The Distance of the γ-Ray Binary 1FGL J1018.6–5856

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ABSTRACT. The recently discovered γ-ray binary 1FGL J1018.6–5856 has a proposed optical/NIR counterpart 2MASS 10185560–5856459. We present Strömgren photometry of this star to investigate its photometric variability and measure the reddening and distance to the system. We find that the γ-ray binary has $E(B - V) = 1.34 \pm 0.04$ and $d = 5.4^{+1.6}_{-2.1}$ kpc. While $E(B - V)$ is consistent with X-ray observations of the neutral hydrogen column density, the distance is somewhat closer than some previous authors have suggested.

1. INTRODUCTION

The Fermi Large Area Telescope source 1FGL J1018.6–5856 (Abdo et al. 2010) was recently discovered to have modulation of its 100 MeV–200 GeV emission with a 16.58 ± 0.04 day period (Corbet et al. 2011a). Swift observations identified a variable X-ray source with a position consistent with the location of the γ-ray source, and radio flux variations were also found using the Australia Telescope Compact Array (Corbet et al. 2011a). Pavlov et al. (2011) observed the source using Chandra and XMM-Newton, finding absorbed power law spectra that are variable in both flux and hardness. The observed variability from radio to giga–electron volt energies implies that 1FGL J1018.6–5856 is a member of the elite group of “γ-ray binaries,” which are high-mass X-ray binaries that also exhibit rare γ-ray emission.

The proposed optical/NIR counterpart of the high-energy source is the Two Micron All Sky Survey (2MASS) 10185560–5856459. Corbet et al. (2011a) find a spectral type of O6 V((f)) for the star, similar to the γ-ray binary LS 5039 (McSwain et al. 2004). Otherwise, knowledge of the optical star in this system is quite limited. In this article, we present Strömgren photometry of 2MASS 10185560–5856459 to investigate the optical variability of the source, the interstellar reddening $E(B - V)$, and the distance.

2. OBSERVATIONS

We observed 2MASS 10185560–5856459 using the Cerro Tololo Inter-American Observatory 0.9 m telescope, operated by the Small and Moderate Aperture Research Telescope System (SMARTS) consortium. We used the SITe 2048 CCD in un-binned quad readout mode with a plate scale of 0.401" pixel−1.

Observations were taken between UT dates 2011 May 20–26 and 2011 June 17–23 using the Strömgren $b$ and $y$ filters.

Bias images and sky flats were taken at the start of every night. We observed four standard stars (Cousins 1987) at a minimum of three different air masses each night. HD 79039, HD 80484, HD 128726, and HD 157795 were used on the May run, and HD 104664, HD 105498, HD 156623, and HD 157795 were used during June. The target was observed once each night in both filters with exposure times of 400–700 s and 200–500 s in $b$ and $y$, respectively.

The data were reduced using standard quadproc and cosmicray routines in IRAF. We used an aperture of 7" to determine the instrumental magnitudes of the target and standards, and we calibrated the apparent magnitudes using the method of McSwain (2004). Due to poor photometric conditions on most nights, we found that only data from UT dates 2011 May 21, May 26, and June 23 were well calibrated. Our quoted errors include both the instrumental and transformation coefficient errors, as described by McSwain (2004). The resulting apparent magnitudes of 2MASS 10185560–5856459 are listed in Table 1. We find that the optical magnitudes of the star are constant within errors, but we recommend more extensive observations to investigate the variability over the complete orbital period.

3. REDDENING AND DISTANCE MEASUREMENTS

We used the mean $b$ magnitudes, with errors added in quadrature to be conservative, to determine the Strömgren $b$ fluxes according to Gray (1998). We converted the $JHK_s$ magnitudes of 2MASS 10185560–5856459 (Skrutskie et al. 2006) to fluxes using the calibration of Cohen et al. (2003). These optical/NIR
fluxes constitute the observed spectral energy distribution (SED) of the optical star in the $\gamma$-ray binary.

Corbet et al. (2011b) present an optical spectrum of the star, which they classify as O6 V((f)). The lack of emission in the H$\alpha$ or He II $\lambda$4686 is indicative of an unevolved main-sequence star with relatively weak stellar winds. They do observe weak emission in N III $\lambda$4634, which is normal in main-sequence O-type stars. We used the calibration of Martins et al. (2005) to estimate the physical properties of the star, listed in Table 2. We used the calibration of Martins et al. (2005) to estimate $R$ and $T_{\text{eff}}$; interpolating between the evolutionary tracks for nonrotating stars from Schaller et al. (1992). We repeated our distance and reddening measurements for the possible extrema of $T_{\text{eff}}$ and $\log g$, which results in the more realistic error bars $E(B-V) = 1.34 \pm 0.04$ and $d = 5.4 ^{+1.6}_{-2.1}$ kpc.

Another potential source of error is the lack of precisely measured $T_{\text{eff}}$ and $\log g$ for 2MASS 10185560–5856459. Based on the absence of strong emission lines, the main-sequence nature of the hot star is well constrained and we allow a range of $3.80 \leq \log g \leq 4.25$. $T_{\text{eff}}$ is less well constrained, so we allow a 10% error in this quantity to provide a more generous range in the allowed $E(B-V)$ and $d$. For each $T_{\text{eff}}$ and $\log g$ model, we determined $R_*$ by interpolating between the evolutionary tracks for nonrotating stars from Schaller et al. (1992). We repeated our distance and reddening measurements for the possible extrema of $T_{\text{eff}}$ and $\log g$, which results in the more realistic error bars $E(B-V) = 1.34 \pm 0.04$ and $d = 5.4 ^{+1.6}_{-2.1}$ kpc.

The observed neutral hydrogen column density from Chandra observations is $nH = 0.64 ^{+0.19}_{-0.17} \times 10^{21}$ atoms cm$^{-2}$ (Pavlov et al. 2011). Their XMM-Newton observation was best fit using somewhat smaller errors for $nH, 0.64 ^{+0.048}_{-0.039} \times 10^{22}$ atoms cm$^{-2}$. Using the relation $nH/E(B-V) = 5.8 \times 10^{21}$ atoms cm$^{-2}$ mag$^{-1}$ (Bohlin et al. 1978), the Chandra detections predict a possible range for the optical reddening of $0.81 < E(B-V) < 1.43$. Thus, our measurement of $E(B-V)$ is consistent with their results for $nH$ from Chandra.

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Fig. 1.—Optical/NIR spectral energy distribution of 2MASS 10185560–5856459. The reddened Tlusty model SED with $T_{\text{eff}} = 38,900$ K, $\log g = 3.92$, and $E(B-V) = 1.34$ is also shown, normalized to the best-fit distance $d = 5.4$ kpc. The error bars on the observed broadband fluxes are smaller than the points shown.
Our distance measurement also agrees well with the value from Corbet et al. (2011b), who estimate $5 \pm 2$ kpc. On the other hand, our measurement is somewhat smaller than the estimate of $9 \pm 3$ kpc by Pavlov et al. (2011). We attribute this difference to the refined value of $E(B-V)$ available, due to our Strömgren photometry of the source. With our improved distance, the unabsorbed luminosities of the Chandra and XMM-Newton observations should be revised downward to 36% of the values provided by Pavlov et al. (2011).

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