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A DARK ENERGY CAMERA SEARCH FOR MISSING SUPERGIANTS IN THE LMC AFTER THE ADVANCED LIGO GRAVITATIONAL-WAVE EVENT GW150914

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ABSTRACT

The collapse of a stellar core is expected to produce gravitational waves (GWs), neutrinos, and in most cases a luminous supernova. Sometimes, however, the optical event could be significantly less luminous than a supernova and a direct collapse to a black hole, where the star just disappears, is possible. The GW event GW150914 was detected by the LIGO Virgo Collaboration via a burst analysis that gave localization contours enclosing the Large Magellanic Cloud (LMC). Shortly thereafter, we used DECam to observe 102 $\deg^2$ of the localization area, including 38 $\deg^2$ on the LMC for a missing supergiant search. We construct a complete catalog of LMC luminous red supergiants, the best candidates to undergo invisible core collapse, and collected catalogs of other candidates: less luminous red supergiants, yellow supergiants, blue supergiants, luminous blue variable stars, and Wolf–Rayet stars. Of the objects in the imaging region, all are recovered in the images. The timescale for stellar disappearance is set by the free-fall time, which is a function of the stellar radius. Our observations at 4 and 13 days after the event result in a search sensitive to objects of up to about 200 solar radii. We conclude that it is unlikely that GW150914 was caused by the core collapse of a relatively compact supergiant in the LMC, consistent with the LIGO Collaboration analyses of the gravitational waveform as best interpreted as a high mass binary black hole merger. We discuss how to generalize this search for future very nearby core-collapse candidates.

Key words: galaxies: individual (LMC) – gravitational waves – Magellanic Clouds – supergiants – supernovae: general

1. INTRODUCTION

On 2015 September 14 the Advanced LIGO interferometer network detected a high significance candidate gravitational-wave (GW) event (designated GW150914; Abbott et al. 2016b), and two days later the LIGO Virgo Collaboration (LVC) provided spatial localization probability sky maps (LIGO Virgo Collaboration 2015a). The analysis that produced the trigger was sensitive to bursts, suggested a high source mass, and yielded localization contours that enclosed the Large Magellanic Cloud (LMC) at high confidence. Burst-like GW signals could originate from the core collapse of massive stars, such as in a supernova (SN). There is evidence that ∼20% of core-collapse events fail to produce a luminous supernova; see, for example, Kochanek (2015).

Motivated thus, in 2015 September we obtained observations of the LMC with DECam and pursued a search for a potential failed SN through the disappearance of a massive star. The analysis of GW150914 in Abbott et al. (2016b) makes it clear that this GW source did not originate from the death of a massive star in the LMC. Our analysis, however, provides an important template for the follow-up of future burst-like GW events coincident with very nearby galaxies.

2. LIGO EVENT GW150914

On 2015 September 14 at 09:50:45 UT the Advanced LIGO interferometers at Hanford and Livingston recorded burst candidate event GW150914 during Engineering Run 8. This event was triggered by the coherent WaveBurst (cWB) unmodeled burst analysis during real-time data processing. On 2015 September 16, the LVC provided an all-sky localization probability map for the event (LIGO Virgo Collaboration 2015a; Abbott et al. 2016a; see also Aasi et al. 2014) generated from the cWB online trigger. This analysis makes minimal assumptions about signal shape by searching for coherent power across the LIGO network (Klimenko et al. 2008). Nearby stellar core collapses can cause significant signals in the cWB analysis (Fryer & New 2011; Gossan et al. 2016). The cWB map provided spatial localizations of 50% and 90% confidence regions encompassing about 100 and 310 $\deg^2$, respectively. The area enclosing 50% of the total probability of the cWB map passed through the center of the LMC, a 0.2 $L^{\star}$ galaxy at a distance of 50 kpc (Walker 2012; de Grijs et al. 2014); see the dotted lines in Figure 1. The high probability ridge line passed over 30 Doradus and the proto-globular cluster R136.

We recently began an observational program using the wide-field Dark Energy Camera (DECam; Flaugher et al. 2015) on the Blanco 4 m telescope at Cerro Tololo Inter-American Observatory to search for optical counterparts to GW triggers. Our wide-field search for counterparts to GW150914 is described in the companion paper Soares-Santos et al. (2016); an overview of the program is in DES Collaboration et al. (2016). We additionally designed a specific set of observations to search for failed SNe in the LMC, using 5 s i- and z-band observations covering 38 $\deg^2$ centered on the LMC on 2015 September 18 and 27, in seeing of $1\farcs1$–$1\farcs3$.

On 2015 October 3, the LVC revised its analysis: the data were most consistent with a binary black hole merger (LIGO Virgo Collaboration 2015b). On 2016 January 13, the LVC provided new sky maps, the most accurate and authoritative of which was the LALInference analysis using a binary black hole template (LIGO Virgo Collaboration 2016). The new contour enclosing 50% of the total probability shifted southward of the LMC, although the LMC is still inside the 90% contour.

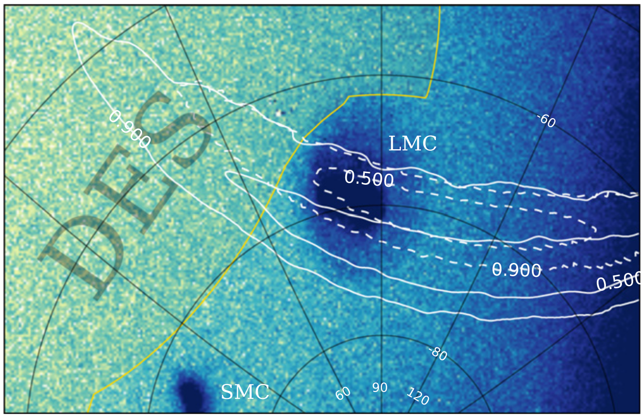

Figure 1. A map of the logarithm of 2MASS J-band star counts around the LMC with the LIGO localization contours shown in white. The contour labels indicate the fraction of the LIGO localization probability enclosed. The dotted contours are for the initial (2015 September) `skyprobcc_cWB_complete` map, while the solid contours are for the final (2016 January) `LALInference_skymap`. There is an island of significant probability in the northern hemisphere in the `skyprobcc_cWB_complete` not present in the `LALInference_skymap`, so the dotted contours do not show the complete 50% or 90% areas. The data are shown on an equal-area McBryde-Thomas flat-polar quartic projection, as is Figure 3.

3. CORE-COLLAPSE SIGNATURES

A normal core-collapse SN in the LMC is a remarkably obvious event—SN1987A was found by eye as a new 5th magnitude object 24 hr after the core collapse, and its neutrino emission provided the first detection of extragalactic neutrinos by Kamiokande and IMB (Bionta et al. 1987; Hirata et al. 1987).

However, it has been argued that up to ~20% of core-collapse SNe are not optically luminous (Kochanek et al. 2008), and there is recent evidence that luminous supergiants specifically are prone to be failed SNe. Two candidates are currently known: the Large Binocular Telescope survey (Gerke et al. 2015) found a 18–25 $M_\odot$ star missing, and a *Hubble Space Telescope* archival survey (Reynolds et al. 2015) found a 25–30 $M_\odot$ star missing. These objects are sufficiently nearby that an SN associated with the event would have been detected by local galaxy SN surveys. In addition, the population of known progenitors to SNe IIP lacks red supergiants above $\gtrsim 17\ M_\odot$ (Smartt et al. 2009), suggesting that that more massive red supergiants end in a failed SN. This line of argument reproduces the current black hole mass function (Kochanek 2015); similarly, the purely theoretical study of core collapses by Sukhbold et al. (2016) reproduces both the neutron star and black hole mass functions. Pre-collapse, red supergiants are very luminous: Smartt (2015) shows that the missing SN progenitors have $\gtrsim 10^{5.1}\ L_\odot$.

4. OPTICAL SIGNATURES OF A FAILED SUPERNOVA

There are three viable signatures for a failed supernova: (1) the star might simply collapse to a black hole; (2) the unbound outer atmosphere of the star may expand and cool, gaining in luminosity as it expands; and (3) there might be a shock from the creation of the neutrinosphere that propagates through the atmosphere to the outer layer, causing a shock breakout flash. We will briefly discuss these potential signatures, and present in Table 1 their magnitudes and colors in filters relevant to the LMC supergiant search described in the next section and to the template preparation program described in the conclusions.

The first signature presents a disappearance experiment: one simply searches for missing stars. In the case of prompt black hole formation, the star's internal pressure support is removed and the stellar photosphere falls into the black hole event horizon in a free-fall time, $t \approx \sqrt{R^3/GM}$. For the Sun this is 1600 s, for the bare helium core of a Wolf–Rayet (WR) star this is 500 s, and for the very tenuously bound outer atmosphere of a $25 M_\odot$ star this is 70 days. What size of star one probes depends on how long past the event the images are obtained:

$$\frac{R}{39 R_\odot} = \left(\frac{M}{20 M_\odot}\right)^{1/3} \left(\frac{t}{\text{days}}\right)^{2/3}. \tag{1}$$

The second signature was noted by Nadezhin (1980): the hydrogen atmospheres of supergiants are so marginally bound to the star that the creation and free streaming of the neutrinosphere during core collapse may remove enough mass to unbind the atmosphere. If the shock from the neutrinosphere creation is energetic enough, it will cause the unbound atmosphere to expand, necessarily cooling and gaining in luminosity as it expands. Lovegrove & Woosley (2013) simulated this process and found that the transient is long, cool, and more likely in their 15 $M_\odot$ models than their 25 $M_\odot$ models. The Nadezhin brightening lasts hundreds of days, with a lower bound in luminosity of the pre-collapse luminosity of the star, but possibly rising to $L \sim 10^{5.5}$–$10^{6.5}\ L_\odot$, presumably with an effective temperature starting close to the pre-collapse star and cooling thereafter. At the distance of the LMC, this luminosity corresponds to $i \sim$ 6.7–9.3. These objects would look much like the supergiant has brightened by a couple of magnitudes.

The third signature is produced by a shock breakout and is studied in Piro (2013), who found that it would present a short, hot transient (~week, 10^4 K, $10^{6.5}$–$10^{7.5}\ L_\odot$). At the distance of the LMC, this would be remarkably bright, $i \approx$ 5.1–7.6, rivaling a standard core-collapse supernova. The existence of a shock breakout depends on sufficient energy in the shock; whether this occurs is unclear.

5. LMC RED SUPERGIANTS

Our search focuses on high-luminosity red supergiants in the LMC; we will consider other candidate failed supernova progenitors in the next section. The two best studies of large numbers of LMC supergiants are by Neugent et al. (2012) and González-Fernández et al. (2015). Both combine 2MASS point-source data (Skrutskie et al. 2006) with astrometric catalogs (UCAC-3 or USNO-B1; Monet et al. 2003), using proper motions to reject Milky Way (MW) stars and then using infrared colors and K magnitudes to select the supergiants. Both studies performed spectroscopy for their final identifications.[57]

These studies did not cover the entire LMC: Neugent et al. (2012) covered ~22 deg^2 (~60% of the LMC) while González-Fernández et al. (2015) covered a ~3 deg^2 field at the densest part of the LMC. The latter analysis recovered about three times as many red supergiants as the former analysis where they overlap. Both studies are also likely incomplete in regions of very high stellar density.

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[57] We will drop the proper subscript s from the 2MASS filter notation K_s throughout this paper for notational simplicity.

Table 1
Predicted Optical Signatures of a Failed Supernova in the LMC

	i	$(g - i)$	K	$(J - K)$	Timescale
Supergiants	8.0–11.5	1.5–2.3	6.0–8.0	0.9–1.4	$\gg$1 year
Disappearance	…	…	…	…	1–100 days
Nadezhin[a]	~6.7–9.3	$\gtrsim$1.5	~4.6–7.1	$\gtrsim$0.9	~1 year
Shock breakout[b]	~5.1–7.6	~0.2	~4.6–7.1	~0.07	~1 week

Notes.
[a] Assuming a supergiant-like spectrum.
[b] Assuming a blackbody spectrum.

5.1. *Constructing an LMC Red Supergiant Catalog*

We construct a catalog of luminous red supergiants in the LMC following a similar analysis to that of González-Fernández et al. (2015). We begin with the 2MASS point-source catalog within 3°.5 from $\alpha, \delta = 79.5, -68.8$ and apply the following selection criteria:

1. $K \leqslant 9$ mag, $(J - K) > 0.9$ mag;
2. the pseudo-color cut of $0.1 \geqslant q \geqslant 0.4$, where $q \equiv (J - H) - 1.8(H - K)$;
3. $10^5 L_\odot < L < 10^6 L_\odot$; and
4. reject stars that have proper motions of $\sqrt{\mu_{\rm ra}^2 + \mu_{\rm dec}^2} > 6$ mas yr^{-1} with $\sqrt{\mu_{\rm ra}^2 + \mu_{\rm dec}^2} > 3\sqrt{\sigma_{\rm ra}^2 + \sigma_{\rm dec}^2}$ in the NOMAD catalog (Zacharias et al. 2004).

The bolometric luminosity cut calculation follows Neugent et al. (2012), namely, the $(J - K)$ color is used to estimate the effective temperature, and the effective temperature is in turn used to calculate the bolometric correction.

This process yields 152 red supergiant candidates. This is smaller than the number of supergiants in either the catalogs of Neugent et al. (2012) or González-Fernández et al. (2015) as these studies go to much lower luminosities than we are concerned with here. This is evident from Figure 2. The highest-luminosity candidates are likely all MW stars; the Neugent et al. data show that 90% of their candidates at $K < 7$ were MW stars. As we aim for completeness, we find this acceptable. In Figure 3, the candidate supergiants are shown overlaid on a stellar density map of the LMC.

6. OTHER FAILED SUPERNOVA PROGENITORS

The red supergiant catalog has the advantage of being well defined and motivated by observational evidence, but it does have uncertainties. These include the calculation of the $10^5 L_\odot$ limit and model uncertainties when mapping the mass to luminosity.

There are more profound uncertainties in the theory. The current theoretical models of core-collapsing stars either have islands of core collapse to black holes at ~$20 M_\odot$ and ~$40 M_\odot$ (O'Connor & Ott 2011; Pejcha & Thompson 2015) or have most stars above ~$20 M_\odot$ core collapsing to black holes (Sukhbold et al. 2016), though examples of core collapse to black holes occur throughout the range $15 M_\odot$–$120 M_\odot$ in the latter study.[58] The lack of explosion depends on many parameters, notably metallicity (Pejcha & Thompson 2015), as the LMC averages half solar metallicity. In theory, a direct

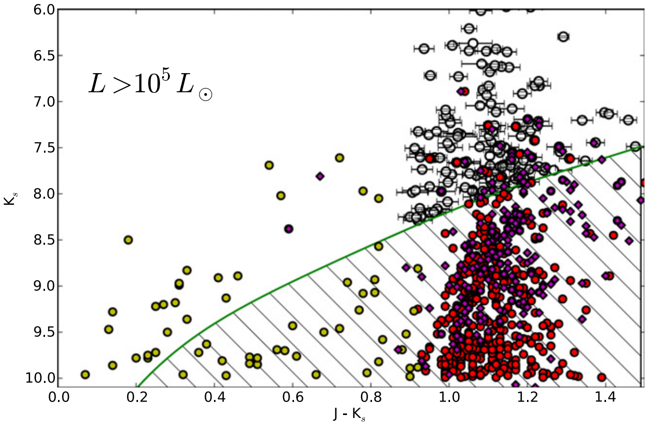

Figure 2. 2MASS $J - K$ vs. K diagram for the Neugent et al. (2012) yellow supergiants (yellow circles) and red supergiants (red circles), González-Fernández et al. (2015) red supergiants (purple diamonds), and the 152 supergiant candidates found here (white circles). For our candidates, the uncertainties in both $(J - K)$ and K are plotted; for K they are smaller than the symbols. The line shows the dividing line for $10^5 L_\odot$.

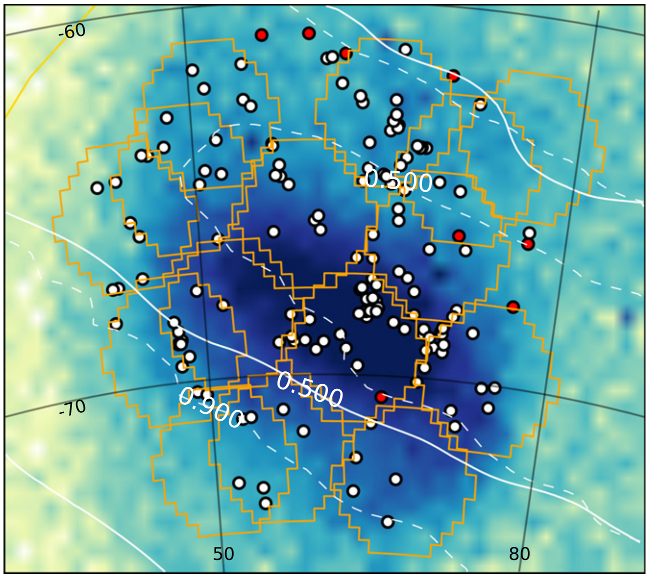

Figure 3. Map of the logarithm of 2MASS J-band star counts around the LMC with the LIGO localization contours shown in white. The DECam i-band images are shown as orange camera outlines; some of the z-band images are offset from these. The white points are the luminous red supergiant catalog developed in this Letter, with those marked red not having a visual inspection. Eight are outside our imaging area. The four remaining fell into chip gaps and/or on bad CCDs.

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[58] Throughout this Letter, masses quoted are zero-age main-sequence masses.

collapse to black holes may occur in many observational classes of massive stars: yellow supergiants, blue supergiants (BSGs), luminous blue variable stars (LBVs), WR stars, sgB[e], and more (see, e.g., Kashiyama & Quataert 2015). Fortunately, these classes of stars have been extensively studied in the LMC.

7. THE SEARCH FOR MISSING LMC SUPERGIANTS IN THE DECam DATA

The area covered in our DECam LMC campaign is shown in Figure 3. The DECam images were analyzed with the DES first cut reductions (Sevilla et al. 2011; Desai et al. 2012; Mohr et al. 2012; R. Gruendl et al. 2016, in preparation), which include producing astrometrically calibrated reduced images. We visually inspected the locations of the red supergiants in our catalog. The supergiants were mostly saturated in the images, so we could not investigate the brightening discussed in the previous section. Our imaging and subsequent visual inspection covered 144 supergiants, 95% of the original catalog, and all of these stars were recovered.

The catalogs of other possible failed SN progenitors are present in the literature. We can check for the disappearance of less luminous red supergiants and yellow supergiants using the catalog of Neugent et al. (2012): 813 of 846 (96%) are in the imaged area and all of these are present in the images. We can check for the disappearance of WR stars using the catalog of Hainich et al. (2014), extensive but known not to be complete (Massey et al. 2015): 105 of 108 (97%) are in our imaged area, and we can confirm that 102 (97%) are present. The three that we cannot confirm are in the very compact cluster R136 and are unresolved in our data. We can check for the disappearance of LBVs using the stars from Smith & Tombleson (2015), which are all the confirmed, not highly reddened, LBVs in the LMC: we recover 16 of 16 (100%) in the DECam imaging. We can check for the disappearance of BSGs, using the catalog in Bonanos et al. (2009); we recover 299 of 299 (100%) of the objects of spectral type O or B and luminosity class I in that catalog in our imaging area. As these catalogs are incomplete (and the coordinates often uncertain), it is difficult to state how confident we are that these kinds of progenitors did not undergo a failed SN in the LMV at the time of GW150914, but given the uncertainty in theoretical predictions for which observational classes of stars undergo a failed SN, a reasonable compromise is to check the known catalogs of potential progenitors.

The physical infall time sets limits on the size of stars that would have visibly diminished in our search. Our observations were at $t = 4$ and 13 days, corresponding to $R < 100 R_\odot$ and $R < 200 R_\odot$. These are larger than the typical radii of WR or BSG stars, but less than that of RSG (see, e.g., Taddia et al. 2016). Observations obtained at $t = 100$, 300 days would have placed limits on stars of radii for RSG, 500–1700$R_\odot$, but the program ceased after the LIGO provided the BBH merger interpretation and shifted the localization contours out of the LMC.

8. DISCUSSION AND CONCLUSIONS

GW150914 was first detected by a LIGO analysis sensitive to a burst of GW and the high probability localization contours enclosed the LMC. Burst-like GW signals could originate from the core collapse of massive stars, perhaps ~20% of which fail to explode as luminous SNe. This motivated us to search for a failed SN in the LMC. We constructed a catalog of 152 high-luminosity LMC supergiants, of which 144 were observed in our DECam imaging; all of these stars are still present after the LIGO event. As the outer envelopes take time to free fall into the event horizon, and our search only obtained early time images, the search is sensitive to $R < 100$–$200 R_\odot$ supergiants disappearing. From our observations, it is unlikely that GW150914 originated from a failed SN in the LMC for a relatively compact supergiant progenitor.The subsequent publication of the GW150914 analysis shows that the GW event is consistent with a merging massive binary black hole model at $z \approx 0.09$ (Abbott et al. 2016b).

The spatial uncertainty present in GW150914 will be a feature of all non-electromagnetic core-collapse triggers. Most models of a core collapse include the formation of a neutrinosphere (see Scholberg 2012 and references therein). Even three decades ago the LMC core collapse that produced SN1987A was detected by two neutrino detectors, Kamiokande and IMB (Bionta et al. 1987; Hirata et al. 1987). Today there are seven neutrino detectors contributing to the SNEWS supernova early warning system (Vigorito & SNEWS Working Group 2011), and the Super-Kamiokande neutrino detector and the IceCube neutrino telescope should detect an LMC core-collapse unassisted (Ikeda et al. 2007; Abbasi et al. 2011). Notably for this Letter, the MeV neutrino burst mode of IceCube did not trigger for ±500 s around the time of GW150914 (Adrián-Martínez et al. 2016), which it would have for a core collapse in the LMC. The spatial localization of the neutrino detectors is several degrees (Adams et al. 2013)—that would be good enough to say the event likely occurred in the LMC, but not where in the LMC it is located.

The use of the luminous red supergiant catalog makes it possible to perform a specific search without prior template imaging, and therefore without difference imaging. A sensible generalization of this technique is to perform very shallow *g*- and *i*-band imaging of very nearby galaxies to prepare template images for difference imaging; *g*-band was added to catch the very blue signature of a breakout shock. Difference imaging in the crowded regions of the LMC will likely be challenging, but would extend the discovery space to other possible low-luminosity core-collapse progenitors, of which there are many. The intervals between local group core collapses are measured in decades, and we should be prepared to learn as much as possible when they do occur.

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