GLOBULAR CLUSTERS AS TESTBEDS FOR TYPE Ia SUPERNOVAE

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ABSTRACT

Fundamental mysteries remain regarding the physics of Type Ia supernovae (SNIa) and their stellar progenitors. We argue here that important clues to these questions may emerge by the identification of those SNIa that occur in extragalactic globular clusters—stellar systems with well-defined ages and metallicities. We estimate an all-sky rate of \( \approx 0.1 \eta (D/100 \text{ Mpc})^3 \text{ yr}^{-1} \) for SNIa in globular clusters within a distance \( D \), where \( \eta \) is the rate enhancement per unit mass as a result of dynamical production channels that are inaccessible in the galactic field. If \( \eta \approx 2–10 \), as suggested by observations and theory, the combined efforts of accurate supernova astrometry and deep follow-up imaging should identify the \( \gtrsim 1\% \) of nearby \( (D < 100 \text{ Mpc}) \) SNIa that occur in globular clusters.

Key words: galaxies: general – globular clusters: general – supernovae: general

1. INTRODUCTION

Many questions remain about the most fundamental aspects of Type Ia supernovae (SNIa), including the triggering and hydrodynamics of the explosions (e.g., Hillebrandt & Niemeyer 2000), and the nature of their stellar progenitors (e.g., Yungelson 2005). The increasing SNIa diversity, with some very bright (e.g., Howell et al. 2006), some very faint (e.g., Kasliwal et al. 2008), and some that do not follow the Phillips (1993) relation (e.g., Jha et al. 2006), has energized the discussion of many possible formation scenarios.

While at most a few percent of white dwarfs (WDs) explode as SNIa (Pritchot et al. 2008), there are only loose constraints on the specific binary evolution pathways (e.g., Iben & Tutukov 1984; Yungelson 2005). There is a consensus that SNIa originate from thermonuclear ignition and burning of a C/O white dwarf in a binary system. Yet it remains uncertain if the event is triggered by accretion from a hydrogen-rich companion or from a merger with another white dwarf (see Branch et al. 1995), referred to as the single-degenerate and double-degenerate scenarios, respectively. In the single-degenerate scenario, the main issues are the nature of the companion, and if mass transfer can be sustained onto the white dwarf at a favorable rate in a sufficient number of systems to match the observed SNIa rate (Maoz 2008). In the double-degenerate scenario, the primary issue is whether off-center carbon ignition can be avoided, as this would transform the C/O white dwarf into an O/Ne/Mg white dwarf (e.g., Nomoto & Iben 1985) rather than generate an SNIa (see, however, Regos et al. 2003).

In fact, evidence is astounding that multiple progenitor scenarios lead to SNIa. In particular, there is a clear disparity in the SNIa rates in late-type galaxies with active star formation and elliptical galaxies that contain mostly old (5–10 Gyr) stars (Mannucci et al. 2005; Scannapieco & Bildsten 2005; Sullivan et al. 2006). This suggests that \( 10^9–10^{10} \) can elapse between the birth of the progenitors and the explosions, a challenge for any single progenitor scenario (DellaValle 1994; Mannucci et al. 2006). Multiple routes to SNIa may well lead to diversity in the explosive outcomes. For example, low-luminosity SNIa are most prevalent in early-type (i.e., E/S0) galaxies, while the most luminous events occur only in star-forming galaxies (e.g., Hamuy et al. 1996).

We propose that the study of SNIa in globular clusters (hereafter GCIa) may provide unique clues to understanding SNIa. Although globular clusters (GCs) and elliptical galaxies are both composed mainly of old stars, there are crucial differences between them. In a given GC, we are certain that all stars were born within 1 Gyr of each other, whereas elliptical galaxies often show evidence for a substantial spread of stellar ages (e.g., Trager et al. 2000). Second, in an individual GC, the stellar metallicities are narrowly distributed, and thus the integrated metallicity is a good measure of the metallicity of any of the constituent stars. Until recently, there was only one known exception (\( \omega \text{ Cen} \)) in the Milky Way (Freeman & Rodgers 1975; Bedin et al. 2004), but more recent work has found that a few massive (greater than \( 10^6 M_\odot \)) GCs have helium-rich subpopulations (e.g., Piotto 2008). In any instance, GCs have metallicities low enough that a single GCIa detection would place strong constraint on theoretical models (Kobayashi et al. 1998; Hachisu et al. 1999; Piro & Bildsten 2008).

GCs are differentiated from the galactic field by their high stellar densities (often \( \gtrsim 10^6 M_\odot \text{pc}^{-3} \)) that trigger frequent close encounters between stars and binaries. Such encounters are responsible for the high incidence of exotic objects in GCs (e.g., Knigge et al. 2008), including X-ray binaries, rapidly spinning radio pulsars, blue stragglers, and cataclysmic variables (e.g., Hut et al. 1992; Sills et al. 1999; Rasio et al. 2000; Pooley & Hut 2006). Dynamics will almost certainly play an important role in the production of GCIa progenitors (Shara & Hurley 2002; Ivanova et al. 2006; Rosswog et al. 2008), likely increasing the GCIa rate per unit mass.

We start in Section 2 by estimating the GCIa rate and discussing the possible dynamical enhancements. The observational challenges to finding a GCIa are discussed in Section 3, where we motivate that the maximum distance for such a search is 100 Mpc. We also explain the need for accurate astrometry of nearby SNe that will enable meaningful follow-up observations. We close in Section 4 by describing the implications of detecting even a single GCIa.

2. THE SUPERNOVA RATE IN GLOBULAR CLUSTERS

GCs have a wide range of \( Z_\odot \) metallicities and contain \( \sim 10^5–10^6 \) greater than 8 Gyr old stars inside a few parsecs. All
galaxies contain GCs, with total numbers scaling as $\sim 100$ GCs per $10^{10}L_\odot$ (Ashman & Zepf 1998). The common measure of the GC number density is the V-band specific frequency,

$$S_N = N_{GC}10^{0.4(M_V + 15)}$$

(1)

where $N_{GC}$ is the number of GCs and $M_V$ is the absolute $V$-band magnitude of the galaxy (Harris & van den Bergh 1981). Typical values of $S_N$ are $\approx 1$ for spiral galaxies and $\geq 2$--5 for ellipticals (Harris 1991). Though standard, $S_N$ is not the best choice for our purposes. We are most interested in the fraction of stellar mass in GCs, $F_{GC} = M_{GC}/M_*$, where $M_{GC}$ is the total mass of the GC system and $M_*$ is the total stellar mass of the galaxy. Given the galactic stellar mass-to-light ratio $Y_V$, $F_{GC}$ is related to $S_N$ by

$$F_{GC} = 1.2 \times 10^{-3} S_N m_3 Y_V^{-1}$$

(2)

where $m_3$ is the mean GC mass in units of $10^3 M_\odot$, and we use $M_{V,0} = 4.8$ for the absolute magnitude of the Sun. Photometric studies of GC systems find $m_3 \simeq 2$, and old elliptical galaxies have $Y_V = 3$, so that $F_{GC} \approx 2 \times 10^{-3}$ for most ellipticals, while it is somewhat less for spirals. For some central dominant ellipticals at the centers of galaxy clusters, $S_N$ can reach 10 (Harris et al. 2009), corresponding to $F_{GC} \approx 10^{-2}$.

Scannapieco & Bildsten (2005) and Mannucci et al. (2005) proposed that the SNIa rate in a galaxy is the sum of two components: one proportional to the total stellar mass $M_*$ and the other proportional to the star formation rate $MS$. Such a model suggests that SNIa rates result from at least two evolutionary channels. For a particular galaxy, the two-component rate can be written as

$$SNR(t) = A M_*(t) + B MS(t)$$

(3)

where $A$ and $B$ are constants. Using a well-characterized sample of SNIa hosts, Sullivan et al. (2006) find basic agreement with Equation (3) and determine $A = (5.3 \pm 1.1) \times 10^{-14} \text{yr}^{-1} M_\odot^{-1}$ and $B = (3.9 \pm 0.7) \times 10^{-14} \text{yr}^{-1} (M_\odot \text{yr}^{-1})^{-1}$.

The value of $A$ is derived from SNIa in E/S0 galaxies with no discernible star formation (i.e., $B = 0$). If these galaxies are truly old, with negligible star formation in the past $\approx 5$--10 Gyr, then a reasonable first guess is that the same rate per unit mass also applies to GCs (the enhancement due to stellar dynamics is discussed below). Adopting the galactic value of $A$ for GCs, the GC rate in a galaxy is $A M_*(F_{GC})$. An estimate of the local cosmic rate density of GCs is obtained as follows.

At low redshift, the total K-band luminosity density is

$$j_k \simeq (5 \pm 0.5) \times 10^{8} L_{\odot} \text{K Mpc}^{-3}$$

$$H_0 = 70 \pm 5 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

(Kochanek et al. 2001) and the fraction in E/S0 galaxies is 40%--50%. Given the mean K-band stellar mass-to-light ratio $Y_K \approx 1$, the contribution to the K rate density from old stellar populations is $A j_k Y_k$. Here we let $Y_k = 1 \pm 0.5$, averaged over all galaxy morphological types, where the uncertainty largely reflects a range of model assumptions, rather than measurement error (e.g., Cole et al. 2001). We find $A j_k Y_k \approx (2.7 \pm 1.5) \times 10^{-5} \text{yr}^{-1} M_\odot^{-1}$. This is consistent with the recent measurement at $z \approx 0.1$ (Dilday et al. 2008), showing the dominance of the old stellar population for the local SNIa rate. The corresponding GCs rate density is then $A j_k Y_k (F_{GC})$, where $(F_{GC})$ is the mean GC mass fraction over a large number of galaxies. If we adopt a plausible value of $(F_{GC}) = 10^{-3}$ (see Equation (2)), we estimate a

$$\text{GC rate from mass alone} \approx 3 \times 10^{-8} \text{yr}^{-1} M_\odot^{-3}$$

(4)

Under our given assumptions, we expect that the net uncertainty in this rate is a factor of $\approx 2$.

However, it has been known for over 30 years that X-ray binaries are $\geq 100$ times more abundant per unit mass in GCs than in the disk (Clark 1975; Katz 1975). Dynamical interactions involving single stars and binaries occur frequently in GCs and naturally account for this overabundance (e.g., Bildsten & Deloye 2004). There are also excellent observational and theoretical arguments that dynamics shape the GC populations of blue stragglers, millisecond pulsars, and cataclysmic variables (e.g., Sills et al. 1999; Rasio et al. 2000; Pooley & Hut 2006).

Recently, Shara & Hurley (2002) and Ivanova et al. (2006) explored the idea that SNIa progenitors can be formed by dynamical means in dense star clusters, leading to a mean enhancement of the GC rate per unit mass, $\eta$. Shara & Hurley (2002) suggest that the number of WD--non-degenerate star binaries is similar in dense clusters relative to the field, although they found strong differences in the masses of the companion stars, which could be important in determining which binaries support stable accretion. The models described in Ivanova et al. (2006) suggest an enhancement of $\eta \approx 1$--7 for single-degenerate progenitors, where the range in $\eta$ reflects variation with metallicity and other parameters.

In the double-degenerate case, Shara & Hurley (2002) showed that the supra-Chandrasekhar WD--WD merger rate is over an order of magnitude higher in dense clusters than in the field. On the other hand, Ivanova et al. (2006) suggest a more modest enhancement of $\eta \approx 2$. Based on recent studies of the prevalence of post-classical novae supersoft sources in M31 GCs, Henze et al. (2008) conclude that the nova rate in GCs may be as much as 10 times higher than in an old field stellar population, and they suggest that GCs may be detectable in future surveys. Overall, it seems conceivable that $\eta \approx 1$--10 and that observed GCs may help differentiate progenitors.

### 3. OBSERVATIONAL CONSIDERATIONS WITHIN 100 Mpc

The maximum distance of interest is set by the need to find the underlying GC. GCs have a distribution of absolute magnitudes given by $dN/dM_V \propto \exp[-(M_V - M_{V,0})^2/2\sigma_V^2]$, where the dispersion is $\sigma_V \approx 1$--1.5 in relatively bright galaxies with $M_{V,0} < -20$. Over a wide range of host galaxy properties, the mean is $M_{V,0} = -7.4$ to within a few percent (e.g., Harris 1991; Jordán et al. 2007) and has been detected at the 100 Mpc distance of the Coma cluster, where the turnover apparent magnitude ($\approx 27.6$) is accessible by the *Hubble Space Telescope* (HST; Harris et al. 2009). Observations from the ground are presently limited to magnitudes of $m_V \lesssim 26$, corresponding to the GC luminosity function turnover at distances of $\lesssim 50$ Mpc.

For a given limiting apparent magnitude $V_{\text{max}}$, the fraction of stellar mass in GCs brighter than $V_{\text{max}}$ is

$$f(V < V_{\text{max}}) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{V_{\text{max}}-M_V} e^{-x^2} \, dx$$

(5)

where $M_V = M_{V,0} + DM - 0.4 (\text{ln} 10) \sigma_V^2$, and $DM$ is the distance modulus. When $DM = 35$ and $V_{\text{max}} = 26$, as $\sigma_V$ increases from 1 to 1.5, $f$ increases from 0.25 to 0.62, while the fraction of globulars with $V < V_{\text{max}}$ varies from 0.05 to 0.14. Even though the fraction of visible clusters may be small, the fraction of stellar mass contained within these clusters can be substantial, and typically exceeds 50% when $DM < 35$ and
\( \sigma_v \) takes its usual values of \( \simeq 1.3-1.5 \). Hence, observations of a galaxy at 100 Mpc for which the GC census is complete for clusters brighter than \( V = 26 \) finds \( \simeq 15\% \) of the globulars by number but \( \simeq 60\% \) of the stellar mass. This is an important point, since a dynamical enhancement in the GCIa rate may favor more massive clusters, making it of considerable interest to pursue GCIa within DM = 35 (Pooley & Hut 2006). At distances greater than \( \simeq 100 \) Mpc, it becomes extremely difficult to identify a significant number of GCs, and those detected in the outskirts of the galaxy will represent only a small fraction of the mass of the GC system.

From Equation (4) and our discussion of the dynamical enhancement of the GCIa rate per unit mass, we estimate a local GCIa rate of \( \approx 0.1 \eta (D/100 \text{ Mpc})^3 \text{ yr}^{-1} \). A plausible value of \( \eta \approx 10 \) results in \( \approx 1 \) GCIa per year within 100 Mpc, which is about 1% of the total SNIa rate within 100 Mpc. What are the prospects for carrying out such a search? The typical SNIa within 100 Mpc would have a peak visual magnitude of \( M_V \approx 16-17 \) and even the subluminous, 1991bg-like SNIa would be found at these distances in the upcoming wide angle (one-tenth of the sky) nearby SNe surveys (e.g., Palomar Transient Factory, SkyMapper, and Pan-Starrs1). The SNIa yields from these new surveys, as well as the increasing numbers from targeted galaxy and cluster searches by Lick Observatory Supernova Search with the Katzman Automatic Imaging Telescope (LOSS-KAIT), Coronal Helium Abundance Spacelab Experiment (CHASE), and Robotic Optical Transient Search Experiment (ROTSE), make the time right for explicit GC identification efforts. In some cases, prior HST or ground-based studies will have GC catalogs to cross-list locations. However, the typical case will require waiting until the SNIa has faded below the GC light.

The few well-studied late-time SNIa light curves reach \( M_V \approx -7 \) after \( \approx 600 \) days (e.g., Sollerman et al. 2004; Lair et al. 2006), at which point their fade rates are 1.4 mag per 100 days in \( BVR \) (Sollerman et al. 2004) with colors of \( V-R \approx -1 \) and \( B-V \approx 0 \), much bluer than a GC. The \( I \) band decays more slowly (\( \approx 1 \) mag in 100 days), again pointing to \( BVR \) for discovery. One possible way to first discern the presence of an underlying GC would be the detection of a modified \( BVR \) color evolution as the redder \( BVR \) colors of the GC \( (V-R \approx 0.4-1) \) begin to shine through.

After identifying a candidate GCIa, high angular resolution observations are required: (1) to confirm that the SNIa and GC lie along the same sightline, and (2) to minimize the likelihood that the SNIa occurred in the host galactic field, in front or behind the GC. If the GC and SNIa are found to overlap within a resolution element of diameter \( \theta \) (in arcsec) the probability that the SNIa occurred in the field is roughly \( L_\theta /L_{GC} \equiv \epsilon \), where \( L_{GC} \) is the GC luminosity and \( L_\theta \) is the luminosity in field stars within the resolution element. A definitive GCIa detection requires a small value of \( \epsilon \), and a correspondingly small value of \( L_\theta \). Since surface brightness, and thus \( L_\theta \), generally falls with increasing galactocentric radius, the strongest GCIa candidates will be located far from the centers of their host galaxies. To illustrate this point more quantitatively, we assume a de Vaucouleurs profile with a surface brightness \( \mu_v = 19.5 \) mag arcsec\(^{-2} \) at the half-light radius, \( R_e \) (e.g., Djorgovski & Davis 1987). We further assume that the target GC has magnitude \( M = -7.5 \) and that the GC is unresolved (the typical GC half-light diameter is \( \lesssim 0.1 \) beyond 10 Mpc). With these assumptions, we find that the radius at which \( L_\theta /L_{GC} = \epsilon \) is given by

\[
\frac{R}{R_e} = \left[\frac{34}{25} + \frac{3}{10} \log \left(\frac{D_{10}^2}{\epsilon}\right)\right]^{\frac{1}{2}},
\]

where \( D_{10} \equiv D/10 \) Mpc. For \( \epsilon = 0.1 \) and \( D_{10} = \sqrt{10} \) (\( \simeq 31.6 \) Mpc) we find \( R/R_e \simeq 3.4 \) when \( \theta = 0.1 \) and \( R/R_e \simeq 0.78 \) when \( \theta = 0.02 \). At a distance of 100 Mpc, the same two \( \theta \) values give \( R/R_e \approx 7.6 \) and \( \simeq 2.3 \). However, at 1\( \prime \) resolution, \( R/R_e \simeq 14.7 \) even when \( D_{10} = \sqrt{10} \). Since typical half-light radii are \( R_e \approx 1-4 \) kpc, it is clear that \( \lesssim 0.1 \) resolution is required to achieve modest \( R \) for small \( \epsilon \), which can only be accomplished from space or with ground-based adaptive optics. Even then, the best candidates will be at distances greater than 10 kpc from the centers of their host galaxies, and require accurate astrometry of both the active SNe and the possible underlying GC. These limits highlight the value of extremely accurate astrometry for making GCIa measurements in the future with large ground-based telescopes.

4. IMPLICATIONS OF A DISCOVERY

A major open question is how a 10 Gyr old stellar population produces an appreciable SN Ia rate, as this requires double-degenerate mergers or stable accretion from relatively low-mass donors, neither of which are currently favored for SN Ia production. While some elliptical galaxies show definite signatures of relatively recent low-level star formation within an otherwise very old system (e.g., Trager et al. 2000), we can be confident that no new stars are forming in old GCs. A single, definitive GCIa detection would demonstrate that, in fact, SNIa do occur in truly old stellar systems.

Second, any systematic trends in GCIa properties with metallicity contain information about the physics of the explosions. GCs are, with few exceptions, extremely uniform in their chemical compositions, and the same cannot be said of elliptical galaxies (e.g., Mehlert et al. 2003). Of course, the metallicity can vary a great deal between GCs, but the metallicity of an individual cluster is readily determined from its photometric colors. The detection of a single [Fe/H] \( \lesssim -1 \) GCIa would place strong constraints on models of stable white dwarf accretion from a nondegenerate companion (e.g., Kobayashi et al. 1998; Hachisu et al. 1999), and analysis of a handful of GCIas would strongly constrain models of SNIa light curves and pre-explosion simmering (e.g., Timmes et al. 2003; Piro & Bildsten 2008).

A potential complication is that the dense stellar environment of the GC may open up exotic paths to SNIa (e.g., Rosswog et al. 2008). We would hope that such an outcome would be revealed in a comparison between the GCIas and the field SNe, both in rates (e.g., Shara & Hurley 2002; Ivanova et al. 2006) and systematic properties, such as light curve shapes. If the rates are sufficiently high, GCIa may prove decisive in implicating nonstandard Ia progenitors such as double-degenerate mergers.

Because it takes approximately two years for a typical Ia to fade to the luminosity of an average GC, GCIa will require late-time observations. This is not common practice, although it would require minimal investment of telescope time for the closest supernovae, as the total rate is only \( \approx 10 \) yr\(^{-1} \) within 30 Mpc. Accurate astrometry of these events is also critical to the later GC search. For the moment, we must appeal to the Ia archives. In the Sterberg catalog,\(^4\) there are 112 SNIa identified from 2005 to 2007 within \( z \approx 0.025 \) (7500 km s\(^{-1} \)). Of these, 34 are hosted by E/S0 galaxies, and six in this subset are separated by more than 1\' from the centers of their hosts. Only careful follow-up observations will tell if the first GCIa has already been detected.

\(^4\) http://www.sai.msu.su/sn/sncat/.
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REFERENCES

Ashman, K. M., & Zepf, S. E. 1998, Globular Cluster Systems (Cambridge: Cambridge Univ. Press)
Bedin, L. R., et al. 2004, 
Bedin, L., & Deloye, C. J. 2004, ApJ, 607, 119
Branch, D., Livio, M., Yungelson, L. R., Boffi, F. R., & Baron, E. 1995, PASP, 107, 1019
Clark, G. W. 1975, ApJ, 199, L143
Cole, S., et al. 2001, MNRAS, 326, 255
Della Valle, M., & Livio, M. 1994, ApJ, 423, L31
Dilday, B., et al. 2008, ApJ, 682, 262
Djorgovski, S., & Davis, M. 1987, ApJ, 313, 59
Freeman, K. C., & Rodgers, A. W. 1975, ApJ, 201, 71
Hachisu, I., Kato, M., & Nomoto, K. 1999, ApJ, 522, 487
Hamuy, M., et al. 1996, AJ, 112, 2438
Harris, W. E. 1991, ARA&A, 29, 543
Harris, W. E., Kavelaars, J. J., Hanes, D. A., Pritchet, C. J., & Baum, W. A. 2009, AJ, 137, 3314
Harris, W. E., & van den Bergh, S. 1981, AJ, 86, 1627
Henze, M., et al. 2008, A&A, in press (arXiv:0811.0718)
Hillebrandt, W., & Niemeyer, J. C. 2000, ARA&A, 38, 191
Howell, D. A., et al. 2006, Nature, 443, 308
Hut, P., et al. 1992, PASP, 104, 981
Iben, I., Jr., & Tutukov, A. V. 1984, ApJS, 54, 335
Ivanova, N., Heinke, C. O., Rasio, F. A., Taam, R. E., Belczynski, K., & Fregeau, J. 2006, MNRAS, 372, 1043
Jha, S., et al. 2006, AJ, 132, 189
Jordán, A., et al. 2007, ApJS, 171, 101
Kasliwal, M. M., et al. 2008, ApJ, 683, L29
Katz, J. I. 1975, Nature, 253, 698
Knigge, C., Dieball, A., Apellaníz, J. M., Long, K. S., Zureck, D. R., & Shara, M. M. 2008, ApJ, 683, 1066
Kobayashi, C., Tsujimoto, T., Nomoto, K., Hachisu, I., & Kato, M. 1998, ApJ, 503, 155
Kochanek, C. S., et al. 2001, ApJ, 560, 566
Lair, J. C., Leising, M. D., Milne, P. A., & Williams, G. G. 2006, ApJ, 132, 2024
Mannucci, F., Della Valle, M., & Panagia, N. 2006, MNRAS, 370, 773
Mannucci, F., et al. 2005, A&A, 433, 807
Maoz, D. 2008, MNRAS, 384, 267
Mehlert, D., Thomas, D., Saglia, R. P., Bender, R., & Wegner, G. 2003, A&A, 407, 423
Nomoto, K., & Iben, I. 1985, ApJ, 297, 531
Phillips, M. M. 1993, ApJ, 413, L105
Piotto, G. 2008, Mem. Soc. Astron. Ital., 79, 334
Piro, A. L., & Bildsten, L. 2008, ApJ, 673, 1009
Pooley, D., & Hut, P. 2006, ApJ, 664, L143
Pritchet, C. J., Howell, D. A., & Sullivan, M. 2008, ApJ, 683, L25
Rasio, F. A., Pfahl, E. D., & Rappaport, S. 2000, ApJ, 532, L47
Regos, E., Tout, C. A., Wickramasinghe, D., Hurley, J., & Pols, O. R. 2003, New Astron., 8, 283
Rosswog, S., Ramirez-Ruiz, E., & Hix, W. R. 2008, ApJ, 679, 1385
Scannapieco, E., & Bildsten, L. 2005, ApJ, 629, L85
Shara, M. M., & Hurley, J. R. 2002, ApJ, 571, 830
Sills, A., et al. 1999, ApJ, 487, 290
Sollerman, J., et al. 2004, A&A, 428, 555
Sullivan, M., et al. 2006, ApJ, 648, 868
Timmes, F. X., Brown, E. F., & Truran, J. W. 2003, ApJ, 590, L83
Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, AJ, 120, 165
Yungelson, L. R. 2005, in Astrophysics and Space Science Library 332, White Dwarfs: Cosmological and Galactic Probes, ed. E. M. Sion, S. Vennes, & H. L. Shipman (Dordrecht: Springer), 163