TWO-POLE CAUSTIC MODEL FOR HIGH-ENERGY LIGHT CURVES OF PULSARS

J. Dyks
Laboratory for High-Energy Astrophysics, NASA/GSFC, Greenbelt, MD 20771;
jinx@milkyway.gsfc.nasa.gov

AND

B. Rudak
Nicolaus Copernicus Astronomical Center, Rabiańska 8, 87-100 Toruń, Poland;
bronek@camk.edu.pl

Received 2003 February 28; accepted 2003 August 12

ABSTRACT

We present a new model of high-energy light curves 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) that satisfies the following assumptions: (1) the gap region extends from each polar cap to the light cylinder; (2) the gap is thin and confined to the surface of last open magnetic-field lines; (3) photon emissivity is uniform within the gap region. The model light curves are dominated by strong peaks (either double or single) of caustic origin. Unlike other pulsar models with caustic effects, the double peaks arise from a crossing two caustics, each of which is associated with a different magnetic pole. The generic features of the light curves are consistent with the observed characteristics of pulsar light curves: (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 possess well-developed wings; (3) there is a bridge (interpeak) emission component; (4) there is a nonvanishing 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 light curves. More importantly, the model in its present form (Zhang & Cheng 2002) is unable to account for the presence of outer wings in the double-peak light curves exhibiting the peak separation of 0.4 to 0.5 in phase. Here we apply the model to the Vela pulsar. Moreover, we indicate the limitation of the model in accurate reproducing of the light curves 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: gamma rays: theory — pulsars: general — stars: neutron

1. INTRODUCTION

The striking feature of the light curves of known gamma-ray pulsars is the relatively long duty cycles as well as phase shifts in comparison to the radio pulses (Thompson et al. 1999; Thompson 2001; Kanbach 2002). The light curve 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 pulse 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 gamma-rays, X-rays, and optical light may come from the same regions.

These properties, along with the spectral properties that are not the subject of this paper, prompted substantial refinements of the physical models of pulsar high-energy activity, both outer gap models (Cheng, Ho, & Ruderman 1986; Romani & Yadigaroglu 1995; Zhang & Cheng 1997) as well as polar cap models (Sturrock 1971; Ruderman & Sutherland 1975; Daugherty & Harding 1982; Sturmer, Dermer, & Michel 1995; see Rudak, Dyks, & Bulik 2002 for recent critical review). Despite reiterated arguments in favor of outer gap models (Baring 2001) and outer gap models (Yadigaroglu & Romani 1995), both classes of models still suffer from serious problems. According to the polar cap model, the characteristic double-peak light curve 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 $\alpha$) of the magnetic axis (the magnetic moment $\mu$) to the spin axis ($\Omega$) 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, Ruderman, & Zhang 2000). However, the model is unable (without additional postulates) to account for the presence of outer wings in the double-peak light curves. More importantly, the model in its present form (Zhang & Cheng 2002) is unable to account for a substantial level of the off-pulse emission in the Crab pulsar. In addition, 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 extension becomes very sensitive to the details of pair creation (Hirotani & Shibata 2001; Hirotani, Harding, & Shibata 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 light curves 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 photons emitted at different altitudes within some regions of the magnetosphere to be 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 in our considerations because it is heavily affected by thermal emission from the neutron star surface in some objects, such as Geminga, which exhibits a complex pattern of soft X-ray pulses (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 also includes the optical band.

The paper is arranged in the following way: in § 2, we introduce the two-pole caustic model for the high-energy light curves 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 that affect pulsar light curves 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 light curves. 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 light curves are mostly determined by the altitudinal extent of the accelerator (polar gap) and by the emissivity profile along the magnetic field lines (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 light curves 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 light curves within this model. Interestingly, Yadigaroglu (1997) also considered photon emission along the entire length of all last open magnetic field lines, thus relaxing the outer gap extent limit (see Yadigaroglu 1997; Fig. 3.1, bottom panel). However, he did not pursue this possibility in any further detail.

Here we propose that the observed high-energy emission from known gamma-ray pulsars originates from the regions already considered by Yadigaroglu (1997). Let us assume that the gap region (the region where particle acceleration is taking place as well as where high-energy photons originate) possesses 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, and photon emissivity is uniform within the gap region. Figure 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 light curves 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 \( r_{in} \) is, therefore, a function of azimuthal angle \( \varphi \), with a minimum value \( r_{in, min} \) in the \((\Omega, \mu)\) plane. For highly inclined rotators, \( r_{in, min} \) becomes a small fraction of the light cylinder radius \( r_{lc} = c/\Omega; r_{in, min}/r_{lc} \approx [2/(3 \tan \alpha)]^2 \) (Halpern & Ruderman 1993); for the inclination angle \( \alpha = 60^\circ \), the ratio is 0.15. However, for azimuthal directions departing the \((\Omega, \mu)\) plane, the inner radius \( r_{in} \) tends to \( r_{lc} \). The radiation region extends out to the light cylinder and the radiation escaping the magnetospheric region comes from particles moving outward along the magnetic lines. In our model we assume, however, that the actual gap extends to the polar cap, i.e., \( r_{in} \sim r_{mc} \) for all azimuthal angles \( \varphi \). 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 magnetosphere. Departures of the retarded field lines from the static case are of the order of $\beta^2$, and they are insignificant, since prominent features in modeled light curves (peaks) that we discuss below arise because of radiation at radial distances $r < 0.75 \, r_{\text{lc}}$. In addition, rotationally driven currents can be neglected: longitudinal currents suspected to flow within the open field line region cannot modify $B$ by a factor exceeding $\beta^2/2$, whereas toroidal currents due to plasma corotation change $B$ barely by $\beta^2$ ($\beta$ is the local corotation velocity in the speed of light units; $\beta = |\mathbf{\beta}|$).

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 $\mathbf{\eta}$ from the corotating frame to its value $\mathbf{\eta}$ in the inertial observer frame:

$$\mathbf{\eta} = \mathbf{\eta}^\prime + \left(\gamma + (\gamma - 1)(\mathbf{\beta} \cdot \mathbf{\eta}^\prime)/\beta^2\right) \mathbf{\beta}/\gamma(1 + \mathbf{\beta} \cdot \mathbf{\eta}^\prime),$$

where $\gamma = (1 - \beta^2)^{-1/2}$. The above formula results directly from the general Lorentz transformation. By replacing $\mathbf{\eta}$ and $\mathbf{\eta}^\prime$ in the formula with $v \mathbf{c}^{-1}$ and $v \mathbf{c}^{-1}$ (respectively), one obtains a general Lorentz transformation for a velocity vector $v$. Photon travel delays were taken into account by adding $r \cdot \mathbf{\eta}/r_{\text{lc}}$ to the azimuth $\phi_{\text{em}}$ of photon emission direction $\mathbf{\eta}$ ($r$ is the radial position of emission point, and $\mathbf{\eta}$ 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 $\phi$:

$$\phi = -\phi_{\text{em}} - r \cdot \mathbf{\eta}/r_{\text{lc}}.$$

Our numerical code performs a ray-tracing 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 Figure 2 in the form of photon mapping onto the $(\zeta_{\text{obs}}, \phi)$ plane, with accompanying light curves for five viewing angles $\zeta_{\text{obs}}$ (the angle between the spin axis and the line of sight). Inclination angle $\alpha = 60^\circ$ and a spin period $P = 0.033$ s were assumed for the rotator. For each magnetic pole, two caustics form in the $(\zeta_{\text{obs}}, \phi)$ 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 light curves due to caustic crossing for large values of $\zeta_{\text{obs}}$ are marked with capital letters from A to D. The dominant-caustics crossing yields two prominent peaks D and B, in the light curve. The peaks consist of photons emitted over a very wide range of altitudes (e.g., for $\alpha \sim \zeta_{\text{obs}} \sim 90^\circ$), 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 light curve 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 light curves shown in Figure 2 do not depend on the rotation period $P$ but solely on the inclination angle $\alpha$ (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 light curves practically for any inclination of magnetic dipole $\alpha \neq 0$ and for any viewing angle $\zeta_{\text{obs}} \neq 0$. For small inclinations ($\alpha \lesssim 30^\circ$), the peaks are broader and it is more probable to observe single-peaked light curves; such light curves form for a wide range of viewing angles for which the conventional 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.

Figure 4 presents a comparison of a light curve calculated within the two-pole caustic model for the Vela pulsar with a light curve obtained for this pulsar with EGRET (Kanbach 1999). The model light curve was calculated for electrons distributed evenly along the polar cap rim; the density profile across the rim was assumed to be the Gaussian function 

$$f(\theta_m) = \frac{1}{\sigma} \exp\left(-\frac{(\theta_m - \theta_{\text{pc}})^2}{2\sigma^2}\right),$$

with $\sigma = 0.025\theta_{\text{pc}}$ ($\theta_{\text{pc}}$ is the magnetic colatitude of magnetic field lines’ footprints at the star surface, and $\theta_{\text{pc}} \approx (r_{\text{ns}}/r_{\text{lc}})^{1/2}$ is the magnetic colatitude of the rim). Photon emission was followed up to $r_{\text{max}} = 0.95r_{\text{lc}}$. The shape of the EGRET light curve 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 off-pulse 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 $r \sim 0.5r_{\text{lc}}$.

Single-peaked gamma-ray light curves 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 light curves 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 light curves 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, 2003, private communication). We agree with Romani that these particular light curves 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 light curves (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 light curves (between A and B) increases with respect to the intensity of the peak D, as the viewing angle \( \zeta_{\text{obs}} \) approaches the value for which the line of sight barely skims the outer gap part of the radiation pattern. For some viewing geometries, the intensity of the outer gap part (A–B) may exceed by a few times the intensity of the peak D. Figure 5 shows an example of such a light curve. Given the low intensity and large width of the peak D, it may stay unresolved in the low-statistics data of \( \text{B1509–58} \), \( \text{B1706–44} \), and \( \text{B1055–52} \).

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 in which 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 light curves 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 light curves of a caustic nature. The generic features in the light curves provided by the two-pole caustic model are consistent with the observed characteristics of pulsar light curves: (1) the most natural (in terms of probability) shape consists of two peaks (separated by 0.4–0.5 in phase for large viewing angles), (2) the peaks possess well-developed wings, (3) there is a bridge (interpeak) emission component, (4) there is a nonvanishing off-pulse emission level, (5) the radio pulse (or pulse precursor, in the case of Crab) 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 light curves 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 et al. 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 was truncated at 0.75\( r_{\text{lc}} \)). 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 light curve, inherent to the two-pole caustic model, emerges for viewing angles \( \zeta_{\text{obs}} \) close to 90°: the trailing peak (together with its wings) assumes the shape that is roughly similar (in the sense of translations in the rotation-phase \( \phi \) space) to the shape of the leading peak and its wings (cf. Fig. 2). Such an 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 Woźnia et al. 2002); these two models lead to approximate “mirror” symmetry in the double-peak light curves. 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

### TABLE 1

| 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 light curve is associated with a different magnetic pole       | –         | –             | –                   | –         | +               |
| Photons emitted along the entire length of the magnetic field lines                         | +         | +             | –                   | –         | +               |
| (The acceleration region is extended)                                                       | –         | –             | –                   | –         | +               |

1. Following the traditional approach (Yadigaroglu 1997), we attribute the single radio pulse (or the precursor in the case of the Crab) to emission associated with the magnetic poles that determines phase zero for high-energy light curves.
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 pileup of polarized radiation with different polarization angles.

Smith et al. (1988) emphasize that the behavior of the polarization as a function of rotation phase for Crab is strikingly similar for both peaks; i.e., the polarization behavior 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 because of crossing the same type of caustic—the dominant caustic associated with the trailing part of the emission region (cf. § 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 light curves 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.

We acknowledge fruitful discussions with A. Harding, K. Hirotani, and A. Muslimov. We thank J. Gil for bringing our attention to the problem of missing wings in the double-peak light curves in the outer gap model and R. W. Romani for pointing out some shortcomings of the two-pole caustic model. Comments by the anonymous referee helped us to clarify the paper significantly. This work was supported by the grant PBZ-KBN-054/P03/2001. Part of the work was performed while J. D. held a National Research Council Research Associateship Award at NASA/GSFC.

REFERENCES

Arons, J., & Scharlemann, E. T. 1979, ApJ, 231, 854
Baring, M. G. 2001, Proc. Tonantzintla Workshop, ed. A. Carramiñana et al. Astrophysics and Space Science Library, Volume 267 (Dordrecht: Kluwer), 167
Cheng, K. S., Ho, C., & Ruderman, M. 1986, ApJ, 300, 590
Cheng, K. S., Ruderman, M. A., & Zhang, L. 2000, ApJ, 537, 964
Chiang, J., & Romani, R. W. 1992, ApJ, 400, 629
Daugherty, J. K., & Harding, A. K. 1982, ApJ, 252, 325
———. 1994, ApJ, 429, 325
———. 1996, ApJ, 458, 278
Dyks, J., & Rudak, B. 2000, MNRAS, 319, 477
———. 2002, A&A, 393, 511
Halpern, J. P., & Ruderman, M. A. 1993, ApJ, 415, 286
Hirotani, K., Harding, A. K., & Shibata, S. 2003, ApJ, 591, 334
Hirotani, K., & Shibata, S. 2001, MNRAS, 325, 1228
Jackson, M. S., Halpern, J. P., Gotthelf, E. V., & Mattox, J. R. 2002, ApJ, 578, 935
Kanbach, G. 1999, Astrophys. Lett. Comm., 38, 17
———. 2002, in Proc. 270 WE-Heraeus Sem., Neutron Stars, Pulsars, and Supernova Remnants, ed. W. Becker, H. J. Völk (New York: AIP), 103
Kuiper, L., et al. 1999, A&A, 351, 119
Morini, M. 1983, MNRAS, 202, 495
Muslimov, A., & Harding, A. K. 2003, ApJ, 588, 430
Romani, R. W., & Yadigaroglu, I.-A. 1995, ApJ, 438, 314
Rudak, B., Dyks, J., & Bulik, T. 2002, in Proc. 270 WE-Heraeus Sem., Neutron Stars, Pulsars, and Supernova Remnants, ed. W. Becker, H. Lesch, & J. Trümper (Garching: MPE Rep. 275), 142
Ruderman, M. A., & Sutherland, P. G. 1975, ApJ, 196, 51
Smith, F. G., et al. 1988, MNRAS, 233, 305
Sturrock, P. A. 1971, ApJ, 164, 529
Tennant, A. P., et al. 2001, ApJ, 554, L173
Thompson, D. J. 2001, in AIP Conf. Proc. 558, High Energy Gamma-Ray Astronomy, ed. F. A. Aharonian & H. J. Völk (New York: AIP), 103
Thompson, D. J., et al. 1996, ApJ, 465, 385
———. 1999, ApJ, 516, 297
Yadigaroglu, I.-A. 1997, Ph.D. thesis, Stanford University
Yadigaroglu, I.-A., & Romani, R. W. 1995, ApJ, 449, 211
Wozniak, A., Dyks, J., Rudak, B., & Bulik, T. 2002, in Proc. XXXVII Moriond Mtg., The Gamma-Ray Universe, ed. A. Goldwurm et al. (Hanoi: The Gioi), 539
Zhang, L., & Cheng, K. S. 1997, ApJ, 487, 370
———. 2002, ApJ, 569, 872