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Two-Pole Caustic Model for High-Energy Lightcurves of Pulsars

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ABSTRACT

We present a new model of high-energy lightcurves from rotation powered pulsars. The key ingredient of the model is the gap region (i.e. the region where particle acceleration is taking place and high-energy photons originate) which satisfies the following assumptions: i) the gap region extends from each polar cap to the light cylinder; ii) the gap is thin and confined to the surface of last open magnetic-field lines; iii) photon emissivity is uniform within the gap region. The model lightcurves are dominated by strong peaks (either double or single) of caustic origin. Unlike in other pulsar models with caustic effects, the double peaks arise due to crossing two caustics, each of which is associated with a different magnetic pole. The generic features of the lightcurves are consistent with the observed characteristics of pulsar lightcurves: 1) the most natural (in terms of probability) shape consists of two peaks (separated by 0.4 to 0.5 in phase for large viewing angles); 2) the peaks posess well developed wings; 3) there is a bridge (inter-peak) emission component; 4) there is a non-vanishing off-pulse emission level; 5) the radio pulse occurs before the leading high-energy peak. The model is well suited for four gamma-ray pulsars - Crab, Vela, Geminga and B1951+32 - with double-peak lightcurves exhibiting the peak separation of 0.4 to 0.5 in phase. Hereby, we apply the model to the Vela pulsar. Moreover, we indicate the limitation of the model in accurate reproducing of the lightcurves

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with single pulses and narrowly separated (about 0.2 in phase) pulse peaks. We also discuss the optical polarization properties for the Crab pulsar in the context of the two-pole caustic model.

Subject headings: pulsars: high-energy radiation, lightcurves

1. Introduction

The striking feature of the lightcurves[2] of known gamma-ray pulsars are relatively long duty cycles as well as phase shifts in comparison to the radio pulses (Thompson et al. 1999, Thompson 2001, Kanbach 2002). The lightcurve shapes fall into three categories. The three brightest gamma-ray pulsars - the Crab pulsar, Vela and Geminga, along with B1951+32 exhibit two well defined, sharp peaks separated in phase by $0.4 - 0.5$, and connected by the interpeak bridge of a considerable level. B1706-44 and B1055-52 show two peaks separated by about 0.2 in phase, whereas B1509-58 exhibits a broad single pulse. Similar properties are present in the X-ray domain of the high-energy emission. Moreover, in the case of the Crab pulsar its optical pulsed emission is usually considered jointly with the high-energy emission: the phase-averaged spectra in gamma and X-rays connect smoothly to optical, and the pulses have similar shapes and phases. This suggests that gammas, X-rays and optical light may come from the same regions.

These properties, along with the spectral properties which are not the subject of this paper, prompted substantial refinements of the physical models of pulsar high-energy activity, both outer-gap models (Cheng et al. 1986, Romani & Yadigaroglu 1995, Zhang & Cheng 1997) as well as polar-cap models (Sturrock 1971; Ruderman & Sutherland 1975; Daugherty & Harding 1982, Sturner et al. 1995), (see Rudak, Dyks & Bulik 2002 for recent critical review). Despite reiterated arguments in favour of polar-gap models (e.g. Baring 2001) and outer-gap models (e.g. Yadigaroglu & Romani 1995), both classes of models still suffer from serious problems. According to the polar cap model, the characteristic double-peak lightcurve forms when the line of sight intersects the polar-cap beam where the highest-energy emission originates: upon entering the beam a leading peak is produced, followed by a bridge emission due to the inner parts of the beam, when the line of sight exits the beam the trailing peak forms. Because of long duty cycles in the high-energy domain on one hand, and narrow opening angles for gamma-ray emission on the other hand, polar cap models have to rely on nearly aligned rotators, where inclination (the angle α) of the magnetic axis

[2]We use the term 'lightcurves' for averaged pulse profiles.

(the magnetic moment $\vec{\mu}$) to the spin axis (the angular velocity $\vec{\Omega}$) is comparable to the angular extent of the polar cap (Daugherty & Harding 1994).

The outer-gap model, on the contrary, prefers highly inclined rotators (Chiang & Romani 1992; Romani & Yadigaroglu 1995; Cheng et al. 2000). However, the model is unable (without additional postulates) to account for the presence of outer wings in the double-peak lightcurves. More importantly, the model in its present form (e.g. Zhang & Cheng 2002) is unable to account for a substantial level of the off-pulse emission in the Crab pulsar. Also on theoretical grounds the existence of outer gaps in the present-day 'vacuum' approach (i.e. with the gap extending between the null surface and the light cylinder) has been questioned. The outer gap remains anchored to the conventional null surface, provided that no current is injected at the boundaries of the accelerator (no pairs are created); otherwise the gap extention becomes very sensitive to the details of pair creation (Hirotani & Shibata 2001, Hirotani et al. 2003).

These problems motivated us to propose a new picture of the origin of high-energy radiation within the pulsar magnetospheres - in regions confined to the surface of last open magnetic field lines (similarly to thin outer-gap accelerators) but extending between the polar cap and the light cylinder. The most important consequence of such extended accelerators, as far as the lightcurves are concerned, is a caustic nature of the high-energy peaks: special relativity effects (aberration of photon emission directions and time of flight delays due to the finite speed of light c) cause that photons emitted at different altitudes within some regions of the magnetosphere are piled up at the same phase of a pulse (Morini 1983; Romani & Yadigaroglu 1995).

The term 'high-energy radiation' used throughout the paper refers to nonthermal radiation in the energy domain of gamma-rays and hard X-rays (i.e. above several keV). The soft X-ray radiation ($0.1 \lesssim E \lesssim 1$ keV) is not included into our considerations because it is heavily affected by thermal emission from the neutron star surface in some objects, like Geminga which exhibits a complex pattern of soft X-ray pulses (e.g. fig.4 in Jackson et al. 2002). For reasons mentioned at the beginning of this section, in the case of the Crab pulsar our definition includes also the optical band.

The paper is arranged in the following way: In section 2 we introduce the two-pole caustic model for the high-energy lightcurves of pulsars and present the results of numerical calculations. Section 3 contains discussion of the generic features of the model as well as comparison with the properties of other models.

2. The two-pole caustic model

Special relativity (SR) effects which affect pulsar lightcurves include the aberration of photon emission directions and the time of flight delays caused by the finite speed of light c. Morini (1983) was the first to prove that these effects were able to produce prominent peaks in pulsar lightcurves. He obtained the peaks of caustic origin in his version of the polar cap model, which included photon emission from high altitudes, where the SR effects are important. Unlike in the case of the Morini's model, in the standard polar cap model the strongest gamma-ray emission takes place very close to the star surface, where the caustic effects are not important and, therefore, pulsar lightcurves are mostly determined by the altitudinal extent of the accelerator (polar gap) and by the emissivity profile along the magnetic field lines (eg. Daugherty & Harding 1996; Dyks & Rudak 2000).

In the recent version of the outer gap model (Chiang & Romani 1992; Romani & Yadigaroglu 1995; Yadigaroglu 1997; Cheng et al. 2000) the peaks in the lightcurves are purely due to the caustic effects – the fact first emphasized by Romani & Yadigaroglu (1995). However, the altitudinal extent of accelerator (limited by the position of the inner boundary of the outer gap) is crucial in limiting the possible shapes of lightcurves within this model. Interestingly, Yadigaroglu (1997) also considered photon emission along the entire length of all last open magnetic field lines, relaxing thus the outer-gap extent limit (see the bottom panel in Fig. 3.1 of his thesis). However, he didn't pursue this possibility in any further details.

Hereby we propose that the observed high-energy emission from known gamma-ray pulsars originates from the regions considered already by Yadigaroglu (1997). Let us assume that the gap region (the region where particle acceleration is taking place as well as high-energy photons originate) posesses the following properties:
- the gap region extends from the polar cap to the light cylinder,
- the gap is thin and confined to the surface of last open magnetic-field lines,
- photon emissivity is uniform within the gap region.

Fig.1 shows schematically the location and the extension of the proposed gap (for the sake of comparison the location of the outer gap is shown as well). The resulting lightcurves are dominated by strong peaks (either double or single) of caustic origin.

In the outer-gap model, the inner boundary of the gap is located at an intersection of the null-charge surface with the last closed field lines. Its radial distance $r_{\rm in}$ is, therefore, a function of azimuthal angle φ, with a minimum value $r_{\rm in,min}$ in the $(\vec{\Omega}, \vec{\mu})$-plane. For highly inclined rotators $r_{\rm in,min}$ becomes a small fraction of the light cylinder radius $r_{\rm lc} = c/\Omega$: $r_{\rm in,min}/r_{\rm lc} \approx [2/(3\tan\alpha)]^2$ (Halpern & Ruderman 1993); for the inclination angle $\alpha = 60^\circ$ the ratio is 0.15. However, for azimuthal directions departing the $(\vec{\Omega}, \vec{\mu})$-plane, the inner

radius $r_{\rm in}$ tends to $r_{\rm lc}$. The radiation region extends out to the light cylinder and the radiation escaping the magnetospheric region comes from particles moving outwards along the magnetic lines.
In our model we assume, however, that the actual gap extends to the polar cap, i.e. $r_{\rm in} \sim r_{\rm ns}$ for all azimuthal angles φ. This assumption is essential for the expected performance of the model since it implies that the observer can detect radiation originating from *both* magnetic hemispheres.

As in the outer-gap model of Chiang & Romani (1992), and Cheng et al. (2000) we assumed that the photon emissivity is uniform everywhere in the proposed gap region. For simplicity, we consider a rigidly rotating static-like magnetic dipole. Departures of the retarded field lines from the static case are of the order of β^2 and they are insignificant since prominent features in modelled lightcurves (peaks) which we discuss below arise due to radiation at radial distances $r < 0.75\, r_{\rm lc}$. Also, rotationally-driven currents can be neglected: longitudinal currents suspected to flow within the open field line region cannot modify $\vec{B}$ by a factor exceeding $\beta^{3/2}$ whereas toroidal currents due to plasma corotation change $\vec{B}$ barely by β^2 ($\vec{\beta}$ is the local corotation velocity in the speed of light units; $\beta = |\vec{\beta}|$).

We considered radiating particles moving from the outer rim of the polar cap toward the light cylinder. The photons were emitted tangentially to local magnetic field lines in the corotation frame, and then they were followed crossing the magnetosphere with no magnetic attenuation. Our treatment of rotational effects in the numerical code used for the calculations is the same as in Yadigaroglu (1997) and in Dyks & Rudak (2002). Specifically, we used the following standard aberration formula to transform the unit vector of photon propagation direction $\hat{\eta}'$ from the corotating frame to its value $\hat{\eta}$ in the inertial observer frame:

$$\hat{\eta} = \frac{\hat{\eta}' + (\gamma + (\gamma - 1)(\vec{\beta}\cdot\hat{\eta}')/\beta^2)\ \vec{\beta}}{\gamma(1 + \vec{\beta}\cdot\hat{\eta}')}, \tag{1}$$

where $\gamma = (1-\beta^2)^{-1/2}$. The above formula results directly from the general Lorentz transformation. By replacing $\hat{\eta}$ and $\hat{\eta}'$ in the formula with $\vec{v}c^{-1}$ and $\vec{v}'c^{-1}$ (respectively), one obtains a general Lorentz transformation for a velocity vector $\vec{v}$.
Photon travel delays were taken into account by adding $\vec{r}\cdot\hat{\eta}/r_{\rm lc}$ to the azimuth $\phi_{\rm em}$ of photon emission direction $\hat{\eta}$ ($\vec{r}$ is the radial position of emission point, and $\hat{\eta}$ is the unit vector of photon propagation direction after aberration effect is included). The result, taken with a minus sign, is a phase of detection ϕ:

$$\phi = -\phi_{\rm em} - \vec{r}\cdot\hat{\eta}/r_{\rm lc}. \tag{2}$$

Our numerical code performs a raytracing followed by a numerical integration of the observed pulse profile. All results described below are just due to the dipolar shape of the magnetic field, the aberration effect (eq. 1), as well as the light travel time delays (eq. 2).

The results are presented in Fig.2 in the form of photon mapping onto the $(\zeta_{\rm obs}, \phi)$-plane, with accompanying lightcurves for five viewing angles $\zeta_{\rm obs}$ (the angle between the spin axis and the line of sight). Inclination angle $\alpha = 60°$, and spin period $P = 0.033$ s were assumed for the rotator. For each magnetic pole two caustics form in the $(\zeta_{\rm obs}, \phi)$-plane: 1) the dominant caustic, and 2) the subdominant caustic.
The dominant caustic (easy to identify in the photon mapping) is associated with the trailing part of the emission region with respect to its magnetic pole. The subdominant caustic (much weaker) is associated with the leading part of the emission region. Characteristic features in the lightcurves due to caustic crossing for large values of $\zeta_{\rm obs}$ are marked with capital letters from A to D. The dominant-caustics crossing yields two prominent peaks D and B, in the lightcurve. The peaks consist of photons emitted over a very wide range of altitudes (e.g. for $\alpha \sim \zeta_{\rm obs} \sim 90°$ almost all altitudes between the star surface and the light cylinder contribute to the peaks; see also fig. 2 in Morini 1983). The subdominant-caustics crossing yields the features A and C, which actually contribute to the trailing wings of the peaks D and B, respectively. Features A and C consist of photons emitted very close to the light cylinder (cf. fig. 9 in Cheng et al. 2000). This result is in clear contrast with the results obtained for the conventional outer-gap model (see Fig.3), where the leading peak (A) is due to the subdominant caustic, and the trailing peak (B) is due to the dominant caustic. Unlike in the outer gap model, in our model each of the two prominent peaks in the resulting lightcurve is associated with a different magnetic pole. Therefore, we propose the name "two-pole caustic model".

The position of the last closed magnetic field lines and the magnitude of special relativity effects are governed by the proximity of the light cylinder and, therefore, the radiation pattern as well as the lightcurves shown in Fig. 2 do not depend on the rotation period P but solely on the inclination angle α (with one exception: the size of blank spots corresponding to polar caps does depend on P). Therefore, the two-pole caustic model is relevant for pulsars with any rotation period. We find that noticeable peaks of caustic origin appear in the lightcurves practically for any inclination of magnetic dipole $\alpha \neq 0$ and for any viewing angle $\zeta_{\rm obs} \neq 0$. For small inclinations ($\alpha \lesssim 30°$) the peaks are broader and it is more probable to observe single-peaked lightcurves; such lightcurves form for a wide range of viewing angles for which the coventional outer gap model predicts no emission. In the GLAST era, the detectability of "moderately inclined pulsars" viewed far from the equatorial plane will serve as a clear discriminator between the two-pole caustic model and the traditional outer gap model.

Fig. 4 presents a comparison of a lightcurve calculated within the two-pole caustic model for the Vela pulsar with a lightcurve obtained for this pulsar with EGRET (Kanbach 1999).

The model lightcurve was calculated for electrons distributed evenly along the polar cap rim; the density profile across the rim was assumed to be the Gaussian function $f(\theta_{\rm m})$, symmetrical about $\theta_{\rm m} = \theta_{\rm pc}$, with $\sigma = 0.025\theta_{\rm pc}$ ($\theta_{\rm m}$ is the magnetic colatitude of magnetic field lines' footprints at the star surface, and $\theta_{\rm pc} \approx \sqrt{(}r_{\rm ns}/r_{\rm lc})$ is the magnetic colatitude of the rim). Photon emission was followed up to $r_{\rm max} = 0.95r_{\rm lc}$. The shape of the EGRET lightcurve is very well reproduced by the two-pole caustic model: the leading peak is narrower than the trailing peak, which connects smoothly with the bridge emission; the leading peak seems to present a separate entity – it does not connect smoothly with the bridge, and is followed by a characteristic 'interpulse bump'. These features result generically from the two-pole caustic model, since it predicts that the trailing peak, the bridge emission, and the 'interpulse bump' arise from sampling a single, continuous radiation pattern from one magnetic pole (cf. Fig. 2a). The leading peak and the offpulse emission are produced by sampling an emission pattern from the opposite pole. The 'interpulse bump' predicted by the two-pole caustic model is not observed in the Crab pulsar. This might be caused by a decline in the photon emissivity above $r \sim 0.5r_{\rm lc}$.

Single peaked gamma-ray lightcurves as the one observed for B1509−58 (Kuiper et al. 1999) can be reproduced in the two-pole caustic model for small viewing angles (Fig. 2b), however, the predicted phase lag between the gamma-ray and the radio peak ($\sim$ 0.1) is smaller than the one observed for B1509−58 ($\sim$ 0.35). Moreover, double-peak lightcurves with small separation between the peaks in B1706−44 (Thompson et al. 1996), and B1055−52 (Thompson et al. 1999) cannot be interpreted in the same way as the lightcurves with wide separation of the peaks.

These difficulties forced Chiang & Romani (1992) (and probably Yadigaroglu 1997) to abandon the geometry of the two-pole caustic model (R. W. Romani, private communication). We agree with R. W. Romani that these particular lightcurves should be interpreted in terms of the outer gap caustics A and B (Figs. 2 and 3). This interpretation can be accommodated by the two-pole caustic model only when the outer gap part of the lightcurves (between A and B in Fig. 2) dominates over the leading peak formed by the trailing caustic D. As can be noticed in Fig. 2, the intensity of the outer gap part of lightcurves (between A and B) increases with respect to the intensity of the peak D, as the viewing angle $\zeta_{\rm obs}$ approaches the value for which the line of sight barely skims the outer gap part of the radiation pattern. For some viewing gometries the intensity of the outer gap part (A–B) may exceed by a few times the intensity of the peak D. Fig. 5 shows an example of such a lightcurve. Given the low intensity and large width of the peak D, it may stay unresolved in the low statistics data of B1509−58, B1706−44, and B1055−52.

Table 1 summarizes major similarities and differences between our model and other models. For these purposes we choose the model of Morini 1983 (it was the first model where caustic effects were noticed) and the model of Smith et al. 1988, along with the polar-cap model and the outer-gap model.

3. Discussion

We introduced a two-pole caustic model for the high-energy lightcurves of pulsars (for the Crab pulsar in particular). The effects of aberration and light travel delays, as well as the geometry of the last closed magnetic field lines are essential for forming the lightcurves of a caustic nature. The generic features in the lightcurves provided by the two-pole caustic model are consistent with the observed characteristics of pulsar lightcurves:
1. the most natural (in terms of probability) shape consists of two peaks (separated by 0.4 to 0.5 in phase for large viewing angles),
2. the peaks posess well developed wings,
3. there is a bridge (inter-peak) emission component,
4. there is a non-vanishing off-pulse emission level,
5. the radio pulse (or pulse precursor, in the case of Crab)[3] comes ahead of the leading peak (by $\sim$ 0.1 in phase for large viewing angles).

Features 1., 3., and 5. are not a unique property of the two-pole caustic model, they can be easily obtained within the outer-gap model (compare the lightcurves in Figs.2 and 3). Feature 2. may in principle be obtained within the outer-gap model, but no consensus exists among the proponents of that model on the actual physical reason behind this feature (Yadigaroglu 1997, Cheng, Ruderman & Zhang 2000). In our model the trailing wings are formed by the subdominant caustics (A) and (C) which often blend with peaks (D) and (B), respectively (the effect of blending is not shown in Fig. 2 since the calculation were truncated at $0.75 r_{\rm lc}$.) Feature 4., however, may play a decisive role in showing the advantage of the two-pole caustic model over the outer-gap model: this particular feature of our model may explain the presence of the significant X-ray flux from the Crab pulsar at pulse minimum discovered by Tennant et al. (2001). It has not been demonstrated so far how such a feature could be obtained within the outer-gap model; in particular, it is absent in the X-ray pulse profile calculated for the Crab pulsar in the recent model of Zhang & Cheng 2002.

An interesting property of the double-peak lightcurve, inherent to the two-pole caustic

[3]Following the traditional approach (e.g. Yadigaroglu 1997) we attribute the single radio pulse (or the precursor in the case of Crab) to emission associated with the magnetic poles; that determines phase zero for high-energy lightcurves.

model, emerges for viewing angles $\zeta_{\rm obs}$ close to 90°: the trailing peak (together with its wings) assumes the shape which is roughly similar (in the sense of translations in the rotation-phase ϕ space) to the shape of the leading peak and its wings (cf. Fig.2). Such effect is not possible in the case of the outer-gap model (cf. Fig.3), nor it is possible in the polar cap model (see Woźna et al. 2002); these two models lead to approximate 'mirror'-symmetry in the double-peak lightcurves. In principle then, this property might also be used to discriminate between the two-pole caustic model and other models.

An important testing-ground for any models will be polarization properties of the high-energy radiation. For the time being, good-quality polarization information is available only for optical light from Crab (Smith et al. 1988). An argument in favor of the caustic origin of the optical peaks of the Crab pulsar is that the degree of polarization drops to minimum values at the phases of both peaks (cf. Fig. 4c of Smith et al. 1988). Such a drop is justified by virtue of the caustic nature of the peaks: it results from a pile-up of polarized radiation with different polarization angles.

Smith et al. (1988) emphasize, that the behaviour of the polarization as a function of rotation-phase for Crab is strikingly similar for both peaks, i.e. the polarization behaviour at the phase of the leading peak repeats at the trailing peak. The outer gap model is able to reproduce this feature, even though each of the two peaks arises from a very different type of caustic in this model: the leading peak is due to the caustic formed close to the light cylinder at the *leading* part of the emission region, whereas the trailing peak is due to the caustic formed within the *trailing* part. Romani & Yadigaroglu (1995) consider the ability to reproduce the double sweep in the polarization position angle to be one of major successes of the outer-gap model. In the two-pole caustic model, the two peaks arise due to crossing the same type of caustic - the dominant caustic associated with the trailing part of the emission region (cf. section 2). We suspect, therefore, that such a double sweep should even more naturally be produced by the two-pole caustic model. A comprehensive treatment of the polarization properties of high-energy radiation in the two-pole caustic model will be the subject in our future work.

We emphasize that the characteristic form of the high-energy lightcurves of pulsars (the double-peak structure with bridge emission in high-energy, preceded by the peak in radio) is an inherent property of a rotating source with a magnetic dipole, with roughly uniform high-energy emissivity along the last open field lines. Two recently proposed models may provide physical grounds for the geometry of the two-pole caustic model: the slot-gap model of Arons & Scharlemann (1979), in the modern version of Muslimov & Harding (2003); and the model of Hirotani et al. (2003) of an outer gap extended on either side of the null surface due to the currents. When a realistic physical model for the extended gaps becomes available, calculations of spectral characteristics within our model will be possible.

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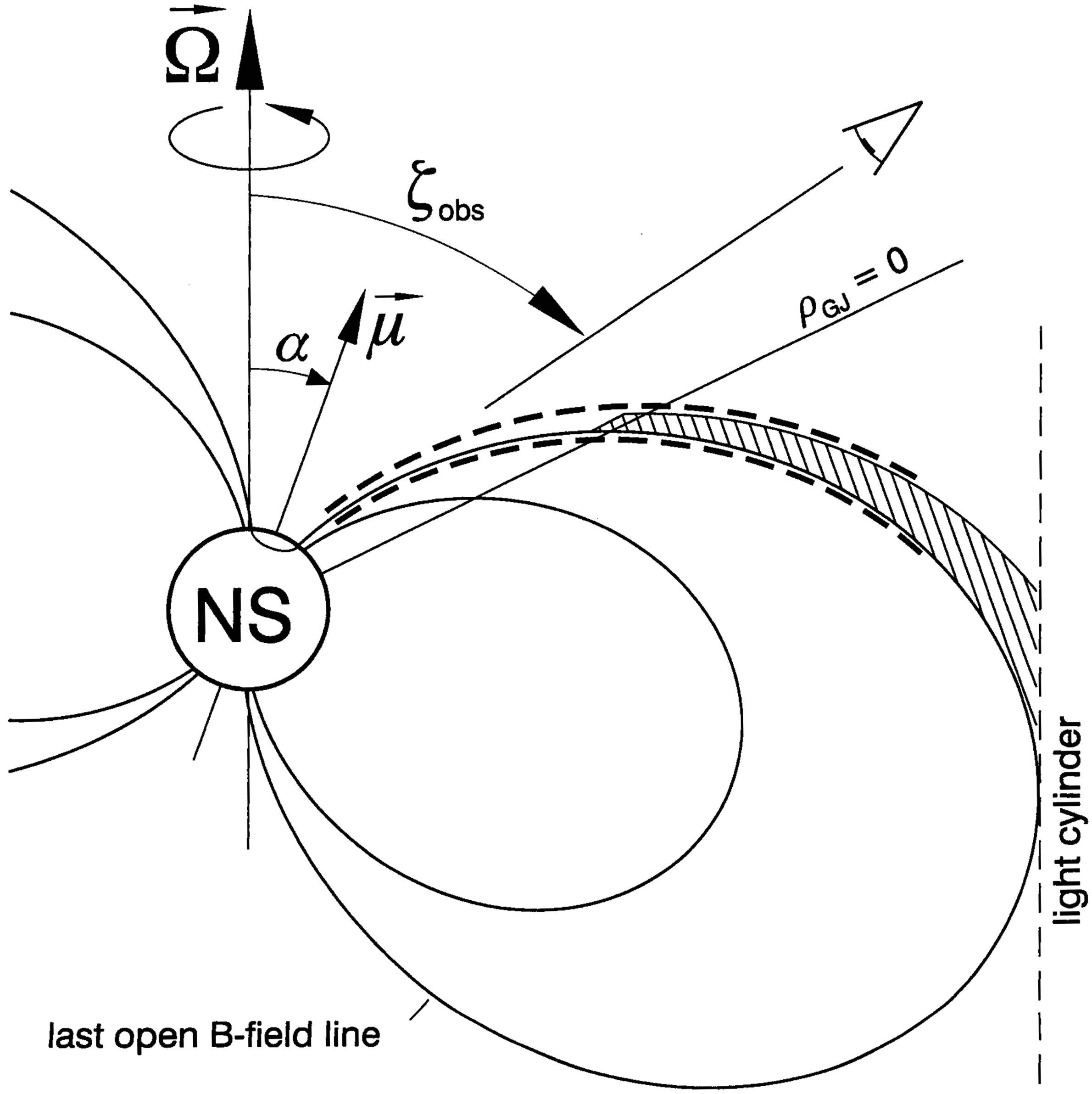

Fig. 1.— Illustration of the two-pole caustic model. The radiating region (within the dashed lines) is confined to the surface of the last closed field lines, and it extends from the polar cap to the light cylinder. For comparison, the conventional outer gap region is shown (shaded area), extending from the surface of the null space-charge ($\rho_{\rm GJ} = 0$, where $\rho_{\rm GJ} \approx -\vec{\Omega} \cdot \vec{B}(2\pi c)^{-1}$ is the Goldreich-Julian charge density) to the light cylinder.

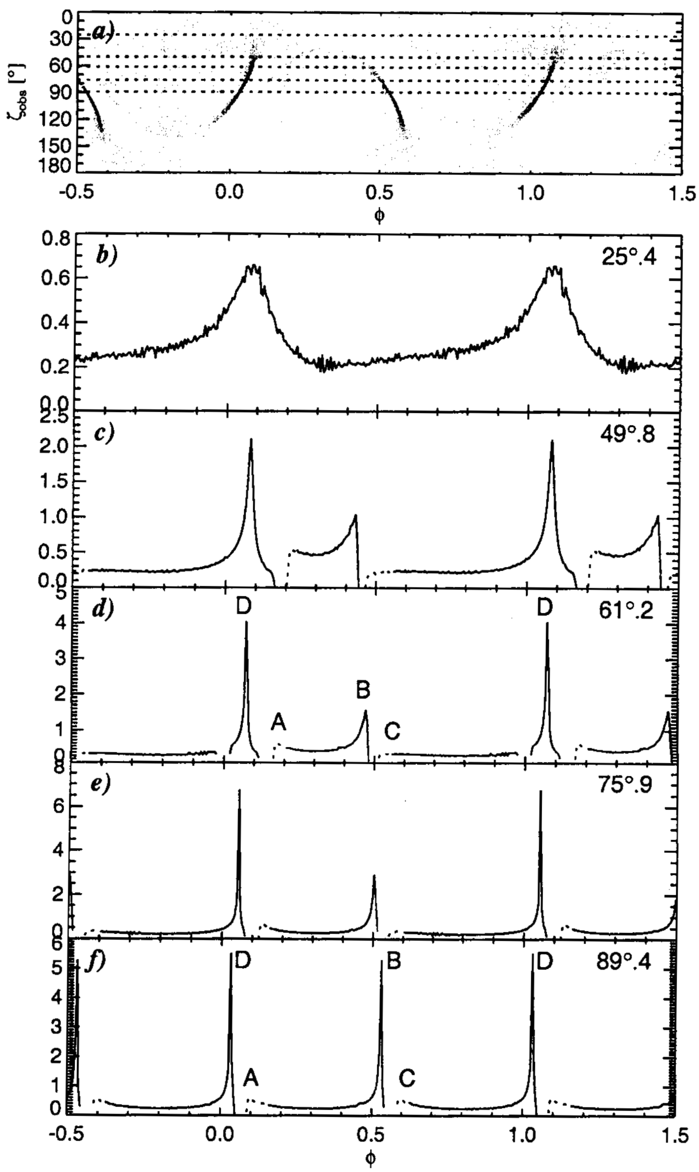

Fig. 2.— Two-pole caustic model results: Panel a): Photon mapping in the $(\zeta_{\rm obs}, \phi)$-plane for the inclination angle $\alpha = 60°$. Notice the location of the polar caps (the white spots; in this particular case their size corresponds to the rotation period $P = 0.033$ s) as well as two dominant caustics formed in the trailing parts of the magnetosphere (with respect to two magnetic poles). Panels b) - f) show the lightcurves for five viewing angles $\zeta_{\rm obs}$ given in the upper-right corners. Photon numbers are in arbitrary units. Within the narrow phase intervals at A and C the lightcurves are drawn with dotted line in order to indicate lower accuracy there due to the proximity of the light cylinder.

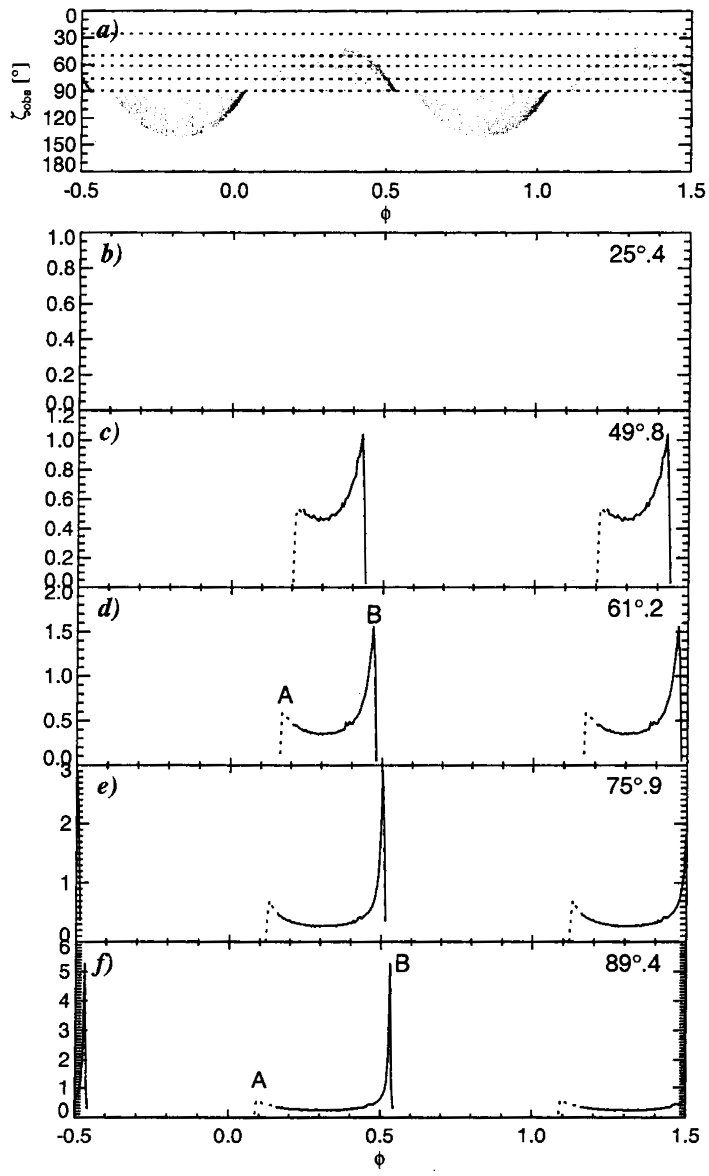

Fig. 3.— The "outer-gap" part of the model from Fig.2: i.e. only those photons are shown which originate within the conventional outer gap region (shaded area in Fig.1), all other photons have been removed. The ordinates in panels b)-f) were rescaled in order to enlarge the double-peak structure consisting now of A and B only.

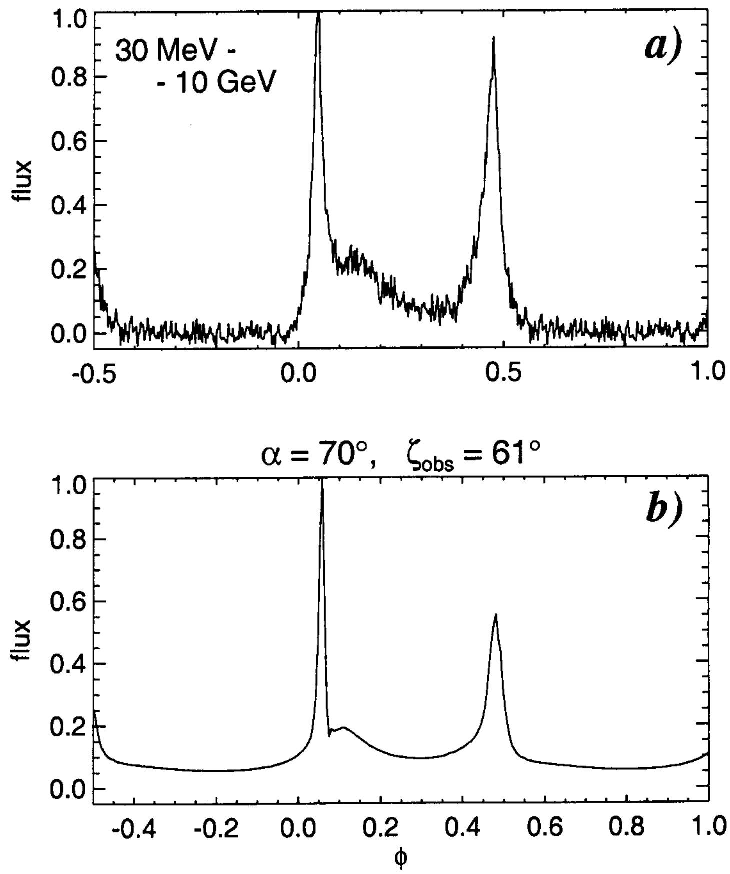

Fig. 4.— Comparison of the lightcurve predicted by the two-pole caustic model (panel b) with the gamma-ray lightcurve of the Vela pulsar obtained with EGRET (Kanbach 1999) (panel a). The model lightcurve was calculated for $\alpha = 70°$ and $\zeta_{\rm obs} = 61°$. The flux on the vertical axis is in arbitrary units.

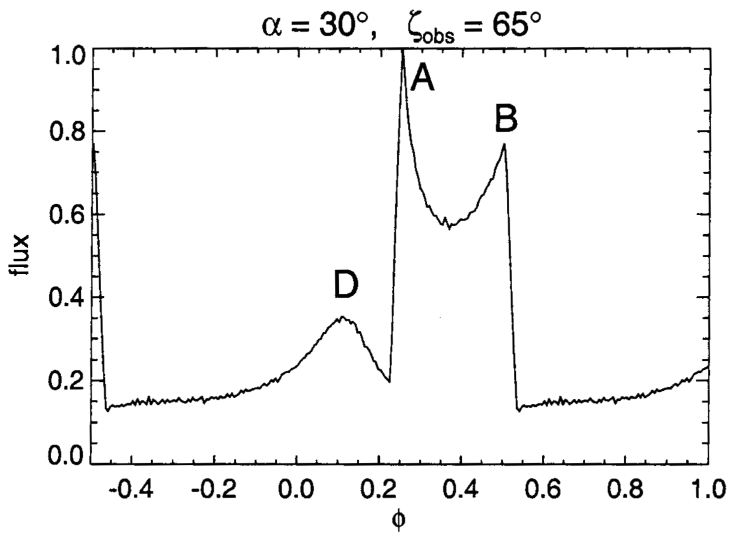

Fig. 5.— An example of a two-pole caustic model lightcurve dominated by the outer gap part of radiation pattern (between A and B). The lightcurve was calculated for $\alpha = 30^\circ$ and $\zeta_{\rm obs} = 65^\circ$.

Table 1: Comparison of models

Characteristics of the model	polar cap	Morini 1983	Smith et al. 1988	outer gap	two – pole caustic
caustic origin of the peaks	–	± (2nd peak)	–	+	+
each peak in the double – peak lightcurve is associated with a different magnetic pole	–	–	+	–	+
photons emitted along the entire length of the magnetic field lines	+	+	–	–	+
(the acceleration region is extended)	–	–	–	+	+