Probing orbital parameters of gamma-ray binaries with TeV light curves

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TeV light curves

- Variability related to the orbital period
- Often double-peak structure

Prokoph et al., ICRC 2019
Maier et al., ICRC 2019
What causes the dip?

- Naively one would expect highest flux at periastron due to the highest energy density of stellar photons
- But that’s where we see the dip!

PSR B1259-63/LS 2883
Gamma-gamma absorption

**LS 5039:** Both location and depth of the minimum can be roughly explained by absorption.

**PSR B1259-63:** Location of the minimum can be explained by absorption but not the depth.
\[ \tau_{\gamma\gamma} = \int_0^l dl \int_0^{4\pi} (1 - \mu) d\Omega \int_{\mu}^{\infty} \frac{2}{\epsilon_{\gamma}(1-\mu)} n_{ph}(\epsilon, \Omega) \sigma_{\gamma\gamma}(\epsilon, \epsilon_{\gamma}, \mu) d\epsilon; \quad \mu = \cos \theta \]

\( e \) – eccentricity
\( i \) – inclination angle
\( \omega \) – longitude of periastron
\( \varphi \) – orbital phase

depends on the distance to the star

\((e, i, \omega, \varphi)\)
Geometry

- Inclination $i$ – the angle between the normal to the orbital plane and direction towards the observer
- Longitude of periastron $\omega$ – the angle between the ascending node and periastron
- Orbital phase $\varphi$ – measured from apastron in the direction of movement
Test case: PSR B1259-63

Orbit:
- $P_{\text{orb}} = 3.4$ years
- Eccentricity = 0.87
- Inclination = 22.2 deg
- Longitude of periastron = 138.7 deg

Pulsar:
- $P = 48$ ms
- $L_{SD} = 8 \times 10^{35}$ erg/s
- $t_c = 3.3 \times 10^5$ years

Star:
- Be star
- $L_{\text{star}} = 2.3 \times 10^{38}$ erg/s
- $T = 27500 – 30000$ K
- $M = 31$ $M_{\odot}$
- $R = 8.1 – 9.7$ $R_{\odot}$
- $D = 2.3$ kpc

Orbital parameters are well determined from observations!

Credits: NASA’s Goddard Space Flight Center/Francis Reddy
Dependence of opacity on parameters

Simplified analytic solution
(look for it in proceedings/forthcoming paper)

Exact numeric solution
Method

- Main assumption: the minimum in the TeV light curve is defined by the highest gamma-gamma absorption.

- For a fixed eccentricity we vary inclination (0°, 90°) and longitude of periastron (0°, 360°) and for each combination of $(i, \omega)$ we calculate the orbital phase at which absorption for a 1 TeV photon would be the highest.

- Gamma-gamma absorption is calculated taking into account only stellar photons (without circumstellar disk) and assuming that gamma-ray emission is produced at the pulsar position.
Test:
PSR B1259-63

- orbital parameters are well determined from observations
Test:
PSR B1259-63

- orbital parameters are well determined from observations

Orbital phase: 154 deg
Time: 2 days before periastron
PSR J2032+4127/ MT91 213

- New member of the class
- Detected in 2017
- Coincident with TeV J2032+413
- Orbital period of 45-50 years
- X-ray dip is not coincident with the gamma-ray dip
- TeV light curve has its minimum about 10-20 days after periastron

VERITAS & MAGIC, 2018
Orbital solutions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right ascension, $\alpha$ (J2000.0)</td>
<td>$20^h32^m13^s119(2)$</td>
<td>$20^h32^m13^s119(2)$</td>
<td>$20^h32^m13^s119(2)$</td>
</tr>
<tr>
<td>Declination, $\delta$ (J2000.0)</td>
<td>$41^\circ 27'24''38(2)$</td>
<td>$41^\circ 27'24''35(2)$</td>
<td>$41^\circ 27'24''34(2)$</td>
</tr>
<tr>
<td>Epoch of frequency, $t_0$ (MJD)</td>
<td>55700.0</td>
<td>55700.0</td>
<td>55700.0</td>
</tr>
<tr>
<td>Frequency, $v_0$ (Hz)</td>
<td>6.980 979(5)</td>
<td>6.980 975(6)</td>
<td>6.980 973(7)</td>
</tr>
<tr>
<td>Frequency time derivative, $\dot{v}_0$ ($10^{-12}$s$^{-2}$)</td>
<td>$-0.5396(5)$</td>
<td>$-0.5538(4)$</td>
<td>$-0.5617(5)$</td>
</tr>
<tr>
<td>Orbital period, $P_b$ (d)</td>
<td>16 000</td>
<td>17 000</td>
<td>17 670</td>
</tr>
<tr>
<td>Epoch of periastron, $T_0$ (MJD)</td>
<td>58053(1)</td>
<td>58069(1)</td>
<td>58068(2)</td>
</tr>
<tr>
<td>Projected semimajor axis, $a$ (light-second)</td>
<td>7138(48)</td>
<td>9022(216)</td>
<td>16335(3737)</td>
</tr>
<tr>
<td>Eccentricity, $e$</td>
<td>0.936(1)</td>
<td>0.961(2)</td>
<td>0.989(5)</td>
</tr>
<tr>
<td>Longitude of periastron, $\omega$ (deg)</td>
<td>52(1)</td>
<td>40(1)</td>
<td>21(5)</td>
</tr>
<tr>
<td>Mass function, $f_m$ ($M_\odot$)</td>
<td>1.5</td>
<td>2.7</td>
<td>15.0</td>
</tr>
<tr>
<td>Glitch epoch, $T_g$ (MJD)</td>
<td>55 810.77</td>
<td>55 810.77</td>
<td>55 810.77</td>
</tr>
<tr>
<td>Frequency, $\Delta v_g$ ($10^{-6}$ Hz)</td>
<td>1.9064(1)</td>
<td>1.9073(1)</td>
<td>1.9076(1)</td>
</tr>
<tr>
<td>Frequency time derivative, $\dot{v}_g$ ($10^{-15}$s$^{-2}$)</td>
<td>$-0.5018(1)$</td>
<td>$-0.545(7)$</td>
<td>$-0.564(6)$</td>
</tr>
<tr>
<td>DM (pc cm$^{-3}$)</td>
<td>114.68(3)</td>
<td>114.67(2)</td>
<td>114.66(2)</td>
</tr>
<tr>
<td>DM time derivative, $DM_1$ (pc cm$^{-3}$yr$^{-1}$)</td>
<td>$-0.02(1)$</td>
<td>$-0.01(1)$</td>
<td>$-0.01(1)$</td>
</tr>
<tr>
<td>rms timing residual, $\sigma_t$ (ms)</td>
<td>0.53</td>
<td>0.44</td>
<td>0.42</td>
</tr>
</tbody>
</table>
PSR J2032+4127: TeV light curve

- Minimum occurs 10-20 days after periastron
- Corresponds to the orbital phase of 216-242 deg for P = 17000 days

VERITAS & MAGIC, 2018
PSR J2032+4127:

e = 0.961 (0.936-0.989)
PSR J2032+4127:

allowed solutions

- Green and red dashed areas correspond to constraints set by optical observations (Ho et al. 2017)
- Strong indication that gamma-gamma absorption is indeed responsible for the dip in the TeV light curve
- TeV light curve (location + depth of the dip) can be successfully used to constrain orbital parameters
- In case of known orbital parameters, connection of the dip to the gamma-gamma absorption can constrain the location of the emitting region
Backup slides
Analytic VS Numeric

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Analytic VS Numeric

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Analytic VS Numeric

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Location of max absorption (for different eccentricity)
Location of max absorption (for different orbital period)