THE SUPERNOVA IMPOSTOR PSN J09132750+7627410 AND ITS PROGENITOR

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ABSTRACT

We report the results of our follow-up campaign of the supernova impostor PSN J09132750+7627410, based on optical data covering ~250 days. From the beginning, the transient shows prominent narrow Balmer lines with P-Cygni profiles, with a blueshifted absorption component becoming more prominent with time. Along the ~3 months of the spectroscopic monitoring, broad components are never detected in the hydrogen lines, suggesting that these features are produced in slowly expanding material. The transient reaches an absolute magnitude $M_V = -13.60 \pm 0.19$ mag at maximum, a typical luminosity for supernova impostors. Amateur astronomers provided ~4 years of archival observations of the host galaxy, NGC 2748. The detection of the quiescent progenitor star in archival images obtained with the Hubble Space Telescope suggests it to be an 18–20 $M_\odot$ white–yellow supergiant.

Key words: galaxies: individual (NGC 2748) – supernovae: general – supernovae: individual (PSN J09132750+7627410, SN 2007sv, SN 1997bs, SN Hunt248)

Supporting material: data behind figure

1. INTRODUCTION

Energetic outbursts of massive stars are often labeled as “supernova impostors” (Van Dyk et al. 2000), since they usually show observational features resembling those of SNe II (Schlegel 1990; Filippenko 1997). However, SN impostors are non-terminal outbursts of massive stars, extra-galactic counterparts of the “Great Eruption” (occurred in the 19th century) of the Galactic luminous blue variable (LBV) η-Car. The mechanisms triggering these events are not yet fully understood (Pauldrach & Puls 1990).

In most cases, SN impostors have been related to major outbursts of LBV stars (e.g., Smith et al. 2010; Tartaglia et al. 2015b), since narrow hydrogen lines present in their spectra have inferred expansion velocities comparable to those of LBV winds (10^3–4 km s^-1). LBVs are evolved, luminous (a few 10^4–6 $L_\odot$) massive stars (>30 $M_\odot$), very close to the Eddington limit, characterized by large instabilities in the outer layers and high mass losses. Nonetheless, LBV-like outbursts have also been linked to lower-mass stars (see, e.g., the case of SN 2008S and other similar transients; Berger et al. 2009; Bond et al. 2009; Botticella et al. 2009; Thompson et al. 2009), while binary interactions can also play an important role in triggering violent mass-loss episodes.

In this context, we report the results of our follow-up campaign of the SN impostor PSN J09132750+7627410 (hereafter PSNJ09+76). Its discovery was announced on 2015 February 10 through an IAU Central Bureau Astronomical Telegram in NGC 2748, which previously hosted two other SNe: the Type Ia SN 1985A (Wild & Schödellnecht 1985; Wegner & McMahen 1987) and the Type Ic SN 2013ff (Brimacombe et al. 2013). PSNJ09+76 was classified as an SN impostor by Tartaglia et al. (2015a) on 2015 February 12.

Hereafter, we will adopt a luminosity distance of $D_L = 23.8 \pm 2.0$ Mpc, hence a distance modulus of $\mu = 31.88 \pm 0.18$ mag, as reported by the Extragalactic Distance Database (Tully et al. 2009). For the foreground Galactic extinction, we will assume $A(V) = 0.073$ mag (Schlafly & Finkbeiner 2011). We adopted no host galaxy contribution to the total extinction, since in the spectra of PSNJ09+76 there is no evidence of the narrow Na ID absorption feature at the recessional velocity of NGC 2748.

2. OBSERVATIONS AND DATA REDUCTION

The follow-up campaign of PSNJ09+76 was carried out using the 1.82 m Copernico telescope equipped with AFOSC located at Mount Ekar, Asiago, Italy; the 10.4 m Gran Telescopio Canarias (GTC) with OSIRIS; and the 2.56 m Nordic Optical Telescope (NOT) with ALFOSC, both located at the Observatorio del Roque de los Muchachos, La Palma, Spain. Additional photometric data, mostly covering the eruptive phases, were provided by public archives and amateur astronomers. The transient was also observed by the UV/Optical Telescope (UVOT) on board the Swift Gamma-ray Observatory. UVOT data (uvw2, uvw1, u, B, V bands) were processed using the HEASARC software (HEASoft11, version 6.17) following the prescription of Poole et al. (2008). The transient field was also observed by the Hubble Space...
The Astrophysical Journal Letters, 823:L23 (7pp), 2016 June 1

Telescope (HST) in the optical domain and the Spitzer Space Telescope (SST) in near-infrared (NIR), and we used these images to perform our analysis on the progenitor of PSNJ09+76 (see Section 5).

Ground-based spectroscopic and photometric data were preprocessed in the usual manner (overscan, bias, and flat-field corrections) using standard IRAF12 tasks. The magnitudes of the transient were measured through a dedicated pipeline (SNOoPY; Cappellaro 2014) and calibrated with reference to a set of field stars. This local sequence was calibrated with reference to Sloan Digital Sky Survey (SDSS13) fields obtained during photometric nights, while their BVRI magnitudes were derived from the Sloan magnitudes following the relations in Chonis & Gaskell (2008). Unfiltered data from the amateur astronomers were calibrated to the r-band.

The spectroscopic calibrations were performed using spectra of standard stars obtained during the same nights (for the flux calibration) and spectra of comparison lamps obtained with the same instrumental setup used (for the wavelength calibration). The wavelength calibration was checked using night sky lines, shifting the spectra in case of discrepancy. The flux calibration was checked using the magnitudes obtained on the closest nights, and a scaling factor was applied if necessary. Finally, we corrected the spectra of PSNJ09+76 for the Galactic foreground extinction and for the redshift ($z = 0.0049$) due to the recessional heliocentric velocity of the host galaxy ($1476 \pm 2$ km s$^{-1}$).

3. PHOTOMETRIC ANALYSIS

The outcomes of our photometric measurements are shown in Figure 1, while the magnitudes in the different bands are reported in the online table.

Our i-band image obtained on 2015 May 25 with ALFOSC (the one with the best seeing among our photometric data, full width at half maximum: FWHM ~ 0.5”) was used to accurately pinpoint the position of the transient (R.A. = 09:13:27.408, decl. = −76:27:40.91; J2000).

About four years of archival data were provided mostly by amateur astronomers and revealed no further eruptive episodes similar to that observed in 2015. The last non-detection prior to the 2015 event is dated 2015 January 6, ~1 month before our first r-band point. The r-band maximum occurred on 2015 February 16 (MJD = 57069.76), and we consider this as the reference epoch for the phases.

After maximum, we note a relatively fast decline in the u-band light curve with a slope of 6.8 mag/100 days. The light curves decline more slowly in the other bands, with 4.3 mag/100 days, 2.8 mag/100 days, and 3.3 mag/100 days in the B-, V-, and g-bands, respectively. The r-band light curve shows a decline rate of 1.9 mag/100 days in the first ~130 days, while it steepens at later epochs. A similar behavior is observed in the i- and z-band light curves, with 1.3 mag/100 days and 0.4 mag/100 days in the first ~100 days, while the slopes increase to 5.2 mag/100 days and 4.8 mag/100 days, respectively, at later phases.

The evolution of the B − V and r − i colors is shown in Figure 1(b). We note that the colors become progressively redder, consistent with a rapid decline of the temperature of the emitting gas. The color evolution at early phases is similar to those of other impostors (Figure 1), although we note that PSNJ09+76 is much redder than the other transients at phases later than ~50 days from maximum.

The r-band absolute light curve is shown in panel (c). Assuming the distance modulus and the extinction reported in Section 1, we infer an r-band absolute peak magnitude of $−13.60 \pm 0.19$ mag, corresponding to a pseudo-bolometric luminosity $\geq 10^{41}$ erg s$^{-1}$ (panel (d)). The comparison with the absolute light curves of similar transients shows that PSNJ09+76 has an absolute light curve similar to those of other SN impostors, with the main outburst having a light curve resembling those of a core-collapse SN, but with a fainter peak magnitude.

4. SPECTROSCOPIC ANALYSIS

The results of the spectroscopic analysis are shown in Figure 2. In panel (a), we show the final sequence of spectra obtained during the ~3 months of our spectroscopic follow-up campaign. A log of the spectroscopic observations is reported in Table 1, along with the information on the instrumental setup used, exposure times, and spectral resolutions.

The spectra at early phases are characterized by a blue continuum with sharp and narrow Balmer lines with P-Cygni profiles, as also noticed by Humphreys & Gordon (2015). The temperature of the pseudo-continuum, estimated through a blackbody fit, rapidly falls from $13,400 \pm 2500$ K to 3400 ± 400 K, in agreement with the estimated broadband color evolution (Figure 1(b)). The H$\alpha$ profile is characterized by a prominent P-Cygni profile at all phases.

In Figure 2(b), we show the detailed evolution of the H$\alpha$ and H$\beta$ regions. The total H$\alpha$ profile is well fitted using a Gaussian component in absorption and a single Lorentzian component in emission. From this fit, at early phases, we derive an FWHM velocity $<700$ km s$^{-1}$ for the emission component and a nearly constant $(900–1000$ km s$^{-1}$) expansion velocity, deduced from the positions of the minimum of the absorption components. Nonetheless, at +39 days and +92 days, we note a second absorption component (Figure 2(b)), suggesting the presence of a slower shell, moving at 300–450 km s$^{-1}$, which is nearly the same value (within the errors) inferred from the FWHM of the narrow emission component at the same phases. The absence of this component at earlier phases, as well as in other spectra at similar phases, is most likely due to insufficient resolution. The velocity inferred from the blue wing of the faster absorption components in the +39 day spectrum is consistent with that of the red wing of the H$\alpha$ emission profile. We do not detect the same features in the H$\beta$ profile, although this might be related to the lower signal-to-noise ratio (S/N) of our spectra at the corresponding wavelengths.

The H$\gamma$ line is also identified at early phases. In our +39 day spectrum, we also identify Fe II (multiplets 27, 37, 38, 42, 48, 49), Ba II λλ4554.0, 4934.1, Na D λλ5889.9, 5895.9, O I at 7774 Å and Ca II (H and K), Ti II (multiplets 1, 19, 20, 31, 34, 41, 51, 82, 105), and, tentatively, the Ba I (multiplet 2). We note that our last (+92 day) spectrum has a much redder continuum, and broad features appear, most likely due to TiO molecular bands in the 6100–6400 Å and 7000–7400 Å regions.

12 http://iraf.noao.edu/
13 http://sdss.org
5. THE PROGENITOR STAR OF PSNJ09+76

Deep archival HST images\(^{14}\) of the host galaxy were obtained on 2001 July 6 (HST ID proposal: 9042; PI: S. Smartt) using the Wide Field Planetary Camera 2 (WFPC2) with the F-450W and F814W filters. Also, three sets of mid-infrared (MIR) SST images were obtained on 2009 December 2, 2010 April 12 (ID proposal: 61063; PI: K. Sheth), and 2014 January 2 (ID proposal: 10046; PI: D. Sanders) using the Infra-Red Array Camera (IRAC) with the 3.6 and 4.5 μm channels (channels 1 and 2, respectively). These data were retrieved from the Spitzer Heritage Archive\(^{15}\) (SHA), hence fully co-added and calibrated. Drizzled HST images (resampled to a uniform grid to correct geometric distortions, with ~0.1 arcsec pixel\(^{-1}\)) obtained through the Hubble Legacy Archive\(^{16}\) (HLA) and Post Basic Calibrated Data (pbcd) SST images (with ~0.6 arcsec pixel\(^{-1}\)), were aligned to our i-band ALFOSC image (with 0.19 arcsec pixel\(^{-1}\)) obtained on 2015

\(^{14}\) http://archive.stsci.edu/hst/search.php

\(^{15}\) http://sha.ipac.caltech.edu/applications/Spitzer/SHA/

\(^{16}\) http://hla.stsci.edu/
Figure 2. (a) Spectral sequence of PSNJ09+76. The phases are reported to the right and are referred to the $r$-band maximum. ⊗ symbols mark the positions of the strongest telluric absorption bands. (b) Evolution of the $H\alpha$ (left) and $H\beta$ (right) line profiles in velocity space. Vertical dashed lines mark the rest-wavelength position of the two lines. (c) Comparison between the spectra of PSNJ09+76 obtained at the epoch of the $r$-band maximum and those of the SN impostors 2007sv and 1997bs at similar phases. All spectra have been dereddened and redshift corrected, and shifted by an arbitrary constant.

| Date       | Phase | Instrumental Setup | Grism or Grating | Spectral Range (Å) | Resolution (Å) | Exp. Times (s) |
|------------|-------|--------------------|------------------|--------------------|----------------|---------------|
| 2015 Feb 12| −5    | Ekar182+AFOSC      | 2xgm4            | 3400−8200          | 14.4           | 2 × 1800      |
| 2015 Feb 16| 0     | Ekar182+AFOSC      | gm4              | 3400−8200          | 14.4           | 2700          |
| 2015 Feb 23| 6     | NOT+ALFOSC         | gm4              | 3500−9000          | 18.1           | 2400          |
| 2015 Mar 11| 23    | Ekar182+AFOSC      | gm4              | 3400−8200          | 14.4           | 2 × 2700      |
| 2015 Mar 26| 38    | GTC+OSIRIS         | R1000B           | 3600−8000          | 7.0            | 2 × 1800      |
| 2015 Mar 28| 40    | Ekar182+AFOSC      | gm4              | 3400−8200          | 14.4           | 2 × 2700      |
| 2015 May 18| 92    | GTC+OSIRIS         | R1000R           | 5000−10000         | 8.0            | 2 × 1800      |

Note. The phases are relative to the maximum.
May 8. Geometrical alignments were performed using the IRAF task GEOMAP and a maximum of 17 common point-like sources between all sets of images. The errors of the geometric transformations are the rms uncertainties given by GEOMAP, obtaining a precision in the corresponding position of PSNJ09 +76 of $<0.020$.\textsuperscript{17}

We identify a source at the position of the transient (within the transformation errors) in both HST and SST images, although, given the different spatial resolution, the source in the SST images is most likely the blend of multiple sources (see Figure 3). HST magnitudes and errors of the source in the VEGAMAG flight system ($F450W = 24.27 \pm 0.17$ and $F814W = 24.00 \pm 0.18$ mag) were obtained using the DOLPHOT package\textsuperscript{18} (Dolphin 2000). The DOLPHOT output provides also a set of parameters that can be used to interpret the nature of the different sources. The detected source has an "object-type" flag of "1," which means that it is likely stellar. Accounting for the extinction ($A_{F450W} = 0.93$ mag, $A_{F814W} = 0.044$ mag) and distance modulus reported before, we estimate for the progenitor candidate the absolute magnitudes of $-7.71 \pm 0.25$ mag and $-7.95 \pm 0.25$ mag for filters $F450W$ and $F814W$, respectively.

The source magnitudes in the SST images were measured using the spot\textsuperscript{19} package, integrating the flux in a $4 \times 4$ pixel area around the position of the progenitor, which included the whole extended source seen in Figure 3 (bottom right panel). We obtained $3.1 \times 10^{-19}$ and $1.7 \times 10^{-19}$, $3.0 \times 10^{-19}$ and $0.8 \times 10^{-19}$, $2.7 \times 10^{-19}$ and $1.4 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, resulting in the approximate magnitudes of 18.3 and 18.0 mag, 18.3 and 18.8 mag, 18.5 and 18.2 mag in channels 1 and 2 from the images obtained with SST on 2009 December 2, 2010 April 12, and 2014 January 2, respectively. As we can see, there is no clear evidence of an excess of emission (e.g., due to dust formation) between 2009 and 2014 at 3.6 µm, but some variability is perceptible at 4.5 µm. However, we note that the resulting magnitudes are likely due to the contribution of multiple sources in the vicinity of the progenitor.

\textsuperscript{17} We obtained the following transformation uncertainties: $(x, y) = 0\farcs013, 0\farcs018$ (11 stars used) and $(x, y) = 0\farcs019, 0\farcs020$ (15 stars used) in the $F450W$ and $F814W$ images, respectively, $(x, y) = 0\farcs066, 0\farcs072$ (16 stars), $(x, y) = 0\farcs047, 0\farcs084$ (16 stars), $(x, y) = 0\farcs078, 0\farcs080$ (17 stars), $(x, y) = 0\farcs066, 0\farcs072$ (16 stars), and $(x, y) = 0\farcs078, 0\farcs034$ (12 stars), $(x, y) = 0\farcs072, 0\farcs090$ (15 stars) for the channel 1 and 2 of images obtained with SST on 2009 December 2, 2010 April 12, and 2014 January 2, respectively.

\textsuperscript{18} http://americano.dolphinsim.com/dolphot/. We used the WFPC2 Module, v.2.0 (updated in 2014 November).

\textsuperscript{19} http://ssc.spitzer.caltech.edu/warmmission/propkit/spot/
6. DISCUSSION AND CONCLUSIONS

In this Letter, we have discussed the outcomes of our photometric and spectroscopic monitoring of the optical transient PSNJ09+76. Its $r$-band absolute magnitude at peak ($M_r = -13.60 \pm 0.19$ mag) is consistent with that expected during giant eruptions of massive stars. In Figures 1(b) and (c), we have shown that the light curves of these transients may differ in terms of absolute magnitudes and color evolutions.

At all phases, the spectra of PSNJ09+76 are characterized by prominent Balmer lines showing sharp and narrow P-Cygni profiles. In our +39 day and +92 day best-resolution spectra, we notice two components in absorption in the Hα profile. Multiple absorptions were also reported in a moderate-resolution spectrum of PSNJ09+76 obtained by Humphreys & Gordon (2015) around maximum. The clear detection of two absorption components suggests the presence of two expanding shells moving at different velocities (namely, $\sim1000$ km s$^{-1}$ and $\sim340$–$450$ km s$^{-1}$). The velocity inferred for the slower component is comparable with the FWHM velocity of the narrow emission component visible in both +39 day and +92 day spectra. This shell, initially photo-ionized, quickly recombines and contributes to a large fraction of the narrow Hα flux. The higher-velocity component is likely due to the presence of a further shell, moving at a higher velocity. The absence (or weakness) of the emission component is indicative that this shell is likely outer. Despite the lack of any evidence of shell–shell collision from our data of PSNJ09+76, we speculate that one of the shells may have been expelled in past outbursts.

The analysis of deep pre-outburst archival images obtained with HST and SST revealed the presence of a source at the position of PSNJ09+76 (within the errors of our relative astrometry). In order to better constrain the nature of the candidate progenitor, we estimated the oxygen abundance at the position of the source following Hakobyan et al. (2009) and the prescriptions of Tremonti et al. (2004) and Pilyugin et al. (2004; see also Pastorello et al. 2015 for more details), which resulted in $12 + \log(O/H) \approx 8.59$ dex. This value is very close to the solar abundance, $8.69 \pm 0.05$ dex (Asplund et al. 2009). However, following Smartt et al. (2009), who sets $12 + \log(O/H) = 8.4$ dex as the dividing line between solar and subsolar metallicity evolutionary tracks, we conclude that the environment of PSNJ09+76 is likely at solar metallicity.

The comparison of the observed photometry with ATLAS synthetic spectra (Castelli & Kurucz 2004) suggests an effective temperature of the quiescent progenitor of $\sim7250$ K (Figure 4), resulting in a luminosity of $\log(L/L_{\odot}) \approx 5$ (with a bolometric correction derived from the synthetic spectrum of $-0.012$ mag). These values of color and luminosity of the recovered precursor candidate suggest a progenitor mass in the range 18–20 $M_{\odot}$ (see Figure 4). Thus, the progenitor candidate of PSNJ09+76 is likely a moderate-mass white–yellow supergiant, possibly an A-F-type star.

Similar results were also obtained by Kankare et al. (2015) and Smith et al. (2010), who found moderate-mass progenitors ($M \lesssim 20 M_{\odot}$) for SNhunt248 and UGC 2773-OT, respectively. The implication from these observational constraints is that not only extremely massive stars can experience large outbursts and hence produce SN impostors.

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20 http://www.stsci.edu/hst/observatory/crds/castelli_kurucz_atlas.html
by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. The Swift analysis software is part of HEASoft (the High Energy Astrophysics Software), which encompasses FTOOLS and XANADU (i.e., XSPEC, XRONOS and XIMAGE for spectral, timing and image analysis respectively). IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Associated Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation. DOLPHOT is a stellar photometry package adapted from HSTPHOT for general use.

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