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A SURVEY ABOUT NOTHING: MONITORING A MILLION SUPERGIANTS FOR FAILED SUPERNOVAE

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ABSTRACT

Extragalactic transient searches have historically been limited to looking for the *appearance* of new sources such as supernovae. It is now possible to carry out a new kind of survey that will do the opposite, that is, search for the *disappearance* of massive stars. This will entail the systematic observation of galaxies within a distance of 10 Mpc in order to watch $\sim 10^6$ supergiants. Reaching this critical number ensures that *something* will occur yearly, since these massive stars must end their lives with a core collapse within $\sim 10^6$ yr. Using deep imaging and image subtraction, it is possible to determine the fates of these stars, whether they end with a bang (supernova) or a whimper (fall out of sight). Such a survey would place completely new limits on the total rate of all core collapses, which is critical for determining the validity of supernova models. It would also determine the properties of supernova progenitors, better characterize poorly understood optical transients (such as η Carina-like mass ejections), find and characterize large numbers of Cepheids, luminous blue variables, and eclipsing binaries, and allow the discovery of any new phenomena that inhabit this relatively unexplored parameter space.

Subject headings: stars: evolution — supernovae: general — surveys

Online material: color figures

1. INTRODUCTION

In general, it is easier to notice a phenomenon by its presence rather than absence. But absence can be the crucial clue, as in the case of the dog that did not bark in the night (Doyle 1892). This is also true in astronomy. For example, while the brightness of supernovae (SNe) enabled their study by naked-eye astronomers, it has only recently been possible to detect the progenitors of such events; although to date almost all were found through serendipity rather than careful planning. With modern 8 m class telescopes, wide field cameras, and image subtraction, it is now possible to conduct a comprehensive survey of massive stars and determine all causes of death. While most will probably die as a bright, core-collapse SN, it is likely that some fraction do not follow this route, producing either an exceedingly dim SN or else completely "fail" and collapse directly to a black hole (BH) with no optical fireworks at all. Little is currently known about the optical signatures of BH formation, even though we believe it is the typical end of the most massive stars ($M \gtrsim 25\ M_\odot$) and could be a common end at lower masses ($8 \lesssim M \lesssim 25\ M_\odot$), given the theoretical challenges to producing successful SN explosions.

Consider a survey that will watch enough supergiants before they suffer a core collapse to make a quantitative study of their final states. Since the remaining lifetime of a star that has reached this phase is $\sim 10^6$ yr, this requires observing at least $\sim 10^6$ supergiants to expect an appreciable number of events over the duration of the survey. Equivalently, one must survey enough galaxies to observe ~ 1 SN yr^{-1}. This number can be attained by monitoring only $\simeq 30$ galaxies within 10 Mpc, as we explain below. While this is a challenging observational project, in the long run there is far more physical information in determining the fates of individual stars of various types than there is in inferring their fates based on the mean properties of their host galaxies. Even modest observing efforts over the next 5 years could either find examples of failed SNe or limit their rates to be significantly below those of normal SNe, with important consequences for both SN physics and efforts to detect gravitational waves.

Importantly, a survey designed to detect disappearance will necessarily also be excellent for appearance studies with guaranteed results on known phenomena such as normal SNe, heavily obscured SNe, η Carina-like outbursts, eclipsing binaries, novae, luminous blue variables (LBVs) and Cepheid variables. These are in turn important for the late phases of massive star evolution, formation rates of binaries with compact objects, total SN rates, and the local distance scale (binaries and Cepheids). Beyond these certainties, new classes of events surely await discovery.

2. AUTOPSIES OF MASSIVE STARS

Searches for SN explosions have exploded (as it were) in the past decade, both locally and at cosmological distances (e.g., Evans 1997; Li et al. 2000; Riess et al. 2004; Astier et al. 2006; Miknaitis et al. 2007; Frieman et al. 2008). Finding SNe is relatively easy because of their enormous peak brightness. Identification of SN progenitors has lagged, because there are few SN host galaxies that, by coincidence, had the required very deep pre-SN images. The existing samples of progenitors (e.g., Smartt et al. 2004; Li et al. 2007) are dominated by red supergiants with estimated initial masses in the expected range ($8\ M_\odot \lesssim M \lesssim 25\ M_\odot$), with at least hints of a dearth of more massive progenitors (see Figs. 1 and 2). We quantify this by comparing the integral distribution of progenitor masses from Li et al. (2007) with the distribution from a Salpeter initial mass function (IMF) for $8\ M_\odot < M < 150\ M_\odot$. We neglect 2000ew (which is simply called low mass) and 2000ds (whose mass limit of $<7\ M_\odot$ is below our $8\ M_\odot$ cutoff); including them would only strengthen the argument that follows. We divided the remaining progenitors into three groups: nine systems with mass estimates, five (2005gl, 2004dj, 1999gi 2001du, and 2004gt) with possible masses, and four (1999em, 1999an, 1999br, and 2001B) with only upper limits on the progenitor mass.

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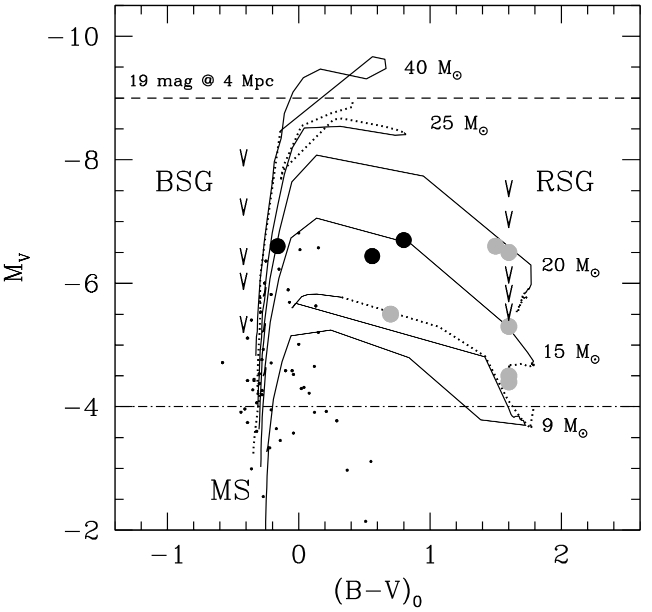

FIG. 1.—Color-magnitude diagram showing evolutionary tracks (Lejeune & Schaerer 2001) for various masses of progenitors at solar metallicity, with the star's last 5×10^5 yr as a dotted line. The labels approximately mark the locations of the main sequence, blue supergiants and red supergiants. The black circles are progenitors in preexplosion images (1987A the bluest, 2004et and 1993J in the yellow range) with measured $B - V$ colors, the gray circles are progenitors without measured $B - V$ colors, and the arrows are upper limits. The points are Wolf-Rayet stars in the Magellanic Clouds (Massey 2002). The horizontal dashed lines mark the typical depth of a SN survey and the depth required for a survey for failed SNe. For the gray points we estimated the $B - V$ color from either the I-magnitude or the measured $V - I$ color assuming the progenitors were K5 supergiants. For the upper limits we used the color of a K5 supergiant for the SN Type II and a fixed blue color for the SN Type Ib/c. The SN progenitors are taken from the tabulation in Li et al. (2007) and references therein.

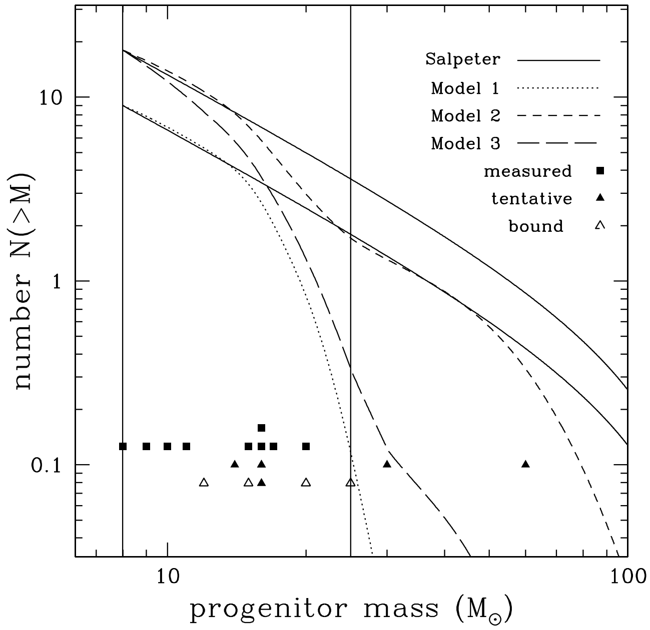

FIG. 2.—Integral progenitor mass distributions $N(>M)$. The filled squares, filled triangles, and open triangles show the well-estimated progenitor masses, possible masses, and upper bounds on the mass from Li et al. (2007), respectively. We consider three models for $N(>M)$ as described in the text. Model 1 is based on only the nine measured progenitor masses. Models 2 and 3 include all 18 estimates and treat the five less reliable, tentative measurements as either measurements (model 2) or upper bounds (model 3). The Salpeter models (*solid lines*) are normalized to either nine SNe for comparison to model 1 or to 18 SNe for comparison to models 2 and 3. The vertical lines demarcate the canonical successful SN mass range of $8\ M_\odot \lesssim M \lesssim 25\ M_\odot$. In all three models, the number of observed high-mass progenitors is less than expected.

We estimate the differential mass distribution of progenitors dN/dM as follows. For each progenitor we have a prior on its mass, the Salpeter IMF $P_S(M) \propto M^{-2.35}$ with $8\ M_\odot \le M \le 150\ M_\odot$, and then a probability distribution $P_i(M_i|M)$ relating the mass M and the mass estimates M_i from Li et al. (2007). Combining the two, the Bayesian estimate for the progenitor mass is the product $P_i(M|M_i) \propto P_S(M)P_i(M_i|M)$ normalized to unity. If a progenitor has a mass estimate, we use a lognormal probability distribution for $P_i(M_i|M)$ based on the reported uncertainties. If a progenitor has only a mass limit M_i, we use a flat probability distribution extending from $8\ M_\odot$ to the mass limit M_i for $P_i(M_i|M)$. The cumulative mass function of progenitors,

$$N(>M) = \int_M^{150 M_\odot} \sum_{i=1}^{N} P_i(M|M_i) dM, \qquad (1)$$

is simply the mass integral of the sum of the $i = 1, \ldots, N$ progenitor probability distributions $P_i(M|M_i)$.

Figure 2 presents three different estimates for $N(>M)$ from the data and compares these estimates to the expectation for a Salpeter IMF. In model 1 we use only the $N = 9$ progenitors with mass estimates. In model 2 we use all $N = 18$ systems, adding the five with tentative mass estimates as measurements. In model 3 we use all $N = 18$ systems, but treat the five tentative mass estimates as upper bounds rather than measurements. The results certainly suggest a deficit of high-mass progenitors, but at low statistical significance. In a sample of 9 (18) progenitors we would expect 1.8 (3.6) of them to be more massive than $25\ M_\odot$, while the current samples include only 0.5 (2); the details clearly depend on how we build the distributions. It is more difficult to address whether the apparent deficit is simply a selection effect. The more massive progenitors should not be intrinsically fainter in the visual bands, even though the bulk of their emission is at shorter wavelengths, but systematic effects such as a correlation between age and extinction could easily produce a similar deficit. For example, Prieto et al. (2008b) found that the progenitor of SN 2008S (which may be a LBV eruption rather than a SN) is so enshrouded in dust that it was only visible from dust emission in the mid-IR.

Moreover, optical searches for SNe and their progenitors provide little direct information on the intriguing question of whether there are massive stars that end their lives by forming BHs without the dramatic visual signature of an explosion. The upper bound on the potential rate of failed SNe is roughly equal to the rate of successful SNe. First, the concordance of massive star formation rates and SNe rates and the nondetection of a diffuse SN neutrino background both indicate that the rate of failed SNe cannot significantly exceed the rate of observed SNe (Hopkins & Beacom 2006). Second, the nonobservation of any neutrino bursts over the last 25 years (Beacom et al. 2001; Alekseev & Alekseyeva 2002; Ikeda et al. 2007) sets a weak upper bound on all core collapses in the Galaxy of $\lesssim$12 events per century (95% confidence) as compared to the rate of roughly 1 SN per century (e.g., van den Bergh & Tammann 1991; Cappellaro et al. 1999).

A crude lower bound may be obtained from the (albeit poorly constrained) formation rate of BHs by all possible mechanisms. A population census of BHs and neutron stars (excepting pulsars) in the Galaxy is presently, impractical because they can only be found through special populations of binaries such as active X-ray binaries or astrometric binaries (Gould & Salim 2002), or through the modest contribution of these compact objects to

Galactic microlensing rates (Gould 2000). The existence of high-mass X-ray binaries (HMXBs), in which we observe a massive BH orbiting a short-lived massive star (like the spectacular system M33-X7 with a 16 $M_\odot$ BH orbiting a 70 $M_\odot$ star [Orosz et al. 2007]), means that the present day BH formation rate is nonzero (Bethe et al. 2007). The observed pattern of stellar element abundances may require that most stars more massive than $\simeq 25\ M_\odot$ collapse to form BHs in order to avoid overproducing heavy elements (Heger et al. 2003).[4] For a Salpeter IMF in which stars with $8\ M_\odot \lesssim M \lesssim 25\ M_\odot$ become neutron stars after a classical SN and higher mass stars become BHs, the BH formation rate is ~25% that of normal SNe. Such simple estimates are consistent with the simulations of Zhang et al. (2007).

Beyond these semiempirical limits we must rely on theoretical studies of core collapse. Despite intense theoretical and computational efforts (in one dimension, e.g., Rampp & Janka 2000; Liebendörfer et al. 2001; Thompson et al. 2003; Sumiyoshi et al. 2005; in two dimensions, e.g., Fryer 1999; Buras et al. 2003, 2006; Livne et al. 2004; Ohnishi et al. 2006; and in three dimensions, e.g., Fryer & Warren 2002), it is difficult to simulate the evolution of any star with realism, and most attempts to produce SNe fail. The steady increase in sophistication of the models over the last four decades has not unambiguously reduced the difficulties, although recently a two-dimensional calculation of a relatively low-mass progenitor (11.2 $M_\odot$) led to a weak neutrino-driven explosion (Buras et al. 2006), and there may be new mechanisms associated with less restrictive simulation geometries (Blondin et al. 2003; Burrows et al. 2006; Scheck et al. 2008). What is particularly worrisome in the history of simulating core collapse is that the theoretical effort is focused on making SNe succeed (particularly for $M \approx 10\ M_\odot$) because they are observed, without significant constraint on whether nature is any more successful at producing explosions than theorists (Gould & Salim 2002). As we have reviewed above, there are no observational constraints barring ~50% of $8\ M_\odot \lesssim M \lesssim 25\ M_\odot$ stars from forming BHs. In short, the rate of BH formation could well be comparable to the rate of normal SNe, even for relatively low-mass progenitors.

The rate of failed SNe depends on the optical signatures of BH formation, and unfortunately, we lack a clear prediction of these signatures. The possibilities literally range from a nearly normal SN to the star simply vanishing. The observed masses of BHs (e.g., Casares 2007) show a distinct gap between neutron stars ($M_{\rm NS} \simeq 1.4\ M_\odot$) and BHs ($M_{\rm BH} \gtrsim 4$), so one would expect a significant difference in the external signatures rather than a simple continuum of properties. Figure 3 sketches possible outcomes.

One scenario entails a successful shock leading to a visible explosion, with collapse to a BH after material falls back onto the neutron star (e.g., Woosley & Weaver 1995). There are arguments from studies of the early-time accretion from the envelope (e.g., Chevalier 1993; Fryer et al. 1996) supporting this route. Balberg et al. (2000; Balberg & Shapiro 2001), building on Zampieri et al. (1998), considered the visible signature from accretion onto a BH following a SN in some detail and found that the detectability of the accreting BH depended critically on the ejected mass of radioactive elements. The accretion luminosity starts as (essentially) Eddington limited and then decreases as a power law, while the radioactive decay–powered luminosity is initially far brighter and decreases exponentially. The time at which accretion dominates is determined by the mass of the ejected radioactive elements, particularly the longer lived ^{44}Ti. For a normal SN (~0.05 $M_\odot$ of ^{56}Ni) the timescale is very long (~10^3 yr), while for a very low energy SNe like 1997D (~$10^{-3}\ M_\odot$ of ^{56}Ni) it can be very short (~years). In all cases, the BH is very faint when it emerges. An alternative is the "collapsar" model with a γ-ray burst and an optical afterglow superposed on a SN (e.g., MacFadyen & Woosley 1999). These cannot be the dominant signature of BH formation, since they are too rare and are likely confined to metal-poor galaxies (Stanek et al. 2006).

The second possibility is that a shock either never forms or stalls before reaching the stellar surface ("prompt" formation; Heger et al. 2003). Given the challenges in producing successful explosions, this could well be a common outcome at all masses. The simple "direct collapse" scenario may be possible if the core collapses directly into a BH with the envelope simply following it in afterward, as seen in some of the simulations of Duez et al. (2004). At higher progenitor rotation rates, Duez et al. (2004) found that there can be a residual accretion disk around the BH. Alternatively, the core collapses to form a neutron star with a stalled shock, followed by an accretion-induced collapse of the neutron star to form a BH. Most studies of this scenario have focused on the collapse and its neutrino signature without examining the fate of the remainder of the stellar envelope (e.g., Baumgarte et al. 1996; Liebendörfer et al. 2004; Sumiyoshi et al. 2007). We are aware of no studies of the expected optical signatures for these scenarios.

Given an ill-constrained rate, only partially explored pathways, and poorly constrained optical signatures, the safest way to proceed is through observations: monitor a large enough sample of massive stars sufficiently deeply to detect all possible outcomes from a classical SN to a direct collapse with no signature other than disappearance.

3. HOW TO WRITE OBITUARIES FOR MASSIVE STARS

The ultimate objective is to monitor the health of a sufficient number of massive stars to directly measure their death rates as a function of luminosity, temperature, and metallicity. There are three distinct challenges in this program: building catalogs of massive stars to observe, recognizing the death of a star, and observing enough stars to have an interesting event rate.

Cataloging is probably the most difficult problem. Although it does not impact the determination of the relative rates of normal and failed SNe, it is important for determining absolute rates. With 8 m telescopes or the *Hubble Space Telescope* (*HST*) it is feasible to regularly measure the flux of a 10 $M_\odot$ supergiant with $M_V \simeq -4$ mag (see Fig. 1). With no extinction this corresponds to $V \simeq 26$ mag (25 mag) at a distance of $D = 10$ Mpc (6 Mpc) and requires typical exposure times for a signal-to-noise ratio of 10 and neglecting the diffuse emission from the galaxy of 60 (6) minutes for a seeing-limited 8 m telescope. For catalogs, the problem is the blending of the stars, since the physical resolution of a ground-based telescope at the galaxy is $5(D/{\rm Mpc})$ pc, and the massive stars tend to be clustered. Ideally, a single epoch of observations with *HST* would greatly simplify producing catalogs while simultaneously providing the flux calibrations needed to use Cepheids or eclipsing binaries to constrain the distance ladder.

Recognizing the death of a star is much easier because image subtraction (e.g., Alard & Lupton 1998) can determine the fate of a star, even if it was confused with other stars in the initial accounting. In all scenarios, the final state is the *absence* of the star, so a robust signature of a star's death would be that its flux disappears and does not reappear. This is more easily done for failed SNe with a minimal optical transient at death, because for normal SNe, it may take many years for the dying star to fade to be

[4] There is the intriguing observation by Muno et al. (2006) of a probable magnetar in a star cluster containing $M \simeq 35\ M_\odot$ stars, but Belczynski & Taam (2008) recently presented a binary evolution scenario in which Roche lobe overflow allows some 50–80 $M_\odot$ stars to form neutron stars.

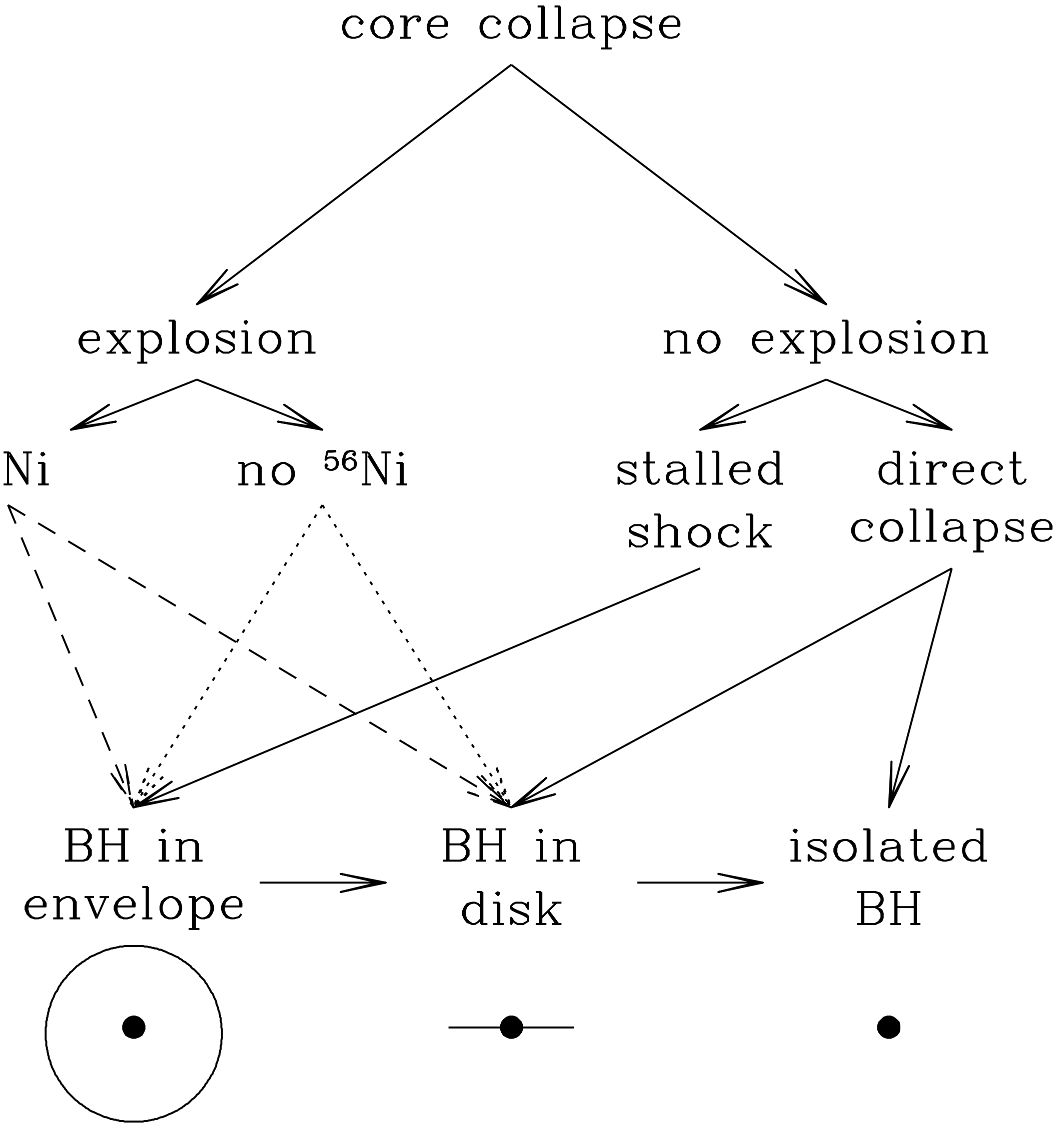

FIG. 3.— Possible outcomes in forming a BH. The optical signatures of the "no explosion" scenarios are little explored.

significantly less luminous than before it died. Other known sources (see § 4) either appear before disappearing (e.g., novae), vary (ir)regularly (Cepheids, LBVs, and eclipsing binaries), or reappear after disappearing (R Coronae Borealis [RCB] stars) on reasonable timescales. As we demonstrate in § 4, the rate of false positives is easily managed.

Finally, the rate of normal core-collapse SNe in the target sample sets a crucial scale for the feasibility of such a survey. The sample must produce roughly 1 normal SN yr^{-1} in order for a limit on failed SNe to be significant. Since one is limited by technology to nearby galaxies, we start with the Karachentsev et al. (2004) catalog of neighboring galaxies, which is designed to be $\sim$80% complete to a distance of 8 Mpc. We estimate the relative core collapse SN rate of the galaxies using the results of Cappellaro et al. (1999) and then normalize the total rate to match that observed for these galaxies from 1970 to 2007 based on the Sternberg Astronomical Institute SN catalogs (see Ando et al. 2005). The resulting predicted and observed rates for the individual galaxies agree well, although the absolute, total normalization ranges from 0.56 SNe yr^{-1} from 1970 to 2007 to 1.1 SNe yr^{-1} if we restrict ourselves to the "modern" era of robotic surveys (1997–2007). We lose 10% of the expected rate by eliminating highly inclined galaxies (axis ratios <0.3). Only 40 galaxies need to be observed (30 northern with decl. $> -10°$)[5] to cover 90% of the expected rate.

For these galaxies, the estimated core collapse SN rates are 0.46–0.90 per year depending on whether we use the lower 1970–2007 or the higher 1997–2007 rate normalizations. A survey restricted to the northern galaxy sample would have modestly lower rates of 0.35–0.71 per year. We suspect, and can argue statistically at roughly 90% confidence, that the higher normalization of the last decade is correct, where the change in efficiency is

[5] In rough order of increasing observational cost per SN, they are M101, M81, NGC 5194, (NGC 5236), NGC 2403, (NGC 4594), M82, NGC 6946, NGC 4258, NGC 4736, NGC 4826, (NGC 1313), IC 342, NGC 2903, (NGC 7793), (NGC 3621), NGC 3627, (NGC 247), (NGC 300), NGC 4236, NGC 925, NGC 4449, NGC 628, (NGC 5068), NGC 3368, M31, NGC 4395, NGC 3077, NGC 4605, NGC 4214, NGC 3351, NGC3344, NGC 6503, M33, (NGC 5253), IC 2574, NGC 672, NGC 5474, NGC 3489 and (NGC 5102). The parentheses indicate Southern galaxies (decl. $< -10°$). The observational cost includes the effects of distance and that M31 and M33 require multiple pointings for a typical 0.25 deg^2 camera. We have not corrected for Galactic extinction and note that the levels for IC 342 ($A_B \simeq 2.4$) and NGC 6946 ($A_B \simeq 1.5$) are uncomfortably high. We also note, however, that NGC 6946 has had 9 SNe over the last century, far more than any other galaxy on this list.

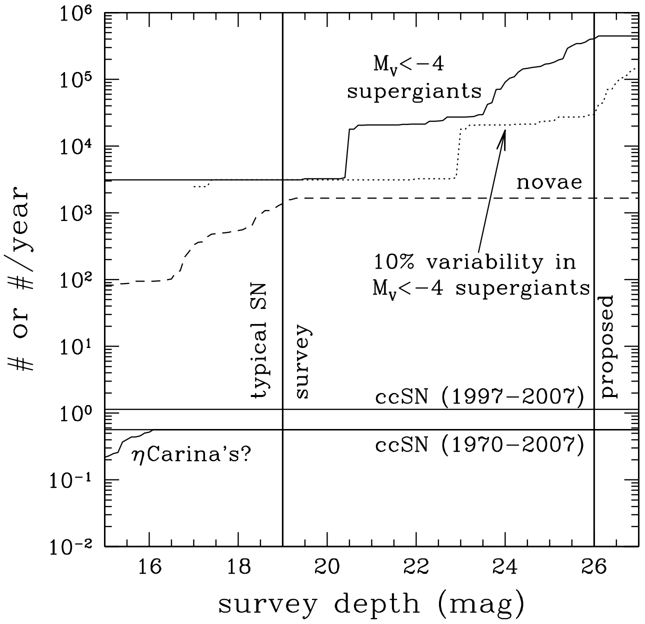

FIG. 4.—Numbers or rates for "expected" sources among the Karachentsev et al. (2004) catalog of nearby Galaxies as a function of survey depth. Explosive luminous events such as SNe, η Carina-like outbursts, and novae are relatively easy to detect, even at the 19 mag depth of a typical local SN survey. Monitoring a sufficient number of massive stars or the variability of those massive stars requires far deeper observations. The conspicuous jumps in the numbers occur where observing the phenomenon in the SMC/LMC, M31/M33 and the M81 group becomes possible. The heavy vertical lines mark the depth of a typical SN survey, and the depth required for the most distant galaxies in our sample.

presumably due to the introduction of automated surveys (e.g., KAIT; Li et al. 2000), enormous improvements in the equipment available to amateurs, and a greater community interest in SNe. In any case, this sample of galaxies has a high enough SN rate that a failure to find candidate failed SNe over a period of 5 years sets an interesting limit.

An alternate way of considering the question is that Hartman et al. (2006) found approximately 1400 $M_V \lesssim -5$ supergiants in their survey of M33. Using the same scalings as for the SN rates, approximately correcting to $M_V < -4$, and normalizing by the luminosity of M33, our neighboring galaxy sample contains approximately $\sim 10^6$ supergiant stars, and so with mean lifetimes of $\sim 10^6$ yr, one should see ~ 1.0 SN yr^{-1} . Figure 4 illustrates the visibility of SNe, η Carina-like outbursts, novae,[6] $M_V < -4$ supergiants, and 10% variability in such stars as a function of survey depth.

4. GUARANTEED SCIENCE

The full yield of a survey for failed SNe will depend on the monitoring cadence that the program can sustain. Several SNe should be found in the galaxies under watch, so deep preexplosion images will be available to identify their progenitors. In some respects, this is similar to other attempts to survey nearby galaxies for later identification of SN progenitors (e.g., Crockett et al. 2007). It differs significantly from these programs in emphasizing monitoring and image subtraction rather than a single epoch. For example, a deep monitoring survey also provides preexplosion progenitor light curves to study variability and to search for signs of binarity (through eclipses). It would also permit the detection of SNe obscured by $A_V \simeq 10$ mag of extinction.

Spectacular outbursts such as that of η Carina in the 19th century (Smith et al. 2003; Morse et al. 2001) and P Cygni (Walborn 1976; Smith & Hartigan 2006) around 1600 CE should be recognizable by a characteristic brightening, reddening, and then decay back to quiescence. A number of extragalactic η Carina-like outbursts have already been identified (the "SN impostors"; see Smith & Owocki 2006 and references therein). The observational campaign required to identify failed SNe would be invaluable in identifying lower luminosity transients associated with such extreme mass-loss events and should measure their rates. This could be extremely important for understanding the role of such outbursts in the late-time evolution and mass loss of massive stars and, potentially, for constraining the physics of their ignition. The survey would expand the number of supergiants for which luminosity variations of order unity would be detected by well over an order of magnitude (see Fig. 4).

Variability will be present in the massive star sample for a range of other reasons. Pulsations, whether periodic like Cepheids or more irregular like LBVs, are easy to recognize given a reasonable number ($\sim$20) of monitoring epochs. Figure 4 illustrates that a full monitoring program for these galaxies would be able to detect relatively weak 10% luminosity variations in $\sim 10^5$ supergiants. Since $M_V \simeq -4$ corresponds to a 10 day Cepheid, essentially all Cepheids useful for distance scale studies (see Macri et al. 2006) would be detected. Eclipsing contact binaries can also be detected with modest numbers of epochs (e.g., Prieto et al. 2008a), but significantly detached systems would probably require a prohibitive number of epochs. Other sources, such as RCB stars or novae, correspond to fainter "progenitors" than the supergiants. An $M_V = -3$ RCB star, if detected, would vanish and then reappear, while a nova would appear and then disappear. Both phenomena are very different from (failed) SNe that start with a luminous star, have a transient of some kind, and then ultimately have no star.

We explore the problem of backgrounds based on our 27 epochs of M81 monitoring data collected from 2007 January 16 to October 15, a span of 272 days, using the Large Binocular Telescope (Prieto et al. 2008a). We characterize the sources by their V-band luminosity, L_0, in the reference image and the change in their luminosity, ΔL, between the first and last epochs. We scale these by the luminosity L_{-3} corresponding to $M_V = -3$ (about 1300 $L_\odot$ or 1100 counts in the reference image). We examine objects with large changes in their flux ($|\Delta L| > L_0/2$) whose change in flux approaches that of a supergiant ($|\Delta L| > L_{-3}$; see Figs. 1 and 5). These criteria will also catch high amplitude variability from objects that are not detected in the reference image. Of approximately 600 variable sources, only 53 meet these criteria, of which 28 faded and 25 brightened. Most of the candidates are Cepheid (29) or other variable (19) stars for which the first and last epochs coincidentally lie at maxima and minima of the light curves. Four sources appear to be novae (two are bright in the first epoch, and two are bright in the last), and one is an artifact (diffraction spike). All but two of the sources are seen as discrete sources in the reference image constructed from a stack of the 12 best epochs. If we only look at the initial and final epochs, where the initial epoch was taken in terrible conditions (FWHM 1.8″), and the final epoch was taken in reasonable conditions (FWHM 1.0″), 24 of the sources are seen in both epochs, and four are seen in neither. For rising sources, 10 are seen in the final but not the initial epoch; while for falling sources, one is seen in the initial but not the final epoch, and two are seen in the final epoch but not the initial. There were no plausible candidates for a failed SNe. We conclude that backgrounds are relatively easily controlled by combining sparse monitoring (to eliminate novae from the initial epochs and to detect the common large-amplitude

[6] Normalized using the Darnley et al. (2006) rates for M31 and assuming all novae peak at $M_V = -11$.

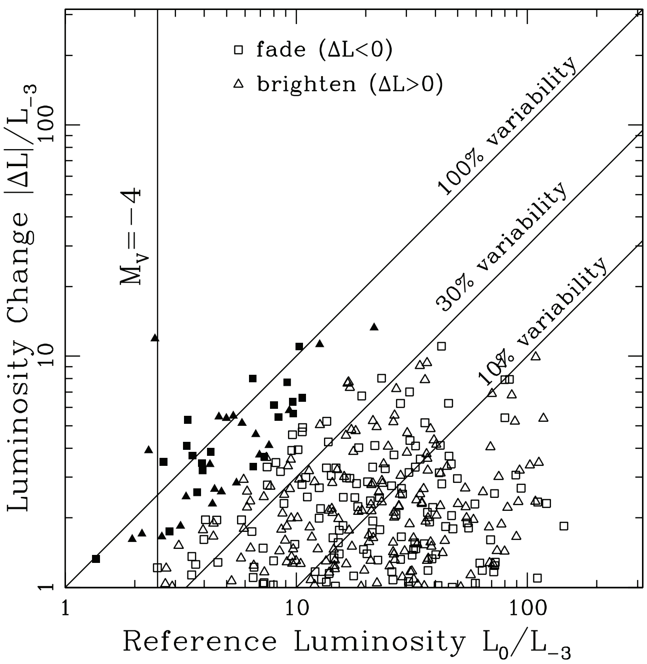

FIG. 5.—Variable sources in M81. The squares (triangles) show sources as a function of their estimated luminosity L_0 in the reference image and their decrease (increase) in luminosity ΔL between 2007 January and October in units of the luminosity $L_{-3} \simeq 1800\ L_\odot$ corresponding to $M_V = -3$. The lines indicate the fractional variability, where a vanishing star should lie on the 100% variability line. We inspected all sources with variability $|\Delta L|/L_0 > 1/2$ and $L_0 > L_{-3}$ (*filled symbols*) and found no candidate failed SNe. [*See the electronic edition of the Supplement for a color version of this figure.*]

variable stars) with direct inspection of the final epoch. This holds even if we restrict our analysis to using only a modest fraction of the epochs available for M81. The steps for confirming a candidate should be to obtain additional epochs to further rule out other sources of variability and to search for X-ray emission from the BH.

5. DISCUSSION

While early reports that a previously known star was "not to be found in the heavens" (Cooper 1847; see also Herschel & Flamsteed 1797) were probably due to issues in cataloging, it is now possible to systematically search for legitimate "lost stars" by direct monitoring. Ultimately, this will enable direct measurement of the rates of SNe and failed SNe based on the properties of the evolved progenitors. An 8 m telescope with a wide field of view camera can simply watch enough supergiants to detect any form of death, whether luminous or not. At its simplest, one subtracts the final image from the initial image and counts the number of sources with supergiant luminosities that go missing. This information, both temporal and spatial, can then trigger searches for coincident bursts of neutrinos (Ando et al. 2005, Kowalski & Mohr 2007) or gravitational waves (Arnaud et al. 2004). In short, a modest investment of observing time over 5 years can begin to measure and limit the fates of individual stars, whether they explode or simply collapse. Moreover, the survey generates a wealth of new information on normal SNe, massive star evolution, binarity, and the local distance scale as it proceeds. Tests using monitoring data for M81 from the Large Binocular Telescope (Prieto et al. 2008a) found no false positives and formally set a limit that the rate of failed SNe is <80 times that of normal SNe at 90% confidence.

Uncovering the existence of such "unnovae" would lead to a number of interesting consequences, including significant changes in our picture of metal enrichment and feedback. It would also change our expectations for event rates in gravitational wave detectors, as significant numbers of what are now expected to be NS-NS binaries would instead be NS-BH or BH-BH binaries, which would both increase the inspiral rates and change the expected signatures of coalescence (Belczynski et al. 2007). The available observational evidence requires that the most massive stars ($M \gtrsim 25\ M_\odot$) become BHs and that many $8\ M_\odot \lesssim M \lesssim 25\ M_\odot$ stars become normal SNe. But theorists should also take seriously the implication from the difficulty of producing successful explosions that many of these less massive stars may also become BHs without a normal SN. Finally, while we argue that we can now detect BH formation even if the signature is for a star to simply disappear, it would be very helpful to have more quantitative estimates of the optical signatures expected for the scenarios in Figure 3.

Using the new generation of telescopes to probe some of these issues is not new. There are several ongoing programs to obtain the data needed to characterize future SN progenitors in this volume (e.g., Crockett et al. 2007). There are trial programs that employ ground-based telescopes to do variability surveys using image subtraction at or near these depths focused on either microlensing (e.g., de Jong et al. 2008), Cepheids and eclipsing binaries (e.g., Prieto et al. 2008a), or other variables (e.g., Rejkuba et al. 2003). What has not been emphasized is that these surveys are on the verge of exploring a kind of "terra incognita," where we can search for any phenomena occurring at the rates of SNe but without the dramatic signatures of SNe. There is some potential for making similar studies with historical data, if the extensive historical data on the Magellanic Clouds, M31, and M33 can be combined to use the long time baselines (50–100 yr) to compensate for the smaller number of stars. In the future, with the advent of large-scale synoptic surveys such as LSST (Tyson 2002), JDEM (e.g., SNAP; Aldering et al. 2004), or EUCLID (e.g., DUNE; Réfrégier et al. 2006), these studies will be very straightforward.

We are reminded of the search for proton decay, a disappearance campaign that has yet to succeed in its primary objective, yet ultimately led to the discovery of "new physics" (massive neutrinos), and demonstrated the feasibility of neutrino astronomy (Hirata et al. 1987; Bionta et al. 1987). In regards to SNe, we have certainly been surprised before, both with the blue supergiant progenitor of SN 1987A and the nondetection of the Cas A SN, to name but a few instances. It would not be surprising, therefore, for such a survey to unexpectedly discover "new astrophysics."

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