An Outer Gap Model of High-Energy Emission from Rotation-Powered Pulsars

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ABSTRACT

We describe a refined calculation of high energy emission from rotation-powered pulsars based on the Outer Gap model of Cheng, Ho & Ruderman (1986a,b). In this calculation, vacuum gaps form in regions near the speed-of-light cylinder of the pulsar magnetosphere along the boundary between the closed and open field line zones. We have improved upon previous efforts to model the spectra from these pulsars (e.g. Cheng, et al. 1986b; Ho 1989) by following the variation in particle production and radiation properties with position in the outer gap. Curvature, synchrotron and inverse-Compton scattering fluxes vary significantly over the gap and their interactions via photon-photon pair production build up the radiating charge populations at varying rates. We have also incorporated an approximate treatment of the transport of particle and photon fluxes between gap emission zones. These effects, along with improved computations of the particle and photon distributions, provide very important modifications of the model gamma-ray flux. In particular, we attempt to make specific predictions of pulse profile shapes and spectral variations as a function of pulse phase and suggest further extensions to the model which may provide accurate computations of the observed high energy emissions.

Subject headings: gamma-rays: emission — pulsars: gamma rays

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1. Introduction

Since the discovery of radio pulsations from rotating neutron stars (Hewish et al. 1968), many theories have been proposed to explain the origin of these emissions. Early models invoke the acceleration of electrons and positrons to extremely high energies such that the radiation emitted by these particles results in an electromagnetic cascade of $e^\pm$ pairs and photons. This avalanche of charges yields the observed coherent radio flux (Sturrock 1971; Ruderman & Sutherland 1975). Unfortunately, attempts at understanding the physics of the pulsar magnetosphere by looking only at the radio observations have met with limited success. A more fruitful approach would be to use the higher energy observations, both in terms of photon energy and in terms of the total available energy to be extracted from the pulsar, to characterize the magnetosphere (Arons 1992). The polar cap models of Harding, Tademaru, & Esposito (1978), Daugherty & Harding (1982), the slot gap model of Arons and his collaborators (Scharlemann, Arons, & Fawley 1978; Arons 1983) and the outer gap model of Cheng, et al. (1986a,b; hereafter CHRa,b) and Ho (1989) have all been attempts to use the high energy observations to reveal nature of the pulsar magnetosphere.

Given the recent data obtained by the instruments aboard the Compton Gamma-Ray Observatory and the identification of additional gamma-ray pulsars, bringing the total to six—Crab, Vela, Geminga (Bertsch et al. 1992), PSRB 1706−44 (Thompson et al. 1992), PSRB 1055−52 (Fierro et al. 1993) and PSRB 1509−58 (Wilson et al. 1992)—it is now appropriate for further efforts to be made towards understanding these objects. In this paper, we present our own attempts at modeling the high energy emission from young, rotation-powered pulsars in the context of a modified outer gap model. In section 2, we summarize the results of a previous paper (Chiang & Romani 1992; hereafter Paper I), in which a geometrical calculation of the emission from the outer gap regions was performed and which was shown to reproduce qualitatively the light curves of all the gamma-ray pulsars. In section 3, we review the details of the outer gap spectral calculation described in CHRa,b and restated later by Ho (1989); and in section 4, we motivate and outline our refinements to the CHR calculation. They consist of dividing the outer gap region into smaller sub-zones in order to account for the variation in magnetic field and photon and particle densities as a function of position in the magnetosphere. We have also included a treatment of the transport of particles and photons from one region of the magnetosphere to another. We find that this transport crucially effects the emission processes in the outer gap. In addition, we perform more detailed radiation and pair creation calculations. In section 5, we present some preliminary results of our multi-zone spectral calculations; and in section 6, we discuss limitations of the model and ways in which it can be further improved.
2. A Simple Model for the Outer Gap Light Curves

In Paper I, we presented our basic geometrical model of emission from the outer gap regions of a pulsar magnetosphere. Adopting the assumptions of CHRa, we defined the outer gap to lie along the boundary of the closed field line region of a magnetic dipole field configuration, bounded on the side closest to the neutron star by the null-charge surface, on which \( \Omega \cdot B = 0 \), and on the outside by the velocity-of-light cylinder. However, in contrast to CHRa, we assumed that gap-type regions could be supported along all field lines on the boundary of the closed region rather than just on the bundle of field lines lying in the plane of the rotation and magnetic dipole axes.

Assuming uniform emissivity along outer gap fields lines with the radiation beamed in the local field direction, we then computed the emission profile of the pulsar projected onto the sky. In this model, the field geometry is that of a dipole in the co-rotating frame, and we have included the effects of relativistic aberration and time-of-flight delays through the magnetosphere. Figure 1 shows the result of our calculation for a nearly orthogonal rotator. As in Paper I, the coordinates of this image are defined so that rotational latitude runs along the vertical axis and rotational longitude runs along the horizontal axis. Hence, an observer line-of-sight corresponds to a horizontal line across the image, and the zero of rotational phase is defined to be where the line-of-sight crosses the plane containing the dipole and rotation axes. A line-of-sight which has a phase separation of \( \sim 145^\circ \) between the two highest peaks in the emission profile is indicated by the dashed line in the image. A combination of the time-of-flight and relativistic aberration calculations allows the observer to see emission from many points along the outer gap at once during certain portions of the pulse phase. Phases where this effect is strongest correspond to the enhancements or peaks of the emission.

Given this emission profile on the sky, it is apparent that the various pulse shapes seen for the gamma-ray pulsars can be accounted for generically by this model. For almost all lines-of-sight, two main peaks with significant emission in the “bridge” region are seen. Thus, pulse shapes such as those of the Crab, Vela and Geminga pulsars are seen if the observer line-of-sight were at rotational latitudes \( \lesssim 20^\circ \), whereas the light curves for PSRB 1706–44 and PSRB 1055–52 correspond to lines-of-sight at higher latitudes near \( \sim 40^\circ \) where the separation of the two peaks is small and may appear as a single, broad peak. Furthermore, this model does not require particularly special alignment of the dipole axis to the rotation axis. So long as the angle, \( \alpha \), between these two axes is relatively oblique (i.e. \( \alpha \gtrsim 45^\circ \)), emission similar to that pictured in Figure 1 will result. The cases where pulsed emission is unlikely to be observed in this model occur when the axes are nearly aligned. In the extreme case of \( \alpha = 0^\circ \), the emission is, by symmetry, completely
unmodulated.

Additionally, because the aberration and time-of-flight effects make it possible to attain the double pulse morphology for emission from a single hemisphere of the pulsar dipole, double pulses with bridge emission are present for more general field configurations than just the neutron star-centered dipole models as invoked by traditional polar cap models and by the outer gap model proposed in CHRa to explain the Crab and Vela pulse profiles. Our geometrical outer gap model also constrains the phase of emission from the polar cap relative to the gamma-ray emission. Either radio or thermal emission, both believed to originate from the polar cap regions, will lead the first (or single) peak of the gamma-ray light curves predicted by our model. Calculations show that the model matches quantitatively the relative phases observed for the individual gamma-ray pulsars as well as predicting relative numbers of detections in good agreement with the present sample (Romani & Yadigaroglu 1993). In addition, Romani & Yadigaroglu (1993) have shown that the position angle variation of the optical polarization of the Crab pulsar (Kristian et al. 1970; Smith et al. 1988) is well matched to predictions of our outer gap model. With these results, the basic geometrical picture is well established and we turn now to addressing the observed spectral variations as a function of pulse phase. These variations, absent in the original outer gap picture, arise as a natural consequence of our geometrical model, but require a careful calculation of local emission properties.

3. Review of the Original Cheng, Ho and Ruderman Calculation

Before proceeding with a description of our spectral calculations, it is appropriate to review the basic outer gap spectral calculation which was presented by CHRa,b. According to CHRa, the outer gap is a vacuum zone which is stable against closure by photon-photon pair-production because of the special geometry of the magnetic field at the boundary of the closed field line region. The deviation from co-rotation charge density in this region results in large potential drops on paths parallel to the local magnetic field. Electrons and positrons produced near the pair-creation boundary of the gap are accelerated to have Lorentz factors of $\Gamma \sim 10^7$. Their energies are radiation-reaction limited by a combination of curvature radiation and inverse-Compton processes. Because the electrons and positrons are highly relativistic, the radiation they emit is beamed along the local field direction. The low energy photons off which the high energy particles inverse-Compton scatter are produced by counter-streaming electron and positron pairs which are created just beyond the outer gap pair boundary and whose momentum vectors can form sizable angles with
respect to the local field direction. These secondary pairs emit synchrotron radiation and also inverse-Compton scatter both ambient and low-energy photons produced from secondary particles traveling in the opposite direction. Because the secondary pairs are created outside the vacuum gap, they do not attain large Lorentz factors and the radiation they emit has greater angular dispersion than that of the highly relativistic primaries. This allows a fraction of the secondary radiation to be projected into the gap zone and forms the pair-production opacity which limits the size of the gap. The gap size is self-consistently controlled by the pair-production of the counter-streaming primary and secondary photon beams, and the radiation processes are themselves maintained via the pair-production processes which provide the radiating charges.

One of the major deficiencies of the outer gap spectral calculations of CHRa and Ho (1989) is that they consider the outer gap as a single, monolithic zone with only single, “characteristic” values of the magnetic field and photon densities which do not vary in space. Furthermore, because of the built-in symmetry of the CHR spectral calculation (see Ho 1989), the spectra for the two peaks (which corresponds to the inward and outward radiation beams) are identical. Therefore, in addition to being unable to account for the emission in the bridge region between the main pulses of the Crab, Vela and Geminga light curves as well as the single broad pulses seen in the light curves of PSRB 1706−44 and PSRB 1055−52, the outer gap model of CHR is also unable to account for the spectral variation seen as a function of phase for the double-peaked gamma-ray pulsars. In our model, the variation in the magnetic field and photon densities will have a significant effect on the resulting radiation and thus provides a natural explanation of the observed spectral variation as a function of pulse phase.

4. Refinements

4.1. Mapping pulse phase to position in the magnetosphere

Figure 2 shows the same outer gap emission calculation as does Figure 1, but with the emission from along just twenty field lines traced from null surface to the light cylinder. This coarser sampling of field lines allows us to infer the approximate location of the emission at each point in phase along a given line-of-sight. Emission points along the field lines are drawn so that the density of points is the same for each line. Therefore, the number of emission points along a given field line from the null surface out to a specified
point on the skymap image will be proportional to the path length from the null surface to that point and will correspond to a specific location in the magnetosphere.

Along the line-of-sight which has the two highest peaks of the emission separated by a Crab- or Vela-like phase difference \(\Delta \phi \simeq 145^\circ\), we see from Figure 2 that the first peak is composed of radiation which comes from fairly high in the gap region and the second peak is composed of photons originating from almost the entire length of a bundle of field lines. By contrast, the emission in the bridge region appears to consist of photons from regions very near the light cylinder and regions very near the null surface but not much from between the two regions.

### 4.2. The Multi-zone Outer Gap

Given that the pulsar spectra vary in phase and that the phases of the emission of the light curves can be mapped back to different locations in the magnetosphere, it is natural to model the spectral emissivity locally and divide the magnetosphere into smaller sub-zones so that each zone can be treated as a separate emission region with a distinct magnetic field intensity and geometry. Figure 3 is an example of how we have divided the outer gap into smaller sub-zones in the plane of the rotation and dipole axes. The photon densities will also be different for each zone, and as we shall see, will differ for the two beaming directions. Since the observed pulsar radiation is mostly beamed along the local field direction\(^3\), we model the gap as a one-dimensional region existing along the last closed field lines, radiate photons along paths initially parallel to the local field direction and ignore the contribution of neighboring zones which are displaced toroidally.

Along with the variation of the magnetic field, which can range from \(B \sim 10^{11}\) G at the null surface for a nearly orthogonally aligned Crab-like pulsar to \(B \sim 10^6\) G in regions near the light cylinder, another important motivation to subdivide the gap region is the possibility of photon and particle transport from one part of the magnetosphere to another. Photon transport is important for two reasons. First, at low energies, the optical depth to photon-photon pair-production is small, meaning that the low energy photons will be able to travel freely from sub-zone to sub-zone. Since the low energy photons contribute most to the pair-creation opacity seen by the high energy energy photons, it is crucial to

\(^3\)For the Crab pulsar, we know that the observed radiation must include a sharply beamed component from optical to gamma-ray energies since the light curves in all these energy bands are sharply peaked at the same points in pulse phase.
include their transport. Figure 4 shows the optical depth to photon-photon pair-production as a function of energy at three points along the gap boundary. Second, assuming that the boundaries of the gap zone follow dipole field lines which are taken to be equipotentials (see CHRa and the next section), the geometry of the outer gap is such that the flux contribution to a given sub-zone from sub-zones farther out in the gap will not be equal to the contribution from those closer to the null surface (see Figure 5). This asymmetry causes the pair-production rate to differ for the inward and outward directions and ultimately leads to a difference in observed photon flux.

The importance of the particle transport can be estimated by comparing the energy lost due to synchrotron emission and inverse-Compton scattering to the total initial energy of the particle. In Figure 6, we have plotted the fraction of energy remaining to each of the secondary electrons and positrons as they cross single sub-zones versus the initial energy of each particle. It is evident that a substantial number of electrons retain a significant fraction of their initial energy after they cross a single sub-zone.

4.3. Other Improvements and Approximations

In addition to dividing the gap into multiple zones and a crude treatment of particle and radiation transport, we have improved upon the methods used to calculate the inverse-Compton photon distributions as well as the electron-positron distributions due to photon-photon pair-production. In CHRb and Ho (1989), very generous approximations were made to calculate these processes and in some cases were not entirely justified. We have been able to calculate semi-analytically the pair and inverse-Compton photon distributions without making the same simplifying assumptions of the previous works.

From the pair-production calculations, we use the angular and energy distribution information of the resulting secondary particles to determine the synchrotron radiation angular distribution in each sub-zone as a function of photon energy. This information is then used with the sub-zone photon acceptance angles (see Figure 4) to determine the amount of radiation passed from sub-zone to sub-zone in the photon transport part of the calculation. However, when determining the distributions of locally generated radiation and particles, we still adopt the approximation that the incident particles and photons in the pair-creation and the inverse-Compton processes impinge upon each other head-on. This assumption is somewhat justified for the photon/photon interactions by the fact that the observed radiation (at least in the case of the Crab) must be beamed.
Another approximation we make, and which limits the predictive power of this model, is our prescription for determining the upper boundary of the outer gap. If we assume that the field lines in the open region are equipotentials and that charges can flow freely along them, the upper boundary of the gap will lie along these field lines. This is implied by our depiction of the gap sub-zones in Figure 3. Ho (1989) chose to parametrize the width of the gap as a fraction of the radius of curvature of the local magnetic field: \( f_g \equiv a_{\text{gap}}/r_{\text{curv}} \). This is a natural parametrization since the rectilinear approximation of the gap potential (CHRb) yields a voltage and a current density through the gap—both of which can be expressed in terms of the parameter \( f_g \). For this paper, which we restrict to the case of the Crab pulsar, we chose a value of \( f_g = 0.3 \), evaluated at the midpoint of the gap, which yields a value of the gap power which is consistent with the observed pulsed radiative power emitted by the Crab, and which is still far less than the total spindown power.

5. Spectral Results

Obtaining the final spectra for all the gap sub-zones requires an iterative calculation to be performed so that the pair-production rates, which depend on the photon-photon optical depths, and the photon fluxes, which depend on the charged particle distributions, are consistent throughout the gap. Ho (1989) presents an example of an iterative, single-zone spectral determination. Our calculation is similar, but entails additional complications due to the transport of radiation and particles from sub-zone to sub-zone.

Following Ho (1989), we use a Crab-like spectrum, taken from the observations, to start off our iterative calculations. The result of the initial iteration of the calculation is shown in Figure 4. The spectra from three points along the gap are shown. The dashed line is the input Crab-like spectrum, and the solid line is the summed flux emitted from each zone. For this initial iteration, the results look promising: In the first sub-zone, which is nearest the star and thus has the strongest magnetic field, the synchrotron contributions dominate the emission and have a characteristically steeper spectrum with photon spectral index \( \gamma \sim 2 \). For the middle and outermost zones, the spectra are progressively flatter and reflect the increased importance of the inverse-Compton processes in the outer magnetosphere where the fields are weaker and the low energy flux is greater because of the larger photon acceptance angles (see Figure 5). Figure 8 shows the relative contribution of the various spectral components to the total spectrum for the innermost and outermost gap zones.

Unfortunately, once the calculation is allowed to converge to a self-consistent solution, the spectra which result exhibit a significant lack of photon flux below several GeV. The
expected power is still being extracted from the gap, except that it is emerging in the form of very high energy photons at energies well above a GeV.

6. Discussion

The root of the problem may lie in several different places. Since the gap power is being extracted as very high energy photons, the solution amounts to reprocessing this flux to lower energies. A more traditional pair-photon cascade would be an obvious means of doing this. There is apparently too little optical depth to pair-creation from just the low energy photons created by the counter-streaming particles themselves, and the magnetic fields are too weak in the outer magnetosphere to contribute to the pair-creation via the Sturrock process, $\gamma B \rightarrow \gamma\gamma$ (Sturrock 1971).

External sources of soft flux, from processes other than the ones described here, may be sufficient to maintain the needed pair-production. One source may be thermal emission originating from polar cap heating by inwardly streaming particles. Recent ROSAT observations of Geminga and PSRB 1055-52 indicate that there is pulsed thermal emission from these pulsars which is consistent with local heating on the surface of the neutron star (Halpern & Holt 1992; Ögelman 1993). However, this emission would most likely affect only the inner portion of the magnetosphere.

A more complicated solution may lie in the manner in which the low energy flux is transported between different regions of the magnetosphere. In the present calculation, the soft photon fluxes are only transported along the gap in the poloidal direction. For the beamed, high energy component of the emission, this approximation is probably valid. However, at lower photon energies ($\varepsilon \lesssim 1$ keV), the beaming is not as strong, particularly if the synchrotron component dominates this part of the spectrum. Therefore, for lower photon energies where the bulk of the radiation is emitted into large angles, the emission from each zone should be treated as if it were almost isotropic rather than beamed along the field lines. Isotropic treatment of the low energy emission may make possible the transport of soft flux from the inner magnetosphere to regions in the outer magnetosphere where it is needed to produce pairs which would in turn produce more secondary radiation, the higher energy component of which would be beamed along the local magnetic field. The difficulty of implementing a calculation with three-dimensional transport is that it requires convergence of the generated spectra at each iteration over all the interacting zones of the magnetosphere at once rather than the relatively simpler task of convergence among the only $\sim 20$ zones at a time in the present calculation.
Another solution may come from a more realistic calculation of the secondary electron distribution function. Throughout our calculation we have assumed that interactions are entirely “head-on”. This assumption makes the form of the pair-production computations sufficiently simple so that they can be performed semi-analytically. However, if we relax this constraint, we see that the threshold for pair-production varies significantly as a function of incident angle. For photons with an angle $\eta$ between their momentum vectors and lab frame energies $\varepsilon_1$ and $\varepsilon_2$, the threshold condition for pair-production is

$$\varepsilon_1 \varepsilon_2 \geq \frac{2m_e^2}{1 - \cos \eta}.$$  

This implies that larger photon energies are required in the lab frame to produce pairs for smaller values of $\eta$, and since the mean energy of the secondary electrons in the lab frame is $\sqrt{\varepsilon_1 \varepsilon_2}$, smaller values of $\eta$ will result in higher mean energies of the created pairs and harder secondary electron distributions.

For a source of photons at the surface of the star such as a hot spot at the polar cap, the inwardly streaming primary photons will see incident angles which are more nearly head-on ($\eta \sim 180^\circ$), whereas the outwardly streaming primary photons will see smaller values of $\eta$. Thus we expect that the inwardly going secondary electrons will have a softer spectrum than the outward ones. This steeper spectrum for the inward secondary electrons could provide the enough low energy photons to enhance the radiation produced by inverse-Compton scattering by the outward flowing electrons, and thus bootstrap the spectrum to produce the observed Crab-like spectrum in the outward beam.

7. Conclusions

We have described our efforts to refine the standard outer gap picture of high energy emission from pulsar magnetospheres. Our light curve calculations, in our more general outer gap geometry, are able to account for the various pulsar profiles seen for the gamma-ray pulsars observed by the instruments aboard the Compton Observatory. These light curve calculations also point to the source of the observed spectral variation with phase seen for the gamma-ray pulsars: there is a clear mapping of location in the magnetosphere to pulse phase. We have thus attempted to carry through the outer gap spectral calculation as outlined by CHRb and Ho (1989) in our modified geometry, including the refinements of radiation and particle transport and improved inverse-Compton and pair-production calculations. Our efforts have met with limited success. The calculation suffers from too
little low energy photon flux and the converged pulsar spectra we produce are too hard for all phases of the pulse profile. However, our results indicate that a realistic computation of the pulsar emission requires at least an approximate three-dimensional treatment of the radiation transport in the outer magnetosphere. Since photon fluxes themselves provide the relevant opacities, this is a computationally difficult, non-linear problem. However, the spectral differences between the competing radiation processes illustrated in our sample calculations do point the way for a more satisfactory description of the high-quality pulsar data from the *Compton Gamma-Ray Observatory*.

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Fig. 1.— The upper panel is the uniform emission from the outer gap projected onto the sky. The dashed line-of-sight corresponds to a difference in phase between the main peaks of \(\sim 145^\circ\) appropriate for a Crab- or Vela-like phase difference. The corresponding light curve is shown in the lower panel.

Fig. 2.— A coarse sampling of emission points in the outer gap. Field lines with different azimuthal angles around the polar cap are followed from the null charge line to the light cylinder in order to determine the origin of emission as a function of pulse phase.

Fig. 3.— An example of the division of the outer gap along a field line into smaller sub-zones.

Fig. 4.— Photon optical depth for the gap sub-zone nearest the null charge surface, the sub-zone in the middle of the gap, and the sub-zone nearest the light cylinder (clockwise from upper left). The solid lines are the optical depths seen by the outward traveling photons, and the dashed lines are the optical depths seen by the inward traveling photons.

Fig. 5.— Photon acceptance angles between sub-zones along an outer gap field line. Darker pixels indicate a larger acceptance angles. The gap sub-zones are numbered starting from the innermost sub-zone at the null-charge line. The vertical axis labels the sub-zone from which the locally generated radiation originates. The horizontal axis labels the sub-zone into which the photons are transported.

Fig. 6.— The fraction of energy lost by particles flowing along the outer gap as they traverse a single sub-zone. The vertical axis is the fraction of energy lost, the horizontal axis is the original electron energy. The darkness of the pixels represent the multiplicities in each bin.

Fig. 7.— The spectra from the self-consistent outer gap calculation for the initial iteration. Gap points 2, 7 and 19 correspond to inner, middle and outer gap sub-zones, respectively (cf. Figure 3).

Fig. 8.— Components of the outer gap spectral calculation for the initial iteration. The dashed line is the synchrotron component, the dotted line is the primary radiation (curvature + inverse-Compton by the primary electrons) and the dash-dotted line is the inverse-Compton component from the secondary electrons. In the upper panel, the spectra from a gap sub-zone near the null-surface are plotted; and in the lower panel, the spectra from a gap sub-zone near the light cylinder are shown.
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