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Supplementary Materials for

PTF 11kx: A Type Ia Supernova with a Symbiotic Nova Progenitor

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Supplementary Material

S1. Spectroscopy

Optical spectra of PTF 11kx were obtained with several different telescopes: the Lick 3 m, Palomar 5 m, KPNO 4 m, WHT, Keck, and Gemini North. Spectra from the High Resolution Echelle Spectrometer (HIRES) on Keck I were reduced using the Mauna Kea Echelle Extraction (`makee`) software package[1]. Spectra from other telescopes and instruments were reduced using standard methods. Journals of observations are given in Tables S1 and S2; UT dates are used throughout this paper. A time series of low-resolution spectra for PTF 11kx is shown in Fig. 1.

S2. Photometry

Photometry in the r band was collected as part of the normal PTF transient search on the Palomar 48 in telescope (*36*). PTF 11kx was also followed by the 2 m Faulkes Telescope North. Between January 27, 2011 and June 9, 2011 (133 days), 46 epochs were obtained in the SDSS g and r bands, and 45 epochs in the SDSS i band. Photometric observations of PTF 11kx were resumed on September 30, 2011. At the location of PTF 11kx there is a substantial background due to the host galaxy. When this is the case, photometry for SNe is usually accomplished through difference imaging analysis, where an image without the SN present is used as a difference imaging template. Reference images for PTF 11kx have not yet been taken on the Faulkes North, and so only preliminary photometry is currently available. To at least roughly subtract the host galaxy, we used SDSS images as difference imaging templates. Visual inspection of the difference images reveals that the host-galaxy background is subtracted successfully, and thus the use of templates from a different instrument does not significantly affect the conclusions that PTF 11kx is a member of the broad/bright SN class. Initial photometry suggests that PTF 11kx declines more slowly at epochs later than $\sim +20$ days than the templates of the same class, which is another indication of circumstellar interaction, and late-time (~ 280 days) photometry confirms this. Data were processed using the `photpipe` reduction pipeline (*37, 38*). Difference imaging was done using `hotpants` (*39*). Source detection and PSF photometry was done using `dophot` (*40*). The photometry was calibrated by comparison of stars in the field of PTF 11kx to magnitudes provided by the SDSS DR8 database (*41*).

S3. SN Light Curve

Comparing the colors of the SN to templates from the SiFTO SN light-curve model (*42*), we estimate that the SN is only moderately extinguished by dust, with the extinction amounting

[1] http://spider.ipac.caltech.edu/staff/tab/makee

to ~ 0.5 mag in the V band. It is commonly assumed that the equivalent width of the Na D lines is correlated with the value for extinction by dust (e.g. *43*), and so the small value of the equivalent width of the non-variable Na D lines also supports this conclusion. While this correlation has been shown to have significant scatter (*44*), this is most relevant for equivalent widths larger than those measured in PTF 11kx. Assuming a concordance cosmology ($H_0 = 70$ km s^{-1} Mpc^{-1}), the absolute B-band magnitude of PTF 11kx is ~ -19.3, which is on the bright end of the SN Ia luminosity function and is consistent with the observed distribution of high-stretch SNe Ia. The date of maximum light (in the B band) of PTF 11kx is January 29, 2011. Comparisons with the broad SN Ia 1999aa (*45*), the "normal" SN Ia 2002er (*45*), and the CSM-interaction SNe Ia 2002ic (*17*) and 2005gj (*46*), are shown in Fig. S1. While the photometry is preliminary, we can draw a few important conclusions: (i) the light curve is of the high-stretch class and is qualitatively similar to that of SN 1999aa and SN 1991T, (ii) the light curve is markedly dissimilar to that of SN 2002ic and SN 2005gj, and (iii) the absolute magnitude at peak is consistent with the population of previously observed SNe Ia.

S4. Radio Observation

PTF 11kx was observed on March 30, 2011 in the X-band using the Expanded Very Large Array (EVLA), yielding a nondetection with a 1σ root-mean-square of 23 μJy. Using a model of SN interaction with a smooth wind puts an upper limit on the inferred mass-loss rate in the wind (*47*) of $\sim 4.5 \times 10^{-6}$ $\mathrm{M}_\odot$ yr^{-1} (v_w/10 km s^{-1})$^{1.65}$, where v_w is the velocity of the wind. The radio emission strength depends on microphysical parameters such as the strength of the magnetic fields generated in the interaction (the ϵ_B parameter), and if these magnetic fields are weaker than has generally been assumed, then the constraints on the rate of mass loss would be less strict by perhaps an order of magnitude (*31*). Estimates of the mass-loss rate for symbiotic novae such as RS Ophuichi are $\sim 3 \times 10^{-7}$ $\mathrm{M}_\odot$ yr^{-1}, well below our constraint (*48*).

S5. Host-Galaxy Properties

The host galaxy of PTF 11kx is SDSS J080913.18+461842.9, a late-type, spiral galaxy. PTF 11kx occurred approximately 6.75" away from the core of the galaxy at (J2000) RA = 08:09:12.87, DEC = +46:18:48.8. The properties of the host galaxy, such as the star-formation rate, mass, and metallicity, are not unusual in any way. The absolute magnitude is $M_g \approx -19.47$, and the metallicity has been derived by (*49*) to be 12 + log(O/H) ≈ 8.93, which is slightly larger than solar. This indicates that PTF 11kx does not obviously arise from an atypical local environment. As a comparison, the host galaxies for SN 2002ic and SN 2005gj were low-luminosity galaxies with corresponding low metallicities, which has been assumed to play a role in the presence of CSM in the SN systems. PTF 11kx demonstrates that CSM interaction can occur in a SN Ia even in a more normal galactic environment.

S6. Alternative Models for CSM-Interaction SNe Ia

As discussed in the main text, PTF 11kx bears similarities to SN 2002ic, an apparent SN Ia with circumstellar interaction. Subsequent to the discovery of SN 2002ic, several alternative models were proposed as possible explanations. Given the association of PTF 11kx with SN 2002ic we question whether any of those models are viable alternatives for PTF 11kx. In PTF 11kx, the multiple shells of CSM, the nonuniform distribution of the CSM, and the long delay between explosion and circumstellar interaction are important additional constraints.

The "SN 1.5" Model: The "SN 1.5" model involves the explosion of the degenerate core of a massive star (*50*). This model cannot explain the long delay in the onset of emission, the nonuniform distribution of CSM, or the multiple shells of material seen in PTF 11kx.

A Luminous Blue Variable Progenitor: The arguments for an LBV progenitor applied only to SN 2005gj (*51*), which had much stronger CSM interaction than SN 2002ic, and were based mainly on the double P-Cygni profile in the Hα line, a feature which is not present in PTF 11kx.

A Peculiar SN Ic: The possibility that SN 2002ic was a SN Ic (*52*) was based on the possible presence of Mg and O in the late-time spectra. The spectra of PTF 11kx shown in Fig. 1 definitively rule out a core-collapse SN in this case.

A Double-Degenerate SN Ia: Subsequent to the suggestion that SN 2002ic had a double-degenerate progenitor (*53*), additional modeling has shown that it is not expected that any significant circumstellar material from the common-envelope phase can remain at the time of the SN explosion (*22*). Moreover, modeling of the possible CSM due to wind generated during the merger process of a double-degenerate progenitor cannot account for the presence of hydrogen (*23*). A double-degenerate progenitor also does not explain the multiple distinct shells of CSM.

Supersoft, Single-Degenerate Progenitor: The model of (*54*) could possibly explain many of the features of PTF 11kx, but our symbiotic nova model naturally explains the low expansion velocity of the CSM (65 km s^{-1} for PTF 11kx instead of ~ 100 km s^{-1}), the multiple shells of CSM, and the delay between explosion and interaction, while the (*54*) model does not.

S7. Rate of SNe Ia with Symbiotic Nova Progenitors

One of the features of PTF 11kx that supports the conclusion that it is from a symbiotic nova progenitor is the prominent H and Ca emission seen ~ 59 days after explosion. The SDSS-II SN Survey had a high degree of spectroscopic completeness for SNe Ia at $z < 0.15$, and the discovery of one CSM-interaction SN Ia (SN 2005gj) in a sample of 80 SNe Ia with

$z < 0.15$ implies a rate of such SNe of $\sim 1\%$ (*55*). The Palomar Transient Factory currently has discovered ~ 1000 SNe Ia with one known example of a CSM-interaction SN Ia (PTF 11kx), but the spectroscopic completeness has not yet been determined or quantified and so this can only be considered an order of magnitude estimate for the rate of CSM-interaction SNe.

However, an important conclusion from the discovery of PTF 11kx is that SNe Ia exist that show CSM-interaction at weaker levels and later onset than SN 2002ic and SN 2005gj. This suggests that there is a continuum of CSM-interaction in SNe Ia. If the continuum of interaction strength extends to lesser values and later onsets, then the signs of interaction would be missed in a large fraction of SNe Ia, as they do not typically have high-signal-to-noise ratio spectroscopic observations at epochs > 60 days after explosion. The discovery of PTF 11kx highlights the importance of more extensive spectroscopic and photometric follow-up monitoring for SNe Ia extending to late times to determine the rate of SNe Ia with significant circumstellar material from the progenitor system. Furthermore, CSM-interaction SNe Ia with greater interaction strength could be classified as SNe IIn and these would contribute an undetermined fraction to the overall SN Ia rate. Therefore, we can only say that SNe Ia with prominent CSM interaction occurring near maximum light is ~ 0.1–1%. Population synthesis modeling predicts the fraction of SNe Ia from the symbiotic binary channel to be $\sim 1\%$ (*33*) to as much as 30% (*34*), which encompasses the range of observational constraints.

The existence of a red giant companion could in principle be detected through radio emission due to interaction of the SN ejecta with the wind from the secondary, but no SN Ia has yet been detected in the radio. However, the mass-loss limits derived via radio nondetections (*47*, *56*) do not generally constrain RS Oph-like systems which has a mass-loss rate of $\sim 3 \times 10^{-7}$ $\mathrm{M}_{\odot}$ yr^{-1}. Moreover, theory and observations suggest that the CSM distribution in symbiotic novae is nonuniform and the expected radio emission taking this into consideration has not yet been modeled. It is therefore unclear what effect this has on the limits derived from nondetection, but it is plausible that this would introduce a viewing-angle dependence that would decrease the chance for detecting the radio signal.

S8. Hα and Ca II Fluxes

Starting with the day $+39$ spectrum, a broad component of the Hα emission begins to appear; the profile can be decomposed into broad and narrow components. The full width at half-maximum intensity (FWHM) and the integrated fluxes in the broad component are given in Table S3. Starting with the day $+56$ spectrum, the Ca II emission begins to have a Gaussian appearance and the residual absorption seen in earlier spectra appears to be gone. The FWHM and the integrated fluxes in the Ca II H&K lines are given in Table S4. To derive these values, the spectra were first spectrophotometrically calibrated to the r-band photometry from the Faulkes 2 m telescope. The Gaussian components of the emission feature were then fit using the deblending function in the `iraf splot` procedure.

S9. Mass Estimates

In the near-maximum-light spectra, the equivalent widths of the Ca II H&K lines are ~ 10 Å. The lines are saturated, and on the square-root portion of the curve of growth, so that the equivalent width, W_λ, is given by

$$W_\lambda = (N \frac{\lambda_0^4}{2\pi c} \frac{g_u}{g_l} A_{ul} \gamma_u)^{1/2}, \tag{1}$$

where N is the column density, λ_0 is the wavelength of the transition, A_{ul} is the Einstein spontaneous emission coefficient, γ_u is the radiation damping constant, and g_u and g_l are the statistical weights of the upper and lower states, respectively. For the Ca II K line, with $\lambda_0 = 3933.6$ Å, this results in $N = 4.44 \times 10^{16}\, W_\lambda^2\, \mathrm{cm}^{-2}$. Thus, the column density in Ca II is $\sim 5 \times 10^{18}\, \mathrm{cm}^{-2}$. We write the total Ca mass as $M_{\mathrm{Ca}} = k \times 4\pi r^2$, where r is the radius at which the material exists and k is the covering fraction. The radius, r, can be estimated from the velocity of the SN ejecta, which we take to be $v \approx$ 25,000 km s^{-1}, and the time at which the Ca goes into emission, which is $\sim +59$ days after explosion. This results in

$$M_{\mathrm{Ca}} = 3.43 \times 10^{-4}\, k\, (\frac{v}{25,000\ \mathrm{km\ s^{-1}}} \frac{t}{59\ \mathrm{days}})^2 (\frac{N}{5 \times 10^{18}\ \mathrm{cm}^{-2}})\ \mathrm{M}_\odot. \tag{2}$$

Assuming a solar composition for the CSM, a value of $k = 1$ would imply a total mass in the CSM shell of $\sim 5.3\ \mathrm{M}_\odot$. Modeling of the light curve for the CSM SNe 1997cy and 2002ic results in an estimate of the mass in the CSM for those SNe of several solar masses (*22*). The total luminosity of PTF 11kx is much less, and the decline rate much greater than that of either SN 1997cy or SN 2002ic, implying that the total CSM mass is also much less. Thus, we conclude that $k \ll 1$, and that the CSM material that generates the Ca II absorption is not uniformly distributed.

UT Date	Exposure Time (s)	SN Phase (days)	Wavelength Range	Median S/N	R $(\lambda/\Delta\lambda)$
20110128	1000	-1	3682-6538	10.4	48000
20110207	1800	+9	4017-8564	6.2	48000
20110218	1800	+20	3682-7993	3.5	48000
20110314	3600	+44	3682-7992	4.2	48000

Table S1. Journal of high-resolution spectroscopic observations. All spectra were taken with the HIRES instrument (*57*) on the Keck I telescope.

UT Date	Telescope	SN Phase (days)	Wavelength Range (Å)
20110126	Lick 3m	-3	$3448 - 10142$
20110128	Palomar 200in	-1	$3490 - 9750$
20110202	Lick 3m	+4	$3440 - 9754$
20110203	KPNO 4m	+5	$3487 - 7570$
20110209	Lick 3m	+11	$3430 - 10138$
20110221	WHT	+23	$3190 - 9279$
20110227	Lick 3m	+29	$3400 - 10000$
20110309	Keck1	+39	$3330 - 10188$
20110312	Keck1	+42	$3948 - 6128$
20110326	Keck1	+56	$3125 - 10233$
20110402	Gemini North	+63	$3815 - 9701$
20110411	KPNO 4m	+72	$3450 - 8451$
20110427	Keck1	+88	$3100 - 10200$
20110608	WHT	+130	$3036 - 9499$

Table S2. Journal of low-resolution spectroscopic observations.

UT Date	SN Phase (days)	σ_v (km s^{-1})	Flux (ergs s^{-1})
20110309	+39	600	1.64e+39
20110326	+56	980	4.36e+39
20110402	+63	1050	4.60e+39
20110427	+88	1590	1.84e+40
20110608	+130	2040	1.29e+40

Table S3. Hα velocity dispersion and integrated flux values.

UT Date	SN Phase (days)	CaII K σ_v (km s^{-1})	CaII K Flux (ergs s^{-1})	CaII H σ_v (km s^{-1})	CaII H Flux (ergs s^{-1})
20110326	+56	780	4.56e+39	610	2.75e+39
20110402	+63	680	2.56e+39	380	1.10e+39
20110427	+88	850	4.42e+39	970	2.72e+39

Table S4. Ca II H & K velocity dispersions and integrated flux values.

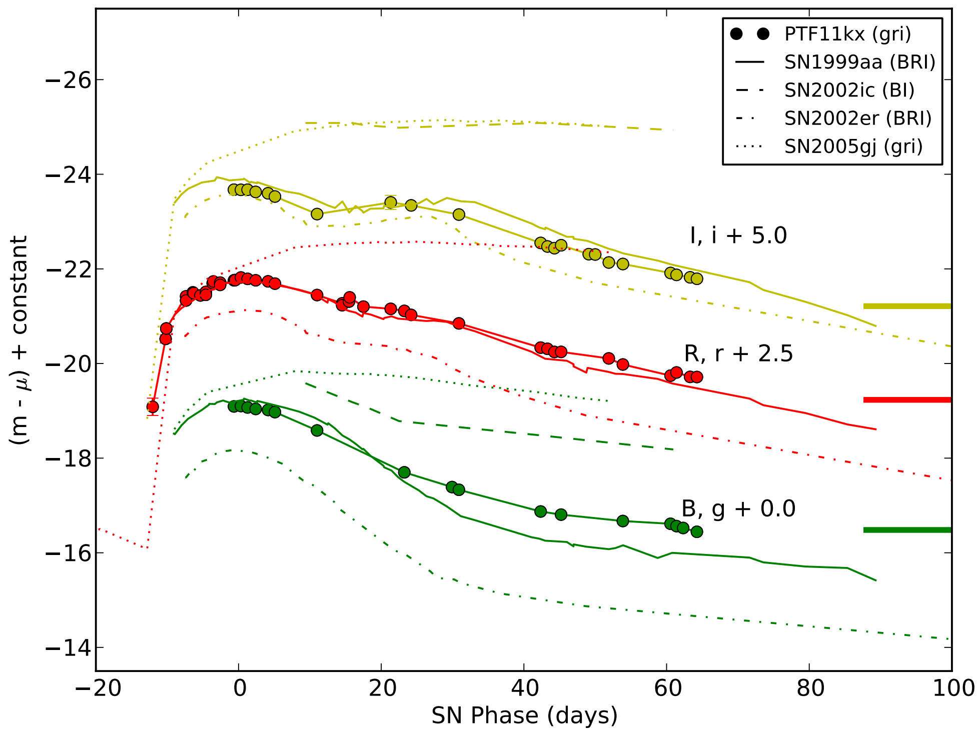

Figure S1: Comparison of the preliminary light curve of PTF 11kx to that of other SNe Ia. The data are the observer-frame magnitudes, without K-corrections. The PTF 11kx and SN 2005gj photometry is given in gri, and the other SNe in some combination of BRI. The red, green, and yellow points denote B/g, R/r, and I/i, respectively. The broad/bright SN 1999aa (solid) and the "normal" SN 2002er (dash-dot) are shown for comparison. Also shown are the CSM-interaction SNe Ia 2002ic (dashed) and 2005gj (dotted). PTF 11kx is much fainter than SN 2005gj and SN 2002ic, indicating a weaker/later onset of CSM interaction. The late-time, approximately constant, brightness of PTF 11kx is marked by the horizontal lines on the right side of the figure. Spectroscopically and photometrically, PTF 11kx bridges the observational gap between SN 1991T/SN 1999aa and SN 2002ic/SN 2005gj.

References

1. H. Aihara *et al*., The eighth data release of the Sloan Digital Sky Survey: First data from SDSS-III. *Astrophys. J. Suppl. Ser.* **193**, 29 (2011). doi:10.1088/0067-0049/193/2/29

2. D. E. Welty, D. C. Morton, L. M. Hobbs, A high-resolution survey of interstellar CA II absorption. *Astrophys. J. Suppl. Ser.* **106**, 533 (1996). doi:10.1086/192347

3. I. P. Pskovskii, *Sov. Astron.* **21**, 675 (1977).

4. M. M. Phillips, The absolute magnitudes of type IA supernovae. *Astrophys. J.* **413**, L105 (1993). doi:10.1086/186970

5. P. Nugent, M. Phillips, E. Baron, D. Branch, P. Hauschildt, Evidence for a spectroscopic sequence among type Ia supernovae. *Astrophys. J.* **455**, L147 (1995). doi:10.1086/309846

6. W. Li *et al*., A high intrinsic peculiarity rate among type Ia supernovae. *Astrophys. J.* **546**, 734 (2001). doi:10.1086/318299

7. G. Garavini *et al*., Spectroscopic observations and analysis of the peculiar SN 1999aa. *Astron. J.* **128**, 387 (2004). doi:10.1086/421747

8. W. Li *et al*., Nearby supernova rates from the Lick Observatory Supernova Search - II. The observed luminosity functions and fractions of supernovae in a complete sample. *Mon. Not. R. Astron. Soc.* **412**, 1441 (2011). doi:10.1111/j.1365-2966.2011.18160.x

9. F. Patat *et al*., Detection of circumstellar material in a normal type Ia supernova. *Science* **317**, 924 (2007). doi:10.1126/science.1143005 Medline

10. A. Sternberg *et al*., Circumstellar material in type Ia supernovae via sodium absorption features. *Science* **333**, 856 (2011). doi:10.1126/science.1203836 Medline

11. J. D. Simon *et al*., Variable sodium absorption in a low-extinction type Ia supernova. *Astrophys. J.* **702**, 1157 (2009). doi:10.1088/0004-637X/702/2/1157

12. D. Kasen, Seeing the collision of a supernova with its companion star. *Astrophys. J.* **708**, 1025 (2010). doi:10.1088/0004-637X/708/2/1025

13. N. N. Chugai, Circumstellar Na I and Ca II absorption lines of type Ia supernovae in the symbiotic scenario. *Astron. Lett.* **34**, 389 (2008). doi:10.1134/S1063773708060030

14. I. Iben, Jr., A. V. Tutukov, Supernovae of type I as end products of the evolution of binaries with components of moderate initial mass (M not greater than about 9 solar masses). *Astrophys. J. Suppl. Ser.* **54**, 335 (1984). doi:10.1086/190932

15. D. Branch, M. Livio, L. R. Yungelson, F. R. Boffi, E. Baron, In search of the progenitors of type Ia supernovae. *Publ. Astron. Soc. Pac.* **107**, 1019 (1995). doi:10.1086/133657

16. M. Hamuy *et al*., An asymptotic-giant-branch star in the progenitor system of a type Ia supernova. *Nature* **424**, 651 (2003). doi:10.1038/nature01854 Medline

17. G. Aldering *et al*., Nearby supernova factory observations of SN 2005gj: Another type Ia supernova in a massive circumstellar envelope. *Astrophys. J.* **650**, 510 (2006). doi:10.1086/507020

18. Additional information is available in the supplementary materials on *Science* Online.

19. R. Walder, D. Folini, S. N. Shore, 3D simulations of RS Ophiuchi: From accretion to nova blast. *Astron. Astrophys.* **484**, L9 (2008). doi:10.1051/0004-6361:200809703

20. F. Patat *et al*., Connecting RS Ophiuchi to [some] type Ia supernovae. *Astron. Astrophys.* **530**, A63 (2011). doi:10.1051/0004-6361/201116865

21. W. M. Wood-Vasey, J. L. Sokoloski, Novae as a mechanism for producing cavities around the progenitors of SN 2002ic and other type Ia supernovae. *Astrophys. J.* **645**, L53 (2006). doi:10.1086/506179

22. N. N. Chugai, L. R. Yungelson, Type-Ia supernovae in dense circumstellar gas. *Astron. Lett.* **30**, 65 (2004). doi:10.1134/1.1646691

23. K. J. Shen, L. Bildsten, D. Kasen, E. Quataert, The long-term evolution of double white dwarf mergers. *Astrophys. J.* **748**, 35 (2012). doi:10.1088/0004-637X/748/1/35

24. A. Conley *et al*., SiFTO: An empirical method for fitting SN Ia light curves. *Astrophys. J.* **681**, 482 (2008). doi:10.1086/588518

25. M. Sullivan *et al*., Rates and properties of type Ia supernovae as a function of mass and star formation in their host galaxies. *Astrophys. J.* **648**, 868 (2006). doi:10.1086/506137

26. D. Maoz, K. Sharon, A. Gal-Yam, the supernova delay time distribution in galaxy clusters and implications for type-Ia progenitors and metal enrichment. *Astrophys. J.* **722**, 1879 (2010). doi:10.1088/0004-637X/722/2/1879

27. D. A. Howell *et al*., The type Ia supernova SNLS-03D3bb from a super-Chandrasekhar-mass white dwarf star. *Nature* **443**, 308 (2006). doi:10.1038/nature05103 Medline

28. J. M. Silverman *et al*., Fourteen months of observations of the possible super-Chandrasekhar mass type Ia supernova 2009dc. *Mon. Not. R. Astron. Soc.* **410**, 585 (2011). doi:10.1111/j.1365-2966.2010.17474.x

29. B. E. Schaefer, A. Pagnotta, An absence of ex-companion stars in the type Ia supernova remnant SNR 0509-67.5. *Nature* **481**, 164 (2012). doi:10.1038/nature10692 Medline

30. W. Li *et al*., Exclusion of a luminous red giant as a companion star to the progenitor of supernova SN 2011fe. *Nature* **480**, 348 (2011). doi:10.1038/nature10646 Medline

31. P. E. Nugent *et al*., Supernova SN 2011fe from an exploding carbon-oxygen white dwarf star. *Nature* **480**, 344 (2011). doi:10.1038/nature10644 Medline

32. A. Horesh *et al*., early radio and x-ray observations of the youngest nearby type Ia supernova PTF 11kly (SN 2011fe). *Astrophys. J.* **746**, 21 (2012). doi:10.1088/0004-637X/746/1/21

33. A. Chiotellis, K. M. Schure, J. Vink, The imprint of a symbiotic binary progenitor on the properties of Kepler's supernova remnant. *Astron. Astrophys.* **537**, A139 (2012). doi:10.1051/0004-6361/201014754

34. Z. Han, P. Podsiadlowski, The single-degenerate channel for the progenitors of type Ia supernovae. *Mon. Not. R. Astron. Soc.* **350**, 1301 (2004). doi:10.1111/j.1365-2966.2004.07713.x

35. G. Lü, C. Zhu, Z. Wang, N. Wang, An alternative symbiotic channel to type Ia supernovae. *Mon. Not. R. Astron. Soc.* **396**, 1086 (2009). doi:10.1111/j.1365-2966.2009.14777.x

36. N. M. Law *et al*., The Palomar Transient Factory: System overview, performance, and first results. *Publ. Astron. Soc. Pac.* **121**, 1395 (2009). doi:10.1086/648598

37. A. Rest *et al*., Testing LMC microlensing scenarios: The discrimination power of the SuperMACHO microlensing survey. *Astrophys. J.* **634**, 1103 (2005). doi:10.1086/497060

38. G. Miknaitis *et al*., The ESSENCE supernova survey: Survey optimization, observations, and supernova photometry. *Astrophys. J.* **666**, 674 (2007). doi:10.1086/519986

39. A. C. Becker *et al*., The Deep Lens Survey transient search. I. Short timescale and astrometric variability. *Astrophys. J.* **611**, 418 (2004). doi:10.1086/421994

40. P. L. Schechter, M. Mateo, A. Saha, DOPHOT, a CCD photometry program: Description and tests. *Publ. Astron. Soc. Pac.* **105**, 1342 (1993). doi:10.1086/133316

41. H. Aihara *et al*., The eighth data release of the Sloan Digital Sky Survey: First data from SDSS-III. *Astrophys. J. Suppl. Ser.* **193**, 29 (2011). doi:10.1088/0067-0049/193/2/29

42. A. Conley *et al*., SiFTO: An empirical method for fitting SN Ia light curves. *Astrophys. J.* **681**, 482 (2008). doi:10.1086/588518

43. M. Turatto, S. Benetti, E. Cappellaro, in *From Twilight to Highlight: The Physics of Supernovae*, W. Hillebrandt, B. Leibundgut, Eds. (Springer, Heidelberg, 2003), p. 200.

44. D. Poznanski, M. Ganeshalingam, J. M. Silverman, A. V. Filippenko, Low-resolution sodium D absorption is a bad proxy for extinction. *Mon. Not. R. Astron. Soc.* **415**, L81 (2011). doi:10.1111/j.1745-3933.2011.01084.x

45. S. Jha, A. G. Riess, R. P. Kirshner, Improved distances to type Ia supernovae with multicolor light-curve shapes: MLCS2k2. *Astrophys. J.* **659**, 122 (2007). doi:10.1086/512054

46. J. A. Holtzman *et al*., The Sloan Digital Sky Survey-II: Photometry and supernova Ia light curves from the 2005 data. *Astron. J.* **136**, 2306 (2008). doi:10.1088/0004-6256/136/6/2306

47. N. Panagia *et al*., A search for radio emission from type Ia supernovae. *Astrophys. J.* **646**, 369 (2006). doi:10.1086/504710

48. F. Patat *et al*., Connecting RS Ophiuchi to [some] type Ia supernovae. *Astron. Astrophys.* **530**, A63 (2011). doi:10.1051/0004-6361/201116865

49. C. A. Tremonti *et al*., The origin of the mass-metallicity relation: Insights from 53,000 star-forming galaxies in the Sloan Digital Sky Survey. *Astrophys. J.* **613**, 898 (2004). doi:10.1086/423264

50. I. Iben, Jr., A. Renzini, Asymptotic giant branch evolution and beyond. *Annu. Rev. Astron. Astrophys.* **21**, 271 (1983). doi:10.1146/annurev.aa.21.090183.001415

51. C. Trundle, R. Kotak, J. S. Vink, W. P. S. Meikle, SN 2005 gj: Evidence for LBV supernovae progenitors? *Astron. Astrophys.* **483**, L47 (2008). doi:10.1051/0004-6361:200809755

52. S. Benetti *et al*., Supernova 2002ic: The collapse of a stripped-envelope, massive star in a dense medium? *Astrophys. J.* **653**, L129 (2006). doi:10.1086/510667

53. M. Livio, A. G. Riess, Have the elusive progenitors of type Ia supernovae been discovered? *Astrophys. J.* **594**, L93 (2003). doi:10.1086/378765

54. Z. Han, P. Podsiadlowski, A single-degenerate model for the progenitor of the type Ia supernova 2002ic. *Mon. Not. R. Astron. Soc.* **368**, 1095 (2006). doi:10.1111/j.1365-2966.2006.10185.x

55. B. Dilday *et al*., Measurements of the rate of type Ia supernovae at redshift $\lesssim$0.3 from the Sloan Digital Sky Survey ii supernova survey. *Astrophys. J.* **713**, 1026 (2010). doi:10.1088/0004-637X/713/2/1026

56. C. R. Eck, J. J. Cowan, D. Branch, A search for radio emission from supernovae with ages from about 1 week to more than 80 years. *Astrophys. J.* **573**, 306 (2002). doi:10.1086/340583

57. S. S. Vogt *et al*., in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 2198, D. L. Crawford, E. R. Craine, Eds. (SPIE, Bellingham, WA, 1994), p. 362.