DISCOVERY OF A WOLF–RAYET STAR THROUGH DETECTION OF ITS PHOTOMETRIC VARIABILITY

COLIN LITTLEFIELD, PETER GARNAVICH, G. H. “HOWIE” MARION, JÓZSEF VINKÓ, COLIN MCCLELLAND, TERRENCE RETTIG, AND J. CRAIG WHEELER

1 Law School, University of Notre Dame, Notre Dame, IN 46556, USA
2 Physics Department, University of Notre Dame, Notre Dame, IN 46556, USA
3 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
4 Astronomy Department, University of Texas, Austin, TX 78712, USA
5 Department of Optics, University of Szeged, Hungary

1. INTRODUCTION

Wolf–Rayet (WR) stars have been enigmatic objects ever since the discovery of the first three WR stars in 1867 (Wolf & Rayet 1867). Their spectra show strong, Doppler-broadened emission lines, primarily from helium and either carbon or nitrogen of various ionization states. The nitrogen-rich variety, which are classified as WN stars, outnumber the carbon-rich WC stars in current surveys of Galactic WR stars (van der Hucht 2001). Lamers et al. (1991) conclusively showed that WR stars are evolved, high-surface-temperature stars that have shed their envelopes via their strong stellar winds. As WR stars lose mass, they expose elements created via hydrogen fusion and, eventually, those from helium fusion as well (Conti 1976). They often have masses between 10 and 25 $M_\odot$ and even as high as 80 $M_\odot$ in some cases (Crowther 2007). WR stars are destined to end their lives as Type Ib/c supernovae and possibly gamma-ray bursts (e.g., Smartt 2009).

WR stars are rare, and only about 500 are known in the Galaxy (e.g., Roman-Lopes 2011). Because these young stars are close to the Galactic plane, WR stars are often obscured by dust. Most recent searches have used infrared wavelengths to avoid dust extinction and find new members of the WR family (e.g., Shara et al. 2009; Wachter et al. 2010; Mauerhan et al. 2011). Here, we report the serendipitous discovery of a new WR star that was selected for study due to its photometric variability. Even weak variability can mark unusual stellar types and will be an important method of identifying rare stars in the era of the Large Synoptic Survey Telescope (Borne et al. 2008).

2. OBSERVATIONS

2.1. Photometry

In 2011 July, we obtained time-resolved photometry of a superoutburst of cataclysmic variable V503 Cygni with a 28 cm aperture Schmidt–Cassegrain telescope atop Jordan Hall on the University of Notre Dame campus. Seventeen nights of time-series data were taken using a commercial SBIG CCD camera and are listed in Table 1.

During data reduction, we noticed seven nearby field stars (Stars A–G in Figure 1) that appeared to vary in brightness on a time scale of hours. Stars A, C, and E are Algol-type eclipsing binaries, and Star F is a W UMa eclipsing binary. Star D appears to be a very low-amplitude Delta Scuti star, and its power spectrum shows a strong signal at 1.33 hr. Star G, a previously identified Be star, is also variable and showed sinusoidal variations on a timescale of hours in data from SuperWASP (Street et al. 2004), although the amplitude is very low in our light curves.

The very red Star B showed weak, irregular variability. Star B corresponds to USNO-B1.0 1336-0379707 with R2 = 12.7 mag and a B2-R2 color of 3.0 mag. Its position at 2000 $\alpha = 20:28:14.554, \delta = +43:39:25.48$ is within 6 arcsec of HBH4203-27 in the Hamburg-Bergedorf Hα emission line catalog (Kohoutek & Wehmeier 1999). The catalog notes that the Hα line of HBH4203-27 is overexposed on a strong continuum, but no further classification is given.

Additional unfiltered observations of Star B by Elena Pavlenko, Maksim Andreev, and Aleksej Sosnovskij at the Crimean Astrophysical Observatory in Ukraine also showed variation (E. Pavlenko 2011, private communication). However, relative photometry of stars with extreme color differences can create the appearance of variability due to differential extinction with air mass. The suspected variability prompted us to obtain a spectrum of the star so that we could ascertain its nature.

2.2. Spectroscopy

We first obtained spectra of Star B using the same 28 cm Schmidt–Cassegrain telescope and CCD camera as for the photometry, but added a “Star Analyser” (manufactured by Paton Hawksley Education Ltd.) 100-line-per-millimeter grism. The resulting spectrum has a dispersion of 23 Å pixel$^{-1}$. Spectra

9 A constantly updated online catalog of Wolf–Rayet stars can be found at http://pacrowther.staff.shef.ac.uk/WReat/.
Figure 1. Red Digitized Sky Survey image around V503 Cyg showing the variable stars (Stars A–G) identified in this study. Star X is the comparison star used in the photometry and Star Y is a check star. Star B is a new Wolf–Rayet star, WR 142b. (A color version of this figure is available in the online journal.)

Figure 2. Discovery spectrum of WR 142b (shifted by a factor of three) compared with the HET spectrum confirming the classification as a WR star.

Table 1

| UT Date (2011) | UT Start (hr) | UT End (hr) | Filter |
|----------------|---------------|-------------|--------|
| Jul 5          | 3.85          | 8.92        | Clear  |
| Jul 8          | 5.02          | 8.59        | Clear  |
| Jul 12         | 4.46          | 7.88        | Clear  |
| Jul 14         | 5.38          | 9.43        | Clear  |
| Jul 16         | 2.65          | 8.16        | Clear  |
| Jul 17         | 2.57          | 5.12        | Clear  |
| Jul 20         | 2.38          | 6.29        | Clear  |
| Jul 21         | 4.21          | 9.12        | Clear  |
| Jul 25         | 2.58          | 7.68        | Clear  |
| Jul 27         | 2.53          | 5.32        | Clear  |
| Jul 30         | 2.84          | 9.16        | Clear  |
| Jul 31         | 2.19          | 4.07        | Clear  |
| Aug 1          | 2.04          | 8.25        | Clear  |
| Aug 2          | 2.74          | 4.65        | Clear  |
| Aug 5          | 2.46          | 8.23        | I-band |
| Sep 12         | 4.92          | 8.81        | I-band |
| Sep 18         | 2.36          | 8.98        | I-band |

The He I line at 7064 Å appears in many emission line objects and could explain the detection of a strong line at 7100 Å, but this helium line is rarely comparable in strength to Hα at 6563 Å. Thus, we attributed the 7100 Å feature to N iv 7115 Å, indicative of a nitrogen-rich WR star. Stars with strong N iv emission often show several He ii emission lines, making the feature at 5400 Å a good match to the 5411 Å He ii line. Usually, the strongest He ii line in the optical is at 4686 Å, but the combination of poor blue sensitivity and extremely red continuum resulted in a low signal-to-noise ratio shortward of 5000 Å.

We then obtained a spectrum of the WR candidate using the 9.2 m Hobby–Eberly Telescope (HET). Three 120 s exposures were taken and combined to avoid saturating the red end of the spectrum. The spectra were obtained with the slit at parallactic angle to avoid differential slit losses and the air mass of the observations ranged between 1.18 and 1.20. A spectrophotometric standard star was observed on the same night with the slit oriented at the parallactic angle. The HET
Table 2  
Emission Lines

| Wavelength | Equ. Width | Flux | ID   | Rest Wavelength |
|------------|------------|------|------|-----------------|
| (Å)        | (Å)        | (10^{-14} erg cm^{-2} s^{-1}) |      | (Å)             |
| 3478.6     | 19.2       | 0.12 | N iv |                 |
| 3887.7     | 5.3        | 0.10 | He ii| 3888            |
| 3970.0     | 4.1        | 0.09 | He ii| 3968            |
| 4025.8     | 3.8        | 0.10 | He ii| 4025            |
| 4056.0     | 20.0       | 0.59 | N iv | 4058            |
| 4098.5     | 26.9       | 0.90 | N iv+He ii| Blend |
| 4199.7     | 9.8        | 0.40 | N iv+He ii| Blend |
| 4314.8     | 9.6        | 0.68 | He ii| 4339            |
| 4516.2     | 6.1        | 0.56 | N iii|                 |
| 4543.1     | 14.8       | 1.5  | He ii| 4542            |
| 4605.2     | 5.1        | 0.55 | N v  | Blend           |
| 4637.0     | 25.8       | 3.3  | N iii| Blend           |
| 4687.6     | 120        | 16.6 | He ii| 4686            |
| 4859.3     | 7.6        | 6.1  | He ii| 4859            |
| 5201.2     | 2.7        | 0.47 | N v  | 4940            |
| 5412.6     | 3.5        | 0.45 | N iv | 5204            |
| 5412.6     | 31.4       | 11.1 | He ii| 5411            |
| 5804.1     | 23.5       | 12.8 | C iv | 5808            |
| 5875.0     | 11.9       | 6.6  | He i | 5875            |
| 5931.6     | 0.28       | 0.17 | He ii| 5932            |
| 5955.7     | 0.22       | 0.14 | He ii| 5953            |
| 5979.6     | 0.21       | 0.13 | He ii| 5977            |
| 6004.3     | 0.27       | 0.18 | He ii| 6004            |
| 6037.9     | 0.76       | 0.51 | He ii| 6037            |
| 6075.7     | 1.1        | 0.78 | He ii| 6074            |
| 6119.7     | 1.6        | 1.2  | He ii| 6118            |
| 6171.7     | 1.3        | 0.92 | He ii| 6171            |
| 6234.6     | 5.4        | 3.8  | He ii| 6234            |
| 6313.2     | 3.5        | 2.8  | He ii| 6312            |
| 6380.4     | 2.5        | 2.1  | He i | 6380            |
| 6406.9     | 7.0        | 6.1  | He ii| 6406            |
| 6561.2     | 67.7       | 65.7 | He ii| 6560            |
| 6665.2     | 2.7        | 2.8  | He ii| 6665            |
| 6684.6     | 14.9       | 16.6 | He ii| 6683            |
| 6876.2     | 13.0       | 17.2 | He ii| 6876            |
| 7062.5     | 12.8       | 19.2 | He i | 7064            |
| 7114.7     | 9.7        | 147  | N iv | 7110            |
| 7180.1     | 15.1       | 20.6 | He ii| 7178            |
| 7596.5     | 22.3       | 44.2 | He ii| 7593            |
| 8240.3     | 27.1       | 71.5 | He ii| 8237            |
| 9348.3     | 11.8       | 31.8 | He ii| 9345            |
| 10122.2    | 118.2      | 527  | He ii| 10120           |

Note. a Possible identification based on Ralchenko et al. (2011).

The nature of WR 142b was firmly established by the HET spectrum, which offered coverage from 4000 Å to just beyond 1 μm, confirmed the emission lines in our original data and revealed many more in both the blue and near-infrared portions of the star’s spectrum (see Figure 2). In particular, we identify a large number of He ii emission lines with the strongest at 4686 Å and 10124 Å. Other lines and their identifications are given in Table 2. These firmly establish Star B as a WR star of the WN class. Relying upon the WR nomenclature scheme set forth in van der Hucht (2001), we named the star WR 142b.

Once the nature of WR 142b was firmly established by the HET spectrum, we obtained Multi-Object Dual Spectrograph (MODS) data with Large Binocular Telescope (LBT). MODS (Pogge et al. 2010) has sensitivity well into the ultraviolet, which allowed us to search for a hot companion as well as any unusual properties of the WR star. Eight individual 120 s exposures were taken with the 400 line mm^{-1} blue grating on 2011 September 27 (UT). A 1.0 arcsec wide slit was employed.

The bias was removed from the images and the data corrected for variations in the flat field. The individual images were combined before a one-dimensional spectrum was extracted. A line identified as N iv at 3478 Å was clearly detected, showing that the sensitivity of MODS extended shortward of 3500 Å.

3. ANALYSIS

3.1. WR Classification

The strong N iv, rich He ii spectrum, and overall lack of carbon emission clearly make this a WN-type WR (Figure 3). Subclassification of WN stars is multi-dimensional, based on the Smith et al. (1996) system. The degree of ionization is characterized by the He ii 5411 to He ii 5875 line ratio. The observed equivalent width ratio is 2.6 for WR 142b, placing it in the WN5 or WN6 class. The N v to N iii ratio is very small, consistent with a WN6 or WN7 star. The LBT spectrum includes the N iv line at 4057 Å and its peak compared with the 4630 Å blend is consistent with a WN5 or WN6 classification. The C iv to He ii 5411 ratio is 0.7 and C iv to He ii 2.0, both at the WN5/6 boundary. We conclude that WR 142b is best matched by a WN6 ionization classification.

The He ii lines have widths of 24 Å (FWHM) before accounting for the instrumental resolution. This is within the range of normal line widths, so WR 142b should not be considered a broad-lined WR star.

Strong He ii emission can hide the presence of hydrogen in the spectrum of WN stars because of the close coincidence of the Balmer lines with the many Pickering series lines of He ii. Smith et al. (1996) note that when hydrogen is present, Hβ and Hγ will increase the flux of the corresponding Pickering lines while leaving the other Pickering lines unperturbed. However, WR 142b shows a monotonically decreasing Pickering series, and we conclude that it does not have detectable hydrogen in its atmosphere.

3.2. Reddening by Dust

The very red color of WR 142b suggests a significant amount of dust extinction local to the WR star or along the line-of-sight. Emission line ratios (Conti & Morris 1990) and the slope of the continuum (Morris et al. 1993) have been used to estimate the reddening of individual WR stars.

The predicted spectrum of hydrogen recombination from a low-density nebula is often compared with the observed emission to estimate extinction. In contrast, the physical processes of the atmospheres of helium-rich WR stars are complex and require detailed modeling to accurately predict the line strengths. Conti & Morris (1990) have used an empirical approach and found that the ratio between the strong UV He ii line at 1640 Å is consistently a factor of 7.6 brighter than the optical 4686 Å line with only a 20% scatter in 30 WR stars. This is very close to the optically thin recombination ratio for these lines. Unfortunately, we have not observed the 1640 Å line, but we do have a measurement of the bright IR line at 1.012 μm.

We have run the “Cloudy” photoionization code (Ferland et al. 1998, version 8.01) with enhanced helium and over a range of temperatures and densities. We find that when the 1640 Å line to 4686 Å flux ratio is 8, the 4686 Å to 10120 Å flux ratio is between 5 and 6. The observed flux ratio is 0.031, meaning the 4686 Å He ii line is between 160 and 200 times fainter than...
The absolute magnitude for these stars is predicted. For a Cardelli et al. (1989) dust law, this corresponds to a reddening of $E(B - V) = 2.15$ to 2.25 mag.

Morris et al. (1993) found that the continua of WN-type WR stars between the ultraviolet (UV) and near-infrared (NIR) wavelengths are well matched by a power law with an index of $-2.72 \pm 0.39$. To create a continuum energy distribution (CED), we estimate the flux in regions of the HET spectra with no significant emission and we add the Two Micron All Sky Survey (2MASS) NIR magnitude measurements ($J = 8.769 \pm 0.021, H = 7.861 \pm 0.017, K = 7.191 \pm 0.020$) converted to flux. The optical and NIR fluxes were obtained at different times for this variable star, but the amplitude of the variation is small and should not dominate the error in the slope estimate. The CED was dereddened using the Cardelli et al. (1989) law until the slope was best fit by a power law with index $-2.72$. This slope is matched with a $E(B - V) = 2.57 \pm 0.14$ mag. The uncertainty in this extinction estimate comes directly from the range of power-law indices in the observed sample of WR stars.

Extinction can also be estimated directly from the near-IR colors using the method of Crowther et al. (2006). They find the unreddened colors for WN6 stars with weak lines are $(H - K)_0 = 0.16 \pm 0.02$ and $(J - K)_0 = 0.18 \pm 0.02$ mag. The absolute magnitude for these stars is $M_K = -4.41 \pm 0.45$. From the WR 142b 2MASS magnitudes, the color excesses are $E(H - K) = 0.51 \pm 0.03$ and $E(J - K) = 1.40 \pm 0.03$ mag. Applying the IR extinction relation of Indebetouw et al. (2005) and combining the two colors, the $K$-band extinction is $A_K = 0.94 \pm 0.10$ mag. Converting to visual extinction using Cardelli et al. (1989), we find $A_V = 8.2$ mag which is in good agreement with the reddening estimated from fitting the UV to IR continuum slope. This consistency is reassuring but hardly surprising since both methods depend on the spectral similarities between WR stars of the same class. The reddening estimates based on the continuum slope appear more reliable than the line ratio technique, so we adopt a reddening of $E(B - V) = 2.6 \pm 0.2$ mag for WR 142b.

### 3.3. Distance

The infrared luminosities of WR stars of a given subtype are fairly consistent (Crowther et al. 2006) and allow the estimate of distances to individual WR stars. As noted in Section 3.2, the unreddened absolute magnitude of stars like WR 142b is $M_K = -4.41 \pm 0.45$ with the error based on the dispersion of four WN5-6 stars. From the 2MASS apparent $K$ magnitude and our estimate of the $K$-band extinction of $A_K = 0.94 \pm 0.10$ mag, the distance modulus of WR 142b is 10.66 $\pm$ 0.46 mag. This corresponds to a distance of $1.4 \pm 0.3$ kpc and a height above the Galactic plane of 70 pc.

Our distance estimate combined with the Galactic longitude of WR 142b (82°) places it in the “Orion Spur.” Moreover, the distance and coordinates of WR 142b are consistent with membership in Cygnus X, a heavily obscured region of strong star formation (Reipurth & Schneider 2008).

### 3.4. Companion?

Van der Hucht (2001) found that 39% of known WR stars harbor companions, usually of the OB type. The companions add absorption lines at blue wavelengths and can generate a UV bump in the continuum of the WR star. Our HET spectrum does not reach far enough into the blue to test for these effects, but we specifically obtained an LBT spectrum to search for evidence of a companion. The blue end of the LBT spectrum is shown in Figure 3. Narrow interstellar absorption features are present, but there is no sign of stellar absorption consistent with a companion, and the spectrum before continuum normalization does not display a strong bump from a hot companion. We find no evidence of a hot companion star to WR 142b.

### 3.5. Infrared Flux

The Cygnus region was observed with the Midcourse Space Experiment (MSX), and the MSX6C point source catalog (Egan et al. 2003) lists a source within 0.6 arcsec of WR 142b.
G081.5744+02.9135 has a measured flux of 0.346 Jy in band A (8.28 μm) but is not detected in the longer-wavelength bands. The low density of IR point sources in the survey combined with the strong positional coincidence suggests that WR 142b is detected at 8.28 μm. The MSX image of the field is shown in Figure 4 and a large amount of dust emission is evident toward WR 142b. In particular, a finger of dust emission extends over the star and may be the cause of the very high estimated extinction.

If we extrapolate the optical/near-IR flux after correcting for our estimated reddening, we predict a flux of $3.1 \times 10^{-15} \text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$ at 8.28 μm. This is nearly a factor of two larger than the MSX-observed flux after a 0.16 mag extinction correction at 8 μm is applied. But given the large extrapolation and variability of the star, the prediction is reasonably close.

If we fit a power-law slope to only the 2MASS magnitudes for WR 142b and extrapolate to 8.28 μm, we predict a flux of $1.74 \times 10^{-15} \text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$, which matches the observed MSX flux. The power-law index using only the NIR continuum is 3.2, which is slightly steeper than when the optical is included. These extrapolations imply no strong mid-IR emission from WR 142b beyond that from the stellar continuum. We conclude that there is no significant circumstellar dust emission from WR 142b and that the large extinction is extrinsic to the star.

### 3.6. Variability

In a study of northern WR stars, Moffat & Shara (1986) found that at least half of the WR stars in their survey display low-amplitude (often 5%) variability in optical wavelengths. Short-period variability in particular WR stars has been the subject of a number of studies (e.g., Chen et al. 2011; Rauw et al. 1996; Oliveira et al. 2011). There are several proposed causes of variability including pulsation, rotational wind modulation and close binary interaction. These studies make use of extensive spectroscopic and photometric data, but even then, they do not always yield clear answers as to the mechanism of variability.

As noted in the photometry section, WR 142b exhibited irregular, low-amplitude variation in our unfiltered observations.

### Table 3

| UT Date (2011) | Julian Day (+2455000) | Average $I^a$ (mag) | Check Star $I^a$ (mag) |
|---------------|------------------------|---------------------|------------------------|
| Jul 10        | 752.8113               | 10.983 ± 0.002      | 12.674 ± 0.004         |
| Aug 5         | 778.7229               | 10.995 ± 0.001      | 12.692 ± 0.003         |
| Sep 12        | 816.7735               | 11.013 ± 0.001      | 12.672 ± 0.003         |
| Sep 14        | 818.6175               | 10.930 ± 0.002      | 12.691 ± 0.006         |
| Sep 16        | 820.6495               | 11.045 ± 0.002      | 12.696 ± 0.006         |
| Sep 18        | 822.7304               | 11.045 ± 0.002      | 12.680 ± 0.002         |
| Sep 22        | 836.6625               | 10.982 ± 0.002      | 12.680 ± 0.006         |
| Mean ± rms    | 10.999 ± 0.040         | 12.684 ± 0.009      |

Note. $^a$ Based on the USNO-B1.0 magnitude for the comparison star of $I = 11.26$ mag. The error estimate includes only Poisson noise.

We subsequently reprocessed the photometry and used suitably red comparison and check stars (Stars X and Y in Figure 1), selected by their $I - K$ colors. The weak variation seen in WR 142b remained present in many of the light curves, but its amplitude never exceeded 0.03 mag.

Since the data were unfiltered, we were concerned that the observed variability might be an artifact caused by differential extinction. To minimize this effect, we obtained time-series photometry on three nights using an $I$-band filter and red comparison and check stars. All of the filtered light curves show low-amplitude variability similar to that observed in the unfiltered data. The variability typically appears as a gradual brightening, followed by a slower fade, but no consistent period is apparent. Crucially, it is independent of air mass, and the check star never displays similar activity. Figure 5 presents a representative photometric time series.

WR 142b also shows night-to-night variability. The average $I$-band magnitude of the star on seven nights over a two-month span is given in Table 3. In particular, the infrared magnitude on 2011 September 14 (UT) was 0.08 mag brighter than it had been...
two days earlier, and two days later, it had faded by 0.11 mag. The root-mean-squared (rms) variation of WR 142b over the six nights was 0.040 mag while the check star, which was four times fainter, varied by only 0.009 mag. We conclude that the weak variability suspected in the unfiltered data is confirmed by the better-controlled I-band photometry.

The lack of a stable periodic variation argues against a binary companion or rotational modulation as the source of variability (Moffat et al. 1988; Hénault-Brunet et al. 2011). Stellar pulsations, which can lead to inhomogeneities in the stellar wind, are a possible explanation for variability in WR 142b. Radiatively driven winds could produce essentially random variations and non-radial pulsations that can have multiple periodicities which interfere with one another (Hénault-Brunet et al. 2011), could be mistaken for random variability over limited observing windows. Further photometric and spectroscopic monitoring of WR 142b is needed to firmly determine the source of its variability.

4. CONCLUSION

We have serendipitously discovered a WR star, WR 142b, by first detecting its photometric variability and then obtaining spectroscopy. An HET spectrum shows emission lines of He I, He II, N IV, and C IV. After examining the strengths of WR 142b spectral lines, we find that it is best classified as a WN6 with no detectable hydrogen and normal line widths. The spectrum shows good evidence for a significant reddening due to dust. We estimate that the reddening is between $E(B - V) = 2.2$ and 2.6 mag and most likely toward the higher value. For a standard dust law the star is dimmed by 8 mag in the $V$ band and would have a visual brightness of $V_0 = 6.6$ mag with no extinction. Based on the near-IR photometry, we estimate that the distance to WR 142b is $1.4 \pm 0.3$ kpc. We do not detect a hot companion despite obtaining LBT spectra sensitive down to 3400 Å.

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