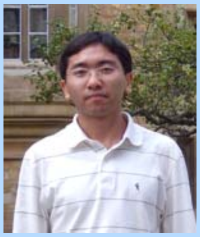

Department of Astrophysical Sciences

Gamma-ray Pulsar Light Curves From Force-Free Magnetospheres

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Abstract: We present the first results of gamma-ray pulsar light curve modeling using the more realistic force-free (FF) pulsar magnetospheric structure. We show that the conventional slot-gap and outer-gap models generally fail to produce the double-peak profile. We propose a novel “annular-gap" model in this field and it is capable of reproducing most features and statistics of Fermi observations of gamma-ray pulsars.

1. Force-free Magnetosphere and Polar Cap

Pulsar magnetosphere is believed to be filled with plasma (Goldreich & Julian, 1969). The plasma is essentially force-free (FF). All previous studies of gamma-ray pulsar light curves adopt a vacuum dipole field configuration, which result in large uncertainties (Bai & Spitkovsky, 2009a). In this work we take the more realistic pulsar magnetosphere model from the 3D time-dependent FF simulations by Spitkovsky (2006). The magnetospheric current and charge density are determined self-consistently from the simulation and the resulting FF field structure differs substantially from vacuum dipole field (Fig. 1). A current sheet is present outside the light cylinder (LC), and the last open field lines (LOFLs) coincide with the strong current layer inside the LC. The shape of the polar cap (where the LOFLs originate) is different between the FF and vacuum dipole field (Fig. 1).

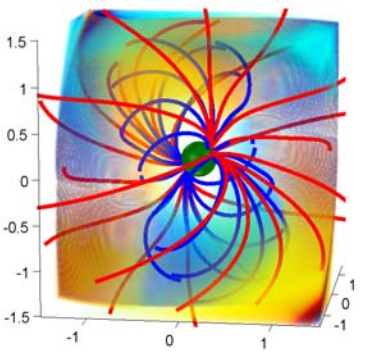
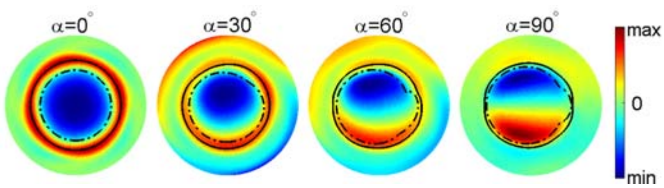


Fig. 1 Left: FF field and current structure for inclination angle $\alpha = 60^\circ$. Blue lines are LOFLs and red lines are open field lines with *a*=0.9 (*a* is the normalized magnetic colatitude relative to the polar cap). Volume filling color and opacity are set by the quantity λ: current per magnetic flux. **Bottom**: polar cap shapes for FF field (solid) and Deutsch field (dash-dotted). Note that the FF polar cap is larger and more circular. Color coded by λ.



2. Conventional Models

We assume constant emissivity along magnetic field lines in the emission zones and have included relativistic effects of aberration and time delay in our light curve calculation. Fig. 2 shows the results for:

1) Two-pole caustic (slot-gap) model (e.g., Dyks et al., 2004): emission zone is assumed to be centered on the LOFLs extending from stellar surface to the LC. Up to 4 peaks can be present due to a larger polar cap.

2) Outer-gap model (OG, e.g., Cheng et al., 2000): emission zone is assumed to be centered on open field lines with *a*=0.9, extending from the null charge surface (NCS) to beyond the LC. Only one prominent peak is present, because a large fraction of field lines does not cross the NCS (see Fig. 3 for details).

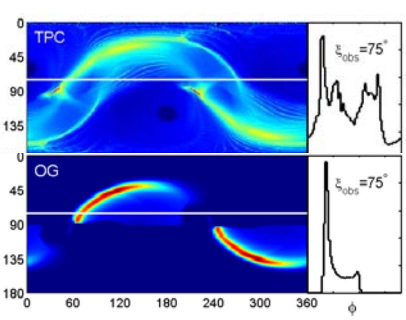


Fig. 2 FF sky map brightness and representative light curve from the two-pole caustic (top) and outer-gap (bottom) models for inclination $\alpha = 60^\circ$. Field lines are traced to 1.0 R_{LC} and 1.2 R_{LC} respectively. Note that the outer-gap sky map is just part of the annular gap sky map (see Fig. 3 and Fig. 4).

3. The Annular Gap Model

We propose a novel annular gap (AG) model for pulsar gamma-ray emission based on the FF field geometry. The emission zone of the AG model is assumed to be centered on the open field lines that lie just inside the LOFLs (*a*=0.9~0.95), extending from the stellar surface to beyond the LC. Fig. 3 illustrates that the AG model is capable of producing double peak light curves by the effect we refer to as “sky map stagnation” (SMS): Emission from the same field line piles up at the same spot of the sky map. This effect is due to the FF field approaches the split monopole field asymptotically. An atlas of light curves is shown in Fig. 4, which demonstrates the robustness of the SMS effect and the AG model.

Fig. 3 FF Sky map of the AG model from the $\alpha = 60^\circ$ rotator. We have chosen *a*=0.9. **a)** and **b)**: Field lines from the north pole, viewed from two directions. **c)**: Line plot of sky map. Line colors correspond to those in a) and b). Color rings in a) and b) are also projected to the sky map. Ring clustering in c) is the SMS. **d)**: Sky map colored by the scalar 4-current (Lorentz invariant, when negative, charge separation is not possible). Grey dots indicate the NCS. Black circle denotes the actual size of the star in the FF simulation, inside which we use GJ charge. Note majority of the field lines do not cross the NCS. **e)** and **f)**: Sky map brightness from the north pole and both poles.

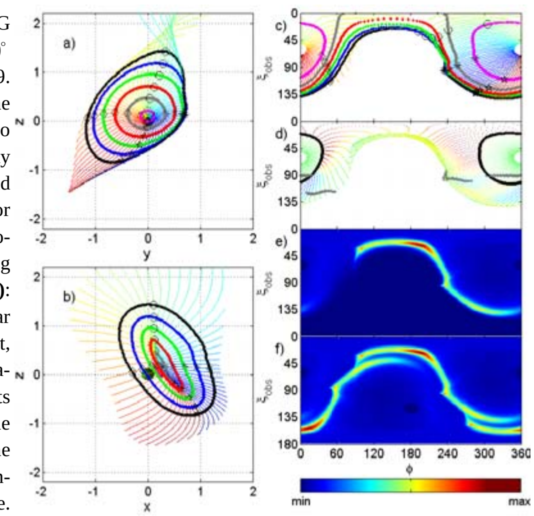
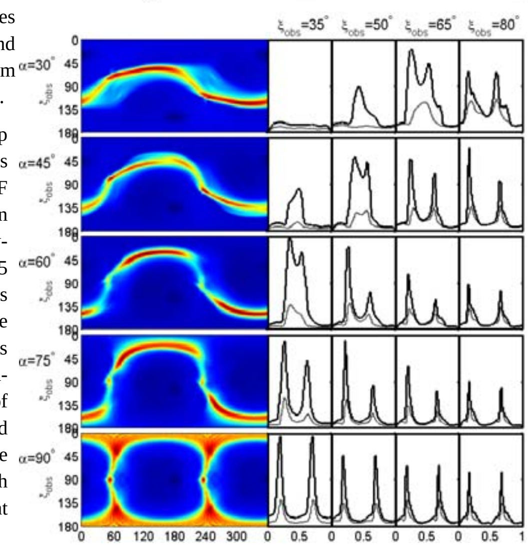


Fig. 4 Atlas of sky map brightness and light curves from the AG model in the FF field, for various inclination angles and observer’s viewing angles. We adopt *a*=0.95 except in the first two rows where *a*=0.9. Field lines are traced to 1.5R_{LC}. Grey curves show contribution from inside 0.9 R_{LC}. Majority of them have widely separated double peaks, others have one peak or two peaks with smaller separation, consistent with Fermi observations.



Conclusions:

1. Gamma-ray pulsar light curves modeled from the vacuum dipole field carry large uncertainties. The more realistic FF field should be used.
2. The two-pole caustic model fails to produce reasonable light curves because the FF polar cap is larger. The outer-gap model can produce only one peak in general as a large fraction of FF field lines do not cross the NCS.
3. The annular-gap model, where emission originates from a thin layer just inside the LOFLs, can produce most features and statistics of gamma-ray pulsar light curves. Its origin is likely to be associated with the current sheet.

For more information see the papers below:

Bai, X.-N. & Spitkovsky, A., 2009a, ApJ, submitted (arxiv:0910.5740)
Bai, X.-N. & Spitkovsky, A., 2009b, ApJ, submitted (arxiv:0910.5741)