ECHELLE SPECTROSCOPY OF $\gamma$-RAY BINARY 1FGL J1018.6$-$5856

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ABSTRACT

We observed the Fermi-discovered $\gamma$-ray binary 1FGL J1018.6$-$5856 at 20 epochs over 50 days using the CHIRON spectrograph, obtaining spectra at $R \approx 25,000$ covering $\lambda\lambda 4090$ $-$ 8908Å. The average spectrum confirms an O6 V((f)) spectral type and extinction $E(B-V) = 1.35 \pm 0.04$. Variable absorption line equivalent widths suggest substantial contamination by wind line features. The limited S/N ratio hindered accurate continuum definition and prevented measurement of a high quality radial velocity curve. Nevertheless, the best data indicate a radial velocity amplitude $\lesssim 40$ km s$^{-1}$ for the He II lines and substantially lower for H I. We argue that this indicates a most likely compact object mass $< 2.2 M_\odot$. While black hole solutions are not excluded, a neutron star source of the $\gamma$-ray emission seems preferred.

Subject headings: gamma rays: stars — binaries: spectroscopic

1. INTRODUCTION

To date only five binaries with high mass secondaries have been detected in the GeV band; 1FGL 1018.6$-$5856 is the only one whose binary period was discovered at these energies [Corbet et al. 2011; Ackerman et al. 2012]. The nature of the $\gamma$-producing compact object in these binaries is unclear: it might be a jet-producing black hole, in analogy to $\gamma$-loud blazars (the ‘$\mu$QSO model’), or the $\gamma$-rays may be generated by the magnetosphere or wind termination shock of an energetic pulsar (the ‘PSR/PWN model’). This latter model certainly applies to the PSR B1259$-$63 system, whose $\gamma$-ray emission is produced via Inverse Compton scattering off wind shock particles when the PWN is compressed near periastron. For 1FGL 1018.6$-$5856 and the other three systems (LS I+61$^\circ$303, LS 5039 and Cygnus X-3), the identity of the compact object is presently unknown. Discovery of $\gamma$-ray pulsations would certainly indicate a neutron star primary. However, the poorly known acceleration in the binaries makes $\gamma$-ray pulse searches prohibitively expensive and the dense plasma produced by the massive secondary winds frustrates radio pulse searches. An alternative approach is to constrain the compact object mass via measurement of the secondary’s radial velocity. Although the high mass and strong winds of the secondary also make this very challenging, even crude constraints can be useful; for example a minimum companion mass $> 3 M_\odot$ would certainly indicate a black hole.

After discovery of a 16.5 d $\gamma$-ray modulation [Corbet et al. 2011], the associated Swift X-ray source was identified with a bright optical counterpart. A low resolution spectrum with the SAAO 1.9 m shows an O6V((f)) companion with an estimated mass $\approx 20 - 30 M_\odot$ and distance $\approx 5$ kpc [Ackerman et al. 2012]. This system is also a radio source and Swift XRT (An et al 2013) and ATCA monitoring detect the orbital modulation in the X-ray and radio band, respectively. Optical photometric monitoring detects no variation, although present constraints are weak. These properties are similar to those of the more compact ($P_b$=3.9 d) $\gamma$-ray binary LS 5039. There spectroscopic and photometric studies (e.g. Sarty et al. 2011) indicate an O6.5V((f)) secondary, a substantial eccentricity $e = 0.24 \pm 0.08$, and a modest mass function $f(m) = 0.0049 \pm 0.0006 M_\odot$. The limit on LS 5039’s photometric variability, 2mmag, implies a high system inclination and/or a small compact object mass. Since the inclination is poorly determined, they can only conclude that $M_1 > 1.8 M_\odot$, allowing both black hole and neutron star solutions.

In this paper we describe a project to study the radial velocity of 1FGL 1018.6$-$5856 using echelle spectroscopy. We adopt the orbital period estimate of Coley et al. (2014) $P_b = 16.549 \pm 0.007$ d with epoch MJD 55403.3 $\pm 0.4$ corresponding to the $\gamma$-ray peak described in Ackerman et al. (2012). An independent Swift/Fermi analysis (An, priv. comm.) confirms this ephemeral. While our results appear to show systematic variation with orbital phase, it is unclear if we have isolated the true radial velocity curve. Nevertheless, our measurements improve the characterization of the companion star, limit the amplitude of its motion and point to the sort of observations needed for a definitive study.

2. OBSERVATIONS AND CALIBRATIONS

The 16.5 d binary period is particularly inconvenient, being too long to cover in a dedicated run, but too short for effective coverage with ad hoc $\sim$ monthly observations. The best solution was queue observing and we were awarded 25h of queue time (NOAO-11B-0092) on the CTIO 1.5 m using the CHIRON fiber-coupled echelle spectrograph [Schwab et al. 2010]. 1FGL 1018.6$-$5856 is relatively faint for CHIRON at $V = 12.5$, so CHIRON was run in the slitless (2.5" fiber aperture) mode for an effective resolution $R \sim 25,000$. The CCDs were binned 4$\times$4 to maximize S/N and minimize readout time. The spectra covered 4090$-$8908Å, with substantial order overlap except in the reddest orders.

Observations were attempted roughly every other night from March 02, 2012 (JD 2455989) to April 20, 2012 (JD 2456022). Four nights were lost to system failures and weather; spectra were obtained on 20 nights (Table 1). We requested 3$\times$1000s exposure on 1FGL 1018.6$-$5856, one night had only a single exposure. For each epoch we obtained ThAr arc exposures immediately before the target observations for wavelength calibration. For the first epoch only we also observed the flux standard HD60753. CHIRON was undergoing final commissioning during these observations, and the obtained S/N was substantially lower than predicted by...
the design plots (predicted peak S/N/extracted pixel $\sim$ 40 in each 1000s exposure). In practice, we obtained S/N/extracted pixel $\sim$ 25 at the order peaks in our best exposures (in line with recent revised 6.5% instrument efficiency). More typical S/N/extracted pixel was $\approx$ 17, with a few epochs much worse. We were not able to ascertain from the night logs why the S/N on source varied so dramatically, although from the low apparent flux at some epochs, we suspect that poor transparency and imperfect fiber acquisition may play a role. In the end we analyzed the 17 epochs with S/N $>$ 15 in the summed, combined spectra. These spectra sample four binary orbits.

Although the CHIRON data distribution included a standard pipeline extraction of the echelle spectra, this was optimized for the relatively red target stars of the instrument’s principal (radial velocity planet search) program. This extraction covered $\lambda\lambda$ 4504 – 8908Å (62 orders); for our blue 06V target 14 additional orders were measurable, extending the spectral coverage to 4090Å.

Standard CCD processing was performed with the IRAF package. A master bias was assembled and subtracted from the target, flat and lamp images. The spectra for each epoch cover 3200s. As this is only 0.2% of the orbital period, intra-epoch velocity smearing was negligible and the three target exposures for each night were median combined with average $\sigma$-clipping to increase S/N and reject cosmic ray events. Combined flat field images were also prepared for each night. These were used to define the apertures for each order. Sufficient inter-order pixels were available to define flanking ‘background’ windows for each order. A linear fit to these backgrounds was used as a local scattered light subtraction. All extractions were performed using variance weighting, modeled by the CCD read noise ($4.5e^{-}$) and gain ($1.3e^{-}$/ADU).

The extracted science spectra for each order were divided by the extracted flat spectrum. This removed the blaze function and summed pixel-to-pixel variations, while maintaining a relatively stable response from the smooth lamp spectrum. In principle, the true response could be determined from the standard star spectrum. In practice, for the queue-selected standard the tabulated fluxes were derived from a spectral model and were too sparse (10Å grid) to fit an accurate sensi-

**TABLE 1**

| Date     | Nexp | $S/N_{6000\AA}$ | $\phi_B$ |
|----------|------|-----------------|----------|
| 03/02    | 3    | 36              | 0.41     |
| 03/06    | 1    | 24              | 0.65     |
| 03/10    | 3    | 12              | 0.89     |
| 03/14    | 3    | 33              | 0.13     |
| 03/16    | 3    | 32              | 0.25     |
| 03/18    | 3    | 44              | 0.37     |
| 03/20    | 3    | 37              | 0.49     |
| 03/22    | 3    | 33              | 0.61     |
| 03/24    | 3    | 3               | 0.73     |
| 03/26    | 3    | 31              | 0.85     |
| 03/28    | 3    | 18              | 0.98     |
| 03/30    | 3    | 18              | 0.09     |
| 04/02    | 3    | 28              | 0.28     |
| 04/04    | 3    | 31              | 0.40     |
| 04/06    | 3    | 21              | 0.51     |
| 04/08    | 3    | 8               | 0.63     |
| 04/10    | 3    | 22              | 0.76     |
| 04/12    | 3    | 20              | 0.87     |
| 04/14    | 3    | 30              | 0.24     |
| 04/20    | 3    | 29              | 0.38     |

![Fluxed CHIRON spectrum from March 02, 2012, corrected for atmospheric and interstellar $E(B-V) = 1.35$ extinction. Telluric features have not been removed. The strongest night sky and absorption lines are visible, along with inter-order gaps for the reddest five orders.](image)

After trimming very low S/N data at the edges of each echelle order, we merged all orders to a single spectrum, average-combining the overlap regions (figure 1). Given our relatively modest S/N for most of the spectra, this procedure generally produced an adequate match between orders. For some epochs, small flux gradients across orders and poor inter-order match were however present. Such imperfections can be attributed to differences in illumination paths of and/or light path shifts between flat and science images. These may be removed by computation of a smoothly varying residual blaze function (Skoda et al. 2008). Although we attempted such corrections, the S/N of our targets and standard exposures did not allow significant improvement. Finally, we divided the merged spectra by a low order function to remove the global lamp response and create normalized spectra appropriate to our kinematic/line study. The S/N weighted combined normalized spectrum from all epochs is shown in figure 2. An absolute fluxed spectrum was computed from the first night’s data where the adjacent standard was used to normalize the fluxes. For each epoch we corrected the normalized spectrum to the heliocenter using the IRAF routines rvcorrect and dopcor.

3. SPECTRUM ANALYSIS
The many DIB features make it particularly challenging to define the true photospheric continuum, in turn this can subtly affect our line centroid estimates.

The DIBs are believed to be generated by PAHs associated with interstellar dust. Thus one expects a correlation between DIB strength and interstellar reddening from dust scattering. Kos et al. (2013) lists fit linear relations for several strong DIBs of the form $EW = a \times E_{B-V} + b$. These relations depend on whether the sight-line is ‘UV shielded’ ($\zeta$-sight-line) or not ($\sigma$-sight-line), and the $A_{7579}/A_{5780}$ EW ratio is used to discriminate these cases. Our value is 0.19 ± 0.01, below the 0.3 threshold, so we treat this as a $\sigma$-sight-line. In table 2 we apply the tabulated coefficients to several well-measured DIBs to estimate the reddening. The inferred $E_{B-V}$ have a surprisingly large scatter, with a weighted average $E_{B-V} = 1.35 \pm 0.04$ (bootstrap error). This value agrees very well with the estimate $E_{B-V} = 1.34 \pm 0.04$ determined by Napoli et al. (2011) from Strömgren photometry. It is similarly in reasonable accord with the $N_H$ estimated from the X-ray spectrum. In turn, this agreement supports the photometric distance estimate $d = 5^{+4.6}_{-2.1}$ kpc.

3.2. Radial Velocity Measurements

To confirm the stability of our wavelength solutions, we measured the night sky lines $\lambda5577.3387$ A and $\lambda6300.304$ A in each processed spectrum, before heliocentric corrections were applied. The rms wavelength variations were 0.0106 Å and 0.0124 Å respectively, i.e. $\sigma_{RV} = 0.6 \text{km s}^{-1}$.

A second stability check was made measuring the very strong Na(D) interstellar doublet $\lambda5889.951/\lambda5895.924$ Å in spectra corrected to the heliocenter. The line centroids display mean redshifts of 2.88 and 2.85 km s$^{-1}$, with spectrum-to-spectrum rms variation of 0.88 and 0.74 km s$^{-1}$, respectively. We conclude that our wavelength solutions are good to better than 1 km s$^{-1}$.

To attempt to measure the photospheric velocity of the companion, we must follow the centroids of the broad ($\sim 300 \text{km s}^{-1}$) H I, He I and He II lines, to a few km s$^{-1}$. This is challenging since the imperfect inter-order fluxing causes significant gradients and steps in the continuum, with a characteristic scale comparable to the typical 50 Å (3000 km s$^{-1}$) order width. Further, for several of the photospheric lines there are strong DIBs in the line wings, which can perturb the continuum. To mitigate this latter effect, we divide the spectrum by the model DIB spectrum. While imperfectly removing all DIBs, this does significantly flatten the continuum in the region of the strongest features.

All photospheric lines were fit with simple Gaussian profiles (test Voigt fitting showed negligible Lorentzian wings). The fitting used the IRAF deblending routine, where the ef-

| DIB   | a$^\dagger$ | b$^\dagger$ | EW     | $E_{B-V}$   |
|-------|------------|------------|--------|-------------|
| Å     | A          | A          | Å      | Å            |
| 5780  | 0.506 ± 0.050 | −0.014 ± 0.032 | 0.709 ± 0.009 | 1.43 ± 0.16 |
| 5797  | 0.124 ± 0.014 | −0.003 ± 0.009 | 0.134 ± 0.006 | 1.10 ± 0.14 |
| 6196  | 0.048 ± 0.004 | 0.001 ± 0.003 | 0.063 ± 0.005 | 1.29 ± 0.12 |
| 6379  | 0.057 ± 0.012 | 0.004 ± 0.008 | 0.119 ± 0.005 | 2.00 ± 0.44 |
| 6613  | 0.192 ± 0.026 | 0.003 ± 0.017 | 0.225 ± 0.006 | 1.16 ± 0.18 |
| 6660  | 0.014 ± 0.004 | 0.009 ± 0.003 | 0.043 ± 0.004 | 2.54 ± 0.82 |

$^\dagger$ Coefficients from Kos et al. (2013).
We also attempted to determine the line centroids using the so-called “mirroring” method (Parimucha & Skoda 2008). This allows one to separately probe the line wings and core. Although we can see that our lines are significantly asymmetric, suggesting absorption in wind/outflow components, we lacked the S/N to measure these structures accurately and compare them across lines and species. This prevented us from using the line shapes to improve our estimate of the systematic (photospheric) radial velocity.

4. RADIAL VELOCITY VARIATIONS

To test for velocity variation, we performed a weighted least-squares fit for the mean velocity of each species. Table 3 shows the velocities, errors, goodness of fit and the probability of constancy. It is unclear how to compare mean velocities between lines, as the effective rest wavelengths depend on the excitation. Also, the measured line centers are somewhat uncertain due to continuum irregularities; for example He II 6527 appears substantially redshifted, due to a continuum gradient and superposed DIB. Finally, the lower excitation lines can be affected by wind absorption and may be blue shifted with respect to He II (Casares et al. 2005; Sarty et al. 2011).

Overall, we infer a net systemic radial velocity of $\sim 40\text{ km s}^{-1}$, but a precise value requires cross-correlation with a simultaneously observed RV standard of similar spectral class. The reduced $\chi^2$ values are, however, interesting. From the low probabilities, we infer that the strong lines do indeed show statistically significant variation.

However, there are certainly large systematic effects, and it is uncertain due to continuum irregularities; for example He II 5875 appears substantially redshifted, due to a continuum gradient and superposed DIB. Finally, the lower excitation lines can be affected by wind absorption and may be blue shifted with respect to He II (Casares et al. 2005; Sarty et al. 2011).

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However, there are certainly large systematic effects, and it is unclear how much of this variation is associated with the photospheric radial velocity. To illustrate, we average the radial velocity from the two strongest H I lines (H$\alpha$ and H$\beta$) and two strongest He II lines ($\lambda$4686 and $\lambda$5412) and plot the values for the highest quality ($S/N_{6000} > 20$) spectra (Figure 3).

Even disregarding the mean radial velocity $\Gamma$ offset between lines, we see that the fluctuations are several times the statistical error. Nevertheless, both sets of velocities show similar trends, with relatively low values in the range $\sim 2.2\text{ km s}^{-1}$.

Like these authors we also see evidence for equivalent width variations through the orbit, especially for H$\beta$ and He II 4686 (Figure 4). However, in our case the minimum absorption strengths appear to lie at $\phi_B \approx 0.2$, close to compact object superposition for the orbit suggested in figure 3.}

**Table 3: Test for Radial Velocity Variations**

| Species | $\lambda_{\text{rest}}$ (Å) | $\Gamma$ (km s$^{-1}$) | $\chi^2$/DoF | Log(Prob) |
|---------|----------------------------|------------------------|---------------|-----------|
| H$\alpha$ | 6562.808 | 43.0 ± 1.1 | 14.7 | -3.9 |
| H$\beta$ | 4861.34 | 22.4 ± 3.0 | 3.6 | -1.2 |
| H$\gamma$ | 4340.48 | 25.5 ± 36.7 | 3.3 | -1.2 |
| He I | 5875.65 | 72.9 ± 4.3 | 20.8 | -5.3 |
| He II | 4685.682 | 44.1 ± 20.9 | 10.7 | -3.0 |
| He II | 5411.52 | 63.3 ± 3.3 | 15.5 | -4.1 |
| He II | 6527.099 | 125.8 ± 15.4 | 5.6 | -1.7 |
pact object). This might indicate denser wind flow through the L3 point. Inspection of the strongest lines show variable wings, suggesting time or phase-dependent views of such outflow.

As for LS 5039, we find that our observed Hα equivalent width, $-1.87$ to $-2.29\text{Å}$, is smaller than the expected $\approx -3.27\text{Å}$ photospheric width for this spectral class (McSwain et al. 2004). Scaling from those authors' estimates (i.e. assuming similar companion mass and asymptotic wind velocity), we find that our lower observed residual absorption equivalent width implies a somewhat larger mass flux, namely $M \approx 0.7 - 1.0 \times 10^{-7}M_\odot y^{-1}$.

4.2. Radial Velocity Model and Implied Mass

Labeling the primary (compact object) 1 and the visible secondary 2, we have a single line spectroscopic binary, with radial velocity measurements constraining the mass function

$$f(M_1) = \frac{M_1^3}{(M_1 + M_2)^2} \sin^3 i = \frac{P}{2\pi G} K_2^3 (1 - e^2)^{3/2}$$

with $K_2 = \Delta v_2/2$ the radial velocity amplitude of the secondary and $i$ the unknown system inclination. Since $\sin i < 1$ and $M_2 > 0$, $f(M_1)$ provides a lower bound to the mass of the primary. Casares et al. (2005) give the mass of an O6 V((f)) star as $26 - 29 M_\odot$, and 50% of the allowed parameter space is consistent with a black hole (BH), although typical BH masses require very small inclinations. For the H I radial velocity amplitude we require $i < 50^\circ$, while for $M_1 > 4.5 M_\odot$ we require $i < 14^\circ$. Thus the likelihood of having having a typical stellar black hole mass seems modest. When we consider that systematic errors may be contributing to the He II radial velocity and that the H I radial velocity amplitude may be closer to the intrinsic amplitude, this only allows $M_1$ to exceed $4.5 M_\odot$ for $i < 11^\circ$ (probability 2%). Thus we conclude that the modest radial velocity amplitude observed for 1FGL J1018.6$-$5856 prefers a neutron star. However, these statistical statements do not exclude either option and a clean measurement of the companion radial velocity would help the situation greatly.

The way forward on determining the mass of 1FGL J1018.6$-$5856 doubtless starts with improved spectroscopy. Our data show that the photospheric lines are quite broad, and likely variable. Accordingly a future campaign on small-medium class telescopes should obtain long-slit, moderate resolution ($R \approx 3000 - 6000$) spectra covering 4000-5500Å, with a collection of several template O6 V radial velocity comparisons. Queue/service observing is almost certainly required in view of the large $P_r$. Higher resolution echelle data from a large telescope can be of use, but will require higher S/N to allow deconvolution of the line shape and isolation of the systematic radial velocity. If the minimum mass exceeds $3 M_\odot$, we can be confident of a black hole primary. But in the more likely event that lower masses are allowed, the inclination becomes critical and one will require very high precision photometry to constrain the small ellipsoidal variations, with the masses of other stellar mass black holes. Farr et al. (2011) find that at 90% confidence the minimum $M_{BH}$ in stellar mass binaries is $> 4.5 M_\odot$. Although they do not separately evaluate this for the high mass systems, like 1FGL J1018.6$-$5856, their figure 2 indicates most probable masses $10 - 20 M_\odot$ and 90% lower mass limits $> 10 M_\odot$. From figure 5 we see that we require $i < 30^\circ$ for $M_1 > 4.5 M_\odot$ (a priori probability 13%), while for $M_1 > 10 M_\odot$ we require $i < 14^\circ$ (probability 3%). Thus the likelihood of having having a typical stellar black hole mass seems modest. When we consider that systematic errors may be contributing to the He II radial velocity amplitude and that the H I radial velocity amplitude may be closer to the intrinsic amplitude, this only allows $M_1$ to exceed $4.5 M_\odot$ for $i < 11^\circ$ (probability 2%). Thus we conclude that the modest radial velocity amplitude observed for 1FGL J1018.6$-$5856 prefers a neutron star. However, these statistical statements do not exclude either option and a clean measurement of the companion radial velocity would help the situation greatly.

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or constraints from light curve fitting at other wavebands.

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