CLUES TO THE NATURE OF SN 2009ip FROM PHOTOMETRIC AND SPECTROSCOPIC EVOLUTION TO LATE TIMES

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Received 2014 February 7; accepted 2014 April 18; published 2014 May 15

ABSTRACT

We present time series photometric and spectroscopic data for the transient SN 2009ip from the start of its outburst in 2012 September until 2013 November. These data were collected primarily with the new robotic capabilities of the Las Cumbres Observatory Global Telescope Network, a specialized facility for time domain astrophysics, and includes supporting high-resolution spectroscopy from the Southern Astrophysical Research Telescope, Kitt Peak National Observatory, and Gemini Observatory. Based on our nightly photometric monitoring, we interpret the strength and timing of fluctuations in the light curve as interactions between fast-moving ejecta and an inhomogeneous circumstellar material (CSM) produced by past eruptions of this massive luminous blue variable (LBV) star. Our time series of spectroscopy in 2012 reveals that, as the continuum and narrow H\textalpha flux from CSM interactions declines, the broad component of H\textalpha persists with supernova (SN)-like velocities that are not typically seen in LBVs or SN impostor events. At late times, we find that SN 2009ip continues to decline slowly, at \textless 0.01 mag day\textsuperscript{-1}, with small fluctuations in slope similar to Type IIn supernovae (SNe IIn) or SN impostors but no further LBV-like activity. The late-time spectrum features broad calcium lines similar to both late-time SNe and SN impostors. In general, we find that the photometric and spectroscopic evolution of SN 2009ip is more similar to SNe IIn than either continued eruptions of an LBV star or SN impostors but we cannot rule out a nonterminal explosion. In this context, we discuss the implications for episodic mass loss during the late stages of massive star evolution.

Key words: circumstellar matter – stars: mass-loss – stars: variables: general – supernovae: individual (2009ip)

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

Type IIn supernovae (SNe IIn) are characterized by bright optical emission caused when explosion ejecta collides with nearby circumstellar material (CSM). This reveals that the progenitor star experienced a significant amount of mass loss prior to core collapse. The physical mechanism driving the mass loss, and the relative contributions to the CSM from winds and episodic eruptions, are not yet well constrained. In the final stages of massive star evolution, the star undergoes a rapid succession of burning phases and exhibits variability during its mass loss episodes. The distribution of material in the CSM can be derived from spectroscopic and photometric fluctuations of SNe IIn which, if the star was monitored for variability in previous years, allows for a connection between pre-explosion mass loss episodes and the material they produce. Luckily, the transient SN 2009ip affords us this rare opportunity.

SN 2009ip was first identified as a photometric transient near host galaxy NGC 7259 by the Chilean Automatic Supernova Search (Maza et al. 2009), and given the designation “SN” without spectroscopic confirmation. Archival imaging of Hubble Space Telescope (HST) images of the progenitor star of SN 2009ip indicated it is very massive, $M = 50$–$80$ $M\odot$ (Smith et al. 2010). Analysis of archival data found a coincident variable source and suggested the transient may in fact be a luminous blue variable (LBV) or a cataclysmic variable (Miller et al. 2009). The LBV hypothesis was quickly confirmed with spectroscopy (Berger et al. 2009), which showed that SN 2009ip was similar to the group of “SN impostors” that look like SNe IIn (e.g., Van Dyk et al. 2000). After peak brightness in 2009, the transient fell but then rose again, in a manner similar to eta Carinae (Li et al. 2009), and experienced a second outburst in mid-2010 (Drake et al. 2010). Extensive analysis and discussion of the evidence for the 2009 and 2010 activity of SN 2009ip as an LBV eruption are provided by Smith et al. (2010) and Foley et al. (2011). In 2012 August, SN 2009ip rebrightened to record luminosity (Drake et al. 2012), maintaining an LBV-like spectrum (Foley et al. 2012), but by 2012 mid-September, the spectral lines had broadened and shifted, indicating material at velocities up to 13,000 km s\textsuperscript{-1}, and showed P-Cygni profiles typical of core–collapse SN explosions (Smith & Mauerhan 2012).

An analysis of spectroscopic and photometric data during the outburst of SN 2009ip from September to December of 2012 was presented in Mauerhan et al. (2013, hereafter JM13). They report Balmer lines with broad P-Cygni profiles and high absorption component velocities characteristic of core–collapse SNe, completely unprecedented by any previous LBV eruption. JM13 observed SN 2009ip to fade and then brighten to
... was supported by Prieto et al. (2013), who present a densely time-sampled light curve from the start of the 2012-B event and find that the rapid rise and bolometric luminosity are similar to other SNe IIn.

The interpretation of SN 2009ip as an SN IIn was challenged by Pastorello et al. (2013, hereafter AP13), who present 3 yr of monitoring of SN 2009ip; we have included their photometry for context in Figure 1. They find that spectra from 2011 September 24 also exhibit material at velocity $\sim 13,000$ km s$^{-1}$, showing for the first time that nonterminal explosions can create such fast ejecta and calling into question the SN diagnosis for SN 2009ip. Instead, AP13 suggest the 2012 activity of SN 2009ip was caused by a pair-instability event during 2012-A, with the 2012-B event caused by ejecta material colliding with the CSM. The scenario of AP13 is fundamentally different from JM13 because the star is not destroyed. This hypothesis is supported by the analysis of Fraser et al. (2013, hereafter MF13), who find a very low upper limit of 0.02 $M_\odot$ on the mass of any synthesized material (e.g., $^{56}$Ni). A similar inference is made by Margutti et al. (2014, hereafter RM14), who analyze extensive multi-wavelength observations of SN 2009ip’s 2012 activity and conclude that the events were not caused by a core collapse but that the true physical mechanism behind the explosive ejection in the LBV’s envelope could not, at that time, be fully distinguished. A full analysis, including late-time observations of SN 2009ip by Smith et al. (2014, hereafter NS14), finds that the broad component of Hα, first announced in Smith & Mauerhan (2012), persisted throughout the 2012-B event, indicating that a significantly more energetic explosion had occurred than considered by RM14. They also find that the late-time spectrum of SN 2009ip no longer resembles an LBV. Combined, the observations of NS14 lead them firmly to the conclusion that a terminal SN explosion had occurred.

This paper presents new, densely time-sampled photometry and spectroscopy for SN 2009ip from the Las Cumbres Observatory Global Telescope Network (LCOGT.net) and other facilities at which we were observing classically at the time. LCOGT is a new system of robotic telescopes dedicated to time domain astrophysics. Telescopes of 1 and 2 m diameter are distributed at five sites around the world, and observation requests are optimized and automatically executed by a real-time adaptive scheduler. Instrumentation includes identical imagers with a full suite of filters on all telescopes and one robotic spectrograph (FLOYDS) on each of the two 2 m Faulkes Telescopes. The distributed aspect of LCOGT makes it flexible, responsive, and unhindered by weather or sunrise. New astrophysical transients are followed as soon as possible for classification and can be reliably monitored on any desired timescale. The LCOGT Network, presented in depth by Brown et al. (2013), currently features the following facilities: McDonald Observatory, Texas USA (one 1 m); Haleakala Observatory, Hawaii (one 2 m+FLOYDS); Sutherland, South Africa (three 1 m); Cerro Tololo, Chile (three 1 m); and Siding Spring, Australia (two 1 m and one 2 m+FLOYDS).

The 2012–2013 activity of SN 2009ip is one of the first astrophysical transients followed with the LCOGT 1 m network and is a great example of the science potential from the combination of reactive follow-up and long-term monitoring with a network that includes photometric and spectroscopic capabilities. The quality, quantity, and extent of these data allow us to provide new insight to the controversial physical interpretation of SN 2009ip, especially during its extended slow decline. In Section 2, we present the observations; in Sections 3 and 4, we interpret the photometry and spectroscopy, respectively, and discuss the results in context with the ongoing debate about the true physical nature of SN 2009ip before concluding in Section 5. A flat cosmology with $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$ is assumed throughout.

## 2. OBSERVATIONS

Here, we present the photometric and spectroscopic observations of SN 2009ip obtained with the imaging cameras and FLOYDS spectrograph on the LCOGT 1 and 2 m telescopes, the Goodman Spectrograph on the 4 m Southern Astrophysical Research (SOAR) Telescope at Cerro Pachon, the Ritchey–Chretien (RC) Spectrograph on the Mayall 4 m telescope at Kitt Peak National Observatory (KPNO), and the Gemini Multi-Object Spectrograph on the 8 m Gemini South Telescope.

### 2.1. LCOGT 1.0 m and 2.0 Photometry

Photometric monitoring of SN 2009ip began on 2012 September 22 with the spectral camera on Faulkes Telescope South (FTS, Siding Spring Observatory, Australia) in filters $g^{\prime}r^{\prime}i^{\prime}$. The spectral camera is a 4096 $\times$ 4096 pixel Fairchild CCD with a 10.5' field of view. As Faulkes South monitored the rise of SN 2009ip, LCOGT’s first three southern 1 m telescopes arrived on site at Cerro Tololo Inter-American Observatory in Chile. Photometric monitoring of SN 2009ip from CTIO began when the telescopes were operational, about one month later on UT 2012 October 21, with the first generation deployment camera: SBIG CCDs with a 15' field of view. In Figure 2, we show one of the first LCOGT $r^{\prime}$ images of SN 2009ip, and in Figure 3, we show the full LCOGT light curve, indicating the point at which the CTIO 1.0 m came online. We monitored...
filters as possible, in Johnson–Cousins filters UBVRI SN 2009ip until the end of 2012 with as close to daily cadence in both CTIO and SAAO Telescopes. Observations were collected in gri filters with the 2.0 m FTS until the 1.0 m telescopes at CTIO became available, as marked. At late times, the 1.0 m photometry was collected with both CTIO and SAAO Telescopes.

Table 1

| Date       | FTS g | FTS r | FTS i | 1 m g | 1 m r | 1 m i | 1 m B | 1 m V | 1 m R |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 2012 Nov 2 | 14.88 ± 0.08 | 14.75 ± 0.07 | 14.97 ± 0.01 | 14.97 ± 0.10 | 14.83 ± 0.06 | 14.94 ± 0.11 | 15.28 ± 0.03 | 14.90 ± 0.03 | 14.60 ± 0.03 |
| 2012 Nov 3 | 14.82 ± 0.11 | 14.71 ± 0.09 | 14.91 ± 0.01 | 14.89 ± 0.10 | 14.78 ± 0.06 | 14.96 ± 0.22 | 15.18 ± 0.05 | 14.84 ± 0.14 | 14.54 ± 0.06 |
| 2012 Nov 4 | 14.79 ± 0.06 | 14.68 ± 0.06 | 14.86 ± 0.03 | 14.86 ± 0.15 | 14.70 ± 0.06 | 14.83 ± 0.14 | 15.13 ± 0.05 | 14.83 ± 0.12 | 14.52 ± 0.04 |
| 2012 Nov 5 | 14.87 ± 0.11 | 14.71 ± 0.09 | 14.90 ± 0.04 | 14.89 ± 0.14 | 14.77 ± 0.11 | 14.90 ± 0.13 | 15.19 ± 0.09 | 14.86 ± 0.13 | 14.55 ± 0.08 |
| 2012 Nov 6 | 14.94 ± 0.12 | 14.79 ± 0.11 | 14.98 ± 0.09 | 14.95 ± 0.08 | 14.81 ± 0.05 | 14.91 ± 0.13 | 15.26 ± 0.06 | 14.90 ± 0.11 | 14.59 ± 0.04 |
| 2012 Nov 7 | ...    | ...    | ...    | ...    | 15.04 ± 0.10 | 14.87 ± 0.04 | 14.98 ± 0.07 | 15.38 ± 0.06 | 14.98 ± 0.02 | 14.66 ± 0.04 |
| 2012 Nov 8 | ...    | ...    | ...    | ...    | 15.16 ± 0.12 | 14.94 ± 0.05 | 15.03 ± 0.14 | 15.51 ± 0.06 | 15.10 ± 0.09 | 14.74 ± 0.03 |
| 2012 Nov 9 | 15.32 ± 0.45 | 15.06 ± 0.39 | 15.27 ± 0.07 | 15.46 ± 0.25 | 15.18 ± 0.14 | 15.30 ± 0.08 | 15.76 ± 0.14 | 15.34 ± 0.16 | 15.01 ± 0.18 |
| 2012 Nov 10| 15.47 ± 0.08 | 15.14 ± 0.08 | 15.34 ± 0.03 | 15.61 ± 0.17 | 15.34 ± 0.14 | 15.45 ± 0.15 | 15.99 ± 0.17 | 15.51 ± 0.15 | 15.14 ± 0.15 |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Figure 2. Image of SN 2009ip taken on 2012 October 21 in r′ with one of the LCOGT 1.0 m telescopes at CTIO.

SN 2009ip until the end of 2012 with as close to daily cadence as possible, in Johnson–Cousins filters UBVRI, Sloan filters g′r′i′, and Pan-STARRS z-short. When SN 2009ip was again accessible in 2013 May, we monitored it with the 1.0 m network, including the new site at the South African Astronomical Observatory (SAAO), with near daily cadence in BVg′r′i′. The reduction and calibration of our photometry is discussed in detail in the Appendix. The photometry has been corrected for Milky Way extinction along the line-of-sight only where explicitly mentioned; otherwise, calibrated observed apparent magnitudes are presented. We present our photometry from the LCOGT 2.0 Faulkes Telescope and CTIO 1 m telescopes in Table 1.

2.2. LCOGT FLOYDS Spectroscopy

Spectroscopic monitoring of SN 2009ip began on UT 2012 September 25 with the new FLOYDS robotic spectrograph on the 2.0 m FTS at Siding Spring Observatory in Australia. A twin spectrograph is located at the Faulkes Telescope North (FTN) on Haleakala, Hawaii. These robotic spectrographs have low resolution and were specifically designed for SNe. The design is a simple folded Schmidt camera, with a double-pass prism and reflective grating. FLOYDS uses a standard reflection grating (235 1 mm−1) as the primary disperser, with a cross-dispersed prism to image the first (5400–10000 Å) and second (3200–5700 Å) order light onto the CCD. This provides an overall wavelength coverage from 3200 Å to 10000 Å in a single exposure. Slit widths range from 0.9 to 6.0 but only the 2.0 slit was used in this work. The resolution in the red is $R \sim 400$, or 16.5 Å per resolution element, and in the blue is $R \sim 690$, or 8.25 Å per resolution element.

The LCOGT FLOYDS spectrographs, and the automatic pipeline with which these spectra were reduced, will be presented in D. J. Sand et al. (in preparation). FLOYDS-FTS achieved first light on 2012 May 7 and was still in commissioning when SN 2009ip was observed. The automated scheduler is always requested to observe at the parallactic angle and obtain a nearby standard star. At that time, the robotic target acquisition software was still being refined, and some of the spectra suffer from flux miscalibration and residual fringing (e.g., 2012 October 4) than FLOYDS spectra being obtained and reduced in the present day. The telluric removal is done in the automatic pipeline but we still label the locations of tellurics in our plots so that incomplete removals are obvious. All FLOYDS spectra are calibrated using a sensitivity function derived from a standard star spectrum observed on the same night and then are flux calibrated with LCOGT photometry from the nearest epoch.

2.3. SOAR Goodman Spectroscopy

Spectroscopy of SN 2009ip was obtained on UT 2012 September 22 with the Goodman High Throughput Spectrograph (Clemens et al. 2004) on the 4 m SOAR Telescope at Cerro Pachon in Chile. This spectrograph has a 4 k \times 4 k
Fairfield imaging CCD. We used the long slit with a 0.84 width, the 600 lines mm\(^{-1}\) grating, and the GG385 order-blocking filter in the “mid-” wavelength option for 4350–7020 Å coverage. These settings result in a read noise of 3.99 electrons, a gain of 2.06 electrons per analog-to-digital units (ADU), and resolution of \(R \sim 1500\) at 5500 Å. Three 600 s exposures of SN 2009ip at the parallactic angle were reduced with standard IRAF procedures, corrected for extinction, flux calibrated with standard star LTT2145, and median combined.

2.4. Mayall Spectroscopy

Spectroscopy of SN 2009ip was obtained nightly from UT 2012 October 11 to 2012 October 15 with the RC Spectrograph on the 4.0 m Mayall Telescope at KPNO. These spectra were also presented in RM14 but have been reduced and calibrated independently for this work. During the first two nights, lower resolution spectra were obtained but, because the spectra from each of these five nights are very similar, we will only present and discuss the higher resolution spectra obtained on the last three nights. For these, the higher resolution grating KPC-22B (632 lines mm\(^{-1}\)) was used in the first order, giving a spectral resolution of \(~2.7\) Å and coverage of \(\lambda = 5500–8000\) Å. All exposure times were 1200 s, with five, three, and four exposures taken on 2012 October 13, 14, and 15, respectively. All Mayall spectroscopy has been calibrated using a sensitivity function derived from a standard star spectrum observed on the same night and then flux calibrated to match the photometric magnitudes of the closest epoch to the time of the spectra’s acquisition.

2.5. Gemini Spectroscopy

Spectroscopy of SN 2009ip was obtained on UT 2013 June 12 with the Gemini Multi-Object Spectrograph on the 8.0 m Gemini South Telescope at Cerro Pachon, Chile (PI: Howell, program GS-2013A-Q-62). We used a 1″ longslit and an exposure time of 900 s for both the B600 and R400 gratings, with the OG515 order blocking filter on the red side. This gave spectral resolutions of 2.7 and 4.0 Å on the blue and red sides, respectively, and coverage over \(\lambda = 3500–9500\) Å. These spectra were reduced and combined with standard procedures.

3. THE LIGHT CURVE OF SN 2009IP

Photometric monitoring of SN 2009ip with the LCOGT network began on 2012 September 22, in between the 2012-A and 2012-B events. We registered no change in magnitude on the next day, 2012 September 23. After this, the transient increased rapidly in brightness, as seen in Figure 4. We chose a nightly cadence but point out that faster cadences are possible at the LCOGT network, down to minute cadences with conventional cameras, and even faster with high-speed photometers if the object is bright. Prieto et al. (2013) present an analysis based on ~hourly observations of the 2012-B rise. They find a very rapid brightening on 2012 September 24 (0.5 mag over 6 hr), consistent with \(L \propto t^2\); this rapid rise is followed by a slower rise to peak that we see clearly in Figure 4.

We find the light curve reaches its plateau-like peak on 2012 October 6 at \(m_g = 13.6, m_r = 13.7\), and \(m_i = 14.0\) mag. For this work we have used the recession velocity for NGC 7259 from the NASA Extragalactic Database,\(^{10}\) \(v = 1782\) km s\(^{-1}\) (Koribalski et al. 2004). Under our assumed cosmology, this is a distance of 25.5 Mpc, and a distance modulus of \(\mu = 32.0\). At the coordinates of SN 2009ip, Milky Way extinction is \(A_g = 0.064, A_r = 0.044, A_i = 0.033\) (Schlegel et al. 1998), and we assume no contribution from host extinction given that SN 2009ip is in the outskirts of NGC 7259. Accordingly, we find that SN 2009ip peaked at \(M_g = −18.5, M_r = −18.3,\) and \(M_i = −18.0\) mag. These results agree well with published observations (e.g., JM13, Prieto et al. 2013, and MF13 use \(\mu = 31.55\) and find \(M \sim −18\) mag; RM14 use a distance modulus of 32.05 and quote \(M_R \sim −18\)).

The peak magnitude of SN 2009ip is brighter than the typical peak of Type II-Plateau (SNe IIP), the most common type of core–collapse explosion, that typically reach \(R \sim −16\) to −17 and only a few reach \(R \sim −18\) (Li et al. 2011). For SNe IIn, the continuum emission is dominated by CSM interaction, the amount of which varies between individual events and causes heterogeneity in peak magnitudes for this class (Li et al. 2011). A peak magnitude of \(M_r = −18.3\) is not unusual for SNe IIn, as we show in Figure 5, and as also shown by MF13 and RM14. Historically, SN 2009ip’s brightest recorded apparent magnitude was \(m_R \sim 18\) or \(M_R \sim −14.5\) (e.g., 2009 August 30; AP13); relative to its past, the 2012 events of SN 2009ip are of an unprecedented luminosity. In general, the total change in magnitude and the smoothness of the light curve are quite distinct from the usual activity of an LBV. In these qualities, SN 2009ip resembles an SN impostor such as 1961V (blue triangles, Figure 5). However, SN 2009ip is significantly brighter than the typical brightest SN impostor, M \sim −14; 1961V is an outlier in this respect. In particular, 1961V is so much like a real SN that new data has been acquired in recent years and the debate still continues (e.g., Kochanek et al. 2011; Van Dyk & Matheson 2012). Furthermore, SN impostors are not typically associated with stars as massive as the known progenitor of SN 2009ip. Interestingly, RM14 and NS14 present further evidence that SN 2009ip is not an entirely unique event: they find a photometric sibling in SN IIn 2010mc, whose light curve is nearly identical to the 2012-A and 2012-B events of SN 2009ip (green circles in Figure 5; Ofek et al. 2013a).

The 2012-B event of SN 2009ip is characterized by bumpy features indicative of irregularities in the CSM created by

\(^{10}\) http://ned.ipac.caltech.edu/
repeated mass loss episodes during past LBV outbursts. The plateau seen immediately before SN 2009ip became inaccessible was speculated to be a return to its quiescent state and mark the end of an outburst, which was not fatal for the progenitor star. However, when SN 2009ip was again accessible in 2012 April, we found it to be still steadily declining.

In the following sections, we leverage the daily cadenced multiband photometry from LCOGT into a detailed analysis of the light-curve features and what they reveal about the physical nature of SN 2009ip. We discuss the observed CSM interaction during the 2012-B event as probe of past mass loss episodes in Section 3.1; the main light-curve “bump” era in greater detail in Section 3.2; the color evolution and a blackbody interpretation for the emitting material in Section 3.3; our derivation of bolometric luminosity and total event energetics in Section 3.4; and finally, the power source of the late-time decline in Section 3.5.

### 3.1. CSM Interaction as a Probe of Past Eruptions

Far from a smooth procession, the light curve of SN 2009ip is more of a roller coaster ride. The photometric evolution is characterized by bumpy features that occur with greater strength in bluer bands, as shown in Figures 4 and 6. For ease of discussion, in Figure 4, we label five main “eras” of the light curve: rise, decline, bump, knee, and ankle. Peak brightness is seen most clearly in bands \( g \), \( B \), and \( U \) on MD = 56,215 (2012 October 5). The light curve shows the obvious “bump” in all bands starting on MD ≈ 56,232 (2012 November 1), which is discussed further in Section 3.2. A more subtle bump follows, seen most clearly in bands \( g \), \( B \), and \( U \) on MD = 56,248 (2012 November 17). The “knee” in the light curve starts on MD = 56,264 (2012 December 1), after which the \( g \) and \( i \) bands drop more quickly than the \( r \), until the “ankle” is reached on MD = 56,278 (2012 December 16) and the light curve flattens out. These features have been discussed in other publications and are evidence of interaction with an inhomogeneous medium, such as shells of CSM previously released during the LBV phase (or disks of material; e.g., Levesque et al. 2014).

Can we associate specific features in the 2012-B light curve with known past eruptions of SN 2009ip? If an explosion at time \( t_{\text{expl}} \) releases ejecta material with velocity \( v_{\text{expl}} \), then the expected time of interaction, \( t_i \), with material from a past eruption moving at velocity \( v_{\text{erupt}} \) since time \( t_{\text{erupt}} \) is given by

\[
   t_i = t_{\text{expl}} + \frac{v_{\text{erupt}}}{v_{\text{expl}} - v_{\text{erupt}}} (t_{\text{expl}} - t_{\text{erupt}}).
\]

Smith et al. (2010) find that the bulk outflow velocity during the 2009 event was \( v_{\text{erupt}} = 550 \text{ km s}^{-1} \). Here, we consider the physical scenario of Smith et al. (2014), that a core–collapse SN occurred at the start of the 2012-A event, after which the 2012-B event was powered by the interaction of fast-moving SN ejecta with material from past eruptions. In this scenario, the modified Julian date for the time of explosion is \( t_{\text{expl}} = 56,148 \), and we measure \( v_{\text{expl}} \approx 4500 \text{ km s}^{-1} \) from the center of the blue side H\( \alpha \) absorption in our high-resolution spectrum in Section 4.

Although multiple velocity components of explosion ejecta have been observed (e.g., RM14), we use \( v_{\text{expl}} = 4500 \text{ km s}^{-1} \) as representative of the bulk of the material. In Figure 7, black stars represent the magnitudes of past eruptions from Pastorello et al. (2013), plotted as a function of \( t_i \), the predicted date at which eruption material would be encountered by the SN ejecta.

Of course, we do not expect that all features will align exactly; the fastest-moving ejecta will reach the CSM first, and the distribution of ejecta velocities will smear out the timescale of interactions. For example, RM14 find three distinct velocity components in the blue side absorption features of H\( \alpha \) from high-resolution spectra of the 2012 event, and past eruptions did not all have precisely the same velocity. Additionally, the material from each eruption has a unique mass and density, and the ejected material is likely to be asymmetrically distributed in the circumstellar environment (e.g., Levesque et al. 2014; Smith et al. 2014). However, in Figure 7, the pattern of past eruptions from 2011 and 2009 does generally agree with the characteristics of the 2012-B event. The temporal spacing of the small deviations in the light curve is about 10–20 days, similar...
Figure 7. Major rebrightening of the 2012-B event of SN 2009ip coincides with the expected time of interaction between $v \sim 500$ km s$^{-1}$ material from past eruptions and $v \sim 4500$ km s$^{-1}$ ejecta from a supernova at the start of the 2012-A event (arrow). Black stars are photometry from past eruptions (AP13) plotted in reverse, at the expected date of interaction, as described in the text. Blue stars are $R$-band photometry for the 2012-A and B events of SN 2009ip from AP13, and orange and red circles are LCOGT $g$- and $r$-band photometry for the 2012-B event.

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

to the expected spacing of interactions between SN ejecta and past material from the 2011 eruptions. Figure 7 also suggests that the abrupt and permanent change in the decline rate at the “ankle” may be related to material from the 2009 eruptions.

The opposing physical interpretation of SN 2009ip put forth by RM14 is that the 2012-A event was a precursor eruption to a stronger eruption at the start of 2012-B, which was subsequently powered by the immediate interaction material ejected in the 2012-A event. This scenario is also plausible under our current analysis. If we instead reflect the historical light curve around the start of the 2012-B event, as done in Figure 7 for the start of the 2012-A event, we find that material ejected at the start of the 2012-B event would encounter the slower moving material from 2011 at around the time of the “bump.” Ultimately, we cannot rule out either scenario based solely on a comparison of the 2012-B light-curve morphology with past eruptions. We continue this discussion of CSM interactions as a probe of past mass loss in Section 4.1, where we use the H$\alpha$ narrow line emission to constrain the amount of mass lost in the 2011 eruption.

3.2. A Detailed Look at the Bump

MF13 fit splines to their Swift UV and UBVRI photometry at the time of the light-curve “bump,” starting on MJD $\sim 56,232$ (2012 November 1), and find that the “bump” occurs earlier in the redder filters. The “bump” itself is likely caused by explosion ejecta encountering an inhomogeneity in the CSM. MF13 point out that dust is not likely to cause this timing offset between UV and optical, suggesting instead that the delay is caused by the UV photons being more susceptible to scattering and therefore taking longer to emerge. The Swift UV data published by MF13 does not exhibit a bump so much as a brief plateau before the decline resumes a couple of days after the optical peak for the bump; this may bias the “bump” UV peak computation. While the optical and UV clearly behave differently, the difference in their UBVRI filters is ambiguous, as the UVB peak dates only differ by $\sim 1$ day. The spline fit to $RI$ filters appears to peak several days earlier but MF13 suggest that undersampling in their $RI$ filters may be the true cause of this difference.

With our near daily cadence and multiband coverage at the time of the “bump,” can we add to this discussion? In Figure 8, we fit our UBVRI and $griz$ photometry with splines and find the bump reaches its peak at the same day in all optical filters. In addition, Figure 9 shows that the evolution in $B-V$ and $g-r$ colors show a brief blueward dip, coincident with the time of the “bump” in the optical. After this, the colors resume their steady redward progression seen over the bulk of the 2012-B event. The presence of dust would cause a bigger change in magnitude in the redder filters and so is unlikely to contribute to the “bump.” This “bump” is likely caused by the ejecta material encountering a denser region of the CSM. This is supported by the spectroscopic evolution in the H$\alpha$ line at this time: the decline rate of the flux in the narrow component flattens out at the time of the “bump,” as discussed further in Section 4.2.
the UBVRI interacting with CSM previously released by the LBV. Material ing at these times, indicating a temporary injection of energy.

Section 3.2. The second, at MJD \( \sim 56,235 \)–56,270, is most prominent in \( U-B \) and coincides with the second bump, seen most clearly in the UBVRI light curve of Figure 6. For both events, the temperature evolution in Figure 10 shows a brief plateau in the cooling at these times, indicating a temporary injection of energy. In general, the color, temperature, and radius that we present agrees well with its interpretation as the explosive ejecta interacting with CSM previously released by the LBV. Material from the 2011 eruptions traveling at \( v_{\text{erupt}} \approx 550 \text{ km s}^{-1} \) since MJD = 55,700, 490 days later on MJD = 56,190, would be at distance \( \sim 2.3 \times 10^{15} \text{ cm} \). This agrees with the radius of the blackbody emitting region having a radius of \( \sim 10^{15} \text{ cm} \), as seen in Figure 10.

After the “knee,” starting at MJD \( \sim 56,270 \), the redward color evolution in \( g-r \) flattens out, and in \( r-i \), it takes a bluerward turn. These observations agree with the published color evolution for SN 2009ip. MF13 present a flattening in all optical colors at this time, with blueward dips after MJD \( \sim 56,270 \) for all colors except \( V-R \), for which the dip starts 5–10 days later. Similarly, RM14 show some flattening in their \( B-V \) color evolution at this time but only their UV–optical colors show such a solid bluerward turn. Unlike the blue deviations associated with small bumps in the light curve, these bluerward turns are not related to an increase in temperature. Instead, at this time, the light-curve decay is steeper in the \( i \) and \( z \) bands, as we show in Figure 4. The slower decline in the \( r \) band at the “knee” is likely influenced by the flux in the \( H\alpha \) emission line, which as we present and discuss in Section 4.2, is simply declining linearly at this time. RM14 remark that at this time, the near-infrared is decaying more rapidly and there is a clear UV-excess over their blackbody fits, and we agree that, in general, SN 2009ip is not well fit by a blackbody at this late time. For this reason, although Figure 7 suggests that the temperature and radius evolution around the time of the “ankle” is related to interactions with material from the 2009 eruptions, we caution that this may not be the correct interpretation.

### 3.3. Color Evolution and Blackbody Interpretation

In Figure 9(b), we show the evolution of SN 2009ip during the 2012-B event in four colors: \( U-B, B-V, g-r, \) and \( r-i \). We also fit blackbody temperature and radius of the emitting region to the LCOGT griz photometry and plot the evolution in Figure 10. Under the interpretation of the 2012-B event as thermal radiation of the CSM that has been excited by the collision with fast ejecta, a blackbody is a useful and appropriate physical approximation to the spectrum.

Together, these figures show that the steady redward progression of all colors is a result of blackbody cooling. The color evolution shows several blueward deviations that coincide with bumps in the light curve. The first, at MJD \( \sim 56,235 \) (2012 November 4), coincides with the bump described in Section 3.2. The second, at MJD \( \sim 56,248 \), is most prominent in \( U-B \) and coincides with the second bump, seen most clearly in the \( U-B \) light curve of Figure 6. For both events, the temperature evolution in Figure 10 shows a brief plateau in the cooling at these times, indicating a temporary injection of energy. In general, the color, temperature, and radius that we present agrees well with its interpretation as the explosive ejecta interacting with CSM previously released by the LBV. Material from the 2011 eruptions traveling at \( v_{\text{erupt}} \approx 550 \text{ km s}^{-1} \) since MJD = 55,700, 490 days later on MJD = 56,190, would be at distance \( \sim 2.3 \times 10^{15} \text{ cm} \). This agrees with the radius of the blackbody emitting region having a radius of \( \sim 10^{15} \text{ cm} \), as seen in Figure 10.

After the “knee,” starting at MJD \( \sim 56,270 \), the redward color evolution in \( g-r \) flattens out, and in \( r-i \), it takes a bluerward turn. These observations agree with the published color evolution for SN 2009ip. MF13 present a flattening in all optical colors at this time, with blueward dips after MJD \( \sim 56,270 \) for all colors except \( V-R \), for which the dip starts 5–10 days later. Similarly, RM14 show some flattening in their \( B-V \) color evolution at this time but only their UV–optical colors show such a solid bluerward turn. Unlike the blue deviations associated with small bumps in the light curve, these bluerward turns are not related to an increase in temperature. Instead, at this time, the light-curve decay is steeper in the \( i \) and \( z \) bands, as we show in Figure 4. The slower decline in the \( r \) band at the “knee” is likely influenced by the flux in the \( H\alpha \) emission line, which as we present and discuss in Section 4.2,
luminosity presented in Hamuy (2003). The results are plotted as green points in Figure 11 and agree within the (rather large) uncertainties of \( L_{\text{bol}} \) derived from blackbody fits. In addition, we show how the integrated bolometric luminosity builds up over time (blue line), with most of the energy released within the first \( \sim 20 \) days, and a final total energy output of \( \sim 3.2 \times 10^{50} \) erg.

Under the simplifying assumption that the bulk of the emission originates in the kinetic energy of the ejecta with a bulk velocity of \( v_{\text{cpl}} = \sim 4500 \) km \( s^{-1} \), the mass ejected in the 2012 explosion is \( \sim 0.1 \) \( M_\odot \). This is only a small fraction of the supposed 50–80 \( M_\odot \) progenitor star (Smith et al. 2010) and suggests that an insufficient amount of the star was unbound in the explosion for it to be a true SN. However, NS14 point out that this is actually a minimum ejecta mass estimate because the CSM is not isotropic (e.g., Levesque et al. 2014), allowing much of the ejecta to escape, and the main brightening may be caused by only the fastest-moving ejecta. NS14 furthermore point out that 0.1 \( M_\odot \) of ejecta would be optically thin within days and that this is directly contradicted by the broad He \( \alpha \) emission component that is present until late in the 2012-B event, as we show in Figure 16. They argue that this indicates ejecta masses of at least 4–6 \( M_\odot \).

3.5. Power Source of the Late-time Decline

When SN 2009ip emerged from behind the Sun in 2013 May, we resumed our photometric monitoring program in \( BVgri \) using the LCOGT 1.0 m network. The calibrated photometry for \( gri \) is shown in Figure 12. Although SN 2009ip is steadily declining, the slope is not constant: on MJD \( \sim 56,410 \), a steeper decay event began and lasted \( \sim 20 \) days. This event is steeper in the \( g \) and \( i \) bands compared to the \( r \)-band filter, as was the “knee” in Figure 4. To emphasize this dip, in Figure 12, we make linear fits to the photometry for dates after MJD \( = 56,440 \) (solid lines) and extend them backward (dashed lines). The best-fit slopes in all bands after this dip are \( <0.005 \) mag \( \text{day}^{-1} \), flatter than the typical decay of \( ^{56}\text{Co} \), which is \( \sim 0.01 \) mag \( \text{day}^{-1} \). The combined evidence of features in the late-time light curve and a slope shallower than a \( ^{56}\text{Co} \) decay indicates the optical emission from SN 2009ip is still influenced by ongoing CSM interaction.

This is not uncommon for SN IIn, as shown in Figure 5, and contributions from \( ^{56}\text{Co} \) decay from a SN cannot be excluded. As a test, if we include only dates 56390 < MJD < 56,430 in the linear fit, the slopes increase to 0.01, 0.009, and 0.019 mag \( \text{day}^{-1} \) in the \( g \), \( r \), and \( i \) bands, respectively. With less complete late-time coverage, a late-time slope consistent with \( ^{56}\text{Co} \) decay could be derived. Without LCOGT’s high-cadence observations at late times, we may well have drawn different conclusions about the late-time decline of SN 2009ip.

When the late-time decline of SNe is powered by the decay of \( ^{56}\text{Co} \) to \( ^{56}\text{Fe} \), which has an \( e \)-folding time of 111 days (or a 77 day half-life), the decline rate is \( \sim 0.01 \) mag \( \text{day}^{-1} \). Type IIn SNe are often seen to remain bright and decline slower than this at late times for a long time (e.g., Zhang et al. 2012), due to the heated CSM. This is exemplified by SN 1988Z and SN 1995G in Figure 5, and also by SN 2009ip in Figure 12. The only place in the SN 2009ip light curve where \( ^{56}\text{Co} \) decay could have been the dominant source of optical emission is the \( \sim 100 \) day window between MJD = 56,290 and MJD = 56,390, when SN 2009ip was behind the Sun. During this time, the \( r \)-band magnitude declined from 17.5 to 18.6 mag, which is an average of 0.01 mag \( \text{day}^{-1} \). We can only use this decline to estimate an upper limit on the potential mass of \( ^{56}\text{Ni} \) synthesized in the explosion. To do so, we use our bolometric luminosity, adopt the earliest possible explosion date (the start of the 2012-A event on MJD = 56,150), and use the expression for nickel mass from Hamuy (2003). We find \( M_{\text{Ni}} < 0.04 \) \( M_\odot \), consistent with previously reported estimates (e.g., MF13). However, for SN 2009ip, this estimate of potential \( ^{56}\text{Ni} \) mass is not very restrictive on the explosion mechanism.

Future monitoring will reveal whether the decline of SN 2009ip exhibits further features of interaction or continues to steadily decline. The faintest recorded historical magnitude since detection as a transient is \( m_V = 21.46 \) mag on 2009 November 24 (AP13), and in archival \( \text{HST} \) images, it was measured to be \( m_{F606W} = 21.8 \) mag (Smith et al. 2010). At the current rate of \( r \)-band decline, SN 2009ip will not pass this magnitude until 2016 mid-January. A complete disappearance would confirm that these events were powered by a terminal SN. Given that massive stars are frequently in binary systems with other massive stars, this may not happen (Sana et al. 2012). If half of the flux in the archival \( \text{HST} \) images actually came from a binary companion, the future magnitude of the remaining companion may be \( m_{F606W} = 22.6 \), easily detectable with \( \text{HST} \).

4. TIME SERIES SPECTROSCOPY OF SN 2009ip

Our spectroscopic time series for SN 2009ip begins on 2012 September 22, at the start of the 2012-B event, when we obtained a spectrum with the Goodman High Throughput Spectrograph at SOAR Telescope, as shown in Figure 13. At this point, the Balmer lines clearly show narrow and broad components and blue-shifted absorption. The narrow \( \text{H} \alpha \) component is a Lorentz profile with \( \text{FWHM} \sim 10 \) Å and a peak wavelength of 6600 Å. The broad component is a Gaussian profile with \( \text{FWHM} \sim 130 \) Å and a peak wavelength of 6590 Å, and the absorption component is fit by a single Gaussian with a \( \text{FWHM} \sim 150 \) Å and a central wavelength of 6500 Å. The absorption component extends to \( \sim 6300 \) Å, evidence of fast-moving material at velocities \( \sim 13,500 \) km \( \text{s}^{-1} \), but the bulk of the material is at velocity \( \sim 4500 \) km \( \text{s}^{-1} \). Aside from the Balmer lines, the second most prominent features are the singly ionized
Under the assumption that the 2012-B event is powered by fast-moving ejecta interacting with a shell of material from the 2011 eruption, as discussed in Section 3.1, we can constrain the amount of mass lost during that episode. Ofek et al. (2013b) provide a thorough examination of multi-wavelength mass loss rate indicators for SN 2009ip. For our calculation, we follow their Equation (4) for the mass of hydrogen, \( M_H \), from the luminosity of the narrow component of H\( \alpha \), \( L_{H\alpha} \):

\[
M_H = \frac{m_p L_{H\alpha}}{\hbar v_{\nu_{H\alpha}} \alpha_{H\alpha}^e n},
\]

where \( m_p \) is the proton mass, \( \hbar \) is Planck’s constant, and \( \alpha_{H\alpha}^e \) is the recombination coefficient at 10,000 K, which is appropriate for our use as we find a blackbody temperature of \( \sim 10,000 \) K in Section 3.3. The term \( n \) is the particle density profile, which we express as

\[
n = \frac{M_H/m_p}{V},
\]

where the volume \( V \) is the shell occupied on MJD \( = 56,192 \) by material ejected at \( 550 \) km s\(^{-1} \) for the 200 days starting on MJD \( = 55,700 \), which was the duration of the 2011 eruptions. At the peak of the 2012-B event, the flux in the narrow component of H\( \alpha \) was \( F_{H\alpha} \sim 5 \times 10^{-15} \) erg cm\(^{-2} \) s\(^{-1} \), which we convert to a luminosity using a distance of 25.2 Mpc as in Section 3. We find that \( M_H \sim 0.1 M_\odot \) of material was released during the 2011 eruptions but note that this is an upper limit, as it relies on the assumption that all of the hydrogen was ionized by the 2012-B ejecta. The implied mass loss rate during the 2011 eruptions is \( \sim 0.18 M_\odot \) yr\(^{-1} \). As described in Ofek et al. (2013b), this
upper limit is significantly higher than mass loss rates derived from, e.g., X-ray observations, but this discrepancy is important because it supports an asymmetric distribution of CSM (e.g., a disk, as in Levesque et al. 2014). For example, if the CSM is in a disk with $\sim 10%$ the volume of the assumed shell, then $M_{\text{H}} \sim 0.01 M_\odot$.

4.2. The Physical Source of H$\alpha$ Evolution

The H$\alpha$ line exhibits three main components in varying strengths: narrow emission, broad emission, and blue side absorption. These components represent the physical evolution of the ejecta and CSM interactions powering the 2012-B event of SN 2009ip. In Figure 16, we show a time series of the H$\alpha$ line from our LCOGT FLOYDS spectroscopic series, labeled with the date and the phase era (rise, decline, bump, knee, and ankle). The five spectra taken with the KPNO Mayall RC spectrograph between October 11–15 fit into the “decline” era after October 9. In the KPNO spectra, the H$\alpha$ emission is dominated by a narrow Lorentzian profile from the CSM emission, and Figure 15 shows how there is effectively no evolution in the spectrum, just as the photometry is nearly constant at this time in Figure 4.

To the H$\alpha$ emission, we fit a single narrow Lorentz profile for dates up to October 20, after which this is combined with a broad Gaussian profile (after first subtracting the continuum). Blue-shifted absorption is clearly present on September 26 and after October 30 but exhibits multiple components so we do not fit the blue-shifted absorption. The broad Gaussian emission is fit to the red side only, with a peak wavelength restricted to within 5 Å of the narrow line peak. In Figure 16, the red line represents this fit to the narrow and broad emission only because we find that not including the absorption components has actually highlighted its shape and contribution to H$\alpha$. In the following two sections, we discuss the possible physical sources of the emission and absorption components in turn.

4.2.1. Narrow and Broad Emission Features

Over the 2012-B event, the width of the narrow component of H$\alpha$ appears to increase from FWHM $\sim 700$ to 1000 km s$^{-1}$, or $\sim 16$ to 20 Å, but this is within uncertainty. As the continuum and the flux in the narrow component decline, the broad component re-emerges at the start of the “bump” era. The width of the best-fit broad component appears to increase from $\sim 10,600$ km s$^{-1}$ on 2012 October 30 to $\sim 15,000$ km s$^{-1}$ on 2012 November 13, encompassing the duration of the “bump,” after which it appears to decrease back to $\sim 10,600$ km s$^{-1}$.

The evolution of the integrated, continuum-subtracted flux in the fit narrow and broad components over the course of the 2012-B event are plotted in Figure 17. The flux in the narrow component rises and declines similar to the light curve, as it should, because the continuum emission is also dominated by CSM interaction. The decline of the flux in the narrow component exhibits a plateau at the time of the “bump,” which is consistent with our interpretation of the “bump” as explosion ejecta interacting with an inhomogeneity in the CSM. Line
emission as broad as that seen at post-“bump” eras of SN 2009ip is typically associated with fast expansion, and this leaves us with several questions: what is the physical cause of the broad emission? Why does its width and integrated flux appear to increase and decrease? How is it related to the light-curve “bump”? The coincidence of the “bump” with an increase in the relative contribution from the broad component seems difficult to resolve with the underlying cause of the “bump” being the result of ejecta encountering an inhomogeneity in the CSM, which is the source of narrow emission. MF13 point out that interaction with a clump of CSM can cause broader emission through photon scattering. If so, we might expect to see a similar increase in the relative contribution from the broad component at the time of the “knee” and/or “ankle”—but Figure 17 has only a few data points at those times, and they suggest a continuing decline. Given that the “knee” is a lower energy feature, and that our spectroscopic sampling at this phase is insufficient to see short timescale changes in the H$_\alpha$ broad component, we cannot confirm the photon scattering hypothesis.

NS14 interpret the 2012-A event as a true SN and the source of the broad component of H$_\alpha$ seen at the start of 2012-A and during the decline of 2012-B. With this model, the broad component is always there but during the 2012-B event, is swamped with continuum and narrow line emission from the subsequent interaction between SN ejecta and CSM. As the continuum luminosity declines, the broad component from the SN is again revealed, and it is simply a coincidence that it re-emerges at the same time as the ejecta encounters a

Figure 15. Spectra of SN 2009ip from the KPNO Mayall 4 m Telescope. The magnitude of SN 2009ip was effectively constant during this time, and the spectra are identical; without arbitrary offsets, they cannot be distinguished from each other. These three spectra fit in between the two “decline” phase spectra in Figure 14. The Earth symbol denotes regions of increased noise where atmospheric telluric lines have been removed.

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

Figure 16. Evolution of the H$_\alpha$ line from FLOYDS time-series spectra, labeled with date and phase era (rise, decline, bump, knee, and ankle). Red lines represents fits to the data: from September 25 to October 20, a single narrow Lorentz profile is fit, after which a broad Gaussian component is also fit (to the red side only). The blue side shows increasingly significant multicomponent absorption features, which we have purposely omitted from the red line fit in order to give a better visual impression of their impact on the broad emission component. The Earth symbol denotes wavelengths of increased noise where atmospheric telluric lines have been removed.

(A color version of this figure is available in the online journal.)
CSM clump and creates the “bump.” In this case, the width and luminosity of the broad component may only appear to rise and decline because the continuum is receding. NS14 further support this interpretation by showing that the Hα equivalent width, $EW = \int (F_\lambda/F_0) d\lambda$, is constantly increasing, as is commonly seen for SNe (NS14). We also measure the EW of Hα for FLOYDS spectra, and find it increases from 100 to 1000 Å from the “rise” to the “ankle,” in agreement with NS14. Note that a continually increasing EW is not at odds with the continually declining integrated line flux in Figure 17: this happens in the case where the continuum flux is declining faster than the line flux.

There remains the third interpretation that the broad emission is generated by another nonterminal eruption of the LBV star. This would explain both the apparent rise and decline of the broad component emission and the appearance of multiple new velocity components of Hα absorption presented by RM14 (discussed further in Section 4.2.2). In the scenario of continuing eruptions of an LBV-phase star, this would be third in a line of three eruptions spaced ~40 days apart. Although the photometric evolution of the 2012-B event is quite distinct from the LBV phase, the 40 day spacing is similar to that seen during the 2011 eruptions in Figure 1. In this scenario, the light-curve “bump” would not represent a CSM inhomogeneity but newly ejected material interacting with the CSM. However, we are skeptical that the widths implied by our fits to the broad component are ~twice that shown in the first spectrum from 2012 September 22 in Figure 13. How could there be a third powerful eruption without a correspondingly large increase in the continuum luminosity? We suspect that the simplest explanation is that the fit width and integrated flux of the broad component is compromised by the receding continuum during this era.

4.2.2. Absorption Features of the Ejecta Components

In Figure 16, the mismatch between data and fit on the blue side emphasizes the complex shape of the Hα absorption profiles. After the “bump,” the blue absorption feature extends to at most ~6300 Å, or ~15,000 km s$^{-1}$, just as it did in the 2012 September 22 spectrum of Figure 13. Such high-velocity ejecta is typical of SN explosions but is also occasionally seen in nonterminal events as presented by AP13, including past eruptions of SN 2009ip. The blue extent of the absorption component indicates the maximum velocity of the ejecta but this could be created by a relatively small amount of mass, which does not require the energy input of a terminal SN. The high-velocity absorption feature is not as constraining as the persistent broad component of Hα discussed in Section 4.2.1. There is also a low-velocity absorption component at ~2000 km s$^{-1}$, most clearly seen starting on November 2.

The appearance of lower velocity components as time progresses is commonly interpreted as due to the photosphere receding into deeper (slower) levels of the explosion. Under the interpretation of NS14, this absorbing material and its P-Cygni profile has been present continuously but was swamped by CSM emission from peak light to around the time of the “bump.” RM14 examine high-resolution spectra of the blue-shifted absorption features and find they represent three distinct velocities (~12,000 km s$^{-1}$, ~5500 km s$^{-1}$, and ~2500 km s$^{-1}$), not a continuum, as would be expected for photospheric recession. These three components appear successively at 9, 28, and 60 days after peak brightness, the latter two roughly corresponding to the “bump” and “knee.” This may be consistent with the interpretation of Martin et al. (2013) of the light-curve features as continued pulsations of the (undead) star. Alternatively, regardless of the explosion type of the primary star, these absorption components may be jets of material released by the binary companion star (Tsebrenko & Soker 2013).

4.3. The Late-time Spectrum

We obtained a late-time spectrum of SN 2009ip, shown in Figure 18, with the Gemini Multi-Object Spectrograph on Gemini South Telescope on 2013 June 12, when SN 2009ip was 249 days past the maximum brightness of the 2012-B event. At this time, it is similar to the spectrum taken on 2012 December...
At phases of $\sim$100 days, MF13 find the spectrum of SN 2009ip is well matched to SN 1998S, a peculiar SN IIn (e.g., Fassia et al. 2000). In Figure 19, we compare with the $\sim$300 day spectrum of SN 1998S (Pozzo et al. 2004). SN 1998S shows a strong, broad Ca ii emission, similar to SN 2009ip. The triple peak in the H$\alpha$ line had emerged by day $\sim$230, as shown by Gerardy et al. (2000), who suggest the triple velocity components are caused by a ring-like disk structure in the CSM. This type of disk has also been suggested for SN 2009ip based on the Balmer decrement during the 2012-B event (Levesque et al. 2014). The fact that we do not see obvious multiple velocity components does not mean there is no disk, as orientation and relative velocities may differ from SN 1998S. In the inset of Figure 18, we look for asymmetry in the H$\alpha$ line by reflecting it about the peak wavelength and comparing the blue and red sides. The excess on the red side could be attributed to asymmetry in the H$\alpha$ emitting region, or as a depression in the blue side due to dust formation. Future confirmation of the CSM geometry will provide better constraints on the energy budget and the true explosion mechanism.

In Figure 19, we also compare our late-time Gemini spectrum with spectra for a typical SNe IIn, SN 1988Z at 115 days post-max (Turatto et al. 1993). At 1–4 months past peak, this object has similar spectral features to those shown by SN 2009ip in Figure 14, including asymmetry and blue-shifted absorption in the H$\alpha$ feature. At these late times, their spectra are quite similar but SN 2009ip shows stronger, broader lines of He i and stronger and broader lines of Fe iii and Ca ii. At the chosen phase, SN IIn 1988Z still retains a broad component similar to that exhibited by SN 2009ip at earlier epochs.

For comparison with the next most similar kind of core–collapse SNe, we also show two late-time spectra from SNe IIP: SN 2004et at $\sim$250 days (Sahu et al. 2006) and SN 1990E at $\sim$250 days (Gómez & López 2000). Although similar to SN 2009ip in the presence of hydrogen and Ca ii, the SNe IIP show broader Balmer lines with P-Cygni profiles, stronger Ca ii emission, do not show the prominent He I, and have a weaker continuum in the blue end—a combination of a cool blackbody spectrum and possibly dust production. They also show prominent lines of forbidden oxygen at $\lambda = 6300, 6346$ Å, marked in light blue in Figure 19, which are not seen in the nebular epochs of SNe IIn 2009ip or 1988Z but are for 1998S. These lines of forbidden oxygen are also prominent in the Type Ic SNe associated with massive star progenitors (Gómez & López 2002). Although the late-time spectrum of SN 2009ip most resembles those of SNe IIn, to verify that a terminal SN explosion has occurred requires a positive identification of the forbidden lines common to the nebular phase spectra of core–collapse SNe. Even at late times, the true nature of SN 2009ip appears to be shrouded by CSM emission.

We also show a comparison to two spectra taken during the 2009 LBV-phase events of SN 2009ip: the thick line is 2009 September 25 and the thin line is 2009 October 22, both from Figure 5 of AP13. On September 25, SN 2009ip was just declining from its second detected outburst of the year, at $R \sim 19$ mag. By October 22, it had been in a plateau at $R \sim 20$ for 20 days, and the H$\alpha$ emission had broadened slightly and lost its blue-shifted absorption feature. It is clear that SN 2009ip has not yet returned to its old quiescent self, as the Fe iii, He i, and Ca ii emission lines are all currently broader and stronger, and more similar to SN impostors and late-phase SN IIn. Only time will tell if SN 2009ip returns to its pre-2012, LBV-phase spectral signature.

16 (the “ankle”) in Figure 14, except that at these later times and in a higher resolution spectrum, the contributions from Fe and possibly O are more obvious and the He and individual Ca lines more distinguished. In Figure 19, we compare the late-time spectrum of SN 2009ip with spectra from an SN impostor, SNe IIn, and SNe IIP taken at similarly late phases, and also with LBV-phase spectra of SN 2009ip. These spectra were obtained from the Online Supernova Spectrum Archive (SUSPECT11) and the Weizmann Interactive Supernova Data Repository (WISEREP12; Yaron & Gal-Yam 2012).

The late-phase spectrum of SN 2009ip is similar to SN 2008S, which was defined as an SN impostor by Smith et al. (2009). SN 2009ip has a flatter continuum flux and stronger helium lines but the H$\alpha$ and calcium lines are equivalently strong. The major difference between SN 2009ip and SN impostor 2008S is the presence of a broad H$\alpha$ component for SN 2009ip, indicating the high expansion velocities of a true SN, as discussed in NS14. Such broad emission is not seen for SN impostors.\[11\] http://nhn.uihn.ou.edu/~suspect\[12\] http://www.weizmann.ac.il/astrophysics/wiserep

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure19}
\caption{Late-time spectrum of SN 2009ip at 249 days since the peak of the 2012-B event, compared with late-time spectra of two SNe IIn, two SNe IIP, an LBV-phase spectrum of SN 2009ip, and an SN impostor. From top to bottom: SN impostor 2008S at $\sim$223 days (Botticella et al. 2009; Smith et al. 2009), SN IIn 1998S at $\sim$300 days (Pozzo et al. 2004), SN IIn 1988Z at $\sim$115 days (Turatto et al. 1993), SN 2009ip at 249 days (this paper), SN 2009ip from 2009 presented in AP13 (two spectra described further in text), SN IIP 2004et at $\sim$250 days (Sahu et al. 2006), and SN IIP 1990E at $\sim$250 days (Gómez & López 2000). All spectra have been normalized, converted to the rest frame of the host, and offsets were added for clarity. We mark the following spectral lines: hydrogen Balmer series (purple-dotted line); singly ionized helium (blue-dashed line); doubly ionized calcium (green dot-dash line); singly ionized forbidden oxygen (light blue); and doubly and triple-ionized iron (orange and red). (A color version of this figure is available in the online journal.)}
\end{figure}
5. CONCLUSION

In this work, we have used high-cadence LCOGT data, with supporting observations from other facilities, to draw the following four main conclusions about SN 2009ip. (1) From our daily photometric monitoring, we observe photometric fluctuations from interactions between fast-moving ejecta and the CSM that reveal inhomogeneities in the CSM distribution. The light curve of the 2012-B event appears congruous with the timescales of past eruptions in 2011 and 2009. (2) The peak brightness and photometric evolution of SN 2009ip is more similar to SNe IIn than LBVs or SN impostors. Our long-term monitoring shows SN 2009ip continues to decline slowly with small fluctuations in the slope, which is shallower than if powered by the decay of Co\(^{56}\). This is similar to both SNe IIn and SN impostors but SN 2009ip has not exhibited any more LBV-like outbursts. (3) Our low- and high-resolution spectra during the 2012-B event exhibit evolving H\(\alpha\) absorption and emission components. The blue-shifted absorption component reveals ejecta at velocities typically seen in SNe but could also be generated by a nonterminal eruption. As the continuum and narrow line emission from CSM interaction fades, the broad emission component persists. This is characteristic of SN-like expansion velocities but not SN impostors or LBVs. (4) The late-time spectrum of SN 2009ip exhibits calcium lines which are more similar to SNe IIP, SNe IIn, and SN impostors than the LBV-phase spectrum of SN 2009ip. Asymmetry in the H\(\alpha\) line at late times hints at dust formation and/or asymmetry in the CSM, such as a disk. However, the late-time spectrum of SN 2009ip does not exhibit the forbidden oxygen lines that are ubiquitous to the nebular phase spectra of Type IIP and Ib/c SNe; without them, we cannot verify that a terminal explosion has occurred.

We find that SN 2009ip best fits into the observational class of SNe IIn; if the progenitor has not suffered a terminal explosion, then perhaps not all SNe IIn are actual SNe. Multiple papers have remarked on the striking similarity—right down to the timing and magnitude of a precursor outburst—between SN 2009ip and SN IIn 2010mc (e.g., RM14, NS14). Far from a serendipitous and magnitude of a precursor outburst—between SN 2009ip and remarked on the striking similarity—right down to the timing SNe IIn; if the progenitor has not suffered a terminal explosion, /ubiquitous to the nebular phase spectra of Type IIP and Ib / without them, we cannot verify that a terminal explosion

We thank Jon Mauerhan for access to the photometry presented in JM13 and discussion about the late-time spectra, including the tip about the red side asymmetry. We thank Andrea Pastorello for access to the spectra presented in AP13 and photometry in Pastorello et al. (2002). We also thank our anonymous referee for their useful feedback and advice.

This research has made use of the LCOGT Archive, which is operated by the California Institute of Technology, under contract with the Las Cumbres Observatory.

This research is based on observations obtained at the Southern Astrophysical Research (SOAR) Telescope, which is a joint project of the Ministério da Ciência, Tecnologia, e Inovação (MCTI) da República Federativa do Brasil, the U.S. National Optical Astronomy Observatory (NOAO), the University of North Carolina at Chapel Hill (UNC), and Michigan State University (MSU).

This research is based on observations obtained at the Gemini Observatory (PI: Howell, program GS-2013A-Q-62), 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).

This research is based on observations obtained at Kitt Peak National Observatory, 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.

This work has made use of the Weizmann Interactive Supernova Data Repository (WISEREP) at http://www.weizmann.ac.il/astrophysics/wiserep, and the SUSPECT database at http://nhn.nhn.ou.edu/~suspect.

This research used the facilities of the Canadian Astronomy Data Centre operated by the National Research Council of Canada with the support of the Canadian Space Agency.

Facilities: LCOGT, SOAR, KPNO, Gemini:South

APPENDIX

CALIBRATION OF LCOGT PHOTOMETRY

All images have been processed through the LCOGT automatic pipelines that perform the bias and flat-field reductions. Since the transient is in the outskirts of its host galaxy, difference imaging is not necessary.

For the 1.0 m images during the main 2012-B event, we extracted the photometry using a pipeline built on the DOPHOT routine (Schechter et al. 1993; Rest et al. 2005, 2013). Every night, with the 1.0 m telescopes, we observed one of the following Landolt and Sloan Digital Sky Survey (SDSS) standard star fields: L92 (00:55:21.39 +00:45:53.5), L95 (03:53:44.61 +00:04:39.0), L101 (09:56:56.03 −00:21:39.9), or L104 (12:42:10.93 −00:32:07.9). For these fields, we use the standard star magnitudes from the SDSS Web site (http://skyserv.sdss3.org/dr9) and from Peter Stetson’s Web site hosted by the Canadian Astronomical Data Center (http://www1.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/community/STETSON/). We use several of the most photometric nights
to determine zero points from the standard fields and derive a local sequence for stars in the field of SN 2009ip. These local sequence stars are listed in Tables 3 and 4. We then use this local sequence to derive a zero point, $z_r$, and color term, $\beta \times c$, for each filter in turn, using the local fields. The color, $c$, is $g - r$ for $g$ and $r$ bands, $r - i$ for $i$ band, and $i - z$ for $z$ band. Typical values for the color term coefficient are $\beta_r \sim 0.09$, $\beta_i \sim 0.03$, $\beta_i \sim 0.07$, and $\beta_z \sim -0.14$. Our calibrations to convert instrumental magnitude in filter $f$, $m_f^i$, to apparent magnitude, $m_f$, is

$$m_f = m_f^i + z_f + \beta \times c.$$  \hfill (A1)

At the time of SN 2009ip, LCOGT was developing a new photometric calibration pipeline for the new network of 1 m telescopes. All of the 2.0 m data, and the late-time data shown in Figure 12, were reduced with that custom pipeline developed by the LCOGT SN team. The pipeline employs standard procedures (PYRAF, DAOPHOT, SWARP) in a PYTHON framework. Point-spread function magnitudes are computed after low-order polynomial fit is used to remove the background contamination. The resulting new photometry matches very well with the original from the DAOPHOT-based pipeline but was adopted to be fast, streamlined, and optimized for future LCOGT imaging.

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