ABSTRACT. We report the fifth confirmed Luminous Blue Variable/S Doradus variable in M31. In 2006, J004526.62+415006.3 had the spectrum of hot Fe II emission line star with strong P Cygni profiles in the Balmer lines. In 2010, its absorption line spectrum resembled an early A-type supergiant with H and Fe II emission lines with strong P Cygni profiles, and in 2013, the spectrum had fully transitioned to an F-type supergiant due to the formation of the optically thick, cool wind which characterizes LBVs at maximum light. The photometric record supports the LBV/S Doradus nature of the variability. Its bolometric luminosity of ∼9.65 mag places it on the H−R diagram near the known LBVs, AE And, Var C in M33, and S Dor.

Online material: color figures

1. INTRODUCTION

The class of stars known in the literature as luminous blue variables (LBVs) are an important phase in the final evolution of evolved massive stars. They may represent a short high-mass-loss stage in which the star sheds much of its outer envelope prior to becoming a Wolf−Rayet star, or as some authors have suggested, they may be the immediate progenitors of some types of Type II supernovae. A classical LBV or S Doradus variable in quiescence (minimum light) resembles a moderately evolved hot star, usually with the spectrum of a B-type supergiant or an Of/late−WN star (Humphreys & Davidson 1994; Vink 2012). During an LBV eruption, the mass loss rate increases, the wind becomes opaque and cool, and its absorption spectrum resembles an A to F-type supergiant. Since this is a shift in the bolometric correction, the star brightens in the visual and appears to move to the right, to lower temperatures on the H−R diagram. This is the LBV’s optically thick wind stage, or maximum light. The origin of the instability that leads to this dramatic change is not understood, but most suggestions involve an instability close to the Eddington limit. The mass loss event can last for several years or even decades, and afterward the star returns to its previous state.

Many stars are called LBVs or candidate LBVs, but few are confirmed, probably due to the infrequency of the LBV “eruption” or maximum light stage. For example, there are only four confirmed classical or normal LBV/S Doradus variables in M31 (see Humphreys et al. 2014). Thus, the discovery of a new LBV in its eruption state is important for understanding their relation to the larger massive star population, the frequency of the LBV eruption, and the duration of this unstable phase. J004526.62+415006.3 was described by Massey et al. (2007) as a “hot LBV candidate.” Its normalized spectrum from 2006 (Fig. 12 in Massey et al. (2007)) showed strong H emission lines with P Cygni profiles and weak Fe II emission lines. In a survey of luminous stars in M31 and M33, Humphreys et al. (2014) noted that its 2010 spectrum closely resembled that of the warm hypergiant J004444.52+412804.0 (Humphreys et al. 2013) with prominent P Cygni profiles in the multiplet 42 Fe II emission lines, strong hydrogen emission with broad wings and P Cygni profiles, and the absorption line spectrum of an early A-type supergiant. A spectrum from 2011 published by Sholukhova et al. (2015) clearly showed that the Fe II lines had weakened. They also noted the change from 2006 and suggested that it is an LBV. A second star, J004051.59+403303.0, was identified as an LBV candidate.

In this paper, we discuss recent spectra and photometry of J004526.62+415006.3 that confirm it is an LBV currently in an optically thick wind state or maximum light.

2. NEW OBSERVATIONS

In addition to the spectrum described in Humphreys et al. (2014), it was observed again on 2013 September 25 and 26 with the Hectospec multiobject spectrograph (MOS) (Fabricant et al. 1998, 2005) on the 6.5 m MMT on Mount Hopkins. The Hectospec has a 1° field-of-view (FOV) and uses 300 fibers, each with a core diameter of 250 μm subtending 1.5′ on the sky. We used the 600 mm−1 grating with the 4800 Å tilt yielding ≃2500 Å coverage with 0.54 Å pixel−1 resolution and R of

1 Based on observations with the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.
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3 Barber Observatory, University of Illinois, Springfield, IL 62703.
4 M31-004526.62 in Humphreys et al. (2014) and Sholukhova et al. (2015).
5 http://www.cfa.harvard.edu/mmti/hectospec.html.
∼2000. The same grating with a tilt of 6800 Å was used for the red spectra with ≈2500 Å coverage, 0.54 Å pixel⁻¹ resolution and R of ∼3600. The spectra were reduced using an exportable version of the CfA/SAO SPECROAD package for Hectospec data. The spectra were all bias-subtracted, flat-fielded, and wavelength-calibrated.

Recent broadband CCD photometry was obtained by J. C. Martin with the 20 in. (0.5 m) telescope at the Barber Observatory in 2013 and 2014, and by Sholukhova et al. (2015) in 2011. We also measured additional magnitudes from Hubble Space Telescope Advanced Camera for Surveys high-resolution channel images observed August 2010 (HST-GO-12056) and January 2012 (HST-GO-12106). The magnitudes are zero pointed to Vega and comparable to Johnson B and Cousins I. All of the spectroscopic and photometric observations discussed here are summarized in Table 1.

### 3. THE SPECTRUM FROM 2006 TO 2013 AND LIGHT CURVE

Phil Massey kindly provided their spectrum from 2006 (Massey et al. 2007) reproduced here in Figure 1. Massey et al. (2007) described J004526.62+415006.3 as a “hot LBV candidate.” The spectrum is dominated by strong hydrogen emission with broad wings and P Cygni profiles and FeII and [Fe II] emission. Some weak absorption lines of He I λ4026, O II λ4070–4076, and S IV λ4116 are visible, suggestive of an early B-type star.

The blue and red spectra from 2010 and 2013 are shown together in Figures 2(a) and (b), respectively. They not only illustrate the dramatic change from the hot emission line star in 2006, but also the transition to a cooler temperature from 2010 to 2013 and the formation of the optically thick cool wind in the 2013 spectrum. Humphreys et al. (2014) classified its 2010 spectrum as an early A-type supergiant (A2eIa). With its strong P Cygni profiles in the multiplet 42 FeII emission lines, they noted its close resemblance to the warm hypergiant J004444.52+412804.0 (Humphreys et al. 2013). The 2013 spectra show the continued evolution of the wind to cooler temperatures. Metallic absorption lines have replaced the Fe II emission spectrum, strong CaII H and K lines are conspicuous, and the P Cygni profiles are gone except for Hα. The blue absorption line spectrum of the optically thick wind is consistent with an early F-type supergiant (∼F2). In the red spectrum, the luminosity sensitive OI λ7774 triplet and the NI (multiplet 3) absorption lines are much stronger. The differences between the 2010 and 2013 spectra illustrate the spectroscopic changes.

### Table 1: Journal of Observations Used in This Paper

| UT date    | Instrument          | Exp. time (minutes) | Wavelength or filters (Å) | Resolution (Å) | Reference          |
|------------|---------------------|---------------------|---------------------------|----------------|--------------------|
| 2006 Sep 19–20 | WYIN/Hydra    | 180                 | 3970–5030                  | 1.5            | Massey et al. (2007) |
| 2006 Sep 21–22 | WYIN/Hydra    | 90                  | 4550–7400                  | 3.4            | Massey et al. (2007) |
| 2010 Oct 10    | MMT/Hectospec | 120                 | 3600–6050                  | 1.9–2.2        | Humphreys et al. (2013, 2014) |
| 2010 Oct 9      | MMT/Hectospec | 90                  | 5500–8000                  | 1.9–2.2        | Humphreys et al. (2013, 2014) |
| 2013 Sep 25     | MMT/Hectospec | 120                 | 3600–6050                  | 1.9–2.2        | This paper         |
| 2013 Sep 25     | MMT/Hectospec | 90                  | 5500–8000                  | 1.9–2.2        | This paper         |

**Photometry**

| UT date    | Instrument          | Exp. time (minutes) | Wavelength or filters (Å) | Resolution (Å) | Reference          |
|------------|---------------------|---------------------|---------------------------|----------------|--------------------|
| 1999–2003 | WFC/INT            | ...                 | ...                       | ...            | Vilardell et al. (2006) |
| 2000 Oct 3–6 | Mosaic CCD/4 m | ...                 | ...                       | ...            | Massey et al. (2006) |
| 2010 Aug 13     | HST/ACS           | ...                 | ...                       | ...            | This paper         |
| 2011 Oct–Nov    | BTA 6 m           | ...                 | ...                       | ...            | Sholukhova et al. (2015) |
| 2012 Jan 11     | HST/ACS           | ...                 | ...                       | ...            | This paper         |
| 2013 Sep 2      | CCD/Barber Obs.  | ...                 | ...                       | ...            | This paper         |
| 2013 Oct 28     | CCD/Barber Obs.  | ...                 | ...                       | ...            | This paper         |
| 2014 Oct 21     | CCD/Barber Obs.  | ...                 | ...                       | ...            | This paper         |
| 2014 Nov 21     | CCD/Barber Obs.  | ...                 | ...                       | ...            | This paper         |
| 2015 Jan 15     | CCD/Barber Obs.  | ...                 | ...                       | ...            | This paper         |

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6 External SPECROAD was developed by Juan Cabanela for use on Linux or MacOS X systems outside of CfA. It is available online at http://iparrizar.mnstate.edu.

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The 2013 spectra show the continued evolution of the wind to cooler temperatures. Metallic absorption lines have replaced the Fe II emission spectrum, strong Ca II H and K lines are conspicuous, and the P Cygni profiles are gone except for Hα. The blue absorption line spectrum of the optically thick wind is consistent with an early F-type supergiant (∼F2). In the red spectrum, the luminosity sensitive O I λ7774 triplet and the N I (multiplet 3) absorption lines are much stronger. The differences between the 2010 and 2013 spectra illustrate the spectroscopic changes.

FIG. 1.—The Fe II and hydrogen emission line spectrum from 2006 (Massey et al. 2007). See the online edition of the PASP for a color version of this figure.
transition and the formation of an optically thick wind typical of LBV/S Doradus variables.

Like other LBVs (Humphreys et al. 2014; Oksala et al. 2013; Kraus et al. 2014), its spectral energy distribution has a small near-infrared excess due to free–free emission, but it was not detected in the Spitzer Infrared Array Camera (IRAC) survey of M31 (Mould et al. 2008) or the Wide-field Infrared Survey Explorer (WISE) source catalog. So it apparently does not have a near-infrared or mid-infrared excess due to dust (see Fig. 11 in Humphreys et al. [2014]). However, the relative strengths of the \([\text{N II}]\) λ5755 and λ6584 emission lines compared to the \([\text{SII}]\) lines in the 2010 spectrum indicate the presence of a relatively dense circumstellar nebula, much denser than expected for an \(\text{H II}\) region (Weis et al. 2015). The outflow velocities from the stellar wind measured from the absorption minima in the \(\text{P Cygni}\) profiles in these spectra are summarized in Table 2. LBVs not only have slow wind velocities during their maximum-light, dense-wind state, but during their quiescent hot state their winds are also slower than those measured the same way in normal supergiants of similar spectral type (Humphreys et al. 2014). J004526.62+415006.3 shows the same pattern, although the outflow measured in the 2010 spectrum is interestingly higher when the star was in transition to the dense wind state.

The light curve is shown in Figure 3. Unfortunately, we do not have either spectra or photometry between 2006 and 2010 to determine the onset of the LBV/S Doradus eruption. However, our spectra demonstrate that the star was in transition to its cool, dense-wind state in 2010, so the outburst probably began in 2010 or shortly before that. Based on the photometry from 1999–2003 to 2012–2014, \(\Delta V\) is surprisingly at most only 0.9 mag, which is too small for the implied change in apparent temperature between the 2006 and 2010–2013 spectra. Thus, we suspect that the earlier photometry is not representative of its minimum-light or quiescent state, and it may have been in an elevated state at that time. Previous photometry also shows that it has had other eruptions; it was measured at \(V = 16.3\) in 1992 (Magnier et al. 1992).

![Figure 2](image_url)

**Fig. 2.** (a) The blue spectra from 2010 (blue) and 2013 (red). Note the development of the absorption line spectrum replacing the \(\text{Fe II}\) emission lines and weakening of the \(\text{P Cygni}\) profiles. (b) Red spectra from 2010 (blue) and 2013 (red). The luminosity sensitive \(\text{O I}\) triplet at 7774 Å in intermediate temperature supergiants in much stronger in 2013.

![Figure 3](image_url)

**Fig. 3.** The light curve based on the data in Table 3. The symbols are B, open blue squares; V, filled green circles, R, red crosses and I, open red triangles. A gap is shown between 2000 and next available data in 2010.

### TABLE 2

#### Outflow Velocities in J004526.62+415006.3

| Date      | Velocity (km s\(^{-1}\)) | Lines          |
|-----------|--------------------------|----------------|
| Sep 2006  | −101 ± 3                 | 3 Hydrogen lines |
| Oct 2010  | −149 ± 6                 | 4 Hydrogen lines |
|           | −138 ± 3                 | 3 Fe II lines   |
| Sep 2013  | −115                     | H\(_\alpha\) only |

### TABLE 3

#### Multicolor Photometry 2000–2015

| Date       | B mag | V mag | R mag | I mag |
|------------|-------|-------|-------|-------|
| 1999–2003  | 17.11 | 17.08 | ...   | ...   |
| 2000 Oct 3–6 | 17.66 | 17.16 | 17.48 | 17.35 |
| 2010 Aug 13 | 17.31 | ...   | ...   | 16.61 |
| 2011 Oct–Nov | 16.82 | 16.37 | 16.08 | ...   |
| 2012 Jan 11 | 16.81 | ...   | ...   | 15.93 |
| 2013 Sep 2  | ...   | 16.23 | 15.93 | ...   |
| 2013 Oct 28 | ...   | 16.27 | 15.99 | ...   |
| 2014 Oct 21 | 16.66 | 16.46 | 16.17 | ...   |
| 2014 Nov 21 | 16.68 | 16.45 | ...   | ...   |
| 2015 Jan 15 | 16.76 | 16.51 | 16.27 | ...   |

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4. RELATION TO OTHER LBVs

Adopting the interstellar extinction $A_v = 1.5$ mag from Humphreys et al. (2014), measured from three different indicators, its visual luminosity at maximum light is $M_v = -9.65$ with a distance modulus of 24.4 mag for M31 (Riess et al. 2012). At maximum light, the bolometric correction will be quite small, corresponding to the early F-type spectrum of the dense wind. $M_{bol}$ is therefore also $\approx -9.65$ mag. The corresponding parameters for the star in its quiescent or hot state are less well determined, but its spectrum from 2006 suggests an early B-type supergiant with a surface temperature on the order of 20,000 K or hotter. On the H–R diagram, J004526.62+415006.3 will thus lie very close to AE And in M31, Var C in M33, and the well-studied progenitor of the class S Doradus (see Fig. 12 in Humphreys et al. [2014]).

Given the lack of photometric data between 2000 and 2010, any additional data from that period or earlier would be appreciated to better define the properties of the progenitor and the onset of the current eruption, as well as future photometric and spectroscopic monitoring.

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