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Cartier, R.; Chen, Ping; Dong, Subo; Dyrbye, S.; Elias-Rosa, N.; Flörs, A.; Fraser, M.; Geier,
S.; Goranskij, V. P.; Kann, D. A.; Kuncarayakti, H.; Onori, F.; Reguitti, A.; Reynolds, T.;
Losada, I. R.; Sagués Carracedo, A.; Schweyer, T.; Smartt, S. J.; Tatarnikov, A. M.; Valeev,
A. F.; Vogl, C.; Wevers, T.; De Ugarte Postigo, A.; Izzo, L.; Inserra, C.; Kankare, E.; Maguire,
K.; Smith, K. W.; Stalder, B.; Tartaglia, L.; Thöne, C. C.; Valerin, G.; Young, D. R.

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*Published in:*
Astronomy and Astrophysics

*DOI:*
10.1051/0004-6361/201935511

*Published: 01/01/2019*

*Document Version*
Publisher's PDF, also known as Version of record

*Please cite the original version:*
https://doi.org/10.1051/0004-6361/201935511

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The evolution of luminous red nova AT 2017jfs in NGC 4470*  


(Affiliations can be found after the references)

Received 21 March 2019 / Accepted 23 April 2019

ABSTRACT

We present the results of our photometric and spectroscopic follow-up of the intermediate-luminosity optical transient AT 2017jfs. At peak, the object reaches an absolute magnitude of $M_V = -15.46 \pm 0.15$ mag and a bolometric luminosity of $5.5 \times 10^{41}$ erg s$^{-1}$. Its light curve has the double-peak shape typical of luminous red novae (LRNe), with a narrow first peak bright in the blue bands, while the second peak is longer-lasting and more luminous in the red and near-infrared (NIR) bands. During the first peak, the spectrum shows a blue continuum with narrow emission lines of H and Fe II. During the second peak, the spectrum becomes cooler, resembling that of a K-type star, and the emission lines are replaced by a forest of narrow lines in absorption. About 5 months later, while the optical light curves are characterized by a fast linear decline, the NIR ones show a moderate rebrightening, observed until the transient disappears in solar conjunction. At these late epochs, the spectrum becomes reminiscent of that of M-type stars, with prominent molecular absorption bands. The late-time properties suggest the formation of some dust in the expanding envelope or an IR echo from foreground pre-existing dust. We propose that the object is a common-envelope transient, possibly the outcome of a merging event in a massive binary, similar to NGC 4490–2011OT1.


1. Introduction

Red Novae (RNe) form a family of optical transients spanning an enormous range of luminosities. This includes faint objects with absolute peak magnitudes $M_V$ from $-4$ to $-6.5$ mag, such as OGLE 2002-BLG-360 (Tyłenda et al. 2013) and V1309 Sco (Mason et al. 2010; Tyłenda et al. 2011), intermediate-luminosity events ($M_V \approx -10$ mag) like V838 Mon (Munari et al. 2002; Goranskij et al. 2002; Kimeswenger et al. 2002; Crause et al. 2003), and relatively luminous objects such as NGC 4490–2011OT1 (Smith et al. 2016), that can reach $M_V = -15$ mag. Objects brighter than $M_V = -10$ mag are conventionally named luminous red novae (LRNe; for a review, see Pastorello et al. 2016, and references therein).

Although the physical processes triggering these outbursts have been debated, there is growing evidence that RNe and their more luminous counterparts are produced by the coalescence of stars with different masses following a common-envelope phase (e.g., Kochanek et al. 2014; Pejcha et al. 2016, 2017; MacLeod et al. 2017, 2018). In particular, the inspiralling motion of the secondary was revealed by the long-term monitoring of V1309 Sco (Tyłenda et al. 2011).

* Table A.1 is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/625/L8

1 The alternative naming “luminous red variable” was also used in the past (e.g., Martini et al. 1999).

The recent discovery of LRNe suggests that common-envelope ejections and/or merging events may also happen in more massive close binary systems (Smith et al. 2016; Mauerhan et al. 2018), with major implications for the evolution of the resulting merger. In this context, here we report the results of our follow-up campaign of a LRN recently discovered in the galaxy NGC 4470: AT 2017jfs.

2. AT 2017jfs, its host galaxy, and reddening

AT 2017jfs2 was discovered by Gaia on 2017 December 26.13 UT (MJD = 58113.13, Delgado 2007) at a Gaia G-band magnitude $17.17 \pm 0.20$. No source was detected at the transient position on 2017 November 30 down to a limiting magnitude of 21.5. The transient was located at $\alpha = 12^h 29^m 37^s 79$ and $\delta = +07^\circ 49^\prime 35^\prime\prime 18$ (equinox J2000.0), in the almost face-on, early-type spiral galaxy NGC 4470.

The source was tentatively classified by the extended-Public ESO Spectroscopic Survey for Transient Objects (ePESSTO; Smartt et al. 2015) as a type-IIn supernova (SN IIn) or a SN impostor (Bufano et al. 2018), and for this reason it was designated with a SN name (SN 2017jfs). In this paper, we show it to be a LRN, hence we adopt the label AT 2017jfs.
3. Photometric evolution

The follow-up campaign started soon after the classification of AT 2017jfs, and continued for about 7 months. Photometry data were reduced following standard prescriptions (see, e.g., Cai et al. 2018), using the SNooPy package (Cappellaro 2014). The magnitudes are listed in Table A.1, available at the CDS, which contains the following information: Column 1 lists the date of the observation, Col. 2 lists the MJD, Cols. 3–11 give the optical and near-infrared (NIR) magnitudes, and Col. 12 reports a numeric code for the instrumental configuration. The multi-band light curves are shown in Fig. 1. The Sloan-u light curve shows a monotonic decline after maximum, with an average rate of \(6.5 \pm 0.9\) mag \(100\) d\(^{-1}\). The photometric evolution in the other bands is somewhat different. The g-band maximum is constrained to \(M_{\text{g}} = 58114.8 \pm 1.8\) (2017 December 27.8 UT) through a low-order polynomial fit (at \(g = 17.35 \pm 0.02\) mag, hence \(M_{\text{g}} = -15.46 \pm 0.15\) mag).

The g-band light curve has a rise time to maximum of about 4 d, followed by a rapid decline \((6.5 \pm 0.2\) mag \((100\) d\(^{-1}\)) until \(~50\) d. The light curve follows a plateau-like evolution until \(~100\) d when it begins a faster decline \((7.0 \pm 0.4\) mag \((100\) d\(^{-1}\)) that lasts until it has faded below the detection threshold. The evolution in the Johnson B and V bands is similar to the g band, although the V-band light curve shows a low-contrast second peak, broader than the early one.

The light curve is remarkably different in the red and NIR bands. The transient reaches a peak at \(r = 17.19 \pm 0.05\) mag on MJD \(= 58115.6\), followed by a fast decline \((6.3 \pm 0.3\) mag \((100\) d\(^{-1}\)) lasting three weeks and reaching a minimum at \(r = 18.32 \pm 0.07\) mag. Subsequently, from about \(50\) d after maximum, the r-band luminosity rises again and reaches a second maximum on MJD \(= 58209.0\), at \(r = 17.68 \pm 0.03\) mag. This second peak is much broader than the early one. Later on, from \(110\) to \(200\) d after the first peak, the r-band light curve declines with a rate of \(3.90 \pm 0.04\) mag \((100\) d\(^{-1}\)). The ir-band light curve is very similar to the two, with a broadening of profile until \(60\) d.

The NIR light curves have a second maximum, brighter than the early one. As an additional feature, GROND (Greiner et al. 2008) observations reveal a moderate rebrightening of the NIR light curves from \(~170\) to \(220\) d. Although we do not have very late spectroscopic observations to support this (Sect. 4), a late-time NIR luminosity excess can be associated with the formation of new dust or IR echoes, occasionally observed in LRNe at late phases (see, e.g., Banerjee et al. 2015; Exter 2016). The late NIR brightening may also be a consequence of the transition to the brown (L-type) supergiant stage, as happened for V838 Mon (Evans et al. 2003; Munari et al. 2007), although this scenario does not comfortably explain the late blue-shift of the H\(\alpha\) emission observed in the late spectra of AT 2017jfs (see Sect. 4).

4. Spectral evolution

We collected 14 epochs of optical spectroscopy, spanning about six months of the evolution of AT 2017jfs. Information on the instrumental configurations is given in Table A.2. Our spectral sequence of AT 2017jfs is presented in Fig. 2, while the comparison with a few LRNe at similar epochs and the line identification are shown in Fig. 3. We remark that the transient lies in a crowded region of NGC 4470, rich in nearby sources. As a consequence, the late spectra show some contamination from host galaxy lines.

The spectral evolution of AT 2017jfs follows a three-phase behavior, as observed in other extra-galactic LRNe. In particular, we note a remarkable similarity with NGC 4490-2011OT1 (Smith et al. 2016; Pastorello et al. 2019) at all phases. At early epochs (until \(3\)–\(4\) weeks after the first \(g\)-band peak) the spectrum of AT 2017jfs shows a blue continuum, dominated by prominent H lines in emission, with a mean FWHM of \(~50\) km s\(^{-1}\), and an half maximum velocity \(v_{\text{FWHM}} \sim 700\) km s\(^{-1}\) (corrected for spectral resolution). In this period, the temperature inferred from a black-body fit to the spectral continuum, \(T_{\text{BB}}\), decreases from about \(7800 \pm 700\) K (in the +9.5 d spectrum) to \(6000 \pm 600\) K (in the +23.4 d spectrum). Emission lines from a number of Fe II multiplets are also detected, along with O I. The Ca II NIR triplet is also identified in emission, while the H&K feature, which is usually prominent in absorption in other LRNe (see Fig. 3, top panel), is marginally detected in AT 2017jfs.

With time, the continuum becomes redder and the spectrum experiences an evident metamorphosis. During the second peak, from \(~50\) to \(~4\) months, the red spectrum (\(T_{\text{bb}} = 4300 \pm 700\) K at \(82.3\) d) is dominated by a forest of metal lines in absorption.

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3 https://ned.ipac.caltech.edu/
The H lines become much weaker, showing now a P Cygni profile (see Fig. 2, left panel), although an over-subtraction of the unresolved Hα at the same phases as the left panels (after correcting for the host galaxy redshift $z = 0.007809$ as reported in NED). Only the highest-S/N spectra are shown. The absorptions visible at velocities 0 and $+1000 \, \text{km s}^{-1}$ in late spectra can be partly due to an over-subtraction of the unresolved Hα and [NII] $\lambda 6583$ from the host galaxy background.

From about 5 months after maximum (hence during the steep, late luminosity decline; see Sect. 3), the spectrum changes again, becoming much redder ($T_{\text{bol}} \approx 2950 \pm 150 \, \text{K at 157 d}$) and closer to that of a M-type star. Hα is now mostly in emission, with an evident blue-shift of its peak (by about $400 \, \text{km s}^{-1}$; see Fig. 2, right), and a deep absorption at the rest velocity. While an over-subtraction of the contaminant H II lines deduced from the wavelengths of absorptions is about $450 \, \text{km s}^{-1}$, some of the absorption lines visible at this stage are likely due to neutral metals, in particular Fe I at red wavelengths.

As observed in similar transients (e.g., Pastorello et al. 2019), the late-time spectrum is also characterized by broad absorption bands. The features are generally identified as being due to molecules, in particular TiO and VO, although CN and CaH are not ruled out (see Fig. 3, top panel).

5. Evolution of the temperature and the radius

The double-peaked light-curve evolution and the major spectroscopic transition from an SN IIn-like spectrum to that of a late-type star are two remarkable properties of LRNe (Pastorello et al. 2019). The photometric information in particular can be used to study how the spectral energy distribution (SED), the effective temperature, and the photospheric radius evolve with time.

To this aim, the SED is computed for a few representative epochs, and the observed data are fitted by a single black-body model to the fluxes in the blue optical bands. The resulting black-body fits are shown in Fig. 4 (left panel). The double-peaked light-curve evolution and the major spectroscopic transition from an SN IIn-like spectrum to that of a late-type star are two remarkable properties of LRNe (Pastorello et al. 2019). The photometric information in particular can be used to study how the spectral energy distribution (SED), the effective temperature, and the photospheric radius evolve with time.

To this aim, the SED is computed for a few representative epochs, and the observed data are fitted by a single black-body model to the fluxes in the blue optical bands. The resulting black-body fits are shown in Fig. 4 (left panel).
the bolometric luminosity of the blue peak in AT 2017jfs is twice that of the red peak. This is a major difference with NGC 4490–2011OT1, where the red peak was twice as luminous as the early blue peak (see Pastorello et al. 2019, their Fig. 11). This discrepancy is likely a consequence of the large UV contribution during the blue peak that was not accounted for in the pseudo-bolometric light curve of NGC 4490–2011OT1.

Using the Stefan-Boltzmann law, with the luminosities and temperatures estimated above, we infer the evolution of the radius at the photosphere for AT 2017jfs (Fig. 4, bottom-right panel). The radius $R$ at blue peak slightly exceeds $5 \times 10^4$ cm ($R \approx 7700 R_\odot$). After a modest decline, the radius rapidly increases reaching ~$19000 R_\odot$ at about 80 d, and then remains roughly constant until ~6 months. During the last month of the monitoring campaign of AT 2017jfs, we observe a further fast increase in the photospheric radius, which exceeds $33000 R_\odot$ at 215 d. This rise in the photospheric radius and the dramatic decline of the effective temperature at very late phases favor the generation of new dust, like in RN V838 Mon (Bond 2003). This is also consistent with the blueshift of the Hα emission shown in Fig. 2 (left).

6. Discussion and conclusions

Pastorello et al. (2019) presented optical data for a wide sample of extra-galactic LRNe, all of them showing double-peaked light curves with maximum absolute magnitudes $M_V$ in the range $-12.5$ to $-15$ mag. They discuss the observational similarity of LRNe with fainter ($M_V > -10$ mag) RN discovered in the Milky Way, and agree with Kochanek et al. (2014) and Smith et al. (2016) that all these transients are explained in a similar binary-interaction framework. Most likely, they result from stellar merging events that occurred after the ejection of the common envelope. Lipunov et al. (2017) and MacLeod et al. (2017) discuss the structured light curves of LRNe. A plausible scenario for the double-peak light curve of AT 2017jfs invokes an initial mass outflow as a consequence of the merging event, followed by a later interaction with the common envelope. This would produce the first luminosity peak and the spectra resembling those of type-IIn SNe. During the second peak, the photospheric radius ($\sim 2 \times 10^5 R_\odot$) is likely coincident with that of the ejected common envelope. With the temperature decline, the H recombines, and the released radiation determines the broad red maximum. According to Metzger & Pejcha (2017), the double-peak light curve of LRNe is explained with a modest mass ejection following the coalescence, with the early peak being due to the release of thermal energy from the fast ejecta in free expansion along the polar axes. The late red peak would result from shock-powered emission in the collision between the fast shell and pre-existing material in the equatorial plane. This would also generate a cool dense shell, which is an ideal site for late dust formation, as likely observed in AT 2017jfs. Barsukova et al. (2014) provided a somewhat different interpretation. The rapid coalescence generates a violent forward shock which leads the photospheric temperature to largely increase, producing the blue light curve peak. This phase is followed by the fast adiabatic expansion of the envelope with thermal energy carried out with some delay to the outer layers producing the broad red maximum.

Kochanek et al. (2014) proposed that the wide range of peak luminosities observed in RN/LRN events (over 4 orders of magnitudes in luminosity) is tightly connected with the total mass of the binary system, with faint RN having progenitor systems of the order of $1 M_\odot$ and intermediate-luminosity events like V838 Mon of $\leq 10 M_\odot$. Luminous transients such as AT 2017jfs,
Due to the limited number of objects discovered so far and incomplete data sets, RNe/LRNe are still not fully understood. Well-sampled, multi-band light curves extending to longer wavelengths and high-S/N spectra with good resolution are essential tools for improving their characterization. Discovering new LRNe at larger distances and RNe outside the Local Group is crucial for understanding the physics of these objects, and for providing reliable intrinsic rates. These are key objectives of the Large Synoptic Survey Telescope (LSST Science Collaboration 2009) and other future-generation surveys.

Acknowledgements. We thank Rubina Kotak for useful suggestions. YZC is supported by the China Scholarship Council (No. 201606040170). MF is supported by a Royal Society - Science Foundation Ireland University Research Fellowship. NER acknowledges support from the Spanish MICINN grant ESP2017-82674-R and FEDER funds. S.Bose, PC and SD acknowledge Project 11573003 supported by NSFC. This research uses data obtained through the Telescope Access Program (TAP), which has been funded by the National Astronomical Observatories of China, the Chinese Academy of Sciences, and the Special Fund for Astronomy from the Ministry of Finance. S.Benetti is partially supported by PRIN-INAF 2017 “Toward the SKA and CTA era: discovery, localization, and physics of transient sources.” (PI: M. Giroletti). We thank Las Cumbres Observatory and Evottoh Lorand University (ELTE) for their continued support of ASAS-SN. ASAS-SN is supported by the Gordon and Betty Moore Foundation through grant GBMF5490 to the Ohio State University and NSF grant AST-1515927. Development of ASAS-SN has been supported by NSF grant AST-0908086, the Mt. Cuba Astronomical Foundation, the Center for Cosmology and AstroParticle Physics at the Ohio State University, the Chinese Academy of Sciences South America Center for Astronomy (CAS-SACA), the Villum Foundation, and George Skestos.

References
### Appendix A: Additional data

#### Table A.2. General information on the spectra of AT 2017jfs.

<table>
<thead>
<tr>
<th>Date</th>
<th>MJD</th>
<th>Phase (days)</th>
<th>Instrumental configuration</th>
<th>Exptime (s)</th>
<th>Res (Å)</th>
<th>Range (Å)</th>
</tr>
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<td>58124.31</td>
<td>+9.5</td>
<td>NTT+EFOSC2+gm13</td>
<td>600</td>
<td>18</td>
<td>3650–9200</td>
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<tr>
<td>2018 Jan 10</td>
<td>58128.26</td>
<td>+13.5</td>
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<td>3600</td>
<td>18</td>
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</tr>
<tr>
<td>2018 Jan 17</td>
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<td>3350–7450</td>
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<td>7.8</td>
<td>5100–9250</td>
</tr>
</tbody>
</table>

**Notes.** The phases are from the $g$-band maximum. NTT = 3.58 m New Technology Telescope (ESO-La Silla, Chile); NOT = 2.56 m Nordic Optical Telescope (La Palma, Canary Islands, Spain); P200 = 5.1 m (200-inch) Hale Telescope (Mt. Palomar, California, USA); GTC = 10.4 m Gran Telescopio Canarias (La Palma, Canary Islands, Spain); BTA = 6.05 m Bolshoi Teleskop Alt-azimutalnyi (Special Astrophysical Observatory, Karachay-Cherkessian Republic, Russia).