SN 2011A: A LOW-LUMINOSITY INTERACTING TRANSIENT WITH A DOUBLE PLATEAU AND STRONG SODIUM ABSORPTION*

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ABSTRACT

We present optical photometry and spectroscopy of the optical transient SN 2011A. Our data span 140 days after discovery including BVRI u'g'r'i'z' photometry and 11 epochs of optical spectroscopy. Originally classified as a type IIn supernova (SN IIn) due to the presence of narrow Hα emission, this object shows exceptional characteristics. First, the light curve shows a double plateau, a property only observed before in the impostor SN 1997bs. Second, SN 2011A has a very low luminosity (M_V = -15.72), placing it between normal luminous SNe IIn and SN impostors. Third, SN 2011A shows low velocity and high equivalent width absorption close to the sodium doublet, which increases with time and is most likely of circumstellar origin. This evolution is also accompanied by a change in line profile; when the absorption becomes stronger, a P Cygni profile appears. We discuss SN 2011A in the context of interacting SNe IIn and SN impostors, which appears to confirm the uniqueness of this transient. While we favor an impostor origin for SN 2011A, we highlight the difficulty in differentiating between terminal and non-terminal interacting transients.

Key words: circumstellar matter – stars: mass loss – supernovae: general – supernovae: individual (2011A)

1. INTRODUCTION

It is generally accepted that the majority of massive stars with zero-age main sequence masses ⩾8 M⊙ (Smartt 2009) end their lives as core-collapse supernovae (CC SNe), with the possibility that some directly form black holes with no visible supernovae (Smartt 2015). CC SNe are classified in two groups according to the absence (SNe Ib/c) or presence (SNe II) of H I lines (Filippenko 1997). The ejected material from an SN explosion is sometimes observed to interact with

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1. Narrow emission (v_{FWHM} < few hundred km s^{-1}) formed by the photoionization of the high density pre-existing CSM from the prompt emission of the SN. The high density has furthermore been attributed to a high mass-loss rate (Chugai et al. 2004).
2. Intermediate emission (v_{FWHM} < few thousand km s^{-1}) possibly produced from the shock interaction of the SN blast within a dense shell of clumpy CSM or with a dense equatorial wind (Chugai & Danziger 1994).
3. Broad emission (v_{FWHM} ≥ 10^4 km s^{-1}) most likely due to SN ejecta as a result of multiple scattering by thermal electrons in the opaque CS gas (Chugai 2001). The presence of this broad Hα emission without broad surrounding circumstellar material (CSM), related to progenitor mass-loss episodes prior to explosion (Chevalier 1981; Fransson 1982). When the CSM is sufficiently dense, a strong CSM–ejecta interaction can begin shortly after explosion; this is often observed as a type IIn supernova (SN IIn henceforth; Schlegel 1990; Chugai & Danziger 1994). These objects are characterized by prevalent blue continua and narrow emission lines in their spectra superimposed on broader emission profiles. The Hα emission typically dominates the spectrum and often has multiple components consisting of the following (e.g., Salamanca et al. 1998).
P Cygni absorption is usually considered to be caused by a dense wind (Chugai 1990).

Measured parameters of these components can provide valuable information on progenitor properties and late time evolution (such as the mass-loss rate or wind velocity), through the observed properties of their CSM.

Observations of SNe IIn published to date (see, e.g., Kiewe et al. 2012; Zhang et al. 2012; Taddia et al. 2013) have allowed researchers to probe the immediate environment of these explosions and point toward significant diversity among various SNe IIn. The high mass-loss rates calculated from the observations of various SNe IIn (e.g., Kiewe et al. 2012; Taddia et al. 2013; Moriya et al. 2014) have prompted several authors to assign luminous blue variable stars (LBVs) in several cases as immediate progenitors of SNe IIn. LBVs, as defined by Humphreys & Davidson (1994), are some of the most luminous stars, with episodic and violent mass-loss events with mass-loss rates $\geq 10^{-3} M_\odot \text{yr}^{-1}$. Classic examples of LBVs are Eta Carinae and P Cygni. Direct detection of the extremely luminous progenitor of SN 2005gl (Gal-Yam & Leonard 2009) also supports this possibility. However, in stellar evolutionary models, the LBV phase follows a blue giant star state (Crowther 2007; Gräfener & Hamann 2008), most likely with mass loss driven by the bi-stability jump (Vink 2011), and it is then followed by a H-poor WN star (nitrogen-rich Wolf–Rayet). In this scenario the LBV star loses its H envelope, becomes a Wolf–Rayet star, and then explodes as an SN. Thus, LBVs have been placed in the post-main sequence, but not the final pre-SN phase (Schaller et al. 1992; Langer 1993; Stothers & Chin 1996; Maeder et al. 2005; Maeder & Meynet 2008; Dwarkadas et al. 2010), but see Groh et al. (2013) for recent modeling suggesting that some stars could indeed end their lives during this phase.

There have been a number of cases where transients have originally been defined as SNe IIn, but the link to a definitive SN event (i.e., the terminal stage of a star’s life) is questionable. Such events have been defined as SN “impostors” (Van Dyk et al. 2000; Maund et al. 2006), which are believed to be luminous non-terminal eruptions of massive stars instead of SNe. There are multiple cases of such events, e.g., the ongoing transient SN 2009ip (Pastorello et al. 2013; Fraser et al. 2013; Mauerhan et al. 2013; Prieto et al. 2013; Margutti et al. 2014; Smith et al. 2014). SN impostors are generally claimed to be LBV transients with peak luminosities lower than SNe (M $\geq -14$), such as SN 1997bs ($M_V \sim -13.8$; Van Dyk et al. 2000), SN 2000ch ($M_R \sim -12.8$; Wagner et al. 2004; Pastorello et al. 2010), SN 2002kg ($M_v \sim -9.6$; Weis & Bomans 2005; Maund et al. 2006; Van Dyk et al. 2006), SN 2007sv ($M_B \sim -14.2$; Tartaglia et al. 2015), SN 2008S ($M_R \sim -13.9$; Kochanek 2011; Smith et al. 2009), and 2008 NGC 300-OT ($M_V \sim -12$ to $-13$; Bond et al. 2009; see also the compilation paper by Smith et al. 2011). However, unambiguous evidence that all transients classified as “impostors” are actually non-terminal events is lacking. Indeed, for the first transient identified as a SN impostor, SN 1997bs, it has been claimed that no surviving star is present (Li et al. 2002; Adams & Kochanek 2015). Adams & Kochanek (2015) have argued that the scenario where the surviving star is obscured by dust created in the eruption is excluded.

Given that SN impostors and SNe IIn show similar spectroscopic features, such as the presence of narrow emission lines (in particular H I lines), differentiation based solely on spectral analysis is rendered difficult, and constraining the nature of their progenitors (e.g., ZAMS mass) has been problematic. Indeed, the detection of narrow emission lines is merely evidence for high density material close to the SN and it appears that this high density CSM can be produced by a number of different progenitor scenarios. Indeed, it has even been observed in SNe Ia (e.g., SN 2002ic, Hamuy et al. 2003; SN 2011kx, Dilday et al. 2012).

While observations of individual SNe IIn have been used to argue for LBV progenitors or LBV transients, statistical investigations of their environments within host galaxies have pointed to lower mass progenitors. Anderson et al. (2012) and Habergham et al. (2014) found a low correlation between SNe IIn and host-galaxy H I regions. It was found that SNe IIn show a degree of association with star formation (SF) similar to SNe IIP, which are thought to arise from stars at the lower end of the CC SNe scale, with masses between 8 and $16 M_\odot$ (Smartt 2009). Therefore, these results suggest that a significant fraction of SNe IIn arise from relatively low-mass progenitors. This is somewhat surprising given that the LBV phase is thought to be associated only with very massive stars ($\sim 30–80 M_\odot$). Contrary to the above, we note that recent results suggest that a significant fraction of SNe IIn could arise from electron capture SNe (Smith 2013) with AGB progenitor stars (Botticella et al. 2009; Prieto et al. 2009). Also, Smith & Tomlison (2015) argue that LBV stars are the product of binary kicks due to their isolated environments.

In this paper we present optical photometry and spectroscopy of the transient SN 2011A, originally classified as an SN IIn (Stritzinger et al. 2011). Given the properties of the transient, we discuss its characteristics in comparison to other SN IIn and SN impostors with the aim of defining the nature of the transient and constraining its properties. Due to the fact that it is unclear whether SN 2011A was a true SN, we refer to it as “transient” throughout the paper.

The paper is organized as follows. Section 2 contains a description of the observations and in Section 3 we discuss our results, first analyzing light and color curves and then using spectroscopy to derive physical parameters for the transient. In Section 4 we discuss our results and we conclude with a summary in Section 5.

2. OBSERVATIONS

2.1. Discovery

SN 2011A was discovered on an unfiltered image (apparent magnitude $\sim 16.9$) on 2011 January 2.30 UT with the 0.41 m “PROMPT 4” telescope located at Cerro Tololo (Pignata et al. 2011) on behalf of the CHASE project (Pignata et al. 2009). The transient was located at $\alpha = 13^h 01^m 01^s 19.19 \pm 0.12, \delta = -14^\circ 31' 34'' 8 \pm 0.07'$ (J2000.0), 21' east and 46'5 south of the center of the galaxy NGC 4902 at $z = 0.008916$ (Theureau et al. 2007; see NED).13 NGC 4902 is a luminous Sb galaxy ($M_B = -21.40$). Stritzinger et al. (2011) classified the object as an SNe IIn due to the presence of prevalent narrow Balmer lines in the spectrum. The most recent pre-explosion nondetection on archival images was dated 2010 July 13.05 (limiting magnitude 18.5), providing extremely weak constraints on any explosion time or previous variability. All observations are presented with respect to the discovery date, 2011 January 2.30 UT. In Figure 1 the field of the transient is displayed.

13 http://ned.ipac.caltech.edu/
2.2. Photometry

Optical photometry was obtained with the Panchromatic Robotic Optical Monitoring and Polarimetry Telescopes (PROMPT; Reichart et al. 2005) at the Cerro Tololo Inter-American Observatory, RATCam mounted on the 2.0 m Liverpool Telescope (LT; Steele et al. 2004) at the Observatorio del Roque de los Muchachos on the Canary Island of La Palma, with EFOSC2 (Buzzoni et al. 1984) mounted on the 3.6 m New Technology Telescope (NTT) at the La Silla Observatory, the 2.2 m telescope at the Calar Alto (CA) Observatory with the optical imager/spectrograph CAHOS, and from the imager AFOSC mounted at the 1.82 m reector telescope at the Asiago Observatory. All images were analyzed after automated reductions (bias and flat-field correction and astrometric solution) had been applied and all the science images were host-galaxy subtracted.

Photometry of the transient was computed relative to a sequence of 19 stars in the field of NGC 4902, which we calibrate using catalogs from Landolt (1992, 2007) for B, V, R, I bands and Smith et al. (2002) for u′, g′, r′, i′, z′ bands. Instrument-specific color terms were derived using several epochs of standard field observations. The resulting B, V, R, I, u′, g′, r′, i′, z′ magnitudes of the local sequence stars are reported in Table 1, which correspond to the averages from n photometric nights (n = 2 for the z′ filter and n ≥ 3 for the remaining filters), and the uncertainties are the standard deviations from the mean.

Differential photometry of the transient was done relative to the local sequence. To obtain instrumental magnitudes, we used the IRAF14 package SNOOPY.15 Photometry for SN 2011A is presented in Table 2 and the resulting light curve is displayed in Figure 2. Errors come from the point-spread function (PSF) fit and the local sequence magnitudes.

2.3. Visual-wavelength Spectroscopy

Optical spectroscopy of SN 2011A was acquired using the GOODMAN spectrograph at the Southern Astrophysical Research (SOAR) 4.1 m Telescope, the WFCCD at the du Pont telescope located at Las Campanas Observatory (LCO), the GMOS spectrograph mounted on Gemini-North on the summit of Mauna Kea, EFOSC2 on the 3.6 m NTT at La Silla, the ALFOSC imager/spectrograph on the 2.5 m Nordic Optical Telescope (NOT) at La Palma, and IMACS mounted on the Baade telescope at LCO. In total we obtained 11 optical spectra mostly covering the optical range from ~3500 to 9000 Å except for three spectra, one covering only the Hα emission and the others ~4200–7000 Å. A log of the optical observations is given in Table 3.

Spectroscopic reductions were performed using standard IRAF routines. All data were debiased, flat-fielded, and cleaned of cosmic rays. Extracted one-dimensional (1D) spectra were wavelength calibrated using He–Ne–Ar/Hg–Ar/Th–Ar lamps (depending on the instrument) and the calibrations were corrected using bright night-sky emission lines. However, for the Gemini spectrum the wavelength calibration was computed before the 1D spectrum extraction. Flux calibration was determined with spectrophotometric standard stars (Hamuy et al. 1992, 1994). Atmospheric absorption features were not removed except for spectra 2.0, 64.0, and 85.9 using a telluric standard (Hamuy et al. 2006). The spectra are not corrected for Milky Way or host-galaxy extinction. The spectral sequence is shown in Figure 3.

3. RESULTS

3.1. Photometry

3.1.1. A Rare Double Plateau

One of the defining photometric features of SN 2011A, displayed in Figure 2, is the presence of a double plateau. The V-band light curve exhibits an initial plateau which lasts ~15 days with a slope of ~0.37 mag x 100 days−1. Subsequently, the light curve declines ~0.39 mag in ~10 days. Then there is a second plateau phase which lasts ~15 days with a slope of 0.29 mag x 100 days−1, which is flatter and longer lasting at redder wavelengths. For the remaining observed epochs the light curve declines with a slope of 2.8 mag x 100 days−1. If we look at the entire V-band light curve, SN 2011A declines ~2.1 mag x 100 days−1. To our knowledge this double plateau has only been seen previously in the transient SN 1997bs (see Section 4.1.2). Some other SNe such as SN 1993J (Richmond et al. 1994), SN 2006aj (Campana et al. 2006), or SN 2011dh (Arcavi et al. 2011) present interesting characteristics (double-humped profile) that could be similar to our double plateau, but we think that the physics is most likely distinct. Indeed the double plateau seen in SN 2011A is powered by interaction whereas the double peak (in the above events) is first due to the cooling of the shock surface material and then to radioactive decay (Nakar & Piro 2014). We note that the double plateau is not so evident in the Sloan light curves due to less well sampled photometry and noisier data. In the Landolt filters the double plateau is clearly visible in V and R, but less evident in B and I. We are confident that this is a real feature of the transient.

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14 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under cooperative agreement with the National Science Foundation.
15 SNOOPY, originally presented in Patat (1996), has been implemented in IRAF by E. Cappellaro.
### Table 1

*B, V, R, I, u′, g′, r′, i′, z′* Local Sequence Star Magnitudes

| STAR | R.A.    | Decl. | B      | V      | R      | I      | u′     | g′     | r′      | i′     | z′     |
|------|---------|-------|--------|--------|--------|--------|--------|--------|---------|--------|--------|--------|
| 1    | 13:01:01.523 | −14:28:21.35 | 15.78 ± 0.02 | 15.20 ± 0.04 | 14.83 ± 0.03 | 14.46 ± 0.05 | 16.65 ± 0.02 | 15.45 ± 0.02 | 15.05 ± 0.02 | 14.90 ± 0.04 | 14.91 ± 0.01 |
| 2    | 13:01:09.706 | −14:28:07.32 | 17.69 ± 0.05 | 17.06 ± 0.04 | 16.69 ± 0.03 | 16.32 ± 0.05 | 18.87 ± 0.01 | 17.31 ± 0.03 | 16.91 ± 0.01 | 16.74 ± 0.03 | 16.76 ± 0.02 |
| 3    | 13:01:12.549 | −14:29:48.59 | 17.20 ± 0.02 | 16.41 ± 0.02 | 15.95 ± 0.03 | 15.51 ± 0.04 | 18.35 ± 0.09 | 16.75 ± 0.02 | 16.19 ± 0.02 | 15.96 ± 0.03 | 15.94 ± 0.01 |
| 4    | 13:01:13.685 | −14:29:56.09 | 15.68 ± 0.02 | 14.70 ± 0.03 | 14.12 ± 0.03 | 13.65 ± 0.04 | 17.66 ± 0.05 | 15.16 ± 0.04 | 14.38 ± 0.01 | 14.11 ± 0.03 | 14.06 ± 0.01 |
| 5    | 13:01:09.906 | −14:32:40.66 | 15.96 ± 0.01 | 15.10 ± 0.03 | 14.61 ± 0.02 | 14.21 ± 0.41 | 17.60 ± 0.03 | 15.50 ± 0.04 | 14.86 ± 0.01 | 14.65 ± 0.03 | 14.65 ± 0.01 |
| 6    | 13:01:06.445 | −14:34:08.13 | 13.42 ± 0.01 | 12.43 ± 0.03 | 11.87 ± 0.03 | 11.36 ± 0.03 | 15.19 ± 0.02 | 12.88 ± 0.04 | 12.14 ± 0.01 | 11.83 ± 0.03 | 11.74 ± 0.01 |
| 7    | 13:00:54.730 | −14:33:11.10 | 17.33 ± 0.02 | 16.17 ± 0.02 | 15.44 ± 0.02 | 14.84 ± 0.04 | 19.52 ± 0.10 | 16.74 ± 0.04 | 15.72 ± 0.01 | 15.32 ± 0.03 | 15.19 ± 0.01 |
| 8    | 13:00:47.126 | −14:31:26.73 | 16.46 ± 0.01 | 15.55 ± 0.02 | 14.98 ± 0.02 | 14.48 ± 0.04 | 18.27 ± 0.04 | 15.99 ± 0.03 | 15.23 ± 0.02 | 14.94 ± 0.03 | 14.87 ± 0.02 |
| 9    | 13:00:45.583 | −14:31:31.08 | 17.99 ± 0.03 | 17.36 ± 0.01 | 17.00 ± 0.03 | 16.66 ± 0.04 | 18.72 ± 0.02 | 17.62 ± 0.02 | 17.24 ± 0.02 | 17.08 ± 0.05 | 17.08 ± 0.01 |
| 10   | 13:00:42.987 | −14:32:14.39 | 16.06 ± 0.01 | 15.42 ± 0.03 | 15.03 ± 0.02 | 14.64 ± 0.04 | 16.95 ± 0.02 | 15.69 ± 0.02 | 15.26 ± 0.02 | 15.08 ± 0.03 | 15.07 ± 0.01 |
| 11   | 13:00:44.202 | −14:28:44.77 | 13.21 ± 0.03 | 12.73 ± 0.03 | 12.44 ± 0.03 | 12.17 ± 0.04 | 14.21 ± 0.02 | 12.92 ± 0.03 | 12.65 ± 0.02 | 12.58 ± 0.03 | 12.64 ± 0.01 |
| 12   | 13:00:44.752 | −14:27:31.79 | 12.69 ± 0.04 | 12.09 ± 0.03 | 11.72 ± 0.02 | 11.38 ± 0.03 | 13.69 ± 0.03 | 12.36 ± 0.01 | 11.94 ± 0.02 | 11.81 ± 0.04 | 11.83 ± 0.01 |
| 13   | 13:00:53.129 | −14:28:40.67 | 13.90 ± 0.02 | 13.11 ± 0.03 | 12.65 ± 0.03 | 12.20 ± 0.04 | 15.15 ± 0.02 | 13.46 ± 0.02 | 12.90 ± 0.02 | 12.66 ± 0.03 | 12.61 ± 0.01 |
| 14   | 13:01:16.297 | −14:32:11.47 | 14.07 ± 0.01 | 13.48 ± 0.03 | 13.15 ± 0.03 | 12.83 ± 0.04 | 14.99 ± 0.02 | 13.72 ± 0.02 | 13.37 ± 0.01 | 13.25 ± 0.03 | 13.30 ± 0.01 |
| 15   | 13:01:00.164 | −14:35:22.03 | 15.98 ± 0.01 | 15.33 ± 0.02 | 14.93 ± 0.02 | 14.63 ± 0.04 | 16.74 ± 0.01 | 15.60 ± 0.02 | 15.16 ± 0.02 | 14.97 ± 0.03 | 14.96 ± 0.01 |
| 16   | 13:00:52.187 | −14:32:20.12 | 13.95 ± 0.01 | 13.16 ± 0.02 | 12.70 ± 0.03 | 12.31 ± 0.04 | 15.35 ± 0.02 | 13.52 ± 0.02 | 12.94 ± 0.02 | 12.75 ± 0.03 | 12.72 ± 0.01 |
| 17   | 13:00:54.651 | −14:29:18.73 | 11.16 ± 0.03 | 10.38 ± 0.02 | ... | ... | ... | ... | 10.65 ± 0.03 | 10.57 ± 0.04 | 10.39 ± 0.03 | 9.74 ± 0.06 |
| 18   | 13:00:56.730 | −14:29:37.00 | 19.93 ± 0.05 | 18.61 ± 0.03 | 17.74 ± 0.01 | 17.10 ± 0.06 | 20.60 ± 1.56 | 19.19 ± 0.10 | 18.09 ± 0.01 | 17.57 ± 0.03 | 17.35 ± 0.02 |
| 19   | 13:00:51.075 | −14:31:37.80 | 10.84 ± 0.02 | 10.33 ± 0.03 | ... | ... | ... | ... | 10.48 ± 0.06 | 10.58 ± 0.05 | 10.41 ± 0.01 | 9.66 ± 0.05 |

**Note.** Errors correspond to the standard deviation from the mean.
| JD-2450000+ | Epoch<sup>a</sup> | B       | V       | R       | I       | i'      | g'      | r'      | i'      | z'      | Telescope/Instrument |
|------------|-----------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------------------|
| 5566.3     | 2.5             | 18.11 ±0.02 | 17.86 ±0.02 | 17.51 ±0.02 | 17.38 ±0.02 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5567.3     | 3.5             | 18.19 ±0.04 | 17.86 ±0.02 | 17.53 ±0.01 | 17.26 ±0.05 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5569.3     | 5.5             | 18.18 ±0.03 | 17.85 ±0.02 | 17.49 ±0.04 | 17.40 ±0.02 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5570.3     | 6.5             | ...       | 17.87 ±0.02 | 17.50 ±0.04 | 17.45 ±0.02 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5573.3     | 9.5             | 18.23 ±0.03 | 17.87 ±0.02 | 17.54 ±0.04 | 17.41 ±0.02 | ... 18.05 ±0.02 | 17.82 ±0.02 | 17.89 ±0.03 | 17.78 ±0.09 | ...      | ...                 |
| 5573.6     | 9.8             | 18.23 ±0.04 | 17.90 ±0.03 | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5575.3     | 11.5            | ...       | 17.89 ±0.02 | 17.56 ±0.06 | 17.33 ±0.04 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5575.7     | 11.9            | 18.22 ±0.06 | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5576.2     | 12.4            | 18.26 ±0.02 | 17.98 ±0.03 | 17.65 ±0.04 | 17.41 ±0.05 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5577.3     | 13.5            | ...       | 17.89 ±0.02 | 17.56 ±0.06 | 17.30 ±0.04 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5579.6     | 15.8            | 18.22 ±0.03 | 17.96 ±0.02 | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5581.3     | 17.5            | 18.35 ±0.03 | 17.95 ±0.02 | 17.57 ±0.04 | 17.55 ±0.03 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5583.3     | 19.5            | 18.50 ±0.04 | 18.02 ±0.03 | 17.62 ±0.06 | 17.45 ±0.05 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5584.3     | 20.5            | ...       | 18.10 ±0.03 | 17.70 ±0.04 | 17.51 ±0.03 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5585.7     | 21.9            | 18.41 ±0.03 | 18.20 ±0.12 | 17.91 ±0.12 | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5588.3     | 24.5            | 18.70 ±0.04 | 18.24 ±0.03 | 17.90 ±0.03 | 17.67 ±0.13 | ... 18.43 ±0.04 | 18.04 ±0.04 | 18.1 ±0.080 | 18.42 ±0.10 | ...      | ...                 |
| 5591.3     | 27.5            | ...       | 17.97 ±0.05 | 17.65 ±0.04 | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5600.3     | 36.5            | ...       | 18.27 ±0.02 | 17.98 ±0.02 | 17.62 ±0.03 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5600.7     | 36.9            | 18.81 ±0.02 | 18.29 ±0.02 | ...      | ...      | 19.65 ±0.06 | 18.51 ±0.02 | 18.20 ±0.02 | 18.20 ±0.01 | 18.14 ±0.04 | ...                  |
| 5602.3     | 38.5            | ...       | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5606.3     | 42.5            | 18.99 ±0.04 | 18.29 ±0.02 | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5610.2     | 46.4            | ...       | 18.40 ±0.04 | 18.06 ±0.03 | 17.58 ±0.05 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5610.6     | 46.8            | ...       | 18.50 ±0.04 | 18.06 ±0.03 | 17.58 ±0.05 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5613.2     | 49.4            | ...       | 18.94 ±0.03 | 18.07 ±0.06 | 17.83 ±0.02 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5615.3     | 51.5            | 19.39 ±0.05 | 18.55 ±0.03 | 18.02 ±0.06 | 17.63 ±0.03 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5615.6     | 51.8            | ...       | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5617.3     | 53.5            | 19.36 ±0.04 | 18.55 ±0.01 | 18.06 ±0.02 | 17.80 ±0.03 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5621.6     | 57.8            | ...       | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5623.2     | 59.4            | 19.53 ±0.01 | 18.71 ±0.05 | 18.08 ±0.04 | 17.61 ±0.05 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5633.2     | 69.4            | ...       | 18.94 ±0.03 | 18.07 ±0.06 | 17.83 ±0.02 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5646.2     | 82.4            | ...       | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5647.1     | 83.3            | ...       | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5651.2     | 87.4            | ...       | 19.54 ±0.06 | 18.44 ±0.05 | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5651.5     | 87.7            | ...       | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5653.1     | 89.3            | ...       | 19.59 ±0.06 | 19.07 ±0.02 | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5661.4     | 97.6            | ...       | 20.20 ±0.22 | 19.30 ±0.11 | 18.79 ±0.20 | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5666.2     | 102.4           | ...       | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |
| 5677.1     | 113.3           | ...       | 19.54 ±0.06 | 19.14 ±0.05 | ...      | ...      | ...      | ...      | ...      | ...      | ...                 |

**Note.** Errors correspond to 1σ uncertainties and come from the PSF fit and the local sequence magnitudes.

<sup>a</sup> Days after discovery 2011 January 2.30 UT.
post discovery. A similar behavior is observed in \((V - R)\) except that the constant color phase of \(-0.30\) mag extends through day \(\sim 40\) before growing redder. For \((R - I)\) we can see an increase from 0 to 0.4 mag in 100 days, but the noise prevents us from ruling out an initial phase of constant color as observed in \((B - V)\) and \((V - R)\).

3.1.3. Extinction and Absolute Magnitude

We attempt to obtain constraints on host-galaxy extinction by analyzing the early color. If we assume that the initial \((B - V) = 0.2\) mag corresponds to maximum light and that the intrinsic color was close to \((B - V) = 0.0\) mag (which is what one might expect for SNe II; see Faran et al. 2014), then \(E(B - V) \sim 0.20 \pm 0.03\) mag (aware of the possibility that SNe IIn may have different colors at maximum than normal SNe II). Using \(R_V = 3.1\) this implies a host-galaxy extinction \(A_V = 0.62 \pm 0.10\) mag.

In addition we also examined the interstellar Na\,I D lines \(\lambda\lambda5889, 5895\) to estimate host-galaxy extinction using the spectrum with the highest resolution taken close to discovery, i.e., that obtained at Gemini-North on 2011 January 4.7 UT. The measurement of the Na\,I D absorption feature equivalent width (EW) yields EW\((D_1, 2) = 2.55 \pm 0.45\) Å. Unfortunately, the relation between \(A_V\) and EW for unresolved Na\,I D lines breaks down at EWs higher than 1 Å (Phillips et al. 2013), preventing us from deriving an independent host-galaxy extinction for SN 2011A. If this detection is due to the interstellar medium (ISM) then this would imply significant host-galaxy extinction. However, later we argue that the absorption is due to CSM material, and hence any connection with host-galaxy extinction is unclear.

Galactic extinction for SN 2011A in the \(V\) band is \(~0.137\) mag (Schlafly & Finkbeiner 2011)\(^{17}\) assuming \(R_V = 3.1\). Using a host-galaxy redshift \(z = 0.008916\) (Theureau et al. 2007) and assuming a \(\Lambda\)CDM cosmology with \(\Omega_M = 0.73, \Omega_{\Lambda} = 0.27,\) and \(H_0 = 73\) \(\text{km} \text{s}^{-1} \text{Mpc}^{-1}\), we obtain a distance of 36.7 Mpc, which implies an absolute magnitude uncorrected for host extinction of \(M_V = -15.10\) mag close to discovery. Aware of the uncertainties in \(A_V\) from the host galaxy \((0.62 \pm 0.10\) mag), we obtain an absolute \(V\)-band magnitude of \(-15.72\) mag. This is low for the SN IIn class \((-16 > M_V > -20\), Richardson et al. 2002), and is high compared to the SN impostors (e.g., SN1997bs has \(M_V > -14\); Van Dyk et al. 2000, or see compilation in Smith et al. 2011). It is therefore difficult to differentiate between an SN IIn or SN impostor origin for this transient using solely its \(M_V\).

3.2. Spectroscopy

As expected for an interacting transient, the spectral sequence presented in Figure 3 is dominated by relatively narrow H\(\alpha\) emission. However, there is significant evolution with time, as will now be discussed.

3.2.1. Spectral Evolution

The spectrum with the highest resolution taken close to discovery \((+2.4\) days) is dominated by Balmer lines, most prominently H\(\alpha\) and H\(\beta\) in emission, with a characteristic width of \(~2400\) \(\text{km} \text{s}^{-1}\) measured using the FWHM. In what

\(^{16}\) Via NED.

\(^{17}\) Via NED.
follows we will refer to these lines as “broad,” although the reader should keep in mind that these velocities are much lower than what is observed in most SNe II \( (v \sim 10^4 \text{ km s}^{-1}) \). We also observe many narrow \((\sim 500-1000 \text{ km s}^{-1})\) P Cygni profiles attributed to Ca \( \upiota \lambda 3933, 3968 \), the Ca \( \Pi \) near-infrared triplet \( \lambda 8498, 8542, 8662 \), and many Fe \( \Pi \) lines. After \( \sim \)day 50, H\( \alpha \) emission is still present but H\( \beta \) is significantly weaker. We see a similar evolution of the Fe \( \Pi \) lines, which are present during the first few days but disappear from day 56.8 onward. The Ca \( \Pi \) triplet is not clearly seen in spectra between days 56.8

| JD -2450000+ | UT Date | Epoch | Telescope/Instrument | Exposure (s) | Grating | Resolution FWHM (Å) | Resolution (km s\(^{-1}\)) | Range (Å) |
|------------|---------|-------|---------------------|-----------|--------|-------------------|-------------------------|---------|
| 5565.8 Jan 4.3 | 2.0 | du Pont/WFCCD WF4K-1 | 600 | Blue Grism | 8.0 | 365 | 3630-9100 |
| 5566.2 Jan 4.7 | 2.4 | Gemini-North/GMOS | 2 × 600 B600+G5307 | 5.2 | 240 | 3580-9100 |
| 5578.7 Jan 17.2 | 14.9 | NOT/ALFOSC | 3 × 1200 Grism 17 | 1.5 | 70 | 6330-6900 |
| 5620.6 Feb 28.1 | 56.8 | SOAR/GOODMAN | 2 × 1200 RALC 300 | 14 | 640 | 4200-8800 |
| 5627.8 Mar 7.3 | 64.0 | du Pont/WFCCD | 1000 Blue Grism | 8.0 | 365 | 3700-9180 |
| 5633.8 Mar 13.3 | 70.0 | SOAR/GOODMAN | 2 × 2700 KOSI 600 | 5.1 | 235 | 4380-7015 |
| 5644.7 Mar 24.2 | 82.9 | NTT/EFOSC2 | 2 × 3600 Grism 11/16 | 14.0 | 640 | 3740-9000 |
| 5649.7 Mar 29.2 | 85.9 | Baade/IMACS | 4 × 2000 300-4.3 Grating | 2.7 | 120 | 4190-9000 |
| 5662.3 Apr 10.8 | 98.5 | NTT/EFOSC2 | 2 × 3600 Grism 11/16 | 14.0 | 640 | 3610-9050 |
| 5675.6 Apr 24.1 | 111.8 | SOAR/GOODMAN | 2 × 2700 KOSI 600 | 7.0 | 320 | 4350-7015 |
| 5708.5 May 27.0 | 144.7 | SOAR/GOODMAN | 2 × 2400 RALC 300 | 10.2 | 470 | 3650-8840 |

Note.

* Days after discovery 2011 January 2.30 UT.
and 85.9 due to noisy data but is still visible on the +98.5 day spectrum, and possibly 144.7 days after discovery.

To understand SNe IIn, it is common practice to analyze the Hα line profile and its evolution. This is shown in Figure 5 where we see considerable temporal variations. Indeed, from discovery to 56.8 days later, our spectra are characterized by prominent “broad” emission ($v \approx 2000\ \text{km s}^{-1}$). Then between 56.8 and 85.9 days post discovery, narrow low-velocity ($600–1100\ \text{km s}^{-1}$) P Cygni absorption appears. After day 85.9 we see again a “broad” emission with no signs of the P Cygni profile. Again, we emphasize the absence in the spectra at all epochs of any kind of high-velocity component ($\sim 10^4\ \text{km s}^{-1}$) characteristic of SN ejecta.

In Figure 6 we show the Hα line evolution splitting it into epochs with and without P Cygni profiles. The P Cygni component is seen in spectra obtained on days +56.8, +64.0, +70.0, and +80.9. The blueshifted absorption velocity has values between 575 and 1060 km s$^{-1}$. It is unlikely that these low-velocity P Cygni profiles can be attributed to the ejecta, which is expected to have velocities of several thousand km s$^{-1}$. Therefore, we argue that this P Cygni component is related to a pre-SN wind. The wind velocity is consistent with an LBV progenitor ($100–1000\ \text{km s}^{-1}$; Smith & Townsend 2007) but is too high for red supergiants ($20–40\ \text{km s}^{-1}$; Smith et al. 2007) and possibly too low for Wolf–Rayet stars ($1000–5000\ \text{km s}^{-1}$; Abbott & Conti 1987).

Our first spectra, taken 2.0 and 2.4 days after discovery, show many strong Fe II features with P Cygni profiles. The velocity measured with respect to the emission from the Fe II multiplet $\lambda\lambda 4923, 5018, 5169$ lines in the +2.4 day spectrum is between 430 and 460 km s$^{-1}$, arguing for a CSM rather than ejecta origin. We also note that these velocities have the same order of magnitude as those derived from the Hα P Cygni feature as absorption at the wavelength of Na I D due to the fact that the Na I D can be blended with the He I $\lambda\lambda 5876$ line (we also note the possible presence of He I at the wavelengths $\lambda\lambda 6678$ and $\lambda 7065$ in the 2.4 day spectrum). Therefore the total blended doublet is measured as a single line. In Figure 8 we present both the EW and velocity evolution and see that the absorption becomes stronger with time. Indeed the EW is initially equal to $\sim 3\ \text{Å}$ and increases to $10\ \text{Å}$ after the first 70.0 days. At the same time, the feature profile evolves. In the first two spectra, only an absorption line is observed, while between days 56.8 and 110.3 a P Cygni profile appears. The velocities are measured from the Na I D center, $5892\ \text{Å}$, with respect to the emission are shown in Table 4. Figure 8 also

Figure 4. Observed $(B − V)$, $(V − R)$, $(R − I)$ color evolution of SN 2011A corrected for Milky Way extinction.

Figure 5. Hα line profile evolution of SN 2011A. The epochs are indicated in black and are with respect to the discovery date (2011 January 2.30 UT = 0 days). The dotted red vertical line represents the rest-frame Hα wavelength at 6562.81 Å.

3.2.2. Variable Low-velocity Absorption Close to Na I D

As seen in the Type IIn SN 1994 W (Chugai et al. 2004), we observe strong absorption near the Na I D doublet wavelength ($\lambda\lambda 5889, 5895$) that becomes stronger with time and has low velocity. This is shown in Figure 7, where the evolution of this feature is presented. The EW and velocity of the line profile were calculated for each epoch. Because the majority of our spectra were taken in low resolution, the sodium doublet is unresolved; hence, we will refer to this feature as absorption at the wavelength of Na I D due to the fact that the Na I D can be blended with the He I $\lambda\lambda 5876$ line (we also note the possible presence of He I at the wavelengths $\lambda\lambda 6678, 7065$ in the 2.4 day spectrum). Therefore the total blended doublet is measured as a single line. In Figure 8 we present both the EW and velocity evolution and see that the absorption becomes stronger with time. Indeed the EW is initially equal to $\sim 3\ \text{Å}$ and increases to $10\ \text{Å}$ after the first 70.0 days. At the same time, the feature profile evolves. In the first two spectra, only an absorption line is observed, while between days 56.8 and 110.3 a P Cygni profile appears. The velocities are measured from the Na I D center, $5892\ \text{Å}$, with respect to the emission are shown in Table 4. Figure 8 also
shows the average Na I D EWs from the ISM for all of the Carnegie Supernova Project (CSP; Hamuy et al. 2006) SNe II (as used in Anderson et al. 2014b). We measure the EW for each SN regardless of the epoch and we averaged these values. This is again further evidence of a CSM origin for this line: the strength is much higher than seen in any other SNe II from the CSP database. Even if the low-resolution spectra prevent us from being sure that the measured absorption close to Na I D position is only due to Na I D and not blending with other lines, the absorption strength is unprecedented.

3.2.3. Wind Velocity

In order to measure the wind velocity we estimate the width of the narrow component of the Hα emission line. For this
estimation we decompose the Hα feature using a least-squares PYTHON script, which solves the best-fit multi Gaussian decomposition. The best fit was performed using three components, so nine parameters are used as input: the FWHM, the amplitude, and the center of each Gaussian corresponding to the three components. Using these values our script provides the best-fit Gaussian parameters, the best FWHM, the amplitude, and the center of each component. The errors on these parameters are derived assuming a reduced chi squared equal to one. In Figure 9 we show the Hα emission line decomposition for spectra taken with ALFOSC (highest resolution spectrum available) on 2011 January 17.2 UT. Our three components fit to the Hα emission line yield velocities of $107 \pm 2$, $467 \pm 14$, and $1971 \pm 35$ km s$^{-1}$. Each velocity component is low compared to other SNe IIn. For comparison, Kiewe et al. (2012) found typical velocities of 2000 km s$^{-1}$ for the intermediate component. We also note that Pastorello et al. (2004) found that for low-luminosity SNe II the expansion velocities range from 3000 to 5000 km s$^{-1}$ during early epochs. Therefore, SN 2011A appears to have ejecta velocities lower than the majority of normal SNe events. This could be evidence for an SN impostor origin, as will be discussed below. In addition, Tartaglia et al. (2015) recently reported a case of an interesting transient, SN 2007sv. From this object the authors, also analyzing the Hα emission line, derived very similar velocity values. Indeed the broad component velocity was estimated as 2000 km s$^{-1}$ (1971 km s$^{-1}$ for SN 2011A), the intermediate component velocity as 600–800 km s$^{-1}$ (467 km s$^{-1}$ for SN 2011A), and the narrow component velocity as 120–150 km s$^{-1}$ (107 km s$^{-1}$ for SN 2011A). In their paper, they conclude that the transient SN 2007sv is most likely an SN impostor, based mainly on its absolute magnitude. Note that the absolute magnitude derived for this transient is $\sim$2 mag fainter than SN 2011A.

Note that from the Gaussian decomposition of the highest resolution spectrum we can calculate the progenitor mass-loss rate using the following formula (Chugai & Danziger 1994; Kiewe et al. 2012):

$$L_{\text{H}} = \frac{1}{2} M \psi \frac{v_{\text{shock}}^3}{v_{\text{wind}}}$$

where $\psi$ is the efficiency of the conversion of mechanical energy into optical energy in the shock wave (we adopt as Kiewe et al. 2012, $\psi = 0.1$), $M$ is the mass-loss rate, $v_{\text{wind}}$ is the unshocked wind velocity derived as described above, and $v_{\text{shock}}$ is the shock velocity. The shock velocity was taken as the FHWM of the intermediate width component. The absolute $L_{\text{H}}$ was then obtained by integrating over the intermediate width feature and taking account of the distance to the SN. We used the same luminosity distance used above, i.e., 36.7 Mpc. We found $M = 0.038 \ M_\odot$ yr$^{-1}$ with a wind velocity of 110 km s$^{-1}$ and a shock velocity about 470 km s$^{-1}$. This mass-loss rate is consistent with values found by Kiewe et al. (2012) and is too high for any class of massive stars other than LBVs in the eruptive phase (Humphreys & Davidson 1994).

4. DISCUSSION

SN 2011A shows a number of interesting properties. In order to understand the nature of the transient, we compare in this section our object with other interacting transients. We discuss the transient in comparison to other events that possibly show similarities. However, in any case where similarities exist, we show that there are other features that confirm the uniqueness of SN 2011A.

4.1. Photometry

4.1.1. Photometric Comparison to other SNe IIn

As stated in the Introduction, the SN IIn group is very heterogeneous in terms of luminosity, light curve shape, and spectral evolution. Based on Kiewe et al. (2012), who proposed to differentiate SNe IIn according to their photometric and spectroscopic characteristics, Kankare et al. (2012)
identify a subclass of SNe IIn in which they included SN 2009kn (Kankare et al. 2012), SN 1994W (Chugai et al. 2004), and SN 2005cl (Kiewe et al. 2012). To see if SN 2011A shares common properties with these SNe and belongs to this subclass, we compare the light curves and spectra (see Section 4.2.2). We also include a comparison with SN 1998S (Fassia et al. 2001), a well studied SN IIn, SN 2005kj (Taddia et al. 2013), which, similar to SN 2011A, shows evidence of low-velocity absorption at Na I D wavelengths, SN 1997bs (Van Dyk et al. 2000) classified as an SN impostor (note that we compare SN 2011A and SN 1997bs in more detail in Section 4.1.2), and SN 2007sv, also recently classified as an SN impostor (Tartaglia et al. 2015). These comparisons are shown in Figure 10, where the V-band light curves are plotted. Note that we do not present the SN 1994W light curve due to the lack of data and because it is very similar to SN 2009kn (Kankare et al. 2012). As we can see in Figure 10, SN 2009kn is brighter than SN 2011A with $M_V \approx -17.5/-18$ and the SN 2009kn light curve does not show a double plateau like SN 2011A. Indeed, after an initially declining plateau phase with a slope equal to 0.018 mag day$^{-1}$, we see a quick fall around 0.08 mag day$^{-1}$ followed by a slow decline phase with a slope of $\sim 1$ mag 100 day$^{-1}$. However, the photometry of SN 2009kn does not cover the first few tens of days from the assumed explosion date. As can be seen in Figure 10, SN 2011A is photometrically very different that other SNe IIn. None of the other selected SNe IIn show a double plateau and they are all $\geq 2$ mag brighter than SN 2011A. Also we remark that SN 2011A is $\sim 2$ mag brighter than the SN impostors. Figure 10 allows us to conclude that SN 2011A is a very rare event that does not share any similarities in the light curve with other SN 1994W-like SNe IIn. An important additional point to note is the origin of the two SNe IIn, SN 1994W and SN 2009kn, used to compare SN 2011A to other SNe IIn. Indeed the origin is not so clear; for example Dessart et al. (2009) argued that maybe SN 1994W was not an SN, but rather the result of two interacting shells of material related to LBV-like eruptions. Also, in the case of SN 2009kn (Kankare et al. 2012) a non-SN origin could not be completely excluded, but also found the observations to be consistent with an electron capture SN. We note that an argument will be presented later that constrains the epoch of the photometry of SN 2011A to be $\sim 50$ days later than shown in Figure 10. However, the main conclusions remain valid: SN 2011A has a luminosity between the two classes of interacting transients, SNe IIn and SN impostors; this event shows a rare double plateau.

In Figure 11 we present the optical colors of SN 2011A together with the color evolution of SN 2009kn, one SN 1994W-like, and the well studied SN 1998S. We do not present the SN 1994W and SN 2005cl colors due to the lack of data. All magnitudes were corrected for Milky Way extinction. Taking the discovery date as the explosion date, the color evolution of SN 2011A looks fairly similar to SN 1998S. Indeed, the $(B - V)$ color becomes redder in SN 1998S between days 0 and 60. However, in $(V - R)$, SN 1998S does not show an initial plateau as in SN 2011A.

The color evolution of SN 2009kn looks similar to SN 2011A in $(B - V)$ and $(V - R)$, but shifted by $\sim 50$ days. This could be explained by the lack of precision in the explosion date for SN 2011A. If we shift our epochs by 50 days (motivated by the spectral analysis in Section 4.2.1), the color...
Figure 12. Comparison of the BVRI light curves of SN 2011A and the impostor SN 1997bs. Photometric data of the SN impostor were taken from Van Dyk et al. (2000). For each band, empty symbols represent SN 2011A and filled symbols SN 1997bs. Squares represent the I-band light curve, triangles the R-band, hexagons the V-band and circles the B-band.

Figure 13. (B − V), (V − R), (R − I) color evolution of SN 2011A (red triangles) compared to the impostor SN 1997bs (Van Dyk et al. 2000) shown in black circles. All colors were corrected for Milky Way extinction and by host-galaxy extinction.

The light curve comparison between SN 2011A and SN 1997bs (which was classified as an SN impostor by Van Dyk et al. 2000) shows similarities. The light curves of both objects in B, V, R, and I bands are shown in Figure 12. For the SN 1997bs explosion date, we chose 1997 April 15th (UT discovery date), which should be valid because an image taken on 1997 April 10th does not show anything at the location of the SN. During the first 15 days of evolution in the R and I bands both objects exhibit a plateau. After this first plateau the two transients show a second plateau but the drop between the two is much larger for SN 1997bs: ~0.5 mag for SN 2011A and ~1 mag for SN 1997bs in R. The B and V bands have also some similarities. Note that while the light curve evolution displayed in Figure 12 appears to be very similar, this may be coincidental given the uncertainty of the SN 2011A explosion date. However, the important observation is the similar double plateau features in both light curves, which may be evidence for the same underlying mechanism, namely, interaction with two separate CSM shells. The optical colors of SN 2011A compared with SN 1997bs are presented in Figure 13. From the (B − V) color we can compare the colors near maximum. For SN 2011A we find ~0.25 mag whereas for SN 1997bs Van Dyk et al. (2000) found 0.67 mag, adding host extinction for 1997bs. Additionally we can compare the color evolution. In the (V − R) color, the evolution looks similar during the first 30 days. For SN 1997bs, a plateau at 0.3 mag for 30 days is seen and then reddening as for SN 2011A. However, in SN 2011A the plateau lasts 50 days. Despite the noise, the (B − V) color exhibits the same trend with a plateau for 20 days and then reddening. Again, in (R − I), SN 2011A and the SN impostor show the same evolution with reddening during the first 40 days. Although the data are noisy, the shape of the reddening is pretty similar. Finally, note that the SN impostor nature of SN 1997bs is not entirely clear, as there is some evidence that the progenitor did not survive until the explosion (Li et al. 2002; Adams & Kochanek 2015). Hence, while SN 2011A shows similarities to SN 1997bs, this is not conclusive proof that the former was an impostor event.

4.1.2. SN 2011A versus SN 1997bs

The light curve comparison between SN 2011A and SN 1997bs (which was classified as an SN impostor by Van Dyk et al. 2000) shows similarities. The light curves of both objects in B, V, R, and I bands are shown in Figure 12. For the SN 1997bs explosion date, we chose 1997 April 15th (UT discovery date), which should be valid because an image taken on 1997 April 10th does not show anything at the location of the SN. During the first 15 days of evolution in the R and I bands both objects exhibit a plateau. After this first plateau the two transients show a second plateau but the drop between the two is much larger for SN 1997bs: ~0.5 mag for SN 2011A and ~1 mag for SN 1997bs in R. The B and V bands have also some similarities. Note that while the light curve evolution displayed in Figure 12 appears to be very similar, this may be coincidental given the uncertainty of the SN 2011A explosion date. However, the important observation is the similar double plateau features in both light curves, which may be evidence for the same underlying mechanism, namely, interaction with two separate CSM shells. The optical colors of SN 2011A compared with SN 1997bs are presented in Figure 13. From the (B − V) color we can compare the colors near maximum. For SN 2011A we find ~0.25 mag whereas for SN 1997bs Van Dyk et al. (2000) found 0.67 mag, adding host extinction for 1997bs. Additionally we can compare the color evolution. In the (V − R) color, the evolution looks similar during the first 30 days. For SN 1997bs, a plateau at 0.3 mag for 30 days is seen and then reddening as for SN 2011A. However, in SN 2011A the plateau lasts 50 days. Despite the noise, the (B − V) color exhibits the same trend with a plateau for 20 days and then reddening. Again, in (R − I), SN 2011A and the SN impostor show the same evolution with reddening during the first 40 days. Although the data are noisy, the shape of the reddening is pretty similar. Finally, note that the SN impostor nature of SN 1997bs is not entirely clear, as there is some evidence that the progenitor did not survive until the explosion (Li et al. 2002; Adams & Kochanek 2015). Hence, while SN 2011A shows similarities to SN 1997bs, this is not conclusive proof that the former was an impostor event.

4.1.3. 56Ni Mass Estimate

One diagnostic to discriminate between SNe and SN impostors is the amount of synthesized 56Ni. For low-mass core-collapse SNe (SNe IIP) one expects to find a 56Ni mass around 0.0016−0.26 M⊙ (Hamuy 2003) whereas for non-terminal explosions we do not expect any 56Ni production because only the outer layers of the star are ejected. For very massive CC SNe produced by progenitors with initial masses between 30 and 100 M⊙, 56Ni masses between 2.3 and 6.6 M⊙ have been predicted (Umeda & Nomoto 2008), and masses between 0.07 and 0.6 M⊙ have been estimated for progenitor masses between 16 and 46 M⊙ (Mazzali et al. 2009). We can obtain a 56Ni mass estimate using the formula from Hamuy
(2003) and the last V-band magnitude (epoch 97.6 days). This value should be taken as an upper limit of the $^{56}$Ni mass because the spectrum at this epoch does not indicate that the emission is being solely powered by radioactivity. Indeed, in this spectrum narrow lines are still present due to interaction.

As stated previously the explosion date is not well constrained and could be 50 days before discovery. Therefore, the $^{56}$Ni mass is calculated assuming the explosion date as the discovery date and also using an explosion date 50 days before discovery. We find 0.01–0.015 $M_{\odot}$ without extinction and 0.03–0.05 $M_{\odot}$ with extinction. In both cases we use an explosion date 50 days before discovery for the upper value. These values are consistent with Hamuy (2003) and lower than Mazzali et al. (2009). Indeed, Hamuy (2003) found SNe II values between 0.0016 and 0.26 $M_{\odot}$ and Mazzali et al. values between 0.07 and 0.6 $M_{\odot}$. If we apply this same approach to SN 1997bs, we find a $^{56}$Ni of 0.003 $M_{\odot}$ based on the V-band magnitude measured 63.5 days after discovery. In conclusion, it is very difficult to set significant constraints on the nature of SN 2011A based on these uncertain $^{56}$Ni mass estimates.

4.2. Spectroscopy

4.2.1. Explosion Date

Unfortunately, the explosion date of SN 2011A is not well determined by pre-explosion images. A fit to the early time spectrum with a blackbody function yields a high temperature (~10,000 K), thus suggesting that the observations possibly began soon after explosion. However, given the interacting nature of SN 2011A, the validity of such a constraint is unclear. To better estimate this parameter, we compare SN 2011A with two other SNe with well constrained explosion times.

First, we consider SN 1994W (Cortini et al. 1994), for which Sollerman et al. (1998) estimated from its R-band data a precise explosion date of 1994 July 14$^{\pm}$2. In Figure 14 we compare our spectrum taken 2.0 days after discovery with an SN 1994W spectrum taken 57 days after explosion. As we can see, the spectra are remarkably similar. A blue continuum characterizes SN 2011A shows two noticeable differences from SN 1994 W: (1) the Ca II near-infrared triplet is more prominent than in SN 1994 W and (2) SN 1994 W shows a narrow P Cygni absorption on top of the broad of H$\alpha$ component, whereas in SN 2011A this feature is not seen and only appears in the spectrum taken +56.8 days after discovery.

Second, in Figure 15 we compare our +2.0 day spectrum with the SN 1997bs spectrum taken on 1997 April 16th (day +1 after discovery) to search for similarities in their light curves. Given that the nondetection was very close to discovery, the explosion date is well constrained for SN 1997bs. The continua look very similar when we apply a reddening of $E(B-V) = 0.24$ mag to SN 1997bs in order to match the continua.
Thanks to these comparisons and the fact that our spectrum taken 2.0 days after discovery has a good match with the SN 1994W spectrum taken 57 days past explosion, it is possible that SN 2011A exploded ~50 days before discovery. Indeed, in both spectra we can see the presence of the same elements with identical line profiles, such as the Fe II multiplet λλ4923, 5018, 5169. This implies that the physical conditions for both spectra were similar and assuming that the evolution is not so different, the epochs are likely similar. This explosion date would then make the color curve between SN 2009kn and SN 2011A consistent (see Section 4.1). While the light curves are very similar between SN 2011A and SN 1997bs, these are most likely related to CSM shells, and therefore any explosion date estimation is less reliable; the explosion date estimation from spectral comparisons is likely to be more valid.

4.2.2. Na I D Evolution

Na I D absorption can have three origins. From the ISM in the line of sight, the CSM ejected by the progenitor ionized by the radiation from the SN and recombined over the following several days to weeks, or from the SN ejecta. The main distinguishing feature between these three components is the velocity. If the absorption is due to the ISM, the velocity will be very low, ~2–15 km s⁻¹ (Fassia et al. 2001). If the component comes from the CSM, the velocity will be higher (few hundred km s⁻¹ as for SN 2011A) and depends on the progenitor. Finally, the component from an SN ejecta would have the highest values of a few thousand km s⁻¹. Though the majority of spectra have low resolution and prevent us from resolving the Na I D absorption line, we believe that the absorption close to the Na I D wavelength position is mostly due to Na I D. Even if some lines like Ba II λ5854 can be blended with Na I D, the absorption strength and velocity are very rare. Indeed, other SNe have shown a similar remarkable increase of Na I D absorption, such as SN 1998A and SN 2009E (Pastorello et al. 2005, 2012), but Pastorello et al. (2013) measured the Na I D velocity for SN 2009E and found a value of ~3000–5000 km s⁻¹. This implies that the absorption line is due the SN ejecta, whereas the velocities measured for Na I D absorption in SN 2011A never get higher than 1100 km s⁻¹, inconsistent with an ejecta origin, but consistent with a CSM origin interpretation.

In the literature we found a small number of cases of CSM Na I D in SNe IIn. Indeed for SN 2009kn (Kankare et al. 2012), SN 1994W (Chugai et al. 2004), SN 1997bs (Van Dyk et al. 2000), and SN 2005kj (Taddia et al. 2013), the velocity is low as for SN 2011A, less than 1100 km s⁻¹. The increase of Na I D absorption, according to Chugai & Danziger (1994), is a result of the increasing Na I ionization fraction.

4.2.3. Dust Formation

Most SN impostor candidates in the literature have no surviving star at the location of the transient, which could contradict the nature of the transient, i.e., non-terminal eruptions of massive stars. However, a simple reason could explain this. The dust formed in a dense shell ejected by the star will obscure the SN impostor. The presence of dust can be deduced in different ways. First, by the presence of an infrared excess due to the thermal emission from dust condensed in the ejecta or from heated pre-existing dust. Unfortunately, we do not have useful infrared data for this transient. Second, by looking at the emission lines. If the spectral feature profiles show a blueshift, this can be attributed to the fact that the red side of the ejecta is blocked by the new dust (Smith et al. 2012, but see Anderson et al. 2014a and Dessart et al. 2015 for an alternative explanation). This effect is possibly seen in our transient. Indeed, in Figure 5 where the Hα emission line evolution is shown, we can see for the spectrum at +111.8 days that the red side is weaker compared to the blue part. This characteristic is not clearly observed after and before this epoch, especially because of the appearance of a P Cygni profile.

The estimated blackbody temperature at late times (3300 K) is also possibly indicative of dust formation. This is because this temperature appears to be too low for the spectra to be dominated by strong Balmer emission lines. This low temperature could be due to dust formation that reddens the object. Multi-band photometry fitting seems to favor an extincted blackbody, but it is difficult to put strong constraints on the blackbody temperature and extinction due to the small wavelength baseline and because our transient is mainly powered by interaction, which implies that using a blackbody fitting could be unrealistic. Any increase in reddening could also be related to the observed increase in Na I D. However, we note that the increase in the latter is more likely due to CSM effects.

4.2.4. CSM Properties

Analyzing the Hα emission line evolution with time together with the light curve allows us to constrain CSM properties. The SN 2011A light curve shows a double plateau. The presence of this rare double plateau leads us to speculate that the CSM is composed of two shells ejected by the pre-SN wind. Over ~15 days there is an initial plateau that corresponds to the interaction between the SN blast wave and the first shell. When the ejecta reaches the edge of the first shell the light curve drops. If we assume that the blast wave speed is constant, and taking the value found in Section 3.2.3, ~2000 km s⁻¹, we find a lower limit width of the first shell of ≥2.6 × 10¹⁴ cm. It is a lower limit due to the fact that the beginning of this shell is not well constrained (because of the uncertainty in the explosion date). Then, there is another weaker plateau that lasts ~15 days in the V band. Again, assuming that the ejecta velocity is constant with time, we find the width for the second shell, ~2.6 × 10¹⁴ cm. A cartoon showing the CSM and the velocities of the different components is presented in Figure 16. This scenario would be similar to that proposed by Dessart et al. (2009) for SN 1994W.

This photometric analysis seems to also consistent with the spectral evolution. In Figure 5 we see that the Hα profile changes with time, from the very broad component at early epochs during the first plateau phase (spectra +2.0, +2.4, and +14.9 days), to a narrower broad component, accompanied with low-velocity Hα absorption (+56.8, +64, +70, +80.9, +85.9 days) during and after the second plateau.

5. CONCLUSIONS

We have presented a detailed study of SN 2011A, initially classified as an SN IIn based on the presence of narrow Hα emission in the spectrum. While the exact nature of the transient remains unclear, SN 2011A shows a number of interesting and unusual properties.
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Figure 16. Cartoon illustration of the CSM composition with the velocity of the different components. The black star represents the transient. Not to scale.

1. A double plateau in light curve likely due to CSM composed of two shells.
2. Low luminosity, $-15.10 \geq M_V \geq -15.72$ (depending on the assumed host-galaxy extinction, 0 or 0.62 mag in the V band).
3. Low P Cygni Hα velocity $\leq 1200 \text{ km s}^{-1}$.
4. Low-velocity absorption close to Na i D $\leq 1100 \text{ km s}^{-1}$.
5. Variable absorption close to Na i D increasing in strength, from 3 to 10 Å in EW.

Given the photometric and spectroscopic properties we have derived for SN 2011A, most importantly its low luminosity and low ejecta velocity together with their comparison to other interacting transients, we believe that SN 2011A is most likely an SN impostor event. However, we also note that our analysis has demonstrated the difficulty in determining whether interacting transients are true terminal events or indeed SN impostors. The reader also must keep in mind that the characteristics used to separate the two events are in general arbitrary and hence detailed studies of future events are needed to further elucidate this issue.

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