PULSAR WINDS

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ABSTRACT

It is argued that pulsar windzones are pulsed γ-ray emitters, and X-ray emitters. The wind consists of a strong subluminal wave, in approximate equipartition with a relativistic electron-positron plasma; it also contains a weak frozen-in magnetic flux. Trailing filaments may be responsible for large-angle particle scattering, giving rise to one-sided X-ray appearance.

EXISTENCE AND GEOMETRY

Our knowledge about ordinary stellar winds comes from emission and absorption lines. Ideally, they tell us the column density, velocity and temperature profile, and chemistry of the wind. Do we have equivalent information about the winds from pulsars?

By definition, a pulsar's windzone begins where the neutron star's oblique magnetic dipole field stops corotating: at the speed-of-light-cylinder. At this distance from the star, centrifugal forces convert azimuthal momenta into off-axis ones, and fields and charges are slingshot outwards. In the absence of mirrors and strong gravity, the outward momentum leaving the speed-of-light-cylinder cannot decrease: a wind blows. This ought to be highly relativistic because the energy density of the electromagnetic field just inside the speed-of-light-cylinder exceeds that in a force-free corotating charge cloud by the strength parameter $f := \Omega_B/\Omega = 10^8 \; B_{12} \; \Omega_1{}^2$, where Ω = angular frequency, Ω_B = cyclotron frequency, and B = surface magnetic field. In the case of the Crab and the other plerions (= filled-center supernova-remnants, like Vela-X, 3C58,...), this wind is held responsible for illuminating the nebula.

The windzone ends at an inner shock front, of radius R_i, where the ram pressure $|\dot{E}|/4\pi R_i{}^2 c$ of the wind equals the pressure p of the shocked material. With $\dot{E} = I\Omega\dot{\Omega}$, ($I$ = moment of inertia $\lesssim 10^{45}$ gcm^2), we

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find

$$R_i = (-I\Omega\dot{\Omega}/4\pi\ c\ p)^{1/2} \approx 10^{18}\ \mathrm{cm}\ \Omega_{2.3}/(\tau_{10.5}p_{-9})^{1/2} , \qquad (1)$$

where $\tau := |\Omega/2\dot{\Omega}|$ is the pulsar's spindown age, and where the numerical values correspond to the present Crab.

In order to evaluate eq. (1) as a function of pulsar age, note that four qualitatively different situations can control the ambient pressure p:

i) The supernova remnant expands supersonically into the ISM. In this case the flow pattern is essentially radial, and the (almost homogeneous) nebular pressure p is controlled by a balance between wind supply and expansion losses. Examples are the Crab, Vela-X, 3C 58.

ii) The remnant's expansion has turned subsonic, but the pulsar's recoil velocity is supersonic w.r.t. the ambient ISM. In this case, the flow pattern is similar to - but more blunt than - that of the solar wind around the Earth' magnetosphere, and $p \approx \rho_{ISM}v_{rel}^2/2$. Filaments may form at the highly unstable contact discontinuity. The binary pulsar 1913+16 is a possible example [Kundt (1980b)], and so are the $2\cdot 10^5$ yr old γ-ray pulsars 0740-28 and 1822-09.

iii) An almost reflection-symmetric flow pattern is expected around elderly, slowly moving pulsars, in which case we have $p = p_{ISM} + \rho_{ISM} \times v_{rel}^2/2$.

iv) A much more complicated situation will arise when a pulsar orbits around a normal star, because of the large density contrast in the two winds, and because of the accelerated orbital motion. Possible examples are the binary pulsar 0655+64, and SS 433 [Kundt (1979b, 1981)], as well as the central regions of most of the kelifons (= shell-type supernova-remnants) [Kundt (1977, 1980a)].

We return to case i). The pressure p inside a young supernova remnant is expected to rise linearly during an initial explosion phase, of duration $R_{SN}/v \lesssim$ day, whereafter it drops as t^{-2} due to the increasing volume to be filled [Pacini & Salvati (1973)]:

$$p \lesssim 3\ L_o/16\pi\ v^3\ t^2 \qquad (2)$$

(R_{SN} = supernova radius, v = expansion velocity). The injected power L is approximated by a power-law $L = L_o(1+t/\tau_o)^{-\alpha}$ where $\tau_o \lesssim 10^3$ yr is the initial pulsar spindown timescale, and $\alpha = (n+1)/(n-1) \approx 7/3$ for the Crab (n = braking index $\approx 5/2$). For times $t > \tau_o$, L_o in the above pressure formula has to be replaced by $(2L_o/(\alpha-1)(\alpha-2))\ (\tau_o/t)^2$, and p drops as t^{-4}.

These formulae apply as long as the nebular pressure exceeds the ram pressure of the ambient ISM. Thereafter, the stalled relativistic wind plasma will reduce its expansion speed such as to remain in rough equilibrium with the confining pressure $p_{ram} = \rho_{ISM}\ v_{exp}^2/2$. Eventually, after slowdown of the filamentary shell, the confining pressure is reduced to that due to the relative velocity v_{rel} between pulsar and ambient ISM.

This pressure evolution, whose details depend primarily on the supernova expansion speed v but also on L_o, τ_o, α, and ρ_{ISM} (if the latter vary from object to object), is drawn in the upper part of Figure 1 for $L_o/v^3 = 2 \cdot 10^{13}$ g/cm, $\rho_{ISM} = 10^{-25}$ g cm^{-3}, $v_{exp} \gtrsim 10^8$ cm/s, $v_{rel} = 10^7$ cm/s, which are typical for the Crab. The bottom part of Figure 1 shows the inner shock radius R_i evaluated from eq. (1). Accordingly, the wind-zone of young plerions has a radius between 0.1 and 1 lyr. In the cases of the Crab and Vela, 2 R_i coincides with the extent of their respective soft X-ray images obtained with the Einstein observatory [Helfand (1981), Mason & Culhane (1978)]. I come back to this point below.

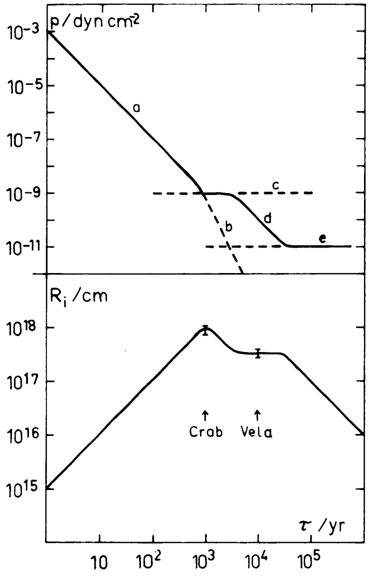

Figure 1. Calculated pressure p in the shocked pulsar wind (above), and inner shock radius R_i against the interstellar medium (below), as functions of age. p is at first controlled by a balance between injection into, and expansion of the supernova remnant (branches a,b); in later stages, the ram pressure exerted by the ambient medium sets a lower limit (due to linear expansion, branch c, decelerated expansion, d, and proper motion,e). R_i is calculated from eq. (1). The bars marked 'Crab' and 'Vela' refer to the sizes of their central X-ray images.

It may be worth mentioning that there is also an outer shock towards the ambient medium, whose approximate radius $R_o \lesssim R_i \sqrt{c/2v}$ follows from the conservation of pulsar-wind rest mass under the assumptions of an almost constant mass density beyond $r = R_i$, and a velocity jump by a factor 2 at $r = R_i$. The region $R_i \leq r \leq R_o$ is the proper supernova shell.

WIND COMPOSITION

In the case of the Crab, the electron number rate $\dot{N}_e$ injected into the nebula can be inferred from its peak luminosity L and the Lorentz factor γ corresponding to the spectral maximum under the assumptions that i) the charges lose their energy to radiation, and ii) post-accelerations inside the nebula can be ignored [Kundt & Krotscheck (1980)] :

$$\dot{N}_e = L/\gamma\, m_e\, c^2 = 4 \cdot 10^{38}\ s^{-1}\ L_{38}/\gamma_{5.5} \quad . \tag{3}$$

This rate exceeds the Goldreich-Julian rate $\dot{N}_{GJ} := B_o R^3 \Omega^2/ec \approx 10^{34}\ s^{-1}$ by more than a factor 10^4, $\dot{N}_{GJ}$ being the maximum particle flow to be extracted from a charge-separated magnetosphere. Very likely, therefore, the charges are produced in vacuum, hence are electron-positron pairs.

Further arguments against the presence of a large fraction of ions in the Crab pulsar wind have been given earlier [Kundt (1980a), Kundt & Krotscheck (1980)] . Briefly they are:

1) The nebular dynamics want particles of decreasing stiffness,

2) A divergence-free current through an almost force-free Goldreich-Julian magnetosphere needs a large excess of neutral plasma [Cheng & Ruderman (1977)],

3) The strong magnetic dipole wave is expected to be radiation-damped by a plasma with more than one e/m-ratio of its particles,

4) The jets feeding the extragalactic radio sources have been suggested to consist of an electron-positron plasma [Kundt & Gopal-Krishna (1980)], and active galactic centers have similar properties to the Crab. (Their central engine may likewise be a rotating magnet [Kundt (1979a)].)

What else does a pulsar wind consist of ? In the vacuum case, the power loss of a fast rotating magnet consists solely of a strong wave. When charges are injected, the wave would still have similar properties to a vacuum wave as long as

$$1 \ll \Omega f^{1/2}/\Omega_e = \Omega_B/\Omega_e\ f^{1/2} = (\dot{N}_{GJ}/2\dot{N}_e)^{1/2} \quad , \tag{4}$$

where $\Omega_e = (4\pi n\, e^2/m)^{1/2}$ is the non-relativistic electron plasma frequency, [Arons (1979), Asseo et al (1978)]. The charges are then boosted to high energies, and the wave-4-momentum is quickly converted into ultrahard γ-rays [Asseo et al (1978)].

But for the Crab and probably for all pulsars, inequality (4) holds in the opposite sense [Kundt (1980c)]. Between one and $(\dot{N}_e/\dot{N}_{GJ})$ light-cylinder radii, ordinary currents dominate over displacement currents, and the wave has a subluminal phase velocity [Kundt & Krotscheck (1980)]. This phase velocity is shared by the $\vec{E} \times \vec{B}$ - drifting charges, and in the absence of incoming radiation, their radiation losses may well be insignificant. There is likely to be near-equipartition between wave and particle energy [Asseo et al (1975)]. The main evidence for the presence of a strong wave in the Crab is the ~30-fold over-pressure when compared with the ram pressure $L/4\pi r^2 c$ [Kundt & Krotscheck (1980)].

Finally, a pulsar wind is expected to convect a frozen-in toroidal magnetic field into the nebula, of opposite sign in the northern and southern hemisphere. The best verification of this flux is the optical polarization pattern measured on the injection sphere at $r = R_i$ by Schmidt & Angel (1979).

A rigorous treatment of pulsar winds has not yet been achieved: Earlier attempts by Michel (1969) and Goldreich & Julian (1970) were unrealistic in assuming a neutral, one-fluid plasma of infinite conductivity ($\vec{E} + \vec{\beta} \times \vec{B} = 0$), thus prohibiting the wave from pushing the charges. Asseo et al (1975) assumed a pure vacuum shape of the electromagnetic wave, and Asseo et al (1978) discarded the (relevant) subluminal dispersion branch.

EMISSION AND ABSORPTION

What are the radiative properties of a pulsar wind? As argued above, a purely outgoing strong wave carrying a super-Goldreich-Julian plasma load may not radiate at all. But the windzone is not empty. In the case of a young pulsar, it is likely to be permeated by i) the intense radiation of the ambient nebula, ii) a bath of low-frequency waves repeatedly reflected by the surrounding filamentary shell, [Kundt & Krotscheck (1980), Kundt (1980a)], and iii) trailing filaments from the past supernova explosion.

A bath of electromagnetic radiation filling the windzone must force the outgoing charges to radiate. In the vacuum case, their synchro-Compton radiation leads to an energy loss rate

$$\dot{\gamma}\, m_e c^2 = \sigma_T\, c\, \varepsilon/4\pi \qquad (5a)$$

with $\varepsilon := F_{ab}\, u^b F^{ac} u_c = \gamma^2 \left[(\vec{E}+\vec{\beta}\times\vec{B})^2 - (\vec{E}\cdot\vec{\beta})^2 \right]$, (5b)

σ_T = Thomson cross section. ε vanishes for an ideal $\vec{E} \times \vec{B}$ - drift. For simultaneous incoming and outgoing radiation, it may be speculated that $\varepsilon \approx 2\gamma^2 B_{in} B_{out}$. If so, the lifetime $\gamma/\dot{\gamma}$ of an outgoing high-energy particle against synchro-Compton losses, measured in units of the escape time to a distance r, is given by

$$\gamma c/\dot{\gamma} r = 2\pi\, m_e c^2/\sigma_T\, \gamma\, B_{in}\, B_{out}\, r \approx 1/\gamma_7 \quad , \qquad (6)$$

the latter for typical Crab parameters. Clearly, more rigorous calculations have to be done. But eq. (6) should at least be applicable at large distances; it predicts that all outgoing charges degrade in the windzone to Lorentz factors $\gamma < 10^7$. The emitted synchro-Compton radiation (for $B \lesssim$ mG) is expected at X-ray energies and above.

Will the windzone-radiation be pulsed or steady? It can only be pulsed if 1) the motion of the particles stays in phase with the wave, and 2) the radiation is emitted almost radially. For velocity differences of order $(1-\beta)c$, phase rigidity throughout $R_i/c \approx 1$ lyr means

$$\gamma \gtrsim (R_i\Omega/c)^{1/2} = 10^5 \quad . \tag{7}$$

And the angular excursions of the charges in the far windzone, of order f/γ, must be smaller than $(c/r\Omega)^{1/2}$ in order to avoid pulse smearing by detouring, whence the stronger condition:

$$\gamma \gtrsim f\ (r\Omega/c)^{1/2} \gtrsim 10^7 \quad . \tag{8}$$

This inequality clearly holds for γ-rays, but is increasingly violated for decreasing photon energies in the X-ray range. I therefore expect pulsed γ-rays from pulsar windzones, and extended (steady) X-ray 'haloes'. This interpretation is supported by the fact that the spectrum of the Crab passes smoothly from pulsed to steady, near 10 MeV, instead of showing a jump (Figure 2).

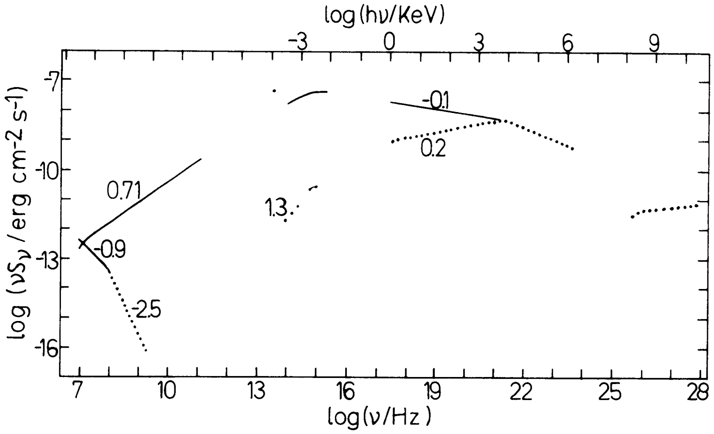

Figure 2. Spectral density of the Crab nebula and its pulsar (dotted)

Naively, therefore, one would expect to see pulsars as pulsed γ-ray points becoming circular X-ray disks when the receiver is tuned to lower 'frequencies'. Instead, the Einstein picture of the Crab looks more complicated than elliptical [Helfand (1980)], with a strong half-moon-shaped enhancement to the north-west, in the wisp region, reminiscent of the one-sidedness of galactic-center sources. This one-sidedness is probably caused by relativistic beaming, in agreement with the fact that the radiation is non-thermal [Strickman et al. (1979)] and polarized [Weisskopf et al. (1978), Silver et al. (1978)] . Note, however, that if the radiating charges come radially from the central pulsar, their velocities must be deflected through angles of order unity in order to point towards us, with an accuracy of order $\gamma^{-1} \approx 10^{-7}$. Only massive obstacles can do this. Is Einstein mapping a signature of trailing filaments ?

The situation is even more confused by the fact that intensity fluctuations, on timescales $\lesssim$ s, by 7 % to 14 %, have been observed in the UHURU band, where only 8 % of the intensity is pulsed [Forman et al (1974), Forman et al. (1976)]. The scatterers should, therefore, be small in number, and no more than a light second in extent, yet of sufficiently large area to intercept more than 10 % of the total flux. Can such constraints be met ? Obviously, improved X-ray observations are called for.

So far we have restricted discussions to emission. In view of the expected low densities in pulsar winds, absorption or scattering can only be important if it happens coherently. As pointed out by Wilson & Rees (1978), coherence can indeed be important for radio waves near the speed-of-light-cylinder. Roughly, the optical depth τ for induced Compton scattering (towards lower frequencies) reads:

$$\tau \gtrsim \sigma_T \int_{r_{em}}^{\infty} n\, ds \; \frac{k\,T_b(\nu_{min})}{m_e c^2} \left(\frac{\nu_{min}}{\nu}\right)^{1/2} \gamma^{-4} \approx \left(\frac{\nu_{min}}{\nu}\right)^{1/2} \gamma_4^{-4} \quad , \qquad (9)$$

the latter for the Crab. Here $\sigma_T \int n\, ds$ is the incoherent depth, T_b = brightness temperature, and the factor γ^{-4} stems from the necessary narrow-angle beaming. Obviously, the wind is opaque to radio waves as long as it contains electrons with Lorentz-factors $\gamma < 10^4$. The radio pulses must, therefore, come from distances or directions where they don't overtake soft electron streams.

OUTLOOK

A deeper understanding of pulsar winds is certainly required for a study of pulsars in binary systems, such as perhaps SS 433 [Kundt (1981)]. Moreover, galactic center sources may have a similar working scheme, with the important distinction that in addition to a relativistic $e^{\pm}$-wind, there is a chopped 'ordinary' stellar wind from the central supermassive rotator [Kundt (1979a)]. Interaction of the two winds can obviously lead to the formation of a pair of antipodal relativistic beams.

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DISCUSSION

VENTURA: What happens to the positrons when they reach the nebula?

KUNDT: Their annihilation rate is negligible due to the low density. Even the total expected galactic annihilation rate (from some 10^3 Crab-like supernova remnants) is of the order of 1% of the observed annihilation flux ($\dot{N} \gtrsim 10^{43}\ s^{-1}$) from the galactic center region (1978, Astrophys. J. Letters 225, L11).

ARONS: I do not agree that ions poison a strong wave and $e^{\pm}$ do not. Both can give transverse currents in the wave which prevent propagation if the density exceeds a certain well known limit; in fact near a pulsar (not far outside the light cylinder), the rest mass effects are completely swamped by relativistic inertia, as is obvious from Asséo's talk. Strong waves, as the name is classically used for EM fields which propagate with phase speed $\geqq c$, cannot exist in the presence of dense plasmas of any sort. Actual spindown might go through MHD winds ($v_{phase} < c$), or there might be more complex winds and waves with spatially separated zones, but the distinction between ions and $e^{\pm}$ as bad and good for propagation is incorrect.

KUNDT: I deal with the 'poisoned' case (not assessed in Asséo's talk) in which the particle rate $\dot{N}$ exceeds the critical 'Goldreich-Julian' rate N_{GJ} by $\gtrsim 10^4$. In this case there exists one stationary drift velocity $c\vec{\beta}$, viz. $\vec{\beta} = \vec{E} \times \vec{B}/B^2$, for which $\vec{E}$ vanishes in the comoving frame. If there are more than one charge species with different $|e/m|$-ratios, I thought they would tend to be boosted to different Lorentz factors, hence experience different post-accelerations by the strong electromagnetic fields, and that in this way the wave power would be converted into ultrahard γ-rays. In other words: I am not convinced that the synchro-Compton losses are the same for plasmas of one or more $|e/m|$-ratios. A quantitative estimate is needed, isn't it?

F.G. SMITH: Observations of the gamma pulse waveform show it to be very similar to radio and optical. This would be surprising if the origin were entirely different.

KUNDT: In my model, all the radiation is produced at distances greater than or equal to the light cylinder, in and beyond the post-acceleration zone. Radio through optical pulses come from near $r = R_c$, hard γ-ray through soft X-ray pulses from beyond. The latter ought to have near-identical pulse shapes — which they do — whereas the former may differ significantly: just think of the Vela pulsar.

MICHEL: Did you try to calculate the pulse shapes expected from the wind source? I attempted to calculate this some years ago and found that I could only get broad pulses. The emission of the radiating surfaces tended to overlap due to the curvature of the surfaces and did not give sharp pulses as observed.

KUNDT: Let $f := eB/m_e c\Omega$ be an effective strength parameter of the perturbing (not outgoing) field in the Crab wind. If particle motions deviate from the radial direction by $\theta \lesssim f/\gamma = 10^{-5}\ f_2/\gamma_7$, and if their radiation is beamed into an opening angle $\lesssim \gamma^{-1}$, then pulse smearing (due to the detour effect of photons coming from different points on a spherical surface) is negligible for max $(\theta,\gamma^{-1}) \leqq 10^{-5}$.