THE MID-INFRARED AND OPTICAL DECAY OF SN 2011fe

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ABSTRACT
We measure the decay rate of the mid-IR luminosity from Type Ia supernova 2011fe between six months and one year after explosion using Spitzer/IRAC observations. The fading in the 3.6 μm channel is 1.48 ± 0.02 mag/100 days, which is similar to that seen in blue optical bands. The supernova brightness fades at 0.78 ± 0.02 mag/100 days in the 4.5 μm channel which is close to that observed in the near-IR. We argue that the difference is a result of doubly ionized iron-peak elements dominating the bluer IRAC band while singly ionized species are controlling the longer wavelength channel. To test this, we use Large Binocular Telescope spectra taken during the same phases to show that doubly ionized emission lines do fade more slowly than their singly ionized cousins. We also find that [Co iii] emission fades at more than twice the radioactive decay rate due to the combination of decreasing excitation in the nebula, recombination and cobalt decaying to iron. The nebular emission velocities of [Fe iii] and [Co iii] lines show a smaller blueshift than emission from singly ionized atoms. The Si ii velocity gradient near maximum light combined with our nebular velocity measurements suggest SN 2011fe was a typical member of the “low velocity gradient” class of Type Ia. Analyzing IRAC photometry from other supernovae we find that mid-IR color of Type Ia events is correlated with the early light curve width and can be used as an indicator of the radioactive nickel yield.

Key words: supernovae: general – supernovae: individual (SN 2011fe, SN 2009ig, SN 2008Q, SN 2005df)
Online-only material: color figure

1. INTRODUCTION
Type Ia supernovae (SN Ia) are widely thought to be the thermonuclear explosions of degenerate white dwarfs (see Livio 2000 for a review). Their high luminosity and uniformity make SN Ia good cosmological distance indicators (Riess et al. 1998; Perlmutter et al. 1999), but a conclusive theoretical model of their explosion mechanism remains elusive. For instance, it is an open question on whether the progenitor consists of a single degenerate white dwarf or two (or both).

Do we know that SN Ia are bright because they synthesize a sizable amount of radioactive 56Ni. Typically, SN Ia produce half a Solar mass of radioactive nickel which decays to cobalt (~1 week timescale) that then decays to stable 56Fe (~three month timescale) emitting energetic γ-rays and positrons (Arnett 1982). Early spectroscopy shows a significant amount of intermediate mass elements (IME) in the outer layers while late-time spectra are dominated by singly and doubly ionized iron-peak elements (Filippenko 1997).

SN Ia explosions may begin with a subsonic burning front, creating a deflagration of the carbon/oxygen white dwarf, but a deflagration alone yields too little energy. Alternatively, a pure detonation would create too much radioactive yield and less IME than typically observed. A “delayed detonation” (DD) better matches the observations. In the DD scenario (Khokhlov 1991), fusion begins as a deflagration but switches to supersonic burning after some of the white dwarf has expanded, allowing carbon fusion at low density.

Recent work has suggested that the dense deflagration region can be offset in position and velocity from the larger, lower density detonation region (Maeda et al. 2010b). This proposition explains a number of observed SN Ia properties near maximum and at later phases and that some diversity in SN Ia may simply be due to random viewing angles.

At late times, when the synthesized material becomes optically thin, the light from SN Ia continues to be powered by radioactive decay. Months to years after the explosion, the long-lived 56Co isotope keeps the nebula glowing by energy deposited from positrons while the γ-rays escape without depositing energy. The photometric decay is expected to be exponential with an e-folding time of 111.3 days or 0.98 mag/100 days, matching that of 56Co decay. But Lair et al. (2006) found the optical decline in the B and V bands is significantly faster than 56Co. In contrast, Sollerman et al. (2004) also demonstrated that the bolometric luminosity, or the total flux across all bands from the optical to the IR, does decay at the expected 56Co energy deposition rate.

SN 2011fe (Nugent et al. 2011) was the closest SN Ia in 25 years (μ ≈ 29.04; Shappee & Stanek 2011) and was extremely well studied at early epochs. It appears to have been a normal SN Ia in terms of light curve, luminosity and spectral development. Here, we present Spitzer IRAC photometry of SN 2011fe between six months and one year after optical maximum. The brightness of SN 2011fe created a unique opportunity for detailed study of a Type Ia event in the mid-IR, but it also appeared close to Earth’s ecliptic pole, allowing several months of continuous Spitzer visibility. To put these results into context, we also compare Spitzer observations of SN 2011fe with data for other SN Ia.

2. OBSERVATIONS
2.1. Spitzer/IRAC
As part of a program to study the late-time properties of SN Ia, we requested low-impact target-of-opportunity observations of SN 2011fe with the Spitzer Space Telescope using the Infrared Array Camera (hereafter IRAC; Fazio et al. 2004). IRAC
photometry was also obtained through *Spitzer* program 80196. The location of the supernova was first visible to *Spitzer* at the end of 2012 January and remained visible until the following September. Four visits were executed over the visibility period providing the best light curve of any SN Ia in the mid-IR. The supernova was observed in IRAC Channel 1 (CH1) and Channel 2 (CH2) which have effective wavelengths of 3.6 μm and 4.5 μm respectively.

Our program also obtained IRAC photometry of SN 2008Q and SN 2009ig, and we re-reduced archival IRAC data on SN 2005df previously presented by Gerardy et al. (2007). These three SN Ia were well-observed at optical wavelengths around maximum light (C. McClelland et al. 2013, in preparation; Foley et al. 2012; Milne et al. 2010) and provide good comparisons to SN 2011fe.

We downloaded post-BCD images through the *Spitzer* Heritage Archive. Each SN Ia was identified in the IRAC images by its celestial coordinates. Aperture photometry was performed after the pixel values were converted to μJy. For SN 2011fe, we used the recommend 5 pixel aperture radius with annular sky radii of 12–20 pixels. Pre-explosion *Spitzer* observations of host galaxy M101 conducted in 2004 provided background estimates for both channels. The position of SN 2009ig in host galaxy NGC 1015 warranted a smaller 3 pixel aperture radius, while sky backgrounds were calculated via averaging the brightness fluctuations of multiple random apertures over areas without obvious point sources. The same was done for SN 2008Q in host galaxy NGC 524 and SN 2005df in NGC 1559. Aperture corrections were taken from the IRAC Instrument Handbook and the results are presented in Table 1.

### Table 1: IRAC Photometry for Selected Type Ia Supernovae

| SN     | Phase (days) | CH1 Flux (μJy) | CH2 Flux (μJy) |
|--------|--------------|----------------|----------------|
| 2008Q  | 222          | 10.21 ± 1.08   | 8.96 ± 1.51    |
| 2008Q  | 560          | 0.38 ± 0.28    | ...            |
| 2008Q  | 739          | ...            | ...            |
| 2009ig | 196          | 13.25 ± 1.41   | 2.44 ± 0.69    |
| 2009ig | 375          | 2.87 ± 1.05    | 1.53 ± 0.81    |
| 2011fe | 146          | 656.73 ± 13.60 | 157.57 ± 6.92  |
| 2011fe | 167          | 483.12 ± 11.91 | 120.97 ± 6.02  |
| 2011fe | 234          | 197.35 ± 7.99  | 84.87 ± 5.14   |
| 2011fe | 351          | 40.89 ± 4.25   | 34.28 ± 3.40   |

photos were obtained at airmasses less than 1.1 so that differential slit losses were minimized.

The spectra were wavelength-calibrated using Neon and Argon emission line lamps taken during the June run. The wavelength solution was then shifted based on the sky line centroids. The MODS spectrograph is very stable and the wavelength shifts applied were less than 2 Å.

MODS flux sensitivity is also very stable, so no flux calibration was applied. Instead, we directly compared extracted electron count rates (proportional to the “analog-to-digital units”) to avoid further uncertainties caused by flux calibrations using different standard stars under varying conditions. To test the stability of the sensitivity, we divided MODS spectra of the standard star HZ 44 obtained in April and June and found the fluxes differed by less than 5% over the spectral range between 3500 Å and 8500 Å. We therefore expect systematic uncertainty on the pixel by pixel decay rates to be less than 0.05 mag/100 Å. At wavelengths shorter than 3500 Å and longer than 8500 Å the difference between the standard star spectra reached 10%, so the decay rates are not as reliable at the extreme ends of the spectra.

The MODS spectra of SN 2011fe are shown in Figure 1. In general, the spectra are typical of a Type Ia supernova a couple hundred days after explosion. Between 4000 Å and 5500 Å there is a clump of emission dominated by forbidden lines of singly and doubly ionized iron. Weaker lines from cobalt, iron and nickel are clearly seen long ward of 5500 Å. These are some of the highest signal-to-noise (S/N) spectra of a Type Ia supernova at late phases ever obtained and they already been used to search for hydrogen emission from SN 2011fe (Shappee et al. 2012).

The relative count rates across the spectra are stable from epoch to epoch, but the total efficiency depends on seeing and cloud cover and these were not well controlled. To simulate a

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4 http://sha.ipac.caltech.edu/applications/Spitzer/SHA
5 http://ned.ipac.caltech.edu/
6 http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/
broadband filter, we multiplied the spectra with a Bessell B-band filter function and integrated the result. From these values we adjusted the relative ADU to match the B-band decay rate of 1.32 ± 0.02 mag/100d found from the late-time photometry of Munari et al. (2013).

LBT spectra of SN 2011fe were also obtained on 2012 May 1 (UT, age of 234 days) with the LUCIFER infrared spectrograph. The spectra covered the J and H bands using three grating settings. Only one epoch of near-IR spectra was obtained so the decay rates at these wavelengths could not be estimated, but the velocity offsets of the two strong [Fe II] lines are measured.

3. ANALYSIS

The mid-IR photometry of SN 2011fe starting at an age of five months and ending about one year after explosion is shown in Figure 2. The light curves are consistent with an exponential decay, so we fit them with a function of the form $F = A_{320}e^{-(t-230)/\tau}$, where $F$ is the observed time varying flux, $t$ is the age since B maximum, $A_{320}$ is the flux at the fiducial time of 230 days, and $\tau$ is the $e$-folding time of the decay. The decay rate can also be described in magnitudes per 100 days by $\Delta = 108.57/\tau$.

The resulting measured decay rates for SN 2011fe are given in Table 2. The 1.48 ± 0.02 mag/100d seen in CH1 is significantly steeper than the 0.78 ± 0.2 mag/100d measured for CH2. The decay observed in the two Spitzer bands straddle the $^{56}$Co rate of 0.98 mag/100d. The decay rate for CH1 is similar to that typically seen in B and V bands, while CH2 has a decay even more shallow than the I band (0.99 ± 0.04 mag/100d; via least-squares fit to photometry from Munari et al. 2013).

The long cadence and greater distance to the other Spitzer-observed Type Ia events resulted in larger uncertainty in the measured decay rates compared with the SN 2011fe data. The CH1 decay rates for SN 2008Q, SN 2009ig, and SN 2005df all appear slightly slower. All the supernovae are consistent in that the CH1 rate is steeper than the CH2 decline rate.

We created a color index based on the flux ratio between the two IRAC channels, or

$$\Delta \chi = \frac{F_{CH1}}{F_{CH2}} + (Z_{CH1} - Z_{CH2}) \text{ mag},$$

where $F_{CH1,CH2}$ are the fluxes measured in $\mu$Jy in CH1 and CH2, and $Z_{CH1,CH2}$ are the magnitude zero points for those passbands, listed in the IRAC Instrument Handbook. Extinction differences between these filters is assumed to be negligible (Flaherty et al. 2007). Because the IRAC decay rates are so different, the CH1–CH2 color varies rapidly in time so we have chosen a fiducial time of 230 days to estimate the color parameter. This age was chosen because the Spitzer archive contains several SN Ia observed near this age, thus reducing any errors caused by interpolation.

The estimated color at 230 days shows a wide range among the supernovae in our sample. To better understand the cause of this diversity, we sought to compare the 230 day color with early-time light curve shape, namely the parameter $\Delta m_{15}(B)$. For SN 2009ig we use the $\Delta m_{15}(B)$ measured by Foley et al. (2012) and for SN 2011fe we use the value from Vinkò et al. (2012). Both SN 2009df and 2008Q have excellent early light curves (Milne et al. 2010; C. McClelland et al., in preparation) and we measure their $\Delta m_{15}(B)$ directly. The $\Delta m_{15}(B)$ values and the measured IRAC colors are given in Table 2.

The four supernovae, 2005df, 2008Q, 2009ig, and 2011fe, show a wide range of early light curve decline rates, and so, a wide range of synthesized radioactive nickel masses. We plot our measured IRAC colors at 230 days versus $\Delta m_{15}(B)$ in Figure 3. There appears to be a robust correlation (albeit with only four data points) indicating that the CH1 to CH2 flux ratio decreases with increasing $\Delta m_{15}(B)$ parameter. Alternatively, we see that the CH1 flux increases relative to CH2 as the amount of synthesized radioactive nickel increases since $\Delta m_{15}(B)$ correlates with nickel yield. Based on this handful of supernovae, the IRAC color appears to be a good indicator of peak optical luminosity, although this is unlikely to be useful for cosmological measurements.

4. DISCUSSION

4.1. IRAC Decay Rates

The radically different late-time decay rates observed at 3.6 $\mu$m and 4.5 $\mu$m is puzzling given that total flux from the optical to near-IR appears to match the $^{56}$Co energy injection rate (Sollerman et al. 2004; Leloudas et al. 2009). The effect is also seen when comparing the faster decay in the B and V bands to the modest I-band decay rate between six months and a year.

$\Delta m_{15}(B)$ (Phillips 1993) is defined as the change in $B$ magnitude from maximum to 15 days post maximum. It is related to the peak luminosity of a SN Ia through the Phillips Relation.

### Table 2

| SN     | $\Delta m_{15}(B)$ (mag) | $\Delta$ CH1 (mag/100d) | $\Delta$ CH2 (mag/100d) | CH1–CH2 @230 days (mag) |
|--------|--------------------------|--------------------------|--------------------------|--------------------------|
| 2005df | 1.09 ± 0.04              | 0.97 ± 0.03              | 0.65 ± 0.09              | −0.64 ± 0.28             |
| 2008Q  | 1.36 ± 0.06              | 1.06 ± 0.24              | ···                      | 0.34 ± 0.22              |
| 2009ig | 0.89 ± 0.02              | 0.93 ± 0.23              | 0.28 ± 0.36              | −1.14 ± 0.41             |
| 2011fe | 1.07 ± 0.06              | 1.48 ± 0.02              | 0.78 ± 0.02              | −0.44 ± 0.08             |
after explosion. The fast optical decline is likely compensated by a slow near-IR decay which after a year becomes a spectacular rise in the importance of the $J$ and $H$ band fluxes.

What do the fast declining wavelength bands ($B$, $V$, $CH1$) have in common and how are they different from the slower ($I$, $J$, $H$, $CH2$) fading bands? As most of the SN Ia spectrum at late-times, the IRAC bands are expected to be dominated by emission from iron-peak elements with a mixture of singly ionized and doubly ionized species. Gerardy et al. (2007) predicted that spectrum covered by CH1 would show strong [Fe III] $3.229 \mu m$ and [Co III] $3.492 \mu m$. In contrast, Maeda et al. (2010b) predicts several strong [Fe II] should dominate the wavelength region spanned by CH2.

We propose that the difference in the observed IRAC decay rates is a result of doubly ionized species being the dominate light source in CH1 and singly ionized iron-peak species supplying the majority of flux in CH2. The relative amounts of emission from singly and doubly ionized species should also vary in the shorter wavelength bands, and we note that the strong [Fe III] 4700 Å blend straddles the $B$ and $V$ band transition and contributes flux to both fast-decaying bands. In contrast, the slow-fading $I$, $J$, and $H$ bands are predominately fed by singly ionized atoms. We predict the $K$-band around 2.2 $\mu m$ should fade like IRAC CH1 since it contains a strong [Fe III] line at 2.218 $\mu m$.

Singly and doubly ionized iron-peak elements exist in very different regions of SN Ia nebulae. Using the W7 prescription (Thielemann et al. 1986), one-dimensional SN Ia nebular models agree that [Fe II] (and [Co II] which has a similar ionization energy) atoms dominate in the inner dense regions while doubly ionized iron occupies the outer volume (e.g., Mazzali et al. 2011; Liu et al. 1997). Generally, the dense regions cool quickly and doubly ionized species recombine while cooling in low density regions is inefficient and they remain dominated by doubly ionized gas. Sollerman et al. (2004) however, notes that photoionization has a major effect on the ionization structure and it is not well modeled in the nebula spectra (Kozma & Fransson 1998).

Sollerman et al. (2004) modeled SN Ia nebular spectra with and without accounting for photoionization. Without including photoionization in the calculation, the [Fe III]/[Fe II] ratio was too small compared with the real spectrum of SN 2000cx at one year old. When including photoionization, the model predicted too much [Fe III] which suggests that real supernovae are intermediate between these two extremes. It is possible that the effects of photoionization in SN Ia nebulae decrease with time as the expansion reduces the density. This should reduce the importance of the doubly ionized species through recombination while increasing the flux of singly ionized species. As the nebula transitions away from significant photoionization, we expect the filters dominated by lines from doubly ionized species will fade more quickly than $^{56}$Co. Meanwhile, the bands dominated by singly ionized atoms will fade more slowly than $\Delta = 0.98$ mag/100$^d$ with the difference in decay rates a clue to the recombination rate.

If the CH1 decay rate is a result of both the excitation decreasing at the $^{56}$Co rate and the recombination rate from [Fe III] $\rightarrow$ [Fe II], then we can approximate it by

$$\exp(-t/\tau_{CH1}) = \exp(-t/\tau_{Co}) \cdot \exp(-t/\tau_{rec}),$$

where $\tau_{CH1}$, $\tau_{Co}$, and $\tau_{rec}$ are respectively the $e$-folding times of CH1, $^{56}$Co, and [Fe III] $\rightarrow$ [Fe II] recombination. Assuming collisional ionization are negligible at late times and photoionization is becoming unimportant, the recombination should go approximately as $\exp(-n_e \alpha_R t)$, where $n_e$ is the electron number density and $\alpha_R$ is the recombination rate coefficient. The recombination coefficient is $\alpha_R \approx 3 \times 10^{-12} \text{ cm}^3 \text{s}^{-1}$ and is nearly constant for temperatures between $10^3$ and $10^6 \text{ K}$ (Nahar 1997). We can solve for the electron density, $n_e = 1/\alpha_R [1/(1/t_{CH1} - 1/t_{Co})]$ and find $n_e = 1.8 \times 10^4 \text{ cm}^{-3}$. Assuming most of the iron peak atoms are doubly ionized, the mass density corresponding to this recombination rate is then approximately $10^{-18} \text{ g cm}^{-3}$.

We can compare this recombination density to the density of the standard W7 model scaled to 250 days after explosion (Mazzali et al. 2011). The scaled W7 density ranges between $10^{-16} \text{ g cm}^{-3}$ in the inner regions to $10^{-17} \text{ g cm}^{-3}$ out at 10000 km s$^{-1}$. Considering the assumptions made in the calculation, this is surprisingly close to the density for a pure recombination process removing doubly ionized species from the nebula.

4.2. Optical Decay Rates from LBT Spectra

The ratio of the June 12 and March 24 count rates as a function of wavelength is shown in Figure 4 in units of mag/100$^d$. The ratio has been scaled to match the B-band decay rate discussed in Section 2. Clearly, the decay rates vary by spectral region and by specific feature. Some of the small-scale variation is due to shifts in emission centroids with time. For example, the bright blend of [Fe III] lines at 4700 Å shifts by about 10 Å redward over the 80 days between spectra. This is shown as a decay rate of 1.4 mag/100$^d$ on the blue side of the feature and a 1.1 mag/100$^d$ decay on the red side. This drift was noted by Maeda et al. (2010b) and appears typical in SN Ia. The total flux of the feature fades by 1.41 mag/100$^d$ which is not surprising given that we have scaled the B-band flux to 1.32 mag/100$^d$ and the 4700 Å line contributed significantly to this filter.
Figure 4. Decline rate $\Delta$ in units of mag/100d from the LBT/MODS spectra from 190 days to 270 days past maximum. The optical spectrum of 2011fe is included for reference. The horizontal dotted line at 1.41 mag/100d represents the calculated $B$-band decline rate, while the horizontal line at 0.98 mag/100d is the energy deposition rate, equal to $^{56}$Co decay. We note that the large fading rate seen from 5700 Å to 6400 Å is Co$_{iii}$ which has an additional loss channel through radioactive decay to iron.

In contrast, the weak features around 6000 Å faded at twice the $^{56}$Co decay rate and show no shift in the line centroid. The 5900 and 6160 Å lines have been attributed to [Co$_{iii}$] emission, but the 5900 Å line may also contain some Na$_i$ D flux.

As noted in Figure 1, the blend of bright lines around 7200 Å fade rather slowly compared with the [Fe$_{iii}$] and [Co$_{iii}$] lines in the blue. The emission around 7200 Å is often attributed to [Fe$_{ii}$] and [Ni$_{ii}$] lines. The line at 8600 Å also shows a slow decay rate and it too has been identified as an [Fe$_{ii}$] feature.

In general, the singly ionized species show the slow decay rates while emission from doubly ionized atoms decays significantly faster than the radioactive decay rate (see Figure 5). This supports our interpretation of the decay rates we observed in the Spitzer bands and that recombination is the likely sink for the doubly ionized species.

[Co$_{iii}$] emission is hit with a triple whammy. The overall energy available for line emission decreases at the $^{56}$Co radioactive decay rate. In addition, recombination of doubly ionized atoms reduces their numbers as demonstrated in the decay rate of [Fe$_{iii}$] lines. But much of the cobalt is radioactive, so its numbers are decreased at twice the radioactive decay rate plus the recombination loss rate.

The emission at 6550 Å has been identified as from [Co$_{iii}$], but it appears to fade at a slower rate the other [Co$_{iii}$] lines. The very strong shift in peak wavelength as the line fades suggests it is a blend with a singly ionized emission feature and that combination makes it appear to fade more slowly than the other [Co$_{iii}$] lines. The NIST Atomic Spectra Database\(^8\) points to strong [Fe$_{ii}$] emission at 6446, 6456 and 6516 Å, while Liu et al. (1997) suggests a combination of [Fe$_{ii}$] and [Ni$_{ii}$] in addition to [Co$_{iii}$]. This feature’s profile is flat-topped in the June spectrum and this makes it difficult to obtain a precise peak velocity.

4.3. IRAC Color Variation in Type Ia Supernovae

Our supposition that emission from doubly ionized species decays at a faster rate than those from singly ionized atoms appears to be supported by the optical spectra. Since IRAC CH1 shows a rapid decay rate, then doubly ionized species should be dominant around 3.6 $\mu$m. Indeed, Gerardy et al. (2007) suggested Fe$_{iii}$ and Co$_{iii}$ lines contribute significantly to the CH1 band. Thus, the CH1−CH2 color observed in the SN Ia might be a good indicator of the ionization ratio within a SN Ia nebula.

We can ask if the correlation between the IRAC color and $\Delta m_{15}(B)$ seen in Figure 3 implies that a [Fe$_{iii}$]/[Fe$_{ii}$] ratio correlates with nickel yield. SN 2003hv possessed notably strong [Fe$_{iii}$] 4700 Å at late times (Mazzali et al. 2011), though the SN had a large $\Delta m_{15}(B)$ of 1.6 (Leloudas et al. 2009), so probably synthesized a relatively small amount of radioactive nickel. This trend is the opposite of that implied by [Fe$_{iii}$] dominating the CH1 bandpass. Mazzali et al. (2011) argued that the very strong [Fe$_{iii}$] emission seen in SN 2003hv might be due to an unusually low nebular density and that the explosion might be peculiar. The [Fe$_{iii}$]/[Fe$_{ii}$] ratio is probably a good indicator of nebular density because the recombination rate is

\(^8\) http://physics.nist.gov/PhysRefData/ASD/lines_form.html
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Figure 5. Decay rate of the total flux for individual emission lines, measured between 2012 March 24 and June 12. The approximate BVRI (Munari et al. 2013), CH1, and CH2 decay rates of SN 2011fe are given for reference.

4.4. Nebular Velocity

Maeda et al. (2010b) suggested that asymmetry in SN Ia explosions could be shown in the nebular spectra. While most SN Ia appear to show little asymmetry in the outer layers of the ejecta (Wang et al. 1996), Maeda et al. (2010a) showed that differences in velocity shifts between ions associated with dense, inner layers could be quite large when compared to velocity shifts of the outer layers. The theory they develop is that of a dense, inner region rich in deflagration products that is offset in position and velocity from the low-density, symmetric outer region. In this scenario, doubly ionized iron-group lines tend to trace outer low-density regions, while their singly-ionized variants trace the dense inner regions.

We measured the wavelength centroids of several major features of the LBT/MODS spectra and found two distinct groups: [Fe III] and [Co III] lines tended to be blueshifted by ~400 km s$^{-1}$, while [Fe II] and [Ni II] features were blueshifted between 1000 and 1500 km s$^{-1}$. A list of these measured lines is given in Table 3. Features made from blends of singly and doubly ionized lines (e.g., the $\sim$5000 and $\sim$5250 Å [Fe II]+[Fe III]) appear to show higher blueshifts, as well, suggesting that their singly-ionized components are dominant. The highly blended $\sim$6550 feature proved difficult to model in this manner; the lack of a narrow, discernible peak meant a large error in identifying individual lines, though Bowers et al. (1997) identified [Co III] 6578 Å as an important component, and the NIST Atomic Spectra Database points to major [Fe II] contributions here, as well. Synthetic spectra and improved atomic transition information is necessary to better determine the shift of individual lines.

Despite the problems of line blending in the optical, it is clear that the velocity shifts of the [Fe III] 4700 Å line and the [Co III] features at $\sim$5900 and $\sim$6200 Å are significantly smaller than the offsets of more than $\sim$1000 km s$^{-1}$ observed in the singly ionized emission lines. Both [Fe III] and [Co III] emission likely originate in the outer, symmetric regions of the nebula.

The large difference in velocity between the [Fe II] and [Fe III] features places SN 2011fe firmly in the “low-velocity gradient” group (see Figure 6). We confirmed this by examining the nebular velocity (defined by Maeda et al. 2010b as the average of the [Fe II] 7155 Å and the [Ni II] 7378 Å velocity shifts) and the early-time Si II velocity gradient, which we calculated using the spectra presented by Parrent et al. (2012) and made publicly available through the Weizmann Interactive Supernova data
The luminosity in the Spitzer/IRAC bands are well fit by an exponential fading. The observed decay rate was $1.48 \pm 0.02 \text{ mag/100d}$ in the $3.6 \mu m$ band and $0.78 \pm 0.02 \text{ mag/100d}$ at $4.5 \mu m$. The fading rate in the CH1 filter is similar to that seen for many SN Ia in the optical B and V filters. The CH2 decline rate is slower than the $^{56}$Co radioactive decay rate.

2. Using SN 2011fe and three other SN Ia observed by Spitzer, we found that the ratio of the flux at 3.6 $\mu m$ to the flux at 4.5 $\mu m$ at an age of 230 days correlates with the light curve decline rate at maximum brightness. Since the light curve shape at maximum is also correlated with the peak luminosity, we expect the CH1–CH2 color index at a fixed age is a good indicator of the radioactive nickel yield of a SN Ia.

3. The series of optical spectra obtained with the LBT show emission features fading at three different rates depending on the element and ionization state. Singly ionized iron–peak elements faded close to the $^{56}$Co radioactive decay rate. Doubly ionized iron lines decayed at a rate similar the $B$-band fading. Finally, doubly ionized cobalt faded at more than twice the $^{56}$Co radioactive decay rate.

4. The optical and near-IR spectra of SN 2011fe show large ($> 1000 \text{ km s}^{-1}$) velocity shifts in the singly ionized emission lines while doubly ionized lines showed significantly smaller offsets.

It has long been known that the decline in radioactive energy input is the cause of the fading luminosity in the nebular phase. Here, we show that the doubly ionized species fade more quickly than the radioactive energy input and suggest that this additional fading is due to recombination. Additionally, doubly ionized cobalt sees a decline in excitation, recombination losses and direct radioactive decay to iron and so it fades at the fastest rate of all the emission lines. The decay rate variation with element and ionization state demonstrated in the LBT spectra nicely explains the range of observed decay rates seen in broadband filters during late-time studies of SN Ia (Lair et al. 2006).

Our mid-IR Spitzer photometry is consistent with the slow fading of singly ionized iron in the CH2 band and doubly ionized oxygen in the CH1 band. It explains the range of observed decay rates seen in broadband filters during late-time studies of SN Ia (Lair et al. 2006).

The observed velocity shift of the singly ionized nebular lines implies a viewing angle of roughly $70^\circ$ from the symmetry axis as defined by Maeda et al. (2010a).

5. CONCLUSIONS

We have analyzed mid-IR photometry and optical spectroscopy of the nearby Type Ia supernova 2011fe at ages between six months to a year after the explosion. We found the following:

- The luminosity in the Spitzer/IRAC bands are well fit by an exponential fading. The observed decay rate was $1.48 \pm 0.02 \text{ mag/100d}$ in the $3.6 \mu m$ band and $0.78 \pm 0.02 \text{ mag/100d}$ at $4.5 \mu m$. The fading rate in the CH1 filter is similar to that seen for many SN Ia in the optical B and V filters. The CH2 decline rate is slower than the $^{56}$Co radioactive decay rate.

- Using SN 2011fe and three other SN Ia observed by Spitzer, we found that the ratio of the flux at 3.6 $\mu m$ to the flux at 4.5 $\mu m$ at an age of 230 days correlates with the light curve decline rate at maximum brightness. Since the light curve shape at maximum is also correlated with the peak luminosity, we expect the CH1–CH2 color index at a fixed age is a good indicator of the radioactive nickel yield of a SN Ia.

- The series of optical spectra obtained with the LBT show emission features fading at three different rates depending on the element and ionization state. Singly ionized iron–peak elements faded close to the $^{56}$Co radioactive decay rate. Doubly ionized iron lines decayed at a rate similar the $B$-band fading. Finally, doubly ionized cobalt faded at more than twice the $^{56}$Co radioactive decay rate.

- The optical and near-IR spectra of SN 2011fe show large ($> 1000 \text{ km s}^{-1}$) velocity shifts in the singly ionized emission lines while doubly ionized lines showed significantly smaller offsets.

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**Table 3**

| Identification | ID Reference | Average Wavelength | $v_{\text{hel}}$ (km s$^{-1}$) | Decline Rate (mag/100d) |
|---------------|--------------|-------------------|-----------------------------|------------------------|
| [Fe ii] 4658 + [Fe ii] 4701 + [Fe ii] 4734 | M10 | 4698 | $-457 \pm 89$ | 1.41 |
| [Fe ii] 4990 + [Fe ii] 5006 | B97 | 4998 | $-1638 \pm 180$ | 1.39 |
| [Fe ii] 5262 + [Fe ii] 5270 | M10, B97 | 5266 | $-362 \pm 296$ | 1.55 |
| [Co ii] 5890 + [Co ii] 5908 | B97 | 5899 | $-422 \pm 56$ | 2.01 |
| [Co ii] 6129 + [Co ii] 6197 | B97 | 6163 | $+146 \pm 165$ | 2.33 |
| [Co ii] 6578 + [Fe ii] 6456 + [Fe ii] 6516 | B97, NIST | 6517 | $+1391 \pm 1850^d$ | 1.65 |
| [Fe ii] 7155 + [Fe ii] 7172 | M10, B97 | 7154 | $-1006 \pm 59$ | 0.85 |
| [Ni ii] 7378 + [Fe ii] 7388 | M10, B97 | 7383 | $-1137 \pm 102$ | 0.81 |
| [Fe ii] 8617 | M10 | 8617 | $-1559 \pm 101$ | 0.47 |
| [Fe ii] 1.257 $\mu m$ | M10 | 1.257 $\mu m$ | $-1223 \pm 95^c$ | $\cdots$ |
| [Fe ii] 1.644 $\mu m$ | M10 | 1.644 $\mu m$ | $-1137 \pm 197^c$ | $\cdots$ |

**Notes.**

a Wavelengths are given in Å unless otherwise noted.
b References: (M10) Maeda et al. 2010b; (B97) Bowers et al. 1997; (NIST) Kramida et al. 2012.
c Velocities are corrected for the M101 redshift of $z = 0.000804$ listed by NED (NASA/IPAC Extragalactic Database; http://ned.ipac.caltech.edu).
d The large uncertainty derives from an assumed 40 Å error in fitting the highly-blended line profile.
e From LBT/LUCIFER spectrum obtained at age 234 days.

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**Figure 6.** Comparison of nebular velocity with respect to host galaxy rest frame to the early-time velocity gradient of Si ii (see Maeda et al. 2010a for details). SN 2011fe is labeled in blue amongst the green low velocity gradient (LVG) SN. The gray, “Intermediate” SN include faint events SN 1986G and SN 2007on, while the high velocity gradient (HVG) is colored pink. Peculiar SN such as SN 2011fe is labeled in blue amongst the green low velocity gradient (LVG) SN.

(A color version of this figure is available in the online journal.)
ionized iron or cobalt in the CH1 filter. From the correlation between the IRAC color index with the radioactive nickel yield, we argue that Co$^{iii}$ is probably the primary source of emission around 3.6 $\mu$m up to a year after explosion. The rapid fading of the Co$^{iii}$ emission will eventually lead to Fe$^{iii}$ or Fe$^{ii}$ becoming dominant in CH1 and a decelerating decay rate in the future.

We also measured the individual line velocities of optical and NIR features and confirm the pattern of velocity offsets seen by Maeda et al. (2010b). That is, emissions from singly ionized species have higher velocity offsets than those from doubly ionized elements. According to Maeda et al. (2010a), this is because the singly ionized species reside in the dense inner region of the nebula where an offset deflagration occurred, while the doubly ionized atoms occupy the outer, low density and more symmetric regions of the nebula. Both the measures of the early and late spectra indicate SN 2011fe was a typical “low velocity gradient” SN Ia viewed at an angle of about 70° relative to the offset axis of the deflagration.

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