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WINDS FROM PULSARS

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RESUMEN

Una suposición común de la teoría actual de pulsares es que éstos se pueden aproximar como axisimétricos, que llenan sus magnetósferas con plasma y crean vientos aproximadamente isotrópicos más allá del "cilindro de luz". Ampliando trabajos en la literatura, proponemos exactamente lo opuesto. Los pulsares son rotadores inclinados, lo que es esencial, tienen volúmenes sustancialmente "vacíos", que se mantienen vaciós por el barrido del plasma por las ondas electromagnéticas de gran amplitud generadas por el componente ortogonal del campo de dipolo magnético (esencial para la inclinación), y que los vientos están dominados por la recolección de las cargas en los domos y toros de plasmas de cargas separadas que rodean los pulsares para formar los chorros y vientos ecuatoriales observados (Nebulosa del Cangrejo).

ABSTRACT

A common assumption of current pulsar theory is that pulsars can be approximated as axisymmetric, fill their magnetospheres with plasma, and create an approximately isotropic wind beyond the "light cylinder." We propose, by extending on work already in the literature, that it is exactly the opposite. Pulsars being inclined rotators is essential, have substantial "empty" volumes, are kept empty by the sweeping away of plasma by the large amplitude electromagnetic waves generated by orthogonal component of the dipole magnetic field (essential, of course, for inclination), and the winds are dominated by wave pickup of the charges in the domes and tori of charge-separated plasma that surround the pulsars to form jets and equatorial winds as observed (Crab Nebula).

Key Words: **ISM: JETS AND OUTFLOWS — PLASMAS — PULSARS: GENERAL — RADIATION MECHANISM: NON-THERMAL**

1. INTRODUCTION

I found a very similar work entitled, "Theory of pulsar winds," (Arons, 2004). Although the topics covered were done so expertly, my views are quite different. So I will start here from scratch, although a comparison of our two works might be of interest.

2. HISTORICAL NOTES

Among the earliest analysis of stellar winds is that of Weber and Davis (1967) on the solar wind torque on the Sun (see also Modisette 1967; Dicke 1964). Since this was parallel to the slowing down observed for the recently discovered pulsars, I generalized this work to rotating neutron stars in the relativistic limit (Michel 1969). The only regret I have over this early work is that Weber and Davis approximated the magnetic field to be radial, which was a reasonable approximation for the Sun (where the complex fields tend to become radial once past the near-in magnetic arcades) but not for pulsars if they are dominated by approximately dipole magnetic fields. The problem is that subsequent authors then feel entitled to continue to make the same approximations (no matter how dubious) in future papers. Thus one can now find publications on such byzantine topics as, "what would happen if the magnetic field lines are not *exactly* radial?"

At this time we had estimates for the magnetic fields necessary for pulsar spin-down (assuming a rotating magnet with magnetic dipole moment *orthogonal* to the rotation axis; Ostriker and Gunn 1969) of the now-familiar values of 10^{12} gauss. But an orthogonal model for a pulsar seemed a bit challenging to analyze. A much simpler proposal was that an aligned magnetic dipole might suffice; a much simpler geometry (Goldreich and Julian 1969:GJ). This work reproduced the charge densities invoked in my 1969 wind paper. This agreement seemed to confirm that the torques on an *aligned* rotator would be comparable to that on an orthogonal rotator, and the former model was certainly the easier to analyze in detail. Indeed, this is what I devoted much research to in the following several years. Other than providing some cartoons (Figure 1), the aligned rotator contained little that was quantitative, so much needed to be done.

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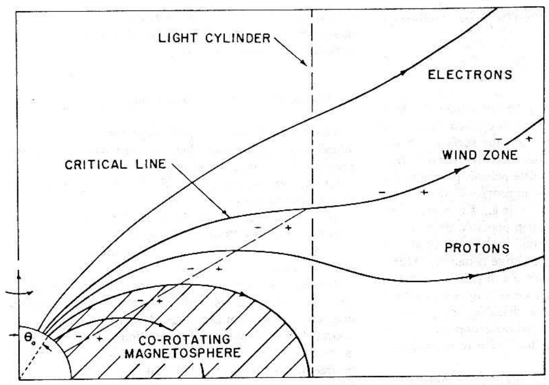

Fig. 1. The aligned MHD rotator according to GJ. Unfortunately the MHD assumption can be directly shown to be invalid, and accordingly leads to numerous paradoxes. Here we see, for example, that the field lines directly below “critical line” would have electrons to the left which somehow become “protons” to the right, if flowing away from the star as assumed.

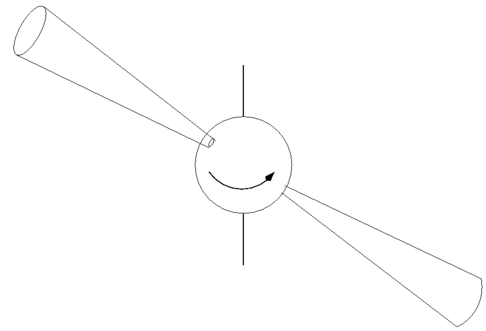

Fig. 2. The phenomenological “hollow cone model”, where “beams” are emitted from the magnetic polar caps. Although not in the least an aligned model, it is often mistaken as supporting the aligned MHD model in Figure 1

If we examine Figure 1, it doesn’t take long to already see a problem. The magnetic field lines labeled “protons” all come from a volume above the magnetic polar regions, which were predicted by the same model to be covered with electrons. So where do these “protons” come from? If they were pulled by electrostatic forces from the polar caps (as assumed in the model), the very same forces would drive the electrons back to the surface. Amazingly, these inconsistencies have come to be so thoroughly disregarded in the pulsar community that few seem in the least disturbed. But if you are trying to put the model into some sort of self-consistent state, these problems do not disappear. One of the authors went around supposing that perhaps the discharge “changed sign” and only on average looked like the cartoon. Equally amazing is that the model has failed to solve a single outstanding problem regarding observed pulsars. There is nothing in the model to explain the required fact that the radio emission be coherent. There is nothing in the model to explain the observed pulse shapes of pulsars; indeed, there would be no pulse for an aligned model (the alibi here was that the model could be tilted off-axis “without changing the physics,” an unjustified (and demonstrably incorrect) claim made to this very day. There is nothing in the model to explain the pulse spectra (no surprise since it neither explains the pulse nor why there should even be emission at radio frequencies). It is hardly surprising that there is nothing in the model to explain special pulsar behavior like nulling, drifting sub-pulses, mode changing, etc.

So the particular promise of the model, namely that it was simpler than the orthogonal rotator as the starting point, was true but it didn’t deliver anything useful despite that simplification, after almost 40 years!

Nevertheless numerous ideas have been inspired such as the “Hollow Cone Model” (Radhakrishnan & Cooke 1969) which comes from the entirely plausible assumption that the magnetic polar caps (being special points in the system) are at or near the site of pulsar radiation. In the simplest (again!) case, these would be confined to within a hollow cone on the sky. Rotation of an (off-axis “aligned” rotator) would then sweep around the sky and form a generic pulse shape. However, none of the obvious statistical restrictions on the distribution pulse shapes (e.g., single pulses, double pulses, etc.) are satisfied in practice. Moreover if the beams are as narrow as implied, there seem to be more observed pulsars than supernovae (Michel 1991a). But such problems are routinely ignored, although fine details of this rough model are used even today to infer the inclination angles (dipole vs spin axis) and observer angle. This cartoon pulsar “model” has risen to the status of “The Standard Pulsar Logo” (Figure 2) if a recent Winter Workshop on Binary Pulsars in Aspen is any guide. It was everywhere, like people impersonating Einstein at APS celebrations.

The most common excuse for diligently citing this work is that it “predicted” a space charge around the rotating star. In fact, the unambiguously entitled paper, “Electric Field Generated by a Rotating Magnetized Sphere” was published several years earlier (Hones and Bergeson 1965) wherein this charge density is calculated in their equation (17). Actually, their expression is more general and accounts for inclination of the dipole. It is clear from the Hones and Bergson discussion that both the charge density and its important consequence (rigid corotation of the magnetosphere with the star) were originally reported by Leverett Davis, Jr. over 20 years earlier (Davis 1947; 1948). Davis and Goldreich were both professors at Caltech during this period (publication of GJ and beyond). Even in the quite different work on pulsar winds (Michel 1969), this density is given implicitly from the frequency relation $\omega_p^2 = \Omega\omega_c$ (equation (30)), where Ω is the rotation frequency of the star.

Unfortunately my work attempting to flesh out the aligned MHD model only revealed problem after problem with the supposed functioning of the model. Eventually, I managed to track the central problem down to a missing piece of physics: the behavior of non neutral plasmas vs that of quasi-neutral plasmas. The MHD approximation was inspired by the latter and is importantly misleading when applied to the former. Specifically, in a quasi-neutral plasma, both signs of charge are present and one or the other can drift along magnetic field lines until plasma occupies all space ("ambipolar diffusion"). In contrast, when only one sign is present (non neutral plasma) the charges are generally trapped. Indeed, a standard piece of laboratory instrumentation, the Penning Trap, accomplishes exactly that, since only one sign of charge can be trapped.

Insofar as the aligned rotator is concerned, this meant that the charges of one sign would be trapped in domes over each pole and charges of the other sign would be trapped in an equatorial torus (Michel 1980). To avoid clumsy wording, we will assume that the domes are trapped electrons as is conventionally done with the aligned models.

I actually felt bad about this result since it seemed only a negative one (the aligned MHD model became irrelevant) and did not seem to point to any obvious new mechanism for pulsars. On the other hand, all the paradoxes vanished as well. So it is amazing to witness the determined efforts expended today at ignoring this essential physics and trying to pretend that an aligned MHD model somehow "works."

I had hoped that an explicit computer simulation would settle the issue and this was accomplished by my student Jürgen Krause-Polstorff (Krause-Polstorff and Michel 1985a,b). The simulation simply tracks what would happen at the star if one makes *exactly the same assumption* as in GJ (the charged particles come from the surface). Rotation induces surface charges and in the simulation these are allowed to escape along the magnetic field lines. For practical numerics, each charge is taken to be huge compared to that of the electron. Eventually there is not enough surface charge left to form another particle and the simulation automatically terminates. The result is, as expected (Figure 3), a dome over each polar cap and a torus. We have recently revisited this program, completely rewritten it, and obtained precisely the same results plus some new ones (Smith, Michel, & Thacker 2001). In particular, one can show that if one tries to start with a completely filled magnetosphere, the configuration *collapses* to the domes plus torus configuration. The idea that a filled magnetosphere is the natural state (and a wind will therefore demand replenishment) is incorrect.

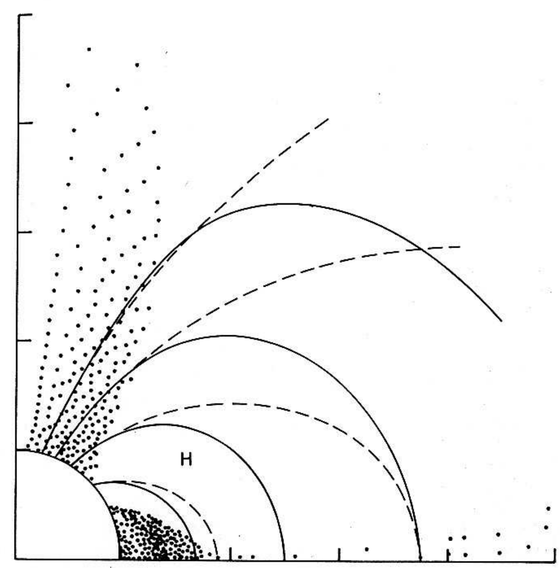

Fig. 3. The non neutral plasma dome and torus configuration that results from directly simulating the assumptions in the aligned MHD (GJ) model without the MHD assumption per se., this assumption being inapplicable to the charge separated magnetosphere that must result.

Over the years a number of other researchers have reproduced in one way or another these same results (Shibata 1989; Rylov 1989; Zachariades 1993; Neukirch 1993; Thielheim & Wolfsteller 1994; Arons & Spitkovsky 2002; Petri, Heyvaerts, & Bonazzola 2002, 2003; Aly 2005). Arons & Spitkovsky have speculated that an instability ("diocotron") disrupts the disk and allows the system to "relax" back to a filled magnetosphere (as if this solved anything, or would even happen). Indeed, the holy grail of pulsar theory seems to be to "restore" the aligned MHD rotator on the assumption that this will give us back a functioning pulsar, *which was never the case to begin with.* In contrast, Pétri et al. claim that the torus could diffuse to "infinity"—owing to this same diocotron instability—fast enough to power a pulsar.

Following the publication of the domes plus torus solution, Leon Mestel has produced a number of papers arguing that once charges cross the light cylinder distance, they would find that $E > cB$ and return to the star to form a closed current loop (leaving the poles and returning to the equatorial zone, or vice versa). See Mestel et al. (1985); Goodwin et al. (2004) and citations therein.

Other than the work of Mestel, people either ignore or are unaware that the GJ model does not work, or they try to revitalize the "pulsar equation" (Michel 1982) which tries to extend the aligned rotator "solutions" to beyond the light cylinder. I had a student Mike Pelizzari try to do this with a simple approximation but only with modest success (ibid), see Figure 4. Recently Contopoulos, Kazanas, & Fendt (1999) and Gruzinov (2005) had much better success in producing smooth magnetic field lines connecting from the star to well beyond the light cylinder. But as pointed out by Scharlemann, Arons, & Fawley (1978), there is no direct way to match current and space charge on curved magnetic field lines. In other words, the particles cannot be simply flying away at near the speed of light. Thus in addition to the expected wind, one must also have a static space charge to make the electrodynamics work. The two are surely mutually inconsistent and since we already have static solutions that work (disk/torus) there is no rational reason to believe in such exotica.

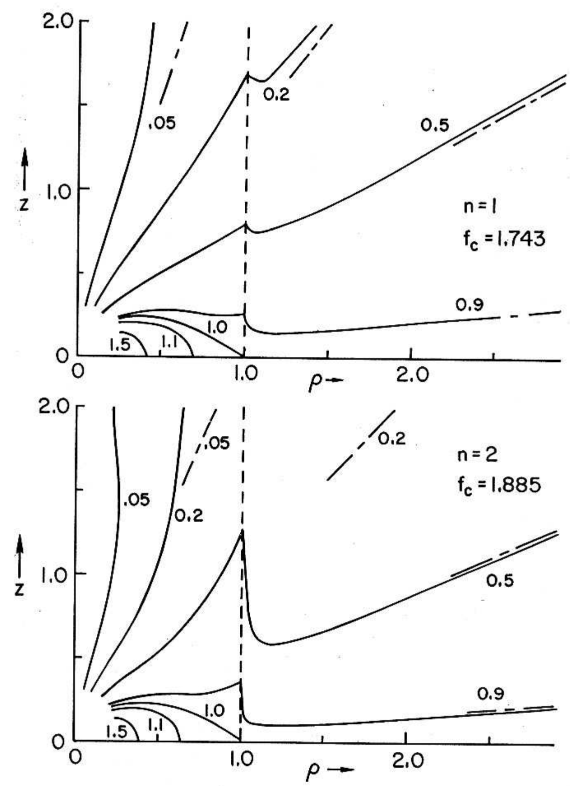

Fig. 4. Early attempts to extend the "pulsar equation" over all of space by Pelizzari. The $n = 1$ case is close, corresponding to solutions assuming the current density scaled as $1 - f^n$, where f labels field lines (see Michel 1991a, p. 266). No great effort was spent trying to do better since the model was unphysical (the space charge would have had to have both stationary and relativistic flow components).

3. NATURAL BUNCHING

Shortly after publishing my book (Michel 1991a) I got around to the question of what happens if a charged particle were introduced into an "empty" magnetosphere, namely just the domes and torus. At large distances the charge would see essentially a point charge and a dipole magnetic field. The particle (electron say) would be accelerated to the neutron star with any corotational velocity declining as it approached the neutron star. What happens next is completely analyzable according to well-known physics relevant to pulsars.

Here we repeat in outline the work presented in Michel (1991b). First the electron Lorentz factor increases. Then the electron begins to radiate strongly at sufficiently high Lorentz factors as the magnetic field lines start to curve more strongly near the star. Eventually all the potential energy is converted into gamma rays instead of further increasing the Lorentz factor ("radiation reaction limited flow"). Owing to the convergence of the magnetic field lines, the gamma rays will cross magnetic field lines and begin to pair produce, and the pairs are almost instantly accelerated to the radiation reaction limited Lorentz factors. In other words, these "secondaries" become primaries. This exponentiating pair production then creates a bunch whose numbers exponentiate on the one hand while its size decreases owing to the converging magnetic field lines. Although one might think of the gamma rays as propagating forward to pair produce, at high Lorentz factors they remain essentially to one side of the original electron as shown

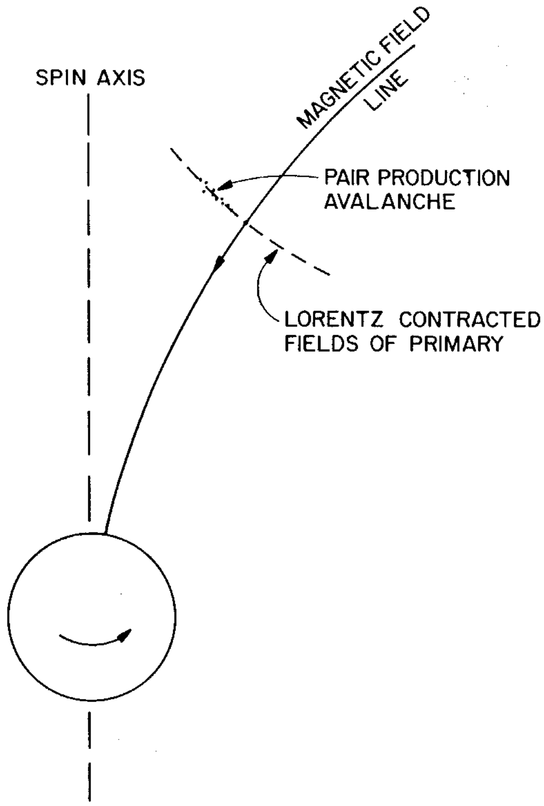

Fig. 5. The cascade developed by an electron attracted to the rotating neutron star charge. The Lorentz compressed electric field of the electron, curved owing to the field line curvature, is causally disconnected from the electron (i.e., represents the curvature radiation gamma rays) and is simultaneously the site of pair production (when the magnetic field there is sufficiently large).

in Figure 5. Meanwhile positrons are being accelerated up out of the magnetic regions as the bunch grows.

It is clear that such bunching opens the possibility of coherent radiation at wavelengths large compared to the bunch size. A simple model gives an incoherent energetic spectrum with a much more intense but low frequency spectrum siting on top of it, Figure 6. Some of the bright close pulsars are actually near enough to see both components. In Figure 7 we show the spectrum of PSR B0950 as measured by Becker et al. (2004), one of several pulsars that show this distinctive pattern. You be the judge.

3.1. *bunching estimates*

In Michel (1991b) we used all of the standard known electrodynamics to calculate the fate of an

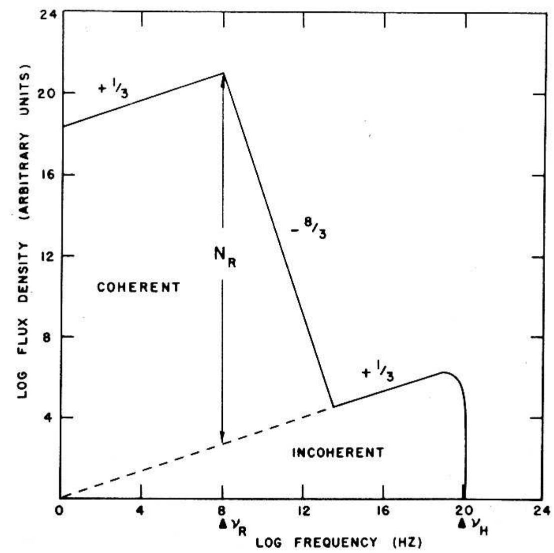

Fig. 6. Elementary spectrum for bunched curvature radiation. The incoherent radiation is boosted by a factor N being the number of electrons in the bunch at wavelengths shorter than the bunch size, with intermediate behavior above until eventually the spectrum is entirely incoherent at short wavelengths despite bunching.

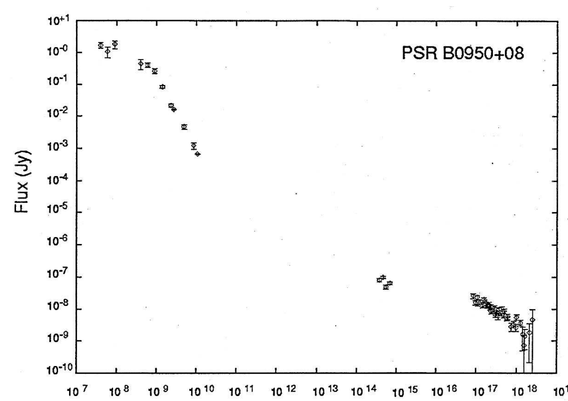

Fig. 7. Spectra actually measured for PSR B0950.

in-falling electron. Figure 8 shows that for a run-of-the-mill 1 second pulsar energetic gamma rays (which begin to be emitted at about 27 neutron star radii above the pole) convert to pairs at about 13 radii and then exponentiate in rapid succession until by 7 radii the bunches reach their maximum charge (namely when the accelerating field at the front of the bunch goes to zero) at the back, and therefore the positrons are no longer ejected from the bunch. Pair production thereafter increases the number of particles without increasing the coherence. The coherent

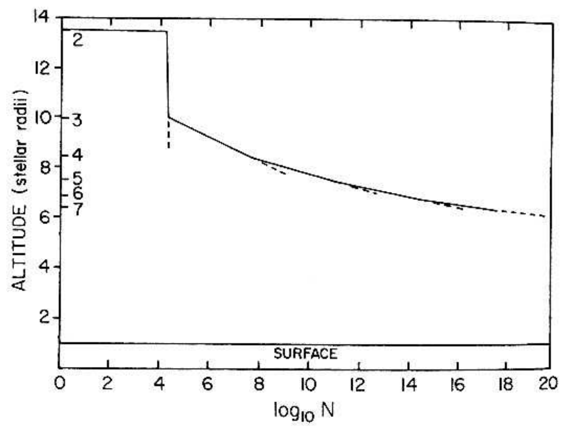

Fig. 8. Exponential growth of a bunch by pair production. The process has been assumed to happen all at once every gamma-ray mean-free-path, which produces the sharp steps. The process also works for "millisecond" pulsars because the much smaller magnetic fields are compensated by the proportionately larger spin rates.

radiation is simply that of the incoherent radiation at a wavelength comparable to the bunch size times the number of particles in the bunch. For shorter wavelengths the bunch radiates more weakly as separate sub-bunches until wavelengths of the order of the inter-particle spacing, at which point it is essentially incoherent despite the bunching. This gives the characteristic double humped spectrum and rapid declining spectral power to higher (radio) frequencies well-known to typify radio pulsars. In Michel (1991b, Table 1) the final electron Lorentz factor was about 10^8, the gamma rays were a few times 10^{11} eV, the bunch contained about 10^{20} electrons and was about 3 meters across. At this point the power in radio was about 2×10^{-5} of the incoherent.

3.2. *Radio as a dirt effect*

It is also known that the radio emission from pulsars is a tiny fraction of the total energy output, as estimated from the slowing down rate. The typical estimates of the fractional power that comes out as radio is about 10^{-5}, which agrees quite well with Table 1 of Michel (1991b) where the degree of coherence is estimated in the last column. The figure of 10^{-5} is to be found in Beskin, Gurevich & Istomin (1988) and illustrated in Fig. 2.19 of Michel (1991a).

4. ROUNDING OUT THE PICTURE

Although this paper was simply a straightforward calculation detailing what should happen if an electron were dropped into an empty neutron star magnetosphere, it drew long and determined referee opposition, partially on the claim that too much x-ray emission would result from the bombardment of the polar caps by such energetic bunches

4.1. *Modulation of x-ray emission*

In fact, the bunches are strongly decelerated before they reach the polar cap because the accelerating field must vanish at the stellar surface and, moreover, within the domes that shield the polar caps. For this reason, the strong acceleration by the overall system charge drops to zero whereas the curvature radiation continues. Consequently, the Lorentz factor of the bunch plummets prior to its reaching the stellar surface. Unfortunately the precise degree is difficult to estimate since we neither know the extent of the domes (except for extremely idealized simulations) nor the exact locus the the magnetic field lines that the bunches follow in any given pulsar. Nor do we have any reason to believe that the fields near pulsars are dipolar. So the issue of x-rays from the pulsar surface owing to bombardment seems difficult to estimate in any general sense.

4.2. *Positron re-excitation*

The bunch formation mechanism provides for a large number of upward propagating positrons to be formed, since they are all ejected from the bunches up along the magnetic field. Given that the downward bunches are on polar cap field lines, the upward positrons are then largely on trajectories that take them to the equatorial wind zone, which means that they will be (largely) swept away in the form of an equatorial wind.

It is interesting to speculate on whether or not a few survive to reach the opposite polar cap, in which case they could serve to maintain the discharge once triggered. We have looked at the case where one has a continuous symmetric cascade, which has very interesting mathematical properties (Michel 1993). However, the upward propagating positrons cannot bunch very effectively since everything is against pair production forming positron bunches (weakening field strength, diverging field lines). On the other hand one need form only one additional pair to replace the original primary electron, but it has to be created high enough that exponential growth creates a dense enough bunch.

4.3. *Jet formation*

While excess positrons are being sent to the equatorial wind zone to be carried away, in the same way the electron-rich bunches are being deposited in the domes, which will cause then to grow in height and also reach the wind zone. An inclined rotator not only sends out linearly polarized waves in the equatorial zone but also sends circularly polarized waves up the rotation axis, which are fully capable of picking up dome electrons and accelerating them along the spin axis (see Michel and Li 1999). At large distances this will appear as a jet.

4.4. *Dipole inclination* essential *theoretically*

It has long been assumed by observers that pulsars are inclined rotators. The aligned rotator only served as an obvious simplification, not as a feature of any real model. The claim, which does not seem to be defended in the published literature—that tilting an aligned rotator was an unimportant perturbation—served to paper over that difference. In fact, tilting the rotator turns it into a source of large amplitude electromagnetic waves which drive away charged particles of either sign. So the model changes dramatically. Indeed, the plausible conclusion is that one ends up with the open cascade *anyway*.

The combination of the disk/torus configuration *and* the wave source from the orthogonal component of the dipole then accomplishes two essential actions for pulsar action. First the huge potential in the disk/torus permits vacuum cascading and the formation of dense bunches capable of generating coherence radio emission of the right order of magnitude. Second, the wave source drives away both signs of charge as rapidly as they are formed. Thus it keeps the system from filling up with plasma which would then short out the huge electric fields needed for cascading in the first place.

4.5. *Sign of charges over magnetic polar caps*

The aligned MHD model supposedly advanced the pulsar problem by providing plasma around the neutron star, and implicitly predicted that those rotating neutron star with *positive* charges over the magnetic polar caps would be radio quiet. Ironically, in the open cascade model neither of these are essential. Even if no plasma could escape to initially form either a dome or a torus, the pair production would supply charges of one sign to form the dome and eject the particles of the other sign into the wave zone. Thus the relative signs make no differences since positron bunches would radiate just like electron bunches.

5. SUMMARY

We have shown that there are two extreme models for pulsars, which we might call the “aligned MHD” model versus the “open cascade” model.

In the aligned MHD model the system is kept in electrical contact to “infinity” by virtue of being entirely filled with space charge separated plasma. Parallel electric fields are, by assumption, zero or minimal.

In the open cascade model, one has domes and a torus of (oppositely charged) particles with necessarily a huge “vacuum” region having strong parallel electric fields in between (“vacuum” not precluding a few energetic charged particles flying about).

We can list the following contrasts:

The system is essentially “empty” in the open cascade model but “filled” in the aligned MHD model. Neither aspect is yet tested observationally although the double pulsar systems like J0737-3039 could change that.

Huge voltage drops are maintained in the first, while they are minimized in the second. Again not directly testable observationally although not ruled out (e.g., the Stark effect, etc.).

Coherent radio emission through bunching is a natural consequence of the first, while no known bunching mechanism exists for the latter (hence some sort of maser mechanism is usually proposed). The open cascade model is broadly consistent with observation both in radio spectrum and in radio luminosity, as discussed above.

The radio emission is initially directed downwards, although once it passes the star it will continue outwards, whereas traditionally the radiation has always been assumed to be upwards from the polar regions in the aligned MHD model, since this is the direction of any putative wind in such models. Both are consistent with hollow cone phenomenology. However, the more complex downward beaming past the star opens up possible explanations of orthogonal mode changing since the radiation must traverse trapped non neutral plasma.

Since pulsars are not aligned, the open cascade model provides a simple superposition of the two components, the dipole magnetic field component aligned with the spin anchors the domes/torus while the orthogonal component excites large amplitude electromagnetic waves that drive away both the upper domes and outer torus to maintain the system in its charged particle starvation condition. In contrast the idea that tilting the aligned MHD system is “not important” defies known physics. The tilted system has to radiate large amplitude electromagnetic waves.

Observation of the Crab pulsar winds (Figure 9) unambiguously show jets and an equatorial outflow, as expected from the open cascade model. Whether

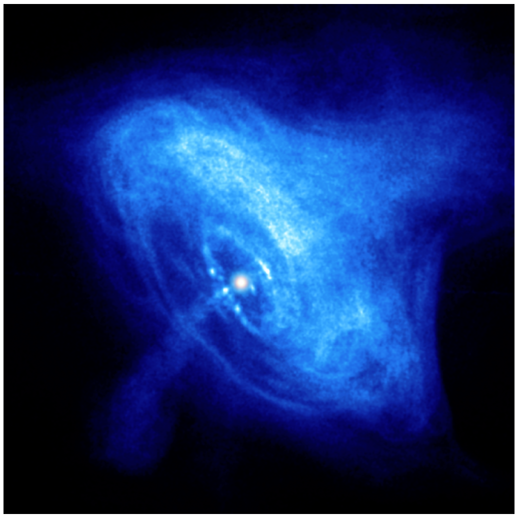

Fig. 9. X-ray image of the Crab Nebula from CHANDRA. Note how the equatorial distribution of wisps and the polar jets exactly mimic the domes and torus distribution expected about a rotating neutron star.

it might be consistent with the aligned MHD model is presently unknown. Note that in either model, the two wind components would have opposite charges!

6. HISTORICAL NOTE

For symmetry, I will conclude with why I now feel less guilty about the business about radial magnetic field lines. It is the aligned MHD pulsar model. This model has led to the belief that MHD is universally applicable everywhere in the Universe. Enthusiasts will doubtlessly be shocked to learn that MHD doesn't even apply to a plethora of laboratory and commercial electronic devices. And that they wouldn't work if it did apply. But one finds it applied to everything from AGNs (Blandford and Znajek 1978) to numerical schemes for general relativistic MHD (De Villiers & Hawley 2003; Gammie, McKinney, & Tóth 2003). Such applications might not be as egregiously suspect as it is for pulsars, but imposing this assumption on Nature has not produced much to rave about even where is seemed plausible (energetic particles in the Earth's magnetosphere, solar flares, etc.).

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REFERENCES

Aly, J. J. 2005, A&A, 429, 779
Arons, J. 2004, Theory of pulsar winds, Adv. Spac. Res., 33, 466-474
Becker, W., et al. 2004, ApJ, 615, 908-920
Beskin, V. S., Gurevich, A. V., & Istomin, Ya. N. 1988, Ap&SS, 146, 205 (1988)
Cheng, K. S., Ho, C., & Ruderman, M. 1986, ApJ 300, 500
Contopoulos, I. Kazanas, D., Fendt, C. 1999, ApJ, 511, 351
Davis, L., Jr. 1947, Phys. Rev., 72, 632
De Villiers, J. P. & Hawley, J. F. 2003, ApJ, 589, 458
Dicke, R. H., 1964, Nature, 202, 432
Davis, L., Jr. 1947, Phys. Rev., 72, 632
Davis, L., Jr. 1948, Phys. Rev., 73, 536
Gammie, C. F., McKinney, J. C., & Tóth, G. 2003, ApJ, 589, 444
Goldreich, P., & W. H. Julian, W. H. 1969, ApJ, 157, 869
Goodwin, S. P., Mestel, J., Mestel, L., Wright, G. A. E. 2004, MNRAS, 349, 213
Gruzinov, A. 2005, Phys. Rev. Lett., 94, 021101
Hones, E. W., Jr., & Bergeson, J. E. 1965, JGR, 70, 4951
Krause-Polstorff, J. & Michel, F. C. 1985a, A&A, 144, 72
Krause-Polstorff, J. & Michel, F. C. 1985b, MNRAS, 213, 43p
Mestel, L., Robertson, J. A., Wang, Y. -M., & Westfold, K. C. 1985, MNRAS, 217, 443
Michel, F. C. 1969, ApJ, 158, 727
Michel, F. C. 1979, ApJ, 227, 579
Michel, F. C. 1980, Ap&SS, 72, 175
Michel, F. C. 1991a, Theory of Neutron Star Magnetospheres, (Chicago: U. Chicago Press)
Michel, F. C. 1991b, ApJ, 383, 808.
Michel, F. C. 1993, in Isolated Pulsars, ed. Van Riper, K. A., Epstein, R., & Ho. C. (Cambridge: Cambridge), p. 202
Modisette, J. L. 1967, JGR, 72, 1531
Neukirch, T. 1993, A&A, 274, 319
Ostriker, J. P., & Gunn, J. E. 1969, ApJ, 157, 1395
Pétri, J., Heyvaerts, J., & Bonazzola, S. 2002, A&A, 384, 414
Pétri, J., Heyvaerts, J., & Bonazzola, S. 2003, A&A, 411, 203
Radhakrishnan, V. & Cooke, D. J. 1969 Ap. Lett., 3, 225
Rylov, Yu. A. 1989, Ap&SS, 158, 297
Shibata, S. 1989, Ap&SS, 161, 187
Smith, I. A., Michel, F. C., & P. D. Thacker, P. D. 2001, MNRAS, 322, 209-217
Scharlemann, E. T., Arons, J., & Fawley, W. M. 1978, ApJ, 222, 297
Spitkovsky, A. & Arons, J. 2002, in ASP Conf. Ser. 271, Neutron Stars in Supernova Remnants, ed. Slane, P. O., & Gaensler. B. M. (San Francisco: ASP), p. 81
Thielheim, K. O., & Wolfsteller, H. 1994, ApJ, 431,718
Weber, E. J., & Davis, L., Jr. 1967, ApJ, 148, 217
Zachariades, H. A. 1993, Ap&SS, 268, 705

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