THE Be STAR HD 215227: A CANDIDATE GAMMA-RAY BINARY

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ABSTRACT

The emission-line Be star HD 215227 lies within the positional error circle of the newly identified gamma-ray source AGL J2241+4454. We present new blue spectra of the star, and we point out the morphological and variability similarities to other Be binaries. An analysis of the available optical photometry indicates a variation with a period of 60.37 ± 0.04 days, which may correspond to an orbital modulation of the flux from the disk surrounding the Be star. The distance to the star of 2.6 kpc and its relatively large Galactic latitude suggest that the binary was ejected from the plane by a supernova explosion that created the neutron star or black hole companion. The binary and runaway properties of HD 215227 make it an attractive candidate as the optical counterpart of AGL J2241+4454 and as a new member of the small class of gamma-ray emitting binaries.

Key words: gamma rays: stars – stars: early-type – stars: emission-line, Be – stars: evolution – stars: individual (HD 215227, AGL J2241+4454)

1. INTRODUCTION

Gamma-ray binaries are a class of high energy and very high energy emitting sources that consist of a massive star and compact companion (Mirabel 2007; Dubus et al. 2010; McSwain 2010). Six such objects are known sources of TeV emission: LS 5039, Cyg X-1, Cyg X-3, LS I +61 303, PSR B1259—63, and HESS J0632+057. The massive star component is a luminous O-star in the first two, a probable Wolf–Rayet star in the third, and a Be star in the last three cases. All these massive stars have winds, and the Be stars also eject mass into an outflowing circumstellar disk. The interaction of this mass loss with a degenerate companion can lead to gamma-ray emission in several ways (Paredes 2008). First, if the companion is a pulsar, then a high speed wind from the mass donor can collide with the pulsar wind in a shock region, and inverse Compton scattering of stellar photons with relativistic electrons in the shock can create gamma rays (Dubus et al. 2010). Second, if the companion is a black hole, then gas accretion can lead to the formation of relativistic jets, and gamma-ray emission may occur by inverse Compton scattering from jet electrons and/or by the decay of neutral pions that originate in inelastic proton–proton collisions (Romero et al. 2007). Recently, Lucarelli et al. (2010) announced the detection with the AGILE satellite (Tavani et al. 2009) of gamma-ray emission above 100 MeV from a new unidentified source, AGL J2241+4454. The source has Galactic coordinates of (l, b) = (100°0, −12°2) with an error circle radius of approximately 0.6°. The source has not yet been detected by the NASA Fermi Gamma-Ray Observatory. The AGILE point sources found to date include pulsars, blazars, supernova (SN) remnants, and high-mass X-ray binaries (Pittori et al. 2009), but there are no cataloged examples of any of these in the region close to AGL J2241+4454 (Lucarelli et al. 2010). We point out two possibilities that deserve further attention. First, Brinkmann et al. (1997) found an X-ray source and probable quasar in this region, RXJ2243.1 + 4441, that may be a possible source of gamma-ray flaring (Vercellone et al. 2008). However, there is no known optical counterpart (radio designation B32241+444), which would probably appear at \( V \approx 16 \) (based upon the observed X-ray flux and an assumed frequency power law with \( \alpha = 1.3 \)). Further multiwavelength observations are required to say anything more about the candidacy of this object. Second, the area contains the Galactic Be star HD 215227 (BD +43° 4279, HIP 112148, MWC 656), which is located at \( (l, b) = (100°1755, −12°3985) \). This object was discovered as an emission-line star by Merrill & Burwell (1943) who estimated a spectral type of B0e, and the star was subsequently assigned types B5:ne (Harris 1955), B3ne (Petrie & Lee 1965), and M. V. McSwain (1965) b0e and back to B0 (Hernández et al. 2005). The classification is difficult because the spectral lines are very broad and weak (the projected rotational velocity is \( V \sin i = 262 \pm 26 \text{ km s}^{-1} \); Yudin 2001) and often blended with emission features. Here, we present new blue spectra of the target, and argue that HD 215227 is a potential optical counterpart of AGL J2241+4454 based upon its probable runaway and binary character.

2. SPECTROSCOPIC OBSERVATIONS

We obtained blue spectra of HD 215227 with the HIA Dominion Astrophysical Observatory 1.8 m telescope on 2010 July 28 and 29. These observations were made with the Cassegrain spectrograph with grating 1200B (1200 grooves mm\(^{-1}\)) in first order, and the spectra cover the range 4260–4669 Å. The detector was the SITE-2 CCD (a 1752 × 532 pixel array with 15 × 15 µm pixels), and the resulting spectra have a resolving power of \( R = \lambda/\Delta \lambda = 4290 \) as measured from the Fe Ar comparison lines. Exposures were 300 s in duration, leading to spectra with a signal-to-noise ratio (S/N) = 100 pixel\(^{-1}\) in the continuum. The spectra were extracted and calibrated using

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6 Fermi LAT Report, 2010 July 30; http://fermisky.blogspot.com/

7 https://www.astroscienca/DAO/dao72.html
standard routines in IRAF, and then each continuum-rectified spectrum was transformed to a common heliocentric wavelength grid in log $\lambda$ increments.

The two spectra are illustrated in Figure 1. There is clear evidence of double-peaked emission from the circumstellar disk that is seen in the core of $\text{H} \gamma$ and in numerous $\text{Fe}$ ii emission lines. The only clear photospheric lines are those of $\text{C}$ ii $\lambda 4267$ and $\text{He}$ i $\lambda \lambda 4387, 4471$. We searched through the Be star spectral survey of Grundstrom (2007), and the closest matching spectrum we found is that of HR 2142 = HD 41335, which is shown for comparison in the top section of Figure 1. HR 2142 is a well known Be binary system that shows deep, narrow, “shell” absorption features at certain phases in its 81 day orbit (Peters 1983). The most prominent shell feature appearing in Figure 1 is the sharp absorption core of $\text{H} \gamma \lambda 4340$. Such absorptions form in cooler, dense disk gas seen in projection against the stellar photosphere (Hanuschik 1995), and their strength may be modulated by azimuthal asymmetries in disk density that can occur in Be binaries (Oktariani & Okazaki 2009).

We estimated a number of stellar parameters for the star by comparing the observed spectra with B-star model spectra from the TLUSTY/SYNSPEC grid of Lanz & Hubeny (2007). The best-fit model parameters from an iterative visual match of the synthetic and two observed spectra are listed in Table 1. The errors given in Table 1 are based on our judgment of the boundary between reasonable and unsuitable solutions, and these are intentionally conservative given our incomplete understanding of emission contamination in the spectrum. We focused first on measurements based upon relative spectral intensity since we found clear evidence of a systematic line weakening due to the presence of disk continuum flux. The projected rotational velocity $V \sin i$ was estimated from the shape of the $\text{He}$ i $\lambda 4471$ and $\text{Mg}$ ii $\lambda 4481$ blend. The effective temperature $T_{\text{eff}}$ derivation was based primarily on the $\text{He}$ i $\lambda 4471$ to $\text{Mg}$ ii $\lambda 4481$ ratio. This ratio increases monotonically with increasing $T_{\text{eff}}$, although the ratio is almost independent of $T_{\text{eff}}$ near $T_{\text{eff}} = 21$ K, which corresponds to the peak of the $\text{He}$ i strength. However, we can estimate $T_{\text{eff}}$ even in this vicinity by the relative strength of the $\text{O}$ ii $\lambda 4417$ blend, which is stronger at higher $T_{\text{eff}}$. The gravity $log g$ was determined by fitting the emission-free parts of the Stark broadened, $\text{H} \gamma$ line wings. We found that the model photospheric spectrum had line depths that were consistently deeper than the observed ones, and this is probably due to disk continuum flux in this spectral region.

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**Table 1**

| Parameter | Value |
|-----------|-------|
| $T_{\text{eff}}$ (K) | 19 ± 3 |
| $\log g$ (cm s$^{-2}$) | 3.7 ± 0.2 |
| $V \sin i$ (km s$^{-1}$) | 300 ± 50 |
| $V_r$ (HJD 2,455,405.9461) (km s$^{-1}$) | 0.2 ± 1.9 |
| $V_r$ (HJD 2,455,406.9124) (km s$^{-1}$) | 2.0 ± 2.4 |
| $F_d/F_*$ | 0.5 ± 0.3 |
| $E(B-V)$ (mag) | 0.02 ± 0.06 |
| $\theta_{1D}$ (10$^{-6}$ arcsec) | 24 ± 5 |
| $M_*$ ($M_\odot$) | 7.8 ± 2.0 |
| $R_*$ ($R_\odot$) | 6.6 ± 1.9 |
| $d$ (kpc) | 2.6 ± 1.0 |
| $z$ (kpc) | $-0.56 ± 0.20$ |
| $V_{\text{TP}}$ (km s$^{-1}$) | 19 ± 17 |
| $V_{\text{TP}}$ (km s$^{-1}$) | 21 ± 17 |
| $V_{\text{TP}}$ (km s$^{-1}$) | 28 ± 24 |

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8 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
region. Consequently, we renormalized the model spectrum by adding a pure continuum component with a disk-to-star, monochromatic flux ratio $F_\text{d}/F_\star$. This renormalized model spectrum is shown as the lower plot in Figure 1. Finally, we estimated the radial velocity $V_r$ for both spectra by cross-correlating the observed and model spectra over the wavelength range including the emission-free H$_\gamma$ wings and H$\alpha$ $\lambda$4387. All these measurements are summarized in Table 1.

The derived stellar parameters suggest a spectral classification of B3 IVne+sh, where the temperature–spectral type relation is taken from Böhm-Vitense (1981), the gravity–luminosity class relation for like stars is adopted from the results of Huang & Gies (2008), and “n” and “e” indicate broad lines and Balmer emission, respectively. The final suffix “sh” is often used to denote the presence of shell lines, which is indicated here by the sharp, central absorption in H$_\gamma$. Note that a similar shell feature may be present in H$\alpha$ $\lambda$4471 in the spectrum from the first night. Wolff et al. (2007) determined a surprisingly low value of projected rotational velocity, $V \sin i = 30 \text{ km s}^{-1}$, compared to our result. We suspect that their spectrum was obtained at a time when the shell lines dominated and that their measurement corresponds to the shell line width.

3. DISCUSSION

The spectral properties of HD 215227 bear some resemblance to those of the gamma-ray binary LS I +61 303, which is a Be star in a 26.4960 day orbit (Aragona et al. 2009). The H$\alpha$ profile in LS I +61 303 displays systematic variations in the ratio of the violet-to-red ($V/R$) peak emission around the time of periastron in this eccentric orbit ($e = 0.54$) binary (Grundstrom et al. 2007; McSwain et al. 2010). We find that the $V/R$ ratio of the H$\gamma$ emission changed significantly in just one day (Figure 1), which is unusually fast for most Be stars (Grundstrom 2007). We suggest that such rapid variability might be associated with the changing tidal effects of a companion on the disk (especially strong near periastron).

If the disk in HD 215227 is modulated with a binary orbit, then the continuum flux from the disk may also show an orbital modulation. We found that the disk contributes $\approx 33\%$ of the total flux in the optical, so we might expect to find some evidence of the orbital modulation in broadband photometry. In fact, Koen & Eyer (2002) found evidence of a 61 day periodicity in the Hipparcos light curve (258 measurements). There are two other sets of photometric measurements from all sky survey experiments. The first set of 101 Cousins $I_C$ measurements were made between 2003 and 2007 by The Amateur Sky Survey (TASS); Droge et al. (2006). The second set of 52 points were made from 1999 to 2000 with the Northern Sky Variability Survey (NSVS; Wozniak et al. 2004). Since these three sets were made with different broadband filters, we assumed that color variations are minimal and then simply subtracted the mean magnitude of each set to form a combined photometric time series. These residual magnitudes are based upon differences from the average values of $(H_g) = 8.78$, $(I_C) = 8.52$, and $(m_V \text{ ROTHER}) = 9.12$ for the Hipparcos, TASS, and NSVS photometry sets, respectively. A discrete Fourier transform period search revealed one significant signal with a period of $60.37 \pm 0.04$ days, an epoch of maximum brightness at HJD 2,455,243.3 $\pm 1.8$, and a semi-amplitude of $0.020 \pm 0.002$ mag. The resulting light curve (Figure 2) displays a low-amplitude, quasi-sinusoidal variation that probably corresponds to the small variations that are expected for an orbital period.

Figure 2. Combined, mean-subtracted, photometry of HD 215227 plotted as a function of cycle phase for a period of 60.37 days. Dark plus signs show the average $\pm$ one standard deviation of the mean in each of eight phase bins.

We note that the Galactic latitude of HD 215227, $b = -12^\circ$, suggests that the star is quite far from the Galactic plane, and hence it may be a runaway star formed by an SN explosion in a binary system (Gies & Bolton 1986; Hoogerwerf et al. 2000). In this scenario, the SN explosion removes most of the mass of the progenitor star, and the stellar companion moves away from the explosion site with a speed comparable to its orbital speed at the time of the explosion. If the SN progenitor was the less massive component at the time of the explosion and if asymmetries in the SN outflow were modest, then the system remains bound as a runaway star with a degenerate companion. The runaway velocities may be large enough to move the system hundreds of parsecs away from the location of the SN over the lifetime of the stellar companion.

The distance to the star is quite uncertain, but we can make an estimate by comparing the expected stellar radius from evolutionary tracks with the angular diameter derived by fitting the spectral energy distribution (SED). We interpolated in the single star evolutionary tracks of Schaller et al. (1992) to derive mass and radius estimates from the derived $T_{\text{eff}}$ and log $g$ parameters (Table 1). We constructed the SED using UV fluxes from the TD1 satellite (Thompson et al. 1978), Johnson magnitudes from Mermilliod (1991; transformed to flux according to the calibration of Cohen et al. 1996), Two Micron All Sky Survey (2MASS) magnitudes (Skrutskie et al. 2006; transformed to flux according to the calibration of Cohen et al. 2003), and an AKARI 9 $\mu$m measurement (Ishihara et al. 2010). The SED (Figure 3) indicates that there is a strong IR excess from the Be star’s disk that extends into the optical range. In order to fit the photosphere of the star alone, we restricted the range to the UV fluxes and $B$-band revised flux without the disk contribution (the lower point plotted at 4443 Å in Figure 3). We adopted a theoretical flux spectrum from the models of R. L. Kurucz11 for solar metallicity, $T_{\text{eff}}$ and log $g$ from Table 1, and a microturbulent velocity of $2 \text{ km s}^{-1}$. This flux spectrum was fit to

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8 http://sallman.tass-survey.org/servlet/markiv/
9 http://kurucz.harvard.edu/grids.html
10 http://skydot.lanl.gov/nsvs/nsvs.php
the restricted set of observations with two parameters: the limb-darkened, angular diameter $\theta_{LD}$ and the reddening $E(B-V)$ (assuming a ratio of total-to-selective extinction $R_V = 3.1$ and the reddening law from Fitzpatrick 1999). The observed and model-emitted fluxes are related by

$$f_λ(\text{obs}) = \theta_{LD}^2 f_λ(\text{mod}) 10^{-0.4 A_λ},$$

where $A_λ$ is the wavelength-dependent extinction (Fitzpatrick 1999). The first parameter $\theta_{LD}$ acts as a normalization factor while $E(B-V)$ defines how the shape of the SED is altered by the extinction $A_λ$. The results for these two fitting parameters are given in Table 1, and the derived $f_λ$ spectrum is plotted as a solid line in Figure 3. We find a very low reddening along this line of sight, $E(B-V) = 0.02$ mag. Earlier estimates consistently arrive at a higher reddening of $E(B-V) \approx 0.3$ mag (Snow et al. 1977; Neckel & Klare 1980; Hernández et al. 2005; Zhang et al. 2005), but all of these estimates are based upon the $B-V$ color and ignore the disk contribution in the optical that makes the star appear too red (Figure 3).

Combining the SED-derived angular size $\theta_{LD}$ with the evolutionary radius $R_*$ yields a large distance, $d = 2.6 \pm 1.0$ kpc, which places the star far beyond the nearby Lac OB1 association (Harris 1955). At this distance, HD 215227 resides well below the Galactic plane at $z = -0.56 \pm 0.20$ kpc. This is an extreme distance for a normal OB star. For example, in the Be star kinematical survey by Berger & Gies (2001), the mean distance is $\langle |z| \rangle = 69$ pc and only one other star (HD 20340 at $z = -0.71$ kpc) out of a sample of 344 has a distance from the plane as large as that of HD 215227. This suggests that HD 215227 is a runaway star that probably obtained its initial high velocity and current position by an SN explosion in a binary. We adopted the proper motions from van Leeuwen (2007) and the average radial velocity and distance from Table 1 to estimate the star’s current peculiar values of tangential $V_{TP}$, radial $V_{RP}$, and space velocity $V_s$ using the method described by Berger & Gies (2001). These peculiar velocities are measured relative to the star’s local standard of rest by accounting for the Sun’s motion in the Galaxy and differential Galactic rotation. Our estimates of the peculiar velocities (Table 1) are not unusually large, but the errors are significant and the star may have decelerated in the gravitational potential of the Galaxy.

The similarity of this Be binary to other gamma-ray binaries, its probable runaway status, and its close proximity to the gamma-ray source location all indicate that HD 215227 may be the optical counterpart of AGL J2241+4454. We encourage additional spectroscopic observations to search for orbital motion and to document the emission-line variability around the orbit. New X-ray and radio observations with good angular resolution will be essential to secure the identification of the target (see the case of HESS J0632+057; Hinton et al. 2009; Skilton et al. 2009). Furthermore, a search for periodic gamma-ray brightening on the 60 day cycle would offer conclusive evidence of the connection with the Be star. If the orbital eccentricity is high, the gamma-ray emission may be restricted to a limited part of the orbit.

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