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MECHANISMS FOR PULSAR ECLIPSE

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ABSTRACT

The steady (DC) component of the 318 MHz emission of pulsar 1957+20 appears to be eclipsed by plasma that is too tenuous for a plasma frequency cutoff. Alternative eclipse mechanisms are considered, including (1) scattering by plasma turbulence, (2) nonlinear decay of electromagnetic waves, and (3) absorption by nonthermal electrons. Several possible observational consequences are discussed.

Subject headings: plasmas — pulsars — stars: binaries — stars: individual (PSR 1957+20, PSR 1744−24A)

1. INTRODUCTION

The pulsar 1957+20 was discovered by Fruchter, Stinebring, & Taylor (1988) to undergo eclipse at 430 MHz for 10% of its 9 hr period. The eclipse is centered at phase 0.25, the far point of the pulsar's orbit, and the eclipse radius $R_E(430) \approx 5 \times 10^{10}$ cm is more than twice as large as the inferred Roche lobe radius $R_R \approx 2 \times 10^{10}$ cm, and ~5 times the companion's radius $R_c \approx 1 \times 10^{10}$ cm, as determined by optical observations.

Attributing the eclipse to a plasma frequency cutoff in an outflow, which would require $n(R_E) > 2 \times 10^9$ cm^{-3}, Fruchter et al. estimated a mass-loss rate of $\sim 10^{16}$ g s^{-1} and noted the implication that the pulsar would be vaporizing the companion. Previous scenarios had suggested (1) that isolated millisecond pulsars were spun up by past companions (Alpar et al. 1982), (2) that bootstrap accreting neutron stars in low-mass X-ray binaries ablate their companions down to several hundredths of a solar mass before the bootstrap accretion mechanism fails (Ruderman et al. 1989b, hereafter RSTE), and (3) that the millisecond pulsar that is a consequence of (1) and (2) could evaporate the remains of the companion via soft γ-rays or other high-energy quanta powered, indirectly, by the pulsar (Ruderman, Shaham, & Tavani 1989a, hereafter RST). The discovery of 1957+20 appeared to support all of these hypotheses, including (3), the strongest. Several theoretical papers (Kluzniak et al. 1988; Phinney et al. 1988; van den Heuvel & van Paradijs 1988) shortly after the discovery evaluated the mass loss at $\sim 10^{16}$ g s^{-1}, attributed the wind excitation to soft γ-radiation, and reiterated the ablation mechanism as a scenario for the formation of solitary millisecond pulsars.

This interpretation encounters several difficulties:

1. Equating the ram pressure ρv_w^2 of the wind (just prior to its termination shock, which is assumed to be near the eclipse radius) with the pressure of the 1.6 kHz radiation of the pulsar implies a wind velocity of

$$v_w \sim 4 \times 10^{-3} c (\epsilon L_{35}/n_9 D_{11}^2)^{1/2} \text{ cm s}^{-1} ,$$

where $D_{11} \times 10^{11}$ cm is the distance between the plasmapause and the pulsar, $L_{35} \times 10^{35}$ ergs s^{-1} is the pulsar's luminosity, $n_9 \times 10^9$ cm^{-1} is the number density at the eclipse radius, and ϵ is the fraction of the total pulsar luminosity that emerges as magnetic dipole radiation proportionately beamed in the orbital plane. The implied wind power, assuming the area of the stand-off shock to be $\sim \pi R_E^2$, can be expressed as the fraction

$$f \approx 2 \times 10^{-3} \frac{R_E^2}{R_c^2} \left(\frac{\epsilon L_{35}}{n_9 D_{11}^2}\right)^{1/2} \tag{1}$$

of the energy incident on the companion. However, this is significantly greater than the fraction of the incident γ-radiation that can be absorbed in the star's atmosphere, unless ϵ is extremely small. Related arguments have been given by other authors (Krolik & Sincell 1990; Rasio, Shapiro, & Teukolsky 1990) who use the fact that the wind velocity must exceed the orbital velocity. It is emphasized that, except for invoking small ϵ, this is a rather general problem and is in fact exacerbated by lowering n_9.

2. The maximum mass loss that can result from the pulsar emission is less than required by observations. Line cooling[1] in the base of the outflow would reduce it further (Eichler & Levinson 1988; Levinson & Eichler 1990).

3. The column density at eclipse egress, judging from the pulse delay immediately following the eclipse, is only $\sim 10^{17}$ cm^{-2}, suggesting a number density of only $\sim 2 \times 10^6$ cm^{-3}, a factor of 10^3 below what is needed for a plasma frequency cutoff. It could be argued that the eclipsing material might have a sharp edge. However, the pulses at 1400 MHz appear to be uneclipsed at phases ~0.22, 0.28 where there is apparently a DC radio eclipse at 318 MHz (Fruchter & Goss 1990). Here the term "DC eclipse" refers to the fact that the time-integrated component of the pulsar emission disappears from a time-integrated radio map; this cannot be explained by mere pulse smearing. The delay of the 1400 MHz pulses during the DC eclipse at 318 MHz is only a fraction of a pulse period, suggesting a plasma frequency below $2\pi \times 318$ MHz. The question then remains, what is the DC eclipse mechanism at 318 MHz at $0.025 < |(\phi - 0.25)| < 0.05$, where the density appears to be less than 10^8 cm^{-3}, and where 1400 MHz pulses are left intact.

Recently, Nice et al. (1990) have reported the eclipsing pulsar 1744−24A. Significantly, they report partial eclipse near the

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[1] Applying the results of Voit & Shull (1988) or Krolik & Sincell (1990), one finds that even the strongest lines are at most marginally thermalized in which case line cooling is important. Levinson & Eichler (1990) present different arguments leading to the same conclusion.

eclipse boundary with little change in the time profile of the partially eclipsed pulses. This is difficult to reconcile with "all or nothing" mechanisms such as a plasma frequency cutoff, or with mechanisms that gradually broaden the pulse profile before eliminating it (regardless of whether it is broadened over an integration time by rapid change in the phase or instantaneously by multipath dispersion.)

Free-free absorption has also been suggested (Wasserman & Cordes 1988; Rasio, Shapiro, & Teukolsky 1989). However, this requires a very cool plasma ($T < 10^3$ K). Since escape from the companion's surface requires $T > 10^6$ K and the eclipse radius is less than 10 times the companion's radius, adiabatic decompression appears insufficient to cool the plasma down to the required value.

This *Letter* suggests DC eclipse mechanisms under the assumption that the plasma frequency in the wind is less than the photon frequency. We suggest that bombardment of the wind by pairs from the pulsar can excite plasma turbulence that could scatter the pulsar radiation. Similarly, a bow shock could generate turbulence as well as enhance the density. We then discuss nonlinear mechanisms, mostly the $2\omega_{pe}$ cutoff, which lowers the density needed for absorption by an additional factor of 4. This mechanism appears to fall short of working for PSR 1957+20. It is further noted that nonthermal electrons could give rise to the eclipse under suitable circumstances.

Finally, several observational tests are noted. The emphasis of this *Letter*, which basically surveys a variety of eclipse mechanisms, is that the observations may be able to discriminate among them.

2. SCATTERING BY PLASMA TURBULENCE

Streaming pairs from the pulsar may excite plasma waves in the wind. Levron et al. (1988) report evidence that strong plasma turbulence can occupy of order 10% of the volume of a plasma that is irradiated by strong electron beams ($\sim 1\%$ of ambient density) and such turbulence is a serious possibility for the wind given that it is bombarded by pairs from the pulsar. Although a self-consistent analysis of such plasma turbulence is well beyond the scope of this paper, one might estimate a characteristic scale of order 10 debye lengths, as Landau damping prevents cascading to lower scales. For ω_{pe}/ω of order 1/10, and temperatures of order 10^6, this gives a characteristic wavelength of order 1 m, comparable to the wavelength of the 318 MHz radiation, and large-angle Raman scattering of this radiation of the plasma waves is possible. Since at 318 MHz there are of order 10^{12} ($n/10^6$ cm^{-3}) electrons per cubic wavelength, even small-amplitude fluctuations could raise the scattering depth by the factor $[\sigma_T \int n_e dl]^{-1} \approx 10^7$ over incoherent scattering that is needed to produce a scattering eclipse. For subluminal plasma waves, scattering in k-space is probably more important than frequency shift, though the latter can also produce a DC eclipse.

A variety of other instabilities, possibly with a bow shock, could produce somewhat longer wavelength magnetic and/or density fluctuations, perhaps on the order of the ion gyroradius. For a field of order 1 G and a temperature of order 10^6 K, this corresponds to a scale of order 10 m. In principle, there can be turbulence on much larger scales, as is typical of the solar wind. However, if the scattering is refractive, i.e., if it is accomplished by very long wavelength, low-frequency, fluctuations, then in general much less is needed to smear pulses by pathlength dispersion than to create a DC eclipse. Since the path traversed from the pulsar to the eclipsing region is about 5 lt-sec for PSR 1957+20, a temporal dispersion of about 2.5 θ^2 s is created among rays that are scattered by an angle θ back into the observer's line of sight. Hence the observations of unbroadened pulses at 1400 MHz during the 318 MHz eclipse constrain the total refractive scattering to $\theta < 10^{-2}$ at 1400 MHz. If the refraction is accomplished by density (rather than magnetic) fluctuations, then the spread in θ has an ω^{-2} dependence, and large-angle scattering at 318 MHz by a succession of smaller angle refractions would be hard to reconcile with the absence of pulse smearing at 1400 MHz. This constrains the nature of the turbulence.

Consider, for example, isotropic turbulence with a Gaussian density correlation function proportional to exp $(-x^2/l^2)$. The differential scattering cross section per unit volume, $d\Sigma/d\Omega$, is given in the Born approximation by (Ishimaru 1978)

$$\frac{d\Sigma}{d\Omega} = \frac{1}{16\sqrt{\pi}} k^4 l^3 \delta^2 \left(\frac{\omega_p}{\omega}\right)^4 e^{-k_s{}^2 l^2} , \tag{2}$$

where δ^2 is the mean square fractional density fluctuation and k is the photon wavevector, and k_s is the change in k caused by the scattering. The total cross section is

$$AD\Sigma = \frac{\sqrt{\pi}}{16} k^2 l D \delta^2 \left(\frac{\omega_p}{\omega}\right)^4 (1 - e^{-4k^2 l^2}) A , \tag{3}$$

where A is the total area of the eclipsing region and D is its length. Note that $AD\Sigma$ is finite, can be less than A, and for $kl > 1$ decreases with k as k^{-2}. Hence, it is possible that most of the 318 MHz radiation is scattered by an angle of order 1 rad and most of the 1400 MHz radiation is not scattered at all, provided that the 318 MHz scattering is accomplished by at most a few large-angle (or large-frequency shift $\Delta\omega/\omega$) scatterings. In this case, l must then be at most several meters or the plasma frequency must be not too much less than $2\pi \times 318$ MHz.

Scattering by magnetically induced fluctuations in the index of refraction would have a stronger frequency dependence than for density fluctuations, and the constraints on the spectral shapes would then relax. But the cyclotron frequency is probably at least an order of magnitude below the plasma frequency for likely field geometries (Fruchter et al. 1990), so magnetically dominated scattering would require $\delta B/B$ to exceed $\delta n/n$ by a similar factor.

If the turbulence is anisotropic the contrast between the scattering cross sections of large and small k photons may be enhanced and the above constraints may need to be relaxed. If the k vectors of the turbulence are aligned with the line of sight during the eclipse, as could be the case for production mechanisms mentioned above, then scattering of higher k photons, which is of smaller angle, is suppressed because it requires a plasma wave with a k vector nearly exactly perpendicular to that of the photon. Also, once the scattering probability approaches unity (this can happen first for low-k photons), multiwave scattering becomes probable, and the selection rules that exist in the Born approximation are relaxed.

Deep enough into the 318 MHz eclipse, the 1400 MHz radiation is scattered appreciably. If the Raman scattering is by relatively narrow band turbulence, the average scattering angle $\Delta k/k$ is likely to be significantly smaller for the higher k photons than for the lower k ones. At high k, pulse smearing could thus set in before DC eclipse, if the scattering angle is too small to accomplish the latter, with the reverse holding true at lower k, where the scattering angle is larger.

3. NONLINEAR ECLIPSE MECHANISMS

In this section we consider parametric decay of the pulsar emission into plasma waves. There are conceivably other nonlinear processes that are important as well if the ratio of the electric field energy to thermal energy density is larger than unity. This does not seem to be the case for PSR 1957+20, however, unless the emission is concentrated into micropulses.

The growth rate for the decay of a photon into two plasmons is given by

$$\Gamma = \frac{k v_q}{4} \tag{4}$$

(Kruer 1988) where v_q is the quiver velocity of the electrons due to the electric field at a particular frequency, $eE/m\omega$.

To evaluate $E(\omega)$, we take the bandwidth to be Γ, so that

$$\frac{E^2(\omega)}{8\pi} = P(\omega)\Gamma \, . \tag{5}$$

Here $\int P(\omega) d\omega$ is the energy density in pulsed electromagnetic waves and is given by

$$P(\omega) = 10^{-12} \, \frac{\text{ergs}}{\text{Hz cm}^3} \, \eta^{-1} D_{10}^2 d_{11}^{-2} J_{30}(\omega) \, , \tag{6}$$

where $D_{10} \times 10$ kpc is the distance to the source, $d_{11} \times 10^{11}$ cm is the distance from the pulsar to the eclipse surface, $J_{30}(\omega) \times 30$ mJy is the source luminosity, and η is the duty cycle of the pulse. Absorption at $2\omega_{\text{pe}}$ by the two plasmon decay is possible if $\Gamma > (1.6\eta \text{ ms})^{-1}$, which by the above considerations occurs if $D_{10} J_{30}/d_{11} > 1$. This criterion is not quite met for 1957+20, where D_{10} is believed to be only ≈ 0.1 (Fruchter et al. 1988; Kulkarni, Djorgoski, & Fruchter 1988). Nevertheless, we consider it because it comes close to working and could be important to other similar sources.

A $2\omega_{\text{pe}}$ cutoff relaxes the density requirements by only a factor of 4, which does not solve the DC eclipse problem. Invoking a shock reduces the thickness and bolsters the density of the outer plasma sheath by an additional factor of several, so a preshock wind density of $\approx 10^8$ cm^{-3} is possibly adequate for a DC eclipse at 318 MHz.

4. ABSORPTION OR COHERENT SCATTERING BY ENERGETIC ELECTRONS

The brightness temperature of the radio emission at the eclipsing material exceeds 10^{17} K at 300 MHz. Hence, even TeV electrons, for any reasonable energy spectrum, will *absorb* the pulsar emission if they are optically thick to some absorption process, i.e., if they achieve the blackbody limit in the inverse emission process. Possible mechanisms include the synchrotron absorption in the magnetic field of the wind, curvature absorption due to large-scale fluctuations in this field, interactions between the electrons and plasma waves, or inverse Comptonization of reflected radio emission of lower frequency. This last mechanism is induced Compton scattering, which may work even with thermal particles. It will be discussed in greater depth elsewhere (Eichler and Gedalin 1991).

The optical depth τ is maximized if the spin-down luminosity of the pulsar is spent on energetic electrons with the Lorentz factor γ such that

$$\gamma^2 \frac{c}{\lambda} = \frac{\omega}{2\pi} \, , \tag{7}$$

where λ is the wavelength of the "wiggler" field, e.g., plasma waves or MHD waves whose wavelength is less than the gyroradius of the magnetic electrons. The pair density at distance $d_{11} \times 10^{11}$ cm from the pulsar is

$$n_{e\pm} \approx 5 \times 10^8 \gamma^{-1} \epsilon_p (b L_{35}/4\pi d_{11}^2) \text{ cm}^{-3} \, , \tag{8}$$

where ϵ_p is the production efficiency, and b is a beaming factor $\approx (\pi\eta)^{-1}$.

First we consider incoherent absorption. The radiation density generated by the pairs in the optically thin limit is

$$U \approx \gamma^2 n_{e\pm} \sigma_T \frac{R_E}{3} U_0 \, , \tag{9}$$

where U_0 is the energy density in the virtual photons that roughly satisfy equation (7). For any reasonable spectrum, this approaches the blackbody limit ($kT_r \sim \gamma m_e c^2$) at frequency ν when

$$U = \frac{8\pi\gamma m_e \nu^3}{c} \, , \tag{10}$$

which, using equation (9), is satisfied when

$$8\pi m_e \frac{\nu^3}{c} = 10^7 \epsilon_p b L_{35} d_{11}^{-2} \left(\frac{\sigma_T R_E}{\text{cm}^3} \right) U_0 \, . \tag{11}$$

At $\nu \approx 300$ MHz, for $b \approx 10$ and the other dimensionless parameters of order unity, the optical depth exceeds unity when $U_0 > 2 \times 10^{-5} \epsilon_p^{-1}$ ergs cm^{-3} if condition (7) is roughly satisfied.

Note that given ϵ_p and condition (7), the value of the characteristic γ does not affect τ and is constrained only by the nature of the available virtual photons. The suggestion that moderately relativistic pairs are efficiently emitted by the pulsar as a heating mechanism (Krolik and Sincell 1990) clearly allows for the possibility that such pairs, with $\gamma \approx 3$, could incoherently absorb the pulsar radio emission ($\omega \approx 10\omega_{\text{pe}}$) via interaction with, say, plasma turbulence at scales c/ω_{pe}. (An alternative source of mildly relativistic electrons could be acceleration by plasma turbulence). For a plasma density of 10^7 cm^{-3}, $\epsilon_p \approx 1$, and plasma temperature $T \approx 10^6$ K, U_0 would have to exceed $10^{-2} nkT$. The experiments of Levron et al. referred to in § 2, which appear to meet this requirement, were done with a beam-to-plasma number density ratio of 10^{-2}, which is in the general neighborhood of the value suggested by equation (8). By equation (6), reflected radio emission at lower frequency could also contain the needed energy density.

For $\gamma < 10^2$, incoherent synchrotron emission seems to be a viable mechanism in that condition (7) (with $2\pi c/\lambda$ replaced by the electron cyclotron frequency), and condition (11) can be satisfied simultaneously. Such modest Lorentz factors, however, may strain pulsar theory. Moreover, for $\epsilon \sim 1$, scaling the pair density back to the light cylinder implies that it could be high enough to absorb the pulsed radio emission close to the pulsar, depending on the geometry of pair production.

If the pairs undergo charged bunching via streaming instabilities, the interaction with radiation can be made more efficient than given in equation (9), optical thickness can be achieved with lower energy density, and synchrotron absorption in a weaker field or curvature absorption is a possibility. Condition (7) generalized to curvature radiation with radius of curvature R_* would imply a maximum γ of about $10^3(R_*/R_E)^{1/3}$, but this condition can also be relaxed somewhat given charge bunching. There is still the underlying assumption that the effective temperature of the bunches remains below the brightness temperature of the radiation.

Density fluctuations in the primary pair wind from the pulsar can also cause coherent scattering, as in § 2. The plasma frequency and the frequency of the radiation, both as seen in the frame of the wind, depend on γ. Their ratio, ω'_p/ω', scales as $(\epsilon_p/\gamma_{\rm th})^{1/2}$, where $\gamma_{\rm th}$ is the typical Lorentz factor due to random motion in the wind frame. In order that the eclipse not be steady, one must argue that the density fluctuations are connected to the interaction with the companion.

5. DISCUSSION

1. The failure of the wind to smear pulses at 1400 MHz, though it allows anisotropic turbulence even on a large scale, appears to at least suggest a low-density wind. If the plasma frequency were even close to 10^3 MHz, it would imply a remarkably smooth wind on intermediate scales, 10^2 cm $\ll L < R_E$. Having considered some mechanisms that might work at low densities, particularly absorption by energetic electrons, we might speculate that the role of the "wind" is played by energetic pairs that have reflected off the companion's magnetosphere, or even the primary pulsar pair wind itself if the eclipse mechanism is somehow tied to the interaction with the companion. The role of the pulsar output in directly causing the eclipse might also help explain the fact that the eclipses are more symmetrical about phase 0.25 than the wind parameters.

2. Though pulse smearing is not required by any of the above eclipse mechanisms, it represents a powerful diagnostic of general conditions in the wind, and increasingly sensitive searches for a pulse smearing sheath around the DC eclipse are forever motivated. Note that there are two types of pulse smearing: (i) the pulse gradually and observably broadens before being diminished (e.g., due to path length dispersion of less than a pulse period), and (ii) the pulse is promptly smeared into an uneclipsed DC component (e.g., due to instantaneous Raman or Brillouin scattering by θ, $10^{-2} < \theta \ll 1$). The phase interval of partial pulse eclipse for PSR 1744−24A appears to be either prompt pulse smearing or a partial DC eclipse. Either possibility would be consistent with the hypothesis that the 318 MHz emission is scattered by a minimum angle or not at all in single-wave interaction, for such scattering would affect the amplitude of the pulse before affecting its breadth. Partial pulse eclipse without any DC eclipse, i.e., prompt pulse smearing, would favor scattering over absorption. If the partial pulse eclipse is always coincident with a partial DC eclipse, then both absorption and large-angle scattering ($\theta \sim 1$) are viable. The extent of partial eclipse should in either case be frequency dependent.

Time-resolving the states of marginal eclipse may be difficult if the eclipse begins when the line of sight is tangent to the eclipsing region. If the eclipsing region is a perfect sphere, for example, then, 1 minute into a 50 minute eclipse, the line of sight is already $R_E/2$. Integration times smaller than 1 minute are therefore motivated to the extent that they are feasible.

We also note that the 1400 MHz radiation of PSR 1957+20 apparently undergoes a pulse eclipse for about 20 minutes without a matching DC eclipse (M. F. Ryba & A. S. Fruchter, private communication). This already causes problems for absorption models if all the observed eclipses are to be accounted for by a single mechanism. As noted in § 2, Raman scattering by turbulence on a well-defined scale could yield DC eclipse without pulse smearing at one frequency, and the reverse at a higher frequency. Detailed modeling of the observations within this framework remains to be done.

3. A nonlinear absorption mechanism might favor the narrow pulse of PSR 1957+20, which reaches a higher level of intensity, than the broad pulse. The argument may be complicated by the fact that the pulses could consist of numerous micropulses. However, it is worth looking for differences in the eclipse radius for the two pulses, and flattening of the pulse shape during marginal eclipse.

6. CONCLUSIONS

Several classes of mechanisms would allow the 327 MHz $= (\omega/2\pi)$ radio emission to undergo a DC eclipse by a wind having a plasma frequency $\omega_{\rm pe}$ of only $\sim 10^{-2}$ to $10^{-1}\omega$: (1) Scattering by small-scale plasma turbulence, (2) processes that are nonlinear in the wave intensity of the pulsar emission, and (3) absorption by energetic particles that can emit (hence absorb) at $\omega \gg \omega_{\rm pe}$. Most of these mechanisms rely on unproven assumptions, and detailed quantitative calculations do not yet have a solid basis. The observational possibilities, however, may be rich enough to discern among the various mechanisms by qualitative considerations.

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