KECK SPECTROSCOPY OF MILLISECOND PULSAR J2215+5135: A MODERATE- $M_{\text{NS}}$, HIGH-INCLINATION BINARY

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ABSTRACT

We present Keck spectroscopic measurements of the millisecond pulsar binary J2215+5135. These data indicate a neutron-star (NS) mass $M_{\text{NS}} = 1.6 M_\odot$, much less than previously estimated. The pulsar heats the companion face to $T_D \approx 9000$ K; the large heating efficiency may be mediated by the intrabinary shock dominating the X-ray light curve. At the best-fit inclination $i = 88.8'$, the pulsar should be eclipsed. We find weak evidence for such eclipses in the pulsed gamma-rays; an improved radio ephemeris allows use of up to five times more Fermi-Large Area Telescope gamma-ray photons for a definitive test of this picture. If confirmed, the gamma-ray eclipse provides a novel probe of the dense companion wind and the pulsar magnetosphere.

Key words: gamma rays: stars – pulsars: general

1. INTRODUCTION

PSR J2215+5135 is a recycled millisecond pulsar (MSP) with $P = 2.6$ ms and $E = 7.4 I_{57} \times 10^{43}$ erg s$^{-1}$ (with $I_{57}$ the neutron star moment of inertia in units of $10^{45}$ g cm$^2$), in a $P_b = 4.14$ hr orbit with a heated low-mass stellar companion. This “redback” (RB; Roberts 2013) system was discovered in 350 MHz Green Bank Telescope observations (reported by Ray et al. 2012) of an unidentified Fermi-LAT (Large Area Telescope; Atwood et al. 2009) gamma-ray source. The radio dispersion measure (69.2 cm pc$^{-3}$) provides a distance estimate $d \approx 3$ kpc.

Schroeder & Halpern (2014, hereafter SH14) obtained high-quality BVR light curves of the companion over many orbits. It varies from $V \approx 18.7$ to 20.2 mag and thus is well measured with modest-aperture telescopes. Fitting these light curves with the ELC code (Orosz & Hauschildt 2000) and a photometry table generated from the PHOENIX model atmospheres (Husser et al. 2013), SH14 inferred a low system inclination and large pulsar mass, $M_{\text{NS}} = 2.45^{+0.32}_{-0.21} M_\odot$. This is potentially very important, since it would be one of the highest-known neutron-star (NS) masses. Such objects can provide strong constraints on the equation of state at supernuclear densities (Lattimer & Prakash 2007; Steiner et al. 2013).

However, their fit showed several peculiarities. The unheated “night” face of the companion was found to have $T_\text{e} = 3790^{+35}_{-25}$ K and the heated “day” side $T_D = 4899^{+33}_{-25}$ K in the ELC fits, in poor agreement with the observed bluer colors; for example Breton et al. (2013) noted that $g - i$ at quadrature suggested $T \approx 6600$ K. Next, the light curve is shifted by $\Delta \phi \approx -0.01$ with respect to the radio-pulse ephemeris. SH14 suggest that the blue colors could be caused by a hot quiescent disk, while the phase shift may be an effect of an intrabinary shock. Also, Gentile et al. (2014) observed the system in the X-rays with CXO, finding an X-ray minimum near orbital phase $\phi \approx 0.25$ (pulsar superior conjunction, radio eclipse), which they interpret as due to variable obscuration of emission from an intrabinary shock around the companion.

To probe these peculiarities, we have obtained Keck spectra across the binary orbit. Our data show no evidence for disk or shock emission lines, but imply much higher system inclination, with higher companion temperatures and stronger pulsar heating. This lowers the inferred pulsar mass, but raises the possibility that the pulsar magnetospheric emission is eclipsed by the companion star. Gamma-ray data currently show limited evidence for such eclipse, but additional observations can test this hypothesis.

2. KECK SPECTROSCOPY

The system was observed on three occasions. In each case we aligned the long slit at position angle 76° (N through E) to include two bracketing stars for monitoring purposes (see the finder chart in Breton et al. 2013). The $R = 17.6$ mag star at USNO-B1 J2000 position $\alpha = 22^h15^m32.03$1, $\delta = +51^\circ35^\prime35^\prime.46$ (C1) appears to show radial-velocity (RV) variations between epochs, so we use the $R = 18.1$ mag star 8° away at J2000 position $\alpha = 22^h15^m33.498$, $\delta = +51^\circ35^\prime38^\prime.88$ (C2) as our reference object.

First, using the DEep Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) on Keck II, we obtained $7 \times 600$ s exposures covering 4450–9060 Å on 2014 October 2 (UT dates are used throughout this paper; MJD 56932) with $\sim$4.7 Å resolution through a 1′-wide slit. These data covered $\phi_B = 0.685\pm0.025$, where $\phi_B$ = 0.75 is optical maximum (“Noon”) and the pulsar ascending node is at $\phi_B = 0$. The radio ephemeris defines $T_{\text{ASC}} = 55186.164485831$ MJD and $P_B = 0.172502104907$ d. For improved blue coverage, we observed again on 2014 October 24 (MJD 56954) by taking $6 \times 600$ s exposures with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on Keck I using the 1′′ slit and the 5600 Å dichroic splitter. The blue-camera 600/4000 grism provided $\sim$4 Å resolution, while the red-camera 400/8500 grating delivered $\sim$7 Å resolution. These data covered wavelengths 3200–10.260 Å and orbital phases 0.501 < $\phi_0$ < 0.723. Finally, we observed with the same setup on 2014 November 20 (MJD 56981), covering orbital phase 0.202 < $\phi_B$ < 0.381 by taking $5 \times 600$ s exposures. Calibration spectra of blue (BD + 28°4211) and red (BD + 17°4708) spectrophotometric standards were obtained during each run. The spectra were subject to standard IRAF reductions, including optimal extraction.
Figure 1 shows the reduced, calibrated LRIS spectra at three orbital phases. The companion is significantly hotter than the SH14 ELC solution, with an effective spectral class A2 V near optical maximum brightness ($T_{\text{eff}} \approx 8970 \text{ K}$) and G0 V near minimum ($T_{\text{eff}} \approx 6030 \text{ K}$), as determined by line-ratio comparison with spectral standards. No strong emission lines or nonthermal component are seen, but a weak variable blue continuum peaking at $\phi_R \approx 0.75$ is not excluded.

We measured the companion absorption line RV variations using the IRAF XCASO script (Kurtz & Mink 1998). For templates we used dwarf star spectra with well-determined RV and spectral class from the Indo-US library of Coudé Feed spectra (Valdes et al. 2004). The cross-correlation statistic was $R \approx 30–60$ (typical spectral class A3) for the day-phase October 24 LRIS data and $R \approx 20–25$ for the night-phase November 20 spectra (typical spectral class G0). With the more-limited blue coverage on October 2, the cross correlations were weaker, giving $R \approx 10–20$ and larger RV uncertainties. Since C1 shows $\approx 50 \text{ km s}^{-1}$ RV variation between epochs, we relied on C2 for our RV tie. This star matched best to a K0 V spectrum. Cross correlation delivered velocity uncertainties of $\approx 2.5 \text{ km s}^{-1}$ (LRIS) and $\approx 3.5–4.0 \text{ km s}^{-1}$ (DEIMOS). To remove residual drift in the wavelength solution, we corrected the pulsar companion velocities to bring the measured C2 velocities into agreement. The C2 measurement errors, plus systematic $3 \text{ km s}^{-1}$ errors estimated from the variance between cross correlations with different templates, were added in quadrature to the individual RV uncertainties to produce the final RV uncertainty. These RVs and errors are plotted in Figure 2 as a function of orbital phase computed from the barycentered times of the exposure midpoints. Lacking velocity-standard observations spanning the companion spectral class during each run, we may have additional systematic uncertainty in the absolute RV.

Figure 3 shows the phased $BVR$ magnitudes and uncertainties published in Figure 2 of SH14; we ignored upper-limit points (generally from epochs of poor photometry), extracting 103 $B$, 55 $V$, and 113 $R$ magnitudes. These data and our new RV measurements were analyzed with two popular light-curve modeling programs: the ELC code and the ICARUS code (Breton et al. 2012). For both we can run in “MSP” mode, with the projected pulsar orbit $x_i = a_1 \sin i = 0.468141433$ It-s from the radio ephemeris. Both codes model pulsar heating of the companion as illumination by a point (X-ray) source, generating filter-specific light-curve models and estimating binary-system parameters via model fits. The temperature model is determined by the underlying temperature of the star (actually $T_c$ of the unheated “night” face), and a heating flux denoted $L_H$. The observed light curves are then sensitive to the orbital inclination $i$ and the mass ratio $q = M_{\text{SS}}/M_r$. The heating power can be related to the effective temperature of the heated face $T_B$ by

$$L_H = (T_B^4 - T_c^4)4\pi (1+q)^2 \sigma / \sin^2 i$$  \hspace{1cm} (1)$$

(effective albedo = 0). The Roche lobe filling factor $f_c$ is also relevant; as concluded by SH14, ELC fits require $f_c \approx 1$. It is also large ($f_c > 0.86$) in the ICARUS fits. SH14 find that the heating center is phase shifted. We concur, but find $\Delta \phi = -0.0089$, smaller than the $\Delta \phi = -0.0140 \pm 0.0005$ of their Table 2.

The two codes have some model differences. For the ELC code, one can simultaneously fit the observed RV points, giving additional sensitivity to $q$ and direct estimates of the component masses. However, the code fits normalized light curves for each band separately, ignoring the instantaneous
colors and observed magnitude. When searching high-quality data for the minimum near a correct physical model, this normalization should not affect the fit values and insulates the results from systematic interband photometry errors. The ICARUS code, in contrast, fits the observed magnitudes directly, using the instantaneous colors and providing estimates of the distance modulus and the extinction.

For the ELC modeling, we wish to compare with the SH14 results, and so we used the same color table (kindly shared by J. Tan) generated from the PHOENIX atmosphere models (Husser et al. 2013) with an extension to \( T_{\text{eff}} > 10,000 \) K from the ATLAS9 atmospheres (Castelli & Kurucz 2004). For the ICARUS code we collected Harris \( BVR \) color tables from the PHOENIX models at the Spanish Virtual Observatory (svz2.cab.inta-csic.es). Our results are summarized in Table 1 and Figure 3.

Our ELC fit to the \( BVR \) magnitudes finds parameters similar to those of SH14, except that their solution lies to the side of a broad minimum; the global minimum lies at considerably higher \( q \approx 7.5 \), with \( \chi^2/\nu = 3.25 \) (the minimum in their estimated 1σ contours is \( \chi^2/\nu = 3.27 \)). These \( \chi^2/\nu \) values are about twice those reported by SH14, but the model light curves and residual plots look quite similar to their results across this range of \( q \). These ELC photometry fits give much lower temperatures and heating powers than allowed by our Keck spectra. The ICARUS photometry fit gives a dramatically different picture, finding \( T_{\text{eff}} \approx 6600 \) K, much more consistent with the spectral estimate. \( L_{\text{eff}} \) is also much larger. The fit does not strongly constrain \( q \). The best fits prefer large extinctions; we fix \( A_V = 0.62 \) mag, the maximum in this direction from the Schlaffe & Finkbeiner (2011) models. The distance modulus is 12.98 mag or \( d \approx 3.9 \) kpc, not inconsistent with the dispersion-measure estimate.

We next explored ELC fits of the combined photometry and spectroscopy RV data sets. Since there are only 18 velocity points, these could be overwhelmed by the photometric data. Accordingly, we fit using the RV points 5 times each, effectively increasing the weights to compete with the photometry sets. Testing with only 1 and as many as 10 RV sets revealed that the fit results are insensitive to this choice, but the fitting converged more rapidly to the minima with the increased RV weights.

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### Table 1

| Param. | SH14 | P\textsuperscript{a} | P/S\textsuperscript{b} | HIT\textsuperscript{c} | ICARUS |
|--------|------|----------------|----------------|----------------|---------|
| \( i \) | 51.6\( ^\circ \) | 51.8 | 52.0 | 88.8 | 75–90 |
| \( q \) | 6.20 ± 0.25 | 7.50 | 7.35 | 6.89 | (0.87–0.99)\textsuperscript{d} |
| \( T_{\text{eff}} \) (K) | 3790\( ^{+35}_{-25} \) | 3780 | 3780 | 6220 | 6637 ± 12 |
| \( \log(L_{\text{eff}}) \) | 33.79 | 33.79 | 33.77 | 34.71 | 34.76 |
| \( \chi^2/\nu \) | (3.29)\textsuperscript{e} | 3.25 | 2.98 | 4.36 | 5.05 |
| \( M_{\text{ES}} \) | 2.45\( ^{+0.22}_{-0.11} \) | 4.14 | 3.88 | 1.59 | … |
| \( M_i \) | 0.396 ± 0.045 | 0.55 | 0.53 | 0.23 | … |

**Notes.**

\( ^{a} \) P: ELC photometric fit.

\( ^{b} \) P/S: ELC photometric/spectral fit ("Best" in Figure 3.)

\( ^{c} \) HIT ELC photometric/spectral fit w/ \( T_{\text{eff}} > 6000 \) K constraint.

\( ^{d} \) Roche fill factor, \( f_c \), increases with \( i \); all \( f_c > 0.9 \) imply \( i \approx 90^\circ \).

\( ^{e} \) Our fit value; SH14 report \( \chi^2/\nu \approx 1.5 \).

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Figure 3. Four-parameter ELC photometry/RV fit \( \chi^2 \) projected onto two planes; large dots indicate low \( \chi^2 \). Square dots are for \( T_{\text{eff}} > 6000 \) K, consistent with the spectroscopic classification. Dotted boxes indicate locations of the fits in Table 1 (measured from finer grids). The "HIT" ELC-fit minimum consistent with the spectroscopy is shown in the inset box of the upper panel; here the point size scales inversely with \( \chi^2 \), decreasing to 0 at \( \Delta \chi^2/\nu = 3.0 \). Upper panel lines show the inferred pulsar mass.

Figure 3 illustrates results from our combined photometry/RV fits, with two panels showing the projected \( \chi^2 \) from a grid of models in four fit parameters. The points are scaled so that large sizes correspond to lower \( \chi^2 \). With a minimum \( \chi^2 \gg \nu \), we must conclude that the models are inadequate (or error bars are underestimated). Thus, no particular fit value or formal uncertainty should be believed and we quote no statistical errors. Nevertheless, the distribution of best (albeit inadequate) fits in parameter space gives a guide to future precise solutions.

First, we note the strong correlation of the "good" solutions in the \( T_{\text{eff}}-L_{\text{eff}} \) plane. Recalling that ELC fits the normalized light curves, we understand that this simply preserves the light-curve peak height; with higher \( T_{\text{eff}} \), larger \( L_{\text{eff}} \) is needed for the same maximum. The best light-curve fits are indeed for low \( i \) low \( T_{\text{eff}} \).
solutions, as found by SH14, since these give broad light curve maxima. However there is a shallower minimum at 6000 K < \( T_e < 7000 \) K, consistent with the colors and spectroscopic temperatures. This local minimum, driven by the small peak-shape color dependance, is less evident in photometry-only fits. The RV data require larger \( q \) than in photometry-only fits, but \( q \) remains poorly constrained, with a wide swath of moderate \( \chi^2 \) displaying many local minima. While the small SH14 \( q = 6.2 \) value is excluded, the global minimum \( i \approx 52^\circ \) is similar to the best-fit photometry-only solution. This solution has an unphysically large pulsar mass \( M_{NS} > 3.88 M_\odot \).

However, if we restrict attention to solutions with \( T_e > 6000 \) K, consistent with the spectroscopic classification (square dots), these form a minimum at large inclination \( i \), and \( q \approx 6.9 \). This shallower but well-defined minimum, shown in detail in the upper-panel inset of Figure 3, has a much more modest \( M_{NS} = 1.59 M_\odot \). In Figure 2, we show the light-curve and RV models for this solution, and the fit residuals. Note the systematic residuals over optical maximum, especially in \( V \) and \( R \). These indicate an incorrect heating model. The correct heating pattern (likely mediated by an intrabinary shock; see below) should have a surface temperature distribution allowing a better match to the light-curve peak. \( T_e \) is also \( \sim 2 \times \) the main sequence \( T_{eff} \) for the inferred companion mass, suggesting subphotospheric heat transport, which may further modify the temperature distribution. We also plot the RV points and model after the same best-fit temperature distribution. We also show that the basic nonsinusoidal terms in the center-of-light velocity are well detected in our spectra.

This solution has very large \( i \), raising the interesting possibility of a pulsar eclipse.

4. THE HIGH-ENERGY ORBITAL LIGHT CURVE

At our large \( i \) ("HiT") fit minimum, we expect the companion to eclipse the pulsar for \( \Delta \phi_p = 25.4 \). The radio-pulse emission is undetected for over half the orbit. However, the ionized companion winds of RB and black-widow pulsars generally prevent radio-pulse detection for sight lines passing well outside the companion Roche lobe, so this alone does not indicate true eclipse.

We have re-examined the 17.0 ks CXO ACIS exposure of PSR J2215+5135 (ObsID = 12466), starting on MJD 55697.1821 and covering 1.14 orbits. As noted by Gentile et al. (2014), there is a clear modulation with a broad minimum at pulsar superior conjunction \( \phi_p \approx 0.25 \) (Figure 4). This modulation might be best interpreted as variable viewing of an X-ray emitting intrabinary shock.

A powerful intrabinary shock can also produce GeV LAT photons (Xing & Wang 2015). However, since an appreciable fraction of the object's gamma-ray flux is pulsed, we can select the magnetospheric component and search for a true pulsar eclipse. Unfortunately, at the BH MSPs, the wind obscuration and \( P_B \) fluctuations make radio timing very difficult. At present, the best ephemeris available is that of Abdo et al. (2013, 2PC), valid MJD 55346–55911, about a fifth of the BH mission to date. We selected 10,951 \( E = 0.1–30 \) GeV Pass 7 reprocessed "Source class" LAT photons within this date window and within \( 2^\circ \) of the pulsar. We compute weights \( w_i \), the probability of being pulsar photons, with the LAT tool\ gsrcprob using the Acero et al. (2015) source spectrum parameters and the local background model; the mean source probability was \( \langle w_i \rangle = 0.037 \). The spin-phase \( \phi_S \) weighted light curve shows two peaks consistent with 2PC results (\( \phi_S = 0.257 \) and \( \phi_S = 0.697 \) relative to the radio-pulse peak). If we extrapolate this ephemeris to the full LAT data set, the peaks are lost. We select \( \Delta \phi_p = 0.1 \) windows centered on the 2PC pulse peaks, to obtain events most dominated by magnetospheric emission. Other phases represent pulsed bridge flux, unpulsed flux from the intrabinary shock (if any), and unmodeled background emission. The middle panel shows the weighted binary light curve from the peak phase window; intriguingly, the minimum bin is at \( \phi_B = 0.25 \), pulsar superior conjunction. The full spin-phase light curve shows no strong eclipse. This suggests an additional uneclipsed gamma-ray component.

Binning clearly affects the minimum's appearance, so we desire an unbinned test for the eclipse significance. For an eclipse width \( \theta_e \), we form the test statistic

\[
\text{TS} = \Sigma_1 \log \left( 1 + w_i \theta_e / (1 - \theta_e) \right) + \Sigma_2 \log (1 - w_i),
\]

where the first sum is over the uneclipsed window and the second is over the eclipse window. Exposure variations are already very small (\( \sim 2\% \)) in the binned light curve, but the likelihood ratio test used here is insensitive to these, since the variations are common to both the null and eclipse scenarios. To estimate the probability distribution of this statistic, we scrambled weights among the pulse peak photons and recomputed TS 10,000 times. At \( \theta_e = 25.4 \), we find a chance probability of 0.080 (\( \sim 1.4 \sigma \)). However, the companion wind and photon opacity may widen the gamma-ray eclipse. Indeed, somewhat wider eclipses, to \( \theta_e \approx 45^\circ \), show larger significance. The best detection is at \( \theta_e \approx 40^\circ \), illustrated in the histogram at right, with a 0.7% (\( \sim 2.45 \sigma \), single trial) probability of a false-positive detection. This is intriguing, but hardly definitive. However, an improved radio ephemeris should provide a factor of \( > 4 \) more photons and better pulse

![Figure 4](https://example.com/figure4.png)
phase isolation, allowing a sensitive test for a magnetospheric (pulse phased) eclipse.

5. CONCLUSIONS

Our spectroscopic study of MSP J2215+5135 does not support the inference, based on companion light-curve-shape fits, of a particularly massive pulsar, instead suggesting a modest \( \sim 1.6 M_\odot \) NS mass. However, the assumed direct heating model is clearly inadequate. Viable high temperature ELC/ICARUS fits give a heating power \( \log[L_H] > 34.7 \), substantially larger than the observed X- and gamma-ray luminosities \( \log[L_x] = 32.0 \) and \( \log[L_\gamma] = 34.1 \) at \( d = 3 \text{ kpc} \) while the light curves show asymmetric residuals. In this it joins several other pulsar binary light curves poorly fit by direct heating (J2051–0827, Stappers et al. 2001; J1810+1744, Breton et al. 2013; J1311–3430, Romani et al. 2015). We argue that this indicates indirect, likely particle, heating via spindown power reprocessed in an intrabinary shock.

With the present direct heating model, the fits are inadequate and the critical binary inclination \( i \) is not robustly determined. Accordingly, the fit masses are indicative only, and the statistical errors are not useful. There is a clear lesson here: with an inappropriate physical model, simple ELC fits to only the light-curve shape can deliver fit minima far from the true solution. Using the observed colors, as in ICARUS, certainly helps, but spectroscopic constraints are also essential. Of course, amendment of the physical model should greatly improve the fit quality and may allow photometry-only solutions with high-quality data.

Our temperature-constrained fits do suggest that the system is viewed nearly edge-on. If so, this presents the interesting possibility that the pulsar magnetosphere will be eclipsed by the companion. Limited by the radio ephemeris available, present evidence for such eclipses is suggestive, but not definitive. However, additional radio data and further analysis of the Fermi LAT photons can produce a strong test of the eclipse hypothesis. If well measured, the width and spectrum of the pulsed flux eclipse can provide an important new tomographic probe of the MSP magnetosphere and of the evaporative companion wind.

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