PULSARS

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1 - A CLADIST'S* VIEW OF THE PULSAR ZOO

Viewed with the eyes of a cladist heaven is a big ZOO of stars and in fact most books on astronomy are written in the spirit of Brehm's animal life. In the eyes of an evolutionist the sky is an instantaneous picture of stellar evolution. There are the (dark) clouds from which stars form by gravitational instability. The Herzsprung-Russel diagram puts active stars into perspective. Novae, supernovae and all possible kinds of burst phenomena show that stellar life is not eternal and the very composition of our earth shows that stellar rebirths are not only a possibility but must have occurred quite frequently. The most spectacular objects in the star ZOO are the pulsars. In the broadest sense pulsars are stars that produce pulsed radiation (and not pulsating stars), with time scales ranging from μ-sec to hours.

Strange enough stars do not like to produce pulsed radiation in the optical but prefer instead the radio, Röntgen and γ-ray band. Consequently and since most stars prefer to produced pulsed radiation in only one frequency band we call these stars radio-pulsars, Röntgen-pulsars and γ-ray pulsars.

There are some 330 radio pulsars and 3 of them have been found to be in binary systems. All radio pulsars emit extremely regular pulsed radiation and careful measurements over many years have led to the conclusion that the radio pulsars are extremely good clocks with a stability $\Delta P/P \sim 10^{-11}$ over several years. While some pulsars do show irregularities in the period of this order of magnitude others have not yet revealed any timing noise ($\Delta P/P < 10^{-12}$ over 5 years) and a statistical analysis of 50 pulsars indicates that if at all noise activity is correlated with the dimensionless quantity $\dot{P}$. Apart from this unresolved timing noise some pulsars also show discrete speed-ups of order $\Delta P/P \sim 10^{-6} - 10^{-8}$. The noisiest pulsar is PSR 0611 + 21 and it also shows the second largest speed-ups. Figures 1 and 2 and Table 1 summarize some of the observations.

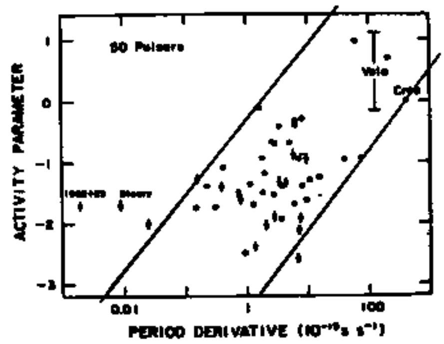

FIGURE 1 - Plot of activity parameter versus period derivative. Arrows denote upper limits.

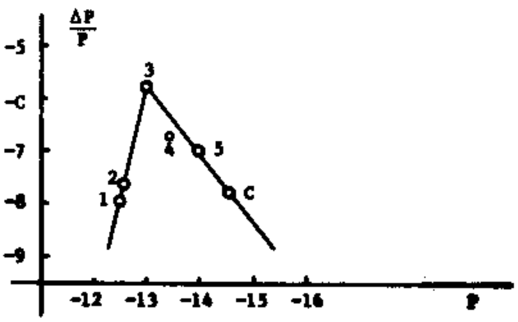

FIGURE 2 - Plot of ΔP/P versus period derivative.

(*) From to clad = to clothe. Cladism in the broadest sense is the attempt to order objects by their morphological appearence. Evolutionism tries to put the objects into a causally related perspective.

TABLE 1

CORRELATIONS OF ACTIVITY PARAMETER WITH OTHER PULSAR PARAMETERS

PARAMETER	CORRELATION COEFFICIENT
Period P	- 0.27 (-0.23)
Period derivative $\dot{P}$	0.51 (0.60)
Spindown age $P/2\dot{P}$	- 0.57 (-0.63)
Chronological age t	- 0.61 (-0.66)
Magnetic field $B_s \propto (P\dot{P})^{1/2}$	0.37 (0.43)
Galactic height z	- 0.08 (-0.14)
Z velocity v_z	0.33 (0.37)
Luminosity L	0.18 (0.20)
White noise	0 ± 0.15 (0 ± 0.18)

Radio pulsars are concentrated in the galactic plane and judged by the distance inferred from their dispersion measure they are rather local objects. Fig. 3 and Table 2 summarize some observational results. The pulsar 1929 + 10 shows a measurable annual parallax so that its distance can be determined directly.

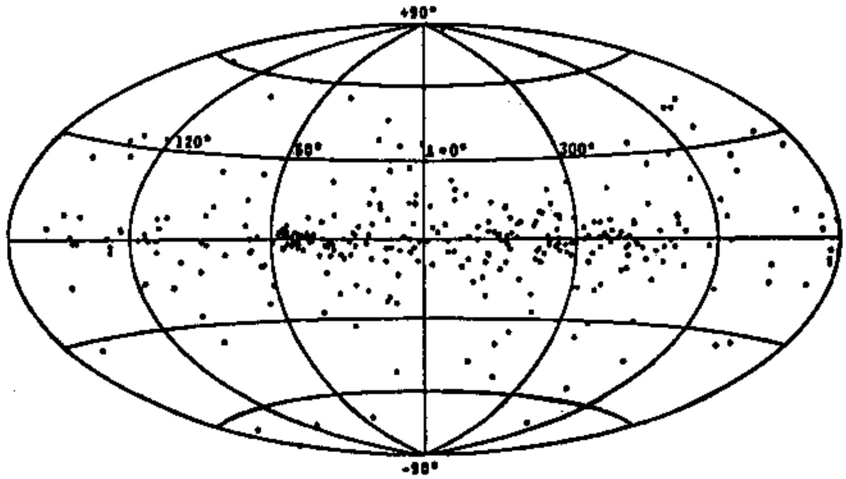

FIGURE 3 - An equal area projection of the distribution of the 330 known pulsars in galactic coordinates. The galactic centre is in the middle of the figure and longitude increases to the left.

TABLE 2

PARAMETER RANGES OF RADIO PULSARS

	P (s)	$\dot{P}$ (10^{-15})	DM $(cm^{-3}pc)$	S_{400} (mJy)	d (kpc)	z (kpc)	τ (Myr)	B_o (gauss)
PSR (min)	0531+21	1952+29	0950+08	1919+20	1929+10	0148+06	0531+21	1913+16
Minimum	0.033	0.002	2.97	1	0.08	-0.94	0.001	2.3E10
Median	0.670	2.35	79	20	2.3	0.00	4.8	1.2E12
Mean	0.842	9.52	109	67	3.3	-0.02	30	1.8E12
RMS Dispersion	0.587	32.9	100	304	3.0	0.38	199	2.3E12
Maximum	4.308	422.4	530	5000	19.3	1.33	3360	2.1E13
PSR (Max)	1845-19	0531+21	1900+06	0833-45	1302-64	1620-08	1952+29	0154+61

P Period

$\dot{P}$ Period derivative

DM Dispersion measure
S_{400} Radio flux at 400 MHz in Milli Jansky
d Distance
z Height above galactic plane
τ $P/2\dot{P}$
B_o Surface magnetic field

The pulsar slow-down resembles in many respects that of the earth, which also shows noise in the length of the day (and maybe even speed-ups).

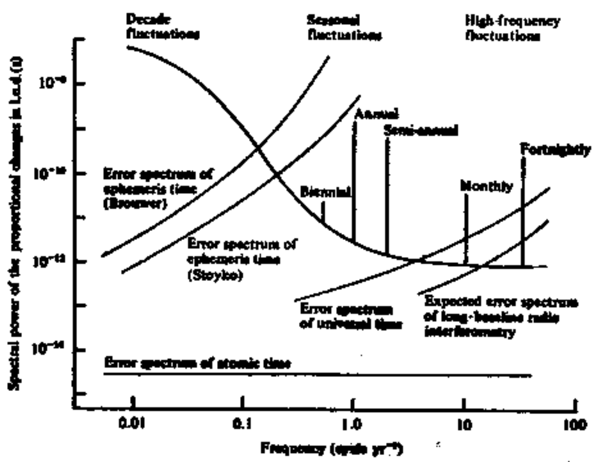

FIGURE 4 - Spectrum of l.o.d. changes based on astronomical observations taken since the early nineteenth century.

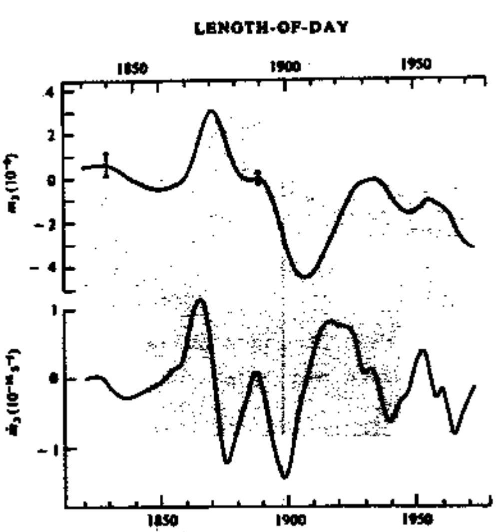

FIGURE 5 - Values of m_3 and $\dot{m}_3$ from 1820 to 1975.

If it is possible to scale pulsar parameters appropriately to earth parameters both astrophysicists and geophysicists might learn from earth other.

Let us turn next to the Röntgen pulsars. Of the 10^3 Röntgen sources discovered so far, some 10% may be related to pulsed sources in the sense of our definition. Of special interest are of course the true pulsars and the so-called bursters. While it has not been possible to extract much information about the underlying objects from single radio pulsars the Röntgen pulsars (and the binary radio pulsar) have added valuable information to our knowledge (without too much theoretical input). Nevertheless it is fair to point out before a discussion of some of the more exciting results that theoretical models are indispensable and the theory is in bad shape. In fact many theories can explain (often in a rather ad hoc manner) some of the observations but no one can explain all (or even most) of the observed facts. The predictive power is around zero. Different approaches have been followed. The first is to discover the underlying mechanism that gives rise to the pulsed emission with the ultimate hope to unveil therby the underlying object. The second is to devise a theory of the underlying object first with the hope to learn something about the radiation mechanism. Observers have moreover followed a more pragmatic approach and have collected sets of parameters which have allowed them to bring some preliminary order in the pulsar ZOO.

In this way it has been shown that many pulsars are neutron stars (some Röntgen pulsars are white dwarfs and possibly one is a black hole).

TABLE 3A

MASSIVE X-RAY BINARIES

a - Examples of persistent strong sources					
SOURCE	TYPE	P_{orb}(d)	P_{pulse}	$m \sin^3 i$	e
SMC X-1	BOI	3.9	$0^s.71$	0.8 + 12.5	0.00
0900-40	BO-5Ib	9.0	283^s	1.4 + 21.3	0.09
Cen X-3	06.5II-III	2.1	$4^s.84$	1.4 + 17.2	0.00
1233-62	B1.5Iab	35.0	698^s	1.4 + 31	0.44
Cyg X-1	09.7Iab	5.6	--	1.5 + 2.4	0.00
b - Examples of weaker or transient pulsating sources					
SOURCE	TYPE	P_{orb}(d)	P_{pulse}	$m \sin i$	e
0115+634	BO	24.3	$3^s.6$	--	0.34
0352+309 (X Per)	09.5III-Ve	581(?)	853^s	--	?
0535+262	BOE	>17	104^s	--	?
1118+615	BOe	--	405^s	--	?
1145-619	B1Vne	--	297^s or 292^s	--	?
1728-247 (GX1+4)	M6III + + hot star	--	138^s → 116^s	--	?

TABLE 3B

LOW-MASS X-RAY BINARIES

SOURCE	Sp. TYPE	P_{orb}	P_{pulse}	M_{opt}	M_x	z
Her X-1	A-F	$1^d.70$	$1^s.2$	2.2	1.3	3 kpc
Sco X-1	Accr. disk	$0^d.787$	---	<1	---	400 pc
1627-673	Accr. disk	41 min	$7^s.7$	0.05	∿1.4(?)	---
2129+47	G-dwarf(?)	$5^h.2$	---	1(?)	---	---
Cyg X-2	F-giant	$9^h.843$	---	0.5-1.1	1.3-1.8	1.5kpc

TABLE 3C

BINARY RADIO PULSARS

NAME	P_{pulse}	P_{orb}	e
PSR 0656+64	$0^s.196$	24^h41^m	0.00
PSR 0820+02	$0^s.865$	3.1 yr	0.00
PSR 1913+16	$0^s.059$	7^h45^m	0.62

By now rather redundant data show that a typical pulsar mass is just about the Chandrasekhar mass $M = 1.4\ M_\odot$. The radius of a neutron star (as inferred from the bursters) is some 10^6 cm as predicted by theory and the moment of inertia $I \sim MR^2$ is around 10^{45} g cm^2 as it must. The surface magnetic field strength is some 10^{12} Gauss as inferred from the Cyclotron observations and the magnetic moment $\vec{M}$ is some 10^{30} Gauss cm^3 as inferred from pulsar slow-down or Röntgen pulsar speed-up in agreement again with the expectation since $M = BR^3$.

At least one subgroup of the Röutgen pulsars is distributed more isotropically about the center of the Galaxy implying that there are some Methusalems among the Röntgen pulsars, which among other things implies that the magnetic field of neutron stars does not decay or can be regenerated (see below).

The γ-ray sources are as yet mysterious objects and there is much to be learned from them in the future.

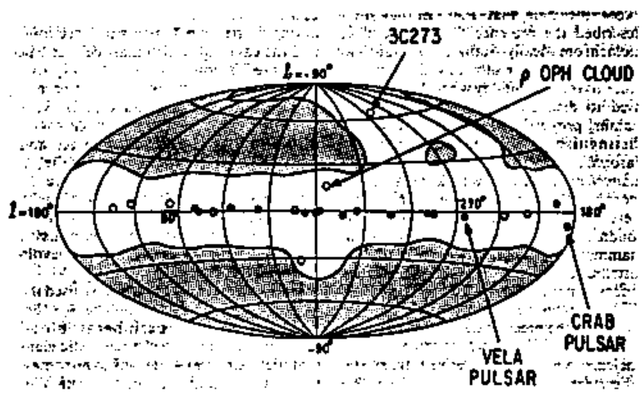

FIGURE 6 - γ-ray sources: a catalogue of unidentified objects. The second COS B catalogue of high-energy gamma-ray sources, shown in galactic coordinates. Observations covered the unshaded region. Filled circles denote sources with measured fluxes $\geq 1.3 \times 10^{-6}$ photons (> 100 MeV) $cm^{-2}\ s^{-1}$, while open circles denote sources below this threshold (from Swanenburg et al., 1981).

In contradistinction to the radio pulsars the γ-ray and Röntgen pulsars are seen all through the Galaxy and their number density peaks at the galactic center.

In the pulsar ZOO there are of course exotic animals and it may be interesting to present some in more detail although it is not clear that they will reveal ultimately more about the nature of pulsars than the bulk of the less spectacular ones.

Top rank has still the Crab nebula pulsar. It served to identify pulsars with rotating neutron stars and to "explain" the energy source and morphology of the supernova remnant to which it is related. It shows pulsed radiation all over the electromagnetic spectrum from the lowest detectable radio frequency up to maybe 10^{12} eV γ-rays!

Competing objects for rank first are SS433 and the binary pulsar. SS433 can be viewed as a scaled-down version of a quasar and is probably also related to a supernova remnant (W50)but no neutron star has yet been discovered at its site. The binary pulsar PSR 1913+16 may enable the (indirect) detection of quadrupole gravitational radiation and thereby test Einstein's formula. It is furthermore the ideal test laboratory for relativistic effects and may soon become the classic textbook example for the latter. Unfortunately PSR 1913+16 is very far away and therefore very weak and can only be studied with the biggest radio telescopes of the world.

Among the Röntgen pulsars (see Table 3) two are of special interest: Her X-1 and Cyg X-1. Her X-1 is probably a system older than 10^8 years and yet shows pulsed radiation and a Cyclotron line corresponding to a magnetic field of $10^{12.6}$ Gauss. Cyg X-1 may be the only good candidate for a black hole.

Among the γ-ray sources one was especially spectacular. In May 1979 a γ-ray source turned on with a period of 8 sec. The rise-time of the first pulse was unresolved but shorter than 1 m sec! This short rise-time is the strongest argument in favour of the hypothesis that such bursts are due to the impact of an asteroid or comet onto a neutron star. For a typical burst energy of 10^{39} erg some 10^{20} g of fuel for each burst are needed. The recurrence rate for the γ-ray bursters is estimated to be one per year and this high rate may present some difficulty for this model at least if one assumes that the asteroids are interstellar. So far no celestial object has been positively identified with an γ-ray burster at other than γ-ray energies.

This ends the cladist's walk through the pulsar ZOO. In the next sections we try to establish pulsar Darwinism and seek (mainly for observational) evidence of pulsar evolution. Clearly some pieces of theory are needed and these are provided in essay form in the next two sections. Each section (including the present one) is self-contained and can be read independently of the others.

2 - THE SLOW-DOWN EPOCHS OF RADIO PULSARS

The relative importance of magnetospheric currents and low frequency waves for pulsar braking is assessed and a model is developed which tries to account for the available pulsar timing data under the unifying aspect that all pulsars have equal masses and magnetic moments and are born as rapid rotators. Four epochs of slow-down are distinguished which are dominated by different braking mechanisms. According to the model no direct relationship exists between "slow-down age" and true age of a pulsar and it leads to a pulsar birth-rate of one event per hundred years.

Based on theoretical arguments about the progenitors of pulsars there exists the possibility that all neutron stars have essentially the same mass (Pines, 1980; Kundt, 1977) M and the same magnetic moment (Ruderman and Sutherland, 1973; Levy and Rose, 1974) $\vec{M}$. The best direct determinations (Taylor et al., 1979; Trümper et al., 1978) support this view and give $M \simeq 10^{33,5}$ g(the Chandrasekhar mass) and $\vec{M} \simeq 10^{30,5}$ Gauss cm^3 and theoretically inferred values for accreting binary systems (Ghosh and Lamb, 1979; Pines, 1980) show a surprisingly small scatter. Can this apparent uniformity for the binary pulsars be reconciled with the timing data for (single) radio pulsars, of which many may also have been binaries for some time?

After the identification of radio pulsars with rotating, magnetized neutron stars (Gold,1968) and the proof that they must be surrounded by a magnetosphere (Goldreich and Julian, 1969;Mestel, 1980) independent of the work function of the neutron stars surface (Sturrock, 1971; Ruderman, 1980) progress in understanding the long-scale aspects of the magnetosphere, which determines the braking of the neutron star's rotation, has been slow (Meste, 1980). The theoretical analysis of pulsar braking is hanpered by two facts: no self-consistent solution for a pulsar magnetosphere has been found and the pulsar timing data seem to reveal more about the neutron star's interior than about its magnetosphere. The profuse wealth of radio observations can at best be used as a diagnostic (Meste, 1980) for the slow-down process. There is nevertheless no lack of theoretical models trying to explain the observational data and in most theories it is assumed that the neutron star is slowed-down by the combined action of a plasma-current-torque and a vacuum-wave-torque. This leads to the well-known result that there is a deficiency in "old" pulsars (as measured by their "slow-down age" $P/\dot{P}$) and the inferred magnetic moments vary by two orders of magnitude. Worse still is the derived pulsar birth rate (Kundt, 1977) of one event per ten years if the half-life of a pulsar is 10^6 years as follows from the standard slow-down theory. These facts are the main excuse to present a new model for pulsar slow-down and it seems appropriate to list the assumptions on which the model is based: (1) "young" pulsars produce so much plasma by means of "sparking" (Sturrock, 1971; Ruderman, 1980) that within the plasma no low-frequency wave can propagate (Asseo, et al., in press; Ozernoy and Usov, 1973). (2) as pulsars "grow older" sparking becomes less effective so that eventually low-frequency waves can be emitted within the plasma. (3)out to the velocity-of-light-cy.inder (i.e., that part of the magnetosphere which, were it to corotate rigidly, would rotate at the speed of light) the Goldreich-Julian (Goldreich and Julian, 1971) model as extended to the oblique rotator by Mestel (Mestel, 1971) describes the long-term aspects of the magnetosphere. Minor modifications such as a current-regulating net charge and discharges due to radiation friction will be worked later into the model. (4) Considerable perpendicularity between magnetic moment and the spin of the neutron star occurs during the first epoch, where the torque is dominated by currents in the plasma. The present mod-1 accounts for this perpendicularity if the star can be treated as a sphere so that free nutation is not possible (Goldreich, 1970; Flowers and Ruderman, 1977). However any other (internal) mechanism which leads to considerable perpendicularity will lead to the same consequences (cf. ref. 18 and the further references quoted therein). The Goldreich-Julian model of the pulsar magnetosphere predicts an excess charge-density in the magnetosphere,

$$q \simeq - \frac{\vec{\Omega}.\vec{B}}{2\pi c} \tag{1}$$

and an average currente

$$\vec{j} \simeq qc\vec{b}_0 \tag{2}$$

along the open field lines which leave away from the surface area ΔF centered on the magnetic poles ("polar caps"). Here $\vec{\Omega}$ is the spin angular velocity, $\vec{B}$ the magnetic field, c the velocity of light and $\vec{b}_0$ a unit vector in the direction of $\vec{B}$. For the star not to charge up indefinitely there must be a back-current which flows along magnetic field lines further away from the centre of the polar cap. It will be regulated by a net charge as discussed below. To close the current charges must flow within the neutron star across the magnetic field lines and it is this current which breaks the neutron star's rotation. In the Goldreich-Julian model it is assumed that energy and angular momentum are dissipated beyond the velocity-of-light-cylinder. Within the velocity-of-light-cylinder the charges move along the magnetic field lines like beads on a wire and by their current provide thus a "magnetic spring" between the neutron star's surface and the matter beyond the velocity-of-light-cylinder. Its torque $\vec{T}$ is given by

$$\vec{T} = - \frac{1}{4\pi r} \int (\vec{r} \cdot \vec{B})\ \vec{r} \times \vec{B} dF \tag{3}$$

where $\vec{r}$ is the radius vector counted from the centre of the star and the integral is over a sphere of radius r. The current of eq. (2) leads to a counteraligment torque (Flowers and Ruderman, 1977) between $\vec{\Omega}$ and $\vec{M}$, in contradistinction to the torque exerted by low-frequency waves propagating in vacuo, which (if not impeded by nutation (Goldreich, 1970)) leads to aligment (Davis and Goldstein, 1970; Michel and Goldwire, 1970). The counteraligment torque is easily understood if one notes that a current flowing through a magnetized sphere will set the sphere into rotation about magnetic dipole axis $\vec{M}$ and the current of eq. (2) is so direct (Lenz'rule) that is reduces the rotation about the original axis. Both in the plasma and in the vacuum case the star acts such as to minimise the applied torque and stores some rotational energy into rotation about a new rotation axis. In the dipole approximation the polar cap surface area ΔF is given by (Goldreich and Julian, 1969; Sturrock, 1971) $\Delta F \simeq 2\pi R^2$ $(\Omega R/c)$where $R \simeq 10^6$ cm is the radius of the star and in a coordinate system centered on the magnetic dipole-axis we find for the toroidal component of the magnetic field

$$B_\phi \simeq - \frac{\vec{\Omega}\vec{B}}{2\pi c} \int \frac{dF}{R \sin \theta} \tag{4}$$

which leads by means of eq. (3) to

$$\vec{T}_{p\ell} = - \alpha \frac{\Omega^2}{c^3} (\vec{\Omega} \cdot \vec{M})\ \vec{M} \tag{5}$$

where $\vec{M} = R^3\vec{B}$ is the magnetic dipole moment and $\alpha \simeq 1$. From the corotating part of the magnetosphere we obtain an induced magnetic field parallel to the rotation axis which leads to an extra torque (by means of the magnetic dipole moment $\vec{M}$) on the star

$$\vec{T}'_{p\ell} = \frac{\gamma}{Rc^2} (\vec{\Omega} \cdot \vec{M})\vec{\Omega} \times \vec{M} \tag{6}$$

where $\gamma \simeq i$. Eq. (5) and (6) may be compared to the vacuum wave torque (Goldreich, 1970; Davis and Goldstein, 1970; Michel and Goldwire, 1970)

$$\vec{T}_w = - \beta \frac{\Omega^2}{c^3} (\vec{M} \times \vec{\Omega}) \times \vec{M} + \frac{1}{Rc^2} (\vec{M} \cdot \vec{\Omega})\ \vec{\Omega} \times \vec{M} \tag{7}$$

with $\beta = 2/3$. It has been common to assume that both plasma and low-frequency waves will (somehow) contribute (more or less equally) to the slow-down torque, which leads to the well-known large scatter in inferred magnetic dipole moments. This assumption will be shown now to be quite wrong. If low-frequency waves cannot propagate within the plasma they cannot exist outside either. Apart from a transition period where the plasma may just allow for low frequency wave propagation (the duration of which is difficult to estimate as it depends on the sparking mechanism) a pulsar is slowed-down exclusively by either the plasma-current-torque eq. (5) or the vacuum-torque eq. (7).

The most favourable conditions for low-frequency wave-emission obtain for the orthogonal rotator and we assume that the plasma which flows out of the velocity of light cylinder fills the space about the equatorial plane, consequently the waves are emitted into a plasma dead-zone centered on the rotations axis. Let us assume that the two zones are separated by a cone of half-angle Ψ (counted from the rotation axis) and as first approximation (Ozernoy and Usov, 1973) that the plasma is infinitely well conducting. This problem can be solved exactly. The solution of the vector-Helmholtz-equation may be taken from Morse and Feshbach (1953). One finds that the TEM-mode dominates and the dominant radiation mode is given by the lowest n for which

$$\frac{n+1}{n} P^1_{n-1} (\cos\Psi) - \frac{n}{n+1} P^1_{n+1} (\cos\Psi) = 0 \tag{8}$$

$$P^1_n (\cos\Psi) = \frac{n(n+1)}{2} \sin\Psi \, F\left(1-n,\, 2+n \,|2|\, \frac{1-\cos\Psi}{2}\right) \tag{9}$$

F in eq. (9) is the hypergeometric function which for noninteger n is regular in the upper hemisphere where eqs. (8) and (9) hold. If we let the conducting cone shrink to the equatorial plane one obtains the well-known Deutsch solution (Deutsch, 1955) with $n = 1$. For a thin plasma sheet ($\Psi = \pi/2 - \varepsilon$) one finds approximately

$$12 = (1-\cos\Psi)(n^2 (n+2)(n+3) - (1-n^2)(1+n)(2-n)) \tag{10}$$

which shows that n is larger than one. The radiated energy rate is

$$\dot{E} \simeq - \frac{2}{3cR^2} (\vec{M} \times \vec{\Omega})^2 \left(\frac{\Omega R}{c}\right)^{2n} \tag{11}$$

For a finite thickness of the plasma sheet the emission of low-frequency waves is so strongly reduced ($n = 2$ for $\Psi = \pi/4$) that the wave pressure cannot balance the plasma pressure at the boundary and the plasma fills the whole space. As an aside we note however that if the plasma is asymmetrically distributed in the two hemispheres, such that one cone has $\Psi > \pi/2$ (plasma swept back ward e.g. by the pulsar's proper motion? (Tademary and Harrison, 1975)) radiation emission is enhanced and such a state may be called superradiant. A young pulsar will therefore be slowed-down exclusively by the plasma current, an old one by the wave-torque and in the transition epoch we may have

$$\dot{\vec{J}} = I\dot{\vec{\Omega}} = (\beta - \alpha)\frac{\Omega^2}{c^3} (\vec{M}\,\vec{\Omega})\,\vec{M} - \beta \frac{\Omega^2}{c^3} M^2 \vec{\Omega} + \gamma \frac{\vec{\Omega}.\vec{M}}{Rc^2} \vec{\Omega} \times \vec{M} \tag{12}$$

where $\vec{J}$ is the angular momentum and I the moment of inertia of the neutron star, $I \simeq 10^{45}\,\mathrm{gcm}^2$. Together with the "equation of motion" for the dipole moment $\vec{M}$, which is frozen into the star

$$\dot{\vec{M}} = \vec{\Omega} \times \vec{M} \tag{13}$$

one obtains easily the evolution of the slow-down. With the help of the first integral

$$\frac{(\Omega^2 \sin^2\chi)^\alpha}{(\Omega^2 \cos^2\chi)^\beta} = \text{const} \tag{14}$$

where χ is the angle between $\vec{\Omega}$ and $\vec{M}$ we obtain for young pulsars, for which $\beta = 0$,

$$\sin \chi = \sin \chi_i \left(\frac{\Omega i}{\Omega}\right) \tag{15}$$

$$\Omega = \Omega_i \left(1 + \text{ctg}^2 \chi_i \left(1 - e^{-\tau}\right)\right)^{1/2} \tag{16}$$

which reads for small times

$$\Omega = \Omega_i \left(1 - \frac{\tau}{2} \text{ctg}^2 \chi_i + \frac{\tau^2}{8} \left(2 \text{ ctg}^2 \chi_i + 3 \text{ ctg}^4 \chi_i\right)\right) \tag{17}$$

where $\tau = 2\alpha\Omega_i^2 \sin^2 \chi_i M^2/Ic^3$ $\tau = t/\tau_e$ is a dimensionless parameter which measures the observer's time t in units of the e-folding time τ_e of the model. The index i refers to initial values. Before we turn to a discussion of eq. (16), which (apart from the demonstration that plasma and vacuum waves cannot coexist) is our main result, let us discuss briefly one further important parameter for pulsar timing observations. The so called braking index $N = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$ is given in our model by

$$N = 3 + 2 \frac{(\beta - \alpha)^2 \cos^2 \chi \sin^2 \chi}{(\alpha \cos^2 \chi + \beta \sin^2 \chi)^2} \tag{18}$$

and is never smaller than three due to torque minimisation. Observationally N is known only reliably for the Crab pulsar (Groth, 1975; Cordes, 1980) where $N \simeq 2{,}5$. Rewriting the energy balance equation in the form

$$\frac{1}{2} (I\Omega^2)^{\cdot} = - \frac{\alpha}{cR^2} (\vec{\Omega} \vec{M}) \left(\frac{\Delta F}{F}\right)^2 \tag{19}$$

where $F = 4\pi R^2$ is the surface area of the neutron star, we see that a braking index smaller than three may be explained if the pulsar's crust is shrinking (Smoluchowski, 1970; Smoluchowski and Welch, 1970; Cordes and Greenstein, 1980) at a rather large rate, or by a slightly larger polar cap $\Delta F/F = (\Omega R/c)^{2/3}$. In fact in some theories (Ter Haar, 1972) the pulse width ΔP and the period P are related as $(\Delta P/P)^2 = \Delta F/F)$ and the observations of the Crab pulsar, where $\Delta P/P \sim 1/5$ is rather large (Ter Haar, 1972), would fit better with $\Delta F/F \approx (\Omega R/c)^{2/3}$ leading to a braking index $N = 3 - 2/3 + 2 \text{ tg}^2 \chi$. In the next section we shall show that a non axisymmetric current flow can also lead to enhanced braking.

Let us show now that the model is flexible enough to account for the available timing data under the severe restriction that all pulsars have the same moment of inertia $I = 40^{45}$ gcm^2 and the same magnetic moment $M = 10^{30,5}$ Gauss cm^3. To obtain t_e from the observations we identify those pulsars with anomalously low period derivative with the stars in our model which pass through the end of the first epoch. We have from the observations $\Omega \simeq 2\pi \text{sec}^{-1}$ which gives $\Omega_i \cdot \sin \chi_i = 2\pi$ sec^{-1} so that

$$t_e \simeq 10^6 \text{ years } I_{45} M_{30,5} \tag{20}$$

Observationally the two most extreme cases are the Crab pulsar and the binary pulsar. Eq.(20) would lead for them to $\sin \chi_i = 10^{-1,5}$ and $\cos \chi_i = 10^{-1,5}$ respectively if we assume that both are young objects. To explain the binary pulsar in this way one needs a nearly orthogonal rotator and one may worry if eq. (12) is still valid for this case. It requires $\beta < 10^{-4}$ and $\cos^2 \chi < 10^{-3}$. For the binary pulsar $(\Omega R/c)^2 < 10^{-5}$, which according to the previous analysis guarantees that $\beta < 10^{-4}$ and inspection of the current as given by eq. (2)shows that it can be closed along the magnetic field lines through the star so that it does not lead to a torque. The braking is then no longer effeted by the current of eq. (2) but comes about through secondary energy losses such as sparking. Taking Ruderman's estimate (Ruderman, 1980) of that energy for the (faster) Crab pulsar of $10^{33} - 10^{34}$ ergs sec^{-1} we see that this would just lead to the observed braking of the binary pulsar. The first epoch, wich lasts some 10^6

years accounts for roughly one half of the pulsars under the assumption that all are born as fast rotators. The other half can be explained in the penultimate epoch of pulsar slow-down, where vacuum waves can be emitted in the presence of plasma so that the period derivative goes back to its "normal" value.

Note that in the present model the "slow-down age" is not related to the true age, only the period itself is a crude measure of it. The mean active life as determined by Ohmic dispation can exceed easily 10^7 years (Flowers and Ruderman, 1977), which brings down the pulsar birth rate by a factor of ten, in comfortable agreement with the more conservative estimates of super-nova rates and the lack of discovered neutron stars at their centers (Helfand,1980).

Before we discuss the final epoch let us discuss some subtle points of the present model. We have so far only assumed that the current of eq. (2) flows on the average without demonstrating how it comes about. Of course a rigourous demonstration requires a self-consistent solution of the magnetosphere problem, so only the following qualitative argument can be given. According to the Goldreich-Julian model particles cannot stay within the velocity of light cylinder for the same reason that they cannot stay within the star: large electric fields would pull them out. The effect is such that the charge with the correct sign as given by eq. (1) will be pulled out, charges with the opposite sign however are pulled in on the same field line. This shows that a pulsar must have a net charge (Jackson, 1976) Q to regulate the plasma out-flow such that the star does not charge up indefinitely. Some of the charge will be distributed over the polar cap ΔF and most of it over the boundary of the corotating magnetosphere and as it must be able to influence the dynamics of the plasma at the velocity-of-light cylinder it must be of the order of

$$Q \simeq \frac{\vec{\Omega}.\vec{M}}{c} \tag{21}$$

Such a charge reintroduces what the Goldreich-Julian model tried to avoid: large electric fields, so that we have essentially shifted the whole problem from the surface of the neutron star to its velocity-of-light-cylinder, sufficiently far away however that the star does not get heated too much (Pines, 1980; Helfand, 1980). Note that the net charge as given by eq.(21) will not give rise to a back-current from the interstellar matter to the pulsar during its "active life" as the pulsar is well shielded by the el.mag.fields of the magnetosphere or the vacuum waves which both fall off like r^{-1} whereas the monopole field falls off like r^{-2} so that the force balance is in fact at the velocity of light cylinder. In the penultimate slow-down era, which is dominated by low-frequency waves this charge and the corotating (quadrupole) charge of the magnetosphere will also radiate and this leads to a friction force on the magnetic field lines with non-vanishing curl. To compensate for this, the particles must drift across magnetic field lines giving rise to a net current out of the corotation zone. For the quadrupole radiation from the corotating magnetosphere we get for the time-scale of the ensuing discharges some 10^6 pulsar periods and a much shorter time scale for the dipole radiation due to the charge given by eq. (21). These discharges may be related to the nulling phenomenon and may give rise to slow-down noise (Cordes, 1980; Cordes and Greenstein, 1980) but not to any directly observable speed-ups as the inertia involved is too small. The present model does not explain why pulsars turn off unless sparking ceases to be regular enough to allow an observer to detect the object as a pulsar, but it appears that even accretion may influence the final era (Wright, 1979) especially if the pulsar has become an aligned rotator by then. An attractive explanation is obtained if one combines the pulsar extinction hypothesis (Michel, 1975; Hill, 1980) with the decay of the magnetic dipole moment (Flowers and Ruderman, 1977) which regulates the physics at the velocity-of-light-cylinder. The observed cut-off period $P \simeq 4$ sec would then not be mainly a consequence of plasma inertia bur rather reflect the time-scale for Ohmic dissipation in the pulsar's crust which may vary considerably from pulsar to pulsar depending on its thermal history at birth. According to the present model such neutron stars will slow-down in the final era by quadrupole radiation (or plasma currents) on a time scale exceeding the age of the universe and only if they traverse dense interstellar matter may they be slowed-down more effectively by accretion (Wright,1979). The γ-ray transient (Terrell, et al., 1980)with a period of 8 sec could in fact be such an old pulsar, whereas the γ-ray source CG 195,5 + 4,5, if its periodicity of 59.35 sec should be confirmed (Özel, et al., 1980), should rather not be identified with an old pulsar according to the present model, which predicts ultimate periods around 10 seconds for dead pulsars, instead of 60 sec as deduced by Michel (1975) under the assumption that the dipole field does not decay.

REFERENCES

01 - Pines, D., Science, 207, 597 (1980); J.de Physique C.2, 111 (1980).
02 - Kundt, W., Naturwiss., 64, 493 (1977).
03 - Ruderman, M.A., Sutherland, P.A., Nature Phys. Sci., 264, 93 (1973).
04 - Levy, E.H., Rose, W.K., Nature, 250, 40 (1974).
05 - Taylor, J.H., Fowler, L.A., Mc Culloch, P.A., Nature, 277, 437 (1979).
06 - Trümper, J., Pietsch, W., Repping C., Voges, W., Straubert, R., Kendizorra, E., Astrophys. J., 219, L 105 (1978).
07 - Ghosh, P., Lamb, F.K., Astrophys. J., 234, 296 (1979).
08 - Gold, T., Nature 218, 731 (1968), Pacini, F. Nature, 219, 145 (1968).
09 - Goldreich, P., Julian W.H., Astrophys. J., 157, 869 (1969).
10 - Mestel, L., Nature Phys. Sci., 233, 149 (1971).
11 - Sturrock, P., Nature, 227, 465 (1970), Astrophys. J., 164, 529 (1971).
12 - Ruderman, M.A., Proc.IAU Symp. nº 95 "Pulsars", 87-98 (1980).
13 - Mestel, L., Proc.IAU Symp. nº 95, 9-24 (1980).
14 - Baym, G., Pethick, Ch., Ann.Rev.Astron.Astrophys., 17, 415 (1979).
15 - Asseo, E., Llobet X., Schmidt, G., Phys. Rev.D, in press.
16 - Ozernoy, L.M., Usov, V.V., Astrophysical Letters, 13, 151 (1973).
17 - Goldreich, P., Astrophys. J., 170, L 11 (1970).
18 - Flowers, E., Ruderman, M.A., Astrophys.J., 215, 302 (1977).
19 - Davis, L., Goldstein, M., Astrophys. J., 159, L 81 (1970).
20 - Michel, F.C., Goldwire, H.C., Astrophysical Letters, 5, 21 (1970).
21 - Smoluchowski, R., Phys.Rev.Lett., 24, 923 (1970).
22 - Smoluchowski, R., Welch, D.O., Phys.Rev.Lett., 24, 1191 (1970).
23 - Morse, Ph.M.M., Feshbach, H., Methods of Theoretical Physics II, p. 1864, Mc Graw Hill 1953, N.Y., London.
24 - Deutsch, A., Annales d'Astrophysique 18, 1 (1955).
25 - Tademaru, E., Harrison, E.R., Nature, 254, 677 (1975).
26 - Groth, E.J., Astrophys. J.Sppl., 29, 453 (1975).
27 - Cordes, J.M., Astrophs. J., 237, 216 (1980).
28 - Cordes, J.M., Greenstein, G., Astrophys. J., 239, 640 (1980).
29 - Ter Haar, D., Physics Rep. 3C, 59 (1972).
30 - Jackson, E.A., Astrophys. J., 206, 831 (1976).
31 - Wright, G.A.E., Nature, 280, 40 (1979).
32 - Michel, F.C., Astrophys. J., 195, L 69 (1975).
33 - Hill, T.W., Astrophys. Letters, 21, 11 (1980).
34 - Terrell, J., Evans, W.D., Klebesadel, R.W., Laros, J.G., Nature, 285, 383 (1980).
35 - Özel, M.E., Dickel, J.R., Webber, J.C., Nature, 285, 645 (1980).
36 - Helfand, D.J., Nature, 285, 133 (1980)
ibid, 283, 337 (1980).

3 - THE ANOMALOUS BRAKING INDEX OF THE CRAB PULSAR: A PLASMA INERTIAL EFFECT

It is shown that a braking index $n = \ddot{\Omega}\Omega/\dot{\Omega}^2$ as low as $n = 2.5$ can be explained in the canonical (geometrical) pulsar slow-down model if plasma inertia is taken into account. Older pulsars where plasma effects are less important should have $n \geq 3$.

A long-standing, unresolved problem for the canonical pulsar slow-down theory (Goldreich and Julian, 1969; Mestel, 1981) has always been to account quantitatively for a braking index n as low as 2.5 as it is observed for the Crab pulsar. Apart from what one may call "models of despair" (Sturrock, 1971; Michel and Dessler, 1981) no plausible explanation has been offered. In fact, as stressed by Radakrishnan (1981), there seems to be a large gap between pulsar theories and pulsar observations. The reason for this is simple: most data gathered by the observers have no apparent bearing on the overall dynamics of the magnetosphere. After some 12 years of extensive timing measurements it has become apparent that those pulsars which slow down fast enough that a second derivative of the rotational frequency Ω should have become measurable by now are much too noisy (and conversely, the noise-free pulsars do not slow down fast enough to show a measurable second derivative within 13 years). Thus in the decades to come we will learn a great deal about pulsar slow-down noise, a situation familar to the geophysicist from the slowing down of the earth (Lambeck, 1980). Without slow-down noise the third derivative of the Crab pulsar and the second derivative of the Vela pulsar could have already yielded valuable information about the dynamics of the pulsar magnetosphere. In such a (for the theoretician) frustrating situation one must be thankful that data of the Vela pulsar have finally become available in published form (Downs, 1981), which lend support to the idea that the Crab is an exception rather than the norm with its (Groth, 1975) $n = 2.5$. Downs tentatively concludes that for the Vela pulsar $n \geq 3$, which is what standard theory predicts. It is then tempting to speculate that the low braking index of the Crab pulsar is related to its youth, i.e. to a plasma effect for young pulsars. Here we wish to report preliminary results of an admittedly crude pulsar model which is capable of explaining these facts in a natural (though phenomenological) way.

The model we adopt for pulsar slowdown is the standard magnetosphere model as worked out by Goldreich and Julian (G.J.) and by Mestel and his group (Meste, 1981; 1980) modified in two essential points: a current-regulating net charge $Q \simeq \vec{\Omega}\vec{M}/c$ ($\vec{M}$: magnetic moment of the neutron star) is included (Heintzmann, 1981) and the return current is allowed for to flow asymmetrically about the outgoing current. We will now show that such a "bipolar" current exerts a much larger torque on the neutron star since the torque does not vanish outside the polar cap (as does the torque of a "monopolar", i.e. symmetric, current).

We start from the G.J. current j_{GJ}

$$\vec{j}_{GJ} = q_{GJ}\, c\vec{B}_o \qquad\qquad q_{GJ} = -\frac{\vec{\Omega}\vec{B}}{2\pi c} \tag{1}$$

Here $\vec{B}_o$ is a unit vector in the direction of the magnetic field $\vec{B}$, q_{GJ} is the G.J. charge density which is necessary to short out the parallel component of the electric field and c is the velocity of light. This current is supposed to flow along the "open field lines" which leave the "polar caps" of area $F = \pi R^2\ (\Omega R/c)$, where R is the radius of the neutron star. The net total current J per cap is therefore

$$J = Q = q_{GJ}\, cF = -\frac{\vec{\Omega}\vec{B}}{2\pi c}\; c\; \left(\frac{\Omega R}{c}\right)\; \pi\; R^2 \tag{2}$$

Clearly this current transports a net charge away from the pulsar and it must therefore be compensated for by a back current of equal magnitude in order not to charge up the pulsar indefinitely. In Heintzmann (1981) and Jackson (1976) it is shown that the order of magnitude of the net charge (including its sign) must be

$$Q_{net} \simeq \frac{\vec{\Omega}\vec{M}}{c} \tag{3}$$

The introduction of a net charge changes the physics of the magnetosphere in an essential way: it is no longer force-free, even not on the average! A parenthetical remark: while it is not clear in detail how such a net charge will be distributed within the light cylinder of the magnetosphere, it is clear that a considerable portion of it must sit right on the polar cap to give rise to a closed (algebraic) current. As a consequence it is no longer clear from symmetry considerations how the total current will flow. As we will now show, this uncertainty introduces a new free parameter into the physics of pulsar slow-down. In principle one can calculate the slowdown torque exerted on the neutron star everywhere: at the surface of the star, at the velocity of light cylinder, or at infinity. As no angular momentum is stored anywhere within the magnetosphere in the canonical model (see, however, the "despair models"), Maxwell's equations permit the evaluation of the torque by means of both

$$\vec{T} = \frac{1}{c}\int \vec{r}\times(\vec{j}\times\vec{B})\, dV = \frac{1}{4\pi r}\int (\vec{r}\vec{B})\ \vec{r}\times\vec{B}\, dF \tag{4}$$

where $\vec{r}$ is the radius vector centered in the neutron star.

A second parenthetical remark: pulsars slowed down by vacuum waves differ fundamentally in this respect from pulsars braked by a plasma current. In the first case it is the coherent radiation reaction which acts on the current carrying charges in the neutron star (which could even be an insulator!); in the second case the neutron star is braked by a (surface) current which is determined from the G.J. current eq. (1) by means of div $\vec{j} = 0$ and which therefore flows across the magnetic field. In the first case angular momentum is transported by a vacuum wave right from the surface to infinity; in the second case the current provides only the magnetic spring between surface and velocity of light cylinder where angular momentum is imparted to the plasma wind (with frozen-in electromagnetic fields (Goldreich,1969).

In a frame having its polar axis aligned with the magnetic pole a "monopolar" current will flow symmetrically about the pole so that

$$j = j_\theta = \frac{\dot{Q}}{2\pi R} \frac{1}{\sin\theta} \delta(r - R) \tag{5}$$

whereas a "bipolar" current in its most extreme case will be of the form

$$j = j_\theta = \frac{\dot{Q}}{R} \frac{1}{\sin\theta} \delta(r - R)\, \delta(\Phi - \phi) \tag{6}$$

i.e. the surface current flow exclusively along the latitude ϕ across the polar cap. Integrating eq. (4) with the current given by eq. (5) we find in coordinates centered on the magnetic pole and where the z-axis coincides with $\vec{b}_o$

$$T_x = T_y = 0 \qquad\qquad T_z = -\frac{\vec{\Omega}\vec{B}}{4c^2} BR^5\, \Omega \sin^2\theta_c \tag{7}$$

whereas for the current of eq. (6) we obtain

$$\begin{pmatrix} T_x \\ T_y \\ T_z \end{pmatrix} = -\frac{\vec{\Omega}\vec{B}}{4c^2} BR^5\, \Omega \begin{pmatrix} \cos\phi\, (\theta_c + \frac{1}{2}\sin 2\theta_c) \\ \sin\phi\, (\theta_c + \frac{1}{2}\sin 2\theta_c) \\ \sin^2\theta_c \end{pmatrix} \tag{8}$$

In the canonical model $\sin\theta_c = \sqrt{\Omega R/c} \ll 1$ and we see that the torque given by eq. (8) is approximately $(\theta_c)^{-1}$ times larger than the torque of the symmetrical current given by eq.(7). In the frame centered on the (unit) rotation vector $\vec{\Omega}_o$ which is inclined by the angle χ to $\vec{b}_o$

$$\begin{aligned} \hat{e}_x &= (\vec{\Omega}_o \times \vec{b}_o) \times \vec{b}_o\, (\sin\chi)^{-1} \\ \hat{e}_y &= \vec{\Omega}_o \times \vec{b}_o\, (\sin\chi)^{-1} \\ \hat{e}_z &= \vec{b}_o \end{aligned} \tag{9}$$

we finally obtain in vector notation (adding the contribution of both caps!) with $\sin\theta_c \simeq \theta_c$ and $\vec{M}_o$ the unit magnetic moment vector

$$\vec{T} = -\frac{\Omega^2(\vec{\Omega}\vec{M})}{2c^3} \{ \vec{M} - 2\frac{\sin\phi}{\theta_c \sin\chi} \vec{\Omega}_o \times \vec{M} - 2\frac{\cos\phi}{\theta_c \sin} (\vec{\Omega}_o \times \vec{M}_o) \times \vec{M} \} \tag{10}$$

For that part of $\vec{T}$ which slows down the star we find

$$\vec{T}\vec{\Omega}_o = -\frac{\Omega^3 M^2}{\theta_c c^3} \cos\phi \sin\chi \cos\chi \propto \Omega^{5/2} \tag{11}$$

Note that the aligned ($\chi = 0$) and orthogonal ($\chi = \pi/2$) rotator are singular cases and the effect of asymmetry vanishes. As can be seen from eq. (11), two situations are possible, depending on the sign of $\cos\phi$. For an isolated pulsar we expect $\cos\phi > 0$, implying slow-down (Lenz rule), whereas for an accreting pulsar $\cos\phi < 0$ is a possibility, implying speed-up! In order to find the magnitude of the effect for an isolated pulsar we proceed as follows. First we estimate the asymmetry of the current flow from purely geometrical considerations, i.e. we determine the shape of the polar cap with respect to the magnetic pole. Two extreme situations are possible:

a - the near-field of an oblique rotator is given by that magnetic field which is obtained if a static (vacuum) dipole field is rotated about an axis $\vec{\Omega}$. Physically this means that the Maxwell displacement current $\frac{1}{c}\dot{\vec{E}}$ is neglected entirely.

b - the magnetic field is given approximately by the vacuum Deutsch solution, i.e., the displacement current $\frac{1}{c}\dot{\vec{E}}$ is overcounted since due to the presence of the plasma we expect $<\frac{1}{c}E_{\parallel}> \approx 0$ for the parallel component $E_{\parallel} = \vec{b}_o\vec{E}$.

For case (a) we find for the shape of the polar cap in coordinates centered on the magnetic pole $\theta = \theta(\sin^2\phi)$, i.e. the shape is symmetrical in ϕ and no geometrical asymmetry effect does occur. For case (b) no analytical determination seems possible and we have carried out some numerical calculations. The preliminary results show large asymmetries of the area of the current with respect to the magnetic poles, and we may tentatively put $\cos\phi \sim 0.5$. Having estimated the geometrical effect we relate it to the dynamics of the pulsar plasma which slows down the pulsar as follows by means of a Gedankenexperiment. Suppose we start to ratate a magnetized neutron star from rest with the final angular frequency Ω. Initially only the G.J. current (Goldreich and Julian, 1969) will flow and the magnetosphere will thereby charge up until a charge of an order given by eq. (3) is reached so that charges will flow back to the surface of the neutron star. By means of their inertia they will deform the magneit field at the velocity of light cylinder, and when they reach the pulsar surface they will end on field lines which lag the outgoing field lines by a lag angle $\cos\phi$ of order unity. Thus we may apply eq. (11) whenever sufficient plasma is produced so that the field configuration can be modified at the velocity of light cylinder. Clearly this will largely depend on the total plasma density produced by sparking (Ruderman, 1981) in the magnetosphere gaps and will therefore be important for young pulsars such as the Crab. Is it also possible that heavy ions may be responsible for the current of young pulsars (Ruderman, 1981), so that again a plasma inertia effect is to be expected.

Apart from enhanced braking the torque as given by eq. (10) gives rise to considerable precession. In connection with ordinary stars such torques were previously encountered for magnetic braking by a stellar wind by Mestel and Selley (1970). These authors made extensive calculations which confirm entirely our qualitative results.

Finally, one may ask why it is now no longer possible to evaluate the torque at the velocity of light cylinder or at infinity. The reason of course is that we are still lacking self-consistent ultrarelativistic plasma-wind solutions which could be matched to our near zone solution at the velocity of light cylinder. The interested reader is referred to the excellent review by Kennel et al. (1979) of this difficult but exciting subject.

REFERENCES

1 - Goldreich, P., Julian, W.M., Astrophys. J., 157, 869 (1969).
2 - Mestel, L., Proc.I.A.U.Symp. nº 95, 9 (1981).
3 - Sturrock, P.A., Astrophys. J., 164, 529 (1971).
4 - Roberts, P.H., Sturrock, P.A., Astrophys. J., 181, 161 (1973).
5 - Michel, F.C., Dessler, A.J., Astrophys. J., 251, 654 (1981).
6 - Radakrishnan, V., Proc.I.A.U.Symp. nº 95, 449 (1981).
7 - Lambeck, K., "The Earth's Variable Rotation: Geophysical Causes and Consequences", Cambridge Univ. Press. (1980).
8 - Downs, G.S., Astrophys. J., 249, 687 (1981).
9 - Groth, E.J., Astrophys. J.Suppl. 29, 431 (1975).
10- Mestel, L., Lecture Notes in Physics, Vol. 124, 145 (1980).
11- Heintzmann, H., Nature, 292, 811 (1981).
12- Jackson, E.A., Astrophys. J., 206, 831 (1976).
13- Ruderman, M.A., Proc.I.A.U.Symp., nº 95, 87 (1981).
14- Mestel, L., Sèlley, C.S., Mon.Not.Roy.Astron.Soc.,149,197 (1970).
15- Kennel, C.F., Fujimura, F.S.,Pellat, R., Space Sci.Rév.,24,407 (1979).

4 - EVOLUTION OF PULSARMAGNETISM BY VIRTUE OF A FARADAY DYNAMO MECHANISM

The evidence that radio-pulsars are slowed-down and Röntgen pulsars accelerated predominantly by magnetic torques is now very strong. Angular momentum is transferred away from the neutron star to the velocity-of -light cylinder (Goldreich and Julian, 1969; Mestel, 1971) or from the Alfven-cylinder down to the neutron star (Pines, 1980; Lamb et al. (1978) by means of a magnetic spring the physical origin of which is an appropiate current flowing along the magnetic field lines. As this current must be closed at the neutron star's surface and no Hall-field can be built-up a Faraday dynamo mechanism is set up. It is pointed out that this mechanism could switch-off a radio pulsar or turn-on a Röntgen pulsar. Many disconcerting pulsar observations could thus be explained, if radio pulsars can be reactivated in the galactic plane by means of accretion of matter in dense clouds and if Röntgenpulsars must first create a sufficiently strong magnetic field to function as a regularly pulsed emitter.

Soon after the identification of pulsars with neutron stars (Gold, 1968; Pacini, 1968) and based on a rather small sample of radio pulsars it was pointed out (Ostriker and Gunn, 1969; Pacini, 1969) that the observation of absence (which at that time might also have been absence of observation) of long period pulsars could be understood if one assumed that the magnetic field decayed on a time-scale of some My. In fact the radius R of a neutron star is so small, typically $R \simeq 10^6$ cm, that the decay time of the magnetic field τ_α, due to Ohmic dissipation

$$\tau_\alpha = \frac{4\sigma R^2}{\pi c^2} \tag{1}$$

amounts to some My, if the conductivity of the neutron star's material is $\sigma = 10^{23}$ sec^{-1}, and for non-degenerate matter this would be a rather large value. However the matter of a neutron star is extremely degenerate and due to the Pauli principle the conductivity σ is many orders of magnitude larger in the main body of a neutron star (Baym et al., 1969). In fact in some part of the neutron star the protons may actually form a type II superconductor (Baym et al., 1969). Consequently only in the crust of a neutron star can the magnetic field decay, typically within some 10 My if the neutron star is hot enough (Heintzmann and Grewing, 1972; Ewart et al., 19) (or if the crust material is very impure), and this would not lead to any appreciable reduction of the neutron star's dipole magnetic moment (Heintzmann and Grewing, 1972). Unimpressed by such theoretical considerations observers continued to discuss their observational results in terms of magnetic field decay (Lyne et al., 1975; Helfand and Tademaru, 1977) and this essentially until today (Cordes and Helfand, 1980).

How to pulsars turn-off then, if magnetic field decay due to Ohmic dissipation is not possible? Three further ideas have been offered. The first is simply a variant of the magnetic field decay hypothesis. It was pointed out that once the current in the crust has decayed the liquid interior would allow the magnetic dipole field to reorient (Flowers and Rudernam, 1977)itself lowering thereby the magnetic energy and form a quadrupole field. This reorientation of the poloidal magnetic field could however be impeded (Flowers and Ruderman, 1977) by the presence of strong toroidal fields which are expected to be produced at the pulsar's birth (Heintzmann et al., 1973) or in the pre-neutron star stage (Rudermann and Sutherland, 1973). The second is based on the fact that external or internal torques may lead to considerable alignment (Jones, 1976; Kundt, 1981) of the pulsar's spin axis with the axis of the magnetic field. While there is probably agreement between pulsar theorists that the angle between dipole axis and spin axis plays an important role in pulsar evolution (Heintzmann, 1981; Rudermann, 1980; Fujimura and Kennel, 1980) it is also evident that it cannot explain pulsar turn-off alone. Therefore some other mechanism must be at work. In line with work by Sturrock (Sturrock,1971) and others (Holloway, 1973; Michel, 1975) Rudermann and his group have developed the idea that sparking in gaps is responsible for the coherent radio emission of radio-pulsars and that the process depends sensitly on surface temperature and rotation period (Ruderman,1980). The following discussion is also in line with these considerations and stresses, as will be seen, the importance of the surface temperature. Summarizing the present state of the art one may say (with respect to the radio-pulsars) that a number of models have been developed which can explain one or a few observed facts but none can satisfactorily explain all or only most of what has been observed. However valuable extra information about neutron stars has come from X-ray observations, calling into doubt the simple picture outlined above. There is (theoretical) evidence (van den Heuvel, 1977) that Her X-1, which has a strong magnetic field as inferred from the cyclotron line (Trümper et al., 1978) and which is quite hot (which should entrance magnetic field decay) is some 500 My old and this argues strongly against magnetic field decay. Furthermore many cyclotron lines have by now been detected in γ-ray bursters and these are probably old, occasionally accreting (binary?) neutron stars. Of special significance (if correctly interpreted as an old neutron star (Heintzmann, 1981) is the γ-ray transient(Terell et al., 1980) with a period of 8 s. Here the most likely explanation is the infall of a comet (Colgate and Petscheck, 1981) on a strongly magnetized neutron star rotating with a period of 8 s, arguing both against magnetic field decay and aligment. It is noteworthy that the possibility of such an extreme event was considered (Colgate and Petscheck,1981) well before the actual discovery, demonstrating that here also theory had some predictive powver. While there is therefore some evidence that old neutron stars posses non-aligned strong magnetic fields there is also ample evidence to the contrary. The group of Röntgen - stars which reveal a magnetic field is quite small, the great majority either conceals their magnetic fields or does not have a strong magnetic field. To these belong all the bursters, which have been studied especially carefully (Lewin and Clark,1980). While these disconcerting observations are hard to reconsile with conventional ideas about neutron stars and their magnetic fields the following observational facts show that a radically new idea for their explanation is needed. Improved pulsar statistics (Lyne, 1980) have fully confirmed the early conclusions (Gunn and Ostriker, 1970) that pulsars are predominantly born in the galactic plane,that they have large peculiar velocities (accounting to some 10^{47} erg of kinetic energy) and that the inferred kinetic ages do not exceed some My. There is therefore every theoretical and observational evidence that neutron stars must be born in supernovae.

No neutron stars have however been detected at the sites of young supernovae (Helfand, 1980), a fact which is especially disconcerting if one recalls that the conventional interpretation of the pulsar data leads to the conclusion that the formation-rate of pulsars is larger than the ocurrence-rate of supernovae (Chevalier, 1981) even if every supernova would lead to the formation of a neutron star (which it does not). Dismissing the possibility that pulsars are born by the dozen, for which there is no observational evidence (Wright, 1979), the only way to explain all these findings is that the magnetic fields of neutron stars evolve as does e. g. the magnetic field of the earth.

The idea that the magnetic field of the earth was fossil (i.e. due to remanent magnetization) was given up around the turn of the century. Through discovery of numerous reversals of the geomagnetic field throughout the geological history of the Earth it became clear that the cause of geomagnetism is a dynamic one and that motions in the liquid core are probably the origin of geomagnetism. What exactly drives the geodynamic is unknown, but the magnetic field is known to have existed for over 3000 My, with about the same strength as it has today, so the power supply must have been long-lasting. Magnetic fields in neutron stars are not believed to be of a dynamical origin within the neutron star itself (Rudermann and Sutherland, 1975) (see however refs. 17 and 39) but there is the possibility to set up a Faraday type dynamo at the surface of the neutron star. We have considered elsewhere the details of the current flow through the magnetosphere (Heintzmann, 1981) and have been able to show now (Heintzmann, and Schrufer, 1981) that the anomalons braking index of the Crab nebula pulsar (the explana-/tion of which has presented a major difficultly for any theory developed so far) can be accounted for quantitatively in this model lending some support to its basic correctness. All we need to know here about the model are the following assumptions. The neutron star is slowed-down (Goldrich and Julian, 1969; Mestes, 1971; Heintzmann, 1981) or accelerated(Pines, 1980; Lamb et al., 1978) by a magnetic torque provided by a current which flows along the magnetic field lines away from the surface area ΔF centeredon the magnetic poles (polar caps). Forward-and return-current are spatially separated. In the simplest case the return-current will flow symmetrically about the forward-current and further away from the center of the polar caps. No Hall-field can be established for geometrical reasons so the current $\vec{j}$ must spiral inwards in order to satisfy div $\vec{j} = 0$. The ratio of the toroidal and the transverse current across the cap is

$$N = \frac{j\phi}{jp} = \frac{eB}{mc} \tau_e = \frac{\sigma B}{en_e c} \qquad (2)$$

Here τ_e is the scattering time of an electron of the current with an ion in the crust. We shall assume that a fossil magnetic field of at least $10^{9,5}$ Gauss is present. Such a field is well below the smallest yet observed pulsar field (which is $10^{10,3}$ Gauss for PSR 1913 + 16) in agreement with the prediction that pulsars with field-strengths below 10^{10} Gauss will not function as pulsars (Ter Haar, 1972) and yet strong enough to force matter to form a "polymer" (quasi one-dimensional) metal (Ruderman, 1971; Kadomtsev and Kudryartsev, 1971) with density $\rho \simeq 10^{4}$ g cm^{-3} corresponding to an electron density $n_e \simeq 10^{27}$ cm^{-3} at the surface. Where and how will the current flow? From Maxwell's equations we obtain with $\vec{j} = \sigma\vec{E}$ (dropping a small term) the diffusion equation for the electric field (and thereby also for the current)

$$\text{rot rot } \vec{E} = -\frac{4\pi\sigma}{c^2}\frac{\partial}{\partial t}\vec{E}$$

with the boundary condition at the polar cap that the tangential component of E be continuous and equal to $-\nabla\phi$ where ϕ is the potential difference across the polar cap which drives a current and which is probably due to a net charge on the pulsar (Heintzmann, 1981). The problem is the inverse to that of Ohmic dissipation (Landau and Lifshitz, 1967) with the result that the current grows on the time-scale (see eq. (1))

$$\tau_g = \frac{2\sigma\Delta F}{c^2} \qquad (3)$$

therefore we may safely take after some years $\sigma > 10^{20}$ s^{-1} and $\sigma/n_e > 10^{-7}$ cm^3 s^{-1}. From eq. (2) we get then $N > 10^4\, B_{12}$ (where B_{12} means B in units of 10^{12} Gauss). The transverse polar current, which breaks the pulsars rotation or speeds the pulsar up in case of accretion can be inferred from observation (for known poloidal magnetic field-strength) so that we can both compute the toroidal component of the current by means of eq. (2) and the magnetic field generated by it. Putting $\Delta F = \pi R^2\theta^2$ where for pulsars typically (Ter Haar, 1972) $\theta \simeq 10^{-1,5}$, and using for the torque T the relation (Heintzmann, et al., 1973)

$$T = I\dot{\Omega} \simeq -B_p B_t R^3\theta^3 \qquad (4)$$

we obtain for the dynamo field

$$\delta\vec{B}_p \simeq \frac{\sigma\, I\, \dot{\Omega}\, \vec{B}_p}{e\, n_e c\, R^3\theta^3 |B_p|} \qquad (5)$$

Here I is the moment of inertia of the neutron star ($I \simeq 10^{45}$ g cm^2), and Ω the spin angular velocity of the pulsar. The index p means poloidal the index t toroidal. As a consequence of Lenz' rule δB_p is directed oppositely to the primordial magnetic field if the pulsar is slowed-down under the action of the self-generated current (anti-dynamo) and it is parallel to B_p (dynamo) if the pulsar is accelerated by the current due to accretion.

Under terrestrial conditions N << 1. For copper (very pure crystals) (Kittel, 1966) at 4°K it is possible to achieve $\tau_e = 10^{-9}$ sec so that even with a 100 k Gauss field n = 0,1, too small to give rise to an interesting dynamo. For ordinary copper however (Kittel, 1966) $\tau_e \simeq 10^{-14}$ sec so that with the same magnetic field $N \simeq 10^{-6}$, which is hard to measure. For neutron stars however the effect is very large, and we may accept for a moment the hypothesis that radio pulsars turn-off (as they cool below a certain temperature) and that Röntgen pulsars show pulsed emission (if they accrete enough) due to the dynamo mechanism, eq. (5) and see what this implies. If the conductivity is mainly due to electron-phonon scattering (Ewart, et al., 19) we have $\sigma \simeq 10^{20}\, T_6^{-5}$ i.e. the conductivity is extremely temperature dependent. In the case of radio pulsars it is convenient to turn around eq. (5) and solve for the temperature. We obtain for pulsars near the cut-off line (Ritchings, 1976; Fujimura and Kennel, 1980) (which show nulling and which we identify tentatively with pulsars which are about to turn-off) with $\dot{\Omega} \simeq -10^{-10}$ s^{-2}, $\theta \simeq 10^{-1}$, $B_p \simeq \delta B_p \simeq 10^{12}$ Gauss a temperature $T \simeq 10^{4,7}$ °K, a temperature that a pulsar could easily sustain with the help of a little reheating (due to the return current (Ruderman, 1980)). For Röntgen pulsars we may on the other hand put $T \simeq 10^7$ °K for the surface temperature and $\theta \simeq 10^{-1,5}$ to obtain $\delta B_p \simeq 10^{12}$ Gauss in good agreement with the observations if we use (Rappaport and Joss, 1977; Lamb et al., 1978) $\dot{\Omega} \simeq 10^{-12}$ s^{-2} as inferred from the speed-up.

Having established the relevance of the unipolar dynamo mechanism for pulsar evolution it seems worthwhile to examine the observational evidence with more scruting and this will be done in a forthcoming paper. One interesting prediction of the present model would be that due to the extreme temperature dependence of the dynamo effect pulsars could suddenly turn on for a short period due to a sudden heating (Harwit and Salpeter, 1973) and it would be interesting to know, whether such events have already been observed but not recorded in published form. To this end observers at independent observatories could check through their data together (as is e.g. done with the X-ray data).

<u>REFERENCES</u>

1 - Goldreich, P., Julian, W.H., Astrophys.J., 157, 869 (1969).
2 - Mestel, L., Nature Phys. Sci., 233, 149 (1971).
3 - Pines, D., Science, 207, 597 (1980), J.Phys. C. 2, 111 (1980).
4 - Lamb, F.K., Pines, D., Shaham, J., Astrophys.J., 224, 969 (1978).
5 - Gold, T., Nature, 218, 731 (1968).
6 - Pacini, F., Nature, 219, 145 (1968).
7 - Ostriker, J.P., Gunn, J.E., Nature, 223, 813 (1969).
8 - Pacini, F., Nature, 224, 160 (1969).
9 - Baym, G., Pethick, C., Pines, D., Nature, 224, 673 (1969).
10- Baym, G., Pethick, C., Pines, D., Nature, 224, 674 (1969).
11- Heintzmann, H., Grewing, M., Z.Physik, 250, 254 (1972).
12- Ewart, G.M., Guyer, R.A., Greenstein, G., Astrophys.J., 202, 238 (19).
13- Lyne, A.G., Ritchings, R.T., Smith, F.G., MNRAS, 171, 579 (1975).
14- Helfand, D.J., Tademaru, E., Astrophys. J., 216, 842 (1977).
15- Cordes, J.M., Helfand, D.J., Astrophys. J., 239, 640 (1980).
16- Flowers, E., Ruderman, M.A., Astrophys.J., 215, 302 (1977).
17- Heintzmann, H., Kundt, W., Schrüfer, E., Astron. Astrophs., 27, 45 (1973).
18- Rydermann, M.A., Sutherland, P.G., Nature, 246, 93 (1973).
19- Jones, P.B., Nature, 262, 121 (1976).
20- Kundt, W., Astron.Astrophy., 98, 207 (1981).
21- Heintzmann, H., Nature, 292, 811 (1981).
22- Rudermann, M.A., Proc.IAU Symp., nº 95, 87-98 (1980).
23- Fujimura, F.S., Kennel, C.F., Astroph.J., 236, 245 (1980).
24- Sturrock, P.A., Nature, 227, 465 (1970), Astroph.J., 164, 529 (1971).
25- Holloway, N., Nature, 264, 6 (1973).
26- Michel, F.C., Astrophys. J., 192, 713 (1974), 198, 683 (1975).
27- van den Heuvel, E.P.J., Ann. N.Y. Acad.Sci., 302, 14 (1977).
28- Trümper, J. et al., Astrophys.J.Lett., 219, L 105 (1978).
29- Mazets et al., Nature, 290, 378 (1981).
30- Terell, J. et al., Nature, 285, 383 (1980).
31- Colgate, S.A., Petscheck, A.G., Astrophys.J., 248, 771 (1981).
32- Harwit, M., Salpeter, E.E., Astrophys.J.(Lett), 186, L 37 (1973).
33- Lewin, W.H.G., Clark, G.W., Ann.N.Y.Acad.Sci., 336, 451 (1980).
34- Lyne, A.G., IAU Symp. nº 95, 423-433 (1980).
35- Gunn, J.E., Ostriker, J.P., Astrophys. J., 160, 979 (1970).
36- Helfand, D.J., Nature, 285, 133 (1980), 283, 337 (1980).
37- Chevalier, R.A., IAU Symp. nº 95, pp. 403-416 (1981).
38- Wright, G.A.E., Nature, 277, 363 (1979).
39- Sedakrian, D.M., Nature, 228, 1074 (1970).
40- Heintzmann, H., Schüfer, E., Astron.Astrophys.Submitted (1981).
41- Ter Haar, D., Physiscs Rep. 3C, 59 (1972).
42- Ruderman, M.A., Phys. Rev.Lett., 27, 1306 (1971).
43- Kadomtsev, B.B., Kudryartsev, V.S., JETP Lett., 13, 9, 42 (1971).
44- Landau, E.D., Lifshitz, E.M., vol. 8, nº 45, Akademie Verlag, Berlin (1967).
45- Kittel, Ch., Introduction to Solid State Physics, 3r Ed. §7 (1966), Wiley, N.Y.
46- Ritchings, R.T., MNRAS, 176, 249 (1976).
47- Rappaport, S., Joss, P.C., Nature, 266, 683 (1977).

5 - GHOST SUPERNOVA REMNANTS: EVIDENCE FOR PULSAR REACTIVATION IN DUSTY MOLECULAR CLOUDS?

There is ample albeit ambiguous evidence in favour of a new model for pulsar evolution, according to which pulsars may only function as regularly pulsed emitters if an accretion disc provides a sufficiently continuous return-current to the radio pulsar (neutron star). On its way through the galaxy the pulsar will consume the disc within some My and travel further (away from the galactic plane) some 100 My without functioning as a pulsar. Back to the galactic plane it may collide with a dense molecular cloud and turn-on for some ten thousand years as a Röntgen source through accretion. The response of the dusty cloud to the collision with the pulsar should resemble a supernova remnant ("ghost supernova remnant") whereas the pulsar will have been endowed with a new disc, new angular momentum and a new magnetic field (Heintzmann, 1981).

The cladistic view of pulsars associates at least four different classes of objects with neutron stars:

1 - the radio pulsar;
2 - the Röntgen pulsars and some Röntgen point sources;
3 - the Röntgen bursters which are exploding neutron stars;
4 - the γ-ray bursters, where the burst mechanism may be due to cometary collisions with neutron stars.

While for the Röntgen and γ-ray sources accretion is vital for the radiation mechanism it has been argued (Shvartsman, 1971; Wright, 1973) that for radio pulsars accretion is lethal in so far as it may suppress the basic radiation mechanism or even turns-off radio pulsars completely (Meyer, 1973). In fact the Röntgen pulsars may provide indirect evidence as none functions as a radio pulsar that too much accretion and therefore too much plasma around the neutron star inhibits the radio radiation mechanism or at least its detection (Davidson and Ostriker, 1973) due to the large dispersion of the radio waves in the plasma. However just how much accretion a radio pulsar can undergo before it turns-off is not clear. Here we shall pursue the alternative idea that pulsars only function as such if they accrete electro-dynamically rather than gravitationally via a return-current from a small accretion disc.

Pulsar evolution may then be determined completely by the presence of absence of an accretion disc and its properties. The following scenario puts the four classes of neutron stars into an evolutionist's perspective:Neutron stars with a massive companion will function as Röntgen sources.

Neutron stars with a light companion have smaller accretion discs and the accretion flow may be unstable leading to irregular Röntgen emission (Shvartsman, 1971). Some of the X-ray bursters may belong to this group.

Neutron stars with an accretion disc freshly acquired from a dense dust cloud may mark the transition from a binary to a single neutron star and may also be related to some burst sources. Fragmentation of the disc may under favourable circumstances lead to the formation of asteroids or comets and their collision with the neutron star may give rise to γ-ray bursts.

Most of these objects will be runaways as at least one supernova has occurred at their births and single neutron stars will consequently leave the galactic plane where they were born and may consume or loose their accretion discs so that they turn-off. Back to the galactic plane these single neutron stars may collide with a dense dust cloud and acquire a new accretion disc together with a new magnetic field and new angular momentum (Heintzmann, 1981).

We will show below that there is ample indirect observational evidence supporting the existence of a disc so we shall not defend the theoretical necessity of it here in detail. Suffice it to say that the standard pulsar model (Goldreich and Julian, 1969; Mestel, 1971) suffers from one major defect in that it does not explain how the steady current which brakes the pulsar's rotation comes about without charging-up the neutron star indefinitely. One way out of this dilemma (Jackson, 1976; Heintzmann, 1981) is to give up force freeness of the magnetosphere and to consider a net charge on the pulsar

$$Q = \frac{\vec{\Omega}\vec{M}}{c} \tag{1}$$

($\vec{\Omega}$ is the spin angular velocity vector, $\vec{M}$ the magnetic dipole moment and c the velocity of light). Although its electric force on a proton is some 10^8 times larger than the gravitational force such a net charge on the pulsar will not lead immediately to a return current from the interstellar medium since the pulsar is well shielded by a relativistic wind (Heintzmann, 1981; Kennel et al., 1979; Ostriker et al., 1970). Consequently this wind will blow a hole in the interstellar matter (Meyer, 1973; Ostriker et al., 1970) and if the pulsar "collides"with a cloud of molecules and dust the wind will sweep-up the cloud material, ionize it and generate an equipartition magnetic field. The shock front will act now like a magnetic bottle if cooling via dust is efficient enough and as a result we will have strongly enhanced accretion. Note that gravity alone is not sufficient to provide the necessary accretion rate (Meyer, 1973; Ostriker et al., 1970; Favian, 1977) for supersonically moving pulsars to build up an accretion disc which can quench the relativistic wind of the pulsar. However for a velocity $v \sim 10^7$ cm sec^{-1} of the pulsar we find that the equipartition magnetic field in the shock is $B \sim (8\pi\, m\, n\, v^2)^{1/2} \sim 10^{-3,5}$ Gauss for $n = 100$ cm^{-3}, i.e. typical for the magnetic field of a young supernova remnant. A particle in such a field will be trapped provided its Larmor radius r_L is much smaller than the shock thickness and provided cooling is efficient enough to inhibit appreciable evaporation (diffusion out of the bottle) and it is here that dust may play the essential role. Hence dense molecular clouds are the best sites for pulsar regeneration and for the formation of ghost supernova remnants. In fact careful observations (Glushak et al., 1981; Weiler et al., 1974) of active radio pulsars have shown that the interaction of a pulsar with the interstellar medium does not lead to the formation of radio halos or (mini) ghost supernova remnants as proposed originally by Blandford et al. (1973), which lends support to the idea the dust may in fact play a crucial role. Once enough matter has been accreted and cooled down a Rayleigh-Taylor instability will develop (Meyer,1973) and the matter will come down in blobs of size

$$r_{RT} \simeq L/4\pi G\rho Mc \simeq 10^{14}\ \text{cm}\ L_{30}\ \rho_{-21}^{-1}\ M_{\odot}^{-1} \tag{2}$$

(L is the luminosity of the pulsar, ρ the matter density in the shock). Due to angular momentum conservation the matter may not fall directly on the neutron star (as is usually assumed) but it may be stored in a disc as discussed for accreting Röntgen (binary) sources (Fabian, 1977; Elsner and Lamb, 1976; Ghosh and Lamb, 1979) or radio pulsars (Roberts and Sturrock, 1973; Michel and Dessler, 1981). Regulated by the net charge and not by gravity the disc may now provide a sufficiently regular return current so that away from the molecular cloud the Röntgen pulsar may turn into a radio pulsar again and continue its journey through the galaxy.

In the light of this new model for pulsar evolution we wish to reassess the observational data. Clearly the model was devised from the beginning so that is explains the most important discordant observations: the large discrepancy between the inferred birth-rate of pulsars and the observed occurrence rate of supernovae (Heintzmann, 1981) and the observed absence of neutron stars at the sites of young supernova remnants (Helfand et al., 1980). To see this we note that the encounter probability of a pulsar with a dusty dense cloud is of order unity (Wright, 1979) as between one and ten percent of the total mass of the galaxy is found to be in dense clouds (Solomon et al., 1979) concentrated in the galactic plane so that the major uncertainty of our estimate lies in the amount of dust needed to allow for the formation of a ghost supernova remnant. With an encounter probability of order unity the number of pulsars actually born in supernovae is reduced by the factor $A_G/T_p \simeq 100$ where A_G is the age of the galaxy and T_p the period of oscillation across the galactic plane ($T_p \simeq 100$ My). The actual birth of a neutron star, i.e. a supernova, may therefore well be a rare event and many supernova remnants may actually be ghost supernova remnants. To estimate where the line must be drawn for the latter we accept for the Röntgen-luminosity of the neutron star(Fabian, 1977) $L_x = 10^{38}$ erg sec^{-1} and a typical cloud diameter of 1 pc so that the accreting neutron star will radiate some 10^4 years depositing 10^{49} ergs in the cloud typical of a type I supernova. Apart from the occurrence rate of true supernovae our model agrees with every aspect of the standard model: the pulsars are concentrated near the galactic plane since the dusty clouds are there, and the velocity vectors of the radio pulsars point predominantly away from the galactic plane as the radio pulsars turn on as such only after leaving the cloud.

While none of the aspects of our model are radically new the combination of them does lead to a major revision of the presently accepted scenario of pulsar evolution and we have sought therefore for further evidence for or against the present model. Surprisingly the predictive power of the model is quite large and we find it convenient to group predictions and observations into two categories: active radio pulsars and dead radio pulsars associated with ghost supernova remnants or non binary Röntgen sources.

5.1 - ACTIVE RADIO PULSARS

If pulsars do in fact have a disc around them some dispersion must be intrinsic and therefore interesting changes of the dispersion measure may be observable. A prediction of our model would be that the dispersion measure changes on a time scale of 10^6 years. Such changes of dispersion measure are observable for pulsars which show fine structure in the pulses and have in fact been observed (Isaacman and Rankin, 1977) at the level of 10^{-4} over five years in case of the Crab nebula pulsar and such changes are not easily explainable by any extant model. Clearly the effects of a time varying accretion disc should be strongest for nearby pulsars where most of the dispersion measure could thus be intrinsic and of spacial interest would be the observation of a pulsar with freshly acquired disc or a disappearing disc. The loss of a disc should therefore be correlated with an anomalously low dispersion measure. As a matter of fact there is observational evidence for all of these effects which are difficult to explain otherwise.

The pulsar 0904 + 77 was discovered clearly (Taylor and Hughenin, 1969) in 1969 and has disappeared since then for more than 10 years. Its dispersion measure was very low(Manchester and Taylor, 1981) (DM $\approx$ 10 $\pm$ 10) and compatible with zero. This pulsar may actually be considered as an extreme case of nulling pulsars and it is generally believed that nulling pulsars are turning off their radiation. According to the present model such pulsars should have weak return-currents and hence small $\dot{P}$ a fact which is known to be true already(Ritchings, 1976). Since timing noise is correlated with (Cordes and Helfand, 1980) $\dot{P}$ we have a natural explanation for this fact. Analysis of Ritchings' data (Ritchings, 1976) for nulling pulsars gives an average dispersion measure DM = 37.7 pc cm^{-3} whereas <DM> = 100 pc cm^{-3} for all pulsars (Manchester and Taylor, 1981). This result is probably not a selection effect as the absolute radio fluxes of nulling pulsars do not deviate from those of the remaining pulsars.

Evidence for freshly accumulated discs may therefore come from pulsars which show appreciable timing noise. Here the noisiest pulsar is PSR 0611+22 and this pulsar turns out to be one of the most interesting radio pulsars discovered so far. It has been associated with the(ghost?) supernova remnant (Davies et al., 1972) IC 443 and with the HII region (Sharpless, 1959)Sh249, so that IC 443 could actually be an old ghost supernova remnant. We shall come back to this source below. PSR 0611+22 is noisier than the (younger) Crab-and Vela-pulsars. It shows the second largest speed-ups ever observed (Manchester, 1980) in pulsars. The next noisiest pulsar is (Manchester, 1980) PSR 0740-28 a pulsar which shows pulsed γ-radiation (Amico and Scarsi, 1980). An example contrary to our model would be PSR 1055-52 if it were really associated with the unpulsed X-ray source (Helfand, 1980) of intensity $L_x \sim 10^{33,6}$ erg sec^{-1} as this pulsar is rather noise-free. However the offset between the radio pulsar and the Röntgen source is 3" and the two sources may therefore not be related.

A complete statistical analysis is certainly required to add more weight to our findings and this will be possible soon if the complete Röntgen data collected by the Einstein satellite have been published and if the timing noise analysis if extended to a larger set of pulsars than is available at present.

5.2 - GHOST SUPERNOVA REMNANTS AND NON BINARY RÖNTGEN POINT SOURCES

As mentioned already IC 443 may actually be a ghost supernova remnant. Our main arguments in favour of this interpretation are its estimated energy (Fesen and Kirshner, 1980) of E $\sim 10^{49}$ ergs and the pronounced one sidedness of the remnant (De Noyer, 1979; Fesen and Kirshner,1980). As a second possibility for a ghost supernova remnant we suggest SNR G 109.1-1.0. It contains an X-ray pulsar of the right period P = 3,48 sec, it may be related to the molecular cloud (Heydari-Malayeri et al., 1981) Sh2-152 and is unusually bright optically (Blair et al.,1981).

Further candidates may be found among the objects listed by Ryle et al. (1978) and Montmerle (1979), who actually calles our ghost supernova remnants SNOBS (Supernova Remnants associated with OB stars).

In addition we mention three further candidates not included in these lists:

1 - the North Galactic Spur, which is commonly interpreted as due to a supernova and which seems to end into a neutral interstellar cloud (Frisch, 1981);

2 - the γ-ray sources in the Orion molecular cloud and in the ρ-Ophiuchi complex (Bignami and Morfill, 1980; Swanenburg et al., 1981).

As far as the bursters and the Sco-like sources are concerned models have already been developed (Fabian, 1977; Baan, 1977; Abdulwahab and Morrison, 1978) which although different in detail agree with the present one in that they depart from the general belief that Röntgen point sources must be of binary nature. The observational situation can be interpreted in two alternative ways. After vigourous efforts to uncover the binary nature of the bursters (Lewin, 1981; Lewin and Joss, 1981) finally a Sco-like source (Marshall and Millit, 1981) and an X-ray burster (Pedersen and Paradijs, 1981) show evidence of binary nature. This then either means that it is very difficult to detect a binary orbital period in such systems (because they have a light companion) or else that most of such systems are not of binary nature. In any case the general argument that Röntgen point sources must be of binary nature because of the high accretion rate needed to make a neutron star shine as a Röntgen source can be countered by the observation that especially the burst sources are related to the galactic bulge (Lewin and Clark, 1980; Vivekanand and Narayan, 1981) and eight burst sources out of fourteen within 10^{o} from the galactic outer lie in globular clusters, condensation islands for molecular clouds?

To conclude the list of evidence in possible favour of our model we note that on purely theoretical grounds but model independently (Vivekanand and Narayan, 1981; Phinney and Blandford, 1981) is has been shown that the pulsar birth rate is $0.048^{+0.014}_{-0.011}$ pulsars yr^{-1} $galaxy^{-1}$ and that many pulsars make their first appearance at periods greater than 0.5 s. This "injection", which runs counter to present thinking is probably connected with the physics of pulsar radio emission and can now be understood in the context of our model.

REFERENCES

1 - Heintzmann, H., Nature, submitted, 1981.
2 - Shvartsman, V.F., Sov.Astron.A.J., 14, 527 (1970), 15, 342 (1971).
3 - Wright, G.A.E., Nature, 280, 40 (1979).
4 - Meyer, F., in: Einheit und Vielheit (ed.Scheibe, E.), pp.183-190 (1973)Vandenhoeck, Göttingen.
5 - Davidson, K., Ostriker, J.P., Astrophys. J., 179, 585 (1973).
6 - Goldreich, P., Julian, W.H., Astrophys.J., 157, 969 (1969).
7 - Mestel, L., Nature Phys. Sci., 233, 149 (1971).
8 - Jackson, E.A., Astrophys.J., 206, 831 (1976).
9 - Heintzmann, H., Nature, 292, 811 (1981).
10- Kennel, C.F., Fujimura, F.S., Pellat, R., Space Science Review, 24, 407-436 (1979).
11- Ostriker, J.P., Rees, M.J., Silk, J., Astrophys.Lett., 6, 179 (1970).
12- Fabian, A.C., Nature, 268, 608 (1977).
13- Elsner, R.F., Lamb,F.K., Nature, 262, 356 (1976).
14- Glushak, A.P., Pynzar, A.V., Udal'tsov, V.A., Sov.Astron., 25, 182 (1981).
15- Weiler, K.W., Goss, W.M., Schwarz, U.J., Astron.Astrophys.,35, 473 (1974).
16- Blandford, R.D. et al., Astron. Astrophys., 23, 145 (1973).
17- Ghosh, P., Lamb, F.K., Astrophys.J.,234,296 (1979).
18- Roberts, D.H.,Sturrock, P.A., Astrophys.J.,181,161 (1973).
19- Michel, F.C., Dessler, A.J.,Astrophys.J., 251, 654 (1981).
20- Helfand, D.J., Chanan, A., Novik, R., Nature, 283, 337 (1980).
21- Solomon, P.M., Scoville, N.Z., Sanders, D.B., Astrophys.J.Lett.,232,L89 (1979).
22- Isaacman, R., Rankin, J.M., Astrophys.J.,214,214 (1977).

23- Taylor, J.H., Huguenin, G.R., Nature, 221,816 (1969).
24- Manchester, R.N., Taylor, J.H., CSIRO Preprint nº 2530 (1981).
25- Ritchings, R.T., MNRAS 176, 249 (1976).
26- Cordes, J.M., Helfand, D.J., Astrophys.J., 239, 640 (1980).
27- Davies, J. G., Lyne, A.G., Seiradakis, J.D., Nature, 240, 229 (1972).
28- Sharpless, S., Astrophys.J. Suppl., 4, 257 (1959).
29- Manchester, R.N., IAU Symp. nº 95, pp. 267-276 (1980).
30- Amico, D.N., Scarsi, L., Lecture Notes in Physics, 124, pp.67-87 (1980).
31- Helfand, D.J., IAU Symp. nº 95, pp. 343-350 (1980).
32- De Noyer, L.K., MNRAS, 183, 187 (1978), Astrophys.J.Lett., 228,L41,232, L165 (1979).
33- Duin, R.M., van der Laan, H., Astr. Astrophys., 40, 111 (1975).
35- Levine et al., Astrophys. J.Lett., 228, L99 (1979).
36- Rappaport, S. et al., Astrophys.J., 227, 285 (1979).
37- Fesen, R.A., Kirshner, R.P., Astrophys. J., 242, 1023 (1980).
38- Fahlman, G.G., Gregory, P.C., Nature, 293, 202 (1981).
39- Heydari-Malayeri, M., Kahane, C., Lucas, R., Nature, 293, 549 (1981).
40- Blair, W.P., Kirshner, R.P., Nature, 291, 132 (1981).
41- Ryle, M. et al., Nature, 276, 571 (1978).
42- Montmerle, Th., Astrophys.J., 231, 95 (1979).
43- Frisch, P.C., Nature, 293, 377 (1981).
44- Bignami, G.F., Morfill, G.E., Astron.Astrophys., 87, 85 (1980).
45- Thomson, D.J., Nature, 291, 109 (1981).
46- Swanenburg et al., Astrophys.J.Lett., 243, L69 (1981).
47- Baan, W.A., Astrophys.J., 214, 245 (1977).
48- Abdulwahab, M., Morrison, P., Astrophys.J.Lett., 221, L33 (1978).
49- Lewin, W.H.G., Sci.American, pp.60-70, May 1981.
50- Lewin, W.H.G., Joss, P.C., Space Sci.Rev., 28, 3-87 (1981).
51- Marshall, N., Millit, J.M., Nature, 293, 379 (1981).
52- Pedersen, H., Paradijs, J., Lewin, W.H.G., Nature, 294, 725 (1981).
53- Lewin, W.H.G., Clark, G.W., Ann.N.Y.Acad.Sci., 336, 451 (1980).
54- Inoue,H. et al., Astrophys.J.Lett., 250, L71 (1981).
55- Vivekanand, M., Narayan, R., J.Astrophys.Astr., 2, 315 (1981).
56- Narayan, R., Vivekanand, M., Nature, 290, 571 (1981).
57- Phinney, E.S., Blandford, R.D., MNRAS, 194, 137 (1981).