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AN OVERVIEW OF THE PHYSICAL ISSUES ON PULSAR WINDS

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RESUMEN

El misterio central sobre los vientos de pulsares, ha sido el mecanismo para convertir la energía magnética (i.e., flujo de Poynting) en energía cinética de partículas, mediante la cual las radiaciones iluminan toda la nebulosa como es el caso en el Cangrejo. Se han propuesto fuertes choques magneto-dinámicos han sido propuestos pero resulta un poco incierta la forma en que este mecanismo opera. La reconección magnética (o calentamiento inductivo) puede proveer tal conversión y resulta muy prometedora para explicar los rasgos vistos alrededor de la región ecuatorial, pero ésta probablemente no se aplica a la región polar debido a que aparentemente no hay láminas alternantes de corriente. En su lugar, postulamos que ciertas inestabilidades resistivas operan y producen regiones localizadas de disipación de energía ("nudos" o "puntos calientes"). Tales inestabilidades parecen inevitables para cerrar las corrientes alrededor del pulsar y disipar los flujos de energía.

ABSTRACT

The central mystery on pulsar winds has been the mechanism to convert magnetic energy (i.e., Poynting flux) to particle kinetic energy, from which the radiations light up the whole nebula in the case of Crab. Strong MHD shocks have been a popular candidate but exactly how it comes about is quite uncertain. Magnetic reconnection (or inductive heating) may provide such a conversion and is quite promising in explaining the features seen around the equatorial region, but it probably does not apply to the polar region since there is no apparent alternating current sheets. Instead, we postulate that certain resistive instabilities will operate and produce localized energy dissipation regions ("knots" or "hot spots"). Such instabilities seem inevitable in order to close the currents around the pulsar and dissipate flow energies.

Key words: **ISM: INDIVIDUAL OBJECTS (CRAB NEBULA)**

1. INTRODUCTION

The Crab Nebula is by far the best studied pulsar wind system with its rich history of multiwavelength observations. It is probably the only object that offers enough information to seriously put constraints on physical models. Despite the wealth of data, we still do not really understand the wind production, propagation and termination, some of which are attributed to our lack of knowledge of how pulsar works. The recent *HST* observations (Hester et al. 1995 and henceafter); from the well-known "wisps" to the newly discovered "knots" (merely $\sim$ 1500 AU away from the pulsar), have rejuvenated much interests in pulsar wind studies. In this proceeding, we will attempt to give a brief overview of several theoretical issues by discussing a few pulsar wind models, *not* to enlist and summarize every model (or every aspect) on pulsar wind. Hester et al. (1995) and Michel (1991, Ch. 9) serve as excellent reviews on observations and theoretical models, respectively. A slight more emphasis is given on the works after 1990.

2. DIMENSIONAL NUMBERS

The period and spin-down rate of Crab are 0.0331 s and 4.7×10^{-13} respectively. The rotational energy loss $I\Omega\dot{\Omega} \sim 5 \times 10^{38}$ ergs s^{-1}. The torque on the pulsar is presumably from the coupling between pulsar magnetosphere and the surrounding medium, most likely via an electromagnetically dominated stellar wind. This explains why the spin-down luminosity of most pulsars exceeds, by several orders of magnitudes ($\sim 10^5$), the power detected in the pulses themselves. The fact that the Crab's braking index 2.59 (< 3) (Lyne, Pritchard, & Smith 1988) is consistent with the view that the energy is lost via a stellar wind, instead of vacuum spindown.

The whole Crab nebula is a few pc in size with a rather well-defined axis of cylindrical symmetry (e.g., Hester et al. 1995), which is believed to be the pulsar spin axis. At a fraction of pc scale, the synchrotron nebula is a fascinating region consisting of x-ray and optical torus, complex "wisps", and x-ray and optical jets (but curiously jets are not present in VLA maps, Bietenholz & Kronberg 1992). An even smaller inner region (~ 0.1 pc) immediately surrounding the pulsar is underluminous in radio, optical and x-rays. The Crab nebula also serves as a yardstick for high energy radiations and Haymes (Haymes et al. 1968) made one of the first hard x-ray to gamma-ray observations of the nebula. The total nebula's radiative output is 10% of the total rotational energy loss, with most of the emission (peak of νf_ν) between 1 keV to 1 MeV and extending up to ~ 10 TeV (requiring electrons with Lorentz $\gamma \approx 10^7$), presumably from the inverse-Compton scattering of the synchrotron photons by the same energetic electrons. A comprehensive study on the gamma-ray emissions by De Jager et al. (1996) seems to indicate that the nebular synchrotron spectrum cuts off at ~ 25 MeV, which implies that electrons (positrons) are accelerated on a timescale of a gyroperiod ($\sim$ a few hours for TeV electrons) to account for the synchrotron burnoff. They were also able to constrain the mean magnetic field $\bar{B} \sim 0.2$ mG and place a lower limit on the time-averaged lepton injection rate $\dot{N} > 4 \times 10^{40}$ s^{-1} (we will come back to this point).

3. MODELS

We can roughly divide the past theoretical efforts into wind formation, propagation, and termination, with most of them devoted to propagation. The lest understood is the formation which is tightly linked to how pulsars function, but unfortunately it serves as the starting point (or inner boundary condition) for the flows. Thus, most wind theories arbitrarily specify MHD flow parameters at one point in a magnetic flux tube and calculate the subsequent evolution of the flow in that flux tube.

Although there have been many papers on the pulsar winds in the last 30 years, a sequence of seminal works can nevertheless be singled out. The understanding of solar wind (Weber & Davis 1967) and the discovery of Crab pulsar (1968) apparently led Michel (1969) to construct the first relativistic wind model from compact objects. We now discuss them one by one.

1. Michel (1969) and Goldreich & Julian (1970). The pulsar magnetic field was simplified as a split-monopole and symmetric about the star's rotation axis and plasma pressure (i.e., "cold" wind) and gravity were ignored. Upon rotating the star, the magnetic fields are forced to wind up into a spiral and particles on the field lines are accelerated by the magnetic slinging. By solving a set of algebraic equations (continuity, momentum and energy), the flow is shown to pass through a sonic point (disappears in zero pressure limit), Alfvén point (which corresponds to the speed of transverse (B_r) Alfvén wave) and only asymptotically approach the magnetosonic point (compressional (B_ϕ) Alfvén wave speed). A key parameter is $\sigma = e\Omega B a^2/mc^2$, which physically is the maximum Lorentz factor the particles can attain if all the Poynting flux went into the particles. They found that the maximum (proper) flow speed is only $\sigma^{1/3}$, though highly relativistic (γ can be $\sim 10^7$), it is still *sub*-Alfvénic.

2. Rees & Gunn (1974). It is essentially a hydrodynamic model, and the arguments are straightforward. All the energies coming out of the pulsar must be confined in a volume which expands at a rate $\dot{R}_{\rm neb} \ll c$. Thus, there should be a place R_s where the ram pressure balances the total pressure within the nebula, $L/cR_s^2 \approx L/\dot{R}_{\rm neb}R_{\rm neb}^2$, which gives $R_s/R_{\rm neb} \sim (\dot{R}_{\rm neb}/c)^{1/2} \sim 0.1$. This wind zone $R < R_s$ was identified with the underluminous region surrounding the pulsar. This study basically set the stage (i.e., the wind propagation zone, the shock, and the postshock flow) for many subsequent models.

3. Kennel & Coroniti (1984). Adopting Rees & Gunn picture, they were probably the first group who did the detailed MHD shock calculations for the nebula. They argued that in order to match the boundary conditions at the remnant, the pulsar wind is terminated by a strong MHD shock that is essentially hydrodynamic in nature (i.e., the flow is dominated by the particle pressure). They characterized the flow using $\sigma_{\rm kc} = \sigma/\gamma$, or $\sim B^2/4\pi n u \gamma m c^2$ (in the shock frame and upstream). They showed that $\sigma_{\rm kc}$ must be $\sim 10^{-3}$, i.e., the relativistic wind coming out of the pulsar has to be extremely "hot" or very dense (high n). Copious pair production in the magnetosphere was suggested as a possible way to provide the high plasma density, which also solves the dilemma of trying to shock what otherwise would be a Poynting-flux dominated flow.

4. Coroniti (1990) and Michel (1994). Coroniti's work was probably the first to recognize the influence of the time-dependent structure of the wind on energy transport. For a pulsar with mis-aligned rotation and magnetic axes, the asymptotic wind magnetic field near the rotational equator should consist of stripes of oscillating toroidal field separated by neutral sheets. Coroniti has shown that even an initially high σ_{kc} flow will be subject to progressive field annihilation of the opposite polarity stripes, thus heating the plasma as the wind propagates out. Michel interpreted the process as "inductive heating" (rather than the fancier word "reconnection") due to the shortage of the plasmas to maintain the current (since $n \propto 1/r^2$ faster than $B \propto 1/r$). The interruption of the current introduces the induction E field which eventually accelerates the plasmas. Both of them showed that the initially dominant Poynting flux is converted into particle thermal and directed kinetic energy before 3×10^{15} cm, well within the inner underluminous region (3×10^{17} cm).
5. Begelman & Li (1994) and references therein from the same group. They pointed out analytically that in an axisymmetric and precisely radial flow, the toroidal magnetic pressure and tension forces cancel each other, hence the plasma acceleration is very inefficient. However, if the flux surfaces deviate from purely radial even slightly (faster), the flow will become super-magnetosonic and significant acceleration can be achieved (see also Blandford & Payne 1982). The deviation from pure radial was dubbed "magnetic nozzle", which after the flow passes through the fast point, continues to convert the magnetic energy into particles, though σ is shown to be declining logarithmically with r.

To summarize, a cold, steady-state and ideal MHD flow based on split-monopole geometry will *always* stay Poynting flux dominated if it is injected with $\sigma_{\rm kc} \gg 1$, and the flow only approaches the magnetosonic point asymptotically. But independent estimates on the Crab nebula suggests that the flow must have $\sigma < 1$ in order to pressure confine the flow within the remnant. This apparent paradox may be partly alleviated if (1) we consider that the time-dependent magnetic field (at least along the equatorial region) is "striped" and likely dissipates; and (2) the magnetic flux surfaces are (even slightly) collimated towards rotation axis.

4. PHYSICAL ISSUES AND PROBLEMS

It is clear that the global flow pattern of a magnetized wind has yet to be established, even qualitatively. The central question is how the flow terminates or how the energy transported by magnetic stresses is released.

1. *Shocks.* Shocks are expected both observationally and psychologically, but it yet has to be reconciled with the fact that strong shocks are generally impossible in the Poynting energy flux. Note that even in the "striped" equatorial region where the conversion from magnetic energy to particle energy is highly plausible, the aligned component which is also convected away with the flow will still dominate at large distances, rendering the flow below magnetosonic speed, hence no shocks (Michel 1994). The flow just slows down from (essentially) the speed of light to match the remnant expansion speed, just like subsonic flow in ordinary hydrodynamics.

   In Begelman & Li's works, it is shown that it is *possible* to get asymptotically kinetic energy dominated, cold MHD flow, but admittedly the conversion is very inefficient. One generally needs the global force-balance to solve for the field and flow geometries (not necessarily force-free). They emphasized the deviation from pure radial geometry of field lines but the fast point they got is only a few light-cylinder radii away from the pulsar, rather uncomfortably close.

   Another motivation for having shocks is to explain the synchrotron spectrum of the nebula from radio to TeV, which is well explained by a power-law electron injection distribution. Over the years, the formula "shocks = power-law electron distributions" has been widely accepted even though we do not really understand how shocks accelerate electrons, especially when the magnetic fields are *transverse*, not the *parallel* geometry people usually wanted for diffusive shock acceleration (but see Gallant & Arons 1994). It should be pointed out that any accelerator for which a fractional gain in energy ($dlnE$) by a few particles is accompanied by a larger fractional loss ($-dlnN$) in number of the remainder will give a power-law (Michel 1991; Colgate 1994): $dN/N = -s(dE/E)$.
2. *Dense stellar wind or charge-starved flow.* The particle injection rate from the pulsar to the wind is estimated to be $\dot{N} \sim B\Omega^2 a^3/e \sim 10^{34}$ particles/s (Michel 1991), which is assuming that *all* particles having access to field lines beyond the light-cylinder are centrifugally expelled. We could not get $\dot{N}$

from radio pulse observations due to our ignorance of pulse emission mechanism. As mentioned above, De Jager et al. argued that $\dot{N} \geq 10^{38}$ leptons/s, *if* the particles are only accelerated once. Kennel & Coroniti (1984) also suggested that one could obtain 10^{38} by assuming that 10^4 $e^{\pm}$ are produced per current-carrying primary.

The real problem is whether particles are injected at very high energy at the base of the wind and decelerate since, or they are being reaccelerated in the wind. Unlike the Sun, pulsars do not have a (virtually) infinite plasma reservoir, it probably "makes" (either extracting particles from surface or via pair-production) just enough plasma to keep the currents flowing and support the wave propagation. Consequently, the initial wind will always be Poynting dominated and charge-minimum. Afterall, the magnetic energy convected away with the flow will eventually be transferred back to particles one way or the other (i.e., reacceleration must occur). This way, the system can adjust itself between particle and fields to reach equipartition (Michel 1991; see also Michel 1998, this volume).

3. *Vacuum waves or plasma waves.* There is an uncertainty as to what is the fate of the orthogonal dipole component which produces large amplitude electromagnetic waves beyond the light-cylinder. As pointed out in Michel (1991), this wave can either propagate through the plasma (phase velocity larger than c) or the plasma moves with the wave (phase velocity less than c). We believe the second case is more likely. The 30 Hz radio waves are below all the "natural" frequencies of the surrounding plasmas, so they will either be reflected or absorbed. But the point is that these waves have nowhere to go if reflected, except to exert further pressure. This is somewhat analogous to the RF heating of tokamak plasma (or laser fusion). The $E\&M$ waves from the antennae are eventually absorbed by the plasmas (matching the plasma frequency or cyclotron frequency with the heating waves).

   It can be shown that the linearly polarized waves from the equatorial region (Ostriker & Gunn 1971) and the circularly polarized waves from the pole (Michel & Li 1997) can both strongly accelerate particles by essentially "picking" them up (from rest) and the particles try to move with the wave. By the time the particles finally "slip" out of phase with the waves, they have already reached a typical energy of $\gamma \sim 10^7$. Once enough particles have been picked up and absorb wave energies, the vacuum waves have been turned into plasma waves and the flow can be regarded as a MHD fluid.

4. *Current flows and MHD instabilities.* The magnetic field flowing out with the wind forms a helical structure around the rotation axis, with a longitudinal current flowing along the open field lines. These currents *must* be closed since the pulsar (and nebula) is surrounded by a conducting medium. The currents might return along the equatorial plane and along the boundary between the closed and open magnetosphere (the exact current flow is very much an open issue for further research). The current closure requires that the currents move across magnetic surfaces somewhere on the loop, so, an impedance has to exist and energy is released there (i.e., $\mathbf{J} \cdot \mathbf{E}$) along with an electric potential drop.

   It is well-known in fusion studies that a cylindrical magnetic field configuration is generally unstable to *kink* instabilities, driven by current running along the magnetic field (cf., Bateman 1978). Such instabilities, found in free-boundary plasmas surrounded by a vacuum region, can result in large distortions that send plasmas to the wall (see also Colgate 1978). In other words, the instability has generated enhanced dissipation of the current with the associated rapid transverse motion, and the magnetic surfaces have somehow been "randomized", contrary to the well-nested picture people usually imagine. In the case of a pulsar, as the star rotates, magnetic field lines are wound up tighter and tighter and fluxes are continuously pumped into the "cage" that is confined by the surrounding medium. This accumulation will eventually lead to instabilities. At least *locally*, such instabilities effectively reduce the separation of magnetic surfaces and initiate field line topology changes (with reconnection being the extreme case). Consequently, the currents flowing along them cross from one surface to another and produce an effective electrical resistance in the flow. Furthermore, a localized magnetic field topology change (such as reconnection) can cause effects on much larger scale as the whole system tries to adjust via compression, expansion, etc., (such as the substorm formation in the earth's magneto-tail).

5. SUMMARY

We hope that we have convinced the reader that further studies on Crab nebula, aided by the wealth of observations from all wavelengths, will yield considerable understanding of not only pulsars and their winds, but also the energy dissipation mechanisms in general that are occurring in astrophysical jets, solar flares, etc.

Again, it is inevitable that we have missed many important studies (and people) in this short review on such a large and complicated topic.

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