Are There Two Pulsar Emission Mechanisms?

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Abstract

We show that "core" and "cone" pulsar emission profiles are connected, through standard theoretical models, to dynamical properties of the pulsar emission region. The models predict pair plasma formation only in pulsars which show core-type emission. Emission models which assume turbulence driven by relative velocities of the pair swarms probably apply to coral pulsars. If conal pulsars are pairless, however, a different emission mechanism is required for these objects.

Subject Headings: pulsars:general – radiation mechanisms:nonthermal – plasmas

1 Introduction

Many of the observed properties of pulsars, such as radio luminosity and pulse timing characteristics, are fairly uniform over the set of pulsars. However, observations show two distinct types of radiation source geometries in pulsars, identified as "core" and "cone" (*e.g.*, Rankin 1990; Lyne & Manchester 1988). Rankin suggests that these source morphologies indicate distinct emission mechanisms, while Lyne & Manchester disagree. The question of the emission mechanism in the two regions is a perilous issue to debate when a complete theory for even one emission process is lacking. We show in this paper, however, that clues for the existence of two different emission processes can be extracted from current models of polar cap dynamics. In addition, we show that the distinction between cone and core emission agrees strikingly well with the theoretical clues we find.

Our investigation centers on the conditions required for the formation of a pair plasma above the magnetic polar cap of a rotating neutron star, and the minimal requirements for coherent plasma emission. In particular, we focus on two important points:

1. pair plasma is assumed in essentially all modern emission models; and
2. given the pair plasma as the emission source, collective behavior is needed for coherent emission.

We base our analysis on prevailing theories of relativistic polar cap current flow, which we call the "standard" polar cap model. This "standard" pulsar model is reviewed in Melrose 1992, and Arons 1981; see also books by Lyne & Smith 1990, Michel 1991, and Meszaros 1992, and a general review by Taylor & Stinebring 1986. Michel (1992) and Arons (1992) point out potentially serious problems with the standard model applied to the entire pulsar magnetosphere. Despite these problems, the standard model has been useful in interpreting the general characteristics of radio emission, particularly the sweep of linear polarization angle and the localization of the emission in pulse phase. This suggests to us that that the models are mostly correct in their geometrical picture of the radio-luminous polar cap.

In this paper we review specific versions of the standard polar cap model (*e.g.* Sturrock 1971; Ruderman & Sutherland 1975; and Arons 1983). From these, we find that a pair plasma emission process can apply only to young, short period pulsars. We will show that this theoretical constraint correlates well with the population of pulsars showing core-type emission. We challenge the classical view that aging pulsars cease being radio emitters when they no longer sustain strong pair cascades. Instead, we suggest that they are still radio emitters, but become conal pulsars.

Condition 1 constrains the magnetospheric model by requiring conditions appropriate for the formation of the pair plasma. The pair plasma is created by the annihilation of high energy γ-rays in the magnetic field, and a subsequent cascade of photon emission and annihilation (Sturrock 1971). This requires a region above the polar cap which is optically thick to γ-rays. Following Erber (1966), we define the pair creation parameter χ as

$$\chi = \frac{1}{2}\frac{B}{B_{cr}}\frac{\epsilon}{m_e c^2}\sin\psi \tag{1}$$

In the limit $\chi \ll 1$, the attenuation coefficient of a γ-ray photon in a magnetic field B is

$$\kappa(\chi) \simeq 0.32\frac{\alpha_F}{\lambda\!\!\!^{-}_c}\frac{B}{B_{cr}}e^{-4/3\chi} \tag{2}$$

The physical constants are electron charge e and mass m_e, speed of light c, fine structure constant $\alpha_F = e^2/(\hbar c)$; Compton wavelength $\lambda\!\!\!^{-}_c = \hbar/(m_e c) = 3.9\times10^{-11}$cm, and the critical magnetic field $B_{cr} = m_e^2 c^3/(\hbar e) = 4.41\times10^{13}$G.

A photon of energy ϵ is emitted parallel to the magnetic field, but as it propagates, acquires a finite pitch angle to the magnetic field due to the magnetic field radius of curvature, ρ: the pitch angle after a travelling a distance s is then given by $\sin\psi = s/\rho$. The optical depth after travelling s is then

$$\tau_B \simeq \kappa(\chi)\rho\sin\psi \tag{3}$$

It is clear from equation (2) that the optical depth is extremely sensitive to the parameter χ. Because of this, the value $\chi \sim 0.15$ is often taken as a simple measure of the opacity point. The photon energy ϵ which contributes to χ depends, in turn, on the electric potential above the polar cap (the electric potential accelerates particles in the polar gap which curvature radiate the γ-rays). The necessary condition for the formation of the plasma will be

$$\tau_B > 1 \qquad \text{somewhere in the polar cap region} \tag{4}$$

In the standard model, this condition is readily satisfied only in pulsars with rapid rotation rates and large magnetic fields: that is, only in young pulsars. Several authors (*e.g.*, Sturrock 1971; Ruderman & Sutherland 1975; Chen and Ruderman 1993; Rudak & Ritter 1994) have called this condition the "death line", and inferred that pulsars become radio-quiet when they age past this condition.

Condition 2 in the pair plasma emission model is a mechanism for imposing coherence in the radio emission. A coherent process is expected because the emission has brightness temperature as high as $10^{30}K$, well beyond the synchrotron-Compton limit. Coherence would likely derive from an instability in the plasma. One source of free energy is the relative streaming of the two pair species, needed to maintain corotation, as described by Cheng and Ruderman (1977a). If the relative streaming in the pair plasma develops a two-stream instability, coherence in the radio emission can be maintained, for example by stream bunching or the growth of plasma turbulence. If not, the pulsar pair magnetosphere does not have the means to be radio loud. Therefore, the issue of instability forms an important link between the dynamical properties of the polar cap current flow and the radio emission properties.

The well-known Penrose criterion requires for two-stream instability that the pair plasma components have well-defined peaks in the momentum distribution (Buschauer & Benford 1977; Weatherall 1994). The shape of the momentum distribution of the streams depends on the energy distribution of the pairs when they are created (Daughtery & Harding 1983). Weatherall (1994) argues that the Penrose criterion fails when the pair creation parameter χ is greater than unity (although this does not take into account how the shape of the momentum distribution functions of the streams are altered by particle trapping in the kinetic flow; for example, Arons 1981; Beskin, Gurevich & Istomin 1988). The condition necessary for coherence in the fluid flow model is, then,

$$\chi < 1 \qquad \text{at} \qquad \tau_B = 1 \tag{5}$$

Because χ at the site of pair plasma cration is relatively insensitive to the dynamical parameters in the pulsar magnetosphere, this condition is readily satisfied in most pulsars, with the possible exception of the most energetic ones with short rotation periods. Consequently, the coherence requirement can define a "birth line" for pulsars.

The consequences of equation (4) and equation (5) require connection with theoretical magnetospheric models. In the P and $\dot{P}$ parameter space of pulsars, those which are optically thick to γ-rays (and therefore develop pair-cascades) are generally those with small periods, P, and large spin-down rates $\dot{P}$. This pair-filled, radio strong region (region II in our figures) is bounded by other parts of parameter space which fail either the opacity (region I in our figures) or the coherence (region III in our figures) conditions. It is older pulsars, with larger periods and lower spin-down rates which fail to satisfy condition (4); the radiation mechanism must not be tied to a pair-plasma magnetosphere. Very young neutron stars may fail to satisfy (5); these objects would not be visible as radio pulsars.

Because the conditions at the pair formation region are very sensitive to inferred magnetospheric parameters, these ideas provide an opportunity for testing the theoretical model against basic observable parameters and pulse structure.

2 Connecting Models to Observables

The pulsar rotation period P and spin-down rate $\dot{P}$ are basic observable attributes of pulsars. In order to relate these observable characteristics to the pair-filled *vs.* pair-less discussion above, we must rely on physical models to derive B, ϵ, and τ_B.

The magnetic field is tied to the spin-down rate through calculation of the angular momentum lost by the pulsar – for example, through relativistic particles in a stellar wind (Goldreich & Julian 1969) in aligned rotators, or by low frequency magnetic dipole radiation (Ostriker & Gunn 1969) in oblique-rotators. The angular momentum loss gives a value for the magnetic field

(*cf.* Meszaros 1992)

$$B = 3 \times 10^{19}\, \alpha_i\, (P\dot{P})^{1/2}\, G \tag{6}$$

The geometric term α_i is a function of the angle i between the spin axis and the magnetic axis. We will assume similar spindown properties of aligned and oblique rotators, and use $\alpha_i = 1$. An alternate choice would be $\alpha_i = \csc\, i$, as in the case of angular momentum loss by magnetic dipole radiation alone (*c.f.* Barnard & Arons 1982). This leads to different spindown characteristics of aligned versus oblique rotators (Michel & Goldwire 1970). However, we note that Rankin (1990) finds no evidence that the alignment of the magnetic axis relates to age of the pulsar.

The γ-rays that seed the pair cascade are generally assumed to come from curvature radiation. In this case, their characteristic energy is given by

$$\epsilon = \frac{3}{2} m_e c^2 \frac{\lambdabar_c}{\rho} \gamma_b^3 \tag{7}$$

The γ-rays are emitted by energetic electrons in the rotating magnetic structure above the pulsar polar cap. The primary electron beam acquires its energy γ_b by electrostatic acceleration. A test charge tied to a magnetic field line (co-rotating with the neutron star) feels the electric field $E = -\nabla\phi$, where

$$-\nabla^2\phi = 4\pi(\eta - \eta_R) \tag{8}$$

The beam energy is given by $\gamma_b = e\phi/m_e c^2$. η is the local charge density and η_R, the corotation charge density, is given by (Goldreich-Julian 1969; Mestel 1971):

$$\eta_R \sim -\frac{\Omega \cdot B}{2\pi c} \tag{9}$$

When the charge density is η_R, $E = 0$, which implies a force-free condition in the corotating magnetosphere. Solutions to (8) can be derived in a variety of ways, which differ primarily through the assumed boundary conditions. Solutions for the accelerating potential are reviewed below for gaps devoid of plasma (*e.g.* Ruderman & Sutherland 1975) and for space-charge limited flows with and without vacuum breakdown (following Chen & Ruderman 1977b, and Arons & Scharleman 1979). Although these models give γ_b values which differ only slightly numerically, the physical scalings with P and $\dot{P}$ are different, and lead to different predictions concerning the development of the pair cascade and streaming instability.

Finally, when connecting models to observables, the basic structure of the magnetic field is poorly constrained, in particular as it affects the local field line curvature. The simple expedient of a dipole field has a radius of curvature (at the neutron star's radius, R_*),

$$\rho = \frac{4}{3}\frac{R_*}{\sin\theta_*}, \tag{10}$$

where θ_* is the magnetic colatitude of the magnetic field line. Because this often leads to curvature photon energy which is too low to interest theorists, models abound with line curvature

$$\rho = R_* \tag{11}$$

This modification to the curvature is justified by invoking higher order magnetic multipoles which are presumed to exist near the surface of the neutron star. The choice of field curvature impacts the pair cascade and streaming instability threshold condition.

The models discussed below refer exclusively to polar cap models, as distinguished from the outer gap region (Cheng, Ho & Ruderman 1986a,b). As Cordes (1992) summarizes, the lack of retardation and aberration effects require emission altitudes within $\sim 100 - 1000$ km of the star's surface. In addition, Rankin's work locates the emission regions at no more than ~ 100 km altitude. These limits are well within the light cylinder. Thus, we consider only the polar cap as the source of radio emission.

2.1 The Empty Gap

The empty gap solution of Equation (8) for $\eta = 0$ is

$$\phi = \frac{B\Omega}{2c}h^2, \tag{12}$$

representing the maximum potential drop along an open magnetic field line (Ruderman & Suderland 1975; also Chen & Ruderman 1993). In the empty gap models, the gap height h is generally fixed by the *geometry* of the polar gap (*c.f.* Ruderman & Suderland 1975). The geometric gap height is given by

$$h_{GM} \sim R_* \left(\frac{R_* \Omega}{c}\right)^{1/2} \tag{13}$$

which is equal to the size of the polar cap, *i.e.*, the region connected to field lines which are open beyond the light cylinder. Chen & Ruderman (1993) discuss the death line in the context of this model. Although equation (12) is useful in bounding the acceleration potential, the gap will not be empty if the star's surface readily emits charged particles into the region above the polar cap. This is considered in the models below.

2.2 Space-Charge Limited Flow

When the polar cap acts as a one dimensional cathode, the accelerating potential is modified by the distribution of free charge. In space-charge limited flow, it is assumed that far from the star, the co-rotating flow is force-free and relativistic. Therefore, $\eta = \eta_R$ and $v \sim c$ in the asymptotic flow region. The solution to Poisson's equation (8) gives an asymptotic value for the field $E = 2^{3/4}(4\pi\eta_R Mc^2/Q)^{1/2}$, where M and Q are the mass and charge of the particles supporting the potential. This solution pertains everywhere in the gap except close to the surface where the flow is nonrelativistic, and beyond the geometric height, where the geometry departs from one-dimensional. At the limiting geometric height, the accelerating potential is

$$\phi = 2^{3/4} \left(\frac{2\Omega BMc}{Q}\right)^{1/2} h_{GM} \tag{14}$$

Note that ion-supported potentials above positively charged polar caps are larger than potentials limited by electron flow. Cheng & Ruderman (1977b) [hereafter CR] assume ions with $M/Q \sim 20m_p/e$.

2.2.1 Pulsar characteristics defined by CR

From (14) for the accelerating potential, it follows that the necessary condition for the formation of a magnetosphere, using seed photons from curvature radiation, is (*cf.* CR):

$$\dot{P} > 7.7 \times 10^{-15} \left(\frac{M/Q}{2m_p/e}\right)^{-6/5} \left(\frac{\rho}{R_*}\right)^{8/5} \left(\frac{P}{1\,sec}\right)^{9/5} \tag{15}$$

This result makes an important connection with the observed parameters of pulsars. In Figure 1, the values P and $\dot{P}$ of several hundred pulsars in the database of Taylor, Manchester & Lyne (1993) are shown graphically. Equation (15) defines the region in this parameter space for which the theory predicts a pair-plasma magnetosphere. The demarcation line (the so-called "death line") between the pair-filled regime and pairless regime is shown in Figure 1. For this line we have followed CR, using $(M/Q) = (20m_p/e)$ and $\rho = R_*$. Neutron stars which fall in the region below and to the right of the line, in region I, do not sustain pair magnetospheres.

In the case where the magnetosphere is created, one can also solve for the pair creation parameter at the point where the optical depth is unity. Thus, equation (5) for plasma coherence requires that

$$\dot{P} < 1.9 \times 10^{-9} \left(\frac{M/Q}{2m_p/e}\right)^{-3/2} \left(\frac{\rho}{R_*}\right)^{3/2} \left(\frac{P}{1\,sec}\right)^{2} \tag{16}$$

Equation (16) defines the region in the parameter space for which streaming instability in the pair plasma is viable. In the complementary region, kinetic effects, due to the momentum uncertainty of the pairs at creation, suppress instability. The demarcation line (the "birth line") is shown also in Figure 1. Neutron stars which fall above and to the left of this line, in region III, do not radiate as radio pulsars. Stars falling in region II, in between the two demarcation lines, should be radio-loud pulsars in this model.

Region II in Figure 1 roughly coincides with the part of P and $\dot{P}$ space occupied by pulsars. The fact that the turnoff of the pair plasma creation mechanism correlates – at least qualitatively – with the absence of long period pulsars is a well known feature of the pair discharge model (Sturrock, 1971), and is consistent with the expectation of pair-filled magnetospheres in all radio-loud pulsars. Thus, the CR model would suggest that all radio-loud pulsars do indeed have pair-filled magnetospheres; as they age the pair cascade terminates, and with it the radio emission. However, the CR model achieves this agreement between theory and observations by building in rather faborable circumstances. Most notably, they require a potential drop supported by heavy ions, which is not consistent with what is now known from binding energy calculations. The CR model is also imcomplete in disregarding the effects of the diverging field geometry and the termination of the diode by vacuum breakdown.

2.3 Space-Charge Limited Flow with Vacuum Breakdown

The previous space-charge limited model does not allow for vacuum breakdown in the gap. Gamma-ray curvature photons produced in the gap are absorbed by pair creation on the magnetic field at a *breakdown* height determined where the optical depth is unity

$$\tau_B(h_{GAP}) \sim 1 \tag{17}$$

Equation (17) defines h_{GAP}, the terminated gap height. In Arons & Scharlemann (1979) [hereafter AS], pair creation establishes a second conducting boundary at height h_{GAP}, so that $E = 0$ both at $h = 0$ and at $h = h_{GAP}$. The density in the gap departs linearly from η_R due to curved geometry of the field lines. This departure from the CR picture results in a larger accelerating potential. Solution to Poisson's equation for the one-dimensional diode gives

$$\phi(h) = \frac{1}{2}\frac{\Omega B}{c}\,\sin\,i\,\frac{h_{GAP}}{\rho}\,h^2\left(1 - \frac{2}{3}\frac{h}{h_{GAP}}\right) \tag{18}$$

When h_{GAP} is larger than h_{GM}, as is the case for all but the very shortest period pulsars, the potential solution of equation (18) must be modified to take into account the full three-dimensional geometry of the open flux tube. The potential in the long, narrow diode has the form

$$\phi(h) = \frac{1}{2}\left(\frac{\Omega_* R_*}{c}\right)^{5/2} R_* B\left(\frac{h}{R_*}\right)\sin i \tag{19}$$

up to the gap height h_{GAP}. The gap height must be found self-consistently using γ-ray seeds from curvature radiation and the pair formation opacity, through equations (2) and (17), as described by AS.

2.3.1 Pulsar characteristics defined by AS

AS work out the maximum periods for pulsars forming plasma magnetospheres. Condition 1 on the γ-ray opacity is met in the three-dimensional AS model when

$$\dot{P} > 2.87 \times 10^{-15} P^{11/4} (\sin\ i)^{-3/2} \tag{20}$$

This solution applies to the extreme case of field curvature (equation 11) where $\rho \sim R_*$. Equation (20) follows from AS by assuming that the surface field is much greater than the dipole magnetic field component, which requires large l-pole contributions.

The opacity condition given by Eq (20) is plotted in Figure 2. We use $\sin\ i = 1$ to bound the region where the pair cascade can develop: for smaller inclination angles, the "death line" shifts to smaller P. In marked contrast to the CR model, this line lies well within the region of P and $\dot{P}$ space occupied by pulsars.

It should be pointed out that this result depends on an earlier assumption. If instead of $\alpha_i = 1$ in equation (6) for the angular momentum loss, we had used $\alpha_i = \csc\ i$, then $(\sin\ i)^{-3/2}$ in equation (20) becomes $(\sin\ i)^{1/2}$. Thus, rotators with $i < \pi/2$ could have plasma magnetospheres and fall in region I of Figure 2, because we have underestimated the magnetic field. Nonetheless, for a uniform distribution of inclination angle, the mean value of $(\sin\ i)^{1/2}$ is 2/3, so the maximum period for the majority of pulsars having a given spindown rate $\dot{P}$ would still fall close to the line in Figure 2. Only when there is a tendency or evolutionary trend favoring alignment of the magnetic and rotation axes, would the preponderance of small $\sin\ i$ substantially modify the death line (*cf.* Barnard & Arons 1982). We do not believe this to be the case. The idea of spin axis alignment was advanced by Jones (1976), when magnetic moment decay was postulated in pulsar aging (Lyne, Ritchings & Smith 1975; Ostriker & Gunn 1969). Analysis of observational data relating to core widths of pulsars with interpulses indicates that the distribution of angular parameters is very broad, and shows little variation between younger and older subgroups of pulsars (Rankin 1990).

Because the height of the magnetosphere, h_{GAP}, is itself is set by the production of pairs, in the AS model for dipole field geometry, the pair creation parameter is completely insensitive to the γ-ray energy, and acquires a value of $\chi \sim 0.15$ at the height of the magnetosphere. Therefore, the AS model is *not* constrained by the coherence condition, as given by equation (5), at least in the sense that the two-stream instability in the assumed polar cap current flow (Weatherall 1994) occurs in the entire parameter regime where there are pair magnetospheres. The general possibility of a region III based on stability criteria must still be allowed given the actual kinetic flow of the pair streams, even though we do not predict one here.

An interesting recent extension of this type of model (space-charge limited flow with vacuum breakdown) incorporates general relativistic effects. Musilmov & Tsygan (1992) found that intertial frame dragging increases the parallel electric field over its value in the AS model. Arons (1996) has reconsidered the location of the pair death line in this context. He finds the pair opacity line shifts to include most pulsars if the magnetic dipole is strongly tilted and offset from the star's symmetry axis. The price of this shift, of course, is the introduction of dominant higher order multipole terms in the magnetic field. We suspect the good agreement of the geometrical dipolar picture with radio data argues against such drastic modification; but this question must be tested quantitatively against observations.

The important implication of this class of models is that not all pulsars have pair cascades. If this is true, the absence of long period pulsars must be due to something other than the cutoff of the pair cascade, and the "death line" is only a "pair death line".

3 Are Cone and Core Pulsars Different?

The magnetospheric models described above, which share the same basic physics and differ only in ancillary assumptions, make very different predictions for whether or not pair creation takes place in pulsars. The important differences between the models depend on whether the acceleration region is limited by the geometric divergence of the flow, or by plasma conductivity in the magnetosphere. In addition, the locations of "death" and "birth" lines are sensitive to many uncertainties in the theory, including the applicability of ion *vs.* electron supported space charge flow, whether magnetic line curvatures are closer to simple dipole fields, and magnetic field evolution. Other factors which have not been fully incorporated into published work, but which will affect the location of the "death" and "birth" lines, include γ-ray seeds from some process other than curvature radiation, and also general relativistic effects on the potential drop in the polar cap.

Thus, the theoretical evidence for or against pair cascades suffers from many ambiguities. However, there is strong evidence in the data for two distinct physical situations in the polar cap. Some pulsars show evidence only for emission from a hollow cone, commonly identified as the last open field lines which define the polar cap. This is "conal" emission. Other objects also, or instead, show emission which fills much of the polar cap; this is "coral" emission. Rankin (1983ab, 1986, 1990) has refined this observation with a classification scheme for pulse profiles. Coral emission is prominent in her classes of core-single (S_t) and triple (T). Conal emission is prominent in cone-single (S_d), double (D), and five-component (M) profiles, and also appears in T profiles. Conal emission is linearly polarized, with the classic position angle sweep which led to the first hollow-cone models of pulse geometry (*e.g.*, Radhakrishnan & Cooke 1969). Core emission shows circular polarization, and has a steeper spectrum than conal emission. She finds that core emission comes from altitudes ~ 10 km; and conal emission from altitudes ~ 100 km. Lyne & Manchester (1988) disagree with Rankin on the physical distinction of cone and core emission mechanisms, but agree with her on the basic trends of physical location (within or on the edge of the polar cap), and on spectrum and polarization correlations.

Rankin (1986) noted that cone emission tends to come from older pulsars, and core emission from younger ones. In Figure 3 we plot coral pulsars (core singles) and conal pulsars (cone singles and doubles, and M types), from Rankin's (1990) list. We are struck by how cleanly the two classes avoid each other in $(P, \dot{P})$ space. Furthermore, the two regions are neatly separated by the "pair death line" from the AS model, which we also show in Figure 3. Only pulsars with triple (T) profiles (not plotted), which have mixed core and cone characteristics, are confused about which side of the pair death line they lie on.

One caveat is necessary here. Rankin initially developed her classifications based on polarization and multi-frequency data of average profiles; she later noticed correlations with modulation behavior of single pulses, and incorporated this into her classification scheme (Rankin 1983a, 1986). Having noticed the separation of cone and core objects in age (Rankin 1986; this is equivalent to our separation in $(P, \dot{P})$ space), she recently began including a star's age in her criteria, for single profiles (S_t and S_d) which can be the most elusive to classify (*e.g.* Xilouris *et al.* 1991). None of her earlier classifications are based on the star's age; of the 102 objects we plot in Figure 3, we have established that the classification of 65 of them does not include the star's age. We have not tracked the classification criteria for the remaining 37; of these, 29 are singles. Thus, the separation shown in Figure 3 is robust, and not an artifact of the later classification criteria; fewer than one-third of the stars shown can have had age used as a partial classification criterion.

This suggest two things to us. First, the cone and core classifications are meaningful, and describe two physically different situations in polar caps. Second, different emission mechanisms must be operating in these two regions. Core emission is seen in pulsars in which the pair cascade is taking place. Their coherent radio emission comes from two-stream-driven turbulence in the dense pair swarm. The rapid onset of this instability, and the spread of the pair swarms throughout the open field line region which defines the polar cap, seems consistent with the low-altitude, filled core emission region in these stars. Purely conal pulsars are a distinct class, without a pair cascade. Radio emission in these objects must come from some other plasma process, maybe with a slightly slower growth rate, which takes place only in the shear surface at the edge of the cone. Stars showing both cone and core emission have a complex polar cap, with shear effects on the edge of the polar cap and also pair cascade effects contributing to the total radio emission.

4 Discussion and Conclusions

We have presented evidence from theoretical models suggesting that pair cascades seeded by curvature emision do not occur in the polar caps of slowly rotating pulsars. Because of the sensitivity of model predictions to small changes in model assumptions, as highlighted in the contrast of the CR and AS models, we make this observation cautiously. However, in considering the data, we find that core and cone pulsars lie on opposite sides of the line which, in the AS model, separates pulsars with strong pair cascades from those without pairs. This suggests to us that the cone/core distinction in the data is physically meaningful, and may be telling us where the "pair death line" actually lies – namely, which model assumptions are close to reality. Before now, the inability of polar cap theory to incorporate all pulsars easily within the death line has been considered a shortcoming of detailed pair discharge models. Now, the data suggest that the "death line" in the AS model is in fact real, and is only a "pair-death line"; there seems to be life after death, in that old pulsars continue to be radio-strong.

What follows from this? We suggest either (a) that the seeds for the pair cascade do not come from curvature radiation; or (b) that a pairless emission process is required for conal emission. Regarding the first point, Sturner, Dermer & Michel (1995) sugested that Compton scattering of thermal X-ray photons by the primary beam particles can seed the pair cascade. We find this an interesting idea, but it has not yet been developed far enough to determine its impact on the polar cap structure and accelerating potentials. In addition, it is not obvious that it will explain the separation between conal and coral pulsars shown in Figure 3.

We prefer the second point, that conal pulsars do not contain dense pair plasmas. If so the radiation process must be different from that in coral pulsars. While some theoretical work has been done on the cone/core distinction, it has not considered pairless pulsars. The models of Beskin, Gurevich & Istomin (1988) and of Kazbegi, Machabeli & Melikidze (1991) addressed the core and cone emission types in context of the cyclotron maser-type mechanisms. Rowe (1990, 1992) has developed a free electron maser emission mechanism which has two distinct angular emission geometries, which also suggests core and conal emission. Both models, however, require pair-filled magnetospheres. In addition, the cyclotron maser models are inconsistent with the low-altitude constraints of Cordes (1992) and Rankin (1990).

For pairless conal emission, one is led to think of shear-surface instabilities, which may occur at the interface between a pair-free flow and the static, trapped magnetospheric plasma on the surrounding closed field lines. Arons & Smith (1979) considered an electrostatic shearing instability. They found it was unlikely to be important in the polar cap environment they considered, but suggested other polar cap models may be more favorable for its development. Alternatively, simple bunched curvature emission would be strong from the outer, most curved, field lines; but this mechanism may not develop into a nonlinear regime that can produce coherent radiation (*e.g.* Melrose 1992). We are not aware of any more recent activity in this area; the newer data and our new speculation seem to justify further work on pairless emission.

To end, we note that our suggestion has observational consequences. One immediate possibility is the detection of high-frequency propagation signatures from core pulsars. Eilek (1996) studied signal propagation in the polar cap plasma, and finds that both turbulent pulse broadening and pulse dispersion have flatter frequency dependence than in the cold, unmagnetized interstellar medium. This result suggests high-frequency observations can separate the polar cap signature from that of the ISM. The amplitude of both effects scales with n/γ^3, if n is the plasma density and γ is its Lorentz factor. Pairless pulsars will have $n \sim n_R = \eta_R/e$ (*c.f.* equation 8), and $\gamma \sim \gamma_b = e\phi/m_e c^2$ (the γ of the primary beam; equations 13 and 17). By constrast, pulsars in which a strong pair cascade takes place will have $n \gg n_R$ and $\gamma \ll \gamma_b$. Thus, core pulsars should have high-frequency signatures detectable with current techniques (such as the ~ 10 nsec time resolution observations of the Crab giant pulses by Hankins & Moffett, 1996). We predict that conal pulsars, however, should *not* have detectable signatures, due to their much lower n/γ^3 factor.

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References

Arons, J. 1981, in Proc Internat. Summer School and Workshop in Plasma Physics, ed. T.D. Guyenne (ESA SP-161), 273

———. 1983, in Proc. Workshop on Electron-Positron Pairs in Astrophysics, ed. M.L. Burns, D.K. Harding, & R. Ramaty (AIP), 163

Arons, J. 1992, in IAU Colloq 128 The Magnetospheric Structure and Emission Mechanisms of Radio Pulsars, ed T.H. Hankins, J.M. Rankin, & J.A. Gil (Zielona Gora, Poland: Pedagogical Univ. Press), 56

Arons, J., 1996, in IAU Colloquium 160 Pulsars: Problems and Progress, in press.

Arons, J., & Scharlemann, E.T. 1979, ApJ 231, 854 (AS)

Arons, J., & Smith, D.F. 1979, ApJ 229, 728

Barnard, J.J., & Arons, J. 1982, ApJ 254, 713

Beskin, V.S., Gurevich, A.V., Istomin, Ya. N. 1988, Ap Space Sci 146, 205

Buschauer, R. & Benford, G. 1977, MNRAS 179, 99

Chen, K., & Ruderman, M. 1993, ApJ 402, 264

Cheng, A.F., & Ruderman, M.A. 1977a, ApJ 212, 800

———. 1977b, ApJ 214, 598 (CR)

Cheng, K.S., Ho, C., & Ruderman, M. 1986a, ApJ 300, 500

———. 1986b, ApJ 300, 522

Cordes, J. M., 1992, in IAU Colloq 128 The Magnetospheric Structure and

Emission Mechanisms of Radio Pulsars, ed T.H. Hankins, J.M. Rankin, & J.A. Gil (Zielona Gora, Poland: Pedagogical Univ. Press), 253

Daugherty, J.K., & Harding, A.K. 1983, ApJ 273, 761

Eilek, J. A., 1996, submitted to ApJ

Erber, T., 1966, Rev. Mod. Phys., 38, 626.

Goldreich, P. & Julian, W. H. 1969, ApJ 157, 869

Hankins, T. H. & Moffett, D. A. 1996, in preparation.

Jones, P.B. 1976, Nature, 262, 120

Kazbegi, A.Z., Machabeli, G.Z., Melikidze, G.I. 1991, MNRAS 253, 377

Lyne, A.G. & Manchester, R. N., 1988, MNRAS, 234, 477

Lyne, A.G., Ritchings, R.T., & Smith, F.G. 1975, MNRAS 171, 579

Lyne, A.G., & Smith, F.G. 1990, Pulsar Astronomy (Cambridge Univ. Press)

Melrose, D.B 1992, in IAU Colloq 128 The Magnetospheric Structure and Emission Mechanisms of Radio Pulsars, ed T.H. Hankins, J.M. Rankin, & J.A. Gil (Zielona Gora, Poland: Pedagogical Univ. Press), 306

Mestel, L. 1971, Nature, 233, 149

Meszaros, P. 1992, High-Energy Radiation from Magnetized Neutron Stars (Univ. of Chicago Press)

Michel, F.C. 1991, Theory of Neutron Star Magnetospheres (Univ. of Chicago Press)

Michel, F.C. 1992, in IAU Colloq 128 The Magnetospheric Structure and Emission Mechanisms of Radio Pulsars, ed T.H. Hankins, J.M. Rankin, & J.A. Gil (Zielona Gora, Poland: Pedagogical Univ. Press), 4405

Michel, F.C. & Goldwire, H.C., Jr. 1970, Ap. Letters 5,21

Musilmov, A.G. & Tsygan, A.I., 1992, MNRAS, 255, 61.

Ostriker, J.P., & Gunn, J.E. 1969, Nature, 227, 813

Radhakrishnan, V. & Cooke, D. J., 1969, Ap Lett 3, 225

Rankin, J. M 1983a, ApJ, 274, 333.

————. 1983b, ApJ, 274, 359.

————. 1986, ApJ, 301,901.

———. 1990, ApJ, 352, 247.

Rowe, E.T. 1990, Proc. of Astron. Soc. Aust. 8, 357

Rowe, E.T. 1992, in IAU Colloq 128 The Magnetospheric Structure and Emission Mechanisms of Radio Pulsars, ed T.H. Hankins, J.M. Rankin, & J.A. Gil (Zielona Gora, Poland: Pedagogical Univ. Press), 123

Rudak, B. & Ritter, H., 1994, MNRAS 267, 513

Ruderman, M.A., & Sutherland, P.G. 1975, ApJ 196, 51

Sturner, S.J., Dermer, C.D. & Michel, F. C., 1995, ApJ, 445, 736.

Sturrock, P.A. 1971, ApJ 164, 529

Taylor, J.H., Manchester, R. N. & Lyne, A. G., 1983, ApJ Supp 88, 529

Taylor, J.H., & Stinebring, P.R. 1986, Ann Rev Astron Ap 24, 285

Weatherall, J. 1994, ApJ 428, 261

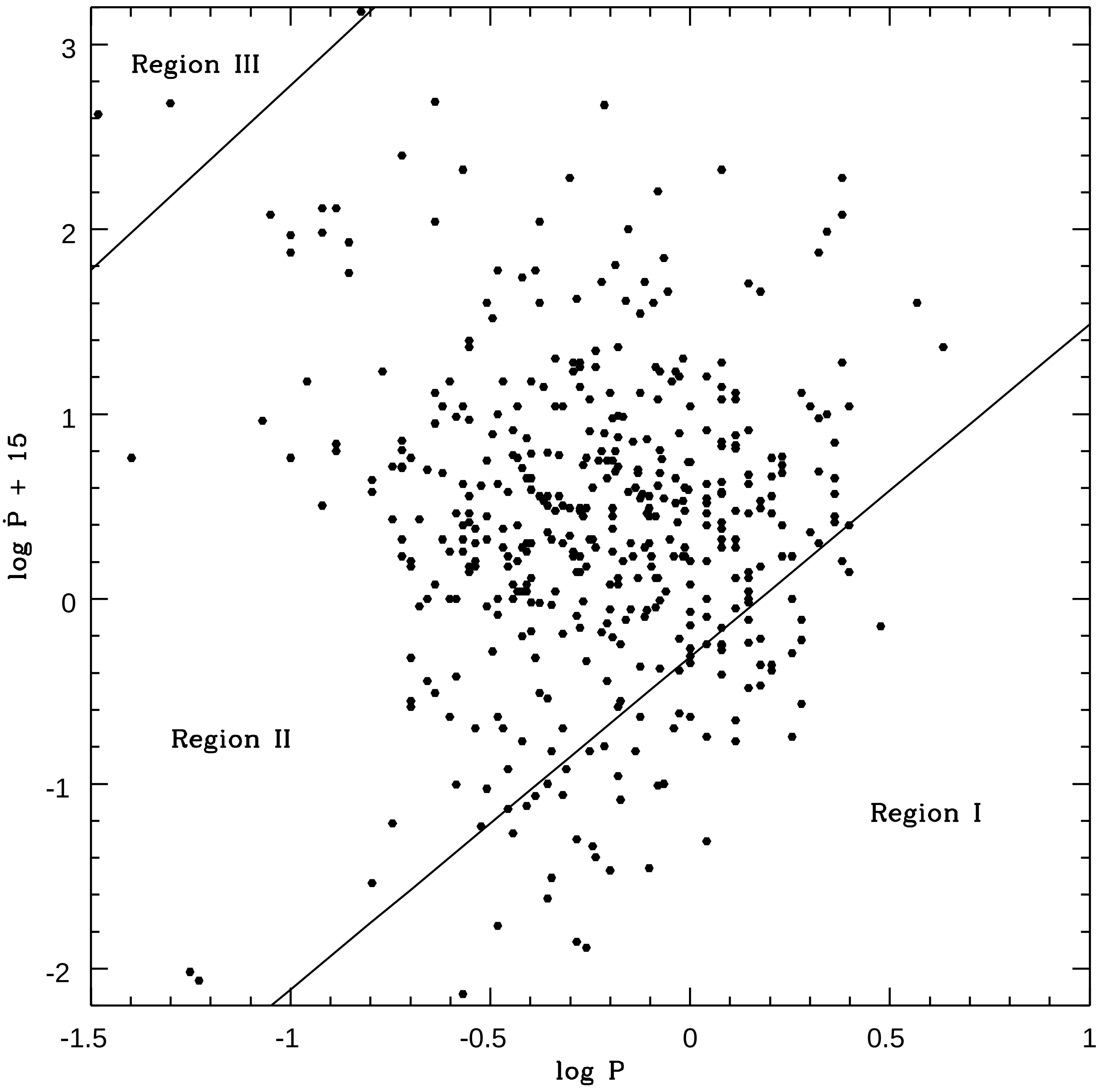
Xilouris, K. M., Rankin, J. M., Seiradakis, J. H. & Sieber, W. 1991, Ast Ap 241, 87

Figure Captions

Figure 1. Distribution of pulsars in period and period spindown (after data in Taylor *et al.* 1993). The two critical lines refer to the CR model. In region I below the death line (equation 15) pulsars cannot maintain pair magnetospheres; in region III above the birth line (equation 16), the pair plasma does not develop radiative coherence from instability. Region II, between the two lines, is where the CR model predicts radio-loud pulsars.

Figure 2. Distribution of pulsars in period and period spindown, and the critical line (equation 20) in the AS model for the pair magnetosphere; in region I below the line pulsars cannot maintain pair plasmas, and in region II they can. There is no region III in this model.

Figure 3. Distribution of pulsars in period and period spindown, according to their classification as core and cone. Core singles are indicated by closed circles; conal singles and doubles and M stars by open circles. The line reproduces the pair-death line of the AS model, from Figure 2.


Region III
Region II
Region I
log Ṗ + 15
log P
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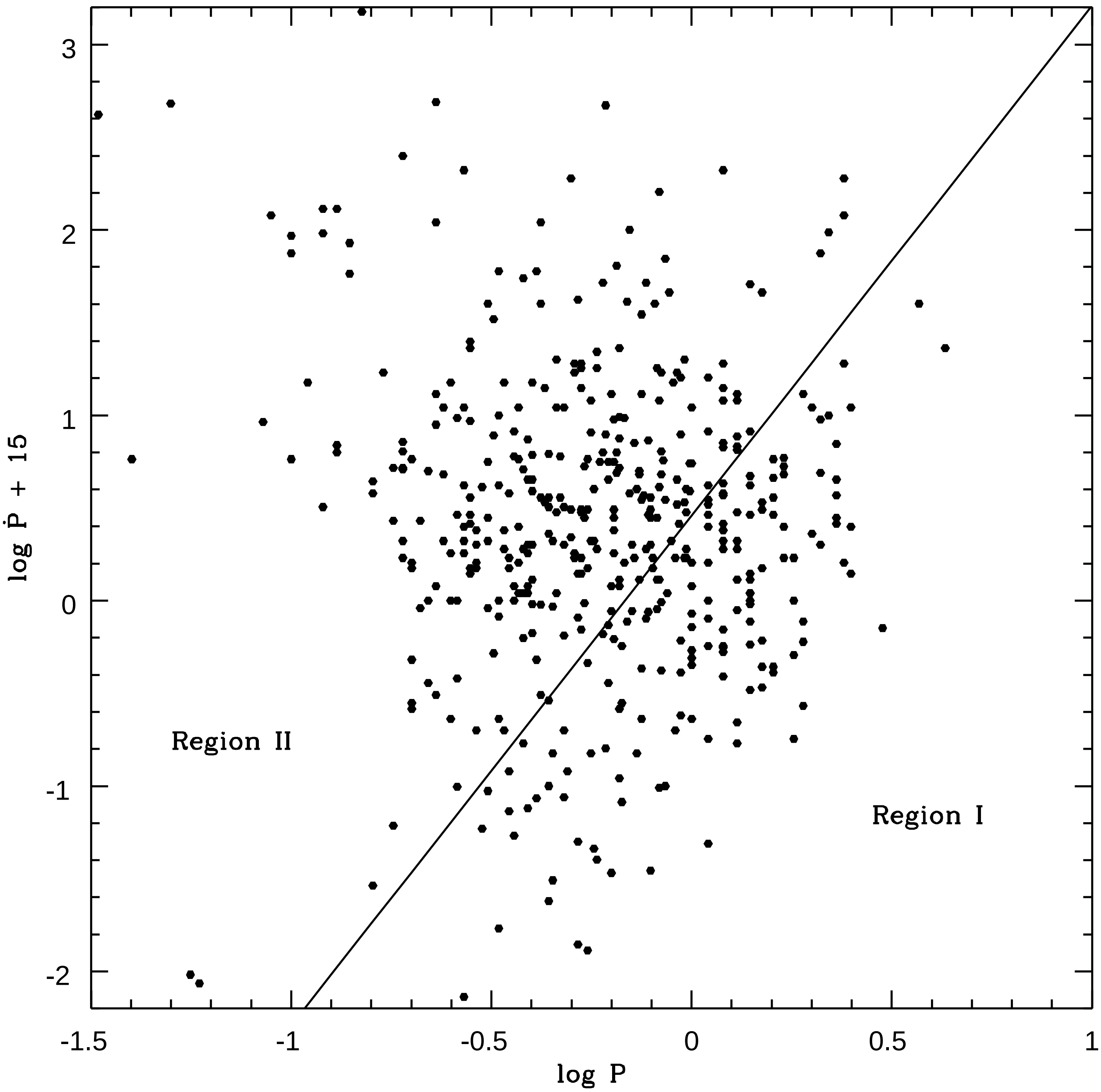
2
1
0
-1
-2
-1.5
-1
-0.5
0
0.5
1



3
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1
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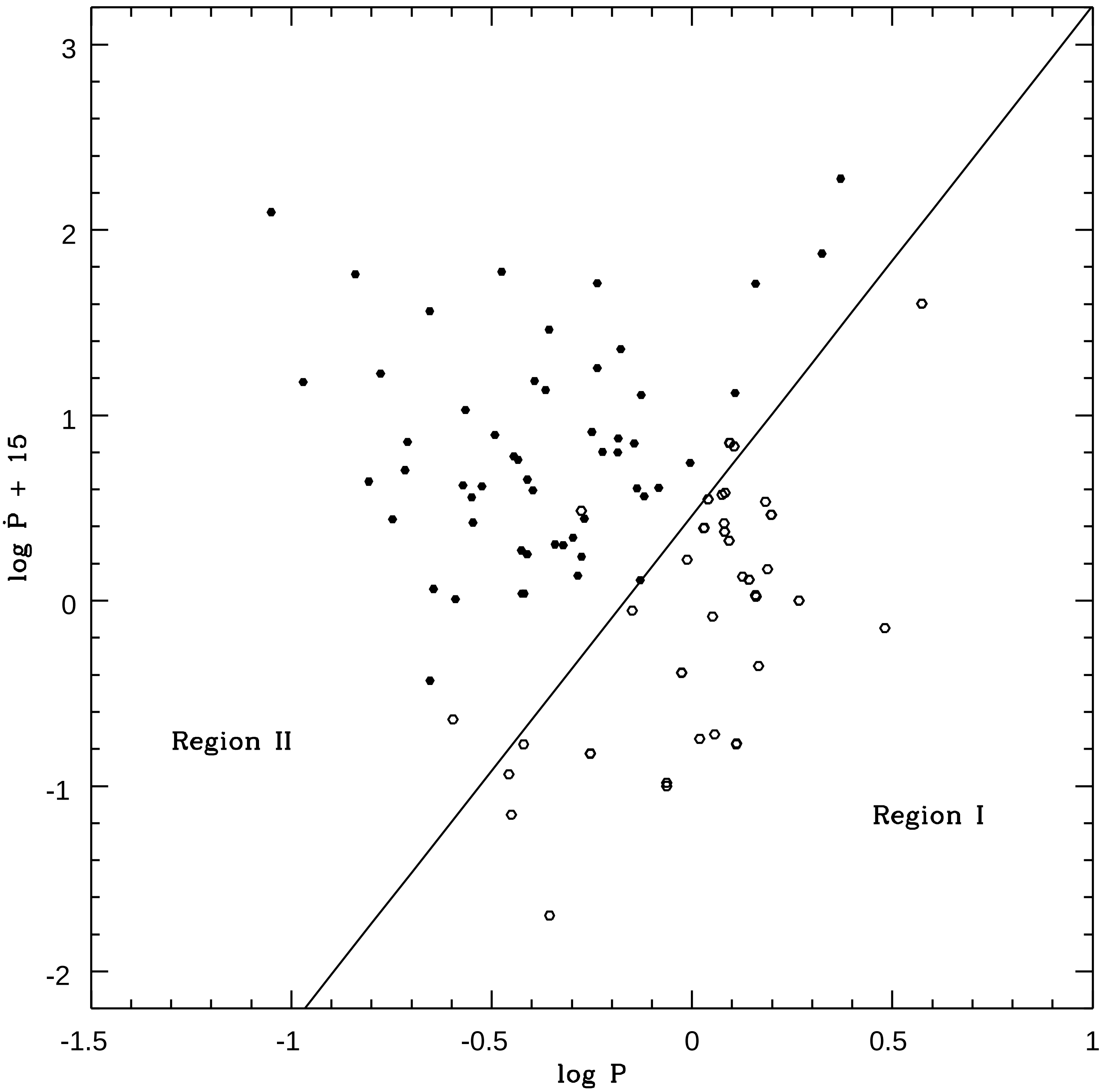
log Ṗ + 15
Region II
Region I
-1.5
-1
-0.5
0
0.5
1
log P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1
log P
Region II
Region I