

VERY LATE PHOTOMETRY OF SN 2011fe

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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 days) of thermonuclear supernovae. In this Letter, we present our photometric data of SN 2011fe taken at an unprecedented late epoch of ≈ 930 days with GMOS-N mounted on the Gemini North telescope ($g = 23.43 \pm 0.28$, $r = 24.14 \pm 0.14$, $i = 23.91 \pm 0.18$, and $z = 23.90 \pm 0.17$) 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 theoretical predicted effects (e.g., infrared catastrophe, positron escape, and dust) that advocate a substantial energy redistribution and/or loss via various processes that result in a more rapid dimming at these very late epochs.

Key words: nuclear reactions, nucleosynthesis, abundances – supernovae: individual (SN 2011fe) – techniques: photometric

Online-only material: color figures

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, the physical processes that lead to, result in, and sustain the transient phenomena that we know as SNe Ia remain relatively uncertain.

While there is almost unanimous agreement that these events are powered by the nuclear burning of massive ($\geq 1 M_{\odot}$) 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 $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ decay chain is responsible for the majority of the energy deposition that leads to the observed luminosity. ^{56}Ni (half-life ~ 6 days) has nearly fully decayed 50 days after the explosion and the light curve is then mostly powered by the decay of ^{56}Co (half-life ~ 77 days). At 300 days the ejecta have become almost completely transparent to γ -rays. Charged decay leptons, most notably the positrons produced in β^+ decay of ^{56}Co , and low-energy X-rays can still deposit their energy and thus determine the UVOIR luminosity of the supernova. This suggests that from this time onward (at least until the internal conversion and Auger electrons produced in the decay of ^{57}Co dominate the energy injection; see, e.g., Seitzzahl et al. 2009), the light curve should show a decline following the decay 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 days 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 conversion of a constant fraction of the energy produced to UVOIR band photons 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 sources of deviation from an exponential light curve decline.

As indicated previously, at late epochs (past 300 days) the observed light curve is mainly powered by the energy deposition of decay positrons. Supernova light curves that follow the ^{56}Co decay cannot be explained by the interaction of free streaming positrons, but require being trapped through a highly tangled magnetic field (see Chan & Lingenfelter 1993; Milne et al. 1999, 2001). In contrast, a radially combed field or no magnetic field would lead to a dimming by a factor of about five compared to a light curve following ^{56}Co at 1000 days past explosion (see Figure 1 in Milne et al. 2001). Recent publications that take into account essential near-IR corrections require almost complete trapping of positrons and thus a tangled magnetic field up to quite late epochs to explain observations (e.g., Stritzinger & Sollerman 2007; Leloudas et al. 2009).

The influence of magnetic field configuration on the light curve shape leads Ruiz-Lapuente & Spruit (1998) to suggest that the light curve form can be used to confirm or rule out certain progenitor scenarios. They suggest that a tangled magnetic field, resulting in full positron trapping, stems from

Table 1
Photometry of SN 2011fe

Date YYYY MM DD	$t - t(B_{\max})^a$ (d)	Filter	Mean Airmass	Seeing (")	t_{exposure} (s)	Magnitude (mag)
2014 Mar 7	909.1	<i>g</i>	1.3	0.57	180×5	23.43 ± 0.28
2014 Mar 27	929.1	<i>r</i>	1.4	0.53	180×5	24.14 ± 0.14
2014 Mar 28	929.9	<i>i</i>	1.4	0.60	180×5	23.91 ± 0.18
2014 Mar 28	929.9	<i>z</i>	1.3	0.57	180×10	23.90 ± 0.17

Note. ^a Assuming B_{\max} at MJD 55814.51 (Pereira et al. 2013).

a Chandrasekhar mass accretion, whereas an edge-lit sub-Chandrasekhar mass scenario might produce radially combed magnetic field configuration, which enhances the escape of positrons and thus predict that this would lead to a deviation of the light curve 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 ~ 500 days, even if all positrons remain trapped (Leloudas et al. 2009). The IRC is predicted to occur when the temperature drops below what is required to excite optical and near-IR atomic transitions ($T \lesssim 1500$ 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 is tauntingly not seen in observational data out to 786 days after explosion for SN 2003hv (e.g., Sollerman et al. 2004; Leloudas et al. 2009; McCully et al. 2014).

A final scenario that might lead to dimming in the UVOIR bands is the formation of dust. Unlike the IRC and positron escape scenarios, the prediction by Nozawa et al. (2011) is that normal SNe Ia are unlikely sites of dust formation and thus predict no extinction or drastic color change 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 ≈ 930 days 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 AND 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 GEMINIUTIL⁵ 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 ACS observations (see Figure 1). We undertook the same operations on Sloan-Digital-Sky Survey (SDSS)-calibrated stars (Aihara et al. 2011) in the field and then used those for the calibration. Finally, we also observed standard fields during the same nights (DLS 1359–11, PG1633+099) to make an additional cross-check for calibration with SDSS, showing consistency in each filter.

Subsequently, we performed our measurements using point-spread function (PSF) photometry with the SNOOPY package. This package is a compilation of IRAF⁶ tasks optimized for supernova (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 SN 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.

Finally, we combined our photometric measurements into a pseudo bolometric luminosity. The *g*-band measurement was taken 21 days earlier than the other bands and hence we applied a dimming correction of 0.15 mag based on a theoretical bolometric light curve model of Röpke et al. (2012). First, we generated a spectral energy distribution (SED; see Figure 2) using the weighted mean wavelengths of the bands as the supporting points. We repeated the same procedure for the photometric data of Tsvetkov et al. (2013), which unlike our photometry uses Bessell *BVR* filters. We used linear interpolation for each band in their light curves to obtain a set of *BVR* magnitudes at 400 days and 550 days. The SEDs generated from the measurements presented in this work and from Tsvetkov et al. (2013) were then integrated between 4000 Å and 8000 Å (this wavelength range was chosen as it is covered by both filter systems), assuming a linear flux distribution between the supporting points (see Figure 2). Furthermore, we assumed that at edges of the magnitude sets, our flux distribution is zero (e.g., at the blue edge of the *B* filter and at the red edge of the *R* filter; same for *g* band and *z* band; see Figure 2). The final pseudo bolometric uncertainties were determined using Monte Carlo techniques. The result can be seen in Figure 3.

⁵ <http://github.com/geminiutil/geminiutil>

⁶ 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).

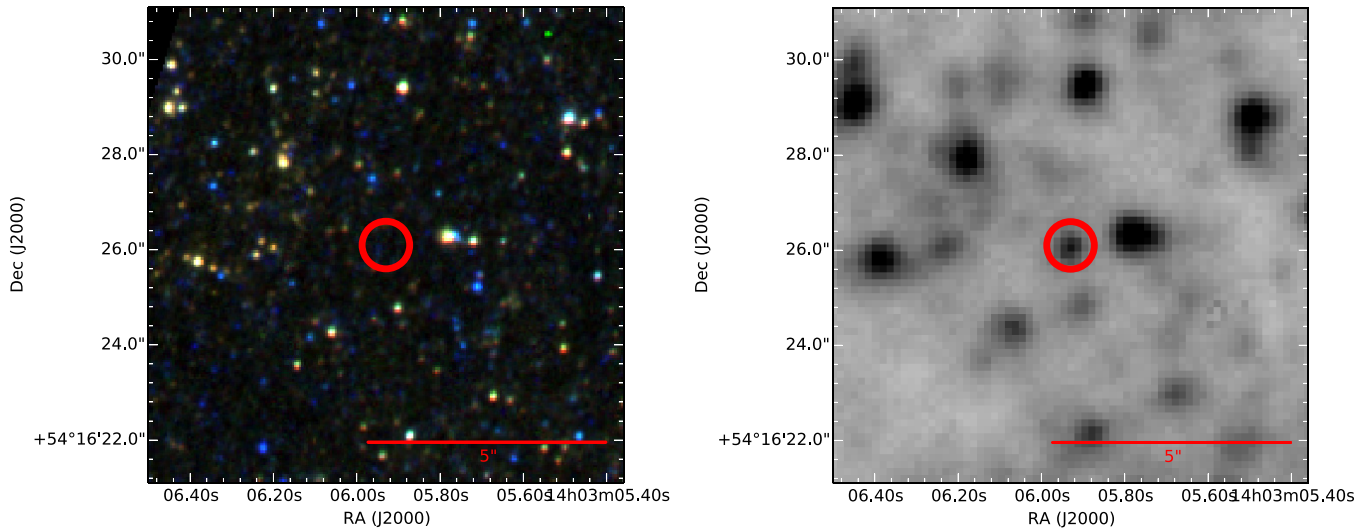


Figure 1. Left: a color composite image from observations taken by the Advanced Camera for Surveys (ACS) under program GO9490 (PI: K. Kuntz) before the explosion of SN 2011fe. The circle diameter is 1". Right: GMOS *g*-band image taken with our program (GN-2014A-Q-24) +909 days past maximum. (A color version of this figure is available in the online journal.)

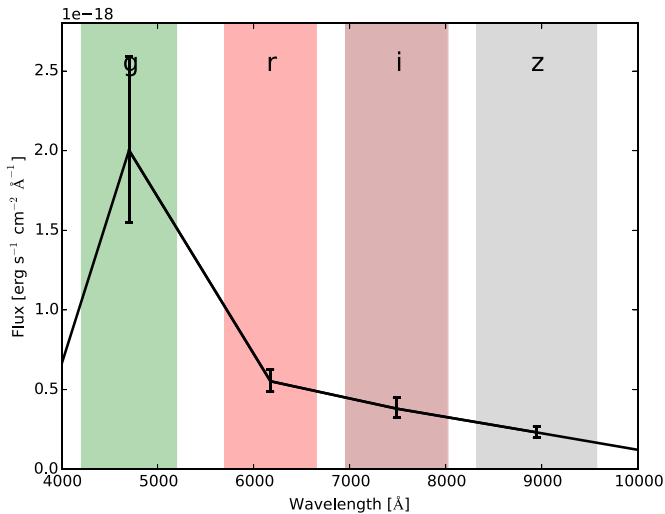


Figure 2. SED constructed from our Gemini photometry at 930 days. The *g*-band photometry was taken 21 days earlier, but has been scaled accordingly using the Röpke et al. (2012) luminosity evolution. (A color version of this figure is available in the online journal.)

3. DISCUSSION

We have acquired optical photometry in the period between 909 days 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 (at 1.5σ) with ^{56}Co decay as seen by the scaled (bolometric) light curve taken from the merger model of Röpke et al. (2012).

The 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. We alleviated this problem by reconstructing an SED out of the filter measurements and then integrating these over a wavelength

range that is covered by both filter sets (4000 Å–8000 Å; see Section 2 for details; see Figure 3).

For a comparison with the observed pseudo bolometric light curve, we opt for an analytic theoretical light curve model of a violent merger (Röpke et al. 2012). This bolometric light curve considers gamma rays as free streaming and assumes complete deposition and instantaneous thermalization of X-rays and positron and electron kinetic energies produced in radioactive decays, which is a good approximation at phases later than 500 days. Under these assumptions, the model closely follows the slope of ^{56}Co decay, and is generic for SNe Ia. In fact, the model light curve for a Chandrasekhar-mass explosion that was also presented by Röpke et al. (2012) is nearly identical at the epochs under consideration. This also means that the presented photometry cannot be used to distinguish between progenitor models. For comparison, we have scaled the bolometric light curves to match the pseudo-bolometric data point generated from the Tsvetkov et al. (2013) data at 550 days.

Figure 3 shows that the observed pseudo bolometric light curve is broadly consistent with the scaled bolometric model by Röpke et al. (2012). The predicted pseudo bolometric luminosity decline in the case of an IRC was calculated from synthetic *BVR* magnitudes (see Figure 9 in Leloudas et al. 2009) in the same way as for the observed data. For the luminosity decline following an enhanced positron escape there only exist true bolometric models, which cover a certain range in ΔL as indicated in Figure 3. The reader should note that this is not a 1σ error bar, but a range of models for different ionization fractions presented in Milne et al. (2001). Finally, both models were anchored at 550 days and Figure 3 shows the predicted declines between 550 days and 930 days.

There is a discrepancy between 400 days and 550 days, where the observations dim more rapidly (and also more rapidly than ^{56}Co decay), but we speculate that the seemingly underluminous data point at 550 days is caused by an increasing amount of flux shifted out of the optical bands into the infrared, which is corroborated by the behavior of SN 2003hv (Leloudas et al. 2009, see Figure 8). After 550 days, SN 2003hv shows a reversed trend (Leloudas et al. 2009).

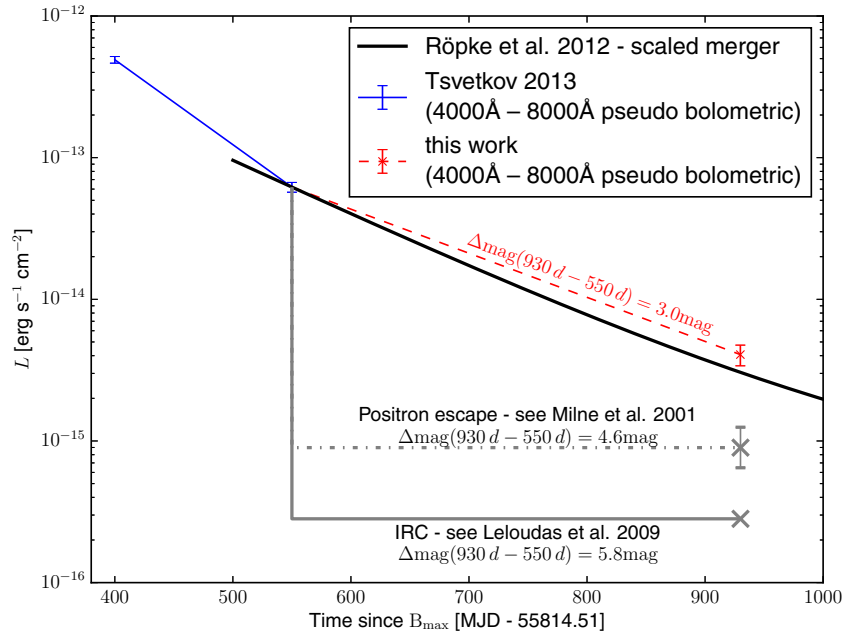


Figure 3. Late-time pseudo bolometric light curve of SN 2011fe (integrated between 4000 Å and 8000 Å). We compare pseudo bolometric measurements composed from *BVR* data of Tsvetkov et al. (2013) to our pseudo bolometric measurements. Phases are reported relative to *B*-band maximum light (MJD 55814.51; Pereira et al. 2013). We added the CO-WD merger bolometric light curve from Röpke et al. (2012) assuming a rise time of 20.8 days to B_{\max} (Pakmor et al. 2012) and scaled to match the pseudo bolometric luminosity at 550 days. Finally, we added the decline between 550 days and 930 days predicted by scenarios with an IRC or positron escape. (A color version of this figure is available in the online journal.)

The most straightforward explanation for the observed pseudo-bolometric evolution is thus a true bolometric light curve decline that indeed follows the radioactive decay of ^{56}Co and ^{57}Co , combined with a temporally slightly varying bolometric correction. This explanation suggests a fully thermalized positron kinetic energy and no IRC. Our data, however, cannot exclude a finely tuned model that, while having a true bolometric evolution that deviates from the radioactive decay slope, still almost perfectly compensates this by a change in the bolometric correction, resulting in a seemingly good fit in the optical.

One such possibility would be a scenario in which a rapid dimming owing to positron escape or an IRC is just compensated by a light echo. In this case, the observed spectrum of SN 2011fe should be similar to the spectrum at maximum light (e.g., Schmidt et al. 1994). We thus compare magnitudes of SN 2011fe, calculated using SYNPHOT⁷ maximum light spectrum ($t - t_{\max} = -0.03$ days) of Pereira et al. (2013; $g = 9.89$, $r = 10.05$, $i = 10.63$ and $z = 10.77$) with our own measurements at 930 days (see Table 1). The comparison shows that at 930 days SN 2011fe has a bluer $g - r$ color [$(g - r)_{930\text{d}} = -0.51$ versus $(g - r)_{\max} = -0.16$] and at the same time a redder $r - i$ color [$(r - i)_{930\text{d}} = +0.23$ versus $(r - i)_{\max} = -0.58$] than at maximum light. The very different colors suggests that the majority of the light is originating in the ejecta and there is no major contribution of scattered light from earlier epochs.

4. CONCLUSION AND 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 full thermalization of all ^{56}Co decay positrons until at least ≈ 930 days past maximum. There is no evidence for various dimming effects that have been suggested by theory. In fact, the dimmed models are more than 4σ outliers compared to the datapoint luminosity at 930 days.

The current data indicate full trapping of positrons (significant positron escape would require the luminosity to be dimmer by a factor of approximately five at 930 days when compared to ^{56}Co decay; see Figure 3), which, combined with the predictions by Ruiz-Lapuente & Spruit (1998), favors the accreting Chandrasekhar mass CO-WD over the sub-Chandrasekhar mass edge-lit CO-WD (the reader should note that only those two models were compared in Ruiz-Lapuente & Spruit 1998). This emphasizes the importance of studying the magnetic field configurations in 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 the optical and near-IR luminosities. This might indicate that the ejecta are currently still above a critical temperature of $T \approx 1500$ 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). A final caveat that might call the previous conclusions into question is that the measurements could be significantly contaminated by a light echo. However, as discussed in Section 3, the colors at the current epoch are significantly different from those at maximum light, allowing at most a very small contribution from a light echo and re-affirming our conclusions.

The fact that SN 2011fe is still relatively bright provides a unique opportunity to study the very late phase behavior

⁷ SYNPHOT is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.

of this SN in unprecedented detail. We aim to continue this project by observing SN 2011fe at future epochs (~ 1500 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.

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Facility: Gemini:Gillett (GMOS)

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