Orbital Modulation of Gamma Rays from PSR J2339-0533

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Abstract

We report on orbital modulation of the 100–600 MeV gamma-ray emission of the $P_B = 4.6$ hr millisecond pulsar binary PSR J2339−0533 using 11 yr of Fermi Large Area Telescope data. The modulation has high significance (chance probability $p \approx 10^{-7}$), is approximately sinusoidal, peaks near pulsar superior conjunction, and is detected only in the low-energy 100–600 MeV band. The modulation is confined to the on-pulse interval, suggesting that the variation is in the 2.9 ms pulsed signal itself. This contrasts with the few other known systems exhibiting GeV orbital modulations, as these are unpulsed and generally associated with beamed emission from an intrabinary shock. The origin of the modulated pulsed signal is not yet clear, although we describe several scenarios, including Compton upscattering of photons from the heated companion. This would require high coherence in the striped pulsar wind.

Unified Astronomy Thesaurus concepts: Millisecond pulsars (1062); Low-mass x-ray binary stars (939); Gamma-ray sources (633); Close binary stars (254); Pulsars (1306); Gamma-rays (637)

1. Introduction

Since the launch of the Fermi Large Area Telescope (LAT; Atwood et al. 2009), the list of millisecond pulsar-binary systems is growing rapidly thanks to its wide field of view, large effective area, and continuous all-sky monitoring. The so-called “spider” binaries, black widows (BWs; with a $<0.1 M_\odot$ companion), and redbacks (RBs; with a 0.1–0.7 $M_\odot$ companion), in which the pulsar wind is evaporating the companion, are believed to be descendants of low-mass X-ray binaries whose neutron star primaries have been spun up over long times by accretion (Alpar et al. 1982).

In these systems, the spindown flux of the pulsar heats the pulsar-facing side of the companion, which manifests as day–night cycles in the optical light curves, and a wind from the companion’s surface collides with the relativistic pulsar wind to form an intrabinary shock (IBS). Pair particles energized in the shocked pulsar wind, likely via shock-driven reconnection, accelerate along the contact discontinuity to mildly relativistic velocities and beam synchrotron radiation in a hollow cone pattern (e.g., Romani & Sanchez 2016; Wadiasingh et al. 2017; Kandel et al. 2019). When the pulsar momentum flux dominates (as is typical for black widows), the IBS wraps around the companion, so that beamed IBS emission reaches the observer at pulsar superior conjunction (companion in front, optical “night side,” binary phase $\phi_B = 0.25$ with respect to the pulsar ascending node). For the RB case, the wind from the more massive companion generally dominates, the shock wraps around the pulsar, and IBS emission should be centered on pulsar inferior conjunction ($\phi_B = 0.75$). This synchrotron emission is quite bright in the X-ray band, giving rise to a characteristic double-peak orbital modulation in the X-ray light curve (e.g., Huang et al. 2012) as the observer’s line of sight cuts through this hollow cone with the binary rotation. The X-ray modulation is sensitive to the system geometry (e.g., wind strengths, inclination) and thus can supplement the optical modeling (e.g., Kandel et al. 2019) in inferring binary properties.

If sufficiently energetic, IBS particles can also produce gamma rays via synchrotron or inverse Compton emission. However, the very bright GeV pulsar magnetospheric emission dominates, making this signal difficult to detect, and only a handful of such detections have been made (Wu et al. 2012; An et al. 2017, 2018; Ng et al. 2018). Hard spectrum $\gamma$-ray modulation is likely due to inverse Compton scattering, while in the case of PSR J2241−5236 the emission is quite soft, with a sub-GeV cutoff, suggesting we may be seeing the upper limit of a beamed synchrotron component (An et al. 2018).

PSR J2339−0533 (J2339 hereafter) is a 2.9 ms pulsar in a 0.19 day orbit with a $0.3 M_\odot$ companion (Romani & Shaw 2011; Kong et al. 2012). It was identified as a pulsar binary by targeted optical studies of the brightest unidentified Fermi-LAT sources with pulsar-like emission, and then confirmed via LAT and radio pulsations (Ray et al. 2020; Pletsch & Clark 2015). Its optical light curve shows strong heating, and pulsar timing characterizes it as an RB with a companion mass $M_2 \approx 0.3 M_\odot$. In the X-ray band, the spectrum is a hard power law, and the light curve shows double-peaked structure bracketing $\phi_B = 0.75$; these are good signatures of RB-class IBS emission (Romani & Shaw 2011; Kandel et al. 2019). With a GeV flux $\approx 3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, this bright source invites a deep search for gamma-ray modulation, using a long 11 yr set of Fermi-LAT data. We show data analyses and the results in Section 2. We then present toy models in an attempt to describe the modulation in Section 3; these are not yet fully satisfactory. We conclude in Section 4. Uncertainties are at the 1$\sigma$ confidence level unless noted otherwise.

2. Observational Data and Analyses

2.1. Data Reduction

Fermi-LAT data collected between 2008 August 4 and 2019 July 28 are downloaded from the public archive$^4$ and analyzed.

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$^4$ https://fermi.gsfc.nasa.gov/ssc
with the Fermi Science Tools (ST) version 1.0.1 along with the most recent instrument response files (P8R3_SOURCE_V2). We select the Front+Back event type in the SOURCE class in an R = 10° region of interest (ROI) centered at the source position. The data are further reduced by requiring the zenith angle < 90°, DATA_QUAL > 0, and LAT_CONFIG = 1. Note that intense solar flares occurred when the Sun was ~7° away from J2339, and we have removed the flare time periods (Section 2.2).

### 2.2. Timing Analysis

J2339 shows significant variability in its binary period, which complicates long-term analysis of the pulsed signal. Such variability is common in RBS, but is particularly strong for J2339. Plotsch & Clark (2015) analyzed ~6 yr of LAT data to describe the variability and proposed that it is associated with a variable companion quadrupole moment. Since the variability is stochastic, their model does not extend to later times; thus, our analysis first requires an updated pulsar timing solution. For each event, we compute a probability weight w_i (Kerr 2011) using the gtscprob tool of Fermi-ST based on the 4FGL model (The Fermi-LAT collaboration 2020), and we fold the events using tempo2 (Edwards et al. 2006) on an initial timing solution to calculate the arrival phases (\( \phi \)). We then gradually increase the time coverage to 11 years and generate a new timing solution by maximizing the unbinned likelihood

\[
\log L = \sum_i \log[w_i f(\phi, t_i)] + 1 - w_i, \tag{1}
\]

where \( f \) is an analytic pulse-profile model and \( \lambda \) is the set of shape parameters. We use the PINT software package\(^5\) (Luo et al. 2018), and adjust the timing parameters, holding the eccentricity fixed at 0. For the position and proper motions we use the GAIA results (Brown et al. 2018; Jennings et al. 2018). The best-fit timing solution and the parameter uncertainties (1σ) are reported in Table 1, and the resulting pulse profiles are presented in Figure 1.

Next we investigate orbital modulation of the source. We inspect the \( R = 3° \) source light curve in three energy bands (100–1000 MeV, 100–600 MeV, and 1000–100,000 MeV) using the \( H \) test (Kerr 2011) and find strong modulation in the pulse-phase-summed low-energy (100–600 MeV) data with \( H = 27 \) corresponding to \( p \approx 2 \times 10^{-5} \); higher-energy modulation is insignificant with \( H \approx 1 \). Note that the two low-energy bands are not independent and accounting for two trials would not affect these results significantly. We find that this low-energy modulation peaks near \( \phi_0 \approx 0.25 \). This is surprising, as for typical RB parameters we expect an IBS maximum to occur near \( \phi_0 = 0.75 \); indeed during the X-ray observations the IBS clearly brackets this phase, implying that (at least at these times) the wind wraps around the pulsar.

As noted above, in the gamma-ray band IBS emission is far fainter than the strong pulsed magnetospheric emission. Thus we would expect that IBS orbital modulation would be stronger in spin phases where the magnetospheric emission is beamed away from Earth. We thus define on- (\( \phi = 0.2–0.78 \)) and off-pulse (\( \phi = 0.78–1.2 \)) intervals (Figure 1) and generate pulse-phase-selected orbital light curves in the 100–600 MeV band using the \( R = 3° \) ROI.

| \( \nu \) (s\(^{-1} \)) | 346.713379220472(2) |
| \( \dot{\nu} \) (s\(^{-2} \)) | \(-1.69452 \times 10^{-15} \) |
| TZRMJD | 56552.1042084326877 |

Note. 1σ uncertainties are shown in brackets, and parameters without the uncertainty are held fixed. \( F_{\nu}'s \) are xth time derivatives of the orbital frequency \( F_{\nu} \).

![Figure 1](image.png)

**Figure 1.** Fermi-LAT gamma-ray pulse profiles of J2339 from an \( R = 3° \) ROI in three energy bands: 0.1–500 GeV (top), 0.1–0.6 GeV (middle), and 0.6–500 GeV (bottom). Red vertical lines show the off-pulse (\( \phi = 0.78–1.2 \)) interval used in our analyses and blue lines denote the average background level estimated using the photon weights: \( \sum(w_i - w_i^2)/N_{\text{bin}} \).

Surprisingly, we find that modulation in the “on-pulse” interval is very strong with \( H \approx 40 (p \approx 10^{-7}; Figure 2 \) left) while that in the off-pulse interval is insignificant with \( H \approx 1 \). Changing the ROI size and/or pulse-phase selection slightly does not alter the results, but they are relatively sensitive to the energy selection; increasing the higher-energy bound reduces the significance (e.g., \( p \approx 2 \times 10^{-4} \) in the 100 MeV–1 GeV band). We further verified that the significance of the 100–600 MeV modulation increases approximately monotonically with time (Figure 2, right).

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\(^5\) https://github.com/nanograv/PINT
We test whether this modulation is induced by exposure variation or flares of nearby sources (e.g., blazars). We compute 30 s binned exposure using the `gtexposure` tool of Fermi ST and fold the exposure using the same timing solution (Table 1); the exposure variation on the orbital period is less than 1%. However, we do find three very bright outbursts in our ROI. We traced these to dramatic solar flare activity in the intervals MJD 55628–55629, MJD 55991–55996, and MJD 56712–56713. We excised these time intervals from the rest of the analysis. We also inspect probability-weighted light curves of three nearby sources including the blazar PKS 2320–035 by folding events within $R = 3^\circ$ centered at the source positions. We then perform $H$ tests on the data of the comparison sources using the same selection criteria as used for J2339 and find that none show significant modulation ($H \leq 3$). Moreover, the shapes of the light curves of the comparison sources differ from that of J2339. Hence, we conclude that the low-energy modulation is intrinsic to J2339. However, it is confined to the on-pulse interval and peaks at pulsar superior conjunction, precisely opposite to expectations for IBS emission beamed along the contact discontinuity.

2.3. Spectral Analysis

We next investigate the spectral properties of the source and the modulated flux. We perform binned likelihood analyses in the 100 MeV–300 GeV band to measure spectral properties of J2339. We follow the standard binned analysis procedure using the 4FGL model with energy dispersion. Because the ecliptic passes through the ROI, we also include Sun and Moon emission\(^6\) and exclude intense solar flare periods (see above) in this analysis. In likelihood fits, we allowed the spectral parameters of J2339, those of the brightest field source (PKS 2320–035), and the normalizations of the diffuse models (gll_iem_v07 and iso_P8R3_SOURCE_V2_v1) and of the Sun and Moon emission to vary, while other source parameters were held fixed at the 4FGL model values. We then gradually free parameters of the next brightest sources in the field and compare the fit statistics using the Akaike Information Criteria (AIC; Akaike 1974) until improvement of the fit is insignificant. In all, we find four point sources, the Sun and Moon emission, and the diffuse models require reoptimization.

J2339 is modeled with a power-law exponential cutoff (PLEXP2) model $dN/dE = N_0(E/E_0)^\Gamma e^{-E/E_0}$. In the model, $E_0$ is the reference energy for $N_0$, and $\Gamma$ is not well constrained due to the lack of high-energy data for J2339 but $\Gamma = 0.67$ provides good fits for bright pulsars (The Fermi-LAT collaboration 2020). We therefore hold these parameters fixed at the 4FGL values $E_0 = 1.1$ GeV and $\Gamma = 0.67$, and note that fixing these parameters does not have a large impact on our investigations below. The best-fit parameters are $N_0 = 9.5 \pm 0.8 \times 10^{-12} \text{ph MeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$, $\Gamma_1 = 1.06 \pm 0.07$, and $a = 7.8 \pm 0.6 \times 10^{-7}$ with $F_{0.1–300 \text{GeV}} = 2.2 \pm 0.1 \times 10^{-8} \text{ph cm}^{-2} \text{s}^{-1}$; these are fully consistent with the 4FGL values. These values may be affected by small uncertainties due to systematic errors in the effective area and the Galactic diffuse model,\(^7\) but their absolute values are not important for our analysis. We note that neither inclusion nor exclusion of the Sun/Moon emission has any significant impact on the results.

Because the orbital modulation is pulse-phase dependent, we examine variations in the pulsar spectrum at different orbital phases. We perform likelihood analyses with on-pulse data in 10 orbital-phase bins, fitting PLEXP2 models and producing spectral energy distributions (SEDs). In the fits, we let the J2339 parameters vary and hold all the other parameters (i.e., for the diffuse and solar/lunar emission, and sources in the ROI) fixed at the phase-averaged values. These are plotted in Figure 3 along with the best-fit spectral models for the orbital-maximum ($\phi_B = 0.25$, black dotted line) and -minimum bins ($\phi_B = 0.75$, red dotted line). At orbital maximum the low-energy index $\Gamma_1$ ($\phi_B = 0.25$) = 1.39 ± 0.14, a fairly typical millisecond pulsar (MSP) LAT spectrum. However, the deficit of low-energy counts near orbital minimum (Figure 4) means that the PL component is fainter and harder, $\Gamma_1(\phi_B = 0.75) = 0.6 \pm 0.3$. Note that the >GeV flux is nearly

\(^6\) https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/solar_template.html

\(^7\) https://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats.html
constant while, as expected, the low-energy flux varies as described in Section 2.2.

We investigate if the orbital modulation of the on-pulse spectrum is produced by additional power-law (PL) emission (e.g., from IBS) to the constant pulsar emission which is best represented by the orbital minimum (PLEXP2) spectrum. Because the additional PL parameters cannot be constrained in all the orbital phase bins separately, we apply this composite model first to the orbital-maximum spectrum (holding the PLEXP2 parameters fixed at the orbital-minimum values) in order to determine a representative photon index: $\Gamma = 2.6 \pm 0.3$. We note that the PL component is detected with a test statistic (TS) of 25; the freely fit PLEXP2 model has a slightly lower $-\log \mathcal{L}$ ($\Delta \log \mathcal{L} = 2$) as compared with the composite model (minimum-fixed PLEXP2 + fit PL), and the latter is not significantly better than the single component model (AIC $p = 0.6$). We then carry out an orbital phase-resolved likelihood analysis with the PLEXP2+PL model by holding the PLEXP2 parameters fixed at those of the orbital minimum and the PL photon index at 2.6. Although the composite model is not significantly better than PLEXP2 in any orbital phase bin, it provides useful parameters for the exploration of physically motivated models (see Section 3).

We also measure the orbital-phase-integrated off-pulse spectrum using a PLEXP2 or a PL model in the likelihood analysis. Because the emission is very faint, we fit the normalization of the PLEXP2 and the normalization and index of the PL model, holding all the other parameters fixed at the phase-average values. The emission is detected with TS of 18 and 19 for the PLEXP2 and PL (with an index of $\Gamma = 2.4 \pm 0.2$) models, respectively.

3. Toy Models for the Orbital Variability

We next seek a plausible origin for this modulation. Since the orbital phase evolution is opposite to that expected from an IBS component (and to that of the observed double-peaked X-ray emission), it is highly unlikely that this is standard IBS shock emission. This is underlined by the fact that the modulation is of pulsed photons. Indeed, it seems to be directly associated with soft counts that follow the pulse profile, as the two spin-phase peaks account for most of the orbital modulation; $P_1 (\phi = 0.3–0.33)$ yields an orbital modulation $H_1 = 22$ and $P_2 (\phi = 0.7–0.75)$ yields $H_2 = 17$, compared to an on-pulse $H = 40$.

Figure 5 compares the pulse profiles at orbital minimum ($\phi_B = 0.6–0.9$) and maximum ($\phi_B = 0.1–0.4$) for the low-energy gamma rays. The stronger pulse at orbital maximum is clearly seen, as well as a small, potential shift in the position and amplitudes of the pulse peaks.

In order to quantitatively compare the pulse profiles at orbital minimum/maximum, we employed the simplest model sufficient to describe the pulse structure, namely a wrapped model.
Lorentzian to describe the first peak (P1) and wrapped Gaussians for the second peak (P2) and the bridge emission between the two, and we used the log likelihood for this model (Equation (1)) to assess the significance of possible shape changes in the pulse. The weights appearing in the log likelihood are typically calculated for a single spectral model, but here we know the spectral shape and intensity varies between orbital maximum and minimum. Because the source is brighter, particularly at low energies, during orbital maximum, weights are overestimated at orbital minimum, potentially inducing an unpulsed component. To adjust the weights to the correct spectrum, we “reweight” each photon \( w \rightarrow \alpha w / ((\alpha w + 1 - w)) \) with \( \alpha \) the flux ratio e.g., \( \alpha_{\text{min}} = f_{\text{min}} / \delta f_{\text{min}}(f_{\text{min}} + f_{\text{max}}) \) for photons (see Kerr 2019, for more details) from orbital minimum and mutatis mutandis for photons from orbital maximum. The spectral models obtained in 10 orbital phase bins (Section 2.3) provide sufficient granularity and are commensurate with the \( \delta f_B = 0.3 \) windows adopted here, so we employ them for the reweighting.

With the corrected weights, we maximize the likelihood for photons from the orbital maximum to obtain a baseline pulse template. We then refit a subset of parameters, e.g., the location and/or position of one or both of the two peaks, to measure the change in log likelihood and thus measure the significance, which we calculate via Wilks’ Theorem, viz. that twice the change in log likelihood under the null hypothesis is distributed as \( \chi^2 \) in the number of free parameters. Our results are shown in Table 2. We find modest evidence for differences in peak parameters, both individually and collectively. The most significant is a shift in the positions of P1 and P2 later and earlier in phase, respectively, at about the 3.3\( \sigma \) level.

To compensate for any discrepancy in the renormalization of the weights, which might mimic an unpulsed component, we repeat our fits with an additional unpulsed component and measure shape changes relative to it. We find little evidence for such a component (1.2\( \sigma \)), and the results in Table 2 are stable (changes of 0.1–0.2\( \sigma \)).

This is remarkable since the standard assumption is that spin-powered pulsar emission is independent of the binary phase. Here, with a circular orbit and the companion tidally locked, there should be no orbital modulation of conditions in the magnetosphere. Averaged over a spin period, the pulsar emission should be constant.

Here we explore possible reasons for the orbital pulse flux variation. The first possibility is that the pulsar emission is intrinsically constant, but absorbed at low energy, with an absorption linked to the wind flows. This is attractive since the binary flux maximum (\( \phi_B = 0.25 \)) spectrum is typical of an LAT MSP. Moreover, the high-energy flux (\( \geq 2 \) GeV) does not

Figure 4. Phase-resolved SEDs divided by the best-fit orbital-maximum spectral model, and absorption model fits (red dashed; see the text). Horizontal lines (i.e., no absorption) are plotted for reference.
show strong orbital variation. Since orbital minimum at \( \phi_B \geq 0.75 \) is at pulsar inferior conjunction, when we are looking through the pulsar wind-filled channel, the absorption should be associated with the swept-back pulsar wind. This absorption needs to be strongest at low energy. Compton scattering with the Klein–Nishina effect (Klein & Nishina 1929) provides such a cross section:

\[
\sigma_{KN} = \frac{3\sigma_T}{4} \left[ \frac{1 + x}{x^3} \left( \frac{2(1 + x)}{1 + 2x} - \ln(1 + 2x) \right) \right. \\
+ \left. \frac{1}{2x} \ln(1 + 2x) - \frac{(1 + 3x)}{(1 + 2x^2)} \right],
\]

where \( \sigma_T \) is the Thomson scattering cross section and \( x = E_v/m_e c^2 \). Remembering that during the minimum phases we are looking along the flow of the post-termination shock (but precontact discontinuity) pulsar wind toward the observer, with bulk motion \( \Gamma_w \), we may take \( x = E_v/\Gamma_w^2 m_e c^2 \). The scattering cross section decreases as \( \sim 1/E_v \) (until pair production of the electron field dominates at higher energies, when it is energy independent).

To implement such a model, we assume a bulk Lorentz factor \( \Gamma_w = 100 \) and model the orbital phase-resolved SEDs as a (fixed) pulsar PLEXP2 function absorbed by \( e^{\tau(E)} \) with \( \tau(E) = C(\phi_B)\sigma_{KN}(E) \) and the effective absorption column \( C(\phi_B) \) varying with orbital phase. All intrinsic pulsar spectral parameters are held fixed at orbital-maximum fit values, leaving the effective absorption column \( C(\phi_B) \) as the only adjustable parameter. Instead of performing likelihood analyses for each phase bin, we divide the measured SEDs (Figure 3) by the fixed (orbital maximum) pulsar model (Figure 4) and vary \( C(\phi_B) \) to fit the ratio in each phase bin. The values are plotted in Figure 6 (right panel) and compared to a simple geometrical estimate of the variation in the column density through the \( e^+/e^- \) of the post-shock pulsar wind. We can assume that the wind expands \( (n \sim 1/r^2) \) or is approximately equatorial \( (n \sim 1/r) \). The former gives a somewhat wider peak and better match to the data. The inferred column density \( C(\phi_B) \) is maximal at \( \phi_B \approx 0.85 \), in reasonable agreement with the pattern from IBS sweepback. Note that we assume that the scattering column starts at a termination shock distance comparable to the standoff of the pulsar wind at the nose; if the denser pair plasma closer to the pulsar dominated, this constant absorption would wash out any orbital phase variation, so the dominant absorption must occur on the scale of the orbital separation \( a \sim 2R_p \).

However, for this model to make any sense we must reach a maximum optical depth \( \tau \sim 1 \) at an observed \( E_v \approx 0.1 \text{GeV} \). Suppose that \( 10^{34}E_{34} \text{erg s}^{-1} \) of the pulsar spindown luminosity (total power \( E_{34} = 2.1 \) considering the Shklovskii effect for J2339; Brown et al. 2018; Jennings et al. 2018) is converted to pairs in a cold wind with bulk Lorentz factor \( \Gamma_w \). This wind is axisymmetric around the pulsar until the closest termination shock at the radius \( n_0 \approx a/3 \), where \( a = 10^{14}a_{14}\text{cm} \) is the orbital separation, so for the pairs to produce an orbital modulation, the bulk of the absorption must be created at or beyond this distance, e.g., by conversion of a high \( \sigma \) (magnetization) wind. For these assumptions, the Thomson scattering depth from a radius \( a \) through this pair plasma is \( \tau \approx \tau_T \rho \phi/(4\pi a n_e c^2) \approx 7 \times 10^{-7}E_{34}/(a_{14}\Gamma_w) \). Since the Klein–Nishina cross section is reduced by \( \sim E_v/(\Gamma_w^2 m_e c^2) \) at gamma-ray energies, this misses by several orders of magnitude. Geometry might increase the column by a factor of a few if, e.g., the Earth line of sight happens to pass through a \( \sim 2D \) electron layer. One might also imagine that neutral H penetrates the IBS and is ionized by the preshock pulsar wind. However, even using all spindown power for ionization rather
than pair production only increases the $e^-$ density by $1.02 \times 10^6 \text{eV}/13.6\text{eV} \approx 8 \times 10^4$. Thus it seems impossible for the pulsar to produce sufficient optical depth distributed over the orbital length scale, as required for an orbitally modulated scattering or absorption.

The alternative is to add pulsed flux to the orbital minimum. Here the likely mechanism involves Compton up-scatter of low-energy photons from the heated companion (e.g., Wu et al. 2012; An et al. 2017; Ng et al. 2018). Such upscattered photons are believed to dominate the orbitally modulated signal from high-mass gamma-ray binaries (Dubus 2013). The Compton power per electron upscattered from a soft photon energy density $u_\gamma$ by the pulsar wind of bulk motion $\Gamma_w$ is

$$P_{\text{ICS}} = \sigma_T c u_\gamma (1 - \beta_w \mu) [(1 - \beta_w \mu) \Gamma_w^2 - 1],$$

with $\mu = \cos \theta_{\text{ICS}}$ the angle between the pulsar wind $e^+/e^-$ (radial toward Earth in the pre-shock flow) and the stellar photons. Here we have the advantage that the power modulation is imparted by the asymmetric (day–night) radiation from the companion, so that the gamma rays may be produced close to the pulsar. Figure 7 illustrates an ICS excess model, with the points showing the companion flux as a function of phase, and a simplified estimate of the associated ICS signal, compared with a PL fit to the orbitally varying LAT data (arbitrary normalization for the y-axis).

We can use either the observed magnitudes $m_e = 18.8$ (and the fit $d \approx 1.25\text{kpc}$ source distance) or the fit stellar temperature $T_{\text{eff}} = 4800\text{K}$ to estimate the photon energy density from the companion (Romani & Shaw 2011; Kandel et al. 2019). In the near zone of the pulsar wind (about $2R_\odot$ from the companion) this is $u_\gamma \approx 0.2\text{erg cm}^{-3}$. As above the pulsar produces electrons at a rate $\dot{N}_e \approx \dot{E}/(\Gamma_w m_e c^2) \approx 2 \times 10^{40}/\Gamma_w \text{e}^-/\text{s}$. Assuming that the Compton upscattering occurs over a distance $\delta r_\odot$ (in solar radius units) then the ICS
luminosity at orbital maximum is

$$L_{\text{ICS,max}} \approx \sigma_T c u \omega 4\pi^2 \dot{N}_e (\delta \sigma/c) \approx 9 \times 10^{26} \Gamma_4 \delta \sigma \text{ erg s}^{-1}.$$ 

This is to be compared with the observed power-law flux, which contributes $\sim 5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ of flux at maximum in a $dN/e = KE^{-2.6}$ component (Figure 7) of which we found a hint in our data fits ($TS = 25$) although an addition of this power-law component is not strongly favored over a simple freely fit PLEXP2 model, providing a modest AIC value of $p = 0.6$ (Section 2.3). At the fit source distance, this is $\sim 2 \times 10^{11}$ erg s$^{-1}$, assuming beaming into $\pi$ steradians. Comparing with $L_{\text{ICS,max}}$, we see that such flux can be produced if $\Gamma_4 \delta \sigma \approx 2 \times 10^{4}$.

Thus this model appears energetically feasible. However, there are a number of less than satisfactory aspects. First, the underlying PLEXP2 model is unusually hard for an LAT pulsar. In fact at $\phi_{\text{BP}} = 0.75$ we fit $\Gamma_4 = 0.6 \pm 0.3$. This is comparable to the smallest values seen for LAT pulsars. Thus in this model we are adding a very soft $\Gamma = 2.6$ variable ICS component (power law) to an unusually hard MSP spectrum (Section 2.3). This is in contrast to the absorption picture, where the PLEXP2 spectrum at maximum is quite typical of LAT MSP. Also we require a large fraction of the spin-down power to go into $e^+/e^-$ in the pre-shock wind. This means that it must become particle dominated (low $\sigma$) relatively early. Since $\Gamma_{\text{w}} \approx 10^{4}$ is inferred for the bulk PWN flow in other pulsars (e.g., Khangulyan et al. 2012), we also infer that it stays in this state for $\delta \sigma \approx 1$, i.e., a good fraction of the way to the IBS termination shock. The ICS estimate above assumes a spherical wind, so an equatorial concentrated wind can help modestly decrease the power requirements. Note that this only helps if the Earth line of sight is covered by this equatorial wind flow— with the optically fit $i \approx 69^\circ$ (Kandel et al. 2019) this concentration is not a large help. It does suggest that interacting binary pulsars observed at large $i$ would be more likely to show ICS orbital modulation.

Most importantly, to keep this emission pulsed in phase with the classic magnetospheric pulsations, the scattering electrons need to be in a precisely phased structure, presumably the striped pulsar wind, over this large distance.

4. Discussion and Conclusions

We have discovered low-energy gamma-ray orbital modulation of J2339 emission in 11 yr of Fermi-LAT data. The modulation is strongest in the “on-pulse” interval. The significance of modulation increases approximately monotonically with time. The variability of exposure and/or nearby bright sources does not explain the modulation. We therefore conclude that the modulation is intrinsic to J2339 and phased with the pulsed magneto- magnetic emission.

The origin of this pulsed flux is not clear. Klein–Nishina limited scattering of the magnetospheric emission by electrons in the pulsar wind seems attractive in that it naturally explains the low-energy dominance and the orbital phase variation of the modulation by linking the scattering depth to the column of electrons in the trailed pulsar wind. And of course a simple energy-dependent attenuation of the pulsed emission is then expected. But the optical depths provided by the expected pulsar pair emission are too low by orders of magnitude. Identifying the modulation as Compton upscattering of companion day-face photons seems energetically more promising although orbitally varying Compton emissivity due to changes in the scattering angle needs to be taken into account for more detailed modeling. But here the challenge is to ensure that the upscattered photons stay in phase with the pulsed emission. This may be possible in a striped wind extending nearly unperturbed to the IBS termination shock, but it is unclear why the ICS “pulse profile” should be so similar to the standard pulsations originating near the pulsar. Additionally, the standard pulsed emission in this scenario is unusually hard, with a very soft component added by the ICS emission. We conclude that additional observations and modeling will be needed to tease out the origin of this remarkable pulse modulation.

Although it is bright, allowing detailed $\gamma$/X/optical study, and relatively strongly heated, J2339’s properties do not seem exceptionally unusual. Thus we might expect to find similar pulse modulation in other spider binaries. Indeed, orbital modulation of gamma-ray flux in pulsar binaries has been reported in a few systems (PSR J1311−3430, PSR J2241−5236, and 3FGL J2039.6−5618; An et al. 2017, 2018; Ng et al. 2018). This is generally attributed to IBS emission, with synchrotron emission or inverse Compton upscattering of stellar photons in the IBS as the suggested production mechanism. In both cases we expect the gamma-ray emission to be beamed along with the bulk motion of the IBS electrons, thus similar to the IBS X-rays (generally away from the MSP for BW, away from the companion for RB). However, if Compton upscattering is strongest at the IBS apex before the shocked pulsar wind has joined the bulk flow, it may be directed away from the MSP in either case. Of course for these IBS models we do not expect the excess gamma-ray emission to be pulsed. This would make IBS gamma-ray detection easiest in the off-pulse phases.

In practice gamma-ray modulation is not always best seen off-pulse. So it seems likely that a pulsed component, like that discovered here, is present in other objects. For example 3FGL J2039.6−5618 shares some properties with J2339; both of them are RBs, and its recently detected gamma-ray maximum occurs near the optical minimum, opposite to the expected IBS phase. It will be interesting to see if 3FGL J2039.6−5618 also exhibits orbital modulation in the “on-pulse” interval. More examples, and more detailed modeling, will certainly help us trace the origin of this phenomenon. Continuously collecting gamma-ray data with the Fermi-LAT and the future AMEGO telescope (McEnery 2019) may give us new insights into pulsar binaries.

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