

Gamma-ray Orbital Modulation in Spider Pulsars: Three Discoveries and a Universal Modulated Fraction

MAKSAT SATYBALDIEV ¹, MANUEL LINARES ^{1,2} AND VITTORIA VECCHIOTTI ^{1,3,4}

¹*Department of Physics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*

²*Departament de Física, EEBE, Universitat Politècnica de Catalunya, Av. Eduard Maristany 16, E-08019 Barcelona, Spain*

³*Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 201210, P. R. China*

⁴*INAF Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi, 5, 50125, Florence, Italy*

ABSTRACT

Compact binary millisecond pulsars (also known as spiders) allow us to probe pulsar winds in their innermost regions, between the light cylinder (radius $\sim 10^7$ cm) and the companion star (at $\sim 10^{11}$ cm). Their flux is known to vary along the orbit, from radio to X-rays. During the past decade, gamma-ray orbital modulation (GOM) has been discovered in a handful of spiders, but its origin remains largely unknown. We present the results of a systematic search for GOM among 43 systems, selecting pulsed 0.1-1 GeV photons and using spin and orbital ephemeris from *Fermi*'s Third Pulsar Catalog. We discover GOM from three spiders – PSR J1124-3653, PSR J1946-5403 and PSR J2215+5135 – and confirm four previous detections. In all seven cases so far, the GOM peaks near the pulsar's superior conjunction. The X-ray orbital light curves are usually in anti-phase, peaking when the pulsar is at inferior conjunction, but we find one case where both gamma-rays and X-rays peak around superior conjunction: PSR J1946-5403. We measure the modulated fractions of the GOM and find consistent values for all seven spiders, with an average $22.0 \pm 2.6\%$. Including eclipsing systems seen edge-on, we find no clear dependence of the modulated fraction on the orbital inclination (within $\simeq 45$ – 90°). Our results challenge previous models proposed to explain GOM in spiders, based on inverse Compton and synchrotron emission close to the companion, since these predict a clear dependence with orbital inclination (stronger modulation at high inclinations). We nearly double the number of GOM detections in spiders, showing that it is more common than previously thought.

Keywords: Millisecond pulsars (1062), High energy astrophysics (739), Compact binary stars (283), Gamma-rays (637)

1. INTRODUCTION

Compact binary millisecond pulsars or *spiders* are binary systems consisting of a millisecond pulsar (MSP) and a low-mass companion in compact orbits with periods $P_b \lesssim 1$ d. The arachnid nickname was inspired by the destructive effect of the pulsar wind on the companion star. Spiders are categorized into two subgroups: *redbacks* with companion masses $M_c \sim 0.1M_\odot$ and *black widows*, which have significantly lighter companions $M_c \sim 0.01M_\odot$ (Roberts 2013; Koljonen & Linares 2025).

Spiders represent the evolutionary link between low-mass X-ray binaries (LMXBs) and MSPs. During the LMXB phase, due to angular momentum transfer via accretion, the neutron star is spun up to millisecond periods (Alpar et al. 1982; Bisnovatyi-Kogan & Komberg 1976). The so-called transitional MSPs switch between a disk or underluminous LMXB state and a rotation-powered redback MSP state, and provided key evidence for this evolutionary link (Archibald et al. 2009; Papitto et al. 2013; Bassa et al. 2014). During the transition from the MSP to the LMXB state, the systems brighten across the optical, X-ray and gamma-ray bands, and the pulsed radio emission disappears (Stappers et al. 2013; Patruno et al. 2014; Takata et al. 2014; Stappers et al. 2014). In the LMXB state, the optical and X-ray emission is dominated by the accretion disk, and the X-ray

flux switches between two distinct modes (Linares et al. 2014). The gamma-rays are believed to originate from the inverse Compton emission of the pulsar wind heated disk and synchrotron radiation of pulsar wind particles heated by collisions with the disk (Veledina et al. 2019).

In the MSP state, spiders emit and exhibit orbital modulation across the entire electromagnetic spectrum. In the radio band, we observe millisecond pulsations from the pulsar often occulted during a large fraction of the orbit around the pulsar’s superior conjunction. These occultations (also referred to as “eclipses”) are produced by the scattering of pulsed radio emission from the pulsar by the ablated material from the companion (Fruchter et al. 1988; Thompson et al. 1994; Blanchard et al. 2025). At optical wavelengths, the emission primarily originates from the companion star and varies throughout the orbit due to irradiation from the pulsar wind and ellipsoidal modulation caused by tidal deformation of the star (Breton et al. 2013; Linares et al. 2017; Strader et al. 2019; Turchetta et al. 2023).

The X-ray emission in the MSP state consists of thermal and non-thermal components. In a few cases, thermal emission is detected from the heated polar caps, and can be pulsed (Guillot et al. 2019). The typically dominant non-thermal component is thought to arise from an intrabinary shock (IBS) formed by the interaction between the pulsar and companion winds (Wadiasingh et al. 2017, 2018; van der Merwe et al. 2020). The X-ray orbital light curve exhibits a distinct single- or double-peaked structure, attributed to Doppler-boosted synchrotron emission from particles accelerated in the shock. The shock geometry depends on the relative strengths of the winds: it can wrap around the pulsar if the companion’s wind has more momentum, or around the companion in the opposite case. When the shock is wrapped around the pulsar, the maximum of the X-ray orbital modulation (XOM) is expected near the pulsar’s inferior conjunction, when the beamed IBS emission crosses the line of sight (Wadiasingh et al. 2017, 2018; van der Merwe et al. 2020).

Pulsed gamma-ray emission in neutron stars originates in the current sheet just outside the light cylinder and peaks at GeV energies (Philippov & Kramer 2022; Hakobyan et al. 2023; Smith et al. 2023; Cerutti et al. 2025). The pulse-averaged gamma-ray flux in isolated pulsars is stable within $< 10\%$ (Kerr 2025). Some of the known spider pulsars exhibit eclipses, showing sharp dips in their gamma-ray light curves (Corbet et al. 2022; Clark et al. 2023). In addition, the gamma-ray flux can also be orbitally modulated. Orbital modulation of the soft gamma-ray flux ($\lesssim 1$ GeV) has been reported in

Table 1. List of the spider pulsars with significant gamma-ray orbital modulation (GOM) reported. See text for details.

Name	Type	GOM type	GOM peak	XOM peak	OOM
J1124-3653	BW	Soft, pulsed	SC [1]	IC [2,3]	1 [4]
J1227-4853	RBt	Soft	SC [5]	IC [6,7]	1 [8]
J1946-5403	BW	Soft, pulsed	SC [1]	SC [3]	* [9]
J2039-5617	RB	Soft, pulsed	SC [10,11]	IC [12,13]	2 [8]
J2215+5135	RB	Soft, pulsed	SC [1]	IC [14]	1 [8]
J2241-5236	BW	Soft, pulsed	SC [15]		1 [8]
J2339-0533	RB	Soft, pulsed	SC [16]	IC [17,18]	1 [8]
J1311-3430	BW	Hard, off-pulse	IC [19,20]		1 [8]
J1702.7-5655	RBc	Full	IC [21]		
J1023+0038 **	RBt	Hard	DN [22]	IC [23]	1 [8]

NOTE—RB: redback; RBt: redback and transitional MSP; RBc: redback candidate; BW: black widow; SC: pulsar’s superior conjunction; IC: pulsar’s inferior conjunction; DN: descending node of the pulsar; OOM: number of maxima in the optical orbital modulation - 1 (irradiated light curve) or 2 (ellipsoidal modulation); *: No optical counterpart confirmed for J1946, but see search in [9]; **: for J1023+0038, the GOM corresponds to the disk state, whereas the XOM is observed in the pulsar state.

Systems with GOM discovered in this paper are highlighted in bold face.

References: [1] - this work, [2] - Gentile et al. 2014, [3] - Sim et al. 2024b, [4] - Draghis et al. 2019, [5] - An 2022, [6] - de Martino et al. 2015, [7] - de Martino et al. 2020, [8] - Turchetta et al. 2023, [9] - Braglia et al. 2020, [10] - Ng et al. 2018, [11] - Clark et al. 2021, [12] - Salvetti et al. 2015, [13] - Romani 2015, [14] - Sullivan & Romani 2024, [15] - An et al. 2018, [16] - An et al. 2020, [17] - Romani & Shaw 2011, [18] - Kandel et al. 2019, [19] Xing & Wang 2015, [20] - An et al. 2017, [21] - Corbet et al. 2022, [22] - Xing et al. 2018, [23] - Bogdanov et al. 2011.

four systems: the redbacks PSR J2039-5617 and PSR J2339-5617, the black widow PSR J2241-5236 and the transitional MSP PSR J1227-4853 (see references in Table 1). In the first two systems, the gamma-ray orbital modulation (GOM) was found to be pulsed, i.e., arising from photons corresponding to the peak of the pulse profile. In all four cases, the soft GOM peaks at the pulsar’s superior conjunction. Interestingly, in systems where orbital modulation is observed in both X-ray and gamma-ray bands, the orbital light curves are in anti-phase: the gamma-ray flux peaks near orbital phase ~ 0.25 (pulsar’s superior conjunction), while the X-ray flux peaks near phase ~ 0.75 (pulsar’s inferior conjunction) (see, e.g., Sim et al. 2024a).

Different types of GOM have been observed in three other spider systems. The black widow PSR J1311-3430 shows off-pulse *hard* orbital modulation (in the 1 – 100 GeV band), peaking at orbital phase $\Phi \approx 0.8$, following the pulsar’s inferior conjunction (Xing & Wang 2015; An et al. 2017). Corbet et al. (2022) reported gamma-ray eclipses and modulation in the candidate redback system 4FGL J1702.7-5655, which peaked about half an orbit after the eclipse and was detected only after MJD ~ 56345 . In addition, Xing et al. 2018 reported a possible GOM at higher energies (> 5.5 GeV) in the disk state of

the transitional MSP PSR J1023+0038, peaking around the descending node of the pulsar. All systems with reported GOM are summarized in Table 1, where we also list information about their XOM and optical orbital modulation. In this work, we focus on searching for and studying *soft and pulsed GOM*.

While the IBS synchrotron emission is widely accepted as the source of XOM, the origin of GOM in spiders remains a matter of debate. Boosted synchrotron emission from electrons along the IBS cannot account for the half-orbit phase shift of the gamma-ray light curve. The first explanation explored by An et al. (2020) involves gamma-ray flux suppression by the swept-back pulsar wind. In this scenario, the intrinsically constant pulsar emission is attenuated at low energies due to orbital phase dependent absorption by the electrons in the pulsar wind. Scattering in the Klein-Nishina regime could produce the modulation in soft gamma-ray band. However, the optical depth achievable within the system was shown to be insufficient to account for the observed amplitude of the GOM (An et al. 2020), so we do not discuss this model below. Since then, two main models have been proposed to explain the GOM in spiders, namely:

i) additional flux from inverse Compton (IC) scattering of companion blackbody photons by pulsar wind particles and IBS electrons (Ng et al. 2018; An et al. 2020; Clark et al. 2021; Sim et al. 2024a). The emission geometry in this scenario naturally explains the observed phasing of the modulation. However, the predicted IC flux is insufficient to match the observations. Matching the observed flux would require the deceleration of the upstream pulsar wind, which would increase the residence time of the electrons and boost the modulated emission. However, such deceleration would suppress or even prevent the formation of the IBS, which is necessary to explain the X-ray data (Sim et al. 2024a).

ii) synchrotron radiation from relativistic leptons ejected by the pulsar interacting with the companion's magnetic field (van der Merwe et al. 2020; Clark et al. 2021; Sim et al. 2024a). This scenario can reproduce both the observed fluxes and the phasing of the modulation, provided the leptons are accelerated to energies of ~ 0.1 PeV and the companion's magnetic field is ~ 1 kG. These conditions are also consistent with the presence of an IBS, allowing it to form and emit as required by the X-ray data.

In this work, we present the results of a systematic search for soft and pulsed GOM from confirmed spider systems using the Third Fermi Large Area Telescope (LAT) Catalog of Gamma-Ray Pulsars (3PC, Smith et al. 2023). In Section 2, we describe the pulsar sample and analysis methods. We present the results of

the search in Section 3, including the discovery of GOM in three spider systems. Finally, in Section 4 we discuss the soft pulsed GOM properties and compare them with other system parameters, in the context of the proposed models.

2. OBSERVATIONS AND ANALYSIS

2.1. Spider pulsar sample

Out of 294 gamma-ray pulsars reported in 3PC, we pre-selected all 47 systems which are also listed as confirmed spiders in the SpiderCat catalog of compact binary MSPs¹ (Koljonen & Linares 2025): 15 redbacks and 32 black widows. Three black widows (PSR J1311-3430, PSR J1745+1017, PSR J2115+5448) and one redback (PSR J0955-3947) in this list had diluted precision timing solutions, pending publications. Since sensitive GOM searches require precise spin and orbital ephemerides, these four systems were excluded from our analysis, leaving a total of 43 systems selected for further investigation (14 redbacks and 29 black widows). For the same reason, we did not include spider candidates, although GOM may be present in some of these systems as well (Ng et al. 2018; Corbet et al. 2022). The final list of studied pulsars and their main properties is presented in Table 2.

All 43 spiders in our sample have Fermi-LAT point-source catalog counterparts (4FGL, Abdollahi et al. 2020, 2022; Ballet et al. 2023), with one exception: PSR J0636+5128. This pulsar is too faint to be included in the 4FGL catalog, which did not use pulsation searches. However, when the data are phase-folded using a precise ephemeris, the pulsar becomes detectable (Smith et al. 2023).

2.2. Fermi-LAT data analysis

To streamline our analysis, we used the public data products from 3PC² (Smith et al. 2023): phased and weighted FT1 event files and timing solutions (.par files). We selected SOURCE class photons with zenith angles $\leq 90^\circ$ from a 3° -radius region of interest (RoI) around each source, covering two different energy ranges: soft 0.1–1 GeV and full 0.1–300 GeV within the timing solution validity period. For each photon, spin and orbital phases were calculated based on the timing model using TEMPO2 (Edwards et al. 2006; Hobbs et al. 2006) with the Fermi plugin (Ray et al. 2011).

¹ Version 1.8.1, at <https://astro.phys.ntnu.no/SpiderCAT>

² https://fermi.gsfc.nasa.gov/ssc/data/access/lat/3rd_PSR_catalog/

Table 2. Main properties of the 43 spider pulsars studied here, from the 4FGL-DR4 (Abdollahi et al. 2022; Ballet et al. 2023) and 3PC (Smith et al. 2023) catalogs: 4FGL counterpart name, spin period P_s , orbital period P_b , phase-averaged 0.1 – 300 GeV energy flux F_g , estimated distance d , spin-down power $\dot{E}$, gamma-ray luminosity in the 0.1 – 100 GeV energy band L_g (the second set of uncertainties is due to the distance) and projected semimajor axis A_1 . In the name column (e) indicates gamma-ray eclipsing binaries, while (t) - transitional systems.

Name	Type	4FGL name	P_s	P_b	$F_g/10^{-12}$	d ,	$\dot{E}/10^{33}$	$L_g/10^{33}$	A_1 ,
			ms	d	erg cm $^{-2}$ s $^{-1}$	kpc	erg s $^{-1}$	erg s $^{-1}$	lt-s
J0023+0923	BW	J0023.4+0920	3.05	0.14	7.8 ± 0.6	$1.8^{+0.5}_{-0.3}$	$12.4^{+1.0}_{-0.7}$	$3.03 \pm 0.21^{+1.97}_{-1.00}$	0.035
J0251+2606	BW	J0251.0+2605	2.54	0.20	4.9 ± 0.4	1.2 ± 0.5	12.8 ± 3.2	$0.80 \pm 0.07^{+0.77}_{-0.51}$	0.066
J0312-0921	BW	J0312.1-0921	3.70	0.10	5.5 ± 0.4	0.82 ± 0.33	9.7 ± 2.4	$0.44 \pm 0.03^{+0.43}_{-0.28}$	0.015
J0610-2100	BW	J0610.2-2100	3.86	0.29	7.2 ± 0.5	2.2 ± 0.7	3.5 ± 1.6	$4.19 \pm 0.27^{+3.09}_{-2.24}$	0.073
J0636+5128	BW	-	2.87	0.07	-	$0.7^{+0.2}_{-0.1}$	$5.60^{+0.06}_{-0.04}$	-	0.009
J0952-0607	BW	J0952.1-0607	1.41	0.27	2.4 ± 0.3	$6.3^{+0.3}_{-0.4}$	≤ 68.5	$11.04 \pm 1.47^{+1.08}_{-1.37}$	0.063
J1023+0038 (t)	RB	J1023.7+0038	1.69	0.20	32.4 ± 0.8	1.37 ± 0.04	42.8 ± 0.4	$7.25 \pm 0.18 \pm 0.43$	0.343
Pulsar State					5.6 ± 1.2				
Disk State					49.2 ± 0.7				
J1048+2339 (e)	RB	J1048.6+2340	4.67	0.25	4.9 ± 0.5	$1.3^{+0.6}_{-0.2}$	$9.7^{+0.9}_{-0.4}$	$1.02 \pm 0.10^{+1.05}_{-0.32}$	0.836
J1124-3653	BW	J1124.0-3653	2.41	0.23	12.5 ± 0.6	1.0 ± 0.4	16.7 ± 0.3	$1.46 \pm 0.07^{+1.41}_{-0.94}$	0.080
J1221-0633	BW	J1221.4-0634	1.93	0.39	5.8 ± 0.5	1.3 ± 0.5	> -165	$1.09 \pm 0.09^{+1.05}_{-0.70}$	0.055
J1227-4853 (t)	RB	J1228.0-4853	1.69	0.29	19.0 ± 1.6	$1.8^{+0.5}_{-0.2}$	$87.3^{+6.7}_{-2.8}$	$6.98 \pm 0.60^{+4.46}_{-1.50}$	0.668
Pulsar State					16.3 ± 2.8				
Disk State					32.0 ± 2.2				
J1301+0833	BW	J1301.6+0834	1.84	0.27	7.7 ± 0.5	1.8 ± 0.1	43.7 ± 8.2	$2.88 \pm 0.18 \pm 0.33$	0.078
J1302-3258	RB	J1302.4-3258	3.77	0.78	10.9 ± 0.5	1.4 ± 0.6	3.6 ± 0.7	$2.67 \pm 0.13^{+2.56}_{-1.71}$	0.928
J1431-4715	RB	J1431.4-4711	2.01	0.45	4.7 ± 0.7	$1.8^{+0.5}_{-0.2}$	$54.3^{+4.5}_{-1.8}$	$1.74 \pm 0.26^{+1.20}_{-0.39}$	0.550
J1446-4701	BW	J1446.6-4701	2.19	0.28	7.7 ± 0.7	1.6 ± 0.6	36.2 ± 0.4	$2.26 \pm 0.20^{+2.17}_{-1.45}$	0.064
J1513-2550	BW	J1513.4-2549	2.12	0.18	7.6 ± 0.6	4.0 ± 1.6	$86.8^{+2.7}_{-2.1}$	$14.27 \pm 1.16^{+13.70}_{-9.13}$	0.041
J1544+4937	BW	J1544.0+4939	2.16	0.12	2.4 ± 0.3	$3.0^{+2.0}_{-1.0}$	$8.4^{+4.4}_{-2.2}$	$2.53 \pm 0.31^{+4.53}_{-1.40}$	0.033
J1555-2908 (e)	BW	J1555.7-2908	1.79	0.23	4.7 ± 0.6	$5.1^{+0.5}_{-0.7}$	> 306	$14.51 \pm 1.88^{+2.98}_{-3.71}$	0.151
J1622-0315	RB	J1623.0-0315	3.85	0.16	7.2 ± 0.7	$1.2^{+0.5}_{-0.2}$	$6.6^{+0.6}_{-0.2}$	$1.31 \pm 0.12^{+1.40}_{-0.36}$	0.219
J1627+3219	BW	J1627.7+3219	2.18	0.17	3.6 ± 0.3	4.5 ± 1.8	≤ 24.8	$8.71 \pm 0.75^{+8.36}_{-5.58}$	0.054
J1628-3205	RB	J1628.1-3204	3.21	0.21	11.3 ± 0.9	$1.2^{+0.6}_{-0.2}$	$11.9^{+2.9}_{-0.9}$	$1.92 \pm 0.16^{+2.53}_{-0.57}$	0.410
J1641+8049	BW	J1641.2+8049	2.02	0.09	2.0 ± 0.3	3.0 ± 1.2	> 48	$2.19 \pm 0.34^{+2.10}_{-1.40}$	0.064
J1653-0158	BW	J1653.6-0158	1.97	0.05	34.3 ± 1.0	$0.7^{+1.6}_{-0.1}$	$7.0^{+12.0}_{-0.8}$	$2.25 \pm 0.07^{+19.48}_{-0.35}$	0.011
J1803-6707	BW	J1803.1-6708	2.13	0.38	4.8 ± 0.5	$1.8^{+0.8}_{-0.3}$	$71.7^{+2.0}_{-0.7}$	$1.94 \pm 0.20^{+2.11}_{-0.56}$	1.062
J1805+0615	BW	J1805.6+0615	2.13	0.34	5.3 ± 0.5	3.9 ± 1.6	$75.9^{+10.7}_{-10.5}$	$9.51 \pm 0.98^{+9.13}_{-6.09}$	0.088
J1810+1744	BW	J1810.5+1744	1.66	0.15	23.3 ± 0.9	$1.9^{+1.1}_{-0.4}$	$36.6^{+3.3}_{-1.2}$	$9.73 \pm 0.39^{+15.14}_{-3.55}$	0.095
J1816+4510 (e)	RB	J1816.5+4510	3.19	0.36	10.6 ± 0.5	$3.4^{+1.2}_{-0.5}$	$53.1^{+0.4}_{-0.2}$	$14.88 \pm 0.70^{+12.35}_{-3.87}$	0.595
J1833-3840	BW	J1833.0-3840	1.87	0.90	2.8 ± 0.4	4.6 ± 1.9	≤ 105.1	$7.29 \pm 1.16^{+7.00}_{-4.66}$	0.061
J1908+2105	RB	J1908.9+2103	2.56	0.15	4.9 ± 0.8	2.6 ± 1.0	$30.9^{+2.0}_{-1.9}$	$3.95 \pm 0.64^{+3.79}_{-2.53}$	0.117
J1946-5403	BW	J1946.5-5402	2.71	0.13	9.8 ± 0.5	1.1 ± 0.5	> 5	$1.56 \pm 0.08^{+1.49}_{-1.00}$	0.044
B1957+20 (e)	BW	J1959.5+2048	1.61	0.38	15.7 ± 0.9	$1.3^{+0.8}_{-0.3}$	$116.9^{+25.7}_{-9.4}$	$3.02 \pm 0.18^{+4.63}_{-1.15}$	0.089
J2017-1614	BW	J2017.7-1612	2.31	0.10	6.5 ± 0.6	1.4 ± 0.6	> -26	$1.61 \pm 0.15^{+1.55}_{-1.03}$	0.044
J2039-5617	RB	J2039.5-5617	2.65	0.23	15.4 ± 0.6	$1.7^{+0.6}_{-0.2}$	$25.4^{+1.8}_{-0.8}$	$5.21 \pm 0.22^{+3.97}_{-1.28}$	0.471
J2047+1053	BW	J2047.3+1051	4.29	0.12	4.3 ± 0.6	2.8 ± 1.1	6.8 ± 1.9	$3.98 \pm 0.52^{+3.82}_{-2.55}$	0.069
J2051-0827	BW	J2051.0-0826	4.51	0.10	2.5 ± 0.3	1.47 ± 0.59	5.5 ± 0.1	$0.65 \pm 0.08^{+0.62}_{-0.41}$	0.045
J2052+1219	BW	J2052.7+1218	1.99	0.11	4.6 ± 0.6	$5.6^{+0.5}_{-0.6}$	$10.5^{+3.4}_{-3.7}$	$16.97 \pm 2.08^{+2.98}_{-3.19}$	0.061
J2129-0429 (e)	RB	J2129.8-0428	7.61	0.64	6.8 ± 0.5	1.8 ± 0.1	20.61 ± 0.05	$2.73 \pm 0.19 \pm 0.34$	1.852
J2214+3000	BW	J2214.6+3000	3.12	0.42	32.6 ± 0.7	0.6 ± 0.3	17.2 ± 1.4	$1.41 \pm 0.03^{+1.83}_{-1.08}$	0.059
J2215+5135	RB	J2215.6+5135	2.61	0.17	18.0 ± 0.8	$2.7^{+1.5}_{-0.5}$	$52.7^{+0.3}_{-0.1}$	$15.26 \pm 0.69^{+21.16}_{-4.91}$	0.468
J2234+0944	BW	J2234.7+0943	3.63	0.42	10.0 ± 0.6	$0.7^{+0.2}_{-0.1}$	$11.1^{+1.3}_{-0.9}$	$0.59 \pm 0.04^{+0.31}_{-0.17}$	0.068
J2241-5236	BW	J2241.7-5236	2.19	0.15	25.0 ± 1.1	1.04 ± 0.05	$26.3^{+0.4}_{-0.3}$	$3.25 \pm 0.14 \pm 0.29$	0.026
J2256-1024	BW	J2256.8-1024	2.29	0.21	8.2 ± 0.5	$2.1^{+0.9}_{-0.5}$	$38.3^{+0.8}_{-0.4}$	$4.25 \pm 0.26^{+4.74}_{-1.78}$	0.083
J2339-0533	RB	J2339.6-0533	2.88	0.19	29.2 ± 0.8	$1.3^{+0.3}_{-0.2}$	$22.5^{+0.5}_{-0.3}$	$5.90 \pm 0.15^{+3.61}_{-1.36}$	0.612

Folded light curves were constructed using spin and orbital phases and probability weights from the `MODEL.WEIGHT` column. These weights represent the probability that a detected gamma-ray photon was emitted by the pulsar, based on the photon energy, arrival direction and source model within the RoI. Uncertainties for the i -th light curve bin are calculated as $\sigma_i^2 = \sum_{j=1}^{N_i} w_j^2 + (\max_{j \in [1, N_i]} w_j)^2$, where N_i is the number of photons in the bin and w_j are the photon weights. The background level was estimated from the weights as $(\sum_i w_i - \sum_i w_i^2)/N_{bin}$ with an uncertainty of $\pm 6\%$ (Smith et al. 2023), where w_i is the weight of the i -th photon and N_{bin} is the number of phase bins in the light curve. The background primarily arises from Galactic diffuse emission, the isotropic gamma-ray background, and contributions from nearby sources. The significance of detected pulsations was determined using the standard weighted H -test with $m = 20$ harmonics (de Jager et al. 1989; de Jager & Büsching 2010; Kerr 2011). This led to a significance of the detected pulsations of $> 5\sigma$.

An example of the timing results is shown in Figure 1, which displays the pulse profile of PSR J2215+5135, the distribution of photon rotational phases over time (aligned using the 3PC ephemeris) and the H-test significance of the detected pulsations, which increases monotonically as more data are accumulated. In this example, the precise phase alignment is achieved by modeling orbital period variations using Gaussian processes (ORBIFUNCS, see Clark et al. 2021). In other cases, the orbital period variations are modeled with a Taylor series expansion around the time of ascending node (using the BTX or ELL1 models).

The weighted H-test was also used to quantify the significance of GOM using the calculated orbital phases. To describe and compare the folded orbital light curves across different systems, we fitted them with a sinusoidal function by maximizing the likelihood

$$\log \mathcal{L} = \sum_j \log [w_j F(\Phi_j) + (1 - w_j)],$$

where $F(\Phi) = \alpha \sin(2\pi(\Phi + \Phi_0)) + 1$ approximates the orbital light curve, Φ is the orbital phase ($\Phi = 0$ corresponds to the pulsars' ascending node), and Φ_0 quantifies the phase shift of the maximum relative to phase 0.25. Thus, the peak phase is given by $\Phi_{max} = 0.25 - \Phi_0$. Although some orbital light curves are not strictly sinusoidal, we use this approach to quantify the amplitude and phase centering of the GOM in an homogeneous way. In this model, the parameter α is the semi-amplitude of the modulation divided by the difference between the average flux and the background level, providing a measure of the fractional semi-amplitude of the

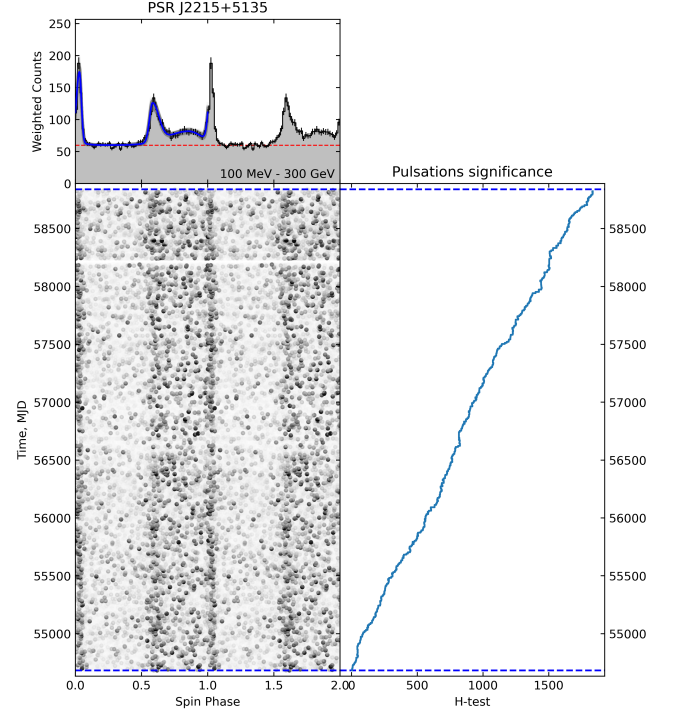


Figure 1. Our gamma-ray timing results for PSR J2215+5135 in the 0.1 – 300 GeV energy band. *Top panel:* the black curve represents the folded light curve, the blue curve shows the template pulse profile, and the dashed red line indicates the background level. *Bottom left:* photon spin phases are plotted against time, with the color representing the weights of the photons. *Bottom right:* the cumulative H-test for pulsations significance is shown over time. Dashed blue lines in the bottom panels indicate the start and end of the timing solution used.

orbital modulation, or modulated fraction (MF) hereafter.

The confidence intervals for the model parameters, α and Φ_0 , were determined using Wilks' Theorem (i.e., assuming that the drop in log-likelihood, $-2\Delta \log \mathcal{L}$, follows a χ^2 distribution with 2 degrees of freedom). For sources with $H < 14$ (corresponding to $< 3\sigma$ significance), we placed 3σ upper limits on the MF. Figure 2 shows two such examples of how we determined uncertainties (left) and placed upper limits (right) on the fitted parameters.

From previous studies it was found that the soft GOM is pulsed, meaning that the modulation arises from photons corresponding to the peak of the pulse profile (see Section 1 and An et al. 2020; Clark et al. 2021; Sim et al. 2024a). We manually identified on- and off-pulse inter-

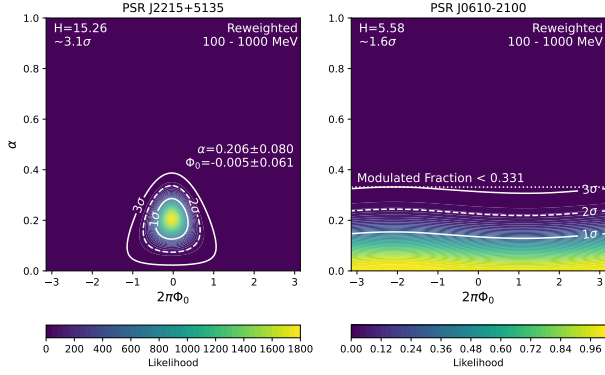


Figure 2. Constraints on the MF (α) and phase shift (Φ_0). *Left:* parameter space for PSR J2215+5135, with the color scale representing the likelihood values. Contours indicate the 1-, 2-, and 3- σ confidence intervals. *Right:* Parameter space for PSR J0610-2100, which does not exhibit GOM. The 3 σ upper limits on the MF are shown.

vals, selected only photons corresponding to these intervals, and then searched for orbital modulation as described. Overall, searching for GOM with on-pulse photons proved to be more sensitive compared to just using all detected photons. For example, for PSR J2215+5135 using all spin phases yields $H = 11.97$, while selecting on-pulse photons results in a higher GOM significance $H = 14.83$.

To ensure a robust and user-independent analysis for selecting on-pulse intervals, we also adopted a reweighting procedure introduced in Kerr (2019) and Clark et al. (2023). This method is based on the pulse shape and modifies the prior weights, w (MODEL_WEIGHT) into posterior weights w' ,

$$w' = \frac{wf(\phi)}{wf(\phi) + 1 - w},$$

where $f(\phi)$ is the pulsar’s template pulse profile. The pulse profile was modeled using a series of wrapped Gaussian functions, with parameters optimized by maximizing log-likelihood, as described in Smith et al. (2023). After folding and binning those reweighted photons to obtain orbital light curves, we refer to them as “reweighted counts”. When the available timing solution does not allow for coherent spin-phase folding (e.g., in the case of PSR J1227-4853, Sec. 3.2.1), we refer to the counts in the orbital light curves as “weighted counts” (since they are still weighted according to the photon arrival directions and energies).

The 3PC catalog and data products that we used include 12 years of Fermi-LAT data, from 2008 to 2020. For the systems with GOM significance $> 2.5\sigma$, we attempted to assess the significance of the GOM using all the available data. The primary obstacle is the valid-

ity interval of the publicly available timing solutions. Many spiders have long-term orbital period variations, driven by changes in the companion’s quadrupole moment (Pletsch & Clark 2015; Shaifullah et al. 2016; Clark et al. 2021). This complicates expanding the ephemeris beyond their validity intervals.

We chose to extrapolate data only for systems with stable timing solutions, i.e., those without high-order (> 2) orbital period derivatives or ORBIFUNC terms. The stability of pulsations was assessed by verifying the presence of pulsations beyond the formal validity range of the timing solution. For these systems (PSR J1124-3653, PSR J1946-5403, and PSR J2256-1024), we analyzed Fermi-LAT data collected between 2008 August 4 and 2025 February 14. Using the same photon selection as described above, P8R3_SOURCE_V3 (Atwood et al. 2013; Bruel et al. 2018) instrument response and generating a 4FGL-DR4-based (Ballet et al. 2023) source model for the RoI with the LATSourceModel/make4FGLxml³ package, we calculated prior photon weights using gtsrcprob. These weights were then reweighted as described previously.

Finally, to compare the MFs with gamma-ray fluxes in Section 4, we calculated the 0.1 – 300 GeV and 0.1 – 1 GeV gamma-ray fluxes of the transitional systems PSR J1023+0038 and PSR J1227-4853, using separately the time intervals before and after their state transitions (Table 2). To do so, we performed a standard binned-likelihood analysis using fermipy (Wood et al. 2017). We selected SOURCE class photons within a 15° RoI, with energies between 0.1 and 300 GeV and zenith angles $< 90^\circ$, and used P8R3_SOURCE_V3 instrument response files. The sky model was based on 4FGL catalog sources, together with the Galactic diffuse model (gll_iem_v07.fits) and isotropic background (iso_P8R3_SOURCE_V3_v1.txt) models. The gamma-ray spectra of PSR J1023+0038 and PSR J1227-4853 were fitted with a PLSuperExpCutoff2 spectral model. During the fit, we allowed the normalizations of sources within 5°, the diffuse background normalization, and the spectral parameters of PSR J1023+0038 and PSR J1227-4853 to vary.

3. RESULTS

We have detected significant soft pulsed GOM ($\geq 3\sigma$; 0.1 – 1 GeV band) in seven spider pulsars: 4 redbacks and 3 black widows (see Table 3). We show in Figure 3 the orbital gamma-ray light curves of these systems (in the 0.1 – 1 GeV energy band, and using reweighted

³ <https://github.com/physicsranger/make4FGLxml>

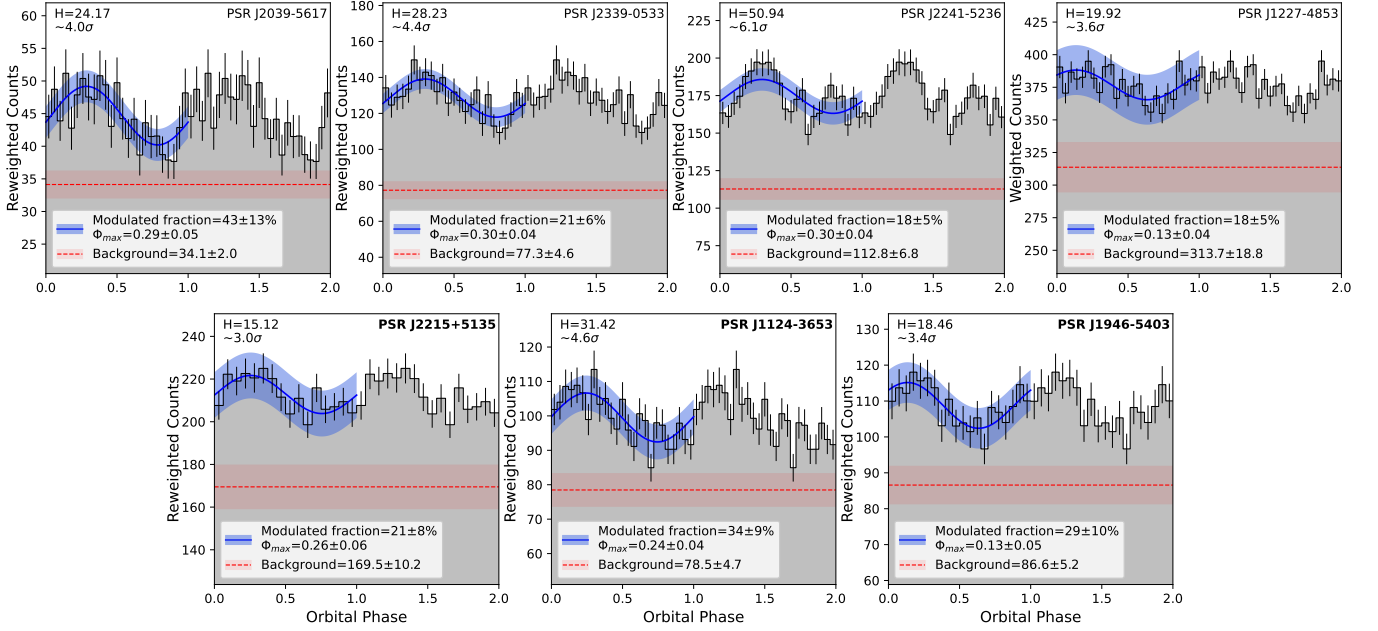


Figure 3. Reweighted, phase-folded gamma-ray light curves in the 0.1–1 GeV energy range for all systems with detected GOM (except for PSR J1227-4853, where regular weights were used; Secs. 2.2 and 3.2.1). The black points represent the folded data and uncertainties. The blue line and shaded area show the sinusoidal fit with its 1σ uncertainty, while the red dashed line and shaded area represent the background level and its uncertainty. Two orbital periods are shown for clarity.

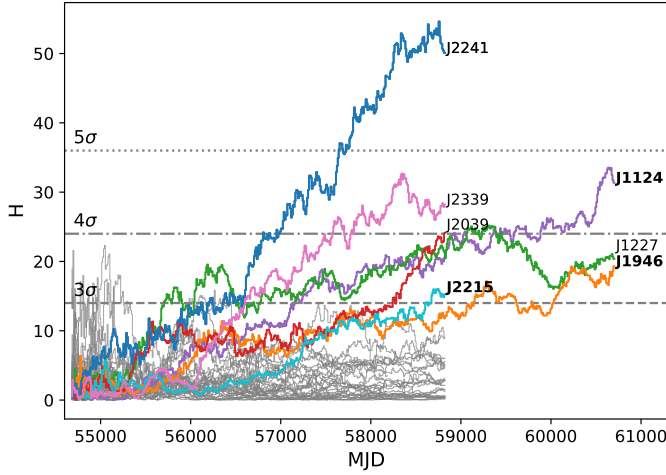


Figure 4. Weighted H-test significance for the seven systems with detected GOM, accumulated over time, using reweighted 0.1–1 GeV photons (except for PSR J1227-4853, where regular photon weights were used). Grey lines indicate systems where no significant GOM was detected. The dashed horizontal lines represent the thresholds for a 3-, 4- and 5- σ confidence level. Systems with newly discovered GOM are shown in bold face.

photons as explained in Section 2.2). The remaining 36 folded light curves, where we did not detect GOM, can be found in Appendix A (Figure A1). The time evolution of the H statistic for these seven systems is

shown in Figure 4. As Fermi-LAT collects more data, the significance of GOM detection increases over time.

To verify that the observed modulation is not caused by exposure variations, we folded the good-time intervals at the orbital period. The relative variations in exposure time with orbital phase do not exceed $\sim 0.5\%$, which is too small to account for the observed modulations.

Thus, we have discovered GOM in three new spider pulsars: PSR J2215+5135 (redback), PSR J1124-3653 and PSR J1946-5403 (both black widows). This nearly doubles the population of spiders with detected soft pulsed GOM. The detected systems show MFs in the range of 18–43% (Figure 3 and Table 3). For the spiders without significantly detected GOM, we place upper limits on the MF (in the range 16–100%, depending mostly on source brightness, see below).

In the following, we present our results on all three systems in which we have discovered GOM (Sec. 3.1), seven systems with previously reported GOM (Sec. 3.2) and five eclipsing spiders (for which we provide MF upper limits, Sec. 3.3).

3.1. Three new discoveries

3.1.1. PSR J1124-3653

Table 3. Significance of GOM, modulated fraction (or upper limits) and phase of maximum flux for the pulsars studied, using reweighted 0.1 – 1 GeV photons. The time range used for the analysis is shown in the last column. Systems where we discover GOM are highlighted in bold face.

PSR	Significance, σ	Modulated Fraction, %	Φ_{max}	Start - Finish, MJD
J1124-3653 *	4.6	$33.7^{+9.0}_{-9.1}$	0.245 ± 0.040	54682-60720
J1227-4853 (t) †* [1]	3.6	$18.0^{+5.4}_{-5.3}$	0.133 ± 0.040	54682-60720
J1946-5403 *	3.4	28.7 ± 10.0	0.133 ± 0.051	54682-60720
J2039-5617 [2]	4.0	$42.5^{+12.6}_{-12.9}$	$0.285^{+0.051}_{-0.040}$	54682-58839
J2215+5135	3.0	20.6 ± 8.0	0.255 ± 0.061	54682-58839
J2241-5236 [3]	6.1	18.3 ± 5.2	0.295 ± 0.040	54682-58839
J2339-0533 [4]	4.4	$20.7^{+5.8}_{-5.9}$	0.295 ± 0.040	54682-58839
J0023+0923	0.2	<52.5	-	54682-58839
J0251+2606	0.3	<66.6	-	54682-58839
J0312-0921	1.3	<51.6	-	54682-59224
J0610-2100	1.8	<33.1	-	54682-58839
J0636+5128	0.1	<80.0	-	54682-58836
J0952-0607	1.5	<100	-	54682-58839
J1023+0038 (t)	0.1	<22.1	-	54682-56500
J1048+2339 (e)	0.5	<100	-	56509-57549
J1221-0633	1.5	<66.7	-	54682-58839
J1301+0833	1.0	<41.9	-	54682-58839
J1302-3258	0.1	<43.9	-	54682-58839
J1431-4715	0.8	<89.5	-	54682-58839
J1446-4701	1.0	<80.1	-	54682-58839
J1513-2550	0.2	<44.2	-	54682-58839
J1544+4937	1.1	<100	-	54682-58839
J1555-2908 (e)	0.2	<49.2	-	54682-58493
J1622-0315	0.2	<100	-	54682-58839
J1627+3219	0.5	<71.4	-	54682-58839
J1628-3205	0.7	<60.5	-	54682-57300
J1641+8049	0.5	<90.4	-	54682-58190
J1653-0158	0.2	<16.1	-	54682-58839
J1803-6707	0.7	<78.0	-	54682-58839
J1805+0615	1.5	<78.6	-	54682-58839
J1810+1744	2.1	<15.7	-	54682-58839
J1816+4510 (e)	0.6	<32.0	-	54682-58839
J1833-3840	1.2	<100	-	57313-58193
J1908+2105	1.0	<84.1	-	54682-58693
B1957+20 (e)	0.5	<30.1	-	54682-57976
J2017-1614	0.2	<60.2	-	54682-58839
J2047+1053	0.6	<100	-	54682-58839
J2051-0921	1.3	<100	-	54682-57874
J2052+1219	1.7	<100	-	54682-58839
J2129-0429 (e)	2.2	<63.9	-	54682-58839
J2214+3000	1.0	<18.9	-	54682-58839
J2234+0944	0.1	<47.8	-	54682-58839
J2256-1024	1.1	<36.7	-	54684-60720

NOTE—Different source types and analysis are indicated: (t) - transitional MSPs, (e) - eclipsing, * - extended analysis beyond 3PC timing solution, †- J1227 using prior photon weights and timing solution from [de Martino et al. \(2020\)](#) (see Sections 2.2 and 3 for details). Discovery references: [1] - [An \(2022\)](#), [2] - [Ng et al. \(2018\)](#); [Clark et al. \(2021\)](#), [3] - [An et al. \(2018\)](#), [4] - [An et al. \(2020\)](#)

PSR J1124-3653 (J1124) is a black widow pulsar with $P_s = 2.41$ ms in a 5.45 h orbit. In X-rays, J1124 exhibits orbital variability, with a maximum at pulsar’s inferior conjunction (Gentile et al. 2014; Sim et al. 2024b).

From our gamma-ray study, we have discovered a sinusoidal modulation from J1124, with a significance of 3.9σ ($H = 22.7$). The gamma-ray pulsations of J1124 are detectable far beyond the 3PC timing solution interval, as we show in Appendix B (Figure B1). Given the stability of the timing solution, we extended the search beyond the original ephemeris validity range to include the full 2008-2025 time range. Using this extended search, in the 0.1 – 1 GeV band with reweighted photons, we find a GOM significance of 4.6σ ($H = 31.42$). The maximum of the GOM coincides with the pulsar’s superior conjunction ($\Phi_{max} = 0.24 \pm 0.04$) and the MF is $34 \pm 9\%$.

3.1.2. PSR J1946-5403

PSR J1946-5403 (J1946) is a black widow pulsar with $P_s = 2.71$ ms and $P_b = 3.12$ h (Camilo et al. 2015). It shows XOM with two peaks centered around pulsar’s superior conjunction (Sim et al. 2024b). This suggests that the companion wind is weaker than that of the pulsar, and the IBS is wrapped around the companion star.

From our standard study in the 0.1–1 GeV band using reweighted photons within the 3PC timing solution, we found indications of GOM, with a significance of 2.8σ . By extending the analysis beyond the 3PC ephemeris time range (from August 2008 to March 2018), we continued detecting pulsations, indicating that the timing solution remains stable over a longer timescale (Figure B1). Including these additional data, we detect GOM with a significance of 3.1σ ($H = 15.51$). We thereby measure a MF of $26 \pm 10\%$ and a peak phase of $\Phi_{max} = 0.13 \pm 0.06$.

3.1.3. PSR J2215+5135

PSR J2215+5135 (J2215) is a redback system with a spin period $P_s = 2.61$ ms and $P_b = 4.14$ h. From an optical study of its strongly irradiated companion, Linares et al. (2018) reported one of the most massive known neutron stars with $M_{NS} \simeq 2.3M_\odot$. This system also exhibits XOM (Sullivan & Romani 2024), characterized by two peaks near the pulsar’s inferior conjunction, $\Phi = 0.75$.

We found soft GOM from J2215 with a significance of 3.0σ ($H = 15.12$) using reweighted photons in the 0.1–1 GeV energy range. The MF of J2215 is $21 \pm 8\%$ and the peak is at the pulsar’s superior conjunction $\Phi_{max} = 0.26 \pm 0.06$. Due to stochastic orbital period variations, it was not possible to expand the dataset beyond the analyzed 3PC interval.

3.2. Previously detected systems

Significant soft GOM had previously been reported in four spider systems: three redbacks (PSR J1227-4853, An 2022; PSR J2039-5617, Clark et al. 2021; PSR J2339-0533, An et al. 2020) and one black widow PSR J2241-5236 (An et al. 2018). We confirm all four detections and present the results of our re-analysis in this Section.

3.2.1. PSR J1227-4853

PSR J1227-4853 (J1227) is a transitional MSP with $P_s = 1.69$ ms $P_b = 6.91$ h. At the end of 2012, it transitioned from a Low-mass X-ray Binary (LMXB) to a pulsar state (Bassa et al. 2014). During the pulsar state, XOM with maximum at the neutron star’s inferior conjunction was observed with XMM-Newton and NuSTAR (de Martino et al. 2015, 2020).

Using timing solutions for the orbit of J1227, including time of ascending node, binary period and its derivatives, An (2022) found GOM in the 60 – 1000 MeV energy band using 12.5 years of Fermi-LAT data, spanning from August 2008 to February 2021. Interestingly, the modulation was detected in both the LMXB and the MSP states.

The 3PC timing solution is valid only from February 2014 to August 2017 (MJD 56707-57970), and we detect gamma-ray pulsations only within this time range. As a result, reweighting can be applied only within this specific validity interval of the timing solution. Within this time range, we do not detect significant GOM using reweighted photons in the 60 – 1000 MeV, 0.1 – 1 GeV, or 0.1 – 300 GeV energy bands. Similarly, using prior probability weights, we do not detect significant modulation in any of these energy bands.

The 3PC timing solution contains 11 orbital frequency derivatives, which are necessary to precisely phase-align pulsations while accounting for stochastic orbital period variation. This prevents reliable extrapolation of the orbital phase model (Clark et al. 2021).

However, using the radio timing solutions for the orbit from An (2022, which does not incorporate information about the pulsar spin) and prior photon weights, along with the time range from August 2008 to February 2025, we confirm the detection of significant GOM in the 60 – 1000 MeV and 0.1 – 1 GeV energy bands. In the latter energy range (our standard band), we measure $H = 19.92$ ($\sim 3.6\sigma$), a MF = $18 \pm 5\%$ and $\Phi_{max} = 0.13 \pm 0.04$.

To study the modulation in the two different states of J1227, we split the LAT dataset at the time of the state transition (MJD 56250, Bassa et al. 2014). The data before this date correspond to the disk state, while the data after correspond to the pulsar state. We detect significant GOM in both states, consistent with the re-

sults reported in An (2022), with $H = 18.50$ ($\sim 3.4\sigma$) in the disk state and $H = 16.19$ ($\sim 3.2\sigma$) in the pulsar state (Figure 5). Despite the state transition being accompanied by a drop in flux, the MFs remain comparable: $MF = 26 \pm 10\%$ before and $MF = 17 \pm 6\%$ after the transition (see Section 4.2). However, while the maximum in the pulsar state is located at the pulsar’s superior conjunction ($\Phi_{max} = 0.26 \pm 0.06$), we find that the peak in the disk state occurs earlier, at $\Phi_{max} = 0.07 \pm 0.06$ (as can be seen in Figure 5).

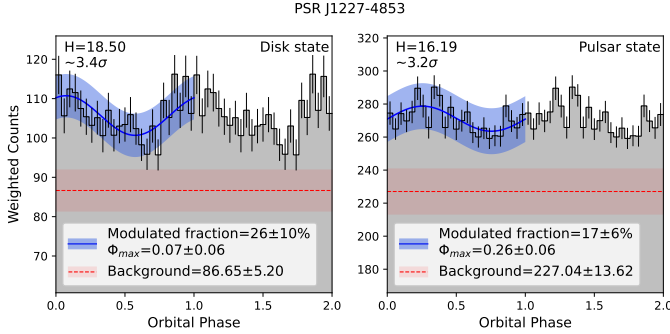


Figure 5. Weighted, phase-folded gamma-ray light curves of J1227 in the 0.1 – 1 GeV band, in the disk (left) and the pulsar (right) states.

3.2.2. PSR J2039-5617

PSR J2039-0533 (J2039) was the first redback MSP system discovered through a blind search for gamma-ray pulsations (Clark et al. 2021). It has $P_s = 2.65$ ms and $P_b = 5.5$ h. J2039 exhibits a typical double-peaked X-ray orbital light curve, centered around the pulsar’s inferior conjunction (Salveti et al. 2015; Romani 2015). From optical light curve modeling, Clark et al. (2021) estimated an orbital inclination of $\sim 75^\circ$.

Before the discovery of pulsations, Ng et al. (2018) found sinusoidal orbital modulation in the gamma-ray flux of 3FGL J2039.6–5618, peaking at the pulsar’s superior conjunction—half an orbit away from the X-ray maximum. Clark et al. (2021) confirmed this detection, showing that the orbitally modulated signal is pulsed. They produced an orbital light curve for photons with energies higher than 100 MeV without selecting or reweighting photons based on the pulse profile or phase, reporting a MF of $24 \pm 5\%$ and a peak phase $\Phi_{max} = 0.25 \pm 0.03$.

In the 0.1 – 300 GeV energy band, we also detect GOM with a significance of 4.0σ , a MF of $25 \pm 8\%$ and $\Phi_{max} = 0.26 \pm 0.05$, in agreement with the results of Clark et al. (2021). Using reweighted 0.1 – 1 GeV photons, we measure a higher MF of $43 \pm 13\%$ with $\Phi_{max} = 0.29 \pm 0.05$ with a significance of 4.0σ . This sug-

gests that the modulation is stronger at lower energies (0.1 – 1 GeV), while higher energy photons (> 1 GeV) introduce additional flux that is not modulated.

3.2.3. PSR J2241-5236

PSR J2241-5236 (J2241) is a black widow pulsar with $P_s = 2.2$ ms and $P_b = 3.5$ h. An et al. (2018) found low-energy (< 1 GeV) orbital modulation in J2241, with the first, stronger peak occurring near the pulsar’s superior conjunction and a second, smaller peak near the pulsar’s inferior conjunction. To explain this, An et al. (2018) suggested that the pulsar and companion winds strength ratio varies, so that the IBS wraps around the companion, but occasionally also around the pulsar. This would produce two peaks at the pulsar’s superior and inferior conjunctions.

A 20 ks Chandra observation of J2241 revealed thermal X-ray emission presumably originating from hot polar caps on the neutron star’s surface (Keith et al. 2011). No significant non-thermal component was detected in the Chandra data (An et al. 2018). Using NICER, Guillot et al. (2019) detected thermal X-ray pulsations from J2241.

We also detect GOM with a significance of 6.1σ using reweighted 0.1 – 1 GeV photons. Since the orbital light curve of this system is peculiar, our sinusoidal model does not fit the data well, as expected (see Figure 3). However, it provides reasonable estimates for the MF ($18 \pm 5\%$) and the location of the stronger peak ($\Phi_{max} = 0.30 \pm 0.04$).

3.2.4. PSR J2339-0533

The redback pulsar PSR J2339-0533 (J2339) is a 2.9 ms pulsar in a 4.6 h orbit. The X-ray light curve of J2339 is double-peaked around the pulsar’s inferior conjunction (Romani & Shaw 2011; Kandel et al. 2019).

An et al. (2020) discovered sinusoidal GOM of J2339 in the 100 – 600 MeV energy band by selecting pulsed photons. The gamma-ray orbital light curve is anticorrelated with the X-ray light curve, similar to J2039. The detection has a false-alarm probability of $p \approx 10^{-7}$. The authors also note that the significance is relatively sensitive to the energy selection, reporting $p = 2 \times 10^{-4}$ for the 0.1 – 1 GeV energy band.

Using the same spin phase selection as in An et al. (2020) for 0.1–1 GeV photons, we also detect GOM with $H = 19.97$, corresponding to $p = 3 \times 10^{-4}$, consistent with An et al. (2020). With our standard analysis using reweighted 0.1 – 1 GeV photons, we find $H = 28.23$ ($\sim 4.4\sigma$) with $\Phi_{max} = 0.30 \pm 0.04$ and a MF of $21 \pm 6\%$.

3.3. Eclipsing binaries

To maximize sensitivity for detecting gamma-ray eclipses, we used reweighted photons in the full Fermi-LAT energy band of 0.1 – 300 GeV as explained in [Clark et al. \(2023\)](#), which provides sufficient photon statistics. Eclipses were confirmed in PSRs B1957+20, J1048+2339, J1555-2908, J1816+4510, J2129-0429, consistent with the results of [Clark et al. \(2023, Figure C1\)](#).

After confirming the presence of eclipses, we used our standard analysis in the soft band (0.1–1 GeV) to search for GOM. We did not detect significant GOM from any of the five eclipsing systems, and we placed upper limits on their MFs.

3.3.1. PSR J1048+2339

The redback MSP PSR J1048+2339 (J1048) has $P_s = 4.67$ ms and $P_b = 6.01$ h. Its 3PC timing solution spans ~ 3 years and exhibits significant orbital period variations, making it difficult to extend over longer timescales. However, it remains sufficient to detect gamma-ray pulsations and observe an eclipse of the pulsar by its companion ([Clark et al. 2023](#)).

We do not detect significant GOM from J1048. Due to the short duration of the ephemeris and the limited number of detected photons, we are unable to place strong constraints on the MF, with an upper limit of $< 100\%$.

3.3.2. PSR J1555-2908

PSR J1555-2908 (J1555) is one of the most energetic MSPs: a black widow pulsar with a spin-down luminosity $\dot{E} > 3.1 \times 10^{35}$ erg s $^{-1}$ and $P_s = 1.79$ ms, $P_b = 5.6$ h.

The timing solution of J1555 spans from August 2008 to January 2019, and we detect significant pulsations throughout this whole time range. However, no significant GOM is detected with an upper limit on the MF of 49%.

3.3.3. PSR J1816+4510

PSR J1816+4510 (J1816) is a redback pulsar with $P_b = 8.66$ h and $P_s = 3.19$ ms. J1816 has one of the brightest and hottest companions among spiders with an effective temperature of $\gtrsim 15000$ K ([Kaplan et al. 2012](#)). It shows both radio and gamma-ray eclipses ([Stovall et al. 2014](#); [Clark et al. 2023](#)).

We do not detect GOM from this system and we place a 3σ upper limit on the MF of $< 32\%$.

3.3.4. PSR B1957+20

PSR B1957+20 (B1957) is the first discovered black widow system: a MSP with $P_s = 1.61$ ms pulsar in 9.17 h orbit around an ultra-light companion. Chandra observations revealed a double-peaked X-ray orbital light curve with maximum emission occurring around

the pulsar’s superior conjunction ([Huang et al. 2012](#)), unlike most (redback) spiders ([Wadiasingh et al. 2017](#)).

Gamma-ray analysis with Fermi-LAT provided evidence for orbital-phase-dependent emission from B1957. [Wu et al. \(2012\)](#) analyzed three years of Fermi-LAT data and reported spectral variations across the orbit, identifying an additional gamma-ray component above ~ 2.7 GeV appearing at the pulsar inferior conjunction. While their analysis suggested potential orbital modulation at low energies, the significance was only $\sim 2.3\sigma$. [Corbet et al. \(2022\)](#) did not find any significant modulation in this system.

In our study, we analyzed Fermi-LAT data from the ~ 11 year period where the 3PC timing solution was valid. We do not find significant GOM from B1957. Using reweighted 0.1 – 1 GeV photons, we place a 3σ upper limit of 30% on the MF.

3.3.5. PSR J2129-0429

The redback system PSR J2129-0429 (J2129) has $P_s = 7.61$ ms and $P_b = 15.25$ h. The X-ray orbital light curve obtained with XMM-Newton and NuSTAR revealed a double-peaked maximum around the pulsar’s inferior conjunction ([Hui et al. 2015](#); [Kong et al. 2018](#)).

For PSR J2129-0429 (J2129), the full energy band light curve (0.1 – 300 GeV) shows the eclipse at phase 0.25 ([Clark et al. 2023](#)). Our analysis in the soft energy band yields tentative evidence of sinusoidal orbital modulation (Figure A1). However, this modulation is not statistically significant (2.2σ in the 0.1 – 1 GeV energy band when using reweighted photons), so we place an upper limit of $< 64\%$ on the MF.

3.4. Pulse profiles

Previous studies have shown that the gamma-ray pulsar tends to be brighter around superior conjunction, corresponding to the orbital maximum of the GOM ([An et al. 2020](#); [Clark et al. 2021](#)). To test this in our detected systems, we produced pulse profiles for six pulsars exhibiting GOM in three orbital phase intervals: orbit-averaged ($0 < \Phi \leq 1$), around the orbital maximum ($0 < \Phi \leq 0.5$), and around the orbital minimum ($0.5 < \Phi \leq 1$). J1227 was not included because of its short ephemeris, during which gamma-ray pulsations are detected (see Section 3.2.1). The photon weights were assigned according to the orbit-averaged pulsar spectrum. The resulting pulse profiles are shown in Figure 6. We find that the profiles around superior and inferior conjunctions differ slightly in flux (weighted counts), but also in shape. Further investigation via orbital phase-resolved spectroscopy (e.g., [An et al. 2020](#)) or pulse profile modeling is beyond the scope of this work.

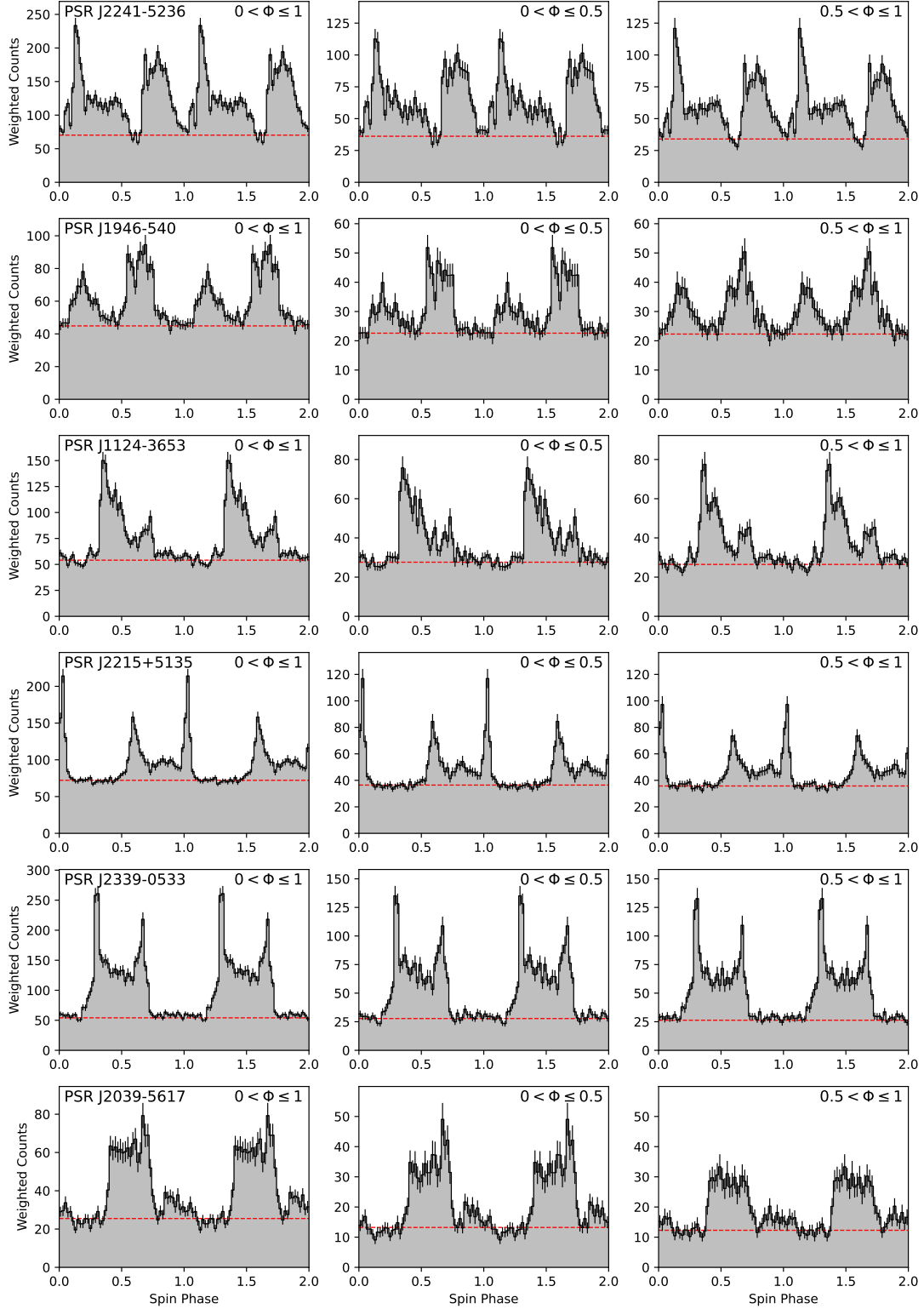


Figure 6. Pulse profiles of six pulsars with detected GOM in the 0.1–300 GeV band, measured in three orbital phase selections: orbit-averaged ($0 < \Phi \leq 1$), near pulsars superior conjunction ($0 < \Phi \leq 0.5$), and at pulsars inferior conjunction ($0.5 < \Phi \leq 1$).

4. DISCUSSION

We have detected significant GOM in seven out of the total 43 spider systems analyzed. We have discovered modulation in the pulsed gamma-ray flux of three spiders: one redback (J2215, Sec. 3.1.3) and two black widows (J1124 and J1946; Secs. 3.1.1 and 3.1.2, respectively). In all three newly discovered cases, the GOM significance drops below 3σ when including the full LAT band (0.1 – 300 GeV), indicating that the modulation is soft. This nearly doubles the number of spiders with detected soft and pulsed GOM (Table 3).

Our results show that GOM in spiders is more common than previously thought. Since we conducted a systematic search across the spider population presented in 3PC, we estimated the significances accounting for trials, i.e., the search over the 43 independent systems. For our new findings, PSR J1124-3653, J1946-5403 and J2215+5135, the post-trial significances are 3.8, 2.2 and 1.6σ , respectively. The significance estimated using the H-test with one harmonic is higher ($m=1$, also known as Rayleigh test; [Buccheri et al. 1983](#); [de Jager et al. 1989](#)), yielding post-trial significances of 4.4, 2.6 and 2.0σ for J1124, J1946 and J2215, respectively. Because the GOM shapes are clearly sinusoidal and their flux maxima align with all other spiders (near the pulsar’s superior conjunction), we consider these detections to be robust.

4.1. A universal modulated fraction

We find that our measured MFs (Figure 7) and $\Phi_{\max}$ (Figure 8) are relatively uniform across all systems, regardless of whether they are redbacks or black widows. Figure 7 shows the distribution of MFs together with their kernel density estimates (KDEs). Fitting the MFs with a constant yields a best-fit value of $\text{MF}=22.0 \pm 2.6\%$, with $\chi^2/\text{d.o.f.} = 5.85/6$. We also find that the MFs show no clear dependence on the orbital period P_b (which differs by a factor $\simeq 2$ across our sample) or other parameters such as gamma-ray luminosity L_g , spin-down power $\dot{E}$ or projected semi-major axis of the pulsar A_1 (which differ by a factor $\gtrsim 10$; see Figure 9).

The gamma-ray flux maxima of all seven detected systems are found near the pulsar’s superior conjunction ($\Phi = 0.25$ in our definition, see Figure 8). XOM has previously been observed in all seven systems except for J2241. Thus, we find that the redback J2215 and the black widow J1124 add to three other redbacks (J1227, J2039 and J2339) that exhibit an *anti-correlation* between gamma-ray and X-ray fluxes (see Figure 8 and references in Table 2). In these five systems, the GOM and XOM are *in anti-phase*: the gamma-ray flux peaks near the pulsar’s superior conjunction, while the X-ray

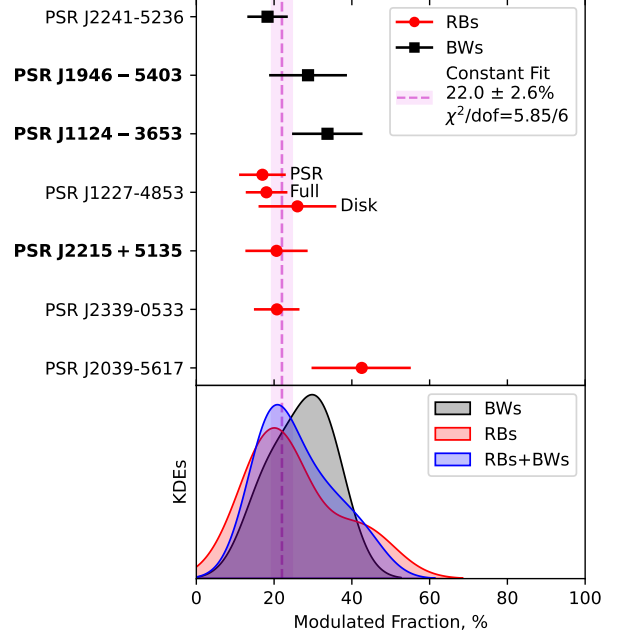


Figure 7. *Top:* Distribution of modulated fractions in the 0.1-1 GeV energy band. *Bottom:* KDEs computed using Gaussian kernels with bandwidth $7^{-1/5}$.

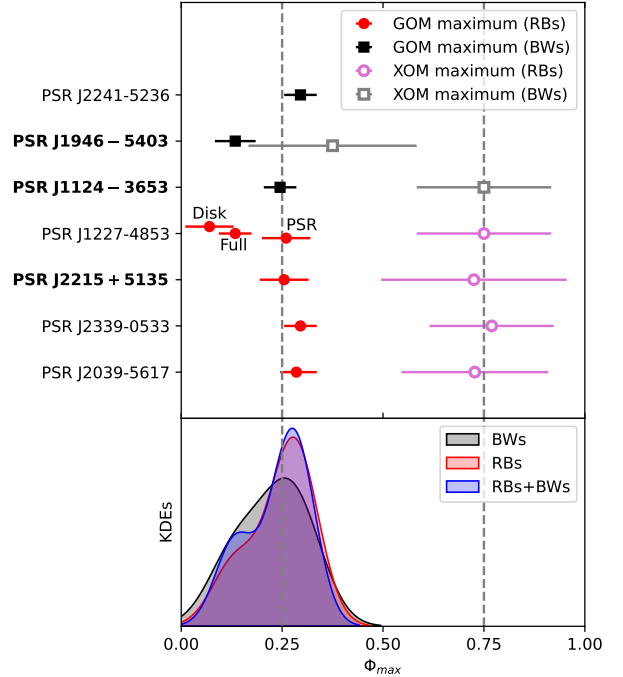


Figure 8. *Top:* Distribution of gamma-ray and X-ray orbital modulation peak phases $\Phi_{\max}$. *Bottom:* KDEs computed using Gaussian kernels with bandwidth $7^{-1/5}$.

flux peaks at inferior conjunction ($\Phi \simeq 0.75$, Fig. 8). In the black widow J1946, however, we find that GOM and XOM are *in phase*: both gamma-ray and X-ray modu-

lations peak at the same orbital phase, near superior conjunction of the pulsar.

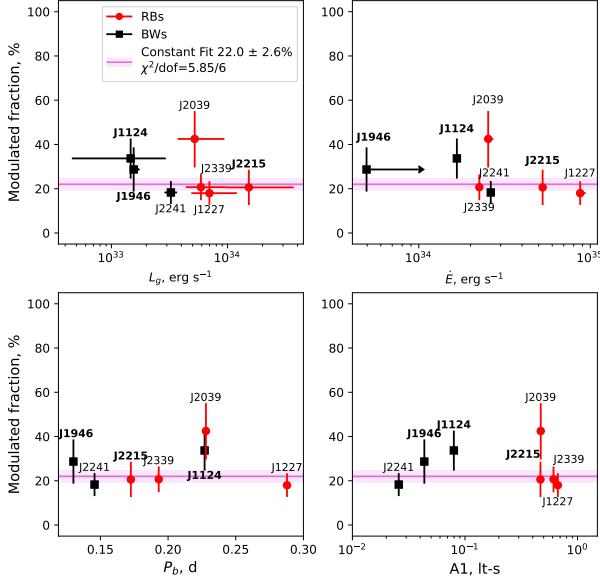


Figure 9. Modulated fractions plotted versus 0.1 – 100 GeV gamma-ray luminosity L_g , spin-down power $\dot{E}$, orbital period P_b and projected semi-major axis of the pulsar $A1$.

Redback companions are about ten times more massive and about twice hotter than black widow companions (factor $\simeq 2$ higher base temperature, [Turchetta et al. 2023](#)). The fact that the MFs are similar across all detected systems (regardless of whether they are redbacks or black widows) suggests a common underlying mechanism for the GOM, independent of the mass and temperature of the companion star. MF and $\Phi_{\max}$ seem also unrelated to the number of maxima in the optical orbital modulation (Table 1), suggesting that the gamma-ray modulation mechanism is independent of the irradiation state of the companion. On the other hand, the phase of the X-ray flux maximum is thought to be determined by the IBS geometry or orientation (Section 1; [Wadiasingh et al. 2017, 2018](#)). Since we always find a soft GOM peak near superior conjunction, independently of the X-ray modulation maximum, we conclude that the origin of the GOM is not directly linked to the IBS orientation.

Figure 10 shows the measured MFs and upper limits, plotted against the gamma-ray flux of each system (F_g , in the 0.1–300 GeV band). We show the MF upper limit and F_g of J1023 in the pulsar state (MJD < 56500), while for J1227 we plot the measured MFs and gamma-ray flux, both averaged as well as separately for disk and pulsar states. Systems with $F_g > 1.5 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$ have GOM detections or stringent upper limits on the

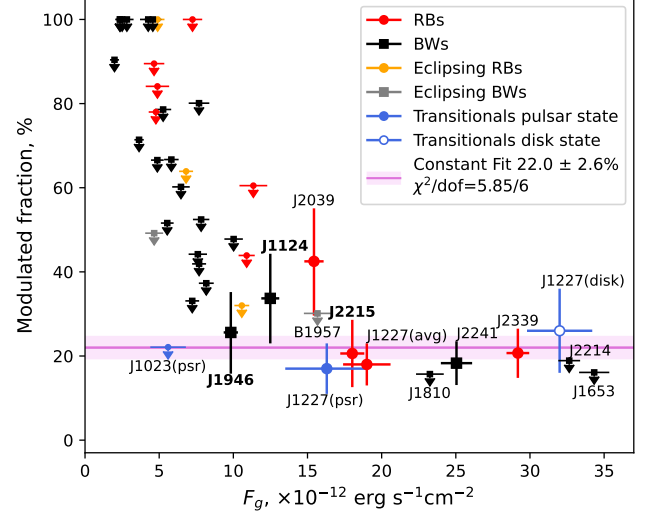


Figure 10. Measured modulated fraction and upper limits as a function of 0.1 – 300 GeV gamma-ray flux.

modulated fraction ($\text{MF} \lesssim 30\%$). This is expected if the MF is independent of F_g , since brighter sources provide more photon counts, allowing for increased sensitivity to potential modulation. Other factors which may contribute to the GOM detectability include the time spanned by the coherent timing solution and the “sharpness” of the pulse profile (Fig. 6).

Three black widows - PSR J1653-0158 (J1653), J1810+1744 (J1810) and J2214+3000 (J2214) - are not detected despite their high gamma-ray fluxes. The corresponding 3σ upper limits on their MFs are 16.1%, 15.7% and 18.9% respectively. These values are close to the constant fit level of $22.0 \pm 2.6\%$. These upper limits are consistent with the average MF within $1-2\sigma$, so we argue that the modulated fraction of the GOM in spider pulsars is universal.

4.2. Transitional MSPs and GOM

As shown by [An \(2022\)](#) and discussed in Section 3.2.1, J1227 exhibits orbital modulation not only in the pulsar state, but also in the disk state. Since gamma-ray pulsations from transitional MSPs have been detected in their pulsar state ([Johnson et al. 2015; Smith et al. 2023](#)), but not in the disk state ([Smith et al. 2023](#)), the additional gamma-ray emission in the disk state is presumably unpulsed. However, the orbital modulation in the disk state remains largely unexplored.

We find that the MF did not change significantly during the disk-to-pulsar state transition: from $\text{MF}_{\text{disk}} = 26 \pm 10\%$ to $\text{MF}_{\text{psr}} = 17 \pm 6\%$ (Section 3.2.1 and Figure 5). The 0.1 – 1 GeV gamma-ray flux from J1227 decreased by a factor $\simeq 2.2$ during the transition, from $F_{\text{disk}} = (20.3 \pm 0.9) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the disk

state to $F_{\text{psr}} = (9.4 \pm 0.5) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the pulsar state. If the additional gamma-ray flux in the disk state were not modulated along the orbit, the MF would be lower in the disk state: it would drop by the same factor $\simeq 2.2$, from the measured $\text{MF}_{\text{psr}} \simeq 17\%$ to an expected 8%. Instead, we find a somewhat higher fractional amplitude in the disk state (26%). Thus, our results suggest that the additional gamma-ray flux in the disk state is also orbitally modulated.

4.3. Orbital inclination and eclipsing systems

As outlined in Section 1, the two main proposed mechanisms to explain GOM in spiders are synchrotron radiation of pulsar wind leptons in the companion’s magnetic field (van der Merwe et al. 2020; Clark et al. 2021; Sim et al. 2024a), and inverse Compton scattering of blackbody photons from the companion by the energetic leptons from the pulsar (An et al. 2020; Clark et al. 2021; Sim et al. 2024a). Here we argue that both scenarios predict a dependence of the MF on the orbital inclination (i), which is not seen in the data.

For six of our seven spiders with detected GOM, we found and compiled from the literature orbital inclinations i determined from optical light curve modeling (Table 4). The five systems showing gamma-ray eclipses are especially interesting, since they allow us to probe GOM at the highest (edge-on) orbital inclinations. Thus, we compiled the lower limits on their i derived by Clark et al. 2023 (also listed in Table 4). The resulting MF- i relation is shown in Figure 11, where we find that edge-on systems do not feature stronger GOM. Remarkably, we find $\text{MF} \lesssim 30\%$ for J1816 and B1957, despite them having $i \gtrsim 80^\circ$. The redback PSR J1908+2105 is seen almost face on ($i < 6^\circ$, Simpson et al. 2025), but it is relatively faint so our upper limits on MF are not constraining and we do not include it in Figure 11 ($\text{MF} < 84\%$; cf. Tables 2 and 3).

In the inverse Compton scenario, electrons and positrons in the pulsar wind up-scatter photons from the companion (Sim et al. 2024a). The resulting flux is proportional to the seed photon energy density along the observer’s line of sight. If blackbody photons from the companion are emitted isotropically with a number density that scales as $1/r^2$ (where r is the radial distance from the center of the star), the line-of-sight seed photon energy density varies with the orbital phase. This phase-dependent variation can produce GOM. Furthermore, systems viewed edge-on, i.e., with high inclination, are expected to exhibit stronger modulation, as the line of sight passes closer to the companion, where photon densities are higher.

Table 4. Orbital inclination estimates obtained from optical light curve modeling of spiders with detected GOM, and lower limits for gamma-ray eclipsing systems.

Name	Type	Inclination	Reference
J1124-3653	BW	$44.9^{+4.0}_{-1.9}$	Draghis et al. 2019
J1227-4853	RBt	$46^\circ \lesssim i \lesssim 65^\circ$	de Martino et al. 2015
J2039-5617	RB	$60^\circ \lesssim i \lesssim 78^\circ$	Clark et al. 2021
J2215+5135	RB	$63.9^{+2.4}_{-2.7}$	Linares et al. 2018
J2241-52364	BW	$49.7^{+2.2}_{-1.9}$	Draghis et al. 2019
J2339-0533	RB	$69.3 \pm 2.3^\circ$	Kandel et al. 2019
B1957+20	BW	$> 84.1^\circ$	Clark et al. 2023
J1048+2339	RB	$> 80.4^\circ$	Clark et al. 2023
J1555-2908	BW	$> 83.1^\circ$	Clark et al. 2023
J1816+4510	RB	$> 79.0^\circ$	Clark et al. 2023
J2129-0429	RB	$> 76.3^\circ$	Clark et al. 2023

NOTE—RB: redback; RBt: redback and transitional MSP; BW: black widow.

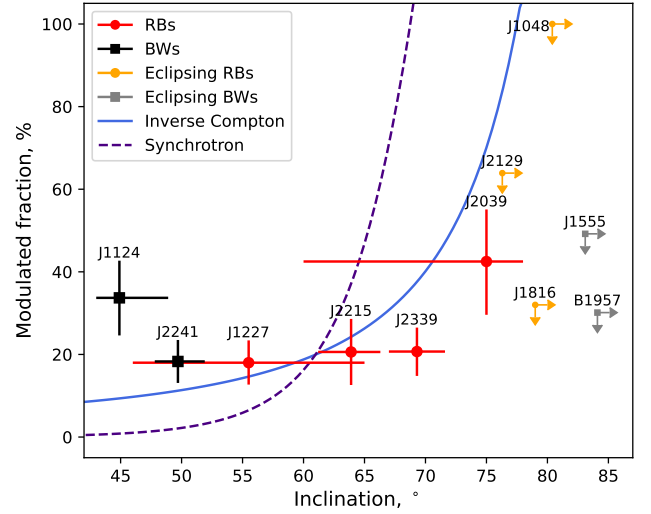


Figure 11. Modulated fractions as a function of orbital inclination (red for redbacks, black for black widows). Upper/lower limits on MF/ i are shown for eclipsing systems, which have tightly constrained inclinations (orange for redbacks and gray for black widows). Solid blue and dashed indigo lines show our predictions for the inverse Compton and synchrotron scenarios, respectively, with an arbitrarily chosen flux normalization.

In the synchrotron scenario, the modulation arises for two reasons. First, the synchrotron peak energy is proportional to the strength of the companion’s dipolar magnetic field, which decreases with distance as $1/r^3$. This peak falls within the LAT energy band near the pulsar’s superior conjunction, when the energetic electrons

pass closest to the companion, so the detected counts are higher⁴. At inferior conjunction, the peak shifts to lower energies since the magnetic field along the line of sight is lower, and the LAT band covers only the high-energy tail of the synchrotron spectrum (so the flux is lower). Second, around pulsar inferior conjunction when the magnetic field along the line of sight is lowest, electrons radiate less efficiently as the synchrotron cooling time becomes longer than the residence time. During that phase, the synchrotron flux becomes proportional to B^2 , giving the lowest gamma-ray fluxes (Sim et al. 2024a). In this synchrotron scenario, the magnetic field of the companion introduces an inclination dependence, similar to the inverse Compton scenario. As a result, edge-on systems are again expected to show stronger modulations.

4.4. Modeling GOM in spiders

We developed a simple analytical model to quantify the MF- i relation in both scenarios. We assume that both inverse Compton and synchrotron emissions are primarily generated at the point along the line of sight closest to the companion star, where pulsar wind electrons interact with the densest photon field and strongest magnetic field, respectively. The distance from the center of the companion to this point is

$$R = a \sin \theta, \quad (1)$$

where a is the binary separation, and θ is the angle between the line of sight and the line connecting the pulsar and its companion. The angle θ depends on both the orbital phase Φ and the binary inclination i , and can be expressed as

$$\cos \theta = \sin(i) \sin(2\pi\Phi). \quad (2)$$

For the inverse Compton scenario, we use Equation (15) from Sim et al. (2024a) describing the bolometric inverse Compton flux. The Φ and i dependence in the flux lies only in the companion's photon field energy density,

$$u_* = \frac{L}{4\pi R^2 c}, \quad (3)$$

where L is the bolometric optical luminosity of the companion star. Thus, we can write the inverse Compton flux as

$$F_{\text{IC}} = K_{\text{IC}} \times u_*(R), \quad (4)$$

⁴ As shown by Sim et al. (2024a), this is true for a companion magnetic field of ~ 1 kG and primary electrons with Lorentz factors $\sim 10^7 - 10^8$.

where K_{IC} is a constant factor, independent of the binary phase and inclination, which characterizes the binary and pulsar wind properties (Sim et al. 2024a).

Inserting (1), (2) into (3), we obtain the photon field energy density as a function of Φ and i :

$$u_*(\Phi, i) = \frac{L}{4\pi a^2 c (1 - \sin^2 i \sin^2(2\pi\Phi))}. \quad (5)$$

Since u_* carries the orbital phase and inclination dependence, and the MF is directly proportional to it at its maximum ($\Phi = 0.25$), we fix the total gamma-ray flux normalization F in order to estimate how the modulation strength depends on inclination. Therefore, we calculate the MF as

$$\text{MF}_{\text{IC}} = \left(\frac{K_{\text{IC}}}{F}\right) \left(\frac{L}{4\pi a^2 c}\right) \frac{1}{1 - \sin^2 i}. \quad (6)$$

The resulting $\text{MF}_{\text{IC}} - i$ relation is shown in Figure 11 with a blue solid line.

To model the synchrotron case, we assume that electrons cool faster than their residence time (ensuring efficient synchrotron emission) and emit at the closest point to the companion, where the magnetic field is highest. The synchrotron spectral energy distribution (SED) then shifts relative to the LAT band as Φ and i change. Since the number of emitting electrons is unknown, our simple model cannot predict absolute fluxes. A full treatment would require integrating losses along the line of sight, as in Sim et al. (2024a). Here, we focus on the relative changes of the SED. Because the LAT band covers only the peak and the high-energy tail of the spectrum, contributions from weaker field regions, which affect mainly the low-energy tail, can be neglected.

We take a simplified approach in which the synchrotron emission is produced by mono-energetic electrons with Lorentz factor γ_0 , propagating in the randomly oriented magnetic field of the companion, B (Sim et al. 2024a; see also Finke et al. 2008). Then, the flux density is

$$f_{\text{SY}}(E) = K_{\text{SY}} \times E \times \tilde{R} \left(\frac{E}{E_c}\right), \quad (7)$$

where K_{SY} is a constant factor and

$$E_c = h \frac{3eB\gamma_0^2}{4\pi mc} \quad (8)$$

is the characteristic (peak) energy of the synchrotron SED. Here, e and m are the charge and mass of the electron, h is Planck's constant, c is the speed of light and $B = B_0(R_0/r)^3$ is the magnetic field in the companion region, where B_0 is the magnetic field strength

at the stellar surface and R_0 the radius of the companion star. Finally, $\tilde{R}$ is given by

$$\tilde{R}(x) = \frac{x}{2} \int_0^\pi d\xi \sin\xi \int_{x/\sin\xi}^\infty dt K_{5/3}(t), \quad (9)$$

where $K_{5/3}$ is the modified Bessel function of the third kind.

Integrating Equation (7) over the 0.1 – 1 GeV band at superior conjunction ($\Phi = 0.25$) for different inclinations, we obtain the dependence of the synchrotron modulation on binary inclination. Fixing the total flux F , we calculate MF as

$$\text{MF}_{\text{SY}} = \frac{1}{F} \int_{0.1 \text{ GeV}}^{1 \text{ GeV}} f_{\text{SY}}(E) dE. \quad (10)$$

The resulting $\text{MF}_{\text{SY}} - i$ relation is shown in Figure 11 with a dashed indigo line, compared with MF_{IC} (blue solid line) and the measured MFs of the detected systems as a function of orbital inclination.

MF_{IC} and MF_{SY} are calculated by adopting typical values for the orbital separation ($a = 10^{11}$ cm) and companion radius ($R_0 = 0.3R_\odot$, typical for redbacks). Moreover, two fundamental parameters in the case of MF_{SY} are the magnetic field at the surface of the companion star B_0 and the Lorentz factor γ_0 . We assume $\gamma_0 = 10^7$ and $B_0 = 1$ kG, as in Sim et al. (2024a), since these values are able to reproduce the observed light curve of a few systems. Despite the wide range of inclinations ($i \simeq 45^\circ - 90^\circ$), we find a lack of correlation between the measured MF and i . This challenges the two main models proposed to explain GOM, since they predict stronger GOM in edge-on systems (see Figure 11).

The absence of stronger gamma-ray modulation at high inclinations disfavors models involving the companion star, and suggests instead that the modulating region is located closer to the pulsar itself. We propose that synchrotron radiation from energetic leptons in the pulsar wind interacting with the magnetic field of the IBS could be a possible mechanism. This would require a relatively strong magnetic field within the shock (perhaps amplified by turbulence, Bell 2004) and a short synchrotron cooling time. This would naturally explain orbital phasing and the inclination independence of our measured MF values. Since we find $\text{MF} \simeq 30\%$ in J1946 (Sec. 3.1.2), where the IBS is presumably wrapped around the companion, the modulation should occur in the central parts of the IBS where the shock tangent is always nearly perpendicular to the line of sight (for large orbital inclinations). Future studies are required to quantify the modulated fraction in this or alternative

models. New detections of GOM or more stringent limits at lower orbital inclinations ($i < 45^\circ$) may also give new clues as to its physical origin.

5. SUMMARY AND CONCLUSIONS

After conducting a systematic search for gamma-ray orbital modulation in 43 spider pulsars, we have discovered three new systems exhibiting soft pulsed GOM (and confirmed four previous detections). We have quantified the modulated fraction in the 0.1 – 1 GeV band, and found this to be approximately constant at $\text{MF} = 22.0 \pm 2.6\%$. In all detected cases, the gamma-ray modulation peaks near the pulsar’s superior conjunction, regardless of the maximum phase of the XOM. In the transitional pulsar J1227, we find a tentative difference in the peak phase of the soft GOM between the disk and pulsar states, but the MFs remain approximately constant throughout the state transition. We find that the measured MFs are relatively uniform and show no clear dependence on inclination. This challenges current models proposed to explain GOM, including those based on synchrotron or inverse Compton emission, which predict a strong dependence of MF on orbital inclination. Instead, we suggest that the region that modulates gamma-rays is closer to the pulsar (rather than the companion star), where the dependence with inclination can be weaker.

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Facilities: Fermi-LAT

Software: Fermi Science Tools (v2.2.0) (Fermi Science Support Development Team 2019); *fermipy* (Wood et al. 2017); *TEMP02* (Edwards et al. 2006; Hobbs et al. 2006; Ray et al. 2011); NumPy (Harris et al. 2020); SciPy (Virtanen et al. 2020); Matplotlib (Hunter 2007)

⁵ <https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi>

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APPENDIX

A. FOLDED ORBITAL LIGHT CURVES

Figure A1 shows light curves folded at the orbital period for the 36 systems analyzed, with no significant GOM detected.

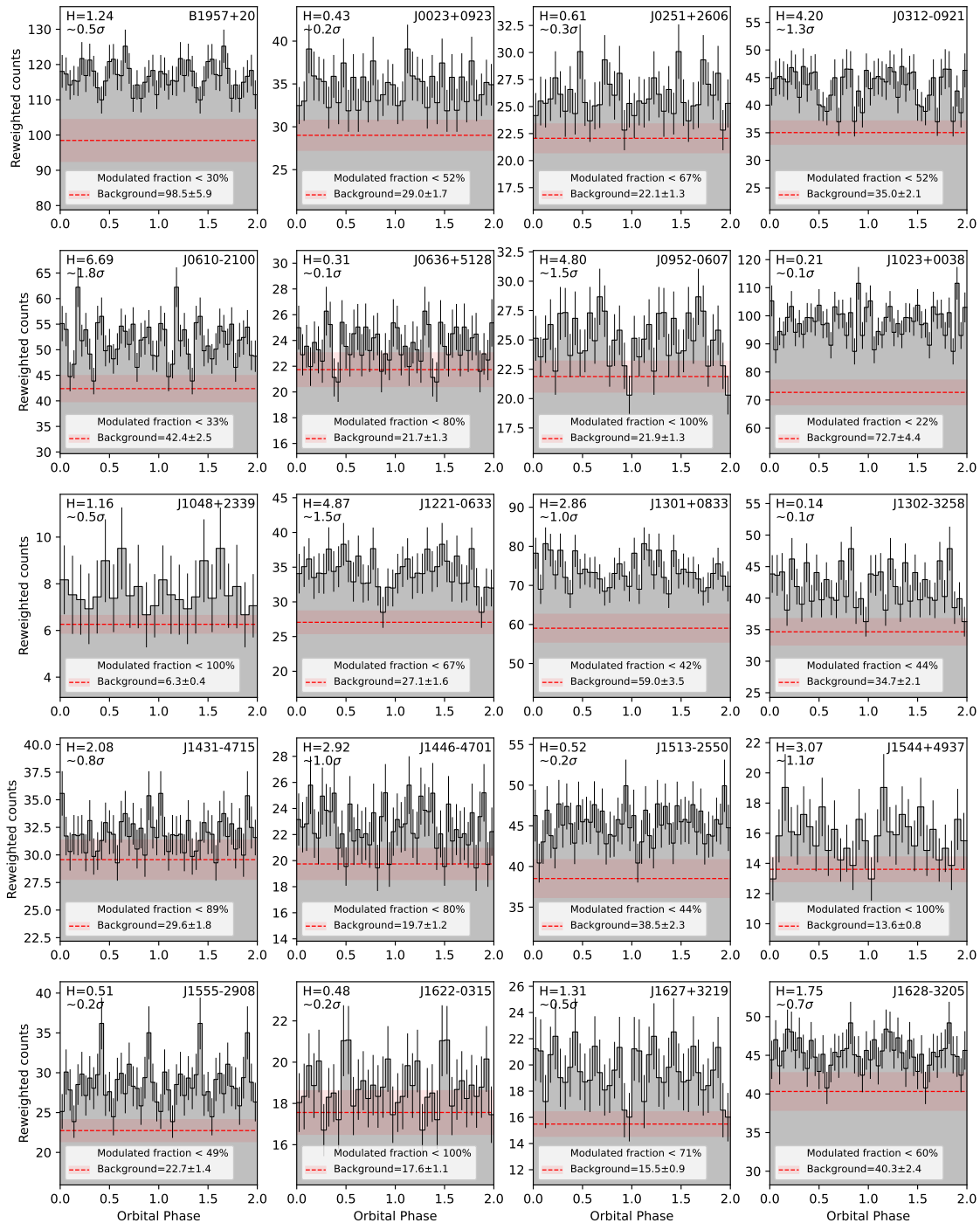


Figure A1. Orbital light curves.

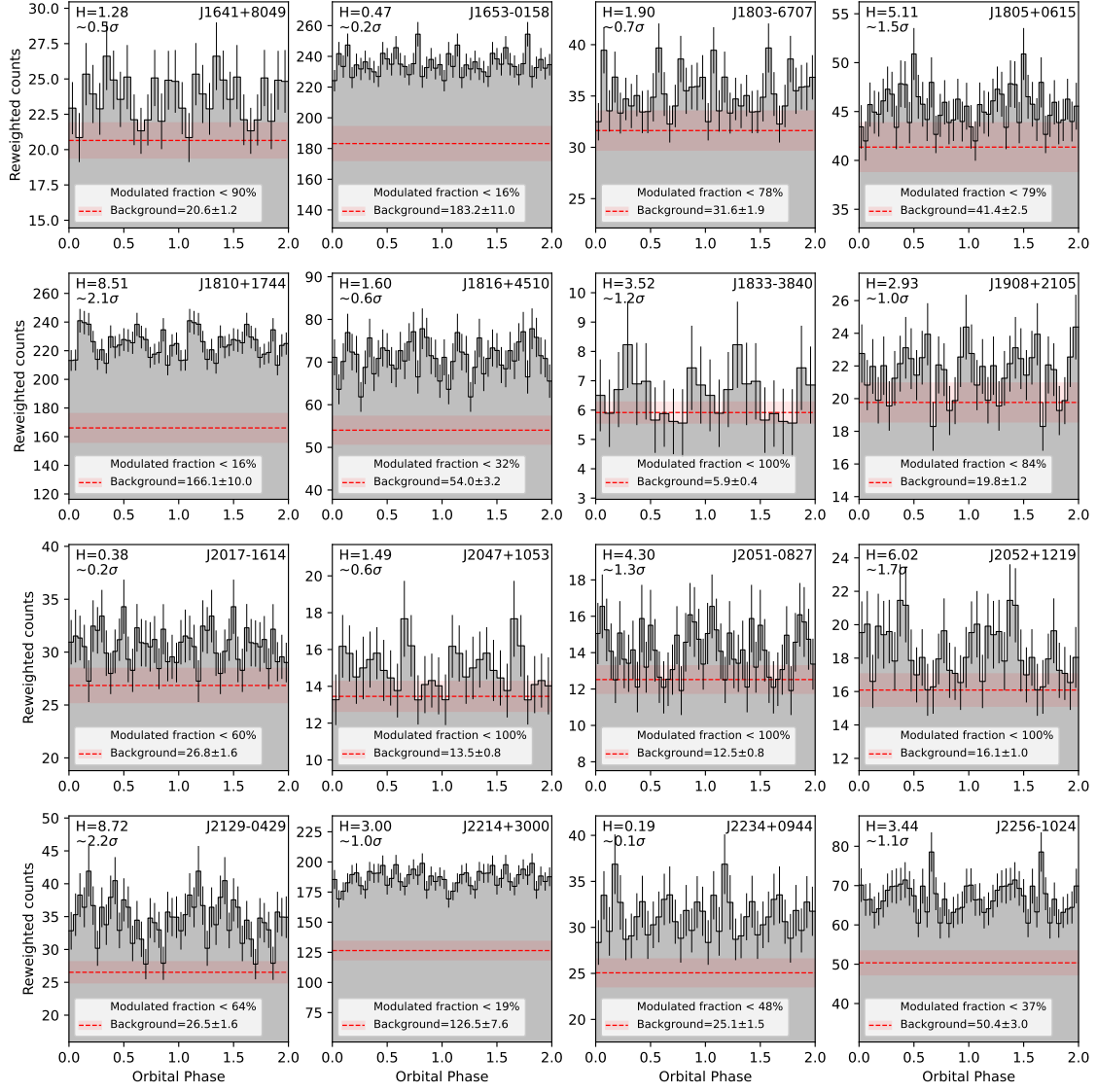


Figure A1. (Continued) Orbital light curves.

B. EXTENDED TIMING PRODUCTS

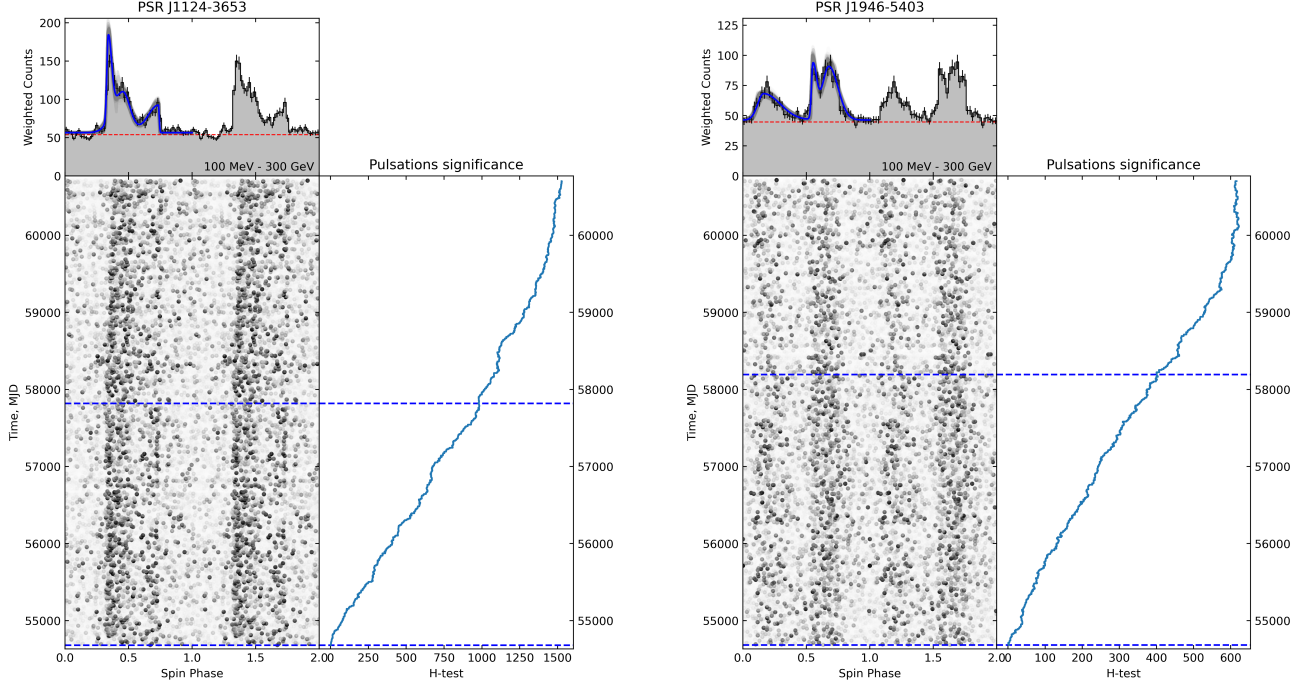


Figure B1. Our gamma-ray timing results for J1124 and J1946 in the $0.1 - 300$ GeV energy band. *Top panel:* the black curve represents the folded light curve, the blue curve shows the template pulse profile, and the dashed red line indicates the background level. *Bottom left:* photon spin phases are plotted against time, with the color representing the weights of the photons. *Bottom right:* the cumulative H-test for pulsations significance is shown over time. Dashed blue lines in the bottom panels indicate the start and end of the timing solution used.

C. FOLDED LIGHT CURVES OF ECLIPSING SYSTEMS

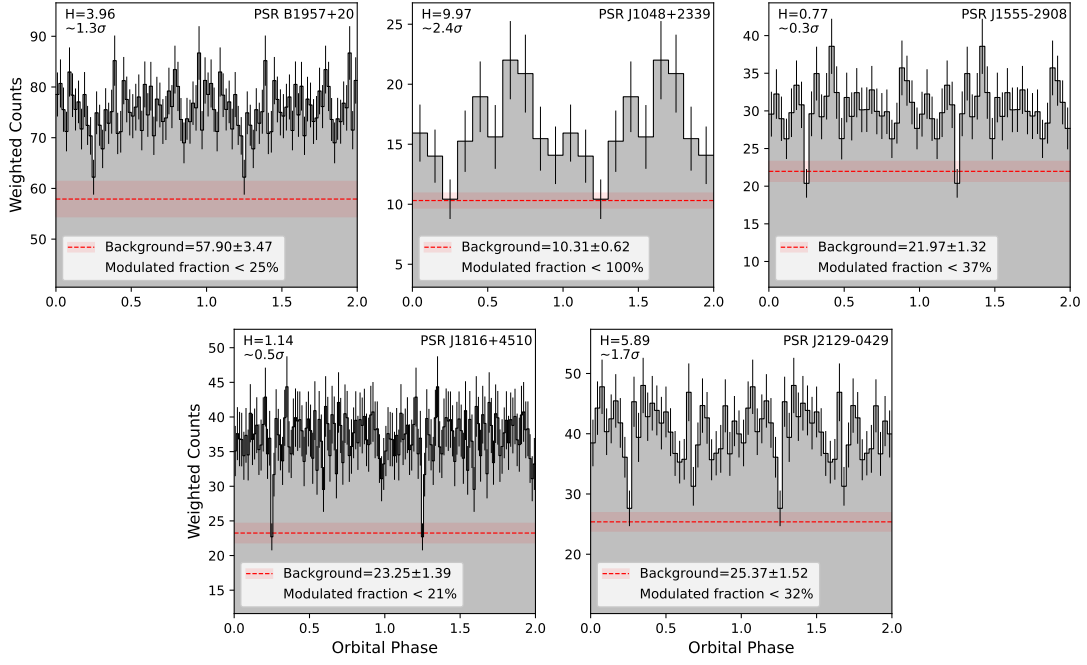


Figure C1. Reweighted gamma-ray light curves of eclipsing systems in the 0.1 – 300 GeV energy range, optimal for eclipse detection. The black points represent the folded data, with uncertainties and the red line represents the background level.

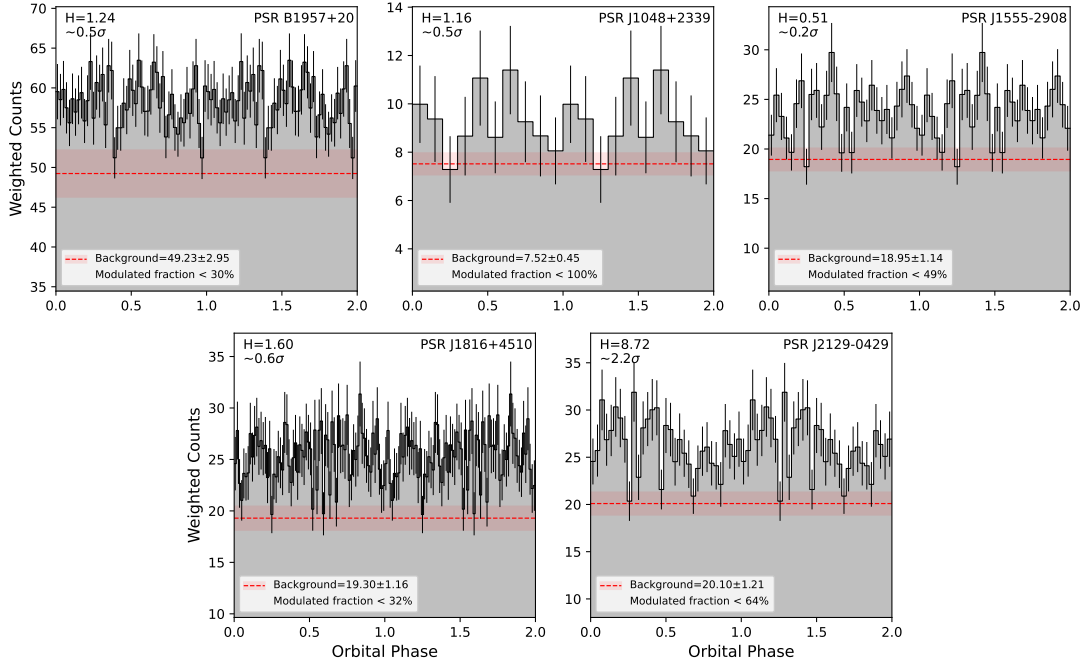


Figure C2. Reweighted gamma-ray light curves of eclipsing systems in the 0.1 – 1 GeV energy range, optimal for GOM detection. The black points represent the folded data, with uncertainties and the red line represents the background level.