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INTERPRETATION OF THE PULSED GAMMA RAY EMISSION FROM VELA

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ABSTRACT

A model is proposed for the Vela pulsar in which the radio emission originates near the surface of the neutron star while the pulsed γ-ray emission (Thompson et al., 1975) is produced by synchrotron radiation near the speed of light cylinder. This model can explain the energy flux, double pulse structure, and phase shift with respect to the radio of the γ-ray emission and offers approximate quantitative predictions for other X- and γ-ray fluxes.

I. INTRODUCTION

Recent results from the SAS-2 high energy (> 35 MeV) γ-ray experiment have shown a strong emission from the direction of the Vela supernova remnant, a large fraction of which is pulsed at the radio period of PSR 0833-45 (Thompson et al., 1975). The γ-ray emission shows a double pulse structure, in contrast to the radio pulsar, which has only one pulse. Based on detailed comparison with two independent sets of radio data, the γ-ray pulses are both out of phase with the radio peak, following it by 13 and 48 msec.

Searches for the Vela pulsar in the optical have given negative results (Kristian, 1970; Chiu, Lynds, and Maran, 1970; Lasker, Bracker, and Saa, 1974) although a tentative identification of a non-pulsing star associated with PSR 0833-45 has been made (Lasker, 1975). Several X- and γ-ray experiments have found small positive pulsed results (Harnden et al., 1972; Harnden and Gorenstein, 1973; Grindlay et al., 1973; Albats et al., 1974). All of these are of substantially lower statistical significance than the SAS-2 result, and none show the double pulse structure. Also, none of these positive results has been confirmed, and unless the pulsar is strongly time-varying, the X-ray observations appear to be in conflict or near-conflict with other measurements (Ricker et al., 1973; Rappaport et al., 1974; Moore et al., 1974). In light of these uncertainties, this discussion will concentrate on the radio and γ-ray observations.

II. THE MODEL

The appearance of two pulses in the γ-ray energy range and the phase shift of both of these pulses from the single radio peak suggest strongly that the radio and γ-ray emissions originate in different physical regions of the pulsar. The basic feature of the model proposed here is that the pulsed radio emission is produced near the surface of the star while the pulsed γ-ray flux originates near the speed of light cylinder.

PSR 0833-45, the Vela pulsar, is assumed to consist of a spinning neutron star with the axis of its dipole magnetic field oriented approximately, but not exactly, at right angles to the spin axis. If the two axes were exactly at right angles, then the radio observations would be expected to show two pulses, one from each polar cap, if any pulsed emission at all were seen. The production of radio photons in this model is assumed to take place near the surface of the neutron star. The production mechanism could be coherent curvature radiation by electrons (Sturrock, 1971; Tademaru, 1971; Ruderman and Sutherland, 1975) or some other mechanism, as reviewed, for example by ter Haar (1972). For the present discussion, the exact radio emission mechanism is not crucial, as long as the radio photons are produced near the polar caps of the neutron star. The appearance of a single radio pulse can then be explained as an orientation effect. The emission region is small in both extent and angle; therefore, the radio beam is sufficiently narrow that only the beam from one of the two polar caps reaches the earth.

In contrast to the radio emission, the observed high-energy γ-ray flux is produced, according to this model, near the speed of light cylinder by synchrotron radiation of electrons which have followed the field lines of the pulsar's dipole magnetic field. This model is, therefore, similar to the one proposed by Shklovsky (1970) for the Crab. A qualitative description of the γ-ray production will show how the observed characteristics can be explained. Following this discussion, a quantitative approach will indicate the feasibility of the proposed mechanisms.

In order for the radio emission to originate near the polar caps of the neutron star, electron acceleration must take place in this region. Once accelerated, the electrons are assumed to propagate through the pulsar magnetosphere along the magnetic dipole field lines. As long as the electrons move strictly along the field lines, they experience no transverse magnetic field. The only energy loss mechanism for such electrons, curvature radiation, causes only a small degradation of the electron energies. At the speed of light cylinder, the electron trajectories are assumed to deviate slightly from the field lines. The electrons then see a transverse magnetic field and rapidly radiate away most of their energy as synchrotron radiation peaked in the γ-ray energy range. Since the deviation from the field lines is small, the radiation itself occurs principally along the direction of the field lines. The geometric configuration of the magnetic field at the speed of light cylinder therefore determines the characteristics of the γ-radiation.

The magnetic field configuration is that of a dipole, but this field cannot corotate with the star all the way from the surface to the speed of light cylinder. The shearing effect of the star's rotation causes the projection of the magnetic field lines on the equatorial plane to show a spiral structure, with a spiral angle of about 45° at the speed of light cylinder due to the approximate equality of the plasma energy density and the magnetic field energy density in this region (Sturrock, 1971). The 13 $\pm$2 msec delay between the radio pulse and the first γ-ray pulse is equivalent to an angle of 52° $\pm$8°. This delay arises naturally in this model from the fact that the radio emission originates near the surface, where the magnetic field does corotate with the polar caps, while the γ-ray flux comes from the speed of light cylinder, where the field lines lag behind the polar caps by the spiral angle.

The appearance of two γ-ray pulses can also be explained in geometric terms. The magnetic dipole field lines above the polar caps diverge rapidly with increasing distance from the surface. A narrow beam of electrons at the surface will, therefore, have much larger extent in both spatial and angular dimensions at the speed of light cylinder. Because of this divergence of the field lines, it then becomes possible to see the second polar cap γ-ray emission as well as the first. The larger emitting region at the speed of light cylinder also accounts for the larger widths of the pulses in the γ-ray energy range as compared to the radio. The γ-ray pulse which follows the radio peak by 13 msec is the one which is associated with the polar cap where the radio emission takes place. The other X-ray pulse comes from the region above the second polar cap, which has a less favorable geometry with respect to the line of sight from the earth. The second pulse could then be expected to be less intense than the first, and the γ-ray data do suggest that the second pulse is weaker. The reason why the two pulses are separated by 0.4 period rather than 0.5 period is not clear, although this effect could also be the result of the asymmetry between the line of sight to the two polar caps.

Based on these largely geometric arguments, this model for the Vela pulsar appears to be promising. The quantitative feasibility of the model remains to be shown below. In this preliminary analysis, some details of the complex problems of particle acceleration and propagation in the pulsar magnetosphere are not treated explicity, or the work of other authors has been assumed to apply to this model.

For a dipole magnetic field, the radial dependence of the field strength is given by

$$B_r = B_R\ (R/r)^3 \qquad (1)$$

where B_R is the field at the surface of a neutron star with radius R and B_r is the field at radius r. In particular, for $r = R_L = cT/2\pi$ (the speed of light cylinder), where c is the velocity of light and T is the pulsar period, $B_r = 10^4$ gauss, assuming that $B_R = 10^{12}$ gauss. Production of 100 MeV γ-rays by synchrotron radiation in a 10^4 gauss field requires electrons with energies of about 10^{12} ev. Acceleration of electrons to energies greater than 10^{13} ev has been predicted for the Vela pulsar (Sturrock, 1971).

If the electron acceleration near the surface of the star takes place along the magnetic field lines, as assumed, for example, by Sturrock (1971), then the particles will move along the field lines with essentially no transverse momentum. The only energy loss mechanism for the electrons will be through curvature radiation, but if the radius of curvature is assumed large ($\sim 10^8$ cm), then 10^{12} ev electrons will lose less than 10% of their energy in the total travel time from the surface to the speed of light cylinder. This constraint on the radius of curvature means that the electrons must be accelerated principally along field lines which lie very close to the axis of the magnetic dipole.

The mechanism by which the electrons deviate from the magnetic field lines near the speed of light cylinder is uncertain. Some external source of energy would be necessary to force the electrons away from these lines. Although they consider the possibility unlikely, Sturrock, Petrosian and Turk (1975) suggest that a high-frequency radio field could couple with the electron gyromotion to produce the required transverse motion. For this calculation, the existence of a mechanism of this type will be assumed.

Once the electron trajectories separate from the field lines, the electrons will begin to radiate. The total power emitted as synchrotron radiation by an electron with energy E (in ev) in a field $B_\perp$ (in gauss) is

$$P = 5 \times 10^{-15} E^2 B_\perp^2 \qquad \text{ev s}^{-1} \tag{2}$$

If the transverse magnetic field seen by the electrons is taken to be 10^3 gauss, i.e. 10% of the total field at the speed of light cylinder, then a 10^{12} ev electron will radiate away over 80% of its energy in the form of γ-rays with a time scale of about 1 msec. Since the electron path is still predominantly in the direction of the field lines, the synchrotron radiation will be strongly peaked along the direction of the field lines, as assumed earlier.

Because the synchrotron mechanism converts electron energy into γ-radiation with high efficiency, the rotational energy loss of the Vela pulsar is ample to explain the observed γ-ray energy flux. The observed time-averaged γ-ray flux F can be expressed in terms of the pulsar luminosity L by

$$F = \frac{L}{\Delta\Omega D^2} \tag{3}$$

where D is the distance to the pulsar, assumed to be 460 pc (Brandt et al., 1971) and $\Delta\Omega$ is the solid angle swept out by the beam, taken to be 1 sr for this calculation. The observed pulsed flux of about 10^{-5} photons $cm^{-2}\ s^{-1}$ above 35 MeV from Vela implies a γ-ray luminosity of 2×10^{37} photons ($E > 35$ MeV) s^{-1} for PSR 0833-45. Assuming a characteristic energy of 100 MeV for the γ-rays, this luminosity is equivalent to 3×10^{33} ergs s^{-1}, which is about 0.5% of the estimated 7×10^{35} ergs s^{-1} rotational energy loss of the Vela pulsar (ter Haar, 1972). As a first approximation, consider the case in which electrons are accelerated to energies on the order of 10^{12} ev and then injected into the region near the speed of light cylinder. From equation (2), the rate of energy loss as γ-rays of these high energy electrons is such that less than 1% of the rotational energy loss of the pulsar needs to appear in the form of high energy electrons at the speed of light cylinder to explain the observed γ-ray emission.

III. DISCUSSION

The implications of this model for other measurements and theoretical studies are significant. Before such applications are discussed, one important consideration is the possible comparison of this model with the Crab pulsar, the only other pulsar known to emit in both radio and γ-rays. The apparent continuity of the NP0532 pulsed spectrum from the optical through γ-ray energy ranges, together with the agreement in phase between the radio and high-energy photon pulses and the relatively narrow γ-ray pulses, argue that the mechanism described here is not responsible for the Crab emission. The Crab is considered to be the only pulsar capable of accelerating protons as well as electrons from its surface (Ruderman and Sutherland, 1975). One possibility, therefore, would be that the Crab emission at all photon energies is due to proton-induced cascades near the surface of the star, and that few energetic particles reach the speed of light cylinder except directly along the field lines, in which case they would not radiate by the synchrotron mechanism. Another possibility would be that the electrons in the Crab are accelerated along field lines with smaller radius of curvature than those postulated for the Vela pulsar. In this case, the curvature radiation losses would result in few energetic electrons reaching the speed of light cylinder. Until other γ-ray pulsars are discovered, it appears impossible to say whether the present model is a general case or one which applies only to Vela.

This model can also be used to predict pulsed fluxes to be expected at other X-and γ-ray energies. A first approximation to the energy spectrum can be obtained by assuming that the electrons are all injected into the emitting region with the same energy. This delta function approximation was used by Sturrock (1971), who calculated a photon energy spectrum with an $E^{-0.5}$ dependence, where E is the photon energy. Normalizing to the SAS-2 measurements, the energy spectrum in the X- and γ-ray range would be $1.4 \times 10^{-3} E^{-0.5}$ KeV cm^{-2} s^{-1} KeV^{-1}, with E expressed in KeV. The expected flux at 1 KeV of 1.4×10^{-3} is well below the pulsed result of Harnden and Gorenstein (1973) but is consistent with the upper limit of Moore et al.,(1974). At 5 KeV, the predicted pulsed flux is well below the upper limit of Rappaport et al. (1974). At 50 KeV, the prediction is an order of magnitude below the pulsed observations of Harnden et al. (1972). If the results of Harnden and Gorenstein or Harnden et al. are confirmed, then the possibility would have to be considered that a second pulse mechanism is responsible for the X-ray emission. More sensitive measurements at X-ray energies should be able to detect the pulsed emission predicted by the present model.

In summary, the model described here offers an explanation of several important features of the radio and γ-ray pulsed radiation from PSR 0833-45. The fact that the model can explain the γ-ray energy flux, double pulse structure, and phase shift with respect to the radio indicates that more detailed work along these lines may be profitable.

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REFERENCES

Albats, P., Frye, G. M., Jr., Thomson, G. B., Hopper, V. D., Mace, O. B., Thomas, J. A., Staib, J. A. 1974, Nature 251, 400.

Brandt, J. C., Stecher, T. P., Crawford, D. L., and Maran, S. P. 1971, Ap. J. 163, L99.

Chiu, H. Y., Lynds, R., and Maran, S. P. 1970, Ap. J. 162, L99.

Grindlay, J. E., Brown, R. H., Davis, J. and Allen, L. R. 1973, Proc. 13th Intl. Cosmic Ray Conf. Denver, 439.

Harnden, F. R., Jr. and Gorenstein, P. 1973, Nature 241, 107.

Harnden, F. R., Jr., Johnson, W. N., III, and Haymes, R. C. 1972, Ap. J. 172, L91.

Kristian, J. 1970, Ap. J. 162, L103.

Lasker, B. M. 1975, preprint.

Lasker, B. M., Bracker, S. D., and Saa, O. 1972, Ap. J. 176, L65.

Moore, W. E., Agrawal, P. C., and Garmire, G. 1974, Ap. J. 189, L117.

Rappaport, S., Bradt, H., Doxsey, R., Levine, A., and Spada, G. 1974, Nature 251, 471.

Ricker, G. R., Gerassimenko, M., McClintock, J. E., Ryckman, S. G., and Lewin, W. H. G. 1973, Ap. J. 186, L111.

Ruderman, M. A. and Sutherland, P. G. 1975, Ap. J. 196, 51.

Shklovsky, I. S. 1970, Ap. J. 159, L77.

Sturrock, P. A. 1971, Ap. J. 164, 529.

Sturrock, P. A., Petrosian, V., and Turk, J. S. 1975, Ap. J. 196, 73.

Tademaru, E. 1971, Ap. and Sp. Sci. 12, 193.

Ter Haar, D. 1972, Phys. Reports 3, 57.

Thompson, D. J., Fichtel, C. E., Kniffen, D. A., and Ogelman, H. B., 1975, Ap. J. (in press).