THE DOUBLE-LINED SPECTRUM OF LBV 1806–20¹

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ABSTRACT

Despite much theoretical and observational progress, there is no known firm upper limit to the masses of stars. Our understanding of the interplay between the immense radiation pressure produced by massive stars in formation and the opacity of infalling material is subject to theoretical uncertainties, and many observational claims of “the most massive star” have failed the singularity test. LBV 1806–20 is a particularly luminous object, $L \sim 10^6 L_\odot$, for which some have claimed very high mass estimates ($M_{\text{initial}} > 200 M_\odot$), based in part on its similarity to the Pistol star. We present high-resolution near-infrared spectroscopy of LBV 1806–20, showing that it is possibly a binary system with components separated in velocity by $\sim 70 \text{ km s}^{-1}$. If correct, then this system is not the most massive star known, yet it is a massive binary system. We argue that a binary, or merged, system is more consistent with the ages of nearby stars in the LBV 1806–20 cluster. In addition, we find that the velocity of $V_{\text{LSR}} = 36 \text{ km s}^{-1}$ is consistent with a distance of 11.8 kpc, a luminosity of $10^{6.3} L_\odot$, and a system mass of $\sim 130 M_\odot$.

Subject headings: binaries: spectroscopic — infrared: stars — stars: early-type — stars: evolution — stars: fundamental parameters — stars: individual (LBV 1806–20)

1. INTRODUCTION

Massive stars are key ingredients and probes of astrophysical phenomena on all size and distance scales, from individual star formation sites, such as Orion, to the early universe during the age of reionization when the first stars were born. As ingredients, they control the dynamical and chemical evolution of their local environs and individual galaxies through their influence on the energetics and composition of the interstellar medium. They likely play an important role in the early evolution of the first galaxies, and there is evidence that they are the progenitors of the most energetic explosions in the universe, seen as gamma-ray bursts. As probes, they define the upper limits of the star formation process, and their presence likely ends further formation of nearby lower mass stars. They are also prominent output products of galactic mergers, starburst galaxies, and active galactic nuclei.

Despite their central role in these varied topics, there is no known firm upper limit to the maximum stellar mass. Such a basic quantity escapes both theory, because of the complex interplay between radiation pressure and opacity, and observation, because of incompleteness in surveying the Galaxy along the plane and the dearth of resolved starburst clusters with masses greater than $10^4 M_\odot$. The most promising cases were made recently by Figer (2003) and Weidner & Kroupa (2004), who give observational evidence for an upper mass cutoff of $\sim 150 M_\odot$ in the Arches cluster and R136, respectively. Finding even a single star with a mass significantly beyond this limit would single-handedly change our understanding of the maximum mass that a star may have.

Of course, each “discovery of the most massive star” must face

the crucial test of singularity. Some such claims have not passed this test, with subsequent observations revealing that the object is actually composed of multiple stars. For instance, Weigelt et al. (1991) find that R136 is actually a massive cluster of stars, rather than a supermassive single star with $M \sim 250\text{--}2000 M_\odot$ (Feitzinger et al. 1980; Panagia et al. 1983). Likewise, Damineli et al. (2000) claim that η Car is binary, with present-day masses of ~ 70 and $\sim 30 M_\odot$, rather than a single star with $M \gtrsim 100 M_\odot$.

Some of the most massive single stars known are near the Galactic center. Figer et al. (1998) identify the Pistol star, in the Quintuplet cluster, as one of the most massive known, with an initial mass of $\sim 200 M_\odot$, and show that the star is single based on their Keck speckle data and spectra; the former reveal that the star is single down to a projected distance of 110 AU (14 mas), while the latter do not show an obviously composite spectrum. Figer et al. (1999a) identify a near-twin to the Pistol star, FMM 362, less than $2'$ from the Pistol star, and Geballe et al. (2000) demonstrate that it had the same spectroscopic and photometric characteristics as the Pistol star at the time of the observations. Presumably, FMM 362 is nearly as massive as the Pistol star.

Kulkarni et al. (1995) identified a luminous source near the soft gamma repeater, SGR 1806–20. Van Kerkwijk et al. (1995) determined that this source has characteristics similar to luminous blue variables (LBVs); i.e., it has $L \gtrsim 10^6 L_\odot$ and a K -band spectrum indicating a spectral type in the range O9–B2, leading them to propose that it is an LBV candidate. Eikenberry et al. (2001, 2004) estimated the properties of the star, finding a luminosity, and thus mass, that is at least comparable to that of the Pistol star. Eikenberry et al. (2004) obtained high-resolution images at Palomar, showing that the star is single down to about 900 AU. Note that the putative binary components of η Car have a maximum separation of 30 AU (Damineli et al. 2000). So, it is possible that LBV 1806–20 is multiple, but it is certainly not a “cluster” in the traditional sense. Even the most compact cluster in the Galaxy, the Arches cluster, has a half-light radius of $\sim 40,000$ AU (Figer et al. 1999b).

In this Letter, we present high-resolution near-infrared spectra of LBV 1806–20 showing that the helium absorption lines are double, suggesting that the star may be binary.

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FIG. 1.—Spectra of the Pistol star and LBV 1806–20 near the $1.70\ \mu\text{m}$ He I transition. The feature in the spectrum for LBV 1806–20 is double (marked by arrows), with the blueward component having a P Cygni signature. The broad feature on the left at $1.688\ \mu\text{m}$ is attributable to an Fe II transition. The two features at 1.691 and $1.698\ \mu\text{m}$ are due to Si II. The weak absorption features near 1.6905 and $1.6960\ \mu\text{m}$ are due to telluric absorption.

2. OBSERVATIONS AND DATA REDUCTION

The data were obtained at Keck on 2003 June 22, using NIR-SPEC (McLean et al. 1998). LBV 1806–20 was observed at high resolution ($R \sim 26,500 = \lambda/\Delta\lambda_{\text{FWHM}}$) from 1.68 to $2.25\ \mu\text{m}$ in three grating settings and at low resolution ($R \sim 2500$) from 2.7 to $4.2\ \mu\text{m}$ in two grating settings. We obtained two exposures per grating setting, with the telescope nodded along the direction of the slit between exposures. The exposure times were 200, 100, and 30 s for the high-resolution short-wavelength, long-wavelength, and low-resolution pointings, respectively.

Quintuplet star 3 (hereafter Q3), which is featureless in this spectral region (Figer et al. 1998; Fig. 1), was observed as a telluric standard (Moneti et al. 1994). Arc lamps containing Ar, Ne, Kr, and Xe were observed to set the wavelength scale. In

FIG. 2.—Spectra of massive stars near the $2.112/2.113\ \mu\text{m}$ He I doublet. The Pistol star, IRS 16NE, and LBV 1806–20 are LBVs or LBV candidates (Figer et al. 1998; Tambllyn et al. 1996; van Kerkwijk et al. 1995), and the remaining stars are B-type supergiants (Figer et al. 1999a; Genzel et al. 1996). All the spectra show a single He I doublet near $2.1125\ \mu\text{m}$, except that for LBV 1806–20, in which it is obviously double (marked by arrows). The broad feature near $2.089\ \mu\text{m}$ is common to LBV spectra and corresponds to an Fe II transition.

FIG. 3.—Spectra of the Pistol star and LBV 1806–20 near the Br γ line. The two absorption lines near $2.160\ \mu\text{m}$ in the spectrum for LBV 1806–20 (marked by arrows) are due to two separate transitions of He I.

addition, a continuum lamp was observed through an etalon filter in order to produce an accurate wavelength scale between arc lamp lines and sky lines (predominantly from OH). A quartz-tungsten-halogen lamp was observed to provide a “flat” image that was divided into the background-subtracted target images.

We subtracted background flux, dark current, and residual bias by differencing the nod pair frames, and we divided the result by the flat-field frame in order to compensate for non-uniform response. We extracted spectra of the objects and applied a wavelength solution based on the locations of arc lines. Finally, we divided the target spectra by the spectrum for Q3 in order to remove telluric effects. Note that we omitted this last step in the case of the spectra near $1.7\ \mu\text{m}$ because Q3 is too faint at such short wavelengths. The final extracted spectra are shown in Figures 1, 2, 3, and 4. They have been individually shifted along the x -axis so that the spectral features are aligned with their vacuum wavelengths at rest.

FIG. 4.—Spectra of the Pistol star and LBV 1806–20 in the $3\text{--}4\ \mu\text{m}$ region. Both spectra have a strong Br α emission line near $4.05\ \mu\text{m}$, a Pf γ (H I 6–5) emission line near $3.74\ \mu\text{m}$, and a set of emission lines in the Humphreys series (H I $n\text{--}6$). Hydrogenic transitions of He I can be seen in absorption just shortward of the Br α lines. The remaining lines are mostly due to Fe II.

FIG. 5.—Galactic rotation curve toward the line of sight of LBV 1806–20 from Brand & Blitz (1993). The cross-hatched region corresponds to our estimate of the systemic velocity of LBV 1806–20 in the LSR frame. The error band limits are $\pm 10 \text{ km s}^{-1}$, where 6 km s^{-1} represents the measurement error and 4 km s^{-1} allows for mass ratios between 1 : 1 and 1 : 1.5.

3. DISCUSSION

3.1. Spectral Analysis

The spectra of LBV 1806–20 and the Pistol star are virtually indistinguishable, except for the morphology of the Fe II and He I lines. The latter are generated in the photospheres and winds of LBVs and are invariably seen in absorption. In LBV 1806–20, the He I lines are obviously double, with a velocity separation of $72 \pm 3 \text{ km s}^{-1}$. The short-wavelength component of the $1.70 \mu\text{m}$ line has a P Cygni signature, indicating that the star responsible for the bulk of the emission lines is blueshifted with respect to the other star. Indeed, none of the emission lines is double, indicating that the redshifted component likely has less luminosity and/or a thinner wind. The velocity separation between the two minima in the components is 106 km s^{-1} , larger than the separation of the components near $2.112 \mu\text{m}$, as would be expected given the P Cygni nature of the profile in the blue component of the $1.700 \mu\text{m}$ line. The He I absorption component near $2.160 \mu\text{m}$ appears to be double (marked by arrows), with a separation of 99 km s^{-1} ; however, we believe that the lines correspond to two expected He I lines with velocity separation of 83 km s^{-1} near that wavelength. Figure 4 does not appear to show any double absorption lines in the spectrum of LBV 1806–20, presumably because of the relatively low spectral resolution of the data (70 km s^{-1} corresponds roughly to 2 pixels in the low-resolution mode). The absorption feature near $4.04 \mu\text{m}$ is likely due to a blend composed of a He I doublet ($5f^3F^\circ - 4d^3D$ at $4.0377 \mu\text{m}$ and $5f^1F^\circ - 4d^1D$ at $4.0409 \mu\text{m}$). The He I absorption blend near $3.703 \mu\text{m}$ ($5d^3D - 4p^3P^\circ$) has a FWHM of 183 km s^{-1} , compared to a FWHM of 152 km s^{-1} for the nearby P γ line at $3.74 \mu\text{m}$.

The Fe II lines are broad in the spectra of both the Pistol star and LBV 1806–20, but they have multiple peaks in the latter. The 1.688 and $2.089 \mu\text{m}$ lines have nearly identical morphology, each with three peaks in similar intensity ratios and relative positions in the spectrum of LBV 1806–20.

The Gaussian shape of the Fe II lines in the spectrum for the Pistol star is likely caused by recombination closer to the photosphere, where the wind velocity has not reached its constant terminal value. In the spectrum for LBV 1806–20, the

iron likely recombines farther out in the wind so that emission is dominated by gas at the terminal velocity, thus causing the flat-top shape of the emission line. This explanation for the variation in the Fe II line shapes in the two stars suggests that LBV 1806–20 has slightly higher ionizing radiation, consistent with the apparent P Cygni nature of the blue component of the He I lines in the spectrum for that star.

Spectra of both stars have similar morphology in the H lines. However, the presence of deeper absorption features in the observed H lines of LBV 1806–20, as well as their narrower nature, are consistent with underlying absorption H lines from the putative companion.

We estimate the line-of-sight velocity for LBV 1806–20 by comparing the vacuum wavelength of the He I line near $2.1125787 \mu\text{m}$ with its measured positions at 2.1125065 and $2.1130192 \mu\text{m}$, as determined by fitting Gaussian profiles to the two absorption components. We adjust the velocity to the heliocentric frame by adding $+0.2 \text{ km s}^{-1}$ to the measured velocity to compensate for Earth motion at the time of observations. We add $+10 \pm 0.4 \text{ km s}^{-1}$ to this value in order to adjust the velocity to the local standard of rest (LSR) frame (Dehnen & Binney 1998). Assuming a roughly equal mass binary, we average the velocities of the two absorption lines, to find a systemic velocity of $V_{\text{LSR}} = 36.4 \text{ km s}^{-1}$; note that a change in this assumption, to a mass ratio of 1 : 1.5, would only induce a change in our estimate of $\pm 4 \text{ km s}^{-1}$. Our estimate is similar to those that we obtain for three nearby hot stars, for which $V_{\text{ave, LSR}} = 35.0 \pm 5.7 \text{ km s}^{-1}$ (see Fig. 2). These velocities contrast with the value in Eikenberry et al. (2004) of $10 \pm 20 \text{ km s}^{-1}$.

The bulk velocity of the LBV 1806–20 cluster can be interpreted in the context of the Galactic rotation curve in Brand & Blitz (1993) in order to estimate its distance. We find a distance of 4.1 or 11.8 kpc (see Fig. 5). Only the high solution is consistent with a location beyond an NH_3 cloud at a distance of 5.7 kpc (Brand & Blitz 1993). This estimate is considerably less than the estimate in Eikenberry et al. (2004) of $15.1^{+1.8}_{-1.3} \text{ kpc}$.

3.2. Mass of LBV 1806–20

For the far distance estimate ($d \sim 11.8 \text{ kpc}$) and the photometry in Eikenberry et al. (2004), we find $M_K = -9.5 \pm 0.1$. It is difficult to convert this value into a luminosity estimate because the range of temperatures, and therefore the K -band bolometric correction, varies widely for LBVs (Blum et al. 1995). However, if we use the BC_K for the Pistol star from Figer et al. (1998), then we arrive at a luminosity of $10^{6.3} L_\odot$. Using Langer's stellar evolution models in Figer et al. (1998), we find an initial mass $\sim 130 M_\odot$ in the case that the object is a single star.

3.3. LBV 1806–20 as a Massive Binary

We suggest that the object is a massive binary, based on the double lines in its spectrum. For a 1 : 1 mass system, the components have initial masses of $65 M_\odot$, assuming a mass-luminosity relation of $M \propto L^\alpha$, where $\alpha \sim 1$. Our present analysis is fairly insensitive to the mass ratio, a topic that we will revisit in a future study.

By comparison, the initial masses of the components in η Car are 120 and $40 M_\odot$ (Damineli et al. 1997; Pittard & Corcoran 2002). Another massive binary system, WR 20a, contains roughly equal mass components, each having $M \sim 70\text{--}80 M_\odot$ (Rauw et al. 2004; Bonanos et al. 2004).

LBV 1806–20 is similar in appearance to a growing group of objects, i.e., the Pistol star, FMM 362, η Car, and others. Whether these objects are single or multiple, they all presumably have at least one evolved component that is massive ($\geq 50 M_{\odot}$), and some are surrounded by circumstellar material produced by massive eruptions.

3.4. The Formation of the Most Massive Stars

Theoretical arguments suggest that stars with initial masses $\geq 150 M_{\odot}$ have hydrogen-burning (main-sequence) lifetimes of about 2 Myr (Bond et al. 1984) and total lifetimes no more than ~ 3 Myr (Meynet et al. 1994). If LBV 1806–20 is single, and it had an initial mass in this range, then it would necessarily be much younger than nearby Wolf-Rayet (W-R) stars in the same cluster that are at least 3 Myr old (Meynet et al. 1994). Eikenberry et al. (2004) suggest that a supernova from a first generation of stars could have triggered the formation of LBV 1806–20 and perhaps other nearby stars. While this mechanism is often invoked to explain multigeneration star formation, it is not the only explanation in this case. Note that the LBVs in the Quintuplet cluster should not live longer than ~ 3 Myr, whereas the other cluster members are 4 Myr old; however, in this case, the original natal cloud must have been strongly sheared by the tidal field in the Galactic center on timescales much less than 2 Myr. A more general explanation for the age discrepancy in both the Quintuplet and the LBV 1806–20 cluster might be that the most massive stars are binary systems

of less massive stars (which can live longer) or that they were binary systems that recently merged (Figer & Kim 2002).

This proposition also resolves the problem of explaining why $200 M_{\odot}$ stars are observed in the Quintuplet cluster, whereas the upper mass cutoff to the initial mass function in the nearby Arches cluster is $\sim 150 M_{\odot}$ (Figer 2003). In fact, if single stars with masses of $\sim 100 M_{\odot}$ exist, then where are the binary systems with such stars? Certainly, some of the most massive stars exist in binary systems, as evidenced by the substantial binary fraction (25%) in the W-R catalog (van der Hucht 2001). Perhaps we are witnessing the ancestors of such systems in these LBVs.

The evidence in this Letter suggests that LBV 1806–20 may be binary, but we will continue to explore the possibility that the double-lined spectra could have an alternate explanation. For instance, perhaps the profile is a composite of an emission feature, generated by a disk or wind, at the systemic velocity and superposed on a photospheric absorption feature. In addition, we will refine the temperature, luminosity, and mass ratio estimates through a more detailed analysis, coupled with wind/atmosphere models (Najarro et al. 2004). In addition, we have begun a spectroscopic monitoring program to detect changes that might indicate a binary nature for LBV 1806–20.

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