Very late photometry of SN 2011fe

W. E. Kerzendorf[1], S. Taubenberger[2], I. R. Seitenzahl[3,2,4], A. J. Ruiter[3,2]
wkerzendorf@gmail.com

ABSTRACT

The Type Ia supernova SN 2011fe is one of the closest supernovae of the past decades. Due to its proximity and low dust extinction, this object provides a very rare opportunity to study the extremely late time evolution ($> 900\,\mathrm{d}$) of thermonuclear supernovae. These late stages allow for a direct measurement of the decay processes of nuclei synthesized in the core of the explosion. In this paper, we present our photometric data of SN 2011fe taken at an unprecedentedly late epoch of $\approx 930\,\mathrm{d}$ with GMOS-N mounted on the Gemini North telescope ($g=23.37\pm0.25$, $r=24.03\pm0.09$, $i=23.90 \pm 0.15$, and $z=23.74 \pm 0.16$) to study the energy production and retention in the ejecta of SN 2011fe. Together with previous measurements by other groups, our result suggests that the optical supernova light curve can still be explained by the full thermalization of the decay positrons of ^{56}Co. This is in spite of several theoretical predictions that advocate a substantial energy redistribution and/or loss via various processes which result in a more rapid dimming at these very late epochs.

Subject headings: supernovae: individual(SN 2011fe) – nuclear reactions – techniques: photometric

1. Introduction

Type Ia supernovae (SNe Ia) constitute explosive endpoints of stellar evolution, are major contributors to galactic chemical evolution, and as distance indicators are one of astronomy's most powerful cosmological tools. Despite their wide-ranging applications, there are still many open questions about the physical processes that lead to, result in, and sustain the transient phenomena that we know as SNe Ia.

While there is almost unanimous agreement that these events are powered by the nuclear burning of massive ($\geq 1M_{\odot}$) carbon/oxygen white dwarfs (CO-WDs), there remain many open questions about the scenarios leading to the creation of these objects, the subsequent ignition, and engines that power the light curves and spectra we observe.

Despite the uncertainty about the specifics of energy generation, the community agrees that the luminosity of SNe Ia is powered by the decay of radioactive nuclei produced in the explosion. The initial energy comes in the form of decay positrons, electrons, x-rays, and γ-rays, which is then reprocessed in the ejecta to UVOIR wavelengths. In particular, the $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ decay chain is responsible for the majority of the energy deposition that leads to the observed luminosity. ^{56}Ni (half-life $\sim$6 d) has nearly fully decayed 50 d after the explosion and the light curve is then mostly powered by the decay of ^{56}Co (half-life $\sim$77 d). At 300 d the ejecta have become almost completely transparent to γ-rays and only the charged decay leptons, most notably the positrons produced in β^{+} decay of ^{56}Co, and low energy x-rays can deposit their energy, and thus determine the UVOIR luminosity of the supernova. This suggests that from this time (at least until the internal con-

---

[1] Department of Astronomy and Astrophysics, University of Toronto, 50 Saint George Street, Toronto, ON M5S 3H4, Canada

[2] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, 85748 Garching, Germany

[3] Research School of Astronomy and Astrophysics, Mount Stromlo Observatory, Cotter Road, Weston Creek, ACT 2611, Australia

[4] Universität Würzburg, Emil-Fischer-Straße 31, 97074 Würzburg

version and Auger electrons produced in the decay of ^{57}Co dominate the energy injection, see e.g. Seitenzahl et al. 2009), the light curve should show a decline following the half-life of ^{56}Co. This has been corroborated by the relatively few normal SNe Ia that have been observed at these late times (e.g. Cappellaro et al. 1997; Sollerman et al. 2004; Lair et al. 2006; Stritzinger & Sollerman 2007; Leloudas et al. 2009). One should specifically mention SN 1992A, which, with observations at 926 d past maximum, before this work held the record for the latest measurement of any spectroscopically normal SN Ia (Cappellaro et al. 1997).

The relatively strict adherence of the supernova light curves to the ^{56}Co-decay at these very late epochs is puzzling, as it requires the trapping of a constant fraction of the energy produced in the decay chain over a relatively long time. This seems to be the case despite theoretical predictions of various effects that might lead to a more rapid dimming in the observed bands and departure of the light curve decline from the ^{56}Co decay rate. Specifically, we will discuss three possible main sources of deviation from the exponential decay light curve. First, Chan & Lingenfelter (1993) suggested that positrons may begin to escape from the supernova (SN) without annihilating as early as a few hundred days after explosion, resulting in a departure from the exponential decline. While some authors (e.g. Milne et al. 1999, 2001) argue for moderate positron escape occurring in some SNe Ia, recent publications that take essential near-IR corrections into account require almost complete trapping of positrons up to quite late epochs to explain observations (e.g. Stritzinger & Sollerman 2007; Leloudas et al. 2009). Ruiz-Lapuente & Spruit (1998) suggest that a magnetic field is responsible for this complete trapping and propose using the light curve shape as an indicator for magnetic field strength and configuration. They argue that a complete trapping (resulting in the bolometric light-curve following ^{56}Co decay) indicates a highly tangled magnetic field, which they suggest can result from the accretion in a Chandrasekhar mass scenario. For an edge-lit sub-Chandrasekhar mass scenario, Ruiz-Lapuente & Spruit (1998) suggest that the magnetic field configuration enhances the escape of positrons and thus predict that this would lead to a deviation from ^{56}Co decay.

A second scenario leading to a departure from ^{56}Co decay, specifically in the UVOIR bands, is the so-called infrared catastrophe (IRC; Axelrod 1980), which predicts that the optical and near-IR light curves drop off much more rapidly after $\sim$500 d, even if all positrons remain trapped. The IRC is predicted to occur when the temperature drops below what is required to excite optical and near-IR atomic transitions ($T \lesssim 1500\,\mathrm{K}$), and cooling suddenly proceeds via fine structure lines emitting in the far-IR. This effect is still predicted by modern supernova radiative transfer codes (e.g. Leloudas et al. 2009), but not seen in observational data (e.g. Sollerman et al. 2004; Leloudas et al. 2009; McCully et al. 2014). The final scenario that might lead to dimming in the UVOIR bands is the formation of dust. However, Nozawa et al. (2011) argue that normal SNe Ia are unlikely sites of dust formations and thus predict no extinction of the light-curve at very late times due to newly-formed dust (this does not necessarily extend to unusual SNe Ia; see Taubenberger et al. 2013).

SN 2011fe (Nugent et al. 2011; Li et al. 2011) is one of the closest SNe Ia in the last century (6.4 Mpc; Shappee & Stanek 2011) and is essentially unattenuated by foreground dust. The last SN Ia that could have been observed in similarly exquisite detail as SN 2011fe (if today's technology had been available) was SN 1972E (Lee et al. 1972). This allows for unprecedented observations of this object out to very late phases and presents us a rare opportunity to test theoretical predictions about the light curve and spectral evolution.

In this work we present photometric observations of SN 2011fe at the extremely late epoch of $\approx$ 930 d past maximum. In Section 2, we give a description of the observations and subsequent data reduction. Section 3 is devoted to discussing the observations when compared to theoretical predictions. We present our conclusions and discuss possible future work in Section 4.

2. Observations & Analysis

We obtained optical photometry in the g, r, i and z bands using GMOS (Gemini Multi Object Spectrograph; Hook et al. 2004) mounted on the Gemini North telescope located at Mauna Kea (program GN-2014A-Q-24). The data were taken on the nights of 2014 March 7, 27 and 28 (see

Table 1) under photometric conditions. The data were then pre-reduced with the GEMINIUTIL[1] package following standard procedures. After careful inspection of the world coordinate system, the images were aligned and combined using SWARP (Bertin et al. 2002). In a final step, we adjusted the astrometric calibration to match Advanced Camera for Surveys (ACS) observations (see Figure 1). We undertook the same operation on standard fields observed during the same nights (DLS 1359-11, PG1633+099) and then used these for calibration purposes.

Subsequently, we performed our measurements using PSF photometry with the SNOOPY package, a compilation of IRAF[2] tasks optimized for SN photometry, developed by F. Patat and E. Cappellaro. SNOOPY constructs the PSF by selecting several clean unblended stars and then performs PSF photometry on the supernova itself. The instrumental SN magnitudes were finally calibrated to the Sloan photometric system (Fukugita et al. 1996) using tabulated atmospheric extinction coefficients and the nightly zero points derived from our standard-field observations. To get a better estimate of the uncertainty of the photometric measurement, SNOOPY uses an artificial star experiment.

For easier comparison with spectra, we have converted the magnitude information from Table 1 into flux units and show the result as a spectral energy distribution in Figure 2.

3. Discussion

We have acquired optical photometry in the period between 909 and 930 days past maximum and are comparing these data to earlier photometry by Tsvetkov et al. (2013) in Figure 3. This comparison shows a decline that is broadly consistent with ^{56}Co decay as seen by the scaled (bolometric) light curve taken from the merger model of Röpke et al. (2012).

This comparison is complicated by the fact that the data from Tsvetkov et al. (2013) are in the Johnson-Cousins photometric system (see Bessell et al. 1998) and our data are in filters that are similar to SDSS (Fukugita et al. 1996). Calculating transformations from one system to the other requires detailed spectral information, which was not obtained with our program. The R-band in the Johnson-Cousin System and the r′-band in the SDSS system are the most similar, and we have thus opted to use these for the comparison. Furthermore, both systems are using different zero points. Therefore, for Figure 3, we have converted both of them to physical units ($\mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}$). Finally, we also compare the light curve measurements to the bolometric light curve of the violent merger model of two CO-WDs (1.1 $M_\odot$ and 0.9 $M_\odot$) of Pakmor et al. (2012), which has been shown to provide a good match to the early spectra and light curves of SN 2011fe (Röpke et al. 2012). We note that at the epochs of comparison, the differences to the other explosion model in Röpke et al. (2012) that also provides a good match to the data – the N100 delayed-detonation model of a near Chandrasekhar-mass WD of Seitenzahl et al. (2013) – are very small.

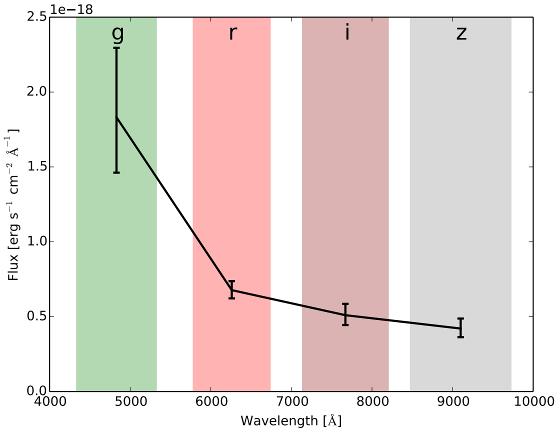

Fig. 2.— The spectral energy distribution constructed from our Gemini photometry at days. The g′-band photometry was taken 21 days earlier, but has been scaled accordingly using the Röpke et al. (2012) luminosity evolution.

We suggest that the apparent inconsistency of the photometry data points with the shown ^{56}Co powered light curve (see Figure 3) can be

---

[1] `http://github.com/geminiutil/geminiutil`

[2] IRAF: the Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation (NSF).

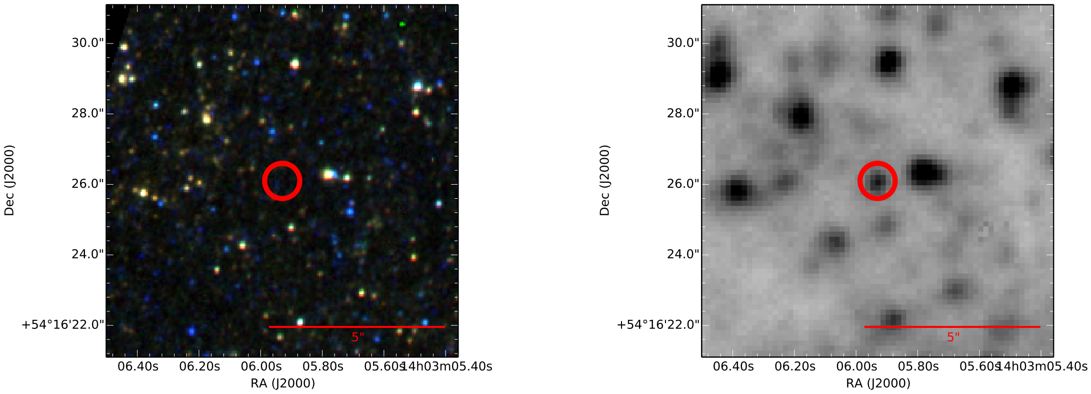

Fig. 1.— **Left side:** A color composite image from observations taken by the ACS under program GO9490 (PI: K. Kuntz) before the explosion of SN 2011fe. The circle diameter is 1″. **Right side:** GMOS g-band image taken with our program (GN-2014A-Q-24) +909 d past maximum.

Table 1: Photometry of SN 2011fe

Date YYYY MM DD	$t - t(\mathrm{B_{max}})^a$ d	Filter	mean airmass	t_{exposure} s	magnitude mag
2014 03 07	909.1	g	1.3	180 × 5	23.37 ± 0.25
2014 03 27	929.1	r	1.4	180 × 5	24.03 ± 0.09
2014 03 28	929.9	i	1.4	180 × 5	23.90 ± 0.15
2014 03 28	929.9	z	1.3	180 × 10	23.74 ± 0.16

[a] Assuming $\mathrm{B_{max}}$ at MJD 55814.51 (Pereira et al. 2013)

mainly attributed to re-distribution of flux over time. Specifically, the discrepancy between the ^{56}Co decay and the data points between 400 d – 600 d, is caused by an increasing amount of flux shifted out of the optical bands into the infrared (see Stritzinger & Sollerman 2007). Thus, we argue, that the combined dataset of this work and Tsvetkov et al. (2013) shows that the evolution of SN 2011fe may still be consistent with fully thermalized positron kinetic energy from the decay of ^{56}Co at the very late phases.

Furthermore, Figure 2 shows that the supernova currently has a high g′-band luminosity. One explanation might come from Fe III lines that are dominant in this wavelength range. This might indicate a relatively high ionization state and thus temperature.

Earlier epochs (around 600 d) show a similar color as at 930 d (comparing B and V to R in the Tsvetkov et al. (2013) and g′ to r′ in our data; see Figure 3). This indicates that there has not been a rapid color evolution and thus maybe not a significant change in ionization state and temperature.

SN 1992A is the only other supernova that has been observed similarly late (Cappellaro et al. 1997). It shows a similar behaviour, suggesting that the current evolution is a normal trend for SNe Ia.

4. Conclusion & Future Work

With the observations of SN 2011fe shown in this work, we have presented the latest photometric data for any SN Ia if one discounts the spectroscopically peculiar SN 1991T, which could be observed even at 2570 days due to a strong light echo produced by dust between the SN and the observer (Sparks et al. 1999). Combining previous photometry from Tsvetkov et al. (2013) with our work shows SN 2011fe to be consistent with

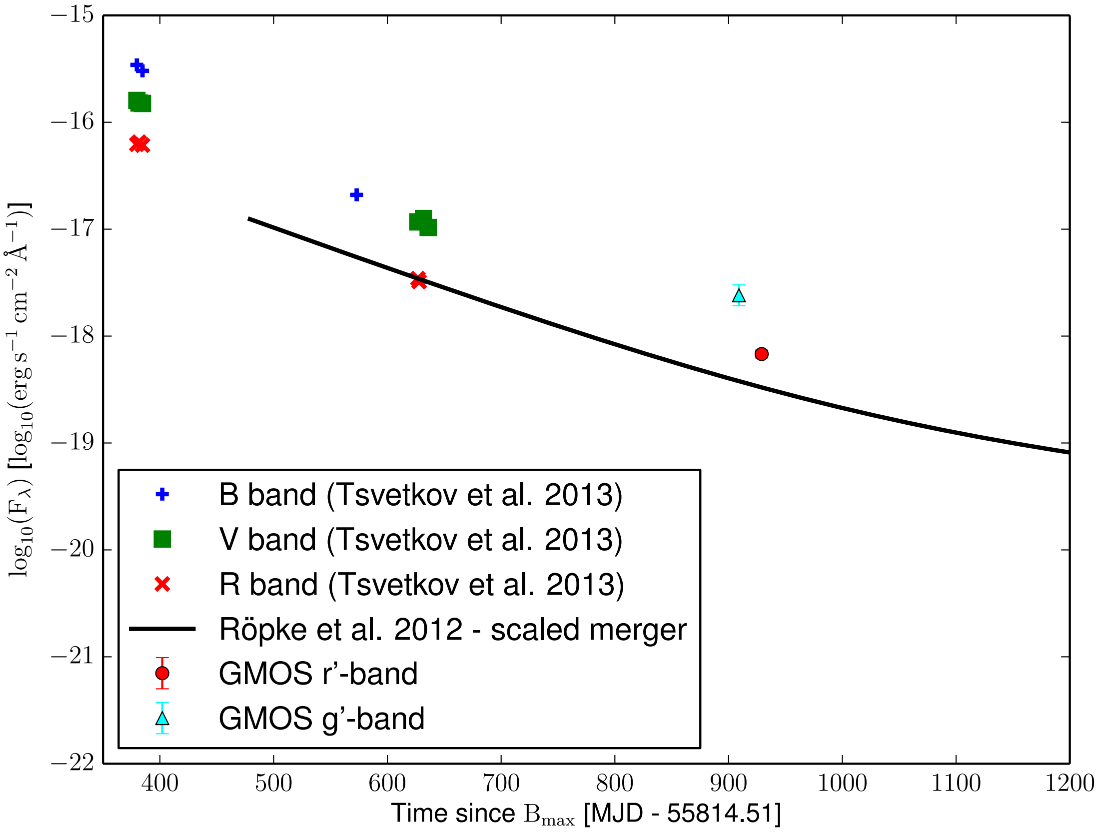

Fig. 3.— Late-time light curve of SN 2011fe. We compare the photometric measurements of Tsvetkov et al. (2013) to our photometric data relative to B-band maximum light (MJD 55814.51; Pereira et al. 2013). The uncertainties on the Tsvetkov et al. (2013) dataset are not shown in the plot and are on average 0.1 mag across all filters. As both systems are defined using different zero points, convert both to physical units ($\mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}$) before plotting. In addition, we added the CO-WD merger bolometric decay curve for the SNe Ia from Röpke et al. (2012) with the given rise time of 20.8 d (to B_{max} Pakmor et al. 2012) and finally scaled to match the R-band photometry of Tsvetkov et al. (2013) at 627 d.

full thermalization of all ^{56}Co decay positrons until at least $\approx 930\,\mathrm{d}$ past maximum. This rules out various dimming effects that have been suggested by theoretical predictions.

The current data indicate full trapping of positrons, which, combined with the predictions by Ruiz-Lapuente & Spruit (1998), favours the accreting Chandrasekhar mass CO-WD over the sub-Chandrasekhar mass edge-lit CO-WD. It also emphasizes the importance of studying the magnetic field configurations in the various competing scenarios (particularly the ones not mentioned in Ruiz-Lapuente & Spruit 1998). Furthermore, the observations are not compatible with the predicted IRC that suggests cooling only via far-IR lines resulting in a complete drop of UVOIR luminosities. This indicates that the ejecta are currently still above a critical temperature of $T > 1500\,\mathrm{K}$. Finally, we can rule out the formation of large amounts of dust on the basis of both the current brightness (Figure 3) and spectral energy distribution (Figure 2) of the supernova. This is consistent with the predictions that normal SNe Ia do not produce dust in significant amounts (e.g. Nozawa et al. 2011).

The fact that SN 2011fe is still relatively bright provides a unique opportunity to study the very late phase behaviour of this SN in unprecedented detail. We aim to continue this project by observing SN 2011fe at future epochs (∼1030 days past maximum) in optical and near-IR bands, allowing us to measure a quasi bolometric luminosity evolution to determine even more precisely the energy deposition in the SN ejecta at such late phases, which can then be more directly confronted with theoretical predictions. Finally, we hope that our results encourage the community to continue observing SN 2011fe with a variety of different techniques.

This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013). IRS and AJR acknowledge funding from ARC Laureate Grant FL0992131. ST acknowledges support by the Transregional Collaborative Research Centre TRR 33 of the German Research Foundation.

We would also like to thank Marten van Kerkwijk for many useful discussions. In addition, we would like to thank the Gemini team for the help they provided using the telescope. In particular, we would like to thank Katherine Roth, who went above and beyond her call of duty to provide help with this program. Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), Ministério da Ciência, Tecnologia e Inovação (Brazil) and Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina).

Facilities: Gemini:Gillett (GMOS)

REFERENCES

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33

Axelrod, T. S. 1980, PhD thesis, California Univ., Santa Cruz.

Bertin, E., Mellier, Y., Radovich, M., et al. 2002, in Astronomical Society of the Pacific Conference Series, Vol. 281, Astronomical Data Analysis Software and Systems XI, ed. D. A. Bohlender, D. Durand, & T. H. Handley, 228

Bessell, M. S., Castelli, F., & Plez, B. 1998, A&A, 333, 231

Cappellaro, E., Mazzali, P. A., Benetti, S., et al. 1997, A&A, 328, 203

Chan, K.-W., & Lingenfelter, R. E. 1993, ApJ, 405, 614

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

Hook, I. M., Jørgensen, I., Allington-Smith, J. R., et al. 2004, PASP, 116, 425

Lair, J. C., Leising, M. D., Milne, P. A., & Williams, G. G. 2006, AJ, 132, 2024

Lee, T. A., Wamsteker, W., Wisniewski, W. Z., & Wdowiak, T. J. 1972, ApJ, 177, L59

Leloudas, G., Stritzinger, M. D., Sollerman, J., et al. 2009, A&A, 505, 265

Li, W., Bloom, J. S., Podsiadlowski, P., et al. 2011, Nature, 480, 348

McCully, C., Jha, S. W., Foley, R. J., et al. 2014, ApJ, 786, 134

Milne, P. A., The, L.-S., & Leising, M. D. 1999, ApJS, 124, 503

—. 2001, ApJ, 559, 1019

Nozawa, T., Maeda, K., Kozasa, T., et al. 2011, ApJ, 736, 45

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

Pakmor, R., Kromer, M., Taubenberger, S., et al. 2012, ApJ, 747, L10

Pereira, R., Thomas, R. C., Aldering, G., et al. 2013, A&A, 554, A27

Röpke, F. K., Kromer, M., Seitenzahl, I. R., et al. 2012, ApJ, 750, L19

Ruiz-Lapuente, P., & Spruit, H. C. 1998, ApJ, 500, 360

Seitenzahl, I. R., Taubenberger, S., & Sim, S. A. 2009, MNRAS, 400, 531

Seitenzahl, I. R., Ciaraldi-Schoolmann, F., Röpke, F. K., et al. 2013, MNRAS, 429, 1156

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

Sollerman, J., Lindahl, J., Kozma, C., et al. 2004, A&A, 428, 555

Sparks, W. B., Macchetto, F., Panagia, N., et al. 1999, ApJ, 523, 585

Stritzinger, M., & Sollerman, J. 2007, A&A, 470, L1

Taubenberger, S., Kromer, M., Hachinger, S., et al. 2013, MNRAS, 432, 3117

Tsvetkov, D. Y., Shugarov, S. Y., Volkov, I. M., et al. 2013, Contributions of the Astronomical Observatory Skalnate Pleso, 43, 94

This 2-column preprint was prepared with the AAS LaTeX macros v5.2.