field changes are expected to result in movements of the stellar crust and changes in the star's surface magnetic field which reflect those in the core below. The difficult part of calculating these changes has been understanding the response of the superconducting protons' array to the push of a changing neutron

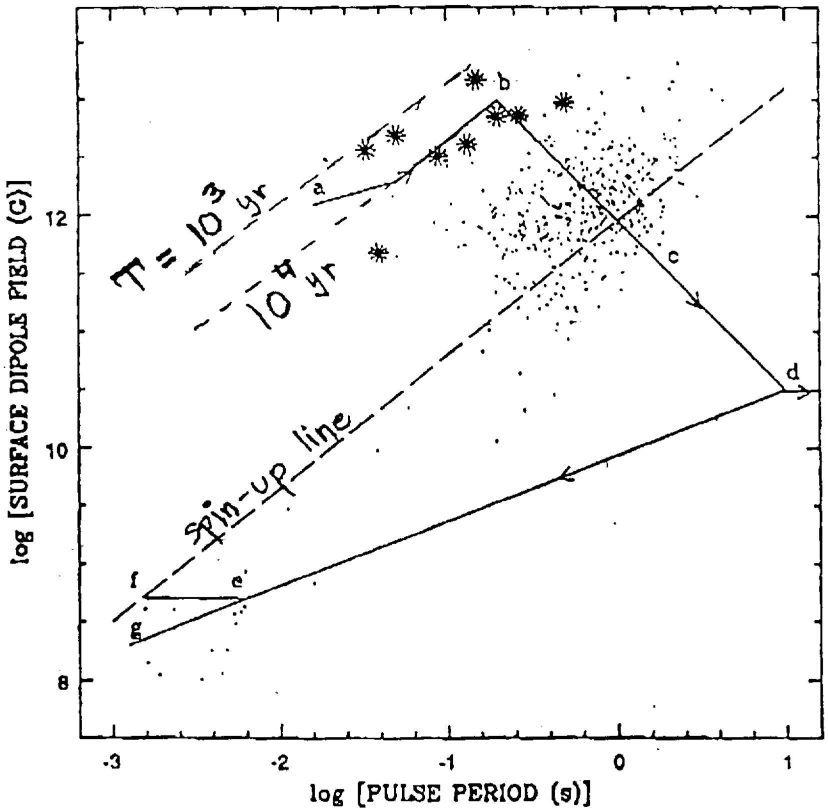

Fig. 1. Evolution of pulsar dipole moments as a function of pulsar period.

vortex array. A quantitative estimate has now been made based upon the relevant micro-physics. The predicted evolution of a pulsar is sketched in Fig. 1 which indicates how the pulsar's magnetic dipole moment (surface dipole field) should vary as the pulsar spins-down, and how it can change for certain of those pulsars in binaries, which long after their death as pulsars, are recycled by spin-up induced by accretion from their comparisons. These field changes would be observable in various ways, e.g., "spin-down indices" in young pulsars, a downward drift in pulsar dipole moments (μ) with μ proportional to spin-rate for pulsars with spin-down ages exceeding 10^4 yrs as long as the surface dipole field remains above 10^{11}G and the age of the star exceeds a few $\cdot 10^6$ yrs, resurrection to millisecond pulsars of dead pulsars in certain binaries, and the pulse shapes of the fastest spinning part of the disk millisecond pulsar population. The spin-down index (n) of very young pulsars with spin-rate Ω is

$$n \equiv \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}.$$

The model predicts $n = 2$ for Vela and $n \sim 5$ for pulsars with periods $P \gtrsim 10^{-1}$ seconds and, for, puslars much younger than Vela

$$3 - n = (3 - n)_{\mathrm{Vela}} \left(\frac{\Omega^2}{\dot{\Omega} B_d}\right) \left(\frac{\Omega^3}{\dot{\Omega} B_d}\right)^{-1}_{\mathrm{Vela}}$$

if the ratio of parenthesis of the RHS < 1, and $3 - n \cong (3 - n)_{\mathrm{Vela}}$ otherwise. Predictions and observations are compared in Table 1 for all pulsars with observed n not contaminated by excessive timing noise.

Pulsar Spin-Down Indices

PSR	T_s(yr)	n	$n_{\rm Model}$	Ref.
Crab	1300	2.5	2.6	Lyne, Pritchard and Smith 1988
1509-58	1500	2.8	3	Kaspi et al. 1994
0540-69	1700	2.5	2.7	Eikenberg et al. 1998
Vela	11000	1.4	2	Lyne et al. 1993

The predicted evolutionary line bcd of Fig. 1 (corresponding to $B_d \propto \Omega$ or $n = 5$) is that expected for the model for older radiopulsars. The pulsars with asterisks in Fig. 1 are in SNR's with typical ages of 10^4 yrs. Their magnetic dipoles are generally larger than those of the older pulsars and the expected evolution is consistent with the observed trend.
Subsequent spin-up $d \rightarrow e \rightarrow f, g$ depends on field geometry. The predicted fraction of orthogonal rotatorss and aligned rotators in the f–g sector of the disk population has been compared with pulse shape observations of this family and some radio polarization data. The agreement of predictions and observations seems good.

3. *Glitches.* The surface magnetic field evolution in the pulsars considered above is not sensitive to details of the associated curst movements. For the warm crusts of very young radiopulsars most of the crustal stress from spin-down induced motion of core-flux should be relaxed by plastic flow ("creep"). For cooler crusts, this is no longer expected to be the case. In cooler spinning-down neutron stars the forced movement of the most strongly magnetized surface patches may be accomplished by large scale crust cracking. The sudden crustal movement might itself be the cause of crustal neutron superfluid vortex line unpinning or it might trigger a hydrodynamically supported unpinning avalanche. Either would cause sudden changes in the stellar spin-period which suggest various features of observed spin-period "glitches", but they seem to differ in their predictions about permanent changes in spin-down rates.
A model in which induced core flux-tube motion strains the crust until it cracks to relieve the excess strain – and the process repeats until most core flux has been pushed out into the neutron star curst – has been developed to describe glitches. It agrees with observations in the following ways.
   a) The Crab pulsars's dipole magnetic field appears to jump in each major Crab glitch, by about the expected amount from a strain relieving crack.
   b) The glitch interval for the Vela pulsar is 3 years. (The only non-calculated parameter is the observed change in the Crab's dipole moment after a glitch.)
   c) The major Crab glitches are only a few times 10^{-2} as strong as the giant ones in the older pulsars. Glitches have not been seen at all in PSR's 1509-58 and 0540-69.
   d) In addition to giant Vela-like glitches the much weaker family of Crab-like glitches

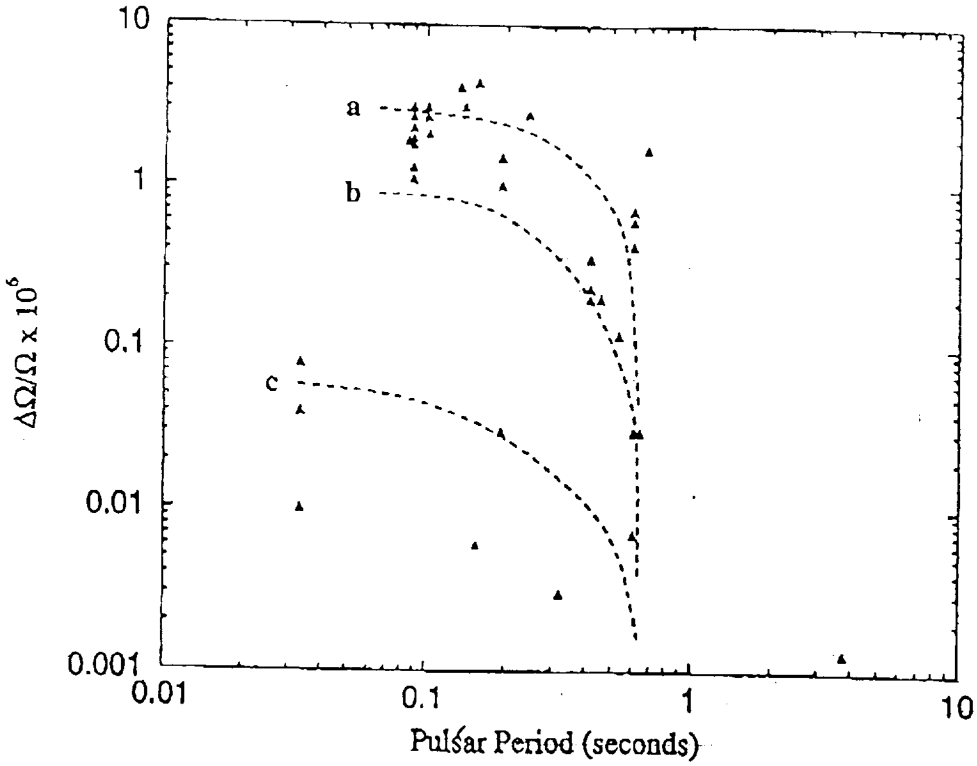

Fig. 2. Observed pulsar glitch magnitudes as a function of pulsar period. The computed curves from the model are the dashed lines.

is also often observed in Vela-like and older pulsars. The spread in observed $\Delta\Omega/\Omega$ within a family is generally less than the separation between families.

e) Glitch magnitudes, $\Delta\Omega/\Omega$, decrease with increasing pulsar period, and significant glitching essentially ceases at $P \cong 0.8$s regardless of pulsar age. This is shown in Fig. 2 which gives reported glitches as a function of puslar period.

f) Crab glitches occur at intervals larger than those between Vela glitches (3 years).

g) At least one Crab pulsar glitch has a resolvable initial rise in spin-rate.

4. *Gamma-Ray Burst Central Engines* [2,3]. To account for the γ-ray emission from cosmologically distant γ-ray burst sources there must be a relatively long-lived central engine to produce the needed γ-ray power. To give the typical fluence in each observed γ-ray sub-burst ("peak"), for the number of peaks, N_p, the time interval between peaks, τ, for the rapid rise times and variability

   a) an energy of $E_0 \sim 10^{51}$erg must be released in each sub-burst observability

   b) for sub-burst no more than $10^{-5} M_\odot$ in baryons may be carried in each successive sub-burst

   c) $N_p \lesssim 10$

   d) between sub-bursts, the central engine should often be dormant for intervals $\tau \sim 1$ s to $\sim 10^3$ s

   e) the engine should be capabile of attaining its peak power within milliseconds and of exhibiting large fluctuations thereafter.

f) there can be great differences within the family of γ-ray burst sources and also between sub-bursts in the same γ-ray burst event.

A model has begun to be developed which seems capable of explaining properties a), c), d), e) and f) and very possibly also b). Neutron stars (or rapidly spinning nuclear density toroids) with millisecond spin-periods and comparable differences in rotation period between different cylinders within them will wind-up interior poloidal field into toroidal ones. This preempts other ways of dissipating the kinetic energy of the initial differential rotation. It has been shown that there is a critical toroidal magnetic field (B_φ) which must be wound up before the torus's magnetic buoyancy propels it to the surface which it almost immediately breaks through. The model give a B_φ (critical) of almost 10^{17}G and a released magnetic energy at the surface of up to 10^{51}ergs. This wind-up and release continues until almost all of the initial kinetic energy in differential rotation is expended. Esitmates of τ, N_p, and reproducibility do not appear to be particularly different from what is required, and the maximum baryon mass carried out in each sub-burst is less than about $10^{-3} M_\odot$ (but an accurate estimate has not been made yet).

Major publications supported:

1) "Models for X-ray Emission from Isolated Pulsars," with F. Wang, J. Halpern, T. Zhu, Ap.J., in press (May 1998).
2) "The Central Engine of Gamma-Ray Bursters," with W. Kluzniak, to be published in Proceedings of Sept. 1997 Compton GRO Conference, Huntsville, AL.
3) "Gamma-Ray Astronomy: Bursting Out All Over," Nature (N&V), 387, 959 (June 26, 1997).
4) "Gamma-Ray Pulsars," J. Astrophys. Ast., 15, 173, (1995).
5) "Neutron Star Magnetic Field Evolution, Crust Movement, and Glitches," with T. Zhu and K. Chen, Ap.J., 492, 267 (1998).
6) "Millisecond Pulsar Alignment: PSR 0437-4715," with K. Chen and T. Zhu, Ap.J. in press (Jan. 1998).
7) "Pulsed $e^{\pm}$ Annihilation γ-Ray Line from a Crab-like Pulsar," with T. Zhu, Ap.J., 478, 701 (1997).
8) "In and Around Neutron Stars," in Unsolved Problems in Astrophysics, eds. J. Bahcall et al., Princeton University Press (1997).
9) "Evolving Magnetic Fields in Neutron Stars," with K. Chen in Proceedings of the Conference to Celebrate Amsterdam's Astronomical Institute, ed. E. van Paradijs (1996), in press.
10) "Pulsar Magnetic Fields and Glitches," in Proceedings of NATO-ASI 1996 Neutron Star Workshop (Lipardi), in press.