PSR J1306-40: An X-Ray Luminous Redback with an Evolved Companion

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Abstract

PSR J1306–40 is a millisecond pulsar (MSP) binary with a non-degenerate companion in an unusually long ~1.097 day orbit. We present new optical photometry and spectroscopy of this system, and model these data to constrain fundamental properties of the binary such as the component masses and distance. The optical data imply a minimum neutron star mass of $1.75 \pm 0.09 M_\odot$ ($1\sigma$) and a high, nearly edge-on inclination. The light curves suggest a large hot spot on the companion, suggestive of a portion of the pulsar wind being channeled to the stellar surface by the magnetic field of the secondary, mediated via an intrabinary shock. The H$\alpha$ line profiles switch rapidly from emission to absorption near the companion inferior conjunction, consistent with an eclipse of the compact emission region at these phases. At our optically inferred distance of $4.7 \pm 0.5$ kpc, the X-ray luminosity is $\sim 10^{33}$ erg s$^{-1}$, brighter than nearly all known redbacks in the pulsar state. The long-period, subgiants-like secondary, and luminous X-ray emission suggest this system may be part of the expanding class of MSP binaries that are progenitors to typical field pulsar–white dwarf binaries.

Key words: binaries: spectroscopic – pulsars: general – X-rays: binaries

Supporting material: machine-readable table

1. Introduction

Millisecond pulsars (MSPs) form in binary systems, where the central neutron star accretes matter and angular momentum from a non-degenerate companion, spinning it up to very rapid spin periods. Although this mass transfer process is expected to last hundreds of Myr or more (Tauris & Savonije 1999), most MSPs in the Galactic field have degenerate white dwarf companions in wide orbits ($P_{\text{orb}} \gtrsim 5$ days), which represent the end stage of the recycling process (Tauris & van den Heuvel 2006).

Recent multiwavelength (optical, radio, and X-ray) follow-up observations of unidentified Fermi-Large Area Telescope (LAT) $\gamma$-ray sources have revealed a substantial number of close neutron star binary systems that host hydrogen-rich secondaries rather than He white dwarfs. Unlike most field MSPs (as described above), these appear to be systems in which the standard recycling process is not yet complete (e.g., Benvenuto et al. 2014), providing valuable insights into the spin-up process. These binaries are classified by the mass of the secondary: “redbacks” have non-degenerate, main-sequence-like companions ($M_e \gtrsim 0.1 M_\odot$), compared to the less massive ($M_e \lesssim 0.05 M_\odot$), highly ablated, semi-degenerate “black widows” (Roberts 2011). Both systems show radio eclipses due to ionized material from the secondary; these eclipses are typically more extensive for redbacks (e.g., D’Amico et al. 2001; Camilo et al. 2015; Cromartie et al. 2016).

A few redbacks have been observed to transition back and forth between an accretion-powered disk state and a rotationally powered pulsar state. These “transitional millisecond pulsars” proved the suspected evolutionary link between some recycled MSPs and neutron star low-mass X-ray binaries (e.g., Archibald et al. 2009; Papitto et al. 2013; Bassa et al. 2014). However, like the bulk of the redback population, the short orbital periods in these systems ($\lesssim 0.5$ day) mean they are unlikely to end their lives as the wide-orbit MSP–He white dwarf binaries that dominate the observed population of MSPs in the field (Chen et al. 2013). Instead, the progenitors to these canonical MSP–white dwarf systems are neutron stars with evolved red giant companions whose orbital periods are $> 1$ day (Tauris & Savonije 1999).

In this context, the MSP binary 1FGL J1417.7–4407 (PSR J1417–4402) was the first MSP binary discovered that is a likely progenitor to the typical MSP–white dwarf binaries (Strader et al. 2015; Camilo et al. 2016). Due to its long-period, red giant companion, and inferred evolutionary track, a new “huntsman” subclass was coined to distinguish unique systems like these from the more common redbacks (Strader et al. 2015; Swihart et al. 2018).

Optical spectra of 1FGL J1417.7–4407 show a strong, persistent double-peaked H$\alpha$ emission profile that is unusual among redbacks in their pulsar states and reminiscent of a classic accretion disk. However, due to the small separation between the peak components, and the stationary profiles as a function of orbital phase in the rest frame of the secondary, this H$\alpha$ phenomenology is likely not due to a disk. Instead, the emission likely comes from a combination of material swept off the companion and a strong intrabinary shock (Camilo et al. 2016; Swihart et al. 2018). Another piece of evidence for an unusually luminous shock is the X-ray luminosity in this system ($\sim 10^{33}$ erg s$^{-1}$), which is higher than other redbacks in the pulsar state. Swihart et al. (2018) discussed the possibility that the shock luminosity in 1FGL J1417.7–4407 is enhanced over typical redbacks by a strong, magnetically driven wind from the tidally locked red giant secondary. The candidate MSP binary 2FGL J0846.0+2820 shows many similarities to 1FGL J1417.7–4407, making it a possible second member of the huntsman subclass, though no radio pulsar has yet been confirmed in this system (Swihart et al. 2017). Pending future evolution studies, it might be reasonable to include other long-period redback-like systems with evolved companions in this class (e.g., PSR NGC 6397A).

The subject of this paper, PSR J1306–40, was discovered in the SUPERB survey (Keane et al. 2018), where it was identified as a candidate redback binary. No pulsar timing...
solution was presented, owing to the frequent eclipses. Linares (2018) found the X-ray spectrum of this source is a hard power law typical of redbacks, and that the X-ray and optical light curves are modulated on the same orbital period, confirming the source as a likely redback. The orbital period is one of the longest known among compact MSP binaries ($P_{\text{orb}} \sim 1.097$ days).

Here, we present the first optical spectroscopy and multi-band optical photometry of PSR J1306–40, and show that it has properties more similar to huntsman-type MSP binaries than classic redback systems. We detail our new optical spectroscopic and photometric observations of the system in Section 2. We model the optical light curves in Section 3, and examine the phase-resolved Hα profiles in Section 4. Finally, we make concluding remarks and discuss this system in the context of known redbacks and its connection to MSP–white dwarf progenitors in Section 5.

2. Optical Observations

2.1. SOAR Spectroscopy

We obtained spectra of the companion to PSR J1306–40 using SOAR/Goodman (Clemens et al. 2004) from 2017 July 11 to 2018 June 9. All data used a 1200 l mm$^{-1}$ grating and a $0.95$ slit, giving a resolution of about $1.7$ Å. Exposure times ranged from 15 to 30 minutes per spectrum, depending on weather conditions. The spectra covered a wavelength range of $\sim 5485$–$6740$ Å. Barycentric radial velocities were determined through cross-correlation with bright standards taken with the same setup, primarily in the wavelength range 6050–6250 Å. The resulting 43 velocities are listed in Table 1. Observation epochs have been corrected to Barycentric Julian Date (BJD) on the Barycentric Dynamical Time system (Eastman et al. 2010).

Even though the SUPERB survey has detected a pulsar in this system (Keane et al. 2018), it has not yet been timed, so the ephemerides must be determined from our data. Using the custom Markov Chain Monte Carlo sampler TheJoker (Price-Whelan et al. 2017), we fit a circular Keplerian model to the data in Table 1 in order to determine the orbital period $P$, BJD time of the ascending node $T_0$, systemic velocity $\gamma$, and the semi-amplitude $K_2$. Here and throughout the paper uncertainties are given at 1σ. We find $P = 1.097195(161)$ days, $T_0 = 2457780.8373(19)$ days, $\gamma = 32.0 \pm 1.8$ km s$^{-1}$, $K_2 = 210 \pm 2$ km s$^{-1}$. (We note that the spectroscopic period we find here is fully consistent with the photometric period found in the discovery paper Linares 2018.) A fit using these median values is shown in Figure 1. For the remainder of this work, we assume the period derived from our spectroscopy.

This fit has an rms scatter of 11 km s$^{-1}$ (compared to a median uncertainty among the velocities of about 8.4 km s$^{-1}$) and a $\chi^2$/ dof of 74/39, perhaps suggesting the fit could be improved. However, we see no clear trends in the residuals. A fit with the eccentricity left free does not find a value significantly different from 0, so there is no evidence that the orbit is non-circular. It may just be that the velocity uncertainties are slightly underestimated. It would be useful to obtain additional radial velocities in the range $\phi = 0.7$–1.0; it is challenging to get complete phase coverage for this system because its period is close to 1 day. Future pulsar timing should improve the ephemerides by orders of magnitude.

| BJD (days) | RV (km s$^{-1}$) | err. (km s$^{-1}$) |
|------------|-----------------|------------------|
| 2457945.5419639 | −119.5 | 6.5 |
| 2457945.6301728 | −16.9 | 7.2 |
| 2457956.5212405 | −123.1 | 6.8 |
| 2457956.5352468 | −107.9 | 6.4 |
| 2457956.5546942 | −95.8 | 8.1 |
| 2457956.5678017 | −65.6 | 8.2 |
| 2457956.5948590 | −57.2 | 7.0 |
| 2457956.6088705 | −38.0 | 6.0 |
| 2457966.4918176 | −27.2 | 7.6 |
| 2457966.5122271 | −18.4 | 20.1 |
| 2457966.5399208 | 38.7 | 7.2 |
| 2457966.5608056 | 49.6 | 8.7 |
| 2457966.5914866 | 115.1 | 10.2 |
| 2457967.5998999 | −1.5 | 12.8 |
| 2457996.4786139 | 231.8 | 8.4 |
| 2457996.4931540 | 238.7 | 8.0 |
| 2457996.5105239 | 228.8 | 9.4 |
| 2458001.4795192 | −144.0 | 11.4 |
| 2458001.4935388 | −124.6 | 10.2 |
| 2458139.7564130 | −136.8 | 7.7 |
| 2458139.7704090 | −117.1 | 6.8 |
| 2458140.7002666 | −194.5 | 9.8 |
| 2458140.7540222 | −166.4 | 8.3 |
| 2458140.7700050 | −150.8 | 7.4 |
| 2458140.7910007 | −158.5 | 8.2 |
| 2458161.6712193 | −121.2 | 7.9 |
| 2458161.6872977 | −107.7 | 7.3 |
| 2458202.5922163 | 177.8 | 8.5 |
| 2458202.5962046 | 197.7 | 9.6 |
| 2458202.8350917 | 190.9 | 7.4 |
| 2458202.8490793 | 176.1 | 7.6 |
| 2458223.5928781 | 231.9 | 7.7 |
| 2458223.8137433 | 41.2 | 8.4 |
| 2458223.8456941 | 32.1 | 14.9 |
| 2458243.7792111 | −87.6 | 8.6 |
| 2458243.6919415 | −112.3 | 10.5 |
| 2458243.7113535 | −125.5 | 9.5 |
| 2458243.7263475 | −141.9 | 10.2 |
| 2458243.7459698 | −130.3 | 9.3 |
| 2458247.5062024 | 131.9 | 11.5 |
| 2458247.5435496 | 160.5 | 14.2 |
| 2458278.5472619 | 197.1 | 15.9 |
| 2458278.5613912 | 183.7 | 15.7 |

Our SOAR spectra also show resolved Hα in emission in most, but not all epochs. We present an analysis of the Hα morphology in Section 4.

2.1.1. Determining the Mass Ratio

By assuming the secondary is tidally synchronized with the pulsar, we can estimate its projected rotational velocity ($v \sin i$) by comparing the rotationally broadened spectra with non-rotating template stars of similar spectral type. The assumption of synchronization is reasonable because this timescale is $\lesssim 1$ Myr for a system with a period of PSR J1306–40 and a typical redback mass ratio (Zahn 1977). Combined with our measurement of the orbital semi-amplitude, we use the $v \sin i$ value to constrain the mass ratio of the binary.

Following similar procedures as described in Strader et al. (2014) and Swihart et al. (2017), we obtained spectra of bright
late-G to mid-K giant stars to use as templates and convolved these with a set of rotational convolution kernels reflecting a range of $v \sin i$ values (including limb-darkening). After cross-correlating the broadened templates with the original, unBroadened spectra, we fit a relation between the FWHM values and the input value of $v \sin i$. We then cross-correlated the spectra of the companion to PSR J1306–40 with that of the unconvolved standard stars and used the FWHM values to estimate the projected rotational velocity.

Our final estimate of $v \sin i$ derived in this manner is $75.5 \pm 3.8 \text{ km s}^{-1}$, where the uncertainty represents the standard deviation of the measurements among all templates and does not account for systematic uncertainties. Along with our measured value of the semi-amplitude, we use this equation, which uses the Roche lobe approximation of Eggleton (1983):

$$v \sin i = K_2 \frac{0.49 q^{2/3} (1 + q)}{0.6 q^{2/3} + \ln(1 + q^{1/3})},$$

where $q = M_2/M_{\text{NS}}$ is the mass ratio. This equation is valid assuming that the secondary fills its Roche lobe and is synchronized. We find that $q = 0.290 \pm 0.031$. This measurement can be directly tested once a timing solution for the pulsar is available.

2.1.2. The Minimum Neutron Star Mass

The binary mass function

$$f(M) = PK_2^2/2\pi G = M_{\text{NS}} \sin^3(i)/(1 + q)^2.$$ We have determined all of these quantities from the spectroscopy alone, except for the inclination. Propagating the uncertainties appropriately, we can determine the minimum neutron star mass $M_{\text{NS}} \sin^3(i) = 1.75 \pm 0.09 M_\odot$. This quantity is independent of the light-curve modeling we carry out in Section 3 and is a robust lower limit. Hence, we see that, consistent with many other redbacks (Strader et al. 2019), the mass of PSR J1306–40 is well in excess of the canonical $1.4 M_\odot$.

2.2. Optical Photometry

We obtained optical $BVI$ photometry of the companion to PSR J1306–40 using ANDICAM on the SMARTS 1.3 m telescope at CTIO over 101 nights between 2017 July 17 and 2018 April 29 (UT). On each night, we took single 340 and 250 s exposures in the $V$ and $I$ bands, respectively, and two 250 s exposures in $B$ that were merged during the reduction process. Data were reduced following the procedures in Walter et al. (2012).

We performed differential aperture photometry to obtain instrumental magnitudes of the target source using fifteen nearby comparison stars as a reference. Absolute calibration was done with respect to the Landolt (1992) standard fields TPheD (2017 July 17–September 03) and RU149 (2018 January 24–April 29). After excluding measurements with large errors, our final data set includes 92, 93, and 95 measurements in the $B$, $V$, and $I$ bands, respectively. The mean observed magnitudes (not corrected for extinction) are $B = 19.21$, $V = 18.35$, and $I = 17.20$, with median errors of $\sim 0.03$ mag in $V$ and $I$ and $\sim 0.06$ in $B$. The SMARTS photometry is listed in Table 2.

| BJD (days) | Band | mag | err |
|------------|------|-----|-----|
| 2457962.46060 | $B$ | 19.104 | 0.104 |
| 2457962.46769 | $V$ | 18.212 | 0.029 |
| 2457962.47235 | $I$ | 17.007 | 0.062 |
| 2457967.46273 | $B$ | 19.357 | 0.099 |
| 2457967.46981 | $V$ | 18.631 | 0.044 |
| 2457967.47448 | $I$ | 17.461 | 0.095 |
| 2457968.46610 | $B$ | 19.334 | 0.073 |
| 2457968.47319 | $V$ | 18.426 | 0.037 |
| 2457968.47785 | $I$ | 17.289 | 0.033 |
| 2457969.47164 | $B$ | 19.140 | 0.062 |

Note. The full SMARTS data set is available in machine-readable format. We show a portion of the table here as a preview of its form and content. Magnitudes have not been corrected for extinction.

This table is available in its entirety in machine-readable form.

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Figure 1. Circular Keplerian fit to the SOAR/Goodman barycentric radial velocities of PSR J1306–40 listed in Table 1.
dimmer due to the effects of gravity and limb-darkening when viewing along the axis connecting the primary and secondary. Overall, the shape and amplitude of the light curves appear broadly consistent with the unfiltered Catalina Sky Survey (Drake et al. 2009) data presented by Linares (2018), suggesting no significant state change has occurred in this system since late 2005.

Another notable feature of the light curves is that the maxima are not symmetric about the expected $\phi = 0.75$. Instead, the light curves slope downward between $0.5 < \phi < 1.0$, suggesting that the source of heating is asymmetric with respect to the rotational axis of the secondary. Similar asymmetric heating has been observed in a number of other redbacks and black widows, and may be common in these systems due to the effects of an asymmetric intrabinary shock, heating mediated by the magnetic field of the secondary, or other magnetic activity such as starspots (e.g., Stappers et al. 2001; Breton et al. 2013; Schroeder & Halpern 2014; Romani et al. 2015a, 2015b; Deneva et al. 2016; Romani & Sanchez 2016; van Staden & Antoniadis 2016; Sanchez & Romani 2017; Cho et al. 2018). We show below that asymmetric heating is a promising (though not unique) mechanism to explain the observed light curves of PSR J1306–40.

### 3. Light-curve Fitting

We modeled the $BVI$ light curves of PSR J1306–40 using the Eclipsing Light Curve (ELC; Orosz & Hauschild 2000) code. Given the recent pulsar detection, we assume there is no accretion disk; the light curves are dominated by a tidally distorted secondary that is being heated on its tidally locked day side. We also assume a circular orbit and fix the orbital period $P$, semi-amplitude $K_2$, and mass ratio $q$ to the values derived from our spectroscopy (Section 2.1). These values immediately set the scale for the system, giving an orbital separation of $\sim 0.85 R_\odot$.

In our most basic model, we fit for the orbital inclination $i$, the Roche lobe filling factor $f_2$, the intensity-weighted mean surface temperature of the secondary $T_{\text{eff}}$, the central isotropic irradiating luminosity from the pulsar, and a phase shift $\Delta \phi$. We characterize the irradiating luminosity indirectly through the most directly observed quantity: the maximum day side

![Figure 2. SMARTS optical photometry of PSR J1306–40. The black lines show the best-fit “No Spot” (dashed) and “Hot Spot” (solid) ELC models from Table 3. Two full orbital phase cycles are shown for clarity.](image)

Table 3. Summary of ELC Fits for PSR J1306–40

| Parameters | No Spot | Hot Spot |
|------------|---------|----------|
| $\text{incl}$ ($^\circ$) | $70.4^{+16.7}_{-7.0}$ | $83.5^{+3.3}_{-4.8}$ |
| filling factor ($f_2$) | $0.88^{+0.06}_{-0.02}$ | $0.94^{+0.04}_{-0.05}$ |
| $T_{\text{eff}}$ (K) | $4728^{+277}_{-277}$ | $4912^{+198}_{-191}$ |
| $T_{\text{day}}$ (K) | $5542^{+275}_{-275}$ | $6187^{+291}_{-281}$ |
| $\Delta \phi$ | $-0.0354^{+0.0036}_{-0.0019}$ | $-0.0228 \pm 0.0039$ |
| $\lambda_{\text{spot}}$ ($^\circ$) | $\cdots$ | $27\pm19$ |
| $\theta_{\text{spot}}$ ($^\circ$) | $\cdots$ | $27\pm19$ |
| $T_{\text{spot}}$ (K) | $\cdots$ | $11063^{+308}_{-214}$ |
| $r_{\text{spot}}$ ($^\circ$) | $\cdots$ | $52^{+2}_{-2}$ |
| $\chi^2$(dof) | $370.3(275)$ | $220.7(271)$ |
| $M_1$ ($M_\odot$) | $2.08^{+0.35}_{-0.34}$ | $1.77^{+0.07}_{-0.03}$ |
| $M_2$ ($M_\odot$) | $0.59 \pm 0.10$ | $0.51^{+0.02}_{-0.01}$ |
| $\log g$ (cgs) | $3.745^{+0.025}_{-0.010}$ | $3.725 \pm 0.005$ |

Notes:
- a) Spot latitude. $\lambda_{\text{spot}} = 0^\circ$ and $\lambda_{\text{spot}} = 180^\circ$ denote the north and south poles, respectively.
- b) Spot longitude. $\theta_{\text{spot}} = 0^\circ$ and $\theta_{\text{spot}} = 180^\circ$ denote the inner Lagrange point and night side of the star, respectively.
the magnetic poles and creating intense localized heating (i.e., one or more hot spots; Tang et al. 2014; Sanchez & Romani 2017).

ELC does not allow us to directly model an offset intrabinary shock or a channeled pulsar wind. But we do have the ability to model its effect on the companion: we can add a hot spot to our underlying model of a heated, tidally distorted secondary. The hot spot is modeled as a circle with a temperature structure that falls off linearly toward the edges. We fit for the central temperature ($T_{\text{spot}}$), size ($r_{\text{spot}}$), and location ($\lambda_{\text{spot}}$, $\theta_{\text{spot}}$) of the hot spot (see Table 3).

Our main result is that adding a single hot spot to the heated, distorted secondary provides an excellent fit to the light curve ($\chi^2$/dof $= 221/271$). The reduced $\chi^2$ in this model is $< 1$ likely due to the overestimation of a subset of the photometric uncertainties. In the best fitting hot spot model, the system is highly inclined ($i \approx 83^\circ$), with a large hot spot near the north pole of the secondary. We show this best-fit model in Figure 2 (solid line) and summarize the posteriors in Table 3.

Using our best hot spot model, the inferred mass of the primary is $M_1 = 1.77^{+0.07}_{-0.03}$, fairly massive for a typical neutron star, but fully consistent with the neutron star masses found in many redback MSPs (e.g., Kaplan et al. 2013; Romani et al. 2015b; Bellm et al. 2016; Strader et al. 2016; Sanchez & Romani 2017; Shabbaz et al. 2017; Linarez et al. 2018; Swihart et al. 2018). The secondary has a mass of $M_2 = 0.51^{+0.02}_{-0.01}$, placing it in the high-mass tail of the redback companion mass distribution (Strader et al. 2019). The inferred gravity of the companion is $log g = 3.725 \pm 0.005$ (egs), suggesting it is slightly evolved off the main sequence, which may be relevant for interpreting the high-energy emission from this system in the context of magnetically driven winds/outflows.

For the hot spot model, we require a small phase shift to obtain adequate fits to the light curves. This is primarily due to the light-curve minimum occurring ~30 minutes earlier than what we expect from our spectroscopic ephemeris. This shift is larger than what we can account for from our formal uncertainties on the orbital period and $T_0$, and the maxima appear roughly centered on the expected $\phi = 0.75$, so this feature of the light curves is likely real. One interpretation of this feature is that in addition to the hot spot, the intrabinary shock could be slightly trailing the companion, leading to off-center heating.

For the hot spot itself, echoing our previous discussion, its best-fit location is centered near the companion’s north pole, consistent with magnetic ducting of intrabinary shock particles. The spot covers roughly $\sim 19\%$ of the surface area of the star, but contributes about a third of the observed $V$-band flux owing to its high temperature. This value is broadly consistent with the contribution from a similar hot spot modeled for the optical light curves of the redback binary 3FGL J0212.1+5320 (Shabbaz et al. 2017).

3.1. Distance

Using the results from our light-curve models, we estimate the distance to the binary by comparing its apparent magnitude to its intrinsic luminosity following similar procedures outlined in Strader et al. (2015) and Swihart et al. (2018). We estimate the bolometric luminosity by assuming $T_{\text{eff}}$ and the inferred radius of the secondary ($R \sim 1.6 R_\odot$) from our best-fit model (Table 3, column 3). We fit 10 Gyr solar metallicity isochrones (Marigo et al. 2008) to estimate bolometric corrections and used these to obtain the predicted absolute magnitude in each band (BVI). Finally, we compared these values to the mean apparent magnitudes after applying extinction corrections using the Schlafly & Finkbeiner (2011) reddening maps to get a distance to the binary: $4.7 \pm 0.5$ kpc. For the remainder of this paper, we adopt this value for the distance. We note that this method has proven successful in the past at estimating reliable distances to similar systems (e.g., Swihart et al. 2018).

However, due to systematic effects such as the unknown metallicity and precise evolutionary state of the star, our estimate is likely uncertain by at least 20%. Future Gaia releases will help us address these systematics.

PSR J1306–40 is listed in Gaia DR2 (with parallax $0.106 \pm 0.027$ mas. Although the current parallax measurement is not significant, we estimate the geometric distance to the binary using a weak distance prior based on an exponentially decreasing space density Galaxy model with a scale length of 0.94 kpc (Bailer-Jones et al. 2018). We also calculated the distance using a larger scale length (1.35 kpc), suggested by Astramadja & Bailer-Jones (2016). The resulting distances are $2.83^{+1.65}_{-0.99}$ kpc and $3.47^{+2.37}_{-1.36}$ kpc, respectively, somewhat smaller than our optically inferred distance but within the uncertainties.

Although the above estimates are uncertain, they are all wholly inconsistent with the dispersion-measure-based distance estimates made using the measured dispersion measure and the (Cordes & Lazio 2002, CL02) or (Yao et al. 2017, Y17) electron density models ($d_{\text{CL02}} \sim 1.2$ kpc and $d_{\text{Y17}} \sim 1.4$ kpc, respectively).

The discrepancies between the light-curve/parallax distances and the dispersion-measure-based estimates are consistent with the results of Jennings et al. (2018), who use Gaia DR2 parallaxes to measure the distances to a number of black widows and redbacks, and find that some dispersion-measure distances, particularly those at high Galactic latitude, are underestimated. This also agrees with previous results for the distances of normal MSPs outside the Galactic Plane (Gaensler et al. 2008; Roberts 2011).

4. Hα Spectroscopy

A number of MSP binaries have shown strong Hα emission lines. In some of these systems, the existence of double-peaked Balmer emission indicates the presence of an accretion disk (e.g., de Martino et al. 2014; Bogdanov et al. 2015), although an intrabinary shock and/or material streaming off the companion have also been used to explain the complex morphology (Sabbi et al. 2003; Swihart et al. 2018). Here we present the phase-resolved Hα profiles and suggest an intrabinary shock near the companion’s surface can explain the origin of the emission.

Throughout most of our spectroscopic monitoring of PSR J1306–40, a moderate Hα emission line was persistent, occasionally showing complex, double-peaked morphology. At other times, the Hα appears only in absorption. We show the phase-resolved Hα profiles in Figure 3. Each spectrum has been corrected to the rest frame of the secondary (dotted line) and arbitrarily shifted in flux to display changes in the profile shape.

When in emission, the Hα profile always peaks directly at or very near the velocity of the secondary. This suggests the
emission is either coming directly from the star or from a region relatively close to the companion’s surface. Since the emission tracks the orbital motion, the line could arise from the stellar chromosphere, as is the case in RS CVn systems (e.g., Drake 2006). However, the emission we observe is broad, with a significant amount of the emission present at velocities \( \gtrsim 200 \text{ km s}^{-1} \) from the radial velocity of the companion. Furthermore, near the companion inferior conjunction (\( \phi = 0.25 \)), the emission line disappears and instead only appears in absorption. Since \( \text{H} \alpha \) absorption is typical in low-mass stars like the companion to PSR J1306–40 (Cram & Mullan 1985; Pickles 1998), it is likely that the emission region is being eclipsed at these phases and we are only seeing \( \text{H} \alpha \) absorption intrinsic to the star.

Such a scenario can be explained by invoking an \( \text{H} \alpha \) emitting intrabinary shock near the companion’s surface. Given our evidence for a rapidly rotating Roche lobe filling companion, it is likely the magnetic field on the surface is enhanced, which can lead to strong winds from the likely subgiant secondary. These winds can then be heated directly by the pulsar’s radiation pressure or through an interaction with the pulsar wind as it forms an intrabinary shock (see Section 3). Given the orbitally modulated X-ray emission found by Linares (2018), such a shock almost certainly exists in this system and can provide a natural explanation for the observed X-ray and \( \text{H} \alpha \) phenomenology.

5. Discussion

We have presented new optical photometry and spectroscopy of the source PSR J1306–40, a redback-like MSP binary with one of the longest known orbital periods among MSPs with non-degenerate companions. Our modeling suggests the companion is somewhat evolved and massive compared to typical redbacks, which may be relevant for interpreting the high-energy emission in the context of an intrabinary shock.

As pointed out by Linares (2018), PSR J1306–40 lies in the error region of the Fermi-LAT \( \gamma \)-ray source 3FGL J1306.8–4031 (Acero et al. 2015), about 3\( ^{\prime} \)4 from its center. In the preliminary LAT 8 year point-source catalog (FL8Y\(^2\)), which includes four additional years of survey data, the updated error region corresponding to the source FL8Y J1306.8–4035 is now \( \sim 60\% \) smaller in area than in 3FGL and has been shifted \( \sim 3^{1/2} \) south, such that PSR J1306–40 lies only \( \sim 0^{\prime}86 \) away from its center. Hence, there is compelling evidence that PSR J1306–40 is indeed associated with a Fermi-LAT \( \gamma \)-ray source.

Although the \( \gamma \)-ray spectra of many MSPs are typically highly curved, the relatively flat 3FGL spectrum shows no significant evidence for curvature with no cutoff up to \( \gtrsim 10 \text{ GeV} \), reminiscent of huntsman MSP 1FGL J1417.7–4407 (Strader et al. 2015; Camilo et al. 2016), which has a red giant secondary in a 5.4 day orbit and also shows a flat \( \gamma \)-ray spectrum. Similar to PSR J1306–40, 1FGL J1417.7–4407 likely has a strong intrabinary shock and a significant wind from the companion that may be influencing \( \gamma \)-ray production (Swihart et al. 2018). Linares (2018) attributed the unusual \( \gamma \)-ray spectrum of 3FGL J1306.8–4031 to contamination from two nearby, active galaxies. We do not rule out this possibility, but given the improved source localization in FL8Y, contamination from other sources may not be important. The upcoming official 4FGL catalog will allow a reassessment of the spectrum of the \( \gamma \)-ray source.

The X-ray light curve shows one maximum and one minimum per orbital period (Linares 2018), which can be attributed to emission from an intrabinary shock that becomes at least partially eclipsed during the inferior conjunction of the companion (e.g., Bogdanov et al. 2011; Rivera Sandoval et al. 2018). Although the minimum X-ray count rate presented by Linares (2018) approaches zero, there is no clear evidence for a total eclipse of the X-ray-emitting region. At our best-fit inclination (\( i = 83^\circ.5 \)), an X-ray-emitting point source would be completely eclipsed between \( \phi \sim 0.21–0.29 \), suggesting the shock is somewhat extended. Additional data will be needed to probe the precise geometry of the shock.

Linares (2018) estimated the epoch of inferior conjunction of the companion from fitting the time of minimum of the X-ray light curve (\( T_{\text{OX}} \)). Comparing this value with our spectroscopic ephemeris, we find the X-ray light curve lags behind the companion orbit by about one hour; the X-ray flux reaches a minimum at \( \phi \sim 0.29 \), with a similar offset needed to match the X-ray maxima. However, \( T_{\text{OX}} \) and our spectroscopic \( T_0 \) are separated in time by 1471 days, approximately 1340 orbital periods. Assuming our uncertainty on the binary period (0.000161 day), building a phase-coherent solution for the radial velocity data backward to the epoch of the X-ray observation results in an absolute uncertainty of \( \sim 12.9 \text{ hr} \), nearly half an orbital period. Therefore, the lag we find is not

\(^2\) https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FL8y/
reliable with the current data. In the future, a precise pulsar timing solution would enable us to check the relative phase alignments between the X-ray and optical light curves.

PSR J1306–40 has a long orbital period and a relatively massive secondary compared to the population of known redbacks in the Galactic field (Strader et al. 2019). In the binary evolution models of Podsiałowski et al. (2002), PSR J1306–40 lies above the bifurcation period that distinguishes systems whose orbits will shrink to become black widows/redbacks and those that will grow to become MSP–white dwarf binaries. The light curves of PSR J1306–40 also show strong signs of irradiation, which can further contribute to an increase in the orbital period if the companion undergoes even low levels of evaporations (Chen et al. 2013). Our light-curve models also suggest that the companion is filling a substantial fraction of its Roche lobe and that it has a somewhat evolved, subgiant-like radius, luminosity, and gravity (log g = 3.725 ± 0.005). Given that PSR J1306–40 has been spun up to obtain its rapid spin period, this would put PSR J1306–40 on a standard Case B evolutionary track of low-mass X-ray binaries that started the mass transfer process after leaving the main sequence, placing it in the late stages of the MSP recycling process that will terminate with a wide-orbit MSP–white dwarf binary (Tauris & Savonije 1999).

The relatively long period and subgiant-like secondary of PSR J1306–40 resemble the huntsman systems 1FGL J1417.7–4407 and 2FGL J0846.0+2820 (Strader et al. 2015; Camilo et al. 2016; Swihart et al. 2017, 2018), which are likely progenitors to the typical MSP–He white dwarf binaries observed in the Galactic field. Another similarity between PSR J1306–40 and at least 1FGL J1417.7–4407 is the X-ray luminosity: Linares (2018) inferred a 0.5–10 keV X-ray luminosity of $8.8 \times 10^{31}$ erg s$^{-1}$ for PSR 1306–40 when using the dispersion-measure-based distance of 1.2 kpc. But at our optical light-curve-inferred distance estimate of 4.7 kpc, the X-ray luminosity of PSR 1306–40 is $\sim 10^{33}$ erg s$^{-1}$, brighter than nearly all known redbacks in the pulsar state—except 1FGL J1417.7–4407.

Detecting radio pulsations in these huntsmen systems has proven difficult even compared to typical redbacks (Camilo et al. 2016; Keane et al. 2018). This difficulty may be related to the strong winds from the evolved companions, which when ionized could eclipse the radio emission more readily than for redbacks with main sequence-like companions.

This high inferred eclipse fraction, and the rarity of these systems due to the shorter length of the red giant phase of evolution compared to the main sequence stage, suggests discovering other huntsman systems may be even more reliant on multiwavelength follow-up of unassociated Fermi-LAT error regions than for typical redbacks. Fortunately, the companions in these systems are intrinsically brighter than redbacks, and thus more readily observable in ground-based optical variability studies.

A precise pulsar timing solution would be a significant step for fully understanding the huntsman PSR J1306–40 and its connection to known redbacks, placing tighter constraints on the orbital dynamics and permitting a search for spin and/or orbitally modulated $\gamma$-ray pulsations in the Fermi data. Additional deep X-ray observations would also be useful to compare with the most recent optical light curves and with detailed intrabinary shock models. The subgiant nature of the nearly Roche lobe filling, highly irradiated companion, and the clear evidence for intrabinary material makes this system a good candidate for future multiwavelength monitoring.

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References
Acero, F., Ackermann, M., Ajello, M., et al. 2015, ApJS, 218, 23
Archibald, A. M., Stairs, I. H., Ransom, S. M., et al. 2009, Sci, 324, 1411
Astraatmadja, T. L., & Bailier-Jones, C. A. L. 2016, ApJ, 832, 137
Bailer-Jones, C. A. L., Rybicki, J., Fouesneau, M., Mantelet, G., & Andrae, R. 2018, AJ, 156, 58
Bassa, C. G., Patruno, A., Hessels, J. W. T., et al. 2014, MNRAS, 441, 1825
Bellm, E. C., Kaplan, D. L., Breton, R. P., et al. 2016, ApJ, 816, 74
Benvenuto, O. G., De Vito, M. A., & Horvath, J. E. 2014, ApJL, 786, L7
Bogdanov, S., Archibald, A. M., Bassa, C., et al. 2015, ApJ, 806, 148
Bogdanov, S., Archibald, A. M., Hessels, J. W. T., et al. 2011, ApJ, 742, 97
Breton, R. P., van Kerkwijk, M. H., Roberts, M. S. E., et al. 2013, ApJ, 769, 108
Camilo, F., Kerr, R. M., Ray, P. S., et al. 2015, ApJ, 810, 85
Camilo, F., Reynolds, J. E., Ransom, S. M., et al. 2016, ApJ, 820, 6
Chen, H.-L., Chen, X., Tauris, T. M., & Han, Z. 2013, ApJ, 775, 27
Cho, P. B., Halpern, J. P., & Bogdanov, S. 2018, ApJ, 866, 71
Clemens, J. C., Crain, J. A., & Anderson, R. 2004, Proc. SPIE, 5492, 331
Cordes, J. M., & Lazio, T. J. W. 2002, arXiv:astro-ph/0207156
Cram, L. E., & Mullan, D. J. 1985, ApJ, 294, 626
Cromartie, H. T., Camilo, F., Kerr, M., et al. 2016, ApJ, 819, 34
D’Amico, N., Possenti, A., Manchester, R. N., et al. 2001, ApJL, 561, L89
de Martin, D., Casares, J., Mason, E., et al. 2014, MNRAS, 444, 3004
Deneva, J. S., Ray, P. S., Camilo, F., et al. 2016, ApJ, 823, 105
Drake, A. J. 2006, AJ, 131, 1044
Drake, A. J., Djurovski, S. G., Mahabal, A., et al. 2009, ApJ, 696, 870
Eastman, J., Siverd, R., & Gaudi, B. S. 2010, PASP, 122, 935
Eggelton, P. P. 1983, ApJ, 268, 368
Gaensler, B. M., Madsen, G. J., Chatterjee, S., & Mao, S. A. 2008, PASA, 25, 184
Jennings, R. J., Kaplan, D. L., Chatterjee, S., Cordes, J. M., & Deller, A. T. 2018, ApJ, 864, 26
Kaplan, D. L., Bhalerao, V. B., van Kerkwijk, M. H., et al. 2013, ApJ, 765, 158
Keane, E. F., Barr, E. D., Jameson, A., et al. 2018, MNRAS, 473, 116
Landolt, A. U. 1992, AJ, 104, 340
Linares, M. 2018, MNRAS, 473, L50
Linares, M., Shahbaz, T., & Casares, J. 2018, ApJ, 859, 54
Marigo, P., Girardi, L., Bressan, A., et al. 2008, A&A, 482, 883
Morin, J. 2012, EAS, 57, 165
Orosz, J. A., & Hawesldt, P. H. 2000, A&A, 364, 265
Papitto, A., Ferrigno, C., Bozzo, E., et al. 2013, Natur, 501, 517
Pickles, A. J. 1998, PASP, 110, 863
Podsiadlowski, P., Rappaport, S., & Pfahl, E. D. 2002, ApJ, 565, 1107
Price-Whelan, A. M., Hogg, D. W., Foreman-Mackey, D., & Rix, H.-W. 2017, ApJ, 837, 20

7
Rivera Sandoval, L. E., Hernández Santisteban, J. V., Degenaar, N., et al. 2018, MNRAS, 476, 1086
Roberts, M. S. E. 2011, in AIP Conf. Ser. 1357, ed. M. Burgay et al. (Melville, NY: AIP), 127
Romani, R. W., Filippenko, A. V., & Cenko, S. B. 2015a, ApJ, 804, 115
Romani, R. W., Graham, M. L., Filippenko, A. V., & Kerr, M. 2015b, ApJL, 809, L10
Romani, R. W., & Sanchez, N. 2016, ApJ, 828, 7
Sabbi, E., Gratton, R., Ferraro, F. R., et al. 2003, ApJL, 589, L41
Sanchez, N., & Romani, R. W. 2017, ApJ, 845, 42
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Schroeder, J., & Halpern, J. 2014, ApJ, 793, 78
Shahbaz, T., Linares, M., & Breton, R. P. 2017, MNRAS, 472, 4287
Stappers, B. W., van Kerkwijk, M. H., Bell, J. F., & Kulkarni, S. R. 2001, ApJL, 548, L183
Strader, J., Chomiuk, L., Cheung, C. C., et al. 2015, ApJL, 804, L12
Strader, J., Chomiuk, L., Sonbas, E., et al. 2014, ApJL, 788, L27
Strader, J., Li, K.-L., Chomiuk, L., et al. 2016, ApJ, 831, 89
Strader, J., Swihart, S., Chomiuk, L., et al. 2019, ApJ, 872, 42
Swihart, S. J., Strader, J., Johnson, T. J., et al. 2017, ApJ, 851, 31
Swihart, S. J., Strader, J., Shishkovsky, L., et al. 2018, ApJ, 866, 83
Tang, S., Kaplan, D. L., Phinney, E. S., et al. 2014, ApJL, 791, L5
Tauris, T. M., & Savonije, G. J. 1999, A&A, 350, 928
Tauris, T. M., & van den Heuvel, E. P. J. 2006, in Compact stellar X-ray sources, ed. W. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 623
van Staden, A. D., & Antoniadis, J. 2016, ApJL, 833, L12
Wadiasingh, Z., Harding, A. K., Venter, C., Böttcher, M., & Baring, M. G. 2017, ApJ, 839, 80
Walter, F. M., Battisti, A., Towers, S. E., Bond, H. E., & Stringfellow, G. S. 2012, PASP, 124, 1057
Yao, J. M., Manchester, R. N., & Wang, N. 2017, ApJ, 835, 19
Zahn, J. P. 1977, A&A, 500, 121