Heated Poles on the Companion of Redback PSR J2339–0533

D. Kandel1 ©, Roger W. Romani1 ©, Alexei V. Filippenko2,3,4 ©, Thomas G. Brink2 ©, and WeiKang Zheng2 ©

1 Department of Physics, Stanford University, Stanford, CA 94305, USA; dkandel@stanford.edu
2 Department of Astronomy, University of California, Berkeley, CA 94720, USA
3 Miller Institute for Basic Research in Science, University of California, Berkeley, CA 94720, USA

Received 2020 July 11; revised 2020 August 30; accepted 2020 September 8; published 2020 October 29

Abstract

We analyze the photometry and spectra of the “redback” millisecond pulsar binary J2339–0533. These observations include new measurements from Keck and the Gamma-Ray Burst Optical/Near-infrared Detector (GROND), as well as archival measurements from the Optical and Infrared Synergetic Telescopes for Education and Research (OISTER), WIYN, Southern Astrophysical Research (SOAR), and Hobby–Eberly Telescope (HET) telescopes. The parameters derived from GROND, our primary photometric data, describe well the rest of the data sets, raising our confidence in our fitted binary properties. Our fit requires hot spots (likely magnetic poles) on the surface of the companion star, and we see evidence that these spots move over the 8 yr span of our photometry. The derived binary inclination \( i = 69.3^\circ \pm 2.3^\circ \), together with the center-of-mass velocity (from the radial-velocity fits) \( K_C = 347.0 \pm 3.7 \) km s\(^{-1}\), gives a fairly typical neutron star mass of \( 1.47 \pm 0.09 M_\odot \).

Unified Astronomy Thesaurus concepts: Pulsars (1306)

1. Introduction

Using optical imaging, Romani & Shaw (2011) and Kong et al. (2012) discovered a binary system with \( P_B = 0.193 \) d coincident with one of the brightest unidentified Fermi/Large Area Telescope (Fermi/LAT) sources, inferring that it was the tidally locked, heated companion of a millisecond pulsar (MSP). Radio observations (Ray et al. 2014, 2020) found a 2.9 ms pulsar at this position, which was generally observed by a particularly powerful companion wind, but occasionally visible at 820 MHz. The connection with the gamma-ray source was confirmed via gamma-ray pulsations (Pletsch & Clark 2015); the source is an \( E = 2.32 \times 10^{34} \) erg s\(^{-1}\) “redback”-type MSP with a low-mass, main-sequence companion. This and the extreme spectroscopic variation (from mid~3500 K M-class spectra at minimum brightness to \( \sim 7000 \) K F-class at maximum brightness) found by Romani & Shaw (2011, hereafter RS11) show that the companion is very strongly heated.

The initial photometry (RS11; Yatsu et al. 2015) sufficed to demonstrate this strong heating, but did not allow a detailed fit for the orbital parameters. Here we report on a new analysis of precision photometry, which shows highly significant asymmetries in the orbital light curves. Such asymmetry has been observed in other heated companions (e.g., Stappers et al. 2001; Schroeder & Halpern 2014), and it has been suggested that these distortions may arise from asymmetric heating from the system’s intrabinary shock (IBS; Romani & Sanchez 2016) or from hot spots on the companion magnetic poles created by precipitating IBS particles (Sanchez & Romani 2017). Recently, Kandel & Romani (2020, hereafter KR20) described a model in which global winds may advect the direct pulsar heating, also producing light-curve distortions. Each of these predicts somewhat different heating patterns. Our photometry, which includes four epochs over eight years, also indicates that the distortions are not constant. We find that a hot spot that shifts location can reproduce these light curves, with a consistent (and constant) geometric parameters for the binary. We combine this geometric information with a reanalysis of the RS11 Hobby–Eberly Telescope (HET) spectroscopic data to infer the neutron star mass as \( 1.47 \pm 0.09 M_\odot \). We conclude with a discussion of the nature of the hot-spot asymmetry and recommendations for future observations that seek to measure the mass of such binaries.

2. Observations

Our principal new photometric data set is derived from an analysis of archival griJHK photometry of PSR J2339–0533 (hereafter J2339) taken on 2017 September 11 and 14, (UT dates are used throughout this paper) with the Gamma-Ray Burst Optical/Near-infrared Detector (GROND) imager on the European Southern Observatory (ESO) 2.2 m telescope (Program 099.A-9014). With \( 150 \times 145 \) s for the optical exposures over the two observing sessions, the data covered 1.89 orbits. We downloaded the image frames and associated bias, flat, and dark frames. After standard IRAF processing and combination of the subexposures in the infrared (IR) frames, we extracted aperture photometry at the pulsar position measured near orbital maximum brightness. The instrumental magnitudes were calibrated against Sloan Digital Sky Survey (SDSS) measurements of field stars in the optical and against Two-Micron All-Sky Survey (2MASS) stars in the near-IR. Unfortunately, with the limited GROND field of view, only a handful of calibration stars were available. The seeing during these observations was poor and variable, with FWHM \( 1.5^\prime - 3.0^\prime \), and the airmass was as large as \( \sim 2.6 \), leading to large apertures and low signal-to-noise ratio (S/N) detections near orbital minimum brightness. Nevertheless, the photometry was quite stable, with useful detections throughout the orbit. We also extracted the IR-channel data, calibrating it against a single nearby 2MASS star. We find that the J-band light curve is of good quality, and \( H \) shows the heating effect, but the combination of limited S/N, large background uncertainties, and low \( T_{\text{eff}} \) sensitivity made the \( K_s \) GROND data nearly useless.

This photometry can be compared with more limited data taken at other epochs. First, optical imaging of J2339 was
obtained at the WIYN 3.5 m telescope with the MiniMo imager on 2011 September 27–28, (5 × 240 s + 2 × 180 s in Gunn g, 9 × 120 s + 240 s in Gunn r, 7 × 120 s + 300 s in Gunn i). We also examined BVRI photometry from 2011 September 22 to October 7, taken by the Optical and Infrared Synergetic Telescopes for Education and Research (OISTER) collaboration (Yatsu et al. 2015) and kindly shared by those authors. Next, photometry at the Southern Astrophysical Research (SOAR) 4.2 m telescope using the Goodman High Throughput Spectrograph (GHTS) in direct imaging mode on 2013 August 12, was collected: 3 × 180 s + 300 s in SDSS u′, 4 × 120 s + 300 s in SDSS g′, 4 × 120 s + 60 s in SDSS r′, 4 × 120 s + 300 s in SDSS i′, and 4 × 600 s in Hα. For all SOAR and WIYN frames, standard CCD reductions were made and the fluxes were calibrated to SDSS stars in the field using u′, g′, r′ (for Gunn r and Hα), and i′ magnitudes. For the WIYN data, the seeing image quality was good (0.6–0.7 arcsec FWHM), and we can see (Figure 1, left) that a faint extended source lies near the pulsar counterpart.

Most recently, on 2019 October 28, we obtained eight 600 s exposures with the Keck I 10 m telescope plus the Low Resolution Imaging Spectrometer (Oke et al. 1995) in long-slit mode, using the 5600 Å dichroic, the 400 line mm⁻¹ (blazed at 4000 Å) blue grism, and the 400 line mm⁻¹ (blazed at 8500 Å) red grating, covering the binary orbital minimum brightness. This gave us spectra in the approximate range 3300–10500 Å, with dispersions of 0.63 Å pixel⁻¹ (blue) and 1.2 Å pixel⁻¹ (red). The atmospheric dispersion corrector allowed us to not have the slit aligned along the parallactic angle (Filippenko 1982), instead rotating the 1″-wide slit so that we could simultaneously observe a nearby brighter G0 star. This enabled us to monitor the system throughput and to detect small shifts in the wavelength solution between frames. In addition, as this comparison (“comp”) star has known and stable SDSS magnitudes, we are able to integrate the extracted pulsar and comp-star spectra over the appropriate wavelength ranges to get accurate relative photometry. This gives the pulsar magnitudes in broad-band filters, up to a possible small grayshift (due to different companion and comparison star slit losses) across the eight exposures. These spectra were followed by two g'/i' image pairs, which served to check comp-star placement and stability. Thus, we have 10 Keck photometric measurements in g and i'/i and eight in other filters.

Of course, the spectral velocity information is also directly useful, and we augment the new Keck spectra with a reanalysis of 48,600 s exposures taken with the HET/LRS as described by RS11 to extract a new radial-velocity curve of the companion.

Although severely blended with the pulsar counterpart in the low-resolution GROND data, we have measured the spectral energy distribution (SED) of the nearby extended source and find it consistent with a galaxy at redshift z ≈ 0.8–0.9 (Figure 1, right). The source is comparable in flux to J2339 at minimum brightness, and with the large apertures needed for the GROND data, it produces substantial contamination in the redder bands.

3. Photometric Fitting

Using a recent recomputation of the gamma-ray ephemeris (An et al. 2020) which provides excellent pulse-phase aligned timing throughout the Fermi mission, including the epochs of all observations described in this paper, we determine the binary phase from the barycentered time of the exposure midpoints. The GROND data set is densely sampled with nearly uniform phase coverage, so we fit these data to best constrain the binary parameters.

The GROND griz light curves (Figure 2) are well sampled and quite smooth. First, the optical maximum brightness is shifted significantly later in phase than pulsar superior conjunction. Any model that does not account for this is completely unacceptable. Accordingly, our minimal direct heating (DH) model must include an arbitrary (not physically justified) phase shift Δφ. Also, the light curve shows
significant asymmetry, with excess emission on the leading side, especially in the bluer colors. This a clear sign of heat redistribution from the subpulsar point.

We also fit for an extra background flux in each band, as the large-aperture GROND extractions (3′′/2 in the optical, 5′′ in the IR) guarantee contamination by the nearby galaxy. The best-fit contamination fluxes do follow the red galaxy spectrum in the optical (Figure 1). The IR fluxes are somewhat larger; this may be due to the larger photometric aperture, but may also implicate a red nonphotospheric contribution from J2339 itself.

The best-fit parameters of this DH model are given in Table 1. With a large χ² per degree of freedom (DoF) of 2.51, it is unable to explain the asymmetric light curve, as can be seen in the fit residuals of Figure 2.

One way to produce light-curve phase shifts and asymmetry is via a global circulation, as in the model developed by KR20, where an equatorial wind redistributes heat from the subpulsar point. This wind is characterized by ϵ = τradωadv, the ratio of radiation time to advection at the equator (prograde for ϵ > 0). Such winds have been inferred for several “hot Jupiters” (Cowan & Agol 2011). The models generally have flows reversing direction at mid-latitudes; in our model, we fit for θc, the angle from the equator at which the flow (with the same ϵ) changes sign. Hydrodynamical models of such flows can show more complex patterns, and Voisin et al. (2020) have recently developed a similar model also incorporating heat diffusion, but our simple prescription captures the bulk heat redistribution with sufficient freedom to use in model fits. The fit with this wind-heating (WH) model implies a super-rotating equatorial wind resulting in the overall phase shift of the light-curve maxima by Δφmax ≈ 0.03. The χ² decrease of this model is large, with strong statistical preference over the DH model.

However, there is good reason to expect that the low-mass stellar companions of redbacks are significantly magnetized so that the companion field can channel energetic pulsar particles to heat its surface at magnetic caps formed by the field footpoints (Sanchez & Romani 2017). Then, we also fit with a single hot-spot (HS) model having a simple Gaussian excess on the companion surface, characterized by amplitude Ahs, radial size rhs, and angular position θhs, φhs. The binary parameters for this model are listed in Table 1. The hot-spot parameters (Table 2) indicate a substantial (32%) temperature excess in a large-radius (47°) pole. This pole is located in the companion’s “southern” hemisphere (across the equator from Earth’s line of sight) and leads the subpulsar point near L1. The fit is superior to that of both the DH and WH models. The χ²/DoF

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**Figure 2.** Light curves (gray) of J2339. Three periods are plotted with φg = 0 at pulsar TASC (ascending node). The solid curves in all three cycles show the best-fit hot-spot model (Table 2, row 3). The dotted curve of cycle 1 shows the DH model with an arbitrary phase shift (fits without a phase shift are completely unacceptable). The dotted curve of cycle 2 illustrates the wind model. Lower panels show fit residuals from the three models, with the hot-spot model (cycle 3) having the smallest residuals.

**Table 1.** 2017 GROND Light-curve Fit Results for J2339

| Parameters | DH + Phase Shift | WH | HS |
|------------|------------------|----|----|
| φ (deg)    | 58.4±0.7         | 55.9±0.3 | 69.3±2.3 |
| fₚ         | 0.9×0.01         | 0.97±0.01 | 0.97±0.02 |
| Lₚ/(10³⁴ erg s⁻¹) | 2.2±0.05       | 2.53±0.04 | 1.48±0.03 |
| Tₛ(K)      | 3183±28         | 3126±28 | 3307±64 |
| d(kpc)     | 1.97±0.01       | 1.97±0.01 | 1.87±0.01 |
| ϵ          | ...              | 0.31±0.04 | ... |
| φhs (deg)  | ...              | 55.3±1.6  | ... |
| Δφ         | -0.03±0.001     | ... | ... |
| χ²/DoF     | 1388/553        | 877/552 | 671/550 |
approaches 1 and the fit residuals reduce greatly (Figure 2, panel 3), showing that the model reproduces the observed asymmetry quite well. One should note that $i$ is substantially higher (and $L_p$ is lower) for the HS model than for the DH and WH models. The other binary parameters are similar.

4. Shifting Hot Spots

Armed with the binary parameters determined by the fit to the GROND data, we can check consistency with the partial light curves provided by our other data sets, which span eight years. First, the sparse WIYN 2011 data show a minimum appreciably brighter than the GROND model curve, with the minimum closer to $\phi = 0.25$ than the GROND data. Near this epoch (2011 September 22–October 7), observations were made using the OISTER. Originally presented by Yatsu et al. (2015), this data set has good phase coverage and shows a phase shift. We have elected to fit these data sets together for the 2011 epoch; if fit separately, both indicate a hot spot at similar $\phi_{hs}$ and $\phi_{hs}$. Next, 2013 SOAR photometry covered only maximum brightness, but also show a peak slightly later in phase than for GROND. Perhaps the best comparison, though, is with the 2019 Keck data. With the spectral points we have multicolor coverage of the orbital minimum, plus a few late $g/I$ points. This minimum is distinctly bluer than in the GROND data, with a flat minimum well centered on $\phi = 0.25$.

Of course, orbital parameters should not change over the eight years. Instead, we posit that the heating pattern has changed; in particular, the position of the magnetic pole (hot spot) may shift and the pulsar illumination may change. Thus, we fit each of the four epochs with the orbital parameters of Table 1, but the hot-spot parameters free. The results are in Table 2 and the resulting light curves are shown in Figures 3 and 4. With limited phase coverage the parameters are not always well constrained, but three interesting features appear: (i) all spots are large, (ii) all are located in the southern hemisphere ($\phi_{hs} < 0$, across the equator from the Earth’s line of sight), and (iii) spots on the “day” (pulsar) side ($\phi_{hs} < 90^\circ$) are more strongly heated (larger fractional temperature increase $A_{hs}$) than the Keck example, which is on the back “night” side. If the hot spots are heated by precipitation of IBS particles ducted to the companion, as in the model of Sanchez & Romani (2017), then fewer particles are captured by field lines extending away from the pulsar, so the weaker heating fit for the Keck example is natural.

As for all redbacks, this companion is a low-mass star, fully convective in the core with a short spin period imposed by tidal locking, so we expect a strong $\alpha - \Omega$ dynamo as well as a strong and frequently refreshed magnetic field. So, magnetic pole hot spots are natural and changes in the dipole axis are plausible. Of course, the regenerated field may assume a random orientation under each regeneration—this is a nominal conclusion from our fit spot locations. However, it is intriguing that all four epochs are consistent with $\phi_{hs} \approx -60^\circ$ to $-80^\circ$; in this case, we might infer that the magnetic axis is relatively stable, but that the differing $\theta_{hs}$ could represent a drifting interior dipole. Such a motion may explain the shifting light curve of redback PSR J1723–2837 interpreted as asynchronous companion rotation by van Staden & Antoniadis (2016). Certainly, our data cannot distinguish these possibilities, but a future sensitive multicolor campaign can probe this feature.

If the companion magnetic field is dominated by a dipole, we might expect particles ducted to both hemispheres, but with lower efficiency toward the back side. So, we fit with opposing spots having identical sizes, but free heating amplitudes $A_{hs}$ for

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Table 2

| Data Set      | Obs MJD | $\phi_{hs}$ (deg) | $\phi_{hs}$ (deg) | $A_{hs}$ | $r_{hs}$ (deg) | Ref.          |
|---------------|---------|-------------------|-------------------|----------|---------------|---------------|
| WIYN + OISTER | 55826–55841 | 65.2 ± 2.4        | -79.3 ± 2.2       | 0.54 ± 0.10 | 31.3 ± 6.3 | Figure 4      |
| SOAR          | 56516   | 85.0 ± 8.0        | -80.1 ± 5.7       | 0.40 ± 0.20 | 40.0 ± 11.5 | Figure 3      |
| GROND         | 58007–58010 | 70.1 ± 1.1        | -53.3 ± 5.1       | 0.43 ± 0.05 | 33.5 ± 14    | Figure 2      |
| Keck          | 58784   | 124.5 ± 17.2      | -59.0 ± 13.8      | 0.10 ± 0.05 | 45.8 ± 11.7 | Figure 3      |

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Figure 3. Left: 2013 ugri SOAR photometric observations, compared with the best-fit HS model (solid curves, Table 2, row 2). Right: 2019 ugri Keck photometry and best-fit HS model (solid curves, Table 2, row 4). For comparison, the dotted g/r curves in both panels are the best-fit HS model for the GROND-epoch solid curves of Figure 2 (Table 2, row 3).

Figure 4. BVRI OISTER photometry from Yatsu et al. (2015) and best-fit HS model (solid curves, Table 2, row 1). The WIYN $g$ (green), $r$ (black), and $i$ (magenta) points at similar epoch are overlaid.
the two hemispheres. For the GROND epoch, we refit the full model; reassuringly, all fit binary parameters are within the uncertainty of single-spot fit values. We find $A_1/A_2 \approx 10$. For the Keck epoch the flux ratio is relatively unconstrained, $1.6 \lesssim A_1/A_2 \lesssim 7.5$, but the brighter (northern) hemisphere pole is poorly constrained mostly because of the lack of data around the light-curve maxima. It will be interesting if future intensive studies can test the expectation that heated poles will have the largest power when closest to the companion nose.

5. Spectral Analysis

We can compare the Keck spectroscopy with the photometric fit model. Figure 5 shows the Keck flux averaged over the four spectra at the light-curve minimum. For comparison, we show the composite model spectrum (blue) and a single-temperature $T_N$ model averaged over the same four Keck nighttime phases. The composite spectrum is computed using the ICARUS code (Bretton et al. 2012) for a model with reduced $\gamma$-ray heating, a shifted hot spot (Table 2, row 4), and excess IR flux attributed to the background galaxy (Figure 1, left). The general agreement is reasonable, with an M3–M1-class spectrum, but the composite model is too blue. The companion also has a strong H$\alpha$ line, with weaker H$\beta$ visible in some spectra.

As they are dominated by molecular bands, the Keck spectra at minimum brightness do not provide good radial velocities. The first spectrum at $\phi_B = 0.046$, however, contains sufficiently strong metal lines that we can fit for a radial velocity using a K1-star template. In addition, the H$\alpha$ line provides good velocities for all spectra. We have also compared with the HET spectra of RS11, remeasuring the radial velocities by fitting with a K1 template while excluding 100 Å ranges around the Balmer absorption features that dominate near optical maximum. No evidence for H$\alpha$ emission is seen in the lower-S/N, lower-resolution HET data. Retaining only the HET points with strong cross-correlation peaks (from the day phases), we obtain the radial-velocity curve of Figure 6. The HET spectra seem to have a wavelength offset, which introduced a substantial $\Gamma \approx -80$ km s$^{-1}$ in RS11; we have chosen to match the Keck velocity solution for the K1 fits, which result in a small positive $\Gamma$.

As emphasized by Linares et al. (2018) and discussed by KR20, different line species have varying temperature sensitivities and so are differently distributed across the face of the companion. By fitting with K1 templates (and excluding the Balmer-line wavelengths), we are most sensitive to the metal lines.

6. System Modeling and Discussion

For a given heating model, the radial-velocity data can be used to infer the companion center-of-mass (CoM) motion. Adopting the GROND-epoch light-curve model (Table 1), we can compute the equivalent width (EW)-weighted radial velocity at each orbital phase, for a given line species. Here, because we use a K1 template to measure the radial velocities, we are most sensitive to the common metal absorption lines. Using a set of archival standard dwarf spectra, we have computed the temperature dependence of the EWs of the strongest Fe, Mg I, and Na I optical lines. Averaging, a simple power-law fit gives EW($T$) = $(3.57/T_{\text{eff}})^{2.71}$. With this prescription, we compute the metal-line radial-velocity curve for a given model and can fit to the spectroscopic data to determine the CoM radial velocity $K$ and $\Gamma$. Although we do not perform a simultaneous fit with photometric data, the spectroscopic fits are marginalized over the geometrical parameters from the end of the GROND photometric Markov Chain Monte Carlo chains, sampling 2$\sigma$ uncertainties. Thus, the mass errors include all uncertainties in the model fitting, spectroscopic and photometric.
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The fit results are given in Table 3 while the best-fit radial-velocity curve is shown Figure 6. For our base model (HS model) this gives a companion CoM velocity amplitude \( K_c = 347.0 \pm 3.7 \) km s\(^{-1}\), a relatively modest neutron star mass of \( 1.47 \pm 0.09 M_{\odot} \), and a companion mass of \( 0.30 \pm 0.02 M_{\odot} \). Note that this companion mass is consistent with its observed spectral class and radial-velocity amplitude different heating models do imply small differences in the CoM have such large masses differences arise from the different inclinations of the \( fi \) would infer large \( \frac{\chi^2}{\text{DoF}} \) are near the underlying CoM velocity is unclear. Interestingly, the largest departures from the model radial-velocity curve are near the inferred hot-spot phase. However, the redshift of the emission line is a puzzle. If it represented outflow from the companion surface, a blueshift would be expected at these phases. Additional spectroscopy with good S/N might follow this line emission into the day side of the orbit, giving clues to its origin.

Note that here we have determined the radial velocities by adopting a cross-correlation fit dominated by metal lines and then using the model surface temperature distribution to map the EW-weighted radial velocity. A more complete analysis would be to generate model spectra for each phase and to cross-correlate these spectra with the data to find the radial-velocity shifts uniformly fit from all spectral features (using a range of species with different \( T \) dependence). For objects such as J2339 with a large (\( >2 \times \)) range in the surface temperature, this would be the best way to connect back- (night) side molecular band shifts with the day-side Balmer-line velocities. We plan to pursue such an analysis in upcoming papers.

Our evidence for secular light-curve variations joins that for other redbacks. It seems that this is a quite common feature of these systems and we speculate that it is associated with time-varying magnetic dipoles on the active companion, heated by precipitating IBS particles. We encourage high-quality multi-band light curves of these systems at few-month separations over several years to probe the physical origin of these variations.

We thank the anonymous referee for a very detailed and careful reading of the manuscript. We are grateful for the excellent assistance of the staffs of the observatories where data were taken. Some of the data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and NASA; the observatory was made possible by the generous financial support of the W. M. Keck Foundation, D.K. and R.W.R. were supported in part by NASA grants 80NSSC17K0024 and 80NSSC17K0502. A.V.F.’s group is grateful for generous financial assistance from the Christopher R. Redlich Fund, the TABASGO Foundation, and the Miller Institute for Basic Research in Science (UC Berkeley).

ORCID iDs

D. Kandel @ https://orcid.org/0000-0002-5402-3107

Roger W. Romani @ https://orcid.org/0000-0001-6711-3286

Alexei V. Filippenko @ https://orcid.org/0000-0003-3460-0103

Wei Kang Zheng @ https://orcid.org/0000-0002-2636-6508

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| Parameters | Phase Shift | WH | HS |
|------------|-------------|----|----|
| \( K_c (\text{km s}^{-1}) \) | 351.3\(_{+3.7}^{+5.3} \) | 353.7\(_{+3.7}^{-3.7} \) | 347.0\(_{+3.6}^{-3.9} \) |
| \( \Gamma (\text{km s}^{-1}) \) | 22.8\(_{+1.1}^{+1.1} \) | 15.2\(_{+1.1}^{-1.1} \) | 17.7\(_{+1.1}^{-1.1} \) |
| \( M_{\text{Co}} (M_{\odot}) \) | 0.20\(_{+0.07}^{-0.07} \) | 2.22\(_{+0.08}^{-0.08} \) | 1.47\(_{+0.09}^{-0.09} \) |
| \( M_{\odot} (M_{\odot}) \) | 0.40\(_{+0.01}^{-0.01} \) | 0.44\(_{+0.01}^{-0.01} \) | 0.30\(_{+0.02}^{-0.02} \) |
| \( \chi^2/\text{DoF} \) | 23/19 | 22/19 | 23/19 |