Modeling and Likelihood Fitting of Gamma-ray and Radio Millisecond Pulsar Light Curves

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We present results from geometric modeling and likelihood fitting of gamma-ray millisecond pulsars (MSPs). We find that MSP magnetic inclination angles do not follow a random angular distribution and there is evidence for higher altitude radio emission.

Pulsed gamma rays have been detected with the *Fermi* Large Area Telescope (LAT) from more than 20 millisecond pulsars (MSPs), some of which were discovered in radio observations of bright, unassociated LAT sources. We have fit the radio and gamma-ray light curves of 19 LAT-detected MSPs in the context of geometric, outer-magnetospheric emission models assuming the retarded vacuum dipole magnetic field [4] using a Markov chain Monte Carlo (MCMC) maximum likelihood technique. We find that, in many cases, the models are able to reproduce the observed light curves well and provide constraints on the viewing geometries that are in agreement with those from radio polarization measurements. Additionally, for some MSPs we constrain the altitudes of both the gamma-ray and radio emission regions. The best-fit magnetic inclination angles are found to cover a broader range than those of non-recycled gamma-ray pulsars.

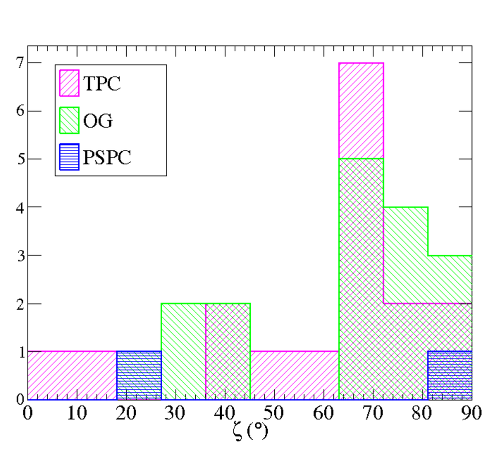
Simulations:

We have simulated MSP light curves using geometric outer gap (OG) [5], slot gap/two-pole caustic (TPC) [6], and pair-starved polar cap (PSPC) [7] gamma ray models with either hollow-cone beam [8] or altitude-limited TPC/OG [9] radio models. We used a resolution of 1° in magnetic inclination angle (α), 1° in viewing angle (ζ), and 5% of the polar cap opening angle in accelerating gap width.

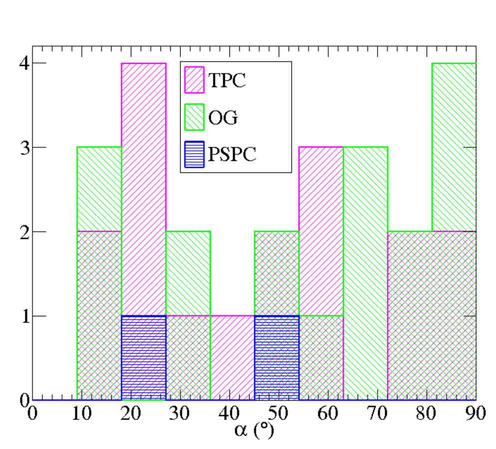
Light Curve Fitting:

We use a MCMC maximum likelihood technique which implements small-world steps [10] and simulated annealing [11] to pick the best-fit parameters.

Best-fit Geometries:



ζ values follow random angular distribution.

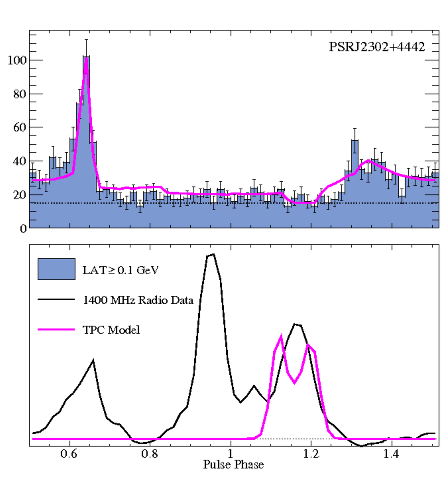


α values favor all angles roughly equally.

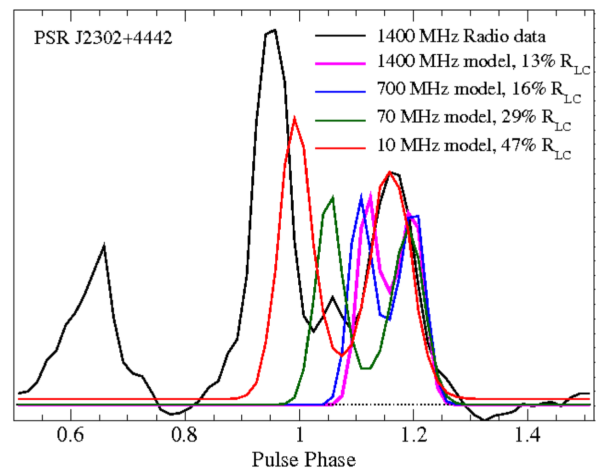
Results:

Of these 19 MSPs, 2 require the PSPC model and 6 have aligned gamma-ray and radio profiles requiring altitude-limited TPC/OG models, where the radio peaks are caustics. Accounting for systematic effects from background estimates, the likelihood significantly prefers one model over another for 9 MSPs. TPC models are more often favored over OG models.

Radio Altitude:

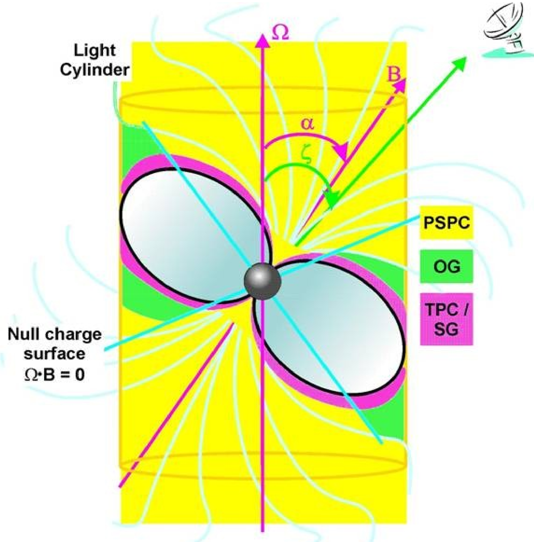


Good gamma-ray model, radio too narrow.



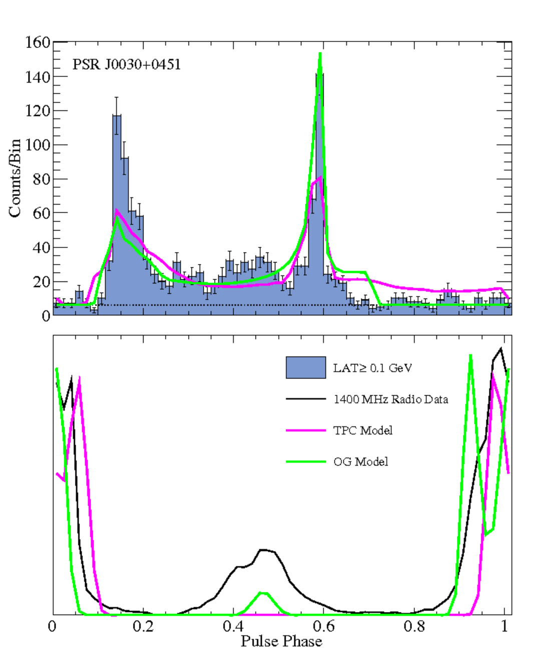
Same geometry but increase cone altitude from formula in [12] by decreasing simulated frequency.

Pulsar Geometry:



TPC and OG models assume emission along last closed field lines, OG only above null charge surface. PSPC assumes emission from full open volume.

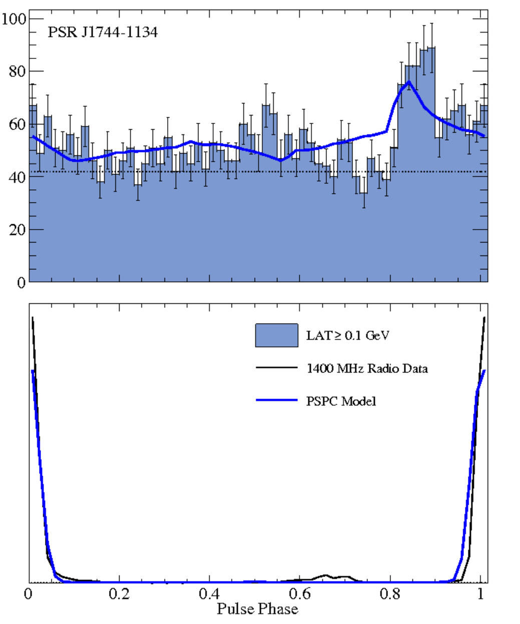
Example Fits:



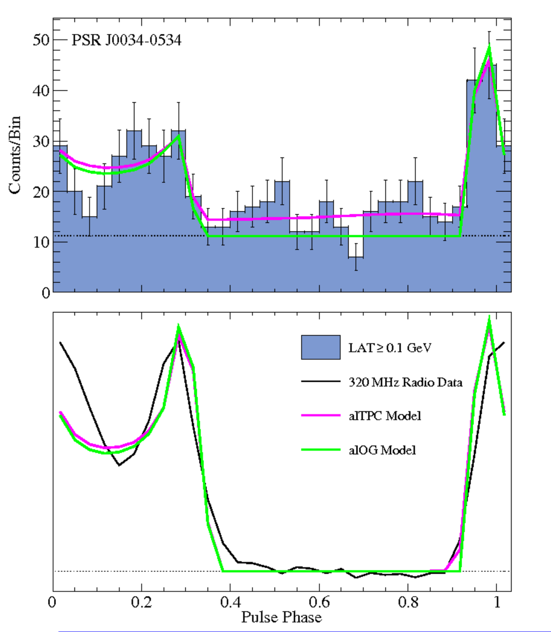
OG: α=81°±9°, ζ=66°+4°-2°
TPC: α=73°±6°, ζ=57°+6°-10°

(Left): Best-fit TPC and OG light curves for PSR J0030+0451, OG model preferred by the likelihood.

PSPC: α=51°+16°-19°, ζ=85°+3°-12°



(Right): Best-fit PSPC light curves for PSR J1744-1134.



alOG: α=12°+32°-12°, ζ=69°+21°-4°
alTPC: α=12°+31°-6°, ζ=69°+7°-4°

(Above): Best-fit altitude-limited TPC and OG light curves for PSR J0034-0534, TPC model preferred by the likelihood.

Conclusions & the Future:

We have placed constraints on the viewing geometries of 19 MSPs detected with the *Fermi* LAT. There is evidence that the MSP radio emission should originate higher in the magnetosphere in some sources. MSP gamma-ray light curves are consistent with outer-magnetospheric emission. We plan to test other magnetic field geometries, fit more MSPs, and explore more radio models.

References:

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