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SELF-FOCUSSED ELECTROMAGNETIC WAVES AND SS 433

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Double jets of matter emitted by neutron stars (or black holes) have been invoked to explain the periodicity in wavelength shifts in SS 433.[1] We attempt to show that the jets need not be beams of particles,[2] but could instead be self-focussed, large-amplitude electromagnetic waves. Our model has several parts: (a) Precession is obtained from a coupling of the wave "nozzle" to the angle of the accretion disk. (b) The beaming comes from self-focussed low-frequency waves. (c) The two beams strike a screen. They bore a hole through this screen, creating a hot spot as they go. Photons escape the hot spot only along a channel opened by the beam, giving a narrow cone of emission. (d) The Milgrom mechanism accelerates neutral gas bunches, by absorption of these photons, to $\beta = 0.28$.

The 161.7 ± 0.3 day period of the SS 433 Doppler shifts can be explained by precession of long double beams.[1] Some nutation or more complicated geometry may have to be added to this picture, but it seems essentially correct kinematically. We shall assume the energy source in SS 433 is a spinning young neutron star surrounded by an accretion disk. The problem of magnetospheric structure with an accretion disk is complex.[3] We shall assume the neutron star has not been significantly slowed by the disk. The disk is fed by a large F-star through a Roche lobe. The neutron star emits a low-frequency electromagnetic wave following the standard pulsar models. If the F-star spin axis and orbital angular momentum are not aligned, disk precession will result. We suppose the F-star spin $\vec{\Omega}$ is not aligned with the neutron-star spin $\vec{\omega}$ also; so as matter from its Roche lobe enters the disk, it induces the plane of the disk to tilt and the neutron-star spin-axis to precess with the 162-day period. Orbital motion of the two stars appears as the 13.1-day period.[4]

The magnetized rotating neutron star has a magnetosphere with regions of charge separation within its speed-of-light cylinder. The low-frequency wave affects particle motion at and beyond the light cylinder.

In this framework the Crab has been interpreted as characterized by a low-density plasma, in the sense that the large amplitude wave has enough strength to evacuate a large cavity around the pulsar:

$$\frac{P_{\text{wave}}}{P_{\text{plasma}}} \approx \frac{E_c^2}{8\pi mc^2 n_c \gamma} >> 1 \qquad (1)$$

where E_c and n_c are the wave electric-field amplitude and plasma density at the light cylinde
γ is the Lorentz factor of the particles accelerated by the interaction with the wave. As shown by Dobrowolny and Ferrari,[5] if $E_c \approx 10^5$ e.s.u. (corresponding to $B_o \gtrsim 10^{11}$ G at the

surface of the star), and $n_c \lesssim 10^8$ cm^{-3}, the wave can sweep away all the particles evaporatin from the magnetosphere and accelerating them up to an asymptotic energy of $\sim 5 \times 10^4\ m_p c^2$. This estimate refers to protons; electrons, even though they could achieve higher energies, are slowed to the proton speed by electrostatic instabilities. A plasma wind then flows away from the pulsar at relativistic speed, mainly in the equatorial plane.[6]

Equation (1) is probably satisfied only for energetic supernovae which evacuate a considerabl volume. In cases such as SS 433, the magnetic dipole radiation is probably absorbed in the equatorial plane but finds the region near the spin axis relatively transparent. The accretion disk will favor beaming normal to the equatorial plane as well, since it will absor the wave near that plane. If the magnetosphere contains closed field lines with trapped plasma, this will absorb the wave, so the only possible exit is through the zone defined by the open field lines. This cone makes an angle $\theta \approx (R_p/R_c)^{1/2}$, where R_p is the neutron star radius. This is probably the smallest emission angle which can occur. For this case the wave-emitting region at the light cylinder will have a dimension $r \approx (R_p R_c)^{1/2}$. We envision the plasma envelope as forming a "throat" which prevents emission except in a narrow cone near the spin axis. We employ a theory[7] for axially symmetric electromagnetic beams propagating in homogeneous plasma. Nonlinear features may lead to dispersion or focussing in the propagation cone. We must specify the Gaussian spatial width of the wave, r_0, and the curvature of the wave front, R, at the light cylinder radius R_c. The propagation can be trapped and focus at a distance $z_f \approx \alpha_0 R \left(\frac{r_0}{R}\right)^2$; i.e. $z_f >> R_c$. Here $\alpha_0 \equiv eE_0/mc\ \omega$, with E_0 the field at the pulsar. Typically, $R \approx R_c$ and $r_0 \leq R_c/10$. For focussing to occur requires the pulsar period $p > n_p^{1/2} \times 10^{-2}$, $P < n_p^{1/2} \times 10^{-1}$.

For the case of SS 433, $z_f \approx 2.5 \times 10^{13} \frac{B_{12}}{p^2}$ cm, where B_{12} is the surface field in 10^{12} G unit and we assume a stellar radius of 10 cm. Thus $P \lesssim$ sec will give an extended beam $\gtrsim 10^{14}$ cm long. The waves propagate as collimated beams of small opening angle Ψ, accelerating and heating any matter which crosses their paths.

Throughout its history SS 433 has presumably been pushing matter outward along the beam axes, sweeping clean the volume above and below the orbital plane. This compresses the matter, forming a screen a distance X above and below the plane, which the beams must eventually strike. They will ionize and accelerate this neutral matter, boring a hole through it. The difference between SS 433 and other objects is the density of this screen, which permits optical emission at low temperatures, rather than synchrotron radiation. Pressure balance between the low-frequency wave and the accelerating matter gives for the gas density in the screen

$$n_s = \frac{2.5 \times 10^{10}}{T_4 M^2} \ \frac{B_{12}^2 R_6^6}{P_{-1}^4 D_{12}}$$

where M is the Mach number of the matter, D_{12} the diameter of the hot spot created by the beam in units of 10^{12}cm, and T_4 is the temperature of the spot in units of 10^4 K, etc. (We have taken the electric field of the wave to be constant beyond the self-focussing point z_f, an optimistic assumption.) Particles confronting the beam are immediately ionized and accelerated. as they heat they undergo collisions, but reach near-relativistic speeds in less than a second. Ions accelerated to $\sim 0.2\ c$ penetrate into the gas cloud most effectively As the cloud becomes ionized, ions penetrate further, until collective deceleration stops them a distance $\sim 10^{23}/n_s \sim 10^{12}$ cm away. The electromagnetic beam illuminates a given spot on the face of the neutral-matter screen for a time $\tau \approx 2 \times 10^4 \frac{D_{12}}{X_{14}}$ sec. Optical photons emitted from the hot spot are easily absorbed while traversing a distance $\sim 10^{12}$cm sideways, if the gas density exceeds 10^3cm^{-3} and $T_4 \leq 1$. However, the accelerated ions and electrons do permit optical emission along the direction of the beam, if they can penetrate the screen — i.e. if the screen depth is less than $\sim 10^{13}$cm. The fast plasma clears a path for the photons. This allows the optical photons from the hot spot to accelerate neutral matter at the back face of the "working tube" formed by the beam heating profile. These photons are the only ones which escape, forming a cone with an opening angle given approximately by the self-focussed angle of the beamed waves. This angle is approximately given by the spot size divided by the distance X from the source to the screen, $\Psi \approx 10^{-2}\ D_{12}/X_{14}$. This is of the order of the spread in velocities observed in the emitting region. (The angular spread of the velocity vectors in the region from which the shifted lines are emitted is approximately $\varphi \lesssim \Delta\lambda/\lambda\beta \approx 3 \times 10^{-2}$, where $\Delta\lambda$ is the observed line width and λ the laboratory wavelength.) This fits our assumption that the electromagnetic beam opens a corridor of angle $\Psi \approx \varphi$ in the neutral-matter screen above and below the neutron star. The narrow opening is necessary to obtain a small velocity spread.

The final stage in the process yields the observed shifted lines in gas clouds of density $\sim 10^{11}$ at $T_4 \approx 1$. In our model this occurs when the photons from the hot spot strike neutral clouds at the rear face of the "working tubes" which the electromagnetic beam is evacuating. We invoke the mechanism of Milgrom,[8] in which the clouds are accelerated to their terminal velocity by radiation pressure due to absorption of photons below the Lyman edge by L_α transitions. This line-locking leads to a definite relativistic $\beta = v/c = 0.28$, as observed. The major difference of our model from the picture Milgrom has proposed is that we use an electromagnetic beam and a hot spot located far from the parent star. This allows a much lower luminosity. Note that, from the values of Abell and Margon,[2] for the angles between the rotation axis and the beam axis and the line of sight, we never come closer than 60° to the beam axis. Thus we never see directly the exciting radiation from the hot spots. They may contribute significantly to the net luminosity of $\sim 10^{39}$ erg/sec seen in the unshifted lines and the continuum radiation. Some of this luminosity undoubtedly comes from the accretion disk around the neutron star, which also probably contributes matter to the electromagnetic beam, thus (by forming the boundary of the self-focussed tube) altering the direction of the beam as the disk precesses.

The emitting clouds are driven away from the hot spot. They are probably composed in part of ions and electrons which were accelerated by the electromagnetic beam, then ploughed through most of the screen, and then recombined into atoms. They then contributed to the pressure which opened the hole in the screen. Such atoms already had considerable kinetic energy, and thus require less of the hot-spot luminosity in order to reach the final $\beta = 0.28$ we observe. The Balmer line emissivity (bound-bound) of the dense clouds is

$$E_{bb} \simeq 210^{-25}\ n^2\ T_4^{-1/2} \ln \frac{I_h}{kT}\ \text{erg cm}^{-3}\text{sec}^{-1}$$

where I_h is the hydrogen ionization potential (13.5 eV). From the relation between luminosit L and mass M^*, $Ln = 10^{24}\ E_{bb}$, we find $M^* \approx 10^{34} n^{-1} L_{34}$. For a volume V of $\sim 10^{37}$ cm^{-3} we note that $V = 10^{24}\ M^* n^{-1}$, and combine these results to find $n \approx 3 \times 10^{10} L_{34}{}^{1/2}$. Note that this agrees with the estimate of the density in the screen, n_s, which we would expect if they come from the same region.

Note that this mechanism will not work if the clouds are presumed to accelerate from close above the accretion disk. Such a picture[9] does not give collimation if acceleration occurs high above the disk (since acceleration is then virtually radial), and if acceleration occurs near the disk no unique β is selected (isntead, higher values of β result). Thus some intermediate process is needed to focus the clouds and provide photons to drive them. Transfer of energy from the neutron star to a screen by way of electromagnetic beams provides such a mechanism.

The recent observation of Spencer[10] suggests that the radio jet may extend far beyond the screen. If it is 5×10^{16} cm long, it may be formed from relativistic electrons which penetrate the screen and fill a cone beyond it. This would produce a cone which would not necessarily follow the same precession as the beam, since the screen can smear out the precessional motion in a feature extended over $\sim 10^{16}$ cm. This is consistent with Spencer's conclusion that the radio jet moved less than 5° during a time when the optical object should have moved 30°.

One virtue of using beams which produce hot spots is that these spots cannot be eclipsed by the F-star. This is not true if most of the continuum radiation must come from the accretion disk. The absence of eclipses argues for hot spots distant from the plane of the F-star and neutron star.

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REFERENCES

1. Abell, G. C. and Margon, B. *Nature*, 279, 701 (1979).
2. Fabian, A. C. and Rees, M. J. *Mon. R. astr. Soc.* 187, 13P (1979).
3. Lamb, F. K. *Proc. S. Chapman Conf.* to be published.
4. Crampton, D. *et al. Astrophys. J. (Lett.)* 235, L131 (1979).
5. Dobrowolny, M. and Ferrari, A. *Astron. Astrophys.* 47, 97 (1976).
6. Benford, G., Bodo, G. and Ferrari, A. *Astron. Astrophys.* 70, 815 (1978).
7. Dobrowolny, M., Ferrari, A. and Massaglia, S. *Mon. Not. R. astr. Soc.* 185, 335 (1978).
8. Milgrom, M. *Astron. Astrophys.* 78, L9 (1979).
9. Katz, J. I. *Ap. J. (Lett.)* 236, L127 (1980).
10. Spencer, R. E. *Nature*, 282, 483 (1979).

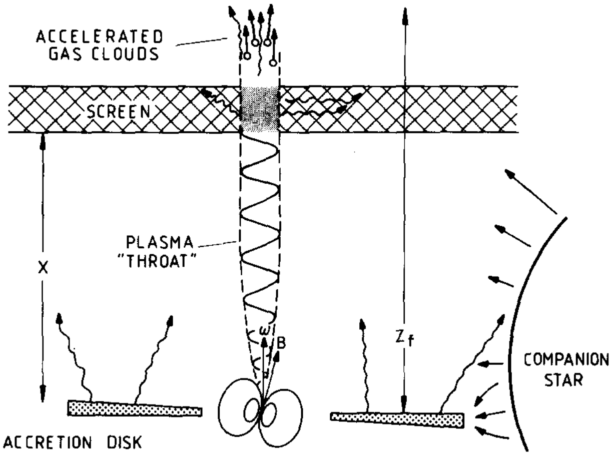

Fig. 1. The spins of binary orbital motion, pulsar, accretion disk and F-star are misaligned. A plasma "nozzle" formed above the disk influences the direction of emission of a low-frequency electromagnetic wave, resulting in the 162-day precession. Nonlinear self-focussing of this wave gives collimation until the wave strikes a high density screen. The beam evacuates a channel which allows photons to escape only in a narrow cone. These photons accelerate the gas clouds observed optically. Relativistic plasma ejected from the channel forms a large radio jet.