CHARACTERIZATION OF THE MOST LUMINOUS STAR IN M33: A SUPER SYMBIOTIC BINARY

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ABSTRACT

We present the first spectrum of the most luminous infrared star in M33, and use it to demonstrate that the object is almost certainly a binary composed of a massive O star and a dust-enshrouded red hypergiant. This is the most luminous symbiotic binary ever discovered. Its radial velocity is an excellent match to that of the hydrogen gas in the disk of M33, supporting our interpretation that it is a very young and massive binary star.

Key words: binaries: symbiotic – galaxies: individual (M33) – H II regions – stars: evolution – stars: massive

1. INTRODUCTION AND MOTIVATION

The existence of core-collapse supernovae with dust-enshrouded progenitors (Prieto et al. 2008; Thompson et al. 2009) or recent mass-loss episodes (Gal-Yam et al. 2007; Smith et al. 2008) is a strong motivator to survey nearby galaxies for such objects. Understanding these luminous, dusty stars is essential to any theory of mass loss from nearby galaxies for such objects. Understanding these luminous, dusty stars is essential to any theory of mass loss from massive stars, an important and unsolved problem in stellar evolution theory. Surveys and studies of such stars have been reported for the Large and Small Magellanic Clouds (Bonanos et al. 2009, 2010), and M33, NGC 300, M81, and NGC 6946 (Thompson et al. 2009; Khan et al. 2010). The Thompson et al. (2009) and Khan et al. (2010) studies demonstrated that the extremely red (optically thick even at 3.6 μm) progenitors of SN 2008S and a very luminous NGC 300 transient are very rare, with only the order of ~1 existing at any instant in a galaxy. This implies that these objects are extremely short-lived phases in the lives of some massive stars.

Khan et al. (2011) recently identified and studied the most luminous mid-infrared source in M33 (which they called “Object X”). Khan et al. (2011) measured the i-band variability of Object X of up to 0.4 mag on a timescale of 1 year. They deduced that “The correlated short-term variability of 0.4 mag (fractional variability of ~45%) definitively indicates that it is a single stellar object rather than multiple objects blended together” (Khan et al. 2011, page 3). We note that this amplitude of variability does not preclude Object X from being a binary, and we will show this to be the case below.

Using multiple surveys’ photometry from the U band to 24 μm, Khan et al. (2011) considered several models for the star, and suggested that a cool hypergiant star, emitting ~10^5 L_☉, best matched the available data. They also predicted that the star might be emerging from the cocoon of dust in which it is embedded, leading to a future brightening in near-IR and possibly even visible bands. The most challenging observation for the Khan et al. (2011) model is the presence of strong Hα emission in Object X, which is evident in comparisons of narrowband and broadband images of the star from the Local Group Galaxy Survey (LGGS; Massey et al. 2006).

Khan et al. (2011) encouraged further study of this extremely luminous star, motivating us to acquire its optical spectrum. As we describe below, the spectrum suggests that Object X is a massive, luminous binary with characteristics reminiscent of Symbiotic Stars (SySt). In Section 2, we describe the data and their reductions. We demonstrate that Object X must be a binary and characterize the underlying stars in Section 3. A brief summary of our results is found in Section 4.

2. OBSERVATIONS AND DATA REDUCTION

The spectra of Object X were obtained with the Hectospec multi-fiber positioner and spectrograph on the 6.5 m MMT telescope (Fabricant et al. 2005), as described in Caldwell et al. (2009). The Hectospec 270 gpm grating was used and provided spectral coverage from roughly 3700–9200 Å at a resolution of ~5 Å. The observations were carried out on the nights of 2014 September 22 and 23. We used the data reduction methodology described by Caldwell et al. (2009). De-biasing and flat-fielding of each frame were followed by the extraction of spectra and wavelength calibration. “Blank sky” fibers spectra from the same exposure were averaged to enable sky subtraction. The instrument response and flux calibration were enable via the spectra of standard stars taken over the course of our observing run. The accuracy of relative line flux ratios is ensured by the application of careful relative flux correction from the standard stars. The total exposure time was 1800 s.

Archival images of Object X were retrieved from LGGS (Massey et al. 2006, 2007), and from the Canada–France–Hawaii Telescope (CFHT) archives. We repeated on the LGGS images the measurements of Object X that have been done by Khan et al. (2011). Following their method, we used DAOPHOT/ALLSTAR (Stetson et al. 1992) for photometry and bright sources in the LGGS catalog for calibration. In the case of the frame in the Hα filter, the emission from the H α region introduced a nonlinear background near Object X. This background introduced significant non-repeatability of the measured brightness of Object X as we varied the DAOPHOT parameters used in point-spread function (PSF) fitting. To overcome this, we fitted a low-order function to the nearby background in order to remove it. The same procedure was carried out for comparison stars. As a result, we obtained a reasonably good fit of the PSF and a brightness that depended only weakly on the DAOPHOT parameters.

We supplemented the photometry of LGGS images with observations carried out with the CFH12K camera (Cuillandre
et al. 2000) on the CFHT 3.6 m telescope located at the summit of Mauna Kea, HI. The method was identical to that used for the LGGS images. The standard stars were chosen from the bright sources in the LGGS catalog that do not appear in the Hartman et al. (2006) list of variable sources.

New images of Object X were taken with the Tenagra II 32" telescope in Arizona. The telescope is instrumented with a STTe-based CCD camera with a resolution of ~0′′/87 per pixel. Two 300 s observations through the I filter were carried out on 2014 October 29. The data reduction was performed using standard IRAF procedures. In these observations, the TENGRA PSF was highly undersampled, and the relatively low signal-to-noise ratio in the images caused the background close to Object X to be dominated by instrument noise. Because of this, we carried out aperture photometry of Object X and nearby standard stars using DAOPHOT. We used standard stars whose brightnesses we measured in the LGGS image.

The optical magnitude of Object X was also estimated by multiplying the spectrum with the V filter function of Bessell (1990) and adding the constant, which was calculated as the average offset between the convolution of the spectrum with the V filter and the V magnitudes measured on the LGGS frame for several Hα-bright stars observed simultaneously with Object X during our September observing run.

3. DISCUSSION

3.1. Variability

Khan et al. (2011) suggested that Object X may conceivably emerge from its self-obscured state and brighten over the next few decades. We find no sign of this, as evidenced by our recent I-band image (Figure 1). In particular, \( I = 20.4 \pm 0.6 \) for Object X derived from this 2014 image when compared to \( I = 19.99 \pm 0.02 \) reported by Khan et al. (2011) indicates that the source is definitely not brightening.

Similarly, we detected Object X at \( V = 22.88 \pm 0.05 \) in the CFHK12 image taken on 1999 October 30, two years before the LGGS observation, and on two other CFHK12 images at \( V = 22.72 \pm 0.07 \) (2001 February 18) and \( V = 22.70 \pm 0.06 \) (2001 October 15). These magnitudes are in very good agreement with our measurements of \( V = 22.86 \pm 0.10 \) derived from the LGGS image, and \( V = 22.8 \pm 0.2 \) estimated from our spectrum. The difference between our LGGS V magnitude and \( V = 23.15 \pm 0.13 \) measured by Khan et al. (2011) most likely originates in our very careful subtraction of the background, which is highly variable in that region due to the nearby Hα region. We conclude that the optical brightness of the Object X has remained stable at \( V = 22.8 \pm 0.1 \) mag over at least the last 15 years. Similarly, the Hα magnitude measured on the LGGS image, \( m(Hα) = 20.4 \pm 0.2 \), reasonably agrees with the value of about 20.7 estimated from the spectrum (described in the next subsection) using the mean flux in a 50 Å interval centered on Hα. It remains to be seen whether Khan et al. (2011)’s prediction of a significant brightening of Object X will, in fact, occur in the coming decades.

3.2. The Hot Star and the Ionized Region

The optical spectrum of Object X observed in 2014 September and normalized to \( V = 22.8 \) is shown in Figure 2, and the emission line fluxes and other measurements from that spectrum are listed in Table 1.

The outstanding feature of this spectrum is the presence of strong, high ionization potential (IP) emission lines, most notably [OIII] 5007. The inescapable conclusion is that Object X has a hot, luminous component, in addition to the cool, infrared-bright component discussed by Khan et al. (2011).

The forbidden [OIII], [OII], [N II], and [S II] to Balmer emission line ratios are consistent with a photoionized Hα region rather than a shock-excited region (Canto 1981) or diffuse interstellar gas (e.g., Hoopes & Walterbos 2003). The average radial velocity from 14 unblended emission lines listed in Table 1 is \(-113 \pm 5 \) km s\(^{-1}\), and there is no trend in the velocity nor in the line widths with the IP (as expected for an Hα region), which means that the lines do not originate in the hot star wind (which is not surprising given the line widths—the FWHMs correspond to the instrumental value).

The Balmer line ratios, \( Hα:Hβ:Hγ = 6.63:1:0.30 \), are consistent with case B recombination and a reddening \( E_{B-V} = 0.92 \pm 0.02 \), adopting the mean extinction law of Cardelli et al. (1989), and \( R_V = A(V)/E(B-V) = 2.5 \) similar to that in the LMC (Misselt et al. 1999).

Mürset & Nussbaumer (1994) demonstrated that the temperatures \( T_h \) of the hot components in symbiotic binary stars can be estimated from a simple formula, \( T_h[1000 \text{ K}] = \lambda_{\text{max}}[\text{eV}] \), where \( \lambda_{\text{max}} \) is the highest observed IP. The accuracy of their method is about \( \pm 10\% \). The highest ionization stage observed in our object is that of O+2, which suggests a lower limit to the ionization temperature \( T_{h} \) of
Figure 2. (Top) Spectrum of Object X observed in 2014 September. (Bottom) Same spectrum dereddened with $E_{B-V} = 0.92$ (see the text). The green and red lines represent the Kurucz model atmosphere spectra with $T_{\text{eff}} = 35,000$ K and $45,000$ K, respectively.

Table 1. Emission Line Fluxes of Object X in M33

| $\lambda_{\text{obs}}$ | ID    | 100 $F(\lambda)/F(\text{H}/\beta)$ |
|------------------------|-------|-------------------------------------|
| 3726.9                 | [O]   | 3728$^b$                           |
| 4338.9                 | H$_1$ |                                     |
| 4859.5                 | H$_{\beta}$ |                                  |
| 4956.7                 | [O]   | 4958.9                              |
| 5004.8                 | [O]   | 5006.8                              |
| 5873.1                 | He I  | 5875.7                              |
| 6546.0                 | [N]   | 6548.1                              |
| 6560.2                 | H$_{\alpha}$ |                                 |
| 6580.8                 | [N]   | 6583.5                              |
| 6672.8                 | He I  | 6678.2                              |
| 6714.0                 | [S]   | 6716.4                              |
| 6728.1                 | [S]   | 6730.8                              |
| 7062.0                 | He I  | 7065.2                              |
| 7134.0                 | [Ar III]| 7135.8                            |
| 7316.9                 | [O]   | 7320$^c$                            |
| 7327.1                 | [O]   | 7330$^c$                            |
| 9065.8                 | [S]   | 9068.6                              |

| $\log F(\text{H}/\beta)^a$ | $v_\parallel$ |
|----------------------------|---------------|
| $-16.25$                   | $-113 \pm 5$ km s$^{-1}$ |

$^a$ In units of erg s$^{-1}$cm$^{-2}$.

$^b$ Blend of two components.

$^c$ Blend of three components.

35,000 K. Kaler (1978) found that in low-excitation optically thick nebulae the [OII]/H$\beta$ intensity ratio correlates well enough with the temperature of the hot ionizing star, $T_h$, to be used alone as a good indicator of the calculated blackbody temperature. In particular, for nebulae for which the [OII] 4686 line is weak or absent, and for which $T_h$ is no more than about 68,000 K, $\log T_h = 4.426 + 4.827 \times 10^{-4} F(5007/H/\beta) - 1.374 \times 10^{-7} F^2(5007/H/\beta)$. The relative emission line flux for our object, $F(5007/H/\beta) = 0.18$ requires a blackbody temperature of the ionizing source of $45,000$ K, which provides an upper limit for $T_h$.

On the other hand, the presence of H$\alpha$ emission lines indicates the presence of a star of spectral type O7 or hotter spectrum. Assuming that case B recombination applies for both the Balmer and H$\alpha$ emission lines, the dereddened $F(\text{H}/\alpha) = 0.18$ requires a blackbody temperature of the ionizing source of $45,000$ K, which provides an upper limit for $T_h$.

In Figure 2, we also show the spectrum dereddened with $E_{B-V} = 0.92$. Superposed on this dereddened spectrum are Kurucz (1979) model atmosphere spectra with $T_{\text{eff}} = 35,000$ K and $45,000$ K, respectively, and scaled to $V = 22.8$. This clearly demonstrates that the optical continuum is dominated by the hot O/B star with the reddening practically identical to that derived from the Balmer decrement. We thus conclude that this hot star is responsible for the ionization of the H$\alpha$ region coinciding with Object X.

Our average $V = 22.8$, $A_V = 2.3$ combined with the true distance modulus $m-M = 24.62$ (Gieren et al. 2013) results in the absolute magnitude of the hot star $M_V = -4.2 \pm 0.5$ (where the error includes the uncertainties in the reddening, $V$ mag, and distance estimates). Adopting the bolometric correction, $BC \sim -3.4 \sim -4.1$ (Kurucz 1979), corresponding to the $T_h$ range indicated by the emission line fluxes, the bolometric magnitude of the hot star is then $M_{\text{bol}} \sim -7.6 \sim -8.3$. The number of photons capable of ionizing hydrogen, emitted by such a star, is sufficient to account for the observed intensities of the Balmer lines.

3.3. The Evolutionary State of the Binary Components of Object X

The hot star luminosity ($\log L \sim 4.9 \pm 5.2$) and effective temperature ($\log T_h \sim 4.51 \pm 4.65$) suggest that it is still on or close to the zero age main sequence. The evolutionary tracks and isochrones for massive stars (e.g., Brott et al. 2011) suggest that the hot star mass is about 20–30 $M_\odot$, and that its age is at most 2–3 Myr. Khan et al. (2011) demonstrated that the infrared SED of Object X can be interpreted in terms of a dust-obscured, massive, $\geq 30 M_\odot$, evolved star, presumably a yellow/red hypergiant. Their finding is consistent with our result since the more evolved component should be also the more massive one.

The average radial velocity of Object X derived from emission lines, $v_\parallel = -113$ km s$^{-1}$, is redshifted with respect to the mean radial velocity of M33. It is also in excellent agreement with the mean velocity of hydrogen gas at the galactic position of Object X, viz. $-105 \pm -112$ km s$^{-1}$ (Rogstad et al. 1976). This means that this velocity shift is due to the galactic rotation, and the system lies close to the galactic disk plane. The maximum reddening internal to M33 is of $E_{B-V} \sim 1.2$ mag (Khan et al. 2011). Thus, the reddening of $E_{B-V} = 0.92$ we estimated for Object X is likely of interstellar origin.
3.4. Object X and D-type SySt

The binary nature of Object X is not surprising given that the binarity and multiplicity fraction in high-mass stars seems to be of the order of 100% (e.g., Mason et al. 2009). What is particularly interesting in the case of Object X is the simultaneous presence of a hot luminous star and the very luminous and presumably evolved component embedded in an optically thick dust shell. Such a binary configuration is reminiscent in some ways of the well known D-type SySt.

Symbiotic binary stars are cool, evolved giants paired with a luminous, hot companion. That companion is often, but not always, a white dwarf star. The ionized, dense nebula that surrounds the binary system emanates from the red giant. Two subclasses of SySt arise from the different kinds of red giants in these binaries. S-type (for “stellar”) SySts cool stars are ordinary red giants. The orbital periods of S-type SySt are typically a few years (Mikołajewska 2012). D-type (for “dusty”) SySts’ cool stars are Mira variables embedded in warm dust (Whitelock 1987); their orbital periods are decades or longer (e.g., Gromadzki & Mikołajewska 2009).

The hot star seems to be located outside the dust shell in both D-type SySt and Object X. In Object X, the reddening toward the emission line region and the hot star is presumably due to foreground reddening in M33. Similarly, in D-type SySt, the reddening toward the Mira component is usually much higher than toward the nebula and the hot continuum (e.g., Mikołajewska et al. 1999). According to Khan et al. (2011), the outer radius of the Object X dust shell is of order of $5 \times 10^{16}$ cm (their cool star model). Adopting this as a minimum binary separation, the binary period must be $\geq 30,000$ years, with a total binary mass of $\geq 50 M_{\odot}$. There is, however, no evidence for any binary interaction in Object X (though even if there is accretion in the binary it will contribute little to the observed luminosity). There is also no significant density gradient in Object X. In particular, the density sensitive ratio of [Sii] 6716/6731 $= 1.3$ indicates $n_e \approx 100$ cm$^{-3}$, which is typical for an HII region but 1–2 orders of magnitude lower than the densities in the outermost regions of D-type SySt nebulae. There are also no detectable [OIII], [SIII], and [NII] auroral lines or any other signatures of higher, $n_e \sim 10^5$–$10^6$ cm$^{-3}$, density regions in Object X. Such high-density regions are observed in D-type SySt, which also show a relationship between nebular density and temperature, and IP; both $n_e$ and $T_e$ increase with IP (e.g., Schmid & Schild 1990).

Both Object X and D-type SySt during a high dust-obscuration phase show very similar near- to mid-IR colors, presumably because of similar dust temperatures. In particular, Gromadzki et al. (2009) demonstrated that the dust-obscured, O-rich symbiotic Miras are located along the line representing a simple model of a cool star (with $T_{\text{eff}} = 2750$) inside a warm ($\sim 800$ K) dust shell of variable optical thickness. Object X does not show any signatures of a cool star (like, e.g., molecular absorption bands); however, its near-IR colors locate it on this model line somewhat above the most obscured SySt, with $A_V \sim 15$. Even a very luminous star, with such a high optical extinction, would not be detectable in the range covered by our spectroscopic observation. Similarly, there is no evidence for the Mira component in optical/red spectra of dust-obscured SySt.

The most remarkable property of Object X remains its total luminosity, viz. absolute magnitude $M_K = -11.2$. That of the most luminous D-type SySt, like, e.g., RX Pup, is 10 times fainter, at $M_K = -8.7$ (Mikołajewska et al. 1999). We conclude that Object X is the most luminous SySt yet discovered.

Finally, the binary composition of Object X, a cool supergiant with an O/B star companion, bears some resemblance to the VV Cep-type stars, a small class of massive binaries. VV Cep stars are composed of a bright red supergiant and an early B main-sequence star and display emission lines of H\alpha and [Fe ii], and occasionally also [Fe iii] and [O iii] (e.g., Cowley 1969). Although VV Cep stars do not show any evidence for the presence of dust shells, one can imagine that if their M-type supergiant component were to be enshrouded in such a thick dust cloud, they would appear very similar to Object X.

4. CONCLUSIONS

We presented and discussed the first optical spectrum of the most luminous infrared star in M33. The main conclusions are as follows.

1. The star is clearly composite, with a hot, luminous O/B star component and a cool, dust-enshrouded companion.
2. The hot star’s temperature lies in the range 35,000 $\lesssim T_{\text{bol}} \lesssim$ 45,000 K and its luminosity is $M_{\text{bol}} = -7.6$ to $-8.3$.
3. The emission line spectrum and total system $M_K = -11.2$ establishes Object X as the most luminous symbiotic binary detected to date.
4. The radial velocity of Object X is an excellent match to that of the hydrogen gas in the disk of M33, supporting our interpretation of Object X as a very young and massive binary star.

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