Theory of Pulsar Winds

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Abstract. I discuss recent work on the nature of relativistic winds from Rotation Powered Pulsars, on the physics of how they transport energy from the central compact object to the surrounding world, and how that energy gets converted into observable synchrotron emission.

1. Introduction

Rotation Powered Pulsars (RPPs) are the prime examples where the electromagnetic extraction of energy from a rotating compact object clearly provides the power for the nonthermal photon emission that distinctively characterizes the world of High Energy Astrophysics. While the fact that the energy extraction reflects electromagnetic torques exerted on a neutron star by the macroscopic electromagnetic fields with which each star is endowed - indeed, the magnitude of that torque allows one to infer the strength of each star’s magnetic moment - has been known since the earliest days of pulsar research (Gold 1968), and indeed was predicted (Pacini 1967) even before pulsars were discovered, 1) the physics of the processes through which the extraction works, 2) the physics of how the rotational energy is transmitted to the surrounding world, and 3) the physics of how that energy transforms into the observed synchrotron radiation from the nebulae around pulsars (when these are observed) have all remained open questions through more than 30 years of pulsar research. Answers to all three questions are of significance not only to the understanding of RPPs themselves, but also to the physics of Active Galactic Nuclei, especially issues of jet formation and blazar emission, and to the workings of Gamma Ray Burst sources, especially to those issues involving the physics of relativistic shock waves and possibly to the nature of the basic engine underlying the GRB phenomenon.

The earliest theoretical answer to 1) and 2) was the vacuum wave theory of electromagnetic spindown, a theory which has never satisfactorily led to useful answers to 3). Modern pulsar theory suggests the answer to 2) is that a RPP throws off its rotational energy in the form of a relatively dense magnetized, relativistic wind of plasma (Michel 1969), largely composed of free electron-positron pairs with an embedded, wound up magnetic field. Support for this idea has always come from X-ray astronomy. Observations of course provide the basic input to all attempts to model these phenomena. Recent advances have been especially powerful drivers of progress on question 3) and to some aspects of question 2).
Study of the Crab Nebula, whose Chandra X-ray picture (Weisskopf et al. 2000) appears in Figure 1, and more recently of other young pulsar wind nebulae (PWN), has been the source of most of the conceptual machinery in this field.

The most widely accepted hypothesis for understanding what we see is that the observed nebular emission is synchrotron radiation from particles heated into a nonthermal distribution of energies by the termination shock waves in the magnetized relativistic $e^\pm$ pair outflow(s) from the underlying pulsar. My focus (obession, if you like) is on the physics of these shock(s) and what that has to tell us about the wind powering the shock. The observations (including optical observations first done by Lampland 1921) demonstrate the intrinsic time variability of this shock transition. Therefore, time dependent modeling of the dynamics of these relativistic flows is needed, with results which yield quite interesting constraints on the central engine, as well as telling us a lot of interesting things about the shocks themselves, conclusions of relevance to AGN and GRB as well as to pulsars and the PWN.

One important fact must be kept in mind in interpreting these rather different looking systems. The Crab is a relatively compact, high magnetic field nebula. At X-ray emitting energies, the radiating particles lose their energy in approximately a flow time from the termination shock in the pairs (perhaps at or just inside the inner X-ray ring) to the outer edge of the visible X-ray torus, if the flow velocity is that of the Rees and Gunn (1974) model (recovered in the MHD model of Kennel and Coroniti 1984a), \[ v = \left( \frac{c}{3} \right) \left( \frac{R_{\text{shock}}}{r} \right)^2. \] This strong cooling is behind the well know fact that the nebular image contracts with increasing photon energy from infrared through 10 keV X-rays - interestingly, what little is known of the nebular size at higher photon energies (Pelling et al. 1987) suggests that nebular image contraction may come to an end in the 100 keV - 1 MeV range, which if true would suggest that the shock heating = “acceleration” is distributed over an observationally resolvable region.

Other nebulae are not always so radiatively efficient. G320.4 around PSR B1509-59 clearly has a much weaker magnetic field, doubtless reflecting different confinement properties of its local interstellar medium, with synchrotron losses affecting the spectra of outflowing particles only at much larger radii, if at all (Gaensler et al. 2002), even at X-ray emitting energies. 3C 58 also seems to have rather low radiative efficiency.

The nebulae’s appearance shows energy injected in equatorial outflow and polar jets. The ratio of polar to equatorial energy flux is not known, nor do we know whether the observed brightness distributions, including the apparent angular gaps between equatorial torii and polar jet, reflect gaps in the energy injection or changes in the energy conversion processes, such that mid latitude energy injection is darker than polar and equatorial phenomena.

2. Energy Flow

However, especially in the case of the Crab, the detailed observations accumulated over many years tell us a lot. The optical polarization in the nebula’s inner minute of arc tells us the magnetic field is toroidally wrapped around the Nubula’s long axis, which is pretty well co-aligned with the pulsar’s rotation axis (Rees 1972, using Woltjer’s 1958 data.) The equatorial wind’s global energy con-
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Observation allows us to define many of the concepts essential to current discussion. According to the gospel of Kennel and Coroniti (1984a), the pulsar’s rotational energy gets carried away in a relativistic magnetohydrodynamic outflow composed of toroidally wound up magnetic field frozen to an electron-positron-heavy ion plasma - curiously, the heavy ions, a feature not in the original Kennel and Coroniti model, remain controversial, although in fact the justification for the pairs is only that theorists cannot think of any other way a pulsar might supply the particle injection rate needed to continuously feed the nebular X-ray source - $N_\pm \sim 10^{38.5-39}$ particles per second for the Crab, much in excess of the fiducial Goldreich-Julian elementary charge loss rate $\sim 10^{34.5} \text{s}^{-1}$ for this pulsar. As has been argued some time ago, a detailed kinetic (non-MHD) look at the equatorial wind’s termination region suggests the presence of a Goldreich-Julian heavy ion current in the equatorial wind (Hoshino et al. 1992, Gallant and Arons 1994), a topic to which I return below.

For a steady wind outflowing radially in a spherical sector opening into a solid angle $\Delta \Omega$, energy conservation reads

$$\dot{E}_R = r^2 \Delta \Omega \left\{ c^2 \beta B^2 \left( \frac{1}{4\pi} \right) + c^2 \beta \gamma \left[ (n_+ + n_-)m_\pm c^2 + n_i m_i c^2 \right] \right\}$$

$$= 4\pi r^2 \frac{\Delta \Omega}{4\pi} c^2 \beta \frac{B^2}{4\pi} \left( 1 + \frac{1}{\sigma} \right), \quad \sigma \equiv \frac{B^2}{4\pi \rho \gamma c^2}, \quad \rho \equiv (n_+ + n_-)m_\pm + n_i m_i, \quad \gamma \gg 1. \quad (1)$$

The ideal MHD theory of Kennel and Coroniti tells us to expect $r B = \text{constant}$, $r^2 \rho = \text{constant}$, $v = \text{constant} \approx c$, $\gamma = \text{constant}$ and therefore $\sigma = \text{constant}$ in the freely expanding wind. Everything known or thought about the pulsar says that where the wind is “launched” ($r \approx R_L \equiv cP/2\pi$, the light cylinder), $\sigma \gg 1$. In the outer magnetosphere and inner wind, the energy is tied up in nonradiating (in the sense of directly observable electromagnetic radiation) EM fields and plasma flow - “the dog doesn’t bark in the night” (Arons 1992). Recent HST (Hester et al. 1995) and Chandra (Mori, these proceedings) observations show various small “knot” and “sprite” features that may be radiative signatures of the expanding wind, but little is clear in this subject.

If $\sigma \gg 1$ everywhere in the wind, as it would be if ideal MHD were everywhere the rule, expression (1) yields the traditional estimate, going all the way back to vacuum wave theory, for the wind’s magnetic field at the radius where the dynamic pressure of the wind is comparable to the total pressure of the nebular bubble, $B_1(\sigma \gg 1) = (4\pi \rho_{\text{nebula}})^{1/2} = 350 \mu G$; the numerical value applies to the Crab Nebula. A comparable estimate for G320.4 yields a little less than 11 $\mu G$ for $B_1$. These values can be fudged to be comparable to the numbers found by applying equipartition estimates to the nebulae. Therefore, in the earliest days of wind theory, everyone felt comfortable with this admittedly crude modeling. Better understanding of the nebular dynamics, in the context of one dimensional flow models, soon disrupted any sense of comfort.
3. Pulsar Wind Nebulae as $\sigma_1$ Probes

Pulsar Wind Nebulae = PWN, formerly known as Plerions (Weiler and Panniga 1978 - the name referred to the closed nebulae that form when the pulsar’s space velocity is negligible), are, in the context of the young and strongly driven systems of interest here, thought to be light weight bubbles confined by inertia or ISM/CSM pressure (ram and static) (Rees & Gunn 1974, Kennel & Coroniti 1984a), fed by the particles and fields from the pulsar. Schematically, their structure is as in Figure 2. They have turned out to yield surprising information on the wind, by providing constraints on $\sigma_1$, the ratio of electromagnetic energy flux to the plasma kinetic energy flux in the wind just interior to the shock wave thought to terminate the wind’s free expansion. In the case of the Crab Nebula, this shock must occur at roughly $10^9 R_L$; the shock radius is also very large, in terms of light cylinder radii, for all the other PWN studied to date. The surprising result, obtained from several points of view, is that $\sigma_1 \ll 1$; typical values obtained have been less than $10^{-2}$. Somehow, between the light cylinder and the wind termination shock, magnetic energy has disappeared without reappearing to us as observable photons, even though back at the light cylinder the outflowing magnetic (and electric) field carried most of the pulsar’s rotational energy. This apparent disappearance of large scale electromagnetic energy in favor of bulk flow kinetic energy, with little visible emission, is what is now called “the $\sigma$ problem.”

The evidence for low $\sigma$ comes from three model dependent sources - modeling the bulk dynamics of the synchrotron emitting bubble (the visible PWN); modeling the radiative emission of the PWN; and modeling the collisionless shock wave that mediates the transition from invisible wind to visible bubble.

3.1. Estimating $\sigma_1$ from PWN expansion velocities

Empirically, observed PWN expand non-relativistically. The MHD jump conditions for the relativistic shock that terminates the wind show that nonrelativistic flow of the lightweight fluid (magnetic field and relativistic plasma emerging from the shock) only if $\sigma_1 \ll 1$ (Kennel and Coroniti 1984a, Gallant et al. 1992), at least so long as the flow is laminar. If the magnetosonic speed is that of a relativistic plasma throughout the bubble, the implications of the jump conditions are preserved (Rees and Gunn 1974, Kennel and Coroniti 1984a), even when the time dependence of the expansion is included (Emmering and Chevalier 1987) and when the one dimensional flow assumption is dropped (Begelman and Li 1992). All these models lead to $\sigma_1 \approx 0.003 - 0.005$ for the equatorial wind in the Crab. Therefore, the magnetic field just inside the wind’s termination shock (treating that shock as having infinitesimal thickness) yields

$$B_1 = \left(\frac{\sigma_1}{1 + \sigma_1}\right)^{1/2} B_1(\sigma_1 \gg 1) = \left(\frac{\sigma_1}{1 + \sigma_1}\right)^{1/2} (4\pi p_{nubula})^{1/2} = 19 \mu G.$$

The numerical value applies to the Crab. The analogous value for G320 is 0.8 $\mu G$ (Gaensler et al. 2002).

Such models have the nice feature of having a decelerating radial flow of the plasma in the bubble, $v = (c/3)(R_{\text{shock}}/r)^2$, which in turn leads to the magnetic field in the bubble increasing linearly with radius, $B = 3B_1(r/R_{\text{shock}})$ until
it reaches approximate equipartition at $R_{eq} = (2/9\sigma_1)^{1/2}R_{\text{shock}}$. For $r > R_{eq}$, deceleration stops. Matching the asymptotic bubble flow velocity to the observed bubble expansion speed (when that can be measured or inferred) is what leads to the inferred low $\sigma_1$.

The quantitative model which allows one to draw this inference assumes toroidally wound $B$ field (as suggested by the theory and by nebular polarization observations), a lightweight fluid composed of pairs and $B$ field. Like all starting models, this one leaves lots unanswered. Where has all the upstream $B$ field gone? How come the inferred upstream flow 4-speed $c/\gamma_1 \approx 10^6c$ in the Crab, is so small compared to the natural acceleration scale $\sim e\Phi_{\text{open}}/m_e c^2 \approx 10^{11}$; the numerical value is for the Crab? The choice of $R_{\text{shock}}$ is unclear - locating the shock in the pairs at the inner X-Ray ring in the Chandra imaging puts the equipartition radius in the midst of the X-ray torus, which is surprisingly small.

3.2. Estimating $\sigma_1$ from radiation modeling of the Bubble

One can also extract $\sigma_1$ by adding a couple of extra bells to the model’s whistle. If one assumes the flow energy goes promptly into power law distributions of pairs right at the shock, via “shock acceleration” (a.k.a. magic), the MHD jump conditions give a lower cutoff to the power law of $\gamma_{\text{min}} \approx 0.6\gamma_{\text{wind}}$, assuming a 3D plasma with ratio of specific heats equal to 4/3. With the spectral slope of the particle distribution as an adjustable parameter, adequate modeling of the high energy photon (optical and harder) spectrum of the Crab can be achieved (Kennel and Coroniti 1984b), with a result for $\sigma$ similar to that obtained from dynamical arguments. One finds $\sigma_1 \approx 0.005$, $N_\pm \approx 10^{38.5}$ s$^{-1} = 10^4\dot{N}_{GJ}$, where $\dot{N}_{GJ} = 2e\Phi_{\text{open}}/e$ is the Goldreich-Julian particles/charge outflow rate and $\Phi_{\text{open}} = (\dot{E}_R/c)^{1/2}$. Interestingly, the inferred pair injection rate is similar to that found in “polar cap” models of pair creation, which yield $\dot{N}_\pm/\dot{N}_{GJ} \equiv \kappa_\pm \approx 4 \times 10^4$ (e.g., Hibschman and Arons 2001) for this pulsar. Standard theoretical scenarios suggest these pairs expand to fill all $4\pi$ steradians around the pulsar, so the factor of 4 discrepancy may reflect no more than the special conditions needed to make the equatorial part of the wind shine brightly, to which I return below.

In the Crab, the fact that the synchrotron cooling time of the accelerated particles that emit the X-rays is comparable to the flow time makes extracting these parameters from radiation models a relatively straightforward issue. Extracting similar parameters for Vela and G320.4, for example, is harder and dependent on more sophisticated modeling, since $t_{\text{flow}} \gg t_{\text{synch}}$. Nevertheless, progress is possible, based on a more sophisticated strategy, with conclusions similar to those from the Crab: $\sigma_1 < 1$, $N_\pm \approx \kappa_\pm$ (polar cap theory)$\dot{N}_{GJ}$. I don’t have space to repeat those arguments here; suffice to say, that properly applying the Kennel and Coroniti model to the recent Chandra observations of the Vela nebula (Helfand et al. 2001) leads to the conclusion that $\sigma_1 < 0.05$, rather than $\sim 1$ - Helfand et al. assumed a constant velocity rather than a decelerating flow downstream of the wind termination shock.
3.3. Estimating $\sigma_1$ from the Kinetic Theory of the Termination Shock: Wisps as Ion Driven Compressions

Driven by curiosity as to just how a highly relativistic, collisionless shock wave in a magnetized medium, with the $B$ field almost transverse to the flow, goes about transforming upstream flow energy into the observed distributions of synchrotron emitting particles, Hoshino et al. (1992) and Gallant and Arons (1994) introduced a theory of the termination shock structure which appears to be of some use in the interpretation of the features seen in the spectacular movies and images of the Crab and other young PWN coming from the HST and Chandra. Dissatisfied with the oft repeated assertion that “shock acceleration” (meaning diffusive Fermi acceleration) in a highly relativistic flow actually works as advertised when the magnetic field is not almost strictly parallel to the flow velocity, these authors found instead that non-thermal acceleration of $e^\pm$ pairs actually might work as a consequence of the flow having much of its energy carried in heavy ions (“protons”). Then the shock structure starts with a thin (shock thickness $\delta \sim$ pair Larmor radius) transition in which the pairs are heated to a downstream thermal distribution with temperature comparable to $\gamma_1 m_\pm c^2$. The heavy ions penetrate this hot magnetized $e^\pm$ plasma, and begin gyrating in the pair shock compressed magnetic field. Such gyration is electromagnetically unstable, with the coherent gyration of the ions degenerating as they collectively emit low frequency electromagnetic waves (technically, magnetosonic waves) in the pair plasma. Resonant cyclotron absorption of these waves by the pairs leads to progressive nonthermal acceleration of the pairs as they flow away from the shock front.

The details of this acceleration scheme still need further development. What has proven to be useful is the observation that the ions’ gyration causes the deposition of the ions’ outflow momentum into a series of compressions of the magnetized pair plasma, in the form of a more or less standing wave whose compressional oscillations emit traveling waves that move into the plasma at larger radii. These features have more than a little resemblance to the X-ray ring and arcs seen in the Crab and G320.4, and to the wave like features seen in the HST movies of the Crab Nebula, as illustrated in Figure 3, which comes from hybrid (MHD flow of pair plasma and Particle-in-Cell treatment of the ions) simulation of the termination shock region (Spitkovsky and Arons 2000, and submitted to ApJ), a region thought to include the moving “wisps” in the Crab.

Rough comparison of the synthesized moving features in the surface brightness to the observations yields $\sigma_1 \approx 0.005$, $\gamma_1 \approx 3 \times 10^6$, $\dot{N}_\pm \approx 3 \times 10^{38}$ s$^{-1}$, $\dot{N}_i \approx 2 \times 10^{34}$ s$^{-1} \approx \dot{N}_{GJ}$. However, serious comparison to the temporal structure observations, now much refined by recent HST and Chandra campaigns (Hester, these proceedings; Mori, these proceedings) will require lifting the spatially 1D assumptions underlying this model. However, it is interesting that the same ideas can be usefully used to describe the inner arc features seen in the single Chandra snapshot of G320.4 (Gaensler et al. 2002; Gaensler et al., these proceedings.)

Most other ideas about the wisp region in the Crab say nothing as definite as is in the model just outlined. Begelman (1999) suggested the wave like features might reflect a Kelvin-Helmholtz instability between equatorial and higher
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latitude flows outflowing with different velocities, an idea which may well have merit in the face of the recent observations - it certainly deserves more quantitative development. Hester (1998) has been more specific, in suggesting the wisp features to be compressions comoving with the flow, created by thermal instability driven by synchrotron cooling. This idea might work in principle, if the X-ray emission in the wisp region has a sufficiently flat spectrum, for then the particles carrying the pressure are subject to rapid synchrotron cooling - a particle spectrum flatter than $E^{-2}$ is required. However, this explanation does not apply to the ring and arc features in the Vela and G320.4 nebulae, where the synchrotron time clearly is much larger than the flow time, a difficulty not a problem for the ion doped wind model’s relevance to these systems.

Lest one think theories of pulsar winds and their interaction with the surrounding nebulae are anything like complete, recent radio observations by Bi-etenholz et al. (2001) strike a cautionary note. All the physical models described to date yield lower cutoffs to the power law distributions of radiating particles at energy $\sim 0.5 \gamma_1 m_\pm c^2$. The inferred value of $\gamma_1$ in the Crab says there should be no observable radio wisps. The observations shown in Figure 4 say otherwise. There is no ready explanation at hand for this fact - some deeper thinking about the shock acceleration problem (if indeed any kind of shock actually does terminate the wind) is needed.

There have been various attempts to wiggle out of the “sigma problem” - e.g., Begelman’s (1998) invocation of MHD kink instabilities and reconnection as a means of turning the stiff ordered toroidal $B$ field into a softer gas of magnetic cells ($B^2/8\pi \propto \text{density}^{4/3}$) - such a soft gas model leads to inferring $\sigma_1 \sim 1$ (not $\gg 1$, however.) Whatever one may think of the physics of such speculations, the high optical polarization in the Crab’s inner regions forbids such cellularization of the $B$ field. Squirting the gas of an equatorial MHD nozzle at the light cylinder (Chiueh et al 1998) seems to have little to do with what little we understand of the dynamics of the flow at the light cylinder, and putting all the flow in polar jets (Sulkanen and Lovelace 1990) violates the obvious fact that most of the energy lost seems to be in the equatorial wind. Dissipation of the wind, considered as wound up magnetic sectors (Coroniti 1990) seems to be too weak (Lyubarskii and Kirk 2001).

Most of the difficulties come from theorists’ consideration only of an unstructured wind in ideal MHD. Coroniti’s (1990) model (and Michel’s original 1971 suggestion) points the way to consideration of winds with wave like structures, which must be present in outflows from oblique rotators, as has been emphasized most recently by Melatos (1998). Perhaps a theory of winds plus strong electromagnetic waves in the outflowing plasma will do better at resolving the origin of small $\sigma_1$, as well as giving us an idea of what leads to polar “jet” formation. In this regard, the very preliminary results shown at this meeting by Spitkovsky may be a harbinger of things to come.

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Figure Captions

Figure 1: a) The Crab Nebula (age = 947 years) in X-rays, with equatorial X-ray torus and inner X-ray ring, plus polar “jets”; b) G320.4 around PSR B1509-58 (spindown age = 1250 years), with a partial X-ray ring around the pulsar and a (visibly) one sided X-ray jet (Gaensler et al. 2002); c) 3C 58 in X-rays, with age 815 years if this is the remnant of SNe 1181, with $T_{\text{spin}}$ of the X-ray pulsar much larger, 3335 years; d) the much older ($T \sim 10^4$ years) Vela PWN years in X-rays.

Figure 2: Schematic of a confined PWN, for which the pulsar space velocity is small compared to the bubble’s expansion speed.

Figure 3: Top Row: Observed time series of the wisp region in the Crab Nebula (Hester et al. 1995). The physical scale of the separation between the pulsar and the main bright wisp to the pulsar’s northwest (the first feature concave to the pulsar) is 7", or 0.15 pc. Middle row: Pair fluid is “stirred” by the instability of the ion stream entering the shock front and executing Larmor gyration in the compressed magnetic field. Each panel shows a snapshot, taken at successive times, of the magnetic field (top curve), ion momentum (middle curve) and ion density (bottom curve), each as functions of radius, with the radii measured in units of the ions’ Larmor radius based on parameters of the upstream flow ($\sim 0.15$ pc in the specific case shown.) New waves are emitted with every turn of the bunched “knot” on the first loop in the ion orbit. Bottom row: Synthetic surface brightness maps, corresponding to each snapshot.

Figure 4: VLA image of the radio wisps around the Crab pulsar (Bietenholz et al. 2001), which suggests the radio emitting electrons in the Crab Nebula have the same source as the particles emitting the harder photons.
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