OBSERVATIONAL CONSEQUENCES OF POLAR CAP THEORIES

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Possible observational consequences are outlined for pulsar models with positive ion outflow at the polar caps together with e^+-e^- pair production discharge there. A characteristic thermal x-ray luminosity is maintained by discharge heating in regions of positive current outflow. A decrease in polar cap thermal x-ray emission may occur during radio nulls. Two mechanisms are identified which can yield temporal modulation of the outflowing ion and e^+-e^- plasmas, and which may lead to modulation of coherent radio emission on observed micro-structure timescales. These are: (1) polar cap temperature oscillations which occur preferentially in pulsars of low surface magnetic field, and (2) the tendency of sparks to migrate toward the convex side of the magnetic field lines.

1. INTRODUCTION

Theories of pulsar emission divide into two classes: the light cylinder models or LCM (Ferguson, this volume), and the polar cap models or PCM. The polar cap models are further subdivided into those with positively charged polar caps and ion outflow, or PCM^+ (Cheng and Ruderman 1980; hereafter CR), and those with negative polar caps and electron outflow, or PCM^- (Arons and Scharlemann 1979).

PCM^+ is unique in that the potential drop above the polar cap is determined by ion outflow due to thermionic emission from the polar cap. The thermionic emission rate is exponentially sensitive to T, the surface temperature, and to E_B, the binding energy of ions in the surface. These properties of the polar cap surface matter may therefore influence coherent radio emission.

PCM^+ predicts thermostatic regulation as follows (CR). Without a pair production discharge to heat the polar cap, it cools rapidly. Ion emission decreases and soon positive current outflow on open field lines cannot be maintained. A charge depleted region (an inner gap) begins to form, and the potential drop ΔV soon exceeds the value needed to sustain a pair production discharge. With such a discharge, the

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polar cap is heated strongly by e^- backflow, tending to raise T, to increase ion emission, and to decrease ΔV. Two possibilities arise: A) ΔV may then decrease below the value needed for pair production discharge, so the discharge cycles on and off on thermal timescales, or B) a quasi-steady equilibrium may be found with simultaneous pair production discharge and ion outflow.

2. OBSERVATIONAL CONSEQUENCES

First, the exponential temperature dependence of thermionic emission assures that T is thermostatically regulated near $kT \simeq E_B/30$. The polar cap thermal x-ray luminosity from regions of positive ion outflow then becomes (CR)

$$L_x^{(1)} \simeq 10^{27}\, E_B^{\,4}\, P^{-1}\, \eta \text{ erg s}^{-1} \tag{1}$$

where the polar cap area is $10^9 P^{-1}\, \eta$ cm^2. This $L_x^{(1)}$ is very sensitive to the surface magnetic field B and less so to P, and may be observable by the Einstein Observatory from nearby pulsars. For comparison PCM^- has predicted $\gtrsim 10^{31}$ erg s^{-1} per polar cap in x-rays from Vela (Arons and Scharlemann 1979).

Second, polar cap thermal x-ray emission may decrease during radio nulls, if radio nulls are associated with a cessation of pair production discharge above the polar cap. This is because the polar cap cools rapidly in the absence of discharge heating. I am conducting an Einstein Observatory search for such an effect. Observation of this effect would be difficult to reconcile with light cylinder models.

Finally, two mechanisms are identified which may lead to temporal modulation of radio emission on millisecond and submillisecond timescales. Small oscillations in polar cap temperature can lead to strong modulation of the outflowing ion and e^+-e^- fluxes. Modulation of coherent radio emission may result. The exponential temperature dependence of thermionic emission means that a 3% temperature change yields an order of unity ion outflow modulation. The corresponding cooling time for the polar cap surface matter is highly uncertain, but may be 0.1 to 1 ms, adopting the parameters in CR. This time is suggestive of observed pulsar microstructure timescales (Cordes 1979a). Polar cap thermal oscillations must occur if there is no equilibrium temperature - that is, no temperature at which heating equals cooling. Using the PCM^+ of CR, I find that discharge heating and radiative cooling cannot be balanced, so thermal oscillations must occur, if

$$B_{12}^{\;2.8}\, P^{-1} \lesssim 5 \tag{2}$$

where $E_B \simeq 2.6\, B_{12}^{\;0.7}$ keV (Flowers et al. 1977). This criterion is obeyed by all five known pulsars with clear microstructure corresponding to a feature in the average correlation function (Cordes 1979b).

Temporal modulation of the outflowing ion and e^+-e^- plasmas on millisecond timescales may also arise from the tendency of a pair production spark discharge to migrate toward the convex side of the magnetic field lines. If the discharge terminates upon reaching a field line of negligible curvature, and if it restarts by pair creation from thermal x-ray photons in the Coulomb field of relativistic ions (Cheng and Ruderman 1977), temporal modulation will occur with a timescale estimated by $2sr_p/c\ell$, where s = curvature radius, r_p = polar cap radius and ℓ = gap height. This timescale is sensitive to the unknown magnetic field line curvature at the polar cap, but is typically 0.1 to 10 ms.

Both polar cap thermal oscillations and spark migration effects may occur simultaneously in the same pulsar, leading to temporal modulation on different timescales. Ferguson and Seiradakis (1977) have observed examples of single pulses from PSR 1133+16 in which microstructure is found on at least two different timescales simultaneously.

REFERENCES

Arons, J. and Scharlemann, E.T.: 1979, Astrophys. J. 231, p. 854.
Cheng, A.F. and Ruderman, M.: 1977, Astrophys. J. 214, p. 598.
Cheng, A.F. and Ruderman, M.: 1980 (CR), Astrophys. J. 235, p. 576.
Cordes, J.: 1979a, Australian J. Phys. 32, p. 9.
Cordes, J.: 1979b, Space Sci. Rev. 24, p. 567.
Ferguson, D.: 1981, this volume.
Ferguson, D. and Seiradakis, J.: 1977, Astron. Astrophys. 64, p. 27.
Flowers, E., Lee, J.-F., Ruderman, M., Sutherland, P., Hillebrandt, W., and Müller, E.: 1977, Astrophys. J. 215, p. 291.

DISCUSSION

WRIGHT: With current of the same sign flowing from both poles, how is the circuit closed?

CHENG: Outer gap discharges may allow the star to remain neutral in very young pulsars, but in typical pulsars it is difficult to maintain a return current with that mechanism. Processes occurring near or beyond the light cylinder, including particle acceleration in low-frequency electromagnetic fields and breakaway of particles from magnetic field lines, may yield a return current. Significant amplification may occur in evacuated regions within the outer magnetosphere. A more detailed reply must await a solution for the globally self-consistent magnetosphere structure.

STINEBRING: With so many time scales available, do you see any difficulty in producing the observed symmetric shape of micropulses through the thermal regulation mechanism?

CHENG: I do not believe that mechanisms for coherent radio emission are sufficiently well understood for your question to be answered with any confidence.