THE ASTROPHYSICAL JOURNAL, **263**:828–834, 1982 December 15

PULSAR NULLING AND DRIFTING SUBPULSE PHASE MEMORY

ALEXEI V. FILIPPENKO AND V. RADHAKRISHNAN[1]
Department of Astronomy, California Institute of Technology

Received 1982 April 23; accepted 1982 June 16

ABSTRACT

The standard polar cap model of pulsar radio emission provides acceptable explanations for a wide variety of observed pulsar characteristics. Nevertheless, we show that it has difficulty accounting for certain details pertaining to drifting subpulses, nulling, and mode changing. In particular, the persistence of drifting subpulse phase memory observed during pulsar nulling, as well as the phenomenon of nulling itself, seem to defy simple explanation.

We attempt to reconcile these difficulties with some modifications of the standard model. It is proposed that avalanche discharges above the polar caps of old pulsars are localized to discrete regions ("flux tubes") because prior to a discharge $\boldsymbol{E} \cdot \boldsymbol{B}$ in gaps between the stellar surface and plasma-filled portions of these tubes is greater than in neighboring regions. During normal operation of a pulsar, the tubes drift in the same manner as described by Ruderman and Sutherland. Nulling is thought to be the manifestation of steady (rather than interrupted) pair production within the flux tubes, and it is shown that the absence of both subpulse drift and coherent radio radiation is consistent with this hypothesis. The predictions of our model are in good qualitative agreement with observations.

Subject headings: hydromagnetics — pulsars — stars: radio radiation

I. INTRODUCTION

Of the many puzzling observational phenomena associated with radio radiation from pulsars, one of the most intriguing is the behavior of subpulse phase during pulsar nulling reported by Unwin *et al.* (1978). These authors observed PSR 0809+74, in which all of the radio radiation occurs in drifting subpulses whose drift rate exhibits comparatively small variations. The particular phenomenon noted by them is the remarkable retention through a null of the subpulse phase (position within pulse envelope) immediately prior to the onset of nulling: after the null, the radiation once again appears in drifting subpulses whose phase is that expected for the first *nulled* pulse. This memory persists in PSR 0809+74 at least as long as the longest null observed, which is 10 pulsar rotation periods (10 P) in the data of Unwin *et al.* (1978) and 13 P in the data of Filippenko, Readhead, and Ewing (1983). It is also significant that the same behavior exists in other pulsars, including one (PSR 0031−07) whose nulls are generally of much greater duration than those of PSR 0809+74. Furthermore, the phase at which the nulls occur is random, implying that the memory mechanism does not restrict the occurrence of nulls to specific portions of the integrated pulse window.

Nulling clearly cannot be due to any kind of eclipsing, obscuration, or deflection of the pulsar's radiation, as in such cases the subpulses would continue to drift through the pulse window, irrespective of whether or not their radiation is received by us. Information regarding the positions of the marching subpulses must be somehow stored during the null, and it is subsequently used to provide a starting point for the drifting pattern when emission of radio radiation recommences. Failure to elucidate the nature of the pulsar memory mechanism has thus far been a major weakness of all nulling theories (e.g., Jones 1981).

It is interesting to note that a memory mechanism of some form was probably already required in order to understand two other phenomena associated with pulsar radio radiation. The first of these is simply the ordinary drifting of subpulses, which indicates that a given "spark" (gap discharge) must occur at or close to the location of immediately preceding sparks. If the discharge process is such that each spark completely dies before the formation of a large potential drop and the next spark, then the location of a given spark will have no relation to that of the previous one without some memory, albeit for as short as $\sim 10\ \mu$s. Of course, it is possible (as suggested in the original model of Ruderman and Sutherland (1975)) that sparks are never fully extinguished, but rather fluctuate quasi-periodically in intensity. This obviates the necessity of a short-term memory.

The second phenomenon which is hard to understand without a memory mechanism of some sort is that of

---

[1] Raman Research Institute, Bangalore, India.

mode changing. In pulsars which exhibit this property, the pulse profile displays occasional but marked changes in shape. The new shape can persist for times which are very long compared to the pulsar rotation period before returning to the previous mode.

This paper represents an attempt to qualitatively explain nulling and the associated phase memory. Only old pulsars will be dealt with, since young pulsars do not exhibit many of the features (such as drifting subpulses and nulling) that will be the focal points of our discussion. In addition, Ruderman (1981) has shown that young pulsars may be associated with a wide variety of complicated phenomena not to be found in older pulsars, and that very different models are probably needed to explain their behavior.

II. THE STANDARD MODEL

a) *Drifting Subpulses*

We will restrict our discussion to the model of Ruderman and Sutherland (1975; hereafter RS) and its subsequent modifications, primarily those of Cheng and Ruderman (1977*a*, 1977*b*, 1979, and 1980; hereafter CR 1977*a*, CR 1977*b*, CR 1979, and CR 1980), Ruderman (1976), and Cheng, Ruderman, and Sutherland (1976). This model, based on the pioneering work of Goldreich and Julian (1969) and Sturrock (1971), reasonably explains a large number of observed pulsar characteristics.

One of the most important of these is the drift of relatively narrow subpulses within the integrated pulse envelope. It is postulated that discharging of the polar gap is achieved by means of localized sparks rather than by a discharge of the entire region above the polar cap, and that the sparks are separated by distances comparable to the height of the polar gap. At the completion of an RS spark "avalanche," the potential drop is substantially below its predischarge value and the sparking regions are completely filled with plasma. However, since charges must still be escaping from the pulsar along a certain set of open field lines, plasma recedes from the stellar surface but does not simultaneously get replenished, and a growing potential drop is manifested across the rapidly forming gap. Since at this moment $\boldsymbol{E}\cdot\boldsymbol{B}$ is not equal to zero in the gap, the plasma region above the empty (gap) field lines cannot corotate with the neutron star; rather, it experiences a small $\boldsymbol{E}\times\boldsymbol{B}$ drift relative to the star's surface. Once the gap potential drop becomes sufficiently large, another discharge forms: the gap in the sparking regions is filled with plasma (making $\boldsymbol{E}\cdot\boldsymbol{B}$ equal to zero), and corotation is once again possible all along the field lines which thread the plasma. It is the occurrence of $\sim 10^5$ of these cycles every second that makes the subpulse drift noticeable and continuous. (We note, however, that nondrifting subpulses often exist in pulsars. One possible explanation is that these are caused by spark discharges in regions of tangled, highly curved magnetic fields fixed with respect to the stellar surface (Flowers and Ruderman 1977).)

b) *Deficiencies of the Model*

An important difficulty is that a discharge does not remain localized (to within the accuracy of the $\boldsymbol{E}\times\boldsymbol{B}$ drift) at its initial position (CR 1977*b*). Rather, it rapidly spreads in the direction opposite the center of curvature of the local magnetic field lines. For example, in a dipole field the spark is confined to a single plane and moves toward the magnetic axis with speed (CR 1980)

$$v_{\text{spark}} \approx \tfrac{1}{2}\,(ch/\rho), \tag{1}$$

where h is the height of the gap, c is the speed of light, and ρ is the radius of curvature of local field lines. Since the radius of the polar cap of a pulsar with period P is given by

$$R_p \approx 10^4 P^{-1/2}\ \text{cm}, \tag{2}$$

the time it takes a spark to cross the cap radius is only ~ 130 μs (with typical values of $P = 1$ s, $h = 5\times 10^3$ cm, and $\rho = 10^6$ cm). Hence, sparks rush toward the polar regions and spread out into large sheets instead of remaining relatively localized and slowly drifting around the pole. In a more general field geometry, they die either by exiting from the polar cap or by reaching a region (such as the magnetic pole) in which field lines have insufficient curvature to sustain them. Of course, this need not occur if the magnetic field geometry is sufficiently complicated, but then the $\boldsymbol{E}\times\boldsymbol{B}$ subpulse drift is also not possible since the sparks remain confined to regions of tangled field lines.

CR (1977*b*, 1980) have discussed this problem and have presented two possible solutions to it. The first is that if local heating effects are significant, then thermal X-rays emitted by the surface "hot spot" associated with a given spark may form electron-positron pairs in the Coulomb field of relativistic ions. The ions are produced by thermionic emission from the hot spot and are accelerated to a Lorentz factor $\gamma_{\text{ion}} \sim 500$ by the intense electric field. This "Lorentz-boosted pair production" is able to restrict the spark to the region near the original discharge, given the assumption that heating from the initial electrons is sufficiently strong to produce thermionic emission.

The validity of this assumption in old pulsars with low surface temperature has become questionable, especially in light of the recent finding that the majority of pulsars "turn on" only after the neutron star rotation period has increased to ~ 0.5 s (Vivekanand and Narayan 1981). From this, Radhakrishnan (1982) has concluded that ion liberation models are unlikely to be applicable to pulsars. The argument is that if ion liberation can occur at any stage, it should work best in young neutron stars, when both the surface temperature and the electric fields have their highest values. Indeed, patch heating should then be able to sustain most (if not all) short period pulsars, even in the absence of fossil heat stored in the neutron star.

The second possibility that CR discuss is that each time a very energetic electron collides with the stellar surface at least one secondary gamma ray of energy greater than 1 MeV is emitted. This high-energy gamma ray subsequently interacts in the usual way with the intense magnetic field and produces an electron-positron pair in the vicinity of the original electron. In this manner, a roughly cylindrical tube of plasma (rather than a plasma sheet) may form around the initial location of the discharge.

It may be noted that *unless* the efficiency of this mechanism is sufficiently high that pair production resulting from the "photon splash" heavily dominates the RS avalanche discharge, the RS part of the electron-positron shower will still drift toward the magnetic axis if the field geometry is simple. (This difficulty also exists with the first mechanism proposed above.) In addition, the sparking regions may spread noticeably if the spatial distribution of the "splash" photons is large, and the width of a subpulse should consequently increase as it drifts through the pulse envelope. This, however, is not observed: subpulses retain their narrow width throughout their entire duration in the pulse window (Filippenko, Readhead, and Ewing 1983).

The main deficiency of the RS model, however, is that it does not explain the peculiar phase behavior during nulls discussed in § I. CR (1977*b*, 1980) attempt to solve this problem by appealing once again to Lorentz-boosted pair production. They argue that even after a long null the area under the last position of the gap discharge is hotter than other regions of the polar cap. Since the probability for surface ion emission is a very sensitive function of surface temperature, sparking is most likely to be reinitiated at the places where it occurred immediately prior to the onset of the null. As will be shown below, this scenario becomes unacceptable when one considers that the surface temperature anomaly must be (*a*) able to last through long nulls, (*b*) selective enough to confine the first spark after nulling to the location of the last spark prior to nulling, and (*c*) able to prevent, during normal operation of the pulsar, spreading of the spark to areas over which it had previously drifted (and which are therefore hot).

CR show that if there is no heat source, then the cooling time t of a hot spot initially at temperature T_0 may be estimated from the expression

$$(T-T_0)/10^6 \approx -2t^{1/2}(T_0/10^6)^4(\rho_5^m)^{-7/6}, \quad (3)$$

where T is the surface temperature at time t and ρ_5^m is the density of the surface in units of 10^5 g cm^{-3}. If we adopt $\rho_5^m \sim 1$, and $T_0 \sim 10^6$ K, this gives a cooling time of a fraction of a second after heating from an electron-positron gap discharge is extinguished. On the other hand, since the current due to emission of ions bound by energy E_b ($E_b \sim 3$–8 keV) is roughly described by the sensitive exponential

$$J_{\rm ion} \propto \min\left[1, \exp\left(30 - E_b/kT\right)\right], \quad (4)$$

CR conclude that a new spark is still most likely to begin at the location of the last spark prior to the null. However, equation (3) shows that so many cooling times elapse during a null spanning 10 s or more that only minute surface temperature irregularities remain, and the entire polar cap is then so cold (in an old pulsar) that according to equation (4), any remaining thermionic emission is completely dominated by background gamma rays impinging on the polar gap in random places.

A weaker argument against Lorentz-boosted pair production as an explanation of phase memory in old pulsars is that it requires the ejection of a positive ion from the relatively cold stellar surface, whereas we have already argued that ion liberation models probably fail to work even in hot young pulsars.

Finally, it may be noted that the RS/CR model makes no specific attempt to explain the phenomenon of nulling itself, aside from the tentative suggestion that the pair production discharges may be extinguished if large fluxes of helium ions are occasionally ejected from the polar cap (CR 1980).

III. FLUX TUBES

In this section, we present modifications of the standard model which are successful in removing some of its difficulties.

Healthy operation of a pulsar gives rise to copious amounts of plasma produced in the gap discharges and augmented by subsequent pair production. When a *limited* portion of the gap above a polar cap is sparking, however, *only those field lines threading the region of discharge* (*and continuing on above it*) *contain plasma*, since other field lines have no source of charged particles. Thus, in old pulsars, whose subpulses tend to be much narrower than the integrated pulse envelope, the plasma is confined to regions which we shall hereafter refer to as "flux tubes" (even at times when portions of the tubes happen to be empty). Outside a plasma-filled flux tube, the density of charged particles is far smaller, perhaps even approaching a vacuum. This is in contrast to the behavior of young pulsars, in which the entire polar gap is probably filled with plasma quasi-periodically. These flux tubes are the localized sparks of the RS model and drift around the magnetic axis in the same manner as described in § II*a*.

After the cessation of an avalanche breakdown, a new gap begins to form near the surface of the neutron star as plasma in the flux tube recedes from the polar cap. Although the details of the electric field above the polar cap are presumably very complicated, we will *assume* that $\boldsymbol{E}\cdot\boldsymbol{B}$ in the empty (gap) portion of a flux tube is greater than along neighboring magnetic field lines outside the tube. Any subsequent breakdown via spark avalanches above the polar cap will therefore occur only in this limited gap region, irrespective of the process of spark initiation.

An intuitive line of reasoning which provides justification for our assumption is to suppose $\boldsymbol{E}\cdot\boldsymbol{B}$ is of comparable strength *throughout* the gap or is largest in regions *between* sparks. In this case, background gamma rays do *not* preferentially initiate sparks at the location of previous discharges. Similarly, even if Lorentz-boosted pair production or the emission of high-energy gamma rays help reinitiate the sparks, we still expect new sparking regions to form occasionally, and this is never seen (Unwin *et al.* 1978).

RS also mention that the formation of a discharge might decrease the neighboring electric field and inhibit the formation of another simultaneous discharge within a distance comparable to the polar gap height. However, they do not state that $\boldsymbol{E}\cdot\boldsymbol{B}$ in these tubes is *always* stronger than in other regions.

One consequence of our assumption is that the *rapid* drift of sparks toward the magnetic axis in a simple field geometry no longer occurs. Since $\boldsymbol{E}\cdot\boldsymbol{B}$ outside a flux tube is smaller than that in the gap portion of the tube, and since the avalanche discharge in the gap can only occur if locally $\boldsymbol{E}\cdot\boldsymbol{B}$ is large enough to produce sufficient acceleration of charged particles, any particle which approaches the edge of the tube will be unable to contribute to the avalanche; electrons and positrons subsequently formed will not be accelerated enough along the magnetic field. This may also eliminate the problem of flux tube spreading, as the width of a given subpulse should remain relatively constant while the subpulse drifts through the pulse envelope.

We have already discussed the difficulties with accepting Lorentz-boosted pair production as a mechanism for the reinitiation of spark discharges at approximately the same location as preceding discharges. On the other hand, the problems are avoided in our model if avalanche discharges are externally triggered, since the triggering occurs preferentially in regions of large $\boldsymbol{E}\cdot\boldsymbol{B}$ (flux tubes). In particular, Radhakrishnan (1980) and Shukre and Radhakrishnan (1982) have shown that background gamma rays can provide effective triggering of spark discharges, and the number of available gamma rays is sufficient to produce $\sim 10^5$ discharges per second.

IV. NULLING AND PHASE MEMORY

a) *Steady Discharge*

If the normal, healthy operation of an old pulsar with drifting subpulses is as described above, what happens when a null occurs? Nulling may be merely the cessation of sparking, but this would require that the plasma-filled flux tubes be evacuated rapidly, and without some sort of memory mechanism we are unable to account for the phenomenon of phase memory. Assuming that localized heating of the polar cap cannot function as a memory mechanism (as argued in § II), we are led to believe that the conventional view of nulling as the cessation of all gap discharges is incorrect, and that a departure from this view is necessary.

As the period of a pulsar increases, the induced electric fields of the homopolar generator decrease; therefore, in order to achieve the potential drop necessary for sparking, the gap thickness h must grow. However, when h approaches the radius of the polar cap, the potential drop across the gap does not continue to increase substantially with h. Rather, the drop approaches a limit (RS)

$$\Delta V=\frac{\Omega\phi}{2\pi c}\approx 6.6\times10^{12}B_{12}/P^2 \text{ V}, \tag{5}$$

where ϕ is the total open field line magnetic flux from the polar cap. The pulsar must stop functioning when this limit becomes less than the potential drop necessary for gap discharge. We suggest that as this limit is slowly approached, and interrupted sparking becomes increasingly more difficult to produce, a configuration can form in which the gap discharges at roughly the same rate as the potential drop would increase in the absence of sparking. In other words, the voltage drop remains roughly constant and for some period of time pair production occurs in a *steady* manner before resuming its interrupted behavior.

That such a configuration may exist is seen by considering the relative growth rates of the potential drop and the RS discharge. During normal operation of a pulsar, the gap discharge grows exponentially in time when the gap thickness h becomes comparable to the mean free path (against pair production) of a photon moving through a magnetic field. However, this avalanche is possible only because initially the growth rate of the gap potential drop ($\Delta V\propto h^2$ for small h) dominates the exponential discharge. The gap thickness becomes slightly larger than the photon mean free path, and the exponential discharge accelerates rapidly. This reduces the gap thickness (and hence the potential drop) to a value below that which is necessary for sparking, and the cycle repeats itself. In an old pulsar, on the other hand, the gap thickness must be large before sparking can occur, and (as shown by RS) the gap electric field far from the stellar surface drops exponentially with height z: $E \propto \exp(-z/R_p)$, where R_p is the radius of the polar cap. The potential drop increases very slowly with gap height, and occasionally conditions may exist such that gap discharge via pair production exactly balances the gap growth. This should clearly happen with greater frequency as a pulsar ages, since slow growth of the potential drop with h is a necessary condition. (Of course, in an extremely old pulsar the potential drop may be insufficient to support any form of discharge at all, and the "pulsar" dies.)

Thus, the weaker dynamo action associated with older pulsars (and generally believed to be responsible for nulling) may manifest itself in an instability between *interrupted* (RS sparks) and *uninterrupted* (steady) current flow, rather than between current flow and the absence of current flow. We now propose that nulling is the transition from the successive avalanche breakdowns to the steadier mode of discharge described above. The absence of coherent radio radiation is therefore caused by *the absence of whatever mechanism operates to produce the high brightness temperatures observed*, *not* to the cessation of current flow from the region of the polar cap. If normal interrupted sparking is resumed in the existing flux tubes, the null is terminated, thereby leading once again to coherent emission of radio radiation.

This scenario is consistent with the phase memory described in § I. During a null, the flux tubes which existed prior to its onset carry a steady discharge, and we will demonstrate that these tubes drift much more slowly than during normal operation of the pulsar. After cessation of the null, gaps containing large electric fields begin to form in the usual manner as plasma within the tubes recedes from the stellar surface. When the potential drop across the gaps attains a sufficiently large value, RS sparking is reinitiated and normal operation of the pulsar is resumed. The flux tubes are once again able to slowly drift around the magnetic pole, maintaining the spacing they had prior to the onset of the null. The tubes will have drifted little during the null (except if it is very long), so the longitude at which they reappear is to first order unchanged.

b) *Drifting During Steady Discharge*

The normal average drift speed of sparks is given by (RS)

$$v_{\text{drift}} = \frac{(\Delta V)c}{BR_{p^+}}, \tag{6}$$

where B is the magnetic field strength near the stellar surface and R_{p^+} is the radius of the polar cap region out of which positive charges flow. When calculating the period of the drifting subpulses, RS use $e\Delta V \sim 10^{12}$ eV in equation (6) and obtain results which agree reasonably well with the observed values. Since the characteristic energy of curvature radiation photons emitted by an electron or positron of energy γmc^2 moving along a field line with local radius of curvature ρ is

$$E_c = \hbar\omega_c = \tfrac{3}{2}(\gamma_{\max})^3(\hbar c/\rho), \tag{7}$$

we see that 10^{12} eV is nearly an order of magnitude larger than the minimum drop necessary for charges to emit photons which are sufficiently energetic to produce additional pairs.

An average potential drop of this size is applicable in a normal pulsar which is undergoing RS (interrupted) sparking for two reasons:

1. The gap height must become comparable to the mean free path (against pair production) of a photon moving through a magnetic field in order to produce an avalanche discharge. This occurs when the potential drop is considerably greater than the threshold drop for pair production.
2. The gap height and potential drop continue to grow at the initial stages of the RS discharges, as mentioned previously.

However, since *steady* discharge occurs at a rate comparable to that of a *dying* RS discharge, the average potential drop is close to the threshold for pair production, or $\sim 10^{11}$ eV according to equation (7). Equation (6) shows that the flux tube drift during nulling is consequently 10 times slower than normal. Thus, the position of a subpulse under the pulse envelope immediately following a short null will be approximately the same as that prior to the null. We conclude, however, that pulsar subpulses should exhibit a slight systematic advance during long nulls.

It is important to mention that observations supporting the above hypothesis already exist in the literature. Indeed, close inspection of Figure 7*c* in Unwin *et al.* (1978) reveals that the initial pulse following a null consists of subpulses which on average occur near the position expected in the *second* (rather than the first) nulled pulse. The investigations of Filippenko, Readhead, and Ewing (1983) confirm and quantify this result, so it is likely that the pulsar "memory" is not perfect.

c) *Nulling*

The question we must next address is whether there is a reason for the absence of intense, coherent radio radiation while the steady discharge is in progress.

As the polar gap repeatedly builds up and gets destroyed, the voltage drop across it must be some periodic function of time. Similarly, the rate of plasma generation (pair production) must also be a periodic function with the same period but not necessarily the same shape. In other words, the rate at which plasma is injected into the pulsar magnetosphere is modulated during normal operation of the pulsar, and in most pulsar radiation models it is *the presence of this modulation which ultimately leads to the emission of coherent radiation*.

For example, consider bunching as a way of producing coherence. One obtains bunching in klystrons as a consequence of a velocity modulation imposed on the electron stream going through the cavity. After some distance along the electron stream, the velocity modulation converts itself into a density modulation, and the bunches subsequently generate coherent radiation. Such bunching cannot occur by definition if conditions are steady in the klystron cavity, and the same is true by analogy in the pulsar gap.

The above discussion is quite general and shows that the steady gap discharge may reasonably give rise to a pulsar null. However, it is instructive to consider at least one specific model of pulsar radiation in detail, and here we shall examine the model originally proposed by RS.

The maximum energy of positrons injected into the near magnetosphere directly from the polar gap is

$$\gamma_{\max} = E_{\max}/mc^2 = 1.2\times10^7 B_{12} h_4^2/P, \qquad (8)$$

where $h_4 \times 10^4$ cm is the gap height. Since $h \sim 5\times10^3$ cm at the start of a gap discharge, the positrons created first will have $\gamma_{\max} \sim 3\times10^6$. These very energetic positrons rapidly emit curvature radiation, mostly within $\sim 10^6$ cm of the stellar surface (where the typical field line radius of curvature is $\sim 10^6$ cm). Equation (7) then indicates that photons produced by the primary positrons are energetic enough to form additional electron-positron pairs of significantly lower energy than that of the primary particles.

As the potential drop in the gap decreases with the development of the gap discharge, the maximum energy of primary positrons also decreases. Since $c\tau \sim \gamma^{-3}$, where τ is the lifetime of primary positrons against curvature radiation, these positrons travel farther than the original primary positrons. As the gap discharge weakens even more, the primary positrons are emitted with such low energy that they are able to reach regions of large ρ, and they subsequently leave the near magnetosphere with negligible additional radiative loss.

Thus, RS show that in general the very energetic primary positrons emitted near the beginning of a gap discharge ultimately lead to comparatively low energy ($\gamma \sim 800$) electrons and positrons, whereas the primary positrons emitted near the end of a discharge lose very little of their energy and are eventually able to catch up with and pass through the more slowly moving pairs. The final result is that the collective Coulomb interaction of the pair plasma with the stream of higher-energy positrons passing through it leads to the classical two-stream instability which greatly enhances the subsequent emission of coherent curvature radiation. Although this mechanism has some inherent difficulties (Benford and Buschauer 1977) and cannot fully account for the observed properties of the coherent beams of radio radiation, most modifications (e.g. CR 1980) still retain its basic principle—that a charged stream of particles must interact with a more slowly moving electron-positron plasma in order to produce the high radio brightness temperatures seen in pulsars.

Based on the above picture, our model of nulling is qualitatively compatible with the absence of coherent radio radiation. Since the discharge we describe corresponds to continuous sparking at a low level, the great majority of positrons ejected from the gap will have a low energy and be able to travel out of the near magnetosphere without suffering large radiative losses. Comparatively few very high energy positrons are created, and there is little subsequent emission of curvature radiation (followed by pair production) to produce a dense pair plasma. Hence, conditions are *not* favorable for the onset of the two-stream instability, in contrast to the normal operation of a pulsar. Single-particle incoherent radiation by the rapidly moving positrons, on the other hand, cannot produce the high ($\sim 10^{30}$ K) brightness temperatures seen in pulsars—and the absence of radio radiation during nulls is therefore to be expected.

We do not, of course, exclude the possible existence of other reasons for the absence of large quantities of coherent radio radiation during times of steady discharge. For example, Arons and Scharlemann (1979) and Arons (1979, 1981) have advanced a model of pulsars with $\boldsymbol{\Omega}\cdot\boldsymbol{B} > 0$ and have concluded that a certain type of steady discharge may prevail during *normal* operation of such a pulsar. A problem with this scenario is that an electron beam undergoing laminar ultrarelativistic flow along curved field lines may not be able to produce radio emission of sufficiently high brightness temperature (Arons 1981). However, the lack of copious radio radiation would be an *attractive* feature if a similar steady discharge could be shown to occur in times of nulling rather than during healthy pulsar operation!

Finally, we note that it is also possible that mode changing is the manifestation of such steady discharges over limited areas of the polar cap region. It is conceivable that at a given time, the available current is sufficient to support RS discharging of only a certain portion of the polar gap; the regions corresponding to the other mode undergo steady discharge instead and are therefore quiescent in their radio emission.

V. SUMMARY

Our main conclusions may be summarized as follows.

Although the standard pulsar model provides adequate explanations of many observed pulsar characteristics, it has difficulty accounting for nulling and mode changing, the persistence of phase memory during nulling, and the lack of rapid drift of sparking regions toward the magnetic axis. These can be qualitatively accounted for by the following hypotheses:

1. $\boldsymbol{E} \cdot \boldsymbol{B}$ in the empty (gap) portions under plasma-filled flux tubes is greater than along neighboring magnetic field lines outside the tubes.

2. Nulling is the manifestation of a continuous, steady discharge in the polar gap rather than complete cessation of sparking.

3. The lack of observable radio radiation during nulling is caused by the absence of the dominant coherence mechanism present during normal operation of the pulsar rather than by the absence of particle flux from the polar cap.

4. Mode changing is the transition of certain regions of the polar cap from an active to a nulling state and vice-versa.

It is a pleasure to thank the numerous colleagues with whom we have discussed some of the ideas presented in this paper, especially Drs. Peter Goldreich, Roger Blandford, and Jonathan Arons. A. V. F. is indebted to the Fannie and John Hertz Foundation and Dr. Peter Goldreich for financial support, and to Dr. A. C. S. Readhead for providing inspiration and some of the observations on which our conclusions are based. V. R. is grateful to the California Institute of Technology for a Fairchild Scholarship during the tenure of which this work was begun.

REFERENCES

Arons, J. 1979, *Space Sci. Rev.*, **24**, 437.
______. 1981, in *IAU Symposium 94*, *Origin of Cosmic Rays*, ed. G. Setti, G. Spada, and A. W. Wolfendale (Dordrecht: Reidel), p. 175.
Arons, J., and Scharlemann, E. T. 1979, *Ap. J.*, **231**, 854.
Benford, G., and Buschauer, R. 1977, *M.N.R.A.S.*, **179**, 189.
Cheng, A. F., and Ruderman, M. A. 1977*a*, *Ap. J.*, **212**, 800 (CR 1977*a*).
______. 1977*b*, *Ap. J.*, **214**, 598 (CR 1977*b*).
______. 1979, *Ap. J.*, **229**, 348 (CR 1979).
______. 1980, *Ap. J.*, **235**, 576 (CR 1980).
Cheng, A. F., Ruderman, M. A., and Sutherland, P. 1976, *Ap. J.*, **203**, 209.
Filippenko, A. V., Readhead, A. C. S., and Ewing, M. S. 1983, in preparation.
Flowers, E., and Ruderman, M. A. 1977, *Ap. J.*, **215**, 302.
Goldreich, P., and Julian, W. H. 1969, *Ap. J.*, **157**, 869.
Jones, P. B. 1981, *M.N.R.A.S.*, **197**, 1103.
Radhakrishnan, V. 1980, in *Non-Solar Gamma Rays* (*COSPAR*), ed. R. Cowsik and R. D. Wills (Oxford: Pergamon Press) p. 163.
______. 1982, *Contemp. Phys.*, **23**, 207.
Ruderman, M. A. 1976, *Ap. J.*, **203**, 206.
______. 1981, in *IAU Symposium 95*, *Pulsars*, ed. W. Sieber and R. Wielebinski (Dordrecht: Reidel), p. 87.
Ruderman, M. A., and Sutherland, P. G. 1975, *Ap. J.*, **196**, 51 (RS).
Shukre, C. S., and Radhakrishnan, V. 1982, *Ap. J.*, **258**, 121.
Sturrock, P. A. 1971, *Ap. J.*, **164**, 529.
Unwin, S. C., Readhead, A. C. S., Wilkinson, P. N., and Ewing, M. S. 1978, *M.N.R.A.S.*, **182**, 711.
Vivekanand, M., and Narayan, R. 1981, *J. Ap. Astr.*, **2**, 315.

ALEXEI V. FILIPPENKO: Department of Astronomy, 105-24, California Institute of Technology, Pasadena, CA 91125

V. RADHAKRISHNAN: Raman Research Institute, Bangalore 560080, India