HOT RELATIVISTIC WINDS AND THE CRAB NEBULA

F.S. Fujimura and C.F. Kennel
Institute of Geophysics and Planetary Physics
University of California, Los Angeles, CA 90024, USA

We review efforts to construct a self-consistent model of pulsar magnetospheres that links the particle source near the pulsar to the outflowing relativistic wind and couples the wind to the surrounding nebula. Pair production source models (Sturrock, 1971; Ruderman and Sutherland, 1975; Arons, 1979) produce outflowing positronic plasmas which are too dense to support a plasma wave of relativistic amplitude (Kennel et al., 1973). Therefore an appropriate description seems to be a relativistic magnetohydrodynamic (MHD) wind. Radiation from a relativistic wind will be collimated forward and can only be observed along the line of sight to the wind source. This makes relativistic winds essentially unobservable and provides an almost invisible method of energy transport. Photons can be emitted in all directions and the existence of the wind inferred only after the wind has been decelerated by a confining shock (causing the flow to become subsonic and non-relativistic).

The magnetic monopole relativistic wind due to an axially symmetric aligned rotator was first considered by Michel (1969). In such analyses, all the differential equations integrate into algebraic conservation laws, so the basic properties of the wind can be easily illuminated. Generalization to realistic magnetic geometry is straight-forward though complicated (Okamoto, 1978). A parameter of the wind, Michel's σ, can be related directly to the properties of the pair production discharge (Kennel et al., 1979). Michel's solution was for a zero radius source and zero initial velocity (u_*) at the source. Michel showed that only the "minimum torque" has a physical solution that extends out to $s=\infty$, where s is the radial distance from the source. The physical solution for the flow has a Mach number (M) less than or equal to 1 (when $M=1$, the flow velocity is equal to the local MHD fast speed), and the asymptotic velocity of the wind ($u_\infty^3=\sigma$) has $M=1$. We performed numerical calculations to find solutions for the cold wind with $u_*=0$. Physical solutions exist only for $0<u_*<u_\infty$ ($u_\infty^3=\sigma\gamma_*$). All physical solutions for the cold relativistic wind are similar to the $u_*=0$ case, i.e. the flow velocity never exceeds $M=1$ so the flow cannot produce a fast shock.

W. Sieber and R. Wielebinski (eds.), Pulsars, 51–52.

To find a relativistic wind that exceeds the fast speed, we generalized the Michel solution by introducing finite isotropic plasma pressure and finite radius. The general form of the wind equations did not change much but the number of parameters and the complexity of the solution increased. For example, the number of unknown parameters at the plasma source increased from two to ten. Attempts to find an analytic solution failed. The solution for the finite-temperature relativistic wind was finally found numerically. It is interesting to note that even though order of magnitude calculations are considered adequate in theoretical astrophysics, the wind solutions required very high precision (i.e. sixteen digits were barely enough for some cases). The calculations (Fujimura and Kennel, 1981) show that as the pressure at the plasma source, P_*, goes to zero, the distance to the fast MDH critical point, s_x, goes to infinity, which is consistent with Michel's cold relativistic wind. For P_* greater than zero, s_x becomes finite; as P_* increases the critical point moves closer to the light cylinder. There are two different regimes. When $\gamma_* \mu_* / \sigma^{1/2} < 1$, the solutions approach Michel's. When $\gamma_* \mu_* / \sigma^{1/2} > 1$, new hot wind solutions emerge with $u_\infty \cong \gamma_* \mu_*$, where γ_* and μ_* are the flow Lorentz factor and enthalpy (in units of mc^2) at the source. The hot wind has $s_x{}^2 = \sigma$.

The above result for the hot relativistic wind, using $\gamma_* \mu_*$ from the outer gap (Cheng and Ruderman, 1977) to calculate the Rankine-Hugoniot relations for a strong fast shock were consistent with observations by Schmidt et al. (1979) for the Crab Nebula. Further calculations of optical radiation and apparent size of the x-ray nebula (Kennel and Fujimura, 1981) seem promising.

Acknowledgements: We are pleased to report interesting conversations with F. Coroniti. This work was supported by NASA NSG-7341.

REFERENCES

Arons, J.: 1979, Space Sci. Rev. 24, p. 437.
Cheng, A. and Ruderman, M.: 1977, Astrophys. J. 216, p. 865.
Fujimura, F.S. and Kennel, C.: 1981, to be submitted.
Kennel, C.F., Schmidt, G., and Wilcox, T.: 1973, Phys. Rev. Letters 31, p. 1864.
Kennel, C.F., Fujimura, F.S., and Pellat, R.: 1979, Space Sci. Rev. 24, p. 407.
Kennel, C.F. and Fujimura, F.S.: 1981, Proc. Dumand Conference.
Michel, F.: 1969, Astrophys. J. 157, p. 1183.
Okamoto, I.: 1978, Mon. Not. R. Astr. Soc. 185, p. 69.
Schmidt, G.D., Angel, J.R.P., and Beaver, E.A.: 1979, Astrophys. J. 227, p. 106.
Ruderman, M. and Sutherland, P.: 1975, Astrophys. J. 196, p. 51.
Sturrock, P.: 1971, Astrophys. J. 164, p. 529.