Radio Pulsar Death

Bing Zhang

(*The Pennsylvania State University, USA*)

Abstract Pulsar radio emission is believed to be originated from the electron-positron pairs streaming out from the polar cap region. Pair formation, an essential condition for pulsar radio emission, is believed to be sustained in active pulsars via one photon process from either the curvature radiation (CR) or the inverse Compton scattering (ICS) seed photons, or sometimes via two photon process. In pulsars with super-critical magnetic fields, some more exotic processes, such as magnetic photon splitting and bound pair formation, will also play noticeable roles. All these effects should be synthesized to discuss radio pulsar death both in the conventional long-period regime due to the turnoff of the active gap, and in the high magnetic field regime due to the possible suppression of the free pair formation. Here I briefly review some recent progress in understanding radio pulsar death.

1 Why Pair Production Essential?

A pulsar drags its magnetosphere to co-rotate. In the observer's rest frame, the local charge density required for co-rotation is the "Goldreich-Julian" (1969) density, which when $r \ll r_{lc}$ (r_{lc} is the light cylinder radius) is approximately $\rho_{\rm GJ} \simeq -(\mathbf{\Omega} \cdot B)/(2\pi c)$, where $\mathbf{\Omega}$ is the angular velocity of the star, and $\boldsymbol{B}$ is the local magnetic field vector. In a simplest GJ magnetosphere, the positive and negative charges are separated from each other in space, and pair production is not required.

Pair production comes in for two reasons. First, it is obligatory. The most prominent feature of pulsar radio emission is its very high brightness temperature (typical value $T_B \sim 10^{25} - 10^{30}$ K). Due to self-absorption, the maximum brightness temperature for any incoherent emission is limited by the kinetic energy of the emitting electrons, i.e. $T_{\rm incoh,max} = \gamma_e m_e c^2/k \sim 6 \times 10^{12} \gamma_{e,3}\,{\rm K}$. The pulsar radio emission mechanism therefore must be *extremely* coherent. Guided by our understanding of other coherent sources in the universe, the emission source is very likely a plasma in which various instabilities can be developed to achieve coherent emission. A pair plasma is therefore required in an otherwise charge-separated magnetosphere.

Second, it is inevitable. A rotating magnetic pulsar is a unipolar generator, with a potential drop across the open field line region

$$\Phi = (B_p R^3 \Omega^2/2c^2) = 6.6 \times 10^{12}\ {\rm V}\ B_{p,12} P^{-2} R_6^3, \tag{1}$$

where B_p is the surface magnetic field at the pole, P is the rotation period, R is the neutron star radius, and the convention $Q = 10^n Q_n$ has been adopted. Such a huge potential is likely dropped along the open field lines (see §2 for the reasons), which accelerates a test particle up to an energy of $\gamma_p m_e c^2 = e\Phi \sim 6.6$ TeV, or $\gamma_p \sim 10^7$ (γ_p is the Lorentz factor of the "primary" particles to be distinguished with the secondary pairs). These particles emit curvature radiation (CR) or inverse Compton scattering (ICS) photons (eqs.[2-4]) during acceleration. These primary γ-rays inevitably materialize in a strong magnetic field or a hot thermal photon bath near the surface (see §2 for detailed discussions).

2 Pulsar Inner Gaps and Pair Production Mechanisms

In a force-free magnetosphere where $\rho = \rho_{\rm GJ}$, the electric field parallel to the local magnetic field, $E_\parallel$, is equal to zero everywhere. In order to have particles accelerated in a pulsar magnetosphere, there must be a deficit of ρ with respect to $\rho_{\rm GJ}$ so that an $E_\parallel$ can be developed. There are two preferred charge-depleted regions, namely gaps, in a pulsar magnetosphere: the polar cap region above the neutron star surface (inner gap), and the region near or beyond the $\boldsymbol{\Omega} \cdot B = 0$ "null charge surface" (outer gap). Since outer gaps can only be developed in young and millisecond pulsars while a much larger population of pulsars have radio emission, it is generally believed that radio emission may not be closely related to the existence of the outer gap. Rather, it should be closely related to an active inner gap which provides copious pairs from the polar cap cascade.

There are two ways to classify the inner gaps. The first way is according to the boundary condition at the pulsar surface, and inner gaps can be divided into two subtypes: a vacuum gap ($E_\parallel \neq 0$ at the surface, Ruderman & Sutherland 1975) and a space-charge-limited flow ($E_\parallel = 0$ at the surface, Arons & Scharlemann 1979). The first type (hereafter VG) requires that the charges (usually positive ions) are tightly bound in the surface, so that a large vacuum gap naturally develops as charges in the polar regions move away from the surface due to centrifugal forces. Such a suggestion, however, is questioned later since calculations show that ion binding energies are usually much smaller than the one required for binding (e.g. Usov & Melrose 1995 for a review). The picture may be still pertained by conjecturing either that some pulsars are more exotic objects with exposed strange quark surface (Xu, Qiao & Zhang 1999; Xu, Zhang & Qiao 2001), or that much stronger (compared with the dipolar field inferred from the P and $\dot{P}$ data) sun-spot like local magnetic fields anchor in the polar caps (Gil & Mitra 2001; Gil & Melikidze 2002). The second type of inner gaps (hereafter SCLF) is the natural outcome of a neutron star (or a strange star with a normal matter crust) with none or weakly distorted dipolar magnetic field configuration. In such a case, charges (either electrons for $\boldsymbol{\Omega} \cdot B > 0$, or ions for $\boldsymbol{\Omega} \cdot B < 0$) will be freely pulled out from the surface. Taking $\rho = \rho_{\rm GJ}$ at the surface, it is natural that a deficit of ρ with respect to $\rho_{\rm GJ}$ will grow as the current flow outwards in the open field line region, since both ρ and $\rho_{\rm GJ}$ follow different $r-$dependences. In the early years of pulsar theories when a general relativistic effect is not noticed, such ρ-deficit growth was believed to be due to the curvature of the pulsar dipolar field lines (Arons & Scharlemann 1979; Arons 1983). In an oblique pulsar, for those field lines curving towards the rotational axis (the so-called favorably curved lines), an decreasing angle between $\boldsymbol{\Omega}$ and $\boldsymbol{B}$ result in a net gain in $\rho_{\rm GJ} \propto \boldsymbol{\Omega} \cdot B$ with respect to the local $\rho \propto |\boldsymbol{B}| \propto r^{-3}$ (r is the radial coordinate of the point of interest) value defined by the magnetic flux conservation. The small $E_\parallel$ gradient generated from a small $(\rho - \rho_{\rm GJ})$ deviation results in an elongated gap compared with VGs. The growth of $E_\parallel$ at the edges of the gap is even smaller, resulting in a "slot gap" (Arons 1983). Later Muslimov & Tsygan (1992) first realized that by taking into account the general relativistic effect, another more prominent acceleration mechanism in the SCLF picture is available. For a Kerr metric, an observer at infinity views that local inertia frames are dragged by the rotating body. This modified the requires "co-rotating" magnetosphere charge density to a relatively smaller value: $\rho_{\rm GJ}({\rm GR}) \simeq -[(\boldsymbol{\Omega} - \Omega_{\rm LIF}) \cdot B]/2\pi c\alpha \simeq -(\boldsymbol{\Omega} \cdot B/2\pi c\alpha)[1 - \kappa_g (R/r)^3]$, where $\alpha \sim 0.78$ and $\kappa_g \sim 0.15 - 0.27$ are some constants depending on the equation of state of the neutron star (Muslimov & Harding 1997; Harding & Muslimov 1998, hereafter HM98). Clearly, besides the "flaring" term due to field line curvature (the $[\mathbf{\Omega}\cdot\mathbf{B}]$ factor), an additional r-dependence of $\rho_{\rm GJ}$ is introduced (the $[1-\kappa_g(R/r)^3]$ factor). It turns out that this component results in a larger $(\rho-\rho_{\rm GJ})$ deviation, and a much faster growth of $E_\parallel$, as long as the inclination angle is not very close to 90° . Such an effect significantly influences the properties of the SCLF gaps (HM98). In the VG scenario, however, since $\rho=0$ in the gap, the frame-dragging modification is only minor, i.e., by a factor of $(1-\kappa_g)\sim 0.85$ (Zhang, Harding & Muslimov 2000, hereafter ZHM00).

The second way to classify inner gaps is according to the source of γ-ray photons that trigger the pair cascade. For a long time since the early pulsar theories, curvature radiation (CR) is regarded as the only source of the primary γ-rays (Sturrock 1971; Ruderman & Sutherland 1975; Arons & Scharlemann 1979). The typical CR photon energy is ($\mathcal{R}$ is the field line curvature)

$$\epsilon_{\rm CR}=(3/2)(\hbar c/\mathcal{R})\gamma_p^3\simeq 76\ {\rm GeV}\ {\mathcal{R}_6}^{-1}\gamma_{p,7}^3\,. \tag{2}$$

The importance of inverse Compton scattering (ICS) off the thermal X-rays near the neutron star surface was gradually appreciated later (e.g. Xia et al. 1985; Daugherty & Harding 1989; Dermer 1990; Sturner et al. 1995). Zhang & Qiao (1996) and Luo (1996), within the frameworks of VG model and the (non-relativistic) SCLF model, respectively, first clearly suggested that the ICS photons may be more energetic and therefore have shorter mean free path to generate pairs than the CR photons. Zhang et al. (1997) further pointed out that there are two preferred ICS photon energies (though K-N limit ignored), so that by combining the CR typical energy, there are altogether three inner gap "modes". The understanding of these three modes were greatly advanced by HM98, Hibschman & Arons (2001a, b, hereafter HA01a, HA01b) and Harding & Muslimov (2001, 2002, hereafter HM01, HM02) within the framework of the relativistic SCLF models. The first ICS mode is defined by the characteristic photon energy due to "resonant" scatterings (which are generally related to transition of electrons between the first Landau state and the ground state, and have much larger cross section than the Thomson cross section), i.e., ($B'=B/B_q$ and $B_q\equiv m_e^2c^3/\hbar e\simeq 4.414\times10^{13}$ G is the critical field)

$$\epsilon_{\rm ICS,R}=2\gamma_p B'(m_ec^2)\simeq 23\ {\rm GeV}\ \gamma_{p,6}B_{12}\,. \tag{3}$$

Scatterings above the resonance (non-resonant scatterings) also contribute to a significant higher energy component in the final IC spectrum. The typical energy of these scatterings is defined by the minimum of the IC-boosted thermal peak energy and the Klein-Nishina limit (i.e. the electron's kinetic energy)

$$\epsilon_{\rm ICS,NR}=\min(\gamma_p^2kT,\gamma_pm_ec^2)=\min(8.6\gamma_{p,4}^2T_6,5.1\gamma_{p,4})\ {\rm GeV}\,. \tag{4}$$

The K-N limit takes over as long as $\gamma_p>5.9\times10^3T_6^{-1}$. Resonant scattering also reaches the K-N regime when $B'>1$.

Gamma-rays produced via CR or ICS can materialize essentially in two ways, i.e., one photon production (1p: $\gamma\rightarrow e^+e^-$) in strong magnetic fields and sometimes two photon production (2p: $\gamma\gamma\rightarrow e^+e^-$). The 1p is believed to be the dominant source of pairs (Sturrock 1971). The pair generation rate exponentially grows as the factor $(1/2)(\epsilon_\gamma/m_ec^2)B'\sin\theta_{\gamma B}$ reaches a critical value of $\sim 1/10$, or in high magnetic fields ($B'>0.1$), as the threshold condition $(1/2)(\epsilon_\gamma/m_ec^2)\sin\theta_{\gamma B}>1$ is reached (Daugherty & Harding 1983), where $\theta_{\gamma B}$ is the incident angle between the gamma-ray and the local magnetic field. These define the *"mean free path" (i.e. attenuation length) of the photons*, l_{ph}, which is shorter for a larger ϵ_γ, for a larger $\theta_{\gamma B}$ (or a shorter pulsar period which gives a larger field line curvature), and for a higher B when the near-threshold effect is not important. In most pulsars, usually more than one generation of pairs are produced. The first generation pairs lose their perpendicular energies through synchrotron radiation (SR), and the resultant secondary γ-rays also usually meet one photon pair production condition, so that a photon-pair cascade develops (Daugherty & Harding 1982, 1996). The remaining parallel energy of the pairs will also be converted to radiation through resonant ICS, and the resulting photons may sometimes (although the condition is more stringent) be converted to further pairs, leading to a full polar cap cascade (Zhang & Harding 2000a).

The 2p process is in principle expected, since the typical energy of primary gamma-rays, ϵ_γ, and the typical energy of the thermal X-rays, ϵ_x, usually satisfy the kinetic condition $\epsilon_\gamma \epsilon_x (1-\cos\theta_{\gamma x}) \geq (m_e c^2)^2$, where $\theta_{\gamma x}$ is the incident angle between the gamma-ray and the X-ray (Zhang & Qiao 1998). However, the mean free path of a typical gamma-ray for 1p is usually smaller than that of 2p, so that a gamma-ray usually has materialized in the strong magnetic field before interacting with the thermal X-rays. To have 2p competitive against 1p, one has to either raise the thermal luminosity and $\theta_{\gamma x}$ or considerably lower the magnetic field. The hot magnetar environment (Zhang 2001) and the low-B millisecond pulsars (Harding, Muslimov & Zhang 2002, hereafter HMZ02) are therefore possible sites where the 2p process may become noticeable.

3 Energy Budget Deathlines and Death Valley

We have shown above that pair production is generally expected in normal pulsars, and in §1 we have made the argument that pair production is almost obligatory in the current radio emission models. *Production of free pairs is the essential condition for pulsar radio emission. The condition that free pair production is prohibited or suppressed therefore defines radio pulsar death* (recent discussions on this topic include, e.g. Arons 2000; ZHM00; HA01a,b; HM02; HMZ02). One important caveat is that free pair production may not be *the sufficient condition* for pulsar radio emission, which is model-dependent and poorly known. There exists a missing link between the pulsar high energy emission theories from which the cascade pair properties are derived, and the pulsar radio emission theories in which various pair properties are required (but see Arendt & Eilek 2002 for a recent attempt to connect the missing link).

When a radio pulsar ages, it slows down so that the unipolar potential drops. The accelerated particles achieve less energies, and their subsequent CR/ICS photons are less energetic. Eventually, these photons no longer pair produce, either via 1p or 2p. No further pair plasma is ejected into the plasma, and the pulsar stops shining in the radio band. A radio pulsar dies. The death of this type is due to inadequate rotational energy budget. The condition defines the so-called energy budget "deathline" (e.g. Ruderman & Sutherland 1975 and many literatures thereafter) in the $P-B_p$ space or $P-\dot{P}$ space. For a star-centered dipole, the surface magnetic field at the pole reads (I and R are moment of inertia and radius of the neutron star, respectively)

$$B_p = 6.4 \times 10^{19}\ \mathrm{G}\ (P\dot{P})^{1/2} I_{45}^{1/2} R_6^{-3}\,. \tag{5}$$

In some work where detailed theories are not needed, the pulsar deathline is conventionally taken as a line of constant Φ (eq.[1]), with a slope 3 in the $P-\dot{P}$ diagram. We'd like to caution here, however, that the real death lines could considerably differ from such a line, since the final potential drop across the gap at the pulsar death is defined by the condition of pair production, which gives a lower Φ with a different slope than 3. In fact, it is not easy to draw a single line to define radio pulsar death, since many factors will affect the position of the deathline. (This is why I did not present any analytical expression of the deathline in this chapter.) What is more relevant should be a "death valley", a term first invented by Chen & Ruderman (1993).

Before moving into detailed discussions about the energy budget deathlines, two more length parameters need to be introduced. One is *the acceleration length*, l_{acc}, which is the typical distance an electron has to travel for acceleration to achieve a typical Lorentz factor $\gamma_{p,c}$, with which the electron's CR/ICR emission photons can pair produce. This is acceleration-model-dependent (VG vs. SCLF). Another one is *the mean free path of the electrons*, l_e, which is the distance of the electron travels before emitting one CR or ICS photon, i.e., $l_e \simeq (\epsilon_\gamma/\dot{\gamma} m_e c^2)c$. This is radiation-mechanism-dependent (CR vs. ICS). These two length parameters, together with *the mean free path of the photon*, l_{ph}, as discussed in §2, are essential for the following discussions. In all the models, a test particle has to be accelerated through a length scale of l_{acc} to reach a Lorentz factor γ_c. This particle emits a test photon (via CR or ICS) with a probability (depends on l_e), and the photon attenuation length is l_{ph}. By minimizing the length $l_{acc} + l_{ph}$, one gets a typical height of the gap, and hence, the potential drop across the gap (ΔV). By demanding ΔV equal to the maximum achievable potential (some fraction of Φ in eq.[1]), one gets a deathline (ZHM00).

Lack of a well-defined deathline is due to many uncertainties involved:

(1) Criterion: In the literatures, there exist essentially two criteria to define the deathlines. ZHM00 adopted the criterion of $l_e \leq l_{acc} + l_{ph}$ (see also Zhang et al. 1997), which ensures that the pair "multiplicity" is at least 1. HA01a adopted a (usually) less demanding criterion for pair production to reach a minimum multiplicity adequate to screen the $E_\parallel$. These could be regarded as the "strong criterion". On the other hand, HM02 proposed a "weak criterion". They did not introduce any demand on l_e, but just evaluated the condition that pair production happens at all. In this criterion, $E_\parallel$ is not necessarily screened, and the pair number density at the deathline may be very low, i.e., could be well below the GJ density. Two comments need to be addressed. First, neither criteria are necessarily the criterion for radio emission. The latter merely defines a pair deathline. Second, the discrepancies between both criteria only step out in the ICS-controlled gaps. For CR-gaps, the difference between these treatments disappear, essentially because $l_e \ll l_{ph}$ in the CR case (ZHM00).

(2) Model-dependence: Clearly different models (VG or SCLF; CR-, RICS-, or NRICS-controlled) result in different ΔV's of the gap, and hence, different deathlines within that particular model (e.g. ZHM00). An adequate study needs to address the parameter regimes for the different modes to dominate so as to achieve a synthesized deathline in the whole $P - \dot{P}$ space (e.g. HA01a, HM01, HM02, for SCLF models). The following essential features are noticeable. In VGs, usually l_{acc} is small and negligible; in SCLFs, l_{acc} is comparable to (although smaller than) l_{ph} for the minimized case; in CR gaps, l_e is small and negligible; while in ICS gaps, l_e is comparable to $l_{ph} + l_{acc}$.

(3) Equation of state (EOS): Since 1p process is the dominant pair formation process in normal pulsars, the magnetic fields in the pair formation region is a crucial parameter to define the deathline in the $P - \dot{P}$ space (although not in the $P - B_p$ space). For the pure dipolar field configuration, equation (5) indicates that the neutron star EOS influences the estimated polar cap surface magnetic fields through influencing I_{45} and R_6. If pair production region is right above the surface (or a fixed altitude above the surface), then different EOSs result in different deathlines. In SCLF models, different EOSs also modify the frame-dragging terms. The combined effects (HMZ02) generally makes a larger difference in short period (e.g. millisecond) regimes than in the long period regime. Softer neutron star EOSs or strange star EOSs tend to facilitate pair production and hence, lower the deathlines.

(4) Unknown surface field configuration: A potentially even more important factor that may influence the surface magnetic field configuration and hence the deathlines is the unknown near-surface magnetic field configuration. It has been long recognized that a CR-controlled gap in a star-centered dipolar field can not sustain pair production in all known pulsars, so that near-surface multipole magnetic fields have long been speculated (Ruderman & Sutherland 1975; Arons & Scharlemann 1979). Several possible distorted magnetic configurations have been discussed in Chen & Ruderman (1993) within the VG models, and these are also valid in discussing other models. The magnetic configuration is the key factor that influences the deathlines although it is sparsely modeled due to many uncertainties involved. Recently, Gil et al. (Gil & Mitra 2001; Gil & Melikidze 2002; Gil et al. 2002) investigated some possible consequences when the polar cap fields are extremely curved and strengthened.

(5) Refined geometry and physics: Most deathline discussions have been analytical. With the "weak criterion" and the assumption of a star-centered dipole, HM01 and HM02 performed detailed numerical simulations to study pulsar deathlines for the CR- and ICS-controlled SCLF gaps, respectively. Refined geometry (e.g. curved spacetime) and physics (e.g. pair formation details) are included. Their results suggest that many of the previous analytical treatments may not be reliable. One important finding is that at the deathlines, the maximum usable potential is only a small fraction of the value expected analytically (cf. ZHM00), and is model-dependent (CR vs. ICS). This cautions us that numerical calculations may be also essential to discuss deathlines in other models under other criteria and/or assumptions.

4 A Death Valley in the High-B Regime?

Two other QED processes can potentially suppress free pair formation in the strong magnetic field regime. These are magnetic photon splitting (sp: $\gamma \to \gamma\gamma$) and bound pair (positronium) formation.

Baring & Harding (1998, 2001, hereafter BH98, BH01) suggested a possible radio pulsar deathline in the high magnetic field regime, due to possible suppression of 1p pair production by magnetic photon splitting. (Strictly speaking, pulsars do not evolve across this line, so the "deathline" is essentially a radio quiescence line.) Such a line, by definition, is defined by $l_{\gamma\to\gamma\gamma} < l_{\gamma\to e^+e^-}$, where l's are the γ-ray attenuation lengths of the relevant processes (sp or 1p), which are dependent on both the field strength and the γ-ray energy, ϵ_γ. By specifying a characteristic ϵ_γ, a deathline in the $P-B_p$ or $P-\dot{P}$ space can be plotted. BH98's photon splitting deathline ($\dot{P} \simeq 7.9\times10^{-13}P^{-11/15}$) is defined by specifying $\epsilon_\gamma = \epsilon_{\rm esc}$, where $\epsilon_{\rm esc}$ is critical energy of the γ-ray that can just evade both 1p pair production and photon splitting.

There are several caveats concerning the BH98 photon splitting deathline:

(1) How many modes split? The BH98 high-B deathline is contingent upon the assumption that photons for both the $\|$ and $\perp$ modes (defined by the electric vector with respect to the magnetic field plain) split in superstrong magnetic fields. Within the linear vacuum polarization treatment, only the $\perp$-mode photons are allowed to split at least for fields below B_q (e.g. Usov 2002). Whether the $\|$-mode photons split in superstrong fields due to non-linear vacuum polarizations is fundamental for all the discussions in this section.

(2) High altitude pair formation? Even if both photon modes split, whether 1p pair production is completely suppressed still depends on some further conditions. If particles can be accelerated at higher altitudes and emit photons, these γ-rays can still produce pairs since the local field has degraded with respect to the high value near the surface (Zhang & Harding 2000b, hereafter ZH00b). For a VG, on the other hand, since downwards photons can not pair produce and there is no free source of the primary electrons, essentially few pairs

could be generated. The magnetosphere would be dead, so strictly speaking, the photon splitting deathline is valid only for such a case (ZH00b).

(3) Model-dependence? Both $l_{\gamma\to\gamma\gamma}$ and $l_{\gamma\to e^+e^-}$ depend on ϵ_γ in different ways. It is more relevant to adopt the characteristic ϵ_γ of a certain type of the VG gap, rather than ϵ_{esc} to define the photon splitting deathlines (Zhang & Harding 2002; Zhang 2001). The deathlines drawn with such a criterion tends to be tilted up with respect to the BH98 deathline in the short period regime, since fast pulsars have larger potentials to accelerate particles to higher energies and the more energetic photons are more facilitated to 1p pair production (Zhang & Harding 2002). Distorted magnetic configurations will also modify the competition between the sp and the 1p processes (e.g. Gil et al. 2002).

(4) 2p pairs in magnetars? Finally, in magnetars, even if 1p pair production could be completely suppressed by photon splitting, 2p pair production typically has a shorter attenuation length in the hot magnetar environment (Zhang 2001). So pair production might not be completely suppressed in magnetars. A photon splitting death valley, if exist, is therefore only valid for the high magnetic field pulsars without substantial magnetic decay but with strong binding at the surface.

Bound pair formation (e.g. Usov & Melrose 1995; Usov 2002) essentially delay the free pair formation front, but in principle does not suppress free pair formation. Its role is similar to the two-mode photon splitting processes in a SCLF gap, i.e., to increase the gap height and the gap potential, which is helpful to interpret pulsar high energy emission within the polar cap models.

5 Concluding Remarks

The following statements may be pertinent:

(1) We now have a clear framework about the particle acceleration and photon-pair cascade in the pulsar polar cap region. Pair production from the polar cap is believed to be an essential condition for pulsar radio emission. The sufficient condition for radio emission, however, is unknown. Personally, I think that radio emission condition should be more stringent than the pair production condition. Thus, (moderate) non-dipolar fields may indeed exist at least in some pulsars. An important advance in the pulsar study in the recent years is the realization that ICS plays a crucial role in stead of CR in determining gap properties at least in some pulsars.

(2) Theories are generally successful to define the conventional radio pulsar death in the long period regime, although many uncertainties prevent us from achieving a solid deathline. A death valley is more pertinent. Without introducing distortions from a star-centered-dipolar configuration, one can not include all pulsars above the deathline. The 8.5 second pulsar (Young et al. 1999) remains a challenge for any pure-dipole model after detailed numerical simulations. A best guess is that an ICS-controlled gap anchors in this pulsar with a moderate non-dipolar near-surface field configuration.

(3) In the high magnetic field regime, pulsar death is not unambiguously defined. There is no strong reason against the possible radio emission from high magnetic field pulsars and magnetars. Possible reasons of apparent radio quiescence of magnetars include (a) the beaming effect; (b) that the coherent condition is destroyed; (c) that the main energy band of the coherent emission is not in radio; or (d) that the soft gamma-ray repeaters and the anomalous X-ray pulsars are not magnetars at all (but might be accretion-powered systems).

ACKNOWLEDGEMENTS I am grateful to Alice Harding, G. J. Qiao, Alex Muslimov, J. L. Han, R. X. Xu, and W. P. Lin for stimulating collaborations, to Jon Arons, Matthew Baring, Janusz Gil for discussions concerning various topics covered in this talk, and to R.

X. Xu for presenting the materials at the meeting on behalf of me.

References

Arendt Jr.P.N., Eilek J. A. ApJ, 2002, 581: 451
Arons J. ApJ, 1983, 266: 215
Arons J. In: M. Kramer et al. (eds) Pulsar Astronomy - 2000 and Beyond (Proc. of IAU 177th Colloquium), ASP Conf. Ser., 2000, 202: 449
Arons J., Scharlemann E.T. ApJ, 1979, 231: 854
Baring M G, Harding A K. ApJ, 1998, 507: L55 (BH98)
Baring M G, Harding A K. ApJ, 2001, 547: 929 (BH01)
Chen K, Ruderman M. ApJ, 1993, 402: 264
Daugherty J K, Harding A K. ApJ, 1982, 252: 337
Daugherty J K, Harding A K. ApJ, 1983, 273: 761
Daugherty J K, Harding A K. ApJ, 1989, 336: 861
Daugherty J K, Harding A K. ApJ, 1996, 458: 278
Dermer C D. ApJ, 1990, 360: 197
Gil J, Melikidze G I. ApJ, 2002, 577: 909
Gil J, Melikidze G I, Mitra D. A&A, 2002, 388: 235
Gil J, Mitra D. ApJ, 2001, 550: 383
Goldreich P., Julian W H. ApJ, 1969, 157: 869
Harding A K, Muslimov A G. ApJ, 1998, 508: 328 (HM98)
Harding A K, Muslimov A G. ApJ, 2001, 556: 987 (HM01)
Harding A K, Muslimov A G. ApJ, 2002, 568: 862 (HM02)
Harding A K, Muslimov A G, Zhang B. ApJ, 2002, 576: 366 (HMZ02)
Hibschman J A, Arons J. ApJ, 2001a, 554: 624 (HA01a)
Hibschman J A, Arons J. ApJ, 2001b, 560: 871 (HA01b)
Luo Q. ApJ, 1996, 468: 338
Muslimov A G, Harding A K. ApJ, 1997, 485: 735
Muslimov A G, Tsygan A I. MNRAS, 1992, 255: 61
Ruderman M A, Sutherland P G. ApJ, 1975, 196: 51
Sturner S J, Dermer C D, Michel F C. ApJ, 1995, 445: 736
Sturrock P A. ApJ, 1971, 164: 529
Usov V V. ApJ, 2002, 572: L87
Usov V V, Melrose D B. Aust J Phys, 1995, 48: 571
Xia X Y, Qiao G J, Wu X J, et al. A&A, 1985, 152: 93
Xu R X, Qiao G J, Zhang B. ApJ, 1999, 522: L109
Xu R X, Zhang B, Qiao G J. AstroParticle Phys, 2001, 15: 101
Young M D, Manchester R N, Johnston S. Nature, 1999, 400, 848
Zhang B. ApJ, 2001, 562: L59
Zhang B, Harding A K. ApJ, 2000a, 532: 1150
Zhang B, Harding A K. ApJ, 2000b, 535:, L51(ZH00b)
Zhang B, Harding A K. Mem.S.A.It, 2002, 73: 584 (astro-ph/0102097)
Zhang B, Harding A K, Muslimov A G. ApJ, 2000, 531: L135 (ZHM00)
Zhang B, Qiao G J. A&A, 1996, 310: 135
Zhang B, Qiao G J. A&A, 1998, 338: 62
Zhang B, Qiao G J, Lin W P, Han J L. ApJ, 1997, 478: 313