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Pulsar Winds

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Abstract. The shock excitation of pulsar powered nebulae (plerions) is discussed, based on recent theoretical work on the structure of relativistic, collisionless magnetosonic shock waves. This theory is used to outline a model in which the γ^{-2} injection spectrum of the Crab Nebula is satisfactorily accounted for. The same theory suggests a model of the "wisp" features in the Crab Nebula which accounts for these time variable features in the surface bightness as compressions associated with the magnetic overshoots *within* the shock structure. It is pointed out that this theory suggests observable variability in the high energy gamma rays from the Crab Nebula ($\varepsilon > 50$ MeV).

1. Why Winds?

All electromagnetic spindown theories suggest the loss of rotational energy from an electromagnetically isolated, magnetized, rotating body should occur at the rate

$$\dot{E}_R = -I\Omega\dot{\Omega}_* = \frac{\Omega_*^4 \mu^2}{c^3} \frac{k_s}{f_A^3}, \tag{1}$$

a result which can be obtaioned from dimensional analysis or from simple considerations of the Poynting flux (*e.g.*, Arons 1993). In (1), μ is the magnetic dipole moment, $\Omega_* = 2\pi/P$ is the angular velocity with P the rotation period, $f_A \equiv R_A/R_L$, R_A is the equatorial radius of the last closed field line, $R_L = cP/2\pi$ is the light cylinder distance, and k_s is the outflow structure function. For the vacuum rotator, $k_s = (2/3)\sin^2 i$ with i the angle between Ω_* and μ, and $f_A = 1$. Expression (1) assumes that at radii comparable to $R_A \sim R_L$, the undisturbed magnetic field of the non-rotating star is dipolar.

Observations of pulsars' P and $\dot{P}$ are consistent with $f_A = 1$ and random values of i, *i.e.*, $< k_s > = < 2\sin^2 i/3 > = 4/9$. However, with μ and i fixed, the vacuum theory predicts $n \equiv \Omega_*\ddot{\Omega}_*/\dot{\Omega}_*^2 = 3$. The three extant observations of n all yield $n < 3$ (Groth 1975, Lyne, Pritchard and Smith 1993, Kaspi *et al.* 1994, Lyne, this meeting). Suggestions to explain this discrepancy (summarized by Blandford & Romani 1988 and Arons 1992) have included increases of μ with time, increases of k_s with time, or f_A being some nonconstant function of Ω_*. At present, variations in μ are unpopular, while variations in k_s and f_A are unquantifiable, either observationally or theoretically. Timing observations alone have been too blunt a tool to tease out the physics of spindown at any level deeper than the thought that the torque is electromagnetically dominated.

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The most likely answer to $n < 3$ lies in the thought that the torque might be exerted by a dense stellar wind, relativistic and probably magnetohydrodynamic (MHD) in character. Theory suggests vacuum spindown, with $f_A = 1$, applies only if the outflow of charged particles over most of 4π steradians satisfies $\dot{N} \ll \dot{N}_R \equiv 2\mu\Omega_*^2/Zecf_A = 4 \times 10^{30}(\mu/10^{30}\text{ cgs})(ZP^2 f_A)^{-1}\text{ s}^{-1}$. For the case of the Crab pulsar, $\dot{N}_R \sim 2 \times 10^{34}\text{ s}^{-1}$. From radio pulse observations, $\dot{N}$ remains unknown because of our ignorance of the pulse emission mechanism, while models of the optical, X-ray and gamma ray emission (*e.g.*, Romani, this meeting) work only if $\dot{N} \gg \dot{N}_R$. The study of plerions, or pulsar driven nebulae, offers the possibility of studying $\dot{N}$ and the physics of pulsar energy loss from the response of the surrounding medium, which in favorable circumstances (the Crab Nebula, 3C58 etc) provide a "box calorimeter" around the pulsar. Study of the quantity and quality of the nebular emission can yield a rich harvest of results on pulsar physics, and by extension all rotation powered compact systems.

The Crab Nebula, with its rich history of multiwavelength studies, remains by far the best case for such study. While many other nebulae are known, only the Crab offers (so far) enough information to seriously constrain physical models.

The fact that the Crab's image decreases in size with increasing photon energy offers ample proof that the synchrotron emitting particles in the Nebula were given their relativistic power law spectrum in energy space at or near the pulsar. The highest energy particles must have their energy continuously resupplied by the pulsar. *IF* the particles get accelerated once, then the X-ray source (1 - 100 keV) must be fed by $\dot{N}_X \simeq 10^{38}$ electrons or positrons/second. The fact that the image contracts to less than half a minute of arc in size at energies approaching 100 keV (Pelling *et al.* 1987) suggests the the one time accelerated particles are injected at or near the pulsar. At larger radii, they lose energy with negligible further acceleration, a view supported by the MHD flow models of the continuum spectrum of the Nebula (Kennel & Coroniti 1984, de Jager & Harding 1992, Gallant & Kirk 1996). The radio Nebula requires the injection of about 10^{40} particles/s (Shklovsky 1970), although this is only an injection rate averaged over the Nebula's age. From either perspective, the pulsar has a particle loss rate many orders of magnitude greater than $\dot{N}_R$. There is little doubt that the simplest model of the spindown torque on the star must be that of a relativistic, MHD wind. In the cartoon approximation, I expect the structure of such a wind to look like Figure 1.

This picture (*e.g.*, Arons 1983) has its roots in the aligned rotator ideas of Goldreich & Julian (1969), but shifts the stresses from their low density, force-free, completely charge separated structure, with currents that can't cross field lines until the circuit closes far away in the external nebula or the insterstellar medium, to a conceptual model in which the dense $e^{\pm}$ plasma formed above the polar caps feeds a dense MHD wind whose inertial stresses within the magnetosphere lead to the formation of open field lines and the formation of the dense wind outflow. The polar current extracted by the starvation electric field supports the toroidal electromagnetic field which allows the wind to carry angular momentum. This current flows away along polar field lines, while the return current (made of heavy ions) gets extracted from an "auroral" ring around the polar cap and flows away along field lines which map into the "striped wind" region in the star's rotational equator. Extraction of these ions occurs because the polar current system includes a dense stream of electrons which precipitate onto the auroral zone (Arons 1983, Longcope & Arons, in preparation). The negative charge of these precipitating electrons attracts the ions up against gravity and flings them away to the outside world, a process often seen in the auroral zone of the Earth's magnetosphere. Because the wound up *and oppositely directed* magnetic fields in the equatorial outflow may be highly dissipative (Coroniti 1990, Michel 1994, Melatos & Melrose 1996), such cartoons suggest the equatorial region might be a zone of maximal dissipation, while the helically wound polar regions might be regions of more ideal MHD flow, focussed by magnetic hoop stress into broad "jet" structures.

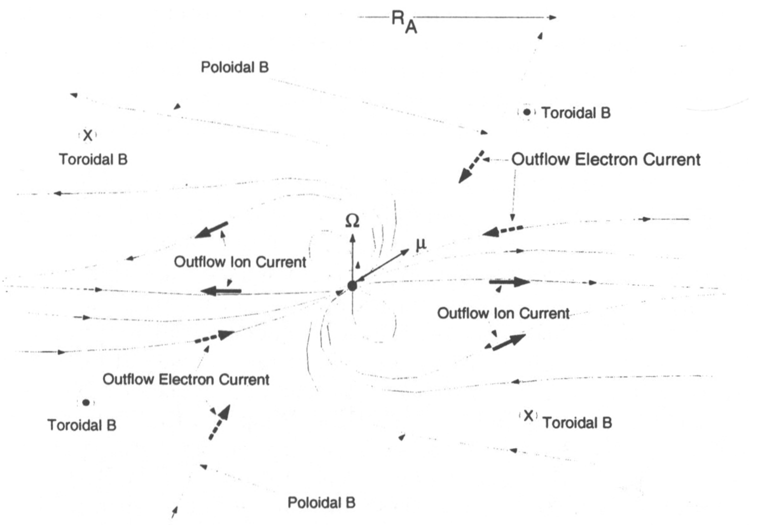

Figure 1. Cartoon structure of an oblique rotator's magnetosphere

2. Observations and Models

The Nebular radiation owes its origin to the pulsar's rotational energy losses. The sum of the Nebula's radiative output comes to about 10% of the total spin down energy loss, with most of the emission between 1 keV and 100 MeV. Simple minimum energy estimates, and more detailed dynamical and radiative modeling (Kennel & Coroniti 1984a,b), show that the synchrotron emission requires electrons and positrons with energy up to $10^{10} m_e c^2 = 10^{16}$ eV. Such 10,000 TeV leptons retain their energy against radiative losses for only a few months, requiring a continuous injection of energy. The spectral form of the emission suggests injection or *in situ* acceleration of power law distributions of high energy leptons - typically, the acceleration process must produce an energy distribution of pairs of the form $N_{\pm}(\gamma) \propto \gamma^{-s}$, with $s \approx 2$. This leads us to the basic physics question of how does the pulsar supply at least 10% of its energy to the Nebula in this form. This same question runs through much of the physics of other nonthermal

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sources powered by central compact objects, most spectacularly exemplified by blazars and radio galaxies with jets.

The pulsar might be the direct source of the fields and the power law distribution of particles. Imaging of the regions around the pulsar, regularly possible at photon energies below a keV, shows the existence of an underluminous "hole" around the pulsar (Schmidt *et al* 1979), with size about 0.1 pc. This suggests that particles flowing out from the pulsar's magnetosphere (size $\approx cP/2\pi = 1500$ km) have much less entropy than is contained in the γ^{-2} injection spectrum inferred from the Nebular emission, out to distances comparable to the size of the hole. On the other hand, the contraction of the Nebular image with increasing photon energy suggests that the injection spectrum forms somewhere interior to the inner structure of the X-ray source, that is, interior to $r \sim 0.3$ pc. Synchrotron aging of the accelerated particles as they *flow* out from this acceleration region then explains the image size as a function of radius (Kennel & Cornoiti 1984b and references therein.) These arguments suggest one focus attention on the region between 0.1 pc and 0.3 pc from the pulsar as the site where the outflow from the pulsar gets transformed into the injected lepton spectrum inferred from the synchrotron models.

Since Lampland's (1921) time, detailed optical, and more recently infrared and radio, imaging has shown that something interesting occurs in this region. One finds the "wisps" (Scargle 1969) to the Northwest and Southeast of the pulsar. The features he called wisp 1 and wisp 2 to the Northwest are known to vary in brightness (perhaps also in position) on a time scale of months. In contrast, the "anvil" and "thin wisp" features have "never" changed, although prior to van den Bergh & Pritchett's (1989) CCD image, the primary observational source for these statements was a collection of photographic plates taken by Baade and analyzed by Scargle in the late 1960s. The "Faint Wisp" to the Southeast was first discovered in van den Bergh & Pritchett's picture. So far, nothing has been reported on its variability, although it does appear in more recent HST images obtained by Hester *et al* (1995). Since these variable features fall right in the region which might be the particle acceleration zone, understanding what they are telling us might be a promising path to unraveling the physics of how this compact object energizes its surroundings.

Rees & Gunn (1974) used simple dynamic pressure balance to suggest this very region is the place where the pulsar's outflow terminates. So long as the pulsar loses energy in relativistic form, and the relativistic energy flow cannot freely penetrate the relativistic particles and fields already in the Nebula, the dynamic pressure $\dot{E}_R/\Delta\Omega r^2 c$ of the pulsar's energy loss, presumed to flow out in a solid angle $\Delta\Omega \leq 4\pi$, balances the static pressure of the relativistic particles and fields in the Nebula at the radius $r_s \approx 0.2$ parsecs, right in the middle of the wisp zone! If this is correct, one is led to Rees & Gunn's suggestion of a relativistic shock wave terminating the wind in the vicinity of the wisps as the means by which the outflow energy gets converted into the power law distributions of injected leptons inferred from the synchrotron models.

Now one can ask, which of the wisp features is the shock wave? Why do they vary? What is the nature of the acceleration process that goes with these enhancements in the surface brightness? What relation do they have to the ultra high energy leptons that radiate the gamma rays? In order to pursue these questions, one must adopt a geometry for the flow, a decision always made ambiguous by the fact that imaging projects a three dimensional system onto the plane of the sky. For the following discussion, I assume the outflow to lie in the same plane as the X-ray torus first inferred by Aschenbach & Brinkmann (1975); the X-ray torus then occurs at projected radii slightly larger than those of the wisps. In this picture, the equatorial wind flows through the wisps and becomes the plasma feeding the X-ray torus. I briefly discuss an alternate picture suggested by Hester *et al.* below.

In its most general form, the wind can be composed of wound up magnetic fields, the associated motional electric field, outflowing electrons, positrons and heavy ions, yielding overall energy conservation for the wind in the radiationless cavity inside 0.1 pc from the pulsar in the form

$$\begin{aligned}\dot{E}_R &= r^2 \int d\Omega \left\{ \frac{c}{4\pi}\mathbf{E}\times\mathbf{B} + \mathbf{v}_{wind}\gamma_{wind}\left[(n_+ + n_-)m_\pm c^2 + n_i m_i c^2\right]\right\} \cdot \hat{\mathbf{r}} \quad (2)\\ &= c\beta_{wind}\gamma_{wind}\dot{N}_i m_i c^2 \left(1 + \frac{m_\pm}{m_i}\frac{n_+ + n_-}{n_i}\right)(1+\sigma).\end{aligned}$$

A successful shock theory of nonthermal particle acceleration requires heavy ions, and they turn out to carry most of the outflowing energy. Within the geometric assumptions, the wind is characterized by the parameters $m_i\dot{N}_i$ (the ion mass loss rate), $(n_+ + n_-)/n_i = \dot{N}_\pm/\dot{N}_i$ (the ratio of the number of leptons lost by the pulsar per second to the number of ions lost per second), the bulk flow Lorentz factor γ_1, and σ, the ratio of the Poynting flux to the kinetic energy flux in the wind.

Applying Rees & Gunn's (1974) dynamic pressure balance argument to the torus geometry of (and assuming essentially all of the pulsar's rotational energy loss is carried by this "equatorial" wind) yields a termination shock radius $r_s \approx 0.2$ pc. However, because $2\pi r_s/cP \sim 10^9$, the magnetic field in the wind is almost precisely transverse, ruling out conventional diffusive Fermi acceleration in shocks as the mechanism for converting flow energy to the injection distribution of high energy pairs.

2.1. Physics of Collisionless, Transverse, Relativistic Shocks

The physics of relativistic, transverse shocks in an electron-positron-heavy ion plasma reveals how to convert the flow energy into the injection spectra inferred from the synchrotron models, and how to interpret the wisps as features of the shock structure (Alsop & Arons 1988, Langdon, Arons & Max 1988, Hoshino & Arons 1991, Gallant *et al* 1992, Hoshino *et al* 1992). The incoming heavy ions collide with the compressed magnetic field, which reflects them coherently and sets them into cycloidal motion as they drift in the crossed motional electric field and the magnetic field *within* the shock structure.

In the drift frame, the ions form a ring distribution in momentum space. The rings are unstable to gyrophase bunching, through the emission of electromagnetic ion cyclotron waves at the ion cyclotron frequency *and its harmonics* - with a relativistic ion ring, high harmonics are excited with growth rates comparable to that of the fundamental. The same kind of structure forms in the pairs at the leading edge of the ion structure, which leaves the ions gyrating in a compressed, heated pair plasma. The pairs heat because they cyclotron reabsorb their own extraordinary modes [$\omega \geq (eB/m_{\pm}\gamma_1)\sigma^{-1/2} \sim 10^{-3}$ s^{-1}], a process which thermalizes the pairs to Maxwellian distributions with temperature $\approx \gamma_1 m_{\pm}c^2$. However, the ion waves are preferentially cyclotron absorbed by the more mobile pairs, a process which transforms the pair distributions into the desired γ^{-2} injection function at energies above $\gamma_1 m_{\pm}c^2$. Particle-in-cell simulations and quasi-linear theory both show this particle spectrum, which forms because the ion cyclotron waves themselves have a power law distribution in k space, extends up to $\gamma_{\pm,max} = (m_i/Zm_{\pm})\gamma_1$ *i.e.*, up to an energy per particle for the pairs equal to the upstream energy per particle of the ions. The same results also show that this nonthermal acceleration mechanism works with 10% to 20% efficiency when $\sigma \ll 1$ and $m_i\dot{N}_i/m_{\pm}\dot{N}_{\pm} > 1$. The simulations show that in the shock frame, the shock is intrinsically unsteady on the ion cyclotron time scale.

2.2. Wisp Structure and Wind Properties

The reflected particle dynamics also suggests an answer to the question, "what are the wisps?" The nonthermal acceleration occurs over a length comparable to the ion gyration radius. The turning points in the ion orbits are places where all the outflow momentum in the ions (which carry most of the momentum and energy under conditions where the nonthermal acceleration works) gets deposited in compressing the magnetic field and the pairs frozen to the field. Such compressions, spaced in radius by the ion Larmor radius, yield enhancements of the surface brightness - it is not hard to show that compression of the magnetic field causes the bolometric synchrotron surface brightness to increase in proportion to B^4. This idea has a chance of working only if the ions have sufficiently high rigidity (large Larmor radii) such that the spacing of the compressions corresponds to the observed wisp spacing on the sky. The simulations show that the coherence in the ion reflection is preserved for several cycloidal cycles, yielding the possibility of forming a series of compressions spaced by the ion Larmor radius.

Gallant & Arons (1994) made a *steady* flow, reflected particle solitary wave model (a "shock wave" without entropy production) which incorporated the necessary spherical expansion of the flow, and used it to compute the surface brightness of the inner Nebula along a 2″ wide strip extending from Southeast to Northwest passing through the pulsar and the wisps. Their results show that the asymmetry between Northwest and Southeast results from the Doppler boosts in the pair flow, which has speed $\sim 0.5c$ in the first compressed region. Notably, the fit to the first two main wisps in the Northwest constrains it all the parameters of the model, including the tip angle of the equatorial wind with respect to the line of sight - no further adjustments are allowed or required to obtain the fit to the faint wisp to the Southeast requires. The wind parameters inferred from the model are

$$\begin{aligned}
m_i\dot{N}_i &\approx 10^{-15}\ M_\odot/\mathrm{yr} = 6\times10^{10}\ \mathrm{g/s} \\
\sigma &\approx 10^{-3} \\
\gamma_1 &\approx 4\times10^6 \approx Ze\Phi_{open}/m_ic^2;\ \Phi_{open} \equiv \Omega_*^2\mu/c^2 \approx 5\times10^{16}\ \mathrm{Volts} \\
B_1 &\approx 3\times10^{-5}\ \mathrm{Gauss} \\
r_{L,ion} &\approx 0.15\ \mathrm{parsecs}
\end{aligned}$$

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$$\dot{N}_{\pm} \approx 5 \times 10^{37}\,\mathrm{s}^{-1}.$$

The ion cyclotron time scale, on which the shock is intrinsically variable, is a few months. This theory suggests the physically interesting conclusion that the shock structure is spread out on the sky, with the wisps identified as the magnetic "overshoots" *within* the shock structure. The shock thickness is several ion Larmor radii, and extends out to the inner edge of the X-ray torus, by which radius the coherent ion gyrations have fully dissipated.

Equally interestingly, the pulsar must have accelerated the ions (and the wind) through most of the total electric potential available on open field lines Φ_{open}. In accord conclusions reached by Rees & Gunn (1974), Kennel & Coroniti (1984a,b) and others, our hybrid kinetic theory of the wisps shows that by the time the wind decelerates at its termination shock, its energy density is plasma dominated ($\sigma \ll 1$).

The rate of pair production inferred from this theory of the wisps is the same as one infers from the requirement that the pulsar supply the number of particles feeding the Nebular X- and γ ray source (Gallant & Arons 1994), but about an order of magnitude below what one infers for the *average* rate of particle injection to the Nebula, based on the total population of particles emitting *radio* synchrotron radiation (Shklovsky 1970), a result which suggests the pulsar was an even more copious producer of pairs in the past. Most interesting of all, the model allows one to directly infer the rate at which the pulsar loses positive charge. This is $Z\dot{N}_i \approx 3 \times 10^{34}\ s^{-1}$, which is just the Goldreich-Julian rate needed to be emitted from an "auroral zone" around the polar cap, to eventually flow away in the rotational equator of the star, if the star is not to become charged up (*e.g.* Arons 1983). This is the first empirical, if model dependent, evidence that such "open circuited" current patterns might really occur in RPPs.

2.3. Variability

Gallant & Arons' (1994) model is time independent by construction, as a "proof of principle". The wisps are known to vary on a time scale of months (Scargle 1969), and the numerical results on shock structure show large variabilty on the ion gyration time scale due to the underlying cyclotron instability of the ion ring. The parameters inferred from the time steady model imply a time dependent theory would show variability on time scales of months. Work in progress (Arons, Gallant & Li, in preparation) suggests the wisps will indeed vary on the ion gyro time $t_i \approx \pi/\omega_{ci2} = \pi m_i c\gamma_1/ZeB_2 \approx 5$ months.

3. Conclusions

These results suggest that study of plerions can yield a rich harvest of insights into the physics of the underlying pulsar. Further work requires both lifting the simplifications of the purely equatorial geometry assumed by Gallant & Arons, incorporating a model of how nonthermal particle acceleration develops with radius, to compare to the spectral observations being collected by the ground based observers, and most of all incoporating time dependence into the generation of synthetic images. In addition, investigations of the time dependence of the gamma ray emission provide another window into the investigation of the wind's properties (Arons 1996).

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