NO STRIPPED HYDROGEN IN THE NEBULAR SPECTRA OF NEARBY TYPE Ia SUPERNOVA 2011fe

Benjamin J. Shappee1,4, K. Z. Stanek1,2, R. W. Pogge1,2, and P. M. Garnavich3

1 Department of Astronomy, The Ohio State University, Columbus, OH 43210, USA; shappee@astronomy.ohio-state.edu, kstanek@astronomy.ohio-state.edu, pogge@astronomy.ohio-state.edu
2 Center for Cosmology & AstroParticle Physics, The Ohio State University, Columbus, OH 43210, USA
3 Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA; pgarnavich@nd.edu

Received 2012 October 12; accepted 2012 November 15; published 2012 December 12

ABSTRACT

A generic prediction of the single-degenerate model for Type Ia supernovae (SNe Ia) is that a significant amount of material will be stripped from the donor star (∼0.5 M⊙ for a giant donor and ∼0.15 M⊙ for a main-sequence donor) by the supernova ejecta. This material, excited by gamma-rays from radioactive decay, would then produce relatively narrow (≤1000 km s−1) emission features observable once the supernova enters the nebular phase. Such emission has never been detected, which already provides strong constraints on Type Ia progenitor models. In this Letter, we report the deepest limit yet on the presence of Hα emission originating from the stripped hydrogen in the nebular spectrum of an SN Ia obtained using a high signal-to-noise spectrum of the nearby normal SN Ia 2011fe 274 days after B-band maximum light with the Large Binocular Telescope’s Multi-Object Double Spectrograph. We put a conservative upper limit on the Hα flux of 3.14 × 10−17 erg s−1 cm−2, which corresponds to a luminosity of 1.57 × 1037 erg s−1. By scaling models from the literature, our flux limit translates into an upper limit of ≤0.001 M⊙ of stripped material. This is an order of magnitude stronger than previous limits. SN 2011fe was a typical SN Ia, special only in its proximity, and we argue that lack of hydrogen emission in its nebular spectrum adds yet another strong constraint on the single-degenerate class of models for SNe Ia.

Key words: supernovae: individual (SN 2011fe) – supernovae: general – white dwarfs

Online-only material: color figures

1. INTRODUCTION

Despite the fact that Type Ia supernovae (SNe Ia) were used to discover the accelerating universe (Riess et al. 1998; Perlmutter et al. 1999), the physical nature of their progenitor systems remains theoretically ambiguous and observationally elusive (for a review see Wang & Han 2012). It is commonly accepted that SNe Ia result from the thermonuclear explosion of a carbon–oxygen white dwarf (WD) in a close binary system, but the nature of the binary companion and the sequence of events leading to the SN explosion are still uncertain. There are two dominant models: the double degenerate (DD) scenario, in which the companion is also a WD (Tutukov & Yungelson 1979; Iben & Tutukov 1984; Webbink 1984), and the single-degenerate (SD) scenario, in which the companion is a non-degenerate object such as a main-sequence (MS) star, a red giant (RG), a sub-giant, or an He star (Whelan & Iben 1973; Nomoto 1982). There are additional minor variations on these basic models of the progenitor system for both the SD channel (e.g., Justham 2011; Wheeler 2012) and the DD channel (e.g., Thompson 2011; Shappee & Thompson 2012). These uncertainties about the progenitor systems for SNe Ia remain a substantial problem for understanding the systematic errors in using SNe Ia to study cosmology (e.g., Wood-Vasey et al. 2007).

One of the observational signatures of the SD model is that the material from the companion should be stripped when struck by the SN ejecta (Wheeler et al. 1975), leading to both immediate signatures from the impact of the SN ejecta on the companion (e.g., Marietta et al. 2000; Meng et al. 2007; Pakmor et al. 2008; Pan et al. 2012b; Liu et al. 2012) and major changes in the companion’s future evolution (Podsiadlowski 2003; Shappee et al. 2012; Pan et al. 2012a). Recently, the hydrodynamic simulations of Pan et al. (2012b) and Liu et al. (2012) have shown that ∼0.1–0.2 M⊙ of solar-metallicity material is expected to be removed from MS companions by the impact of the SN ejecta. These hydrodynamic simulations show that this material will be embedded in low-velocity supernova debris with a characteristic velocity of ∼100 km s−1. However, the line profiles from the stripped material are somewhat uncertain because this material will be asymmetrically stripped (Liu et al. 2012), and the orientation of the binary relative to our line of sight, at the time of explosion, is unknown. This material will be hidden in early-time spectra by higher velocity, optically thick, iron-rich ejecta, but will then appear in late-time, nebular phase spectra (>250 days; Mattila et al. 2005) as the higher velocity ejecta become optically thin.

Only a handful of nebular phase, high signal-to-noise (S/N) SNe Ia spectra have been published in the literature, with the strongest limits on late-time hydrogen flux coming from Mattila et al. (2005) and Leonard (2007). Mattila et al. (2005) obtained late-time low-resolution spectra of SN 2001el, modeled the emission from solar-metallicity material stripped from a non-degenerate companion, and used both to place an upper limit of ≤0.03 M⊙ on the presence of this material. Leonard (2007) obtained deep, medium-resolution, nebular-phase, multi-epoch spectra of SN 2005am and SN 2005cf at distances ∼37 Mpc and ∼32 Mpc, respectively. Using the approach of Mattila et al. (2005), he placed a ≤0.01 M⊙ upper limit on the presence of any low-velocity solar-abundance material in both SNe. These observations seem to firmly rule out MS companions for these three SNe.

However, a more exotic scenario which might evade these constraints has since been proposed by Justham (2011). In this model, a WD is spun up by the mass it accretes from its
non-degenerate companion, allowing the WD to remain stable above the Chandrasekhar mass and giving the companion time to evolve and contract before the SN explosion. This leaves a smaller and more tightly bound companion at the time of explosion, reducing the amount of stripped material. It therefore is of significant interest to put even stronger constraints on the amount of stripped material for other SNe Ia.

At a mere 6.4 Mpc (Shappee & Stanek 2011), the “plain vanilla” Type Ia SN (SN Ia; as described by Wheeler 2012) is an ideal target for obtaining improved constraints. SN 2011fe was discovered less than one day after explosion by the Palomar Transient Factory (Law et al. 2009) in the Pinwheel Galaxy was an ideal target for obtaining improved constraints. SN 2011fe is of significant interest to put even stronger constraints on the explosion, reducing the amount of stripped material. It therefore is of significant interest to put even stronger constraints on the amount of stripped material for other SNe Ia.

A SN 2011fe was saturated in this epoch’s acquisition images, so no reliable photometry was obtained.

Notes. Observational and derived properties of our time series spectra of SN 2011fe. Days since maximum B brightness assume JD $t_{\text{Bmax}} = 2455816.0 \pm 0.3$ (Richmond & Smith 2012). P.A. is the position angle of the spectrograph slit. Par. P.A. and airmass give the range of parallactic angles and airmasses at the start of each separate observation, respectively. Standard stars were observed on the same night as science observations and, when multiple standards were available, the computed response functions from each standard were averaged. Seeing gives the FWHM for the red/blue channels of the spatial profile in the combined two-dimensional spectra. Exposure times are given for the red/blue channels separately. $r'$ magnitude is derived from the acquisition images. Each flux-calibrated spectra was multiplied by a scale factor derived in the $R$ or $r'$ bands to place it on an absolute flux scale.

\* SN 2011fe was saturated in this epoch’s acquisition images, so no reliable photometry was obtained.

Table 1

| UT Date    | Day | HJD  | P.A. (deg) | Par. P.A. (deg) | Airmass | Flux Standards | Seeing (arcsec) | Exposure (s) | $r'$ (mag) | Scale Factor |
|------------|-----|------|------------|----------------|---------|----------------|----------------|--------------|------------|--------------|
| 2011 Nov 23.52 | 73.02 | 55889.02 | −78.0 | −84.3 to −85.7 | 1.60−1.64 | Feige110, G191-B2B | 0.8/0.9 | 360.0/360.0 | ...* | 1.07 |
| 2012 Jan 2.54  | 113.05 | 55929.05 | −124.4 | −134 to −139 | 1.11−1.12 | Feige34 | 0.8/0.9 | 900.0/900.0 | 14.26 ± 0.03 | 1.93 |
| 2012 Mar 24.47 | 194.97 | 56010.97 | −68.5 | 110−124 | 1.15−1.24 | Feige67 | 0.5/0.7 | 2880.0/2160.0 | 16.35 ± 0.01 | 1.77 |
| 2012 Apr 27.27 | 228.77 | 56044.77 | −2.0 | −159−177 | 1.07−1.08 | HZ44, BD+33d2642 | 0.9/1.1 | 3600.0/3600.1 | 17.06 ± 0.01 | 2.20 |
| 2012 Jun 12.16 | 274.66 | 56090.66 | −32.7 | −177−129 | 1.07−1.13 | HZ44 | 0.7/0.7 | 7200.0/7200.0 | 17.95 ± 0.01 | 1.26 |

Notes. Observational and derived properties of our time series spectra of SN 2011fe. Days since maximum B brightness assume JD $t_{\text{Bmax}} = 2455816.0 \pm 0.3$ (Richmond & Smith 2012). P.A. is the position angle of the spectrograph slit. Par. P.A. and airmass give the range of parallactic angles and airmasses at the start of each separate observation, respectively. Standard stars were observed on the same night as science observations and, when multiple standards were available, the computed response functions from each standard were averaged. Seeing gives the FWHM for the red/blue channels of the spatial profile in the combined two-dimensional spectra. Exposure times are given for the red/blue channels separately. $r'$ magnitude is derived from the acquisition images. Each flux-calibrated spectra was multiplied by a scale factor derived in the $R$ or $r'$ bands to place it on an absolute flux scale.

* SN 2011fe was saturated in this epoch’s acquisition images, so no reliable photometry was obtained.

The Astrophysical Journal Letters, 762:L5 (5pp), 2013 January 1

2. OBSERVATIONS

We obtained five high-S/N spectra of SN 2011fe from 73 to 274 days after maximum $B$-band light using the first of the MODS (Pogge et al. 2010) on the LBT. The two channels of MODS allowed us to obtain wide spectral coverage (3200–10000 Å) in a single exposure, which will make these observations useful for many future studies. Details of the observations and the flux standards used are listed in Table 1. All observations were taken through a 1″ wide slit. To perform basic CCD reductions on our spectra, we followed the “MODS Basic CCD Reduction with modsCCDRed” manual. We then performed cosmic-ray rejection using L.A.Cosmic (van Dokkum 2001) and combined each channel’s two-dimensional spectra for each epoch. Next, we extracted the one-dimensional sky-subtracted spectra using the apall task in IRAF. Each spectrum was then wavelength and flux calibrated. We did not attempt to correct small-scale telluric absorption bands as performed by Leonard (2007). This will not adversely affect our results because the telluric absorptions occur on wavelength scales smaller than the Hα emission expected from the SN. This also avoids adding any noise from telluric spectra to our SN spectra.

Because our spectra were taken under non-photometric conditions with a relatively narrow (1″) slit, it is necessary to scale the fluxes of our spectra to place them on an absolute flux scale. To do this, we performed aperture photometry on our Sloan $r'$ (Fukugita et al. 1996) acquisition images using the IRAF package apphot. Because the SN was saturated in the acquisition image of the first epoch, we must treat that spectrum separately. For the remaining epochs, we used the four brightest stars in the image to put our photometry on the Sloan Digital Sky Survey (SDSS; York et al. 2000) Data Release 7 (DR7; Abazajian et al. 2009) magnitude system. Our $r'$-band magnitudes are reported in Table 1. We then scale the spectrum so that its synthetic $r'$-band photometry matches the computed $r'$-band aperture photometry. For the first epoch we scaled the spectrum such that a synthetic $R$-band magnitude (Bessell & Murphy 2012) matches the $R$-band magnitude for its epoch found by interpolating the combined $R$-band light curves of Richmond & Smith (2012) and Munari et al. (2012). To convert from the AB magnitude system (Oke 1974) of our synthetic photometry to the Vega magnitude system reported in Richmond & Smith (2012) and Munari et al. (2012), we use the conversion presented in Blanton & Roweis (2007). The factor by which each spectrum...
We define a continuum by smoothing our spectra on scales large compared to the expected Hα feature, then subtract off this continuum and examine the residuals. We searched for Hα emission within \( \pm 1000 \) \( \text{km s}^{-1} \) (22 Å) about Hα at the redshift of M101, 0.000804 \( \pm 0.000007 \) (de Vaucouleurs et al. 1991). We smoothed the spectrum with a second-order Savitsky–Golay smoothing polynomial (Press et al. 1992) with a width of 60 Å. Our spectrum requires a smaller smoothing scale than that employed by Leonard (2007) for a good continuum fit. It is, however, still significantly larger than the expected velocity width of any Hα feature. Additionally, we smoothed over the telluric feature at 6510–6525 Å before smoothing the rest of the spectrum because the feature was affecting the continuum determination near Hα.

Our nebular phase spectrum and continuum fit are shown in the top panel of Figure 4 in the vicinity of Hα and are binned to their approximate spectral resolution.

We then subtracted the continuum from the binned spectrum and examined the residuals, shown in the bottom panel of Figure 4, for narrow Hα emission. There is no evidence for any Hα emission in the spectrum. The closest possible emission is the hump in the smoothed continuum at \( \Delta \approx 6575–6595 \) Å, which is discussed in Section 3.2. More broadly, we found no narrow emission lines at any wavelength, including regions around Hβ, [O I] \( \lambda \lambda 6300, 6364 \), [O II] \( \lambda \lambda 7319, 7330 \), [O III] \( \lambda \lambda 4959, 5007 \), [Ca II] \( \lambda \lambda 7291, 7324 \), and [N II] \( \lambda \lambda 6548, 6583 \).

### 3.1. Statistical Limit

Following Leonard & Filippenko (2001) and Leonard (2007), we compute a 3σ upper bound on the equivalent width as

\[
W_\lambda(3\sigma) = 3\Delta\lambda \sqrt{W_{\text{line}} / \Delta X} \sqrt{1 / B}
\]

where \( \Delta\lambda \) is the width of a resolution element (in Å), \( \Delta I \) is the 1σ rms fluctuation of the flux around a normalized continuum level, \( W_{\text{line}} \) is the FWHM of the expected spectral feature (in Å), \( B \) is the number of bins per resolution element in the spectrum, and \( \Delta X \) is the bin size of the spectrum (in Å) for the spectrum shown in Figure 4, \( \Delta I = 0.0024 \) Å and \( \Delta X = 4 \) Å leading to \( W_\lambda(3\sigma) = 0.067 \) Å for \( W_{\text{line}} = 22 \) Å.

To translate this equivalent width constraint into a constraint on the amount of material stripped from a non-degenerate...
The Astrophysical Journal Letters, 762:L5 (5pp), 2013 January 1

We obtain five deep, medium-resolution spectra of the nearby “plain vanilla” SN Ia 2011fe with LBT/MODS from 73 to 274 days after maximum B-band light. With the last nebular phase spectrum we place the deepest flux limits on narrow H\(\alpha\) emission yet for an SN Ia. Determining the late-time H\(\alpha\) emission in SNe Ia spectra requires difficult radiative transfer calculations, but linearly scaling from the models of Mattila et al. (2005), our limit translates into an upper limit on the mass of solar-abundance material of \(\leq 0.001 M_\odot\), an order of a magnitude smaller than previous limits (Leonard 2007). However, two important theoretical questions remain. First, the opacity of the high-velocity iron-rich ejecta should be recomputed to confirm when the SN ejecta becomes optically thin. Second, the excitation of H\(\alpha\) emission by gamma-ray deposition should be modeled in detail assuming various velocity profiles with differing amounts of stripped companion material. These issues notwithstanding, our mass limit poses a significant challenge to more exotic SD models proposed to evade previous constraints. Additionally, our limit strongly rules out all MS and RG companions for which hydrodynamic simulations of the SN ejecta’s impact are presented in the literature.

4. SUMMARY

We thank Douglas C. Leonard for discussions and for providing the nebular phase spectra of SN 2005am and SN 2005cf. We also thank Chris Kochanek, Todd Thompson, Jennifer van Saders, Gisella DeRosa, Dale Mudd, and Joe Antognini for discussions and encouragement. We also thank the anonymous referee for his/her helpful suggestions. B.J.S. was supported by a Graduate Research Fellowship from the National Science Foundation. B.J.S. and K.Z.S. are supported in part by NSF grant AST-0908816. This Letter used data obtained with the MODS spectrographs built with funding from NSF grant AST-9987045 and the NSF Telescope System Instrumentation Program (TSIP), with additional funds from the Ohio Board of Regents and the Ohio State University Office of Research. The LBT is an international collaboration among institutions in the United States, Italy, and Germany. LBT Corporation partners are The Ohio State University, and The Research Corporation, on behalf of the University of Notre Dame, University of Minnesota and University of Virginia; the University of Arizona on behalf of the Arizona university system; Istituto Nazionale

H\(\alpha\) line profile rather than the photon noise of our spectrum. For example, there is a small amplitude feature in our spectrum at 6575–6595 Å. To test if this spectral feature could be attributed to material asymmetrically stripped from a companion, we took the velocity distribution of stripped material from Figure 9 of Liu et al. (2012) and assumed it was narrowly distributed along a line (see Figure 11 of Liu et al. 2012). We found that a total flux of \(2.20 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}\) and an angle between the stripped material and our line of sight of 30° best reproduce the feature in our smoothed continuum. To be conservative, we take a less stringent limit on the total \(H\alpha\) flux of \(3.14 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}\), which is weaker than our statistical limit and too large to explain the spectral feature between 6575 Å and 6595 Å shown in Figure 4. This limit corresponds to an equivalent width of 0.12 Å, a total \(H\alpha\) luminosity of \(1.57 \times 10^{35} \text{ erg s}^{-1}\), and 0.001 \(M_\odot\) of solar-abundance material linearly scaling from the models of Mattila et al. (2005). We emphasize that whether this feature is \(H\alpha\) emission or clumpiness in the underlying SN continuum, our conservative flux limit holds.

Figure 4. Nebular phase spectrum of SN 2011fe illustrating our conservative limit of \(3.14 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}\) on the flux of \(H\alpha\) emission. The rest wavelength of \(H\alpha\) is indicated by the vertical red line and the shaded gray region shows where hydrogen emission would be expected (±1000 km s\(^{-1}\) = ±22 Å about \(H\alpha\)). Adopting the models of Mattila et al. (2005), these limits translate into a \(\leq 0.001 M_\odot\) limit on the amount of solar-abundance material stripped from the companion. The vertical dashed gray line marks a large telluric feature. Top panel: SN spectrum binned to the approximate spectral resolution (4.0 Å; black solid); smoothed continuum (solid red); smoothed continuum with \(H\alpha\) limit added (dashed red); smoothed continuum with \(H\alpha\) limit subtracted to show what the underlying continuum would have to be to get the observed spectrum (dashed blue); and smoothed continuum with \(H\alpha\) limit subtracted, assuming the velocity distribution discussed in Section 3.2 (dotted blue). Middle panel: the location of telluric water vapor absorption lines illustrated by the ESO SM-01 Sky Model Mode Version 1.3.1. Bottom panel: SN spectrum with smoothed continuum subtracted (solid black) as compared to the \(H\alpha\) limit (dashed red). The horizontal solid red line marks zero.

(A color version of this figure is available in the online journal.)

3.2. Conservative Limit

Unlike the Leonard (2007) study, the main uncertainty in our \(H\alpha\) limit arises from the continuum determination and the companion, we follow the analysis of Mattila et al. (2005). Mattila et al. (2005) estimate that 0.5 \(M_\odot\) of solar-abundance material 380 days after explosion produces an \(H\alpha\) feature with peak luminosity of \(~3.36 \times 10^{35} \text{ erg s}^{-1} \text{ Å}^{-1}\). Accounting for the distance to M101 and Galactic extinction toward M101 of \(E(B-V) = 0.009 \text{ mag}\) (Schlegel et al. 1998) and assuming \(R_V = 3.1\), the expected \(H\alpha\) peak flux from 0.5 \(M_\odot\) of stripped material in SN 2011fe is \(6.71 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}\). To allow for comparison with Leonard (2007), we initially approximate the \(H\alpha\) feature as a Gaussian with FWHM 22 Å. This feature would then have an equivalent width of \(W_e(0.05 M_\odot) = 5.8 \text{ Å}\). Scaling linearly from the equivalent width of the \(H\alpha\) emission line to the amount of stripped material, we place an upper limit on the amount of solar-abundance material in SN 2011fe of \(5.8 \times 10^{-4} M_\odot\).
REFERENCES

Abazajian, K. N., Adelman-McCarthy, J. K., Ageros, M. A., et al. 2009, ApJS, 182, 543

Bessell, M., & Murphy, S. 2012, PASP, 124, 140

Blanton, M. R., & Roweis, S. 2007, AJ, 133, 734

Bloom, J. S., Kasen, D., Shen, K. J., et al. 2012, ApJ, 744, L17

Brown, P. J., Dawson, K. S., de Pasquale, M., et al. 2012, ApJ, 753, 22

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr, et al. (ed.) 1991, in Third Reference Catalogue of Bright Galaxies, Vols. 1–3, (Berlin: Springer), 2009

Fukugita, M., Ichikawa, T., Gunn, J. E., et al. 1996, AJ, 111, 1748

Iben, I., Jr., & Tutukov, A. V. 1984, ApJS, 54, 335

Justham, S. 2011, ApJ, 730, L34

Kasen, D. 2010, ApJ, 708, 1025

Law, N. M., Kulkarni, S. R., Dekany, R. G., et al. 2009, PASP, 121, 1395

Leonard, D. C. 2007, ApJ, 670, 1275

Leonard, D. C., & Filippo, A. V. 2001, PASP, 113, 920

Liu, Z. W., Pakmor, R., Roepke, F. K., et al. 2012, A&A, 548, A2

Marietta, E., Burrows, A., & Fryxell, B. 2000, ApJS, 128, 615

Mattila, S., Lundqvist, P., Sollerman, J., et al. 2005, A&A, 443, 649

Meng, X., Chen, X., & Han, Z. 2007, PASJ, 59, 835

Munari, U., Henden, A., Belligl, R., et al. 2012, NA, 20, 30

Nomoto, K. 1982, ApJ, 253, 798

Nugent, P. E., Sullivan, M., Cenko, S. B., et al. 2011, Natur, 480, 344

Oke, J. B. 1974, ApJS, 27, 21

Pakmor, R., Roepke, F. K., Weiss, A., & Hillebrandt, W. 2008, A&A, 489, 943

Pan, K.-C., Ricker, P., & Taam, R. 2012a, ApJ, 760, 21

Pan, K.-C., Ricker, P. M., & Taam, R. E. 2012b, ApJ, 750, 151

Patat, F., Cordier, M. A., Cox, N. L. J., et al. 2011, arXiv:1112.0247

Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, ApJ, 517, 565

Podsiadlowski, P. 2003, arXiv:astro-ph/0303660

Pogge, R. W., Atwood, B., Brewer, D. F., et al. 2010, Proc. SPIE, 7735, 77350A

Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. (ed.) 1992, Numerical Recipes in C. The Art of Scientific Computing (2nd ed.; Cambridge: Cambridge Univ. Press)

Richmond, M. W., & Smith, H. A. 2012, JAVSO, in press (arXiv:1203.4013)

Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, AJ, 116, 1009

Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525

Shappee, B. J., Kochanek, C. S., & Stanek, K. Z. 2012, arXiv:1205.5028

Shappee, B. J., & Stanek, K. Z. 2011, ApJ, 733, 124

Shappee, B. J., & Thompson, T. A. 2012, arXiv:1204.1053

Thompson, T. A. 2011, ApJ, 741, 82

Tutukov, A. V., & Yungelson, L. R. 1979, Acta Astron., 29, 665

van Dokkum, P. G. 2001, PASP, 113, 1420

Wang, B., & Han, Z. 2012, NewAR, 56, 122

Webbink, R. F. 1984, ApJ, 277, 355

Wheeler, J. C. 2012, ApJ, 758, 123

Wheeler, J. C., Lecar, M., & McKee, C. F. 1975, ApJ, 200, 145

Whelan, J., & Iben, I. J. 1973, ApJ, 186, 1007

Wood-Vasey, W. M., Miknaitis, G., Stubbs, C. W., et al. 2007, ApJ, 666, 694

York, D. G., Adelman, J., Anderson, J. E., Jr., et al. 2000, AJ, 120, 1579