2FGL J1311.7−3429 JOINS THE BLACK WIDOW CLUB

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ABSTRACT

We have found an optical/X-ray counterpart candidate for the bright, but presently unidentified, Fermi source 2FGL J1311.7−3429. This counterpart undergoes large-amplitude quasi-sinusoidal optical modulation with a 1.56 hr (5626 s) period. The modulated flux is blue at peak, with $T_{\text{eff}} \approx 14,000$ K, and redder at minimum. Superimposed on this variation are dramatic optical flares. Archival X-ray data suggest modest binary modulation, but no eclipse. With the γ-ray properties, this appears to be another black-widow-type millisecond pulsar. If confirmation pulses can be found in the GeV data, this binary will have the shortest orbital period of any known spin-powered pulsar. The flares may be magnetic events on the rapidly rotating companion or shocks in the companion-stripping wind. While this may be a radio-quiet millisecond pulsar, we show that such objects are a small subset of the γ-ray pulsar population.

Key words: gamma rays: stars – pulsars: general

Online-only material: color figures

1 INTRODUCTION

In the most recent Fermi Large Area Telescope (LAT) catalog of 1873 0.1−100 GeV sources, over 1170 have statistically reliable counterpart identifications at lower energy (Nolan et al. 2012). The bulk of these identifications are blazars and spin-powered pulsars, with young pulsars (both radio-selected and Geminga-like γ-ray-selected) dominating at low Galactic latitude. An additional population of millisecond pulsars (MSPs) extends to high latitude among the blazar-associated sources. Identification progress is especially impressive for the bright, well-localized sources that have been studied since early in the Fermi mission. Here we update Abdo et al. (2009a), selecting “bright” sources from the 2FGL catalog as those with $>20\sigma$ detection significance and time-averaged energy flux $F_E > 3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$—there are 249 such sources. All but six presently have lower energy identifications: blazars, pulsars, and a few binaries. The handful of sources not yet associated with one of these source classes provide the best prospect for new types of γ-ray emitters. We have initiated a campaign to characterize these unidentified sources. The first result from this effort is the discovery of dramatic optical and X-ray variability for the high-latitude $(|b|=62^\circ)$ source J2339−0533, implying that it is a short-period “black-widow”-type binary MSP (Romani & Shaw 2011; Kong et al. 2012).

Here we report progress on the next high-latitude unidentified source in this set, 2FGL J1311.7−3429 (hereafter J1311) at $|b|=28^\circ$. With a $43\sigma$ detection significance (the highest among the 2FGL unidentified sources) and an energy flux of $F_{0.1−100\text{GeV}} = 6.2 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (the second brightest UnIDed 2FGL), this is a top candidate for follow-up. The “Variability index” value 19.5 and “Curvature Significance” = 6.3 mark this as a steady source with a substantial spectral cutoff: a prime pulsar candidate. It has been searched for $<30$ Hz γ-ray pulsations (e.g., Abdo et al. 2009b) and for radio pulses down to $\sim$ms periods (Ray et al. 2012) with no detection. Thus, it is unlikely to be an isolated young pulsar or a radio-loud MSP. We describe here an optical campaign to identify and characterize a counterpart.

2 OBSERVATIONS

Initial exposures of the J1311 error region were taken with the MiniMo camera at the 3.6 m WIYN telescope on 2012 February 17 and 18. Exposures were 180 s using the Gunn filter set (2 × g, r, i on 2/17; 5 × g, r on 2/18). Observations were perforce at airmass 2.5−3, seeing was variable, and conditions nonphotometric.

A more extensive image sequence was taken with the SOAR Optical Imager (SOI) at the 4.2 m SOAR telescope on 2012 March 21−23. Here 120 s exposures using Sloan Digital Sky Survey (SDSS) filters were taken, covering one color each night (61 × g′ on 3/21, 74 × r′ on 3/22 and 57 × i′ on 3/23). The camera was binned 2 × 2, allowing fast 11 s read-out and high observation efficiency. Again image quality was highly variable (partly due to loss of wavefront sensor control of the primary).

We searched image archives for exposures covering J1311, finding a sequence (program 086.D-0388) of 170 s VLT/VIMOS exposures taken on March 4 (2 × [3B, 3V, 3I]) and 2011 March 11 (3 × [3B, 3V, 3I]). VIMOS is an array camera with 2′ gaps between the four CCD chips, so the five pointings were offset to cover the full J1311 error region.

In examining the images for variable objects, we paid particular attention to sources coincident with detections in archival X-ray data (see below). One such star was blue and highly variable on short timescales. The NOMAD position of this likely counterpart is 13 11 45.741, −30 34 29.96 (2000.0). While we ensured that this star was covered in all MiniMo and SOI exposures, we found that the counterpart was in the array gap for the first VIMOS pointing on 2011 March 3 and at the extreme edge of a chip, suffering major vignetting, in the second pointing on 2011 March 11.

To quantify the variations, we performed simple aperture photometry of the counterpart and surrounding field stars in all frames. Since the bulk of the imaging was in the SDSS filter...
set, we attempted to reference all photometry to this scale. The MiniMo data were calibrated using $gri$ images in SDSS fields at low airmass; we transferred this calibration to stars in the J1311 field. Unfortunately, the nonphotometric WIYN conditions and passband differences between the SDSS and Gunn sets make the substantial atmospheric extinction corrections for J1311 uncertain. This is not a severe problem for the field stars, which the substantial atmospheric extinction corrections for J1311 passband differences between the SDSS and Gunn sets make low airmass; we transferred this calibration to stars in the J1311 MiniMo data were calibrated using SOAR field stars to establish zero points in the $gri$ images in SDSS fields. Photometry from the SOAR $i'$ flare is connected with a solid line; points for each VLT night are connected with a dashed line. (A color version of this figure is available in the online journal.)

![Figure 1. SOAR/WIYN/VLT photometry of J1311.7–3429. The abscissa is the phase relative to phase 0 (superior conjunction, secondary flux maximum) just before the first observation of each plotted night, using the best-fit $P_b = 5626.00$ s period. Symbols and colors indicate the various telescopes and observing bands. Photometry from the SOAR $i'$ flare is connected with a solid line; points for each VLT night are connected with a dashed line. A color version of this figure is available in the online journal.](image)

2.1. Orbital Period Estimate

The intermittent flaring activity of J1311 compromises simple periodogram or Fourier methods for refining the period. However, the combination of SOAR, WIYN, and VLT exposures give photometry information on 1–3, 7, $\sim 35$, and $\sim 350$ day timescales, which suffices to resolve possible aliases. After referencing all observation mid-point times to the solar system barycenter, we can constrain the phase of the 2012 epoch minima to $\delta \phi \approx 0.02$, giving a best-fit period of $P_b = 5626.00 \pm 0.02$ s. The epoch of (quiescent) maximum light associated with our SOAR $r'$ measurements (presumably pulsar superior conjunction, see below) is barycentric MJD 56099.1795 $\pm 0.0013$.

The approximately sinusoidal nature of the light curve and very large modulation amplitude can be best interpreted in terms of strong companion heating. The inferred heating luminosity is appreciably above any X-ray flux (see below); we infer that accretion power is not dominant and that the heating source is invisible in the optical and faint in the X-ray. We conclude that this is a “black-widow”-type pulsar binary and is the likely counterpart of the $y$-ray source. In this it is remarkably similar to the black widow candidate counterpart for J2339$-$0533. But the $\sim 3$ times shorter orbital period is unprecedented; this is an extreme black widow system.

2.2. Archival X-Ray Light Curve

2FGL J1311.7–3429 has been observed by both the Chandra and Suzaku satellites. One exposure from each facility is available in the NASA archives; an additional exposure has been taken but is not publicly available. The counterpart was detected in both data sets and well localized by Chandra. We analyzed both observations for X-ray spectrum and variability.

The Suzaku observation (ObsID 804018010; PI: Kataoka) started on 2009 August 4 (MJD 55047.2290) and had 33.4 ks of on-source time over 95 ks ($\sim 17$ binary orbits) with exposure in XIS0,1,3. A comparably bright source lies $\sim 1/6$ from the target, so we extracted source counts from a $r'$ radius aperture. Figure 2 (left) shows the combined XIS count rate, both direct aperture counts (histogram) and the background-subtracted aperture-corrected count rate (points). The vertical dotted lines mark the phases of maximum optical light; we see that orbital modulation is difficult to measure since $P_b$ is so close to that of satellites for $g'$ $r'$ observed in low Earth orbit. A clear X-ray flare is seen 5000 s after the observation start.

An ACIS-I exposure of 19.8 ks live time (ObsID 11790; PI: Cheung) was taken starting at MJD 5527.6652. Unfortunately, as for VLT observation 1, the counterpart was directly in the gap between ACIS-I chips. However, the Chandra dither did provide some ($\sim 25\%$ effective live time) exposure and a source coincident with the optical counterpart was well detected with 60 counts. There is no strong evidence for secular X-ray variability on 3000 s timescales. The exposure only covers $\sim 3.5$ orbits. Figure 2 (right) shows the folded X-ray light curves from the Suzaku and Chandra data sets. After the early flare in the Suzaku data is excluded, there is only weak evidence for orbital modulation; note there is an exposure gap for phases $\phi_b = 0.7$–0.8. Similarly, the Chandra data show no strong peak or eclipse. In both light curves there seems to be a slight excess at phases 0.7–1.1. This may indicate additional weaker flaring activity near superior conjunction.

Only crude spectral constraints can be obtained with the limited counts, especially after selecting for Suzaku photons outside of the flare period. If we fit an absorbed power law to the
Figure 2. Left: raw aperture count rate (histogram) and background- and aperture-corrected counts (points) during the Suzaku exposure. Times of optical flux maximum are marked. Right: two periods of the X-ray orbital light curve of J1311.7−3429. Statistical errors are shown for the exposure-corrected bin count rate. For Suzaku, we show the folded data both with and without the bright flare. Horizontal error bars show the extrapolated phase uncertainty. (A color version of this figure is available in the online journal.)

X-ray data we find that \( N_H \) is essentially unconstrained (0.5 ± 6 \( \times \) 10\(^{21} \) cm\(^{-2} \)) but consistent with the limited extinction in this high \( |b| \) direction. We therefore fix at the \( N_H = 5 \times 10^{20} \) cm\(^{-2} \) inferred from the dust maps (HEASARC NH tool) and fit for the power-law index. Using CIAO the Chandra data fit to \( \Gamma = 1.3 \pm 0.5 \). XSPEC fits to the Suzaku XIS0,3 give \( \Gamma = 1.6 \pm 0.8 \). Fixing at \( \Gamma = 1.5 \), we obtain a quiescent unabsorbed flux for the source of \( f_{0.3–10 \text{ keV}} = 2.4 \pm 0.6 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \). A deeper exposure, allowing a better light curve and an orbit-dependent spectral study, is clearly of interest.

3. SYSTEM MODELING

Figure 3 shows two periods of the SOI light curves folded on the ephemeris of Section 2.1. The large quasi-sinusoidal modulation shows that the light curve is dominated by heating of the secondary. The typical \( g–r \approx -0.4 \) near \( \phi = 0 \) suggests \( T_{\text{eff}} \approx 14,000 \text{ K} \). By phase \( \phi = 0.35 \) the color has reddened to \( g–r > -0.1 (T_{\text{eff}} \approx 8000 \text{ K}) \). At flux minimum (\( \phi \sim 0.5 \)) large (up to \( \Delta m = 3 \)) fluctuations dominate. Since relatively small fluctuations can overwhelm the quiescent flux, these prevent any meaningful measurement of color at flux minimum.

We have attempted to model the “quiescent” light curves with the ELC code (Orosz & Hauschildt 2000). A formal fit is not indicated as there are many positive “flare” excursions from any reasonable light curve. However, comparison with a range of models shows that a few of the parameters are significantly constrained. For example, matching the characteristic \( g’–r’ \) at maximum requires heating by a primary luminosity (modeled here as an isotropic “X-ray” flux) of \( \log [L_x (\text{erg s}^{-1})] = 36.0 \pm 0.3 \). Also, to obtain adequate modulation while avoiding an X-ray eclipse requires \( 60^\circ < i < 80^\circ \). At this point other parameters are poorly constrained, although large mass ratios and a near-Roche lobe filling secondary are preferred. However, the basic ELC model seems inadequate for a good fit; a particular challenge is to reproduce the relatively flat maxima and broad “shoulders” in the \( g’ \) and \( r’ \) curves at \( \phi \sim 0.25, 0.75 \). This may be due to limitations of the atmosphere tables. One can substantially improve the fit by modifying the limb-darkening law, but for blackbody surface spectra broad light curves (with adequate heating) require unphysical negative limb-darkening coefficients. Another, more attractive, possibility is that the distribution of surface heating differs from the isotropic form assumed here; the pulsar may primarily heat a portion of the companion star. An illustrative set of curves is shown in Figure 3, assuming a mass ratio \( q = 50 \), orbital semi-major axis \( a = 0.9 R_S \), inclination \( i = 65^\circ \), heating flux \( 10^{36} \text{ erg s}^{-1} \), and a \( T_{\text{eff}} = 4000 \text{ K} \) companion reaching 0.99 of its Roche lobe
radius. The observed $i^\prime$ flux evidently has a substantial added flux even before the bright flare at the epoch observed.

4. DISCUSSION

At this short orbital period, the mean density in the secondary Roche lobe is $\langle p_z \rangle = 46$ g cm$^{-3}$, so the secondary could be a main-sequence star of $<0.15$ $M_\odot$. To reach this period, however, the system very likely passed through a common envelope phase and would have a helium-rich core. The strong heating and near-Roche lobe filling suggest a substellar secondary, but additional observations are needed to determine the state of the secondary core and envelope.

A very rough estimate of the source distance can be made from the $g^\prime - r^\prime = -0.4$ color and $g^\prime = 20.2$ flux at maximum, if we assume that the star nearly fills its Roche lobe at $\approx 0.46 a(M_2/M_\text{tot})^{1/3} \approx 0.1 R_\odot$. Such color indicates $T_{\text{eff}} \approx 14,000$ K (type $\sim$ B6), corresponding to main sequence $M_2 = -0.43$ and $R \approx 3.0 R_\odot$. Correcting for the effective area and the small ($A_g = 0.25$) Galactic extinction in this direction, we get $d \approx 3.9(q/50)^{-1/3}$ kpc. This is likely an overestimate as the secondary should be H-poor, and the temperature of the viewed hemisphere is far from uniform, even at maximum.

If we adopt the view that the X- and $\gamma$-ray emissions come from an energetic pulsar, we can make some additional estimates. Becker (2009) finds that pulsars have $L_X \approx 10^{-3} \dot{E}$, so from the observed X-ray flux we would infer a spin-down luminosity $\dot{E} \approx (10^3)4\pi d^22.4 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1} \approx 2.9 \times 10^{34} \dot{E}_2^2$ erg s$^{-1}$. Gamma-ray pulsars are also observed to follow a heuristic luminosity law $L_{\gamma, \text{heu}} \approx (\dot{E} \times 10^{33}$ erg s$^{-1})^{1/2}$ (Abdo et al. 2010). This is related to the observed flux as $L_{\gamma} = 4\pi f_\alpha F_{\gamma} d^2$, where the beaming-dependent correction factor is $f_\alpha \sim 0.7$–1.3 (Watters et al. 2009). Thus, the observed $F_{\gamma} = 6.2 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ gives a distance-dependent estimate for the spin-down power of $\dot{E} \approx 5.5 \times 10^{34} f_{\gamma}^2 d^4$ erg s$^{-1}$. This is consistent with the X-ray luminosity estimate when $d \approx 0.75 f_{\gamma}^{-1}$ kpc. However, if we match $\dot{E}$ to the ELC-estimated heating flux a distance of $\sim 2$ kpc is preferred.

The nature of the intermittent “flaring” emission is at present unclear. Since the bands were observed sequentially, we do not even know the characteristic color. All we can infer are unclear. Since the bands were observed sequentially, we do

Additional data can greatly improve estimates of the system properties. Simultaneous multicolor photometry covering many periods and flaring events can help us understand the temperatures of the various emitting regions. A complete spectroscopic study of the secondary can place important constraints on the compact object mass and probe the state of the secondary photosphere. Spectra can also improve knowledge of the compact object’s period, orbital epoch, and semi-major axis, each of which are crucial for decreasing the parameter space to be searched for $\gamma$-ray pulses. Of course, a $\gamma$-ray or radio pulsar ephemeris would produce a qualitative change in our knowledge of the system properties. We are pursuing all of these follow-up investigations.

We close with a comment on $\gamma$-ray pulsar population in the bright sample. Figure 4 shows these sources in the curvature–variability plane. The pulsar–blazar separation is excellent; the only pulsar in the blazar region is the Crab, whose $\gamma$-ray contribution would produce a qualitative change in our knowledge of the system properties. The we are pursuing all of these follow-up investigations.

Even if these two sources represent a harbinger of a new source class, we emphasize that this source class must be small, at least for the bright population, in contrast to some suggestions in the literature (Harding et al. 2005; Takata et al. 2011). The statistics in our sample clearly make this case—of the 41 young pulsars in this set only 17 (1/3) are radio selected. In contrast

Figure 4. 2FGL bright sources in the spectral curvature–variability plane. Note the excellent pulsar (PSR)/blazar (AGN) separation. Binaries, a globular cluster (GC), the Galactic center (GC), and the unidentified sources belong to the pulsar group.

(A color version of this figure is available in the online journal.)
there are 12 MSPs in the bright sample, all radio pulsars. Thus, even if all six unidentified sources prove to be radio-quiet MSPs, the radio-loud subset will be at least 2/3 of the γ-ray MSPs, twice the fraction of the young pulsars. Thus, while J1311−3429 may have joined the “black widow” club of pulsars evaporating their companions, it is not yet clear if there is a “radio-quiet MSP” club for it to join. And if such a society does exist, it is very select indeed.

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