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Pulsar Physics without Magnetars

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Abstract Magnetars, as defined some 15 yr ago, are inconsistent both with fundamental physics, and with the (by now) two observed upward jumps of the period derivatives (of two of them). Instead, the class of peculiar X-ray sources commonly interpreted as magnetars can be understood as the class of throttled pulsars, i.e. of pulsars strongly interacting with their CSM. This class is even expected to harbour the sources of the Cosmic Rays, and of all the (extraterrestrial) Gamma-Ray Bursts.

Key words: magnetars — throttled pulsars — dying pulsars — cavity — low-mass disk

1 DEFINITION AND PROPERTIES OF THE MAGNETARS

Magnetars have been defined by Duncan and Thompson some 15 years ago, as spinning, compact X-ray sources - probably neutron stars - which are powered by the slow decay of their strong magnetic field, of strength 10^{15} G near the surface, cf. (Duncan & Thompson 1992; Thompson & Duncan 1996). They are now thought to comprise the anomalous X-ray pulsars (AXPs), soft gamma-ray repeaters (SGRs), recurrent radio transients (RRATs), or 'stammerers', or 'burpers', and the 'dim isolated neutron stars' (DINSs), i.e. a large, fairly well defined subclass of all neutron stars, which has the following properties (Mereghetti et al. 2002):

1) They are isolated neutron stars, with spin periods P between 5 s and 12 s, and similar glitch behaviour to other neutron-star sources, which correlates with their X-ray bursting.

2) They are soft X-ray sources, hotter than pulsars of the same spindown age by a factor of $\gtrsim$3 - whose emission can be explained as due to magnetospheric interactions with the throttling CSM and/or mild accretion - yet mostly without pulsed coherent radio emission. A radio-loud exception has been detected by Camilo et al. (2006).

3) Their spindown is rapid, $\tau = 10^{4\pm1}$ yr, despite ongoing accretion.

4) Their estimated number in the Galaxy is large, comparable to the number of pulsars. Due to their short spindown times (of order 10^4 yr, instead of the $10^{6.4}$ yr at which pulsars die, see next section), their visible number in the sky is reduced by a factor of order $10^{-2.4}$ compared with ordinary pulsars.

5) They may well derive their power ($\lesssim 10^{36}$ erg s^{-1}, for $d \gtrsim 10$ pc) from accretion, whose implied (small) spinup is overcompensated by magnetospheric braking.

6) They are often (some 50%) found near the center of a pulsar nebula (Gotthelf et al. 2000).

Above definition (of the magnetars) meets with insurmountable difficulties: Surface dipole field strengths of $\gtrsim 10^{15}$ G imply internal field strengths of $\lesssim 10^{17}$ G, too high to be anchored by the core of a neutron star; the fields would decay on a dynamical timescale. Secondly, no convincing formation mode for such strong stellar magnetic dipoles is known. The third - and perhaps least indirect - reason against the existence of magnetically powered compact stars is the fact that the two SGRs 1900+14 and 1806–20 both experienced upward jumps in $\dot{P}$ during glitches (which correlated with flares: Marsden et al. (1999), Rea et al. (2006)): A rise in $\dot{P}$ corresponds to an increase of the braking torque, which would be energetically forbidden if powered by the magnetic moment.

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For these (three) reasons, a different explanation is wanted of the class of sources with the above properties 1) through 6). In this communication, I repeat my earlier conclusion (2006, 2007) that this class (of strongly torqued neutron stars) can be understood as the class of "throttled pulsars", i.e. of pulsars whose magnetospheres are indented by a low-mass disk accreted from their CSM. Rather than trying to erase the - by now strongly rooted - name "magnetar", I will keep it in the new sense of a normally magnetized neutron star whose magnetic torque is enhanced by indenting. Note that the spindown torque T of a confined, rotating magnet can be approximated by (Kundt 2005):

$$T(r) \approx r^3 \langle B_r B_\phi \rangle \tag{1}$$

i.e. scales as r^{-3} with increasing confinement r^{-1} of a dipole field $B(r)$, and can grow by as much as a factor of 10^3 in the case of the dying pulsars.

Before elaborating on the problem of the dying pulsars - in the next section - allow me to stress that there are two possibilities of forming throttled pulsars: (1) An old, significantly spun-down pulsar tends to be confined by its CSM once its wind (ram) pressure decreases below the required minimum for blowing a cavity, and: (2) Young, new-born pulsars (like the Crab, Vela, and others) tend to be surrounded by X-ray nebulae which are thought to be inherited from their pre-existing CSM, whose inertia is too large for being instantaneously blown away by the newborn pulsar's wind.

I therefore expect two classes of throttled pulsars (or magnetars): (1) the abundant, low-power class of dying pulsars, and: (2) the rare, high-power class of newly-formed pulsars. Class 1 dominates in the statistics, class 2 may dominate in particle energies. The highest accretion-disk masses (and hence luminosities) are expected near the (thin) molecular-cloud layer of the Galaxy, hence such sources should project onto the Milky-Way disk, as do the SGRs. With all these properties in mind, I expect the class of throttled pulsars to not only have properties 1)–6) above, but in addition: 7) They are - at the same time - the dominant sources of the cosmic rays (of all energies), and of the (extraterrestric) γ-ray bursts (Kundt 2006, 2007).

2 WHY DO PULSARS DIE?

Pulsars (in the strict sense) are isolated, spinning neutron stars which emit a broadband radio through γ-ray pulse once per spin period, and spin down, cf. Kundt & Schaaf (1993), Kundt (1998, 2002, 2005). A typical pulsar magnetosphere is sketched in Figure 1. As is shown in Figure 2, pulsars grow in number linearly with spindown age $\tau := P/2\dot{P}$ until a spindown age of $10^{6.4}$ yr beyond which they become exponentially rare in the $dN/d\log\tau$ vs. $\log\tau$ plot, i.e. have died statistically. For what reason?

For decades, this question has been left open in the literature. Only in 2005 have I convinced myself of the correctness of an early suggestion: that pulsing gets suppressed (or suffocated) as soon as the CSM is allowed to engulf the star's magnetosphere, instead of being blown to large standoff distances by the star's wind, of order 10^{15} cm or larger (Kundt 2007). The equilibrium radius of a pulsar's cavity follows from a balance of the ram pressure $p_{\rm ram} = L/4\pi r^2 c$ exerted by its relativistic wind (driven by magnetic dipole radiation) by the weight of the heavy ambient gas column $p = \int dr\ \rho_{\rm CSM}\ g$, attracted by the neutron star's gravity (Kundt 2005, p.106). For p one gets the barometric-height formula (at constant ambient temperature T):

$$p = p_\infty \exp(u) \quad \text{with} \quad u := GMm/rkT \tag{2}$$

by insertion of $\rho_{\rm CSM} = pm/kT$, $g = GM/r^2$, differentiation of p w.r.t. r, and re-integration w.r.t. u with $p_\infty = p_{\rm CSM}$. p must be balanced by $p_{\rm ram}$ with $L = (2/3c^3)D_\perp^2\Omega^4$. Their equality fixes the product $u^{-2}\exp(u)$, yielding two solutions u_j below its maximum value $e^2/4$ (for $u_{\rm max} = 2$): a stable, outer radius r_o and an unstable, inner radius r_i. Marginal stability (against suffocation) prevails when these two radii coincide, at $u_{\rm max} = 2$, which implies a PSR turnoff period $P_{\rm max} = 2\pi/\Omega_{\rm min}$ of

$$P_{\rm max} \leq 2\pi(2/3\pi e^2)^{1/4}(D_\perp kT/GMmc^2\sqrt{p_{\rm CSM}})^{1/2} = 8s(D_{31}T_3/\sqrt{p_{-12.3}})^{1/2} \tag{3}$$

for an average CSM temperature T in units of 10^3 K, and CSM pressure $p = 10^{-12.3}$ erg cm^{-3}, in agreement with the empirical $P_{\rm max} \gtrsim 8$ s for a typical dipole moment of 10^{31} G cm^3. Note that HI regions have temperatures of order 10^2 K (only), but that a 2-component mixture with a (relativistic) PSR wind has a

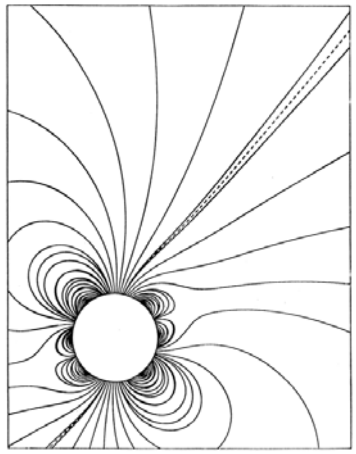

Fig. 1 Plausible pulsar magnetosphere, obtained by adding 6 times a normalized octupole to a dipole inclined at 40 deg, from Chang (1994). Note that a pure magnetic dipole inside a fluid star, without a toroidal bandage, would decay on a dynamical time scale (Flowers & Ruderman 1977).

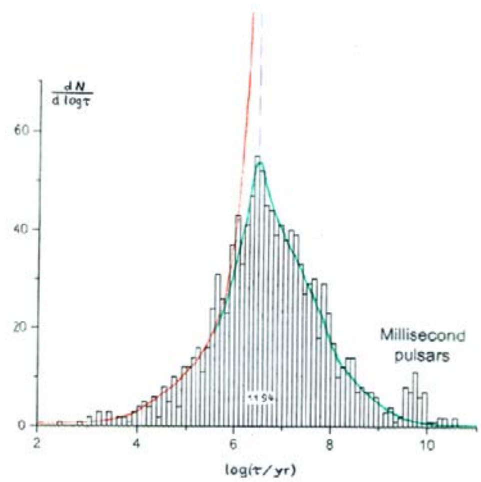

Fig. 2 N = 1194 pulsars plotted linearly w.r.t. their logarithmic spindown age, $dN/d\log\tau$ vs $\log(\tau\ \mathrm{yr}^{-1})$, $\tau = P/2\dot{P}$. For a stationary age distribution, the upper envelope would rise exponentially, as drawn in - both solid and broken - for two extreme interpretations of the noise. Clearly, there is an increasing deficit of detected pulsars for $\tau \geq 10^{6.4}$ yr. The small bump of ms pulsars, of spindown ages between $10^{9.5}$ yr and 10^{10} yr, may be due to those inside globular clusters.

distinctly lower density, hence higher effective temperature T; suffocation will take place when a pulsar drifts through a (cool) dense cloud. The minimal cavity radius r_{cav}, corresponding to $u_{\max} = 2$, reads

$$r_{\mathrm{cav}} = GMm/2kT = 10^{14.9}\ \mathrm{cm}/T_3\ . \tag{4}$$

What happens when a pulsar cavity gets unstable, and collapses (under the weight of its swept-up gas)? This event, which happens just once in the life of a pulsar - when its period exceeds a critical value (of order

8 s, calculated above; an extreme case, of $P > 8.5$ s, has been found by Young et al. (1999)) - will terminate its regular pulsations, because the latter have their average lever arm of emission equal to the speed-of-light radial distance, as dictated by angular-momentum conservation (Kundt 2005). This collapse, or avalanch, from some 10^{15} cm down to some 10^{10} cm in radius, will end up in the formation of a low-mass accretion disk (of mass some $10^{-6} M_{\odot}$) - thanks to angular-momentum conservation - which cuts its way deeply into the former pulsar's magnetosphere.

Note that there should not be a lack of angular momentum for disk formation: Random velocities at the cavity radius are expected not much smaller than solar-system velocities near $r = 10^{15}$ cm, some 0.3 km s^{-1}, and amplify to 0.1 c (!) for a collapse through a factor of 10^{5} in radius, down to $r = 10^{10}$ cm, which r is much larger than the eventual disk's inner edge. And there should not be a lack of mass either, as has been detailed in my answer to Nanda Rea below. A disk of this mass suffices to power an AXP, or an SGR, whereby I have argued repeatedly (even at Vulcano) that the SGRs are not farther from us than 50 pc, hence have powers like all the (other) neutron-star sources.

The corotating magnetosphere will interact strongly with the accretion disk's sharp inner edge - as sketched in Figure 3 - be strained and released by it like a ring of relativistic slingshots, generate cosmic rays, and (relativistic) pair plasma (via magnetic reconnections), and cause both steady and unsteady accretion of inner-disk matter onto the star's surface. These processes are observed as both unpulsed and pulsed radio and X-ray emissions, in extreme cases (of big chunks) even as bursts of γ-ray emission, when the dumped matter has not had enough time to cool down from its (freefall) touch-down temperature (of $2GMm/3Rk \approx 10^{11.5}$ K) to X-ray temperatures, both by energy sharing with surface material, and by radiative cooling.

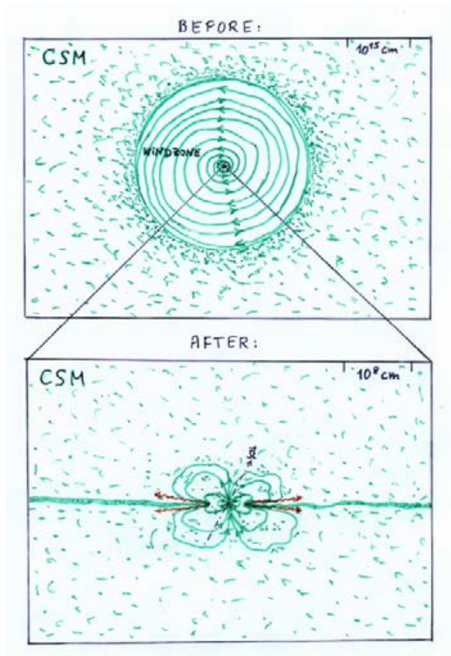

Fig. 3 Cartoon sketching a pulsar's suffocation, on two scales: Once the heavy 'atmosphere' overlying its windzone quenches it, by free-falling down under angular-momentum conservation, it forms a low-mass accretion disk cutting deeply into its corotating magnetosphere, resembling a relativistic grindstone (at its inner edge). CR and impact emissions will be preferentially in the plane of the (inner) disk.

3 THE THROTTLED PULSARS

A few more words are in place to justify our above interpretations. To begin with, the existence of pulsar-wind blown cavities is evidenced by at least 14, by now ≥ 17 mapped bowshocks at X-rays, radio frequencies, Hα, optical continuum and (further) optical lines (Kundt 1998), all of which manifest extremely strong relativistic winds, some 10^4 times Goldreich-Julian (1969, or Hones-Bergeson 1965, or Leverett Davis 1948). The fact that not all (nearby, young) pulsars have detected bowshocks (Hui & Becker 2006) may be due to a multi-component composition of the ISM, with pair plasma as the volume-filling medium.

A pulsar's ram pressure has been shown above to decrease with its period as P^{-4}, hence should reach its critical value (for keeping its cavity inflated) at a typical age of $10^{6.4}$ yr, depending on the (local) density of its CSM. Thereafter, the dying pulsars' expected (average) accretion rate from the ISM has been found unanimously to equal $10^{-17}M_{\odot}$ per year and neutron star, but the corresponding luminosity never identified, after the GRBs were re-interpreted as coming from cosmic distances (during the 90s of the past century).

The present communication maintains that exactly this population of dying pulsars, pulsars with collapsed cavities, has been detected in the form of (seeming) magnetars, or rather throttled pulsars, viz. transient accretors, whose temperatures range from hard γ-rays down to hard and soft X-rays, depending on the mode of accretion: clumpy via Rayleigh-Taylor instabilities - coarse or drizzly - or ionic onto the polar caps, or not at all. Occasionally, when their sky is transiently clear, they can even emit radio pulses. The variety of appearances of these transiently accreting sources has been found as large as could have been predicted, given their known magnetic moments, and known gravitational power of matter dropped into the deep potential well of a neutron-star's surface, and given Chandra's multiple, multi-colour X-ray maps of (yet to be explained) nebulae around young, active pulsars.

4 CONCLUSIONS

Ordinary neutron-star astrophysics is argued to be much more versatile than commonly appreciated, including transient pulsed X-ray and radio sources, cosmic-ray boosters, and even all the γ-ray bursters. No exotically strong magnetic fields are required, or present. Ordinary pulsars with 'dirty' cavities can do it.

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DISCUSSION

KEVIN HURLEY What causes the small bursts and the giant flares in your model, and why are they independent of spindown?

WOLFGANG KUNDT For the dying pulsars, accretion power dominates over spindown power: A luminosity of 10^{36}erg s^{-1} can be obtained by dropping 10^{16}g s^{-1} of matter (from the inner edge of a disk) onto the surface of a neutron star, corresponding to $10^{-10}\,M_{\odot}$ yr^{-1}. Depending on the mode of 'dropping', quasi-Keplerian, ionic onto the polar caps, or drizzly onto an equatorial belt, this dumped matter will reach respective temperatures of $\lesssim 10^{11}$ K ($\lesssim 10$ MeV/particle), 10^8 K, or 10^7 K, whereby in the latter two cases, the accretion energy is shared with an increasing amount of surface material. GRBs require a ricocheting mode of touchdown. A typical (Galactic) GRB involves 10^{36} erg, corresponding to a mass of 10^{16} g of dumped material, whose spinup angular momentum can achieve a relative spinup $\delta\Omega/\Omega$ of the dying PSR of $10^{-14.5}(\delta\Omega/\Omega)_3$, unobservably small.

NANDA REA 1) No accretion mechanism can explain the simultaneous presence of radio and X-ray pulsations (as for XTE 1810). How can you explain that with your disk-accretion model? 2) In order to explain a luminosity of 10^{36} erg s^{-1}, you need an accretion disk with an accretion rate of $\approx 1\%$ of the Eddington mass rate $\dot{M}$. Can you produce that with a disk formed by the ISM?

WOLFGANG KUNDT 1) Relativistic electron-positron plasmas can be generated in magnetic reconnections, as is already demonstrated by our Sun. In accreting neutron-star sources, abundant reconnection will happen at the inner edge of the accretion disk, which cuts deeply into the corotating magnetosphere, whilst X-rays should be emitted both from the bombarded n*'s surface, and from the inner accretion disk. There is accretion if and only if there is disk friction, hence an expected correlation between hard X-rays and radio. 2) As you say, an accretion luminosity of 10^{36} erg s^{-1} requires a dumping rate of 10^{16} g s^{-1} = $10^{-10}M_{\odot}$ yr^{-1}, corresponding to $10^{-6}M_{\odot}$ in 10^4 yr. An imploding hydrogen sphere of radius 10^{16} cm contains $10^{-6}M_{\odot}$ for an average density n of $M/(4\pi/3)r^3m$ = $10^{2.5}$ cm^{-3} typical for the core of an interstellar cloud, or more plausibly achievable by sweeping up a gas cylinder of radius 10^{15} cm, length $10^{18.8}$ cm, and $n = 10^2$ cm^{-3} (during some 10^4 yr, at a relative velocity of $10^{2.3}$ km s^{-1}).