LSQ14efd: observations of the cooling of a shock break-out event in a type Ic Supernova

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ABSTRACT

We present the photometric and spectroscopic evolution of the type Ic supernova LSQ14efd, discovered by the La Silla QUEST survey and followed by PESSTO. LSQ14efd was discovered few days after explosion and the observations cover up to ∼100 d. The early photometric points show the signature of the cooling of the shock break-out event experienced by the progenitor at the time of the supernova explosion, one of the first for a type Ic supernova. A comparison with type Ic supernova spectra shows that LSQ14efd is quite similar to the type Ic SN 2004aw. These two supernovae have kinetic energies that are intermediate between standard Ic explosions and those which are the most energetic explosions known (e.g. SN 1998bw). We computed an analytical model for the light-curve peak and estimated the mass of the ejecta $6.3 \pm 0.5 M_\odot$, a synthesized nickel mass of $0.25 M_\odot$ and a kinetic energy of $E_{\text{kin}} = 5.6 \pm 0.5 \times 10^{51}$ erg. No connection between LSQ14efd and a gamma-ray burst event could be established. However we point out that the supernova shows some spectroscopic similarities with the peculiar SN-Ia 1999ac and the SN-Iax SN 2008A. A core-collapse origin is most probable considering the spectroscopic, photometric evolution and the detection of the cooling of the shock breakout.

Key words: supernovae: general – supernovae: individual: LSQ14efd.
1 INTRODUCTION

Supernovae (SNe) without hydrogen lines in their spectra are classified into two main types: SNe-Ia and SNe-Ib/c (see Filippenko 1997 for a review). SNe-Ia originate from thermonuclear explosions of a carbon-oxygen white dwarf (CO-WD) reaching the Chandrasekhar mass. Two main channels for the origin of type Ia SNe have been proposed: a single degenerate scenario where the CO-WD in a binary system accretes matter from a companion star (Wheeler & Hansen 1971; Whelan & Iben 1973); and a double degenerate scenario for which the SN is the result of a merging of two close WDs after orbital shrinking (Tutukov & Yungelson 1979; Iben & Tutukov 1984; Webbink 1984). A third channel has been recently proposed by Katz & Dong (2012) for which, in a WD triple system, the WDs approach each other and the collision is likely to detonate the WDs leading to a type Ia SN. However, the detailed physics of the explosion are poorly understood and several models have been presented, from the supersonic detonation to the subsonic deflagration (Hillebrandt & Niemeyer 2000). In the last years, several peculiar SNe-Ia were discovered (e.g. Li, Filippenko & Riess 2001; Valenti et al. 2014), suggesting the existence of a variety of explosion mechanisms and/or progenitor systems (e.g. Mannucci, Della Valle & Panagia 2006). Very bright objects, with a luminosity of $\sim 40$ per cent brighter than normal SN-Ia have been observed and are considered to be ‘super-Chandrasekhar’ explosions (Howell et al. 2006; Scalzo et al. 2010; Silverman et al. 2011; Taubenberger et al. 2011). At the other extreme very faint events show unusual observational signatures (e.g. Turatto et al. 1996; Foley et al. 2009; Kasliwal et al. 2010; Perets et al. 2010; Sullivan et al. 2011). A new explosion model was proposed for a particular sub-class of these sub-luminous SNe events that exhibit similarities to SN 2002cx (Li et al. 2003), called type Iax SNe (e.g. 2005hk Phillips et al. 2007; 2008A Foley et al. 2013), which originate from the deflagration of a CO-WD that accretes matter from a companion He star.

Type Ib/c SNe originate from the gravitational collapse of a massive star for which the iron core cannot be supported by any further nuclear fusion reaction or by electron degenerate pressure, hence collapsing into a neutron star or a black hole. They can be divided into two classes: SN-Ib which shows He lines in their spectra and SN-Ic which do not. Two main scenarios are considered for the progenitors of type Ib/c SNe (see reviews by Woosley & Bloom 2006 and Smartt 2009): a single massive Wolf–Rayet (WR) star which has lost its hydrogen envelope, before the collapse of the core, through stellar winds or a binary system (see Panagia & Laidler 1991 for an early suggestion) where the progenitor star loses its H (and He, in the case of SN-Ic) envelope through tidal stripping from the companion star. The measured masses of the ejecta seem to favour the majority being relatively lower mass binary stars, rather than very massive single WR stars (Elridge et al. 2013; Cano et al. 2014; Lyman et al. 2016) and the data for iPTF13bnv seems to be more consistent with a binary system (Bersten et al. 2014; Fremling et al. 2014; Elridge et al. 2015).

Unlike SNe-IIP and IIIb, the progenitors have not been commonly identified in pre-explosion images (see Eldridge et al. 2013; Smartt 2015). One probable detection exists for the progenitor of a Ib SN: namely iPTF13bvn by Cao et al. (2013), which has been studied further by Groh, Georgy & Ekström (2013); Bersten et al. (2014); Eldridge et al. (2015) and Fremling et al. (2014).

Almost two decades of observations have allowed us to divide the SN-Ic population into two sub-classes: standard SNe-Ic, characterized by kinetic energies of $E_{k} \sim 10^{51}$ erg and broad-line (BL), with ejecta velocities of order $\sim 0.1c$ which therefore implies significantly higher kinetic energy ($E_{k} \sim 10^{52}$ erg, e.g. Nakamura et al. 2001). Some high energy, SNe-Ic-BL have been convincingly linked to gamma-ray bursts (GRB; see Kovacevic et al. 2014 for an updated census of GRB-SNe), while the majority of SNe-Ic are not associated with GRBs (e.g. the ratio GRB/SN Ib/c is $< 3$ per cent, Guetta & Della Valle 2007). Some SNe-Ic, such as SN 2004aw (Taubenberger et al. 2006) and SN 2003jd (Valenti et al. 2008a) show physical properties in between those of standard Ic events and SNe-Ic-BL, therefore suggesting the existence of a wide diversity in SNe-Ic in terms of expansion velocity of the ejecta, peak luminosity and kinetic energy (Elmhamdi et al. 2006; Modjaz et al. 2015). In this scenario, it is not clear if the broad variety of observed SNe-Ic and SNe-Ic-BL is due to different sub-classes of SNe-Ic originating from different classes of progenitors or if it is representative of an existing continuum of properties among the different SN-Ic types (Della Valle 2011; Modjaz et al. 2014 Prentice et al. 2016).

The large fraction of peculiar objects, for both SN-Ia and Ic classes, which are now being found has led to cases of ambiguity in determining the physical origin of these hydrogen and helium poor objects. In many cases the physical origin in a thermonuclear or core-collapse explosion is debated e.g. SN 2002bj (Poznanski 2010); SN 2004rc (Rafaja, Fox & Gal-Yam 2004; Rafaja et al. 2005; Leaman et al. 2011) and SN 2006P (Serduke et al. 2006; Leaman et al. 2011; Li et al. 2011). Usually the photometric analysis does not solve the ambiguity that can arise from the early spectroscopy, for example Cappellaro et al. (2015) found a $\sim 40$ per cent difference in the classifications of SN-Ib/c classification using Photometric Supernova Identifier (PSNID) within the SUDARE survey.

Nebular spectra may help, in revealing nucleosynthetic products in the interior part of the star, which are very different in the two mechanisms but it is possible to observe them only for the brightest and nearest sources.

In some cases, early photometric observations may be able to detect the cooling of the shock break-outs which can constrain the progenitor system. One of the main signatures of core-collapse SNe (CC-SNe) is represented by the early emission of X-ray and/or ultraviolet radiation which traces the break-out of the SN shock-wave through the stellar photosphere. After the envelope of the star has been shock heated, it starts cooling and creates an early peak in the optical passband. This event represents the initial stages of a SN event and it typically shows very short duration, from minutes to hours, which makes the detection difficult and has resulted in the number of observed cooling of the shock break-outs being few in number (e.g. SN 1987A, Arnett et al. 1989; SN 1993J, Lewis et al. 1994; SN 2006aj, Campana et al. 2006; SN 2008D, Mazzali et al. 2008; Soderberg et al. 2008 and SN 2011dh Arcavi et al. 2011). This early emission can be interpreted also as an extended envelope or due to outwardly mixed $^{56}$Ni as investigated for the peculiar type Ib/c SN 2013ge (Drout et al. 2016).

The cooling of the shock break-out in a type Ia SN explosion in a WD is too dim and fast to be detectable for extragalactic events (Nakar & Sari 2012; Rabinak, Livne & Waxman 2012), but an early ultraviolet (UV) excess in type Ia SNe is predicted for certain binary progenitor systems. Kasen (2010) shows that the collision between the SN ejecta and its companion star should produce detectable radiative diffusion from deeper layers of shock-heated ejecta causing a longer lasting optical/UV emission, which exceeds the radioactively powered luminosity of the SN for the first few days after the explosion.

Here we present an extensive data set for LSQ14efd which was discovered by the La Silla QUEST (LSQ) survey (Baltay et al. 2014). Some recent cases, such as LSQ14efg (Vreeswijk et al. 2015) and LSQ14fbd (Eldridge et al. 2015), have been studied using Photometric Supernova Identifier (PSNID) in order to constrain the progenitor by comparing the early optical spectra to templates.

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et al. 2013), and monitored by the Public ESO Spectroscopic Survey of Transient Object (PESSTO; Smartt et al. 2015).\textsuperscript{1} Our analysis suggests that LSQ14efd is most similar to SN 2004aw which was originally classified as type Ia SN and re-classified as a type Ic after a long-term followup. We show a detection of the cooling envelope emission after the shock break-out. The photometric and spectroscopic analysis of LSQ14efd shows this is a SN-Ic. However, LSQ14efd shows some ambiguities in its spectroscopic classification with similarities to SNe Iax such as SN 2008A. LSQ14efd is also an interesting object because it shows intermediate properties between ‘standard’ and very energetic SNe-Ic events.

This paper is organized as follows: in Section 2 we present the discovery and the classification of LSQ14efd and we discuss the properties of the host galaxy, the distance and the extinction; in Section 3 we present the optical photometric evolution of LSQ14efd and compare its colour evolution and bolometric light curve with those of other Type Ic and Ia SNe. In Section 4, we present the optical spectroscopic observations and comparison with other SNe. In Section 5, we model the light-curve peak to estimate the main physical parameters of the explosion such as ejected mass, kinetic energy and nickel mass. In Section 6, we summarize our discussion and present our conclusions.

2 DISCOVERY AND HOST GALAXY
LSQ14efd was discovered in an anonymous galaxy on 2014 August 17 UT (MJD = 56 886.81) at the coordinates RA = 03h35m38.74 and Dec. = −58°52′38.3′′. After the discovery, all images from LSQ archive were checked and we found the SN was already visible on the image of August 13, but not in images from August 09, with both images having the same depth. We thus consider the explosion date as August 11 with an uncertainty of 2 d. On 2014 August 18, Tartaglia et al. (2014a) classified LSQ14efd as a Type II SN with an unknown phase, as part of PESSTO. Due to the poor signal to noise (S/N) of the first spectrum, new observations were performed the day after and LSQ14efd was re-classified as a Type Ic SN around maximum (Tartaglia et al. 2014b). They also reported that the best match of the spectrum of this transient was obtained with the peculiar Type Ic SN 2003jd. LSQ14efd is located in an outer region of the host galaxy (see Fig. 1). The distance to the galaxy is not available in the literature. The 2D spectroscopic frames shows the presence of the host galaxy spectrum for which it was possible to identify the H α emission, at a redshift of z = 0.0672 ± 0.0001. Assuming H_0 = 70 km s^{-1} Mpc^{-1}, we then calculate a distance modulus of μ = 37.35 ± 0.03 mag. The Galactic reddening towards LSQ14efd is estimated from Schlegel, Finkbeiner & Davis (1998) to be E(B−V) = 0.0376 ± 0.0015 mag. We considered the internal reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening of the host galaxy as negligible since there is no clear evidence of NaID absorption in the spectra nor significant reddening.

Assuming a Cardelli, Clayton & Mathis (1989) reddening law (R_V = 3.1) we estimate the total V-band extinction towards LSQ14efd to be A_V = 0.12 mag.

2.1 Search for an associated GRB
We have investigated the possibility that LSQ14efd could be related with a GRB event. We have examined the Fermi Gamma-ray Burst Monitor\textsuperscript{2} (GBM; von Kienlin et al. 2014) and the Swift\textsuperscript{3} (Lien et al. 2016) catalogues in a period of time < 20 d from the occurrence of the SN event. The time interval was chosen since it corresponds to the threshold of ≥ 95 per cent confidence level for the association between GRB and type Ib/c SNe (Kovacevic et al. 2014). In this range of time, we found three detections, but none of them were spatially coincident, within the errorbox of the GRB detection, with the SN position. Hence, no association can be found between LSQ14efd and a GRB event.

3 PHOTOMETRIC EVOLUTION

3.1 Data sample and reduction
A photometric monitoring campaign for LSQ14efd, at optical wavelengths, was conducted over a period of 100 d post-discovery, covering 40 epochs, using multiple observing facilities.

The BVRI Johnson-Cousins data were collected with: the 1m from Las Cumbres Observatory Global Telescope Network (LCOGT, Siding Spring, Australia) equipped with the SBIG Camera (BV, 10 epochs); the 1m from LCOGT (South African Astronomical Observatory, South Africa) equipped with the SBIG Camera (BV, 7 epochs); the 1m from LCOGT (Cerro Tololo, Chile) equipped with the Sinistro Camera (BV, 3 epochs); the 3.58 m European Southern Observatory (ESO) New Technology Telescope (NTT, La Silla, Chile) equipped with the ESO Faint Object and Spectrograph Camera (EFOSC2) camera (BVRI, 3 epochs); the 1m Schmidt telescope (La Silla, Chile) equipped with the QUEST camera (V, 10 epochs) 0.6 m ESO TRANsiting Planets and PlanetesImals Small Telescope (TRAPPIST, La Silla, Chile) equipped with TRAPPIST-CAM (VRI, 6 epochs).

g′r′i′ images were collected with: the 1m from LCOGT (Siding Spring, Australia) equipped with the SBIG Camera (BV, 10 epochs);

![Figure 1. An image of LSQ14efd and the anonymous host galaxy, acquired with the New Technology Telescope and the EFOSC2 camera. The field of view is 4 × 4 arcmin².](image-url)

1 http://www.pessto.org

2 http://gammaray.msfc.nasa.gov/GBM/

3 http://swift.gsfc.nasa.gov/archive/
the 1m from LCOGT (South African Astronomical Observatory, South Africa) equipped with the SBIG Camera \((BV, 7\) epochs) and the 1m from LCOGT (Cerro Tololo, Chile) equipped with the Sinistro Camera \((BV, 3\) epochs). A summary of the telescopes and the instruments characteristics are presented in Table 1.

Table 1. Summary of the characteristics of the instruments used during the photometric follow up.

| Telescope             | Camera     | Pixel scale (arcsec/pix) | Field of view (arcmin) | Filters\(^d\) | # of epochs |
|-----------------------|------------|--------------------------|------------------------|--------------|-------------|
| NTT (3.58 m)          | EFOSC2     | 0.24                     | 4 × 4                  | B, V, R; u, g, r, i | 12          |
| COJ (1 m)             | SBIG       | 0.46                     | 15.8                   | B, V, g, r, i  | 10          |
| CPT (1 m)             | SBIG       | 0.46                     | 15.8                   | B, V, g, r, i  | 7           |
| LSC (1 m)             | Sinistro   | 0.38                     | 26.5 × 26.5            | B, V, g, r, i  | 3           |
| ESO (1 m)             | QUEST      | 0.87                     | 2160 × 2760            | V              | 15          |
| TRAPPIST (0.60 m)     | TRAPPISTCAM| 0.65                     | 27 × 27                | B, V, R       | 4           |

Notes. NTT = New Technology Telescope with the optical camera ESO Faint Object Spectrograph EFOSC2; COJ = 1 m Las Cumbres Observatory Global Telescope (LCOGT) with the SBIG camera, site in Siding Spring Observatory; CPT = 1 m LCOGT with the SBIG camera, site in South African Astronomical Observatory; LSC = 1 m LCOGT with the Sinistro Camera, site in Cerro Tololo; ESO = 1 m Schmidt telescope, site in La Silla Observatory; and TRAPPIST = TRAnsit Plants and PlanetesImals Small Telescope.

\(^d\)The NTT \(i\) filter is Gunn.

The early points in the \(V\) band show an initial decline before the rising of the peak. Fig. 2 shows a 2nd order polynomial fit of the early stage of the \(V\)-band light curve without taking into account the first point. We note that it deviates significantly, \(1\sigma\), from the expected rise. A pre-explosion limit has been calculated from the image of August 09. The estimated limit is 20.6 ± 0.2 mag and it is represented by the arrow in Fig. 2.

We interpret this decline as the cooling that occurs soon after the shock break-out event, similar to that observed in other CC-SNe (e.g. SN 1993J, Lewis et al. 1994; SN 2006aj Campana et al. 2006; SN 2008D, Soderberg et al. 2008; SN 2011dh, Arcavi et al. 2011; iPTF15dtg Taddia et al. 2016), as shown in Fig. 3. A direct comparison of the decline observed in LSQ14efd with CC SNe shows good agreement with the behaviour observed in previous cases where very early photometry exists, in particular there is good relative agreement with SN 2008D and similar also to SNe 1993J and 2006aj (see left-hand panel of Fig. 3). An early UV emission pulse has been predicted also for type Ia SNe which generate from an interactive binary system (Pakmor et al. 2008, Kasen 2010) and it has been observed recently (e.g. SN 2012cg, Silverman et al. 2012; iPTF14atg Cao et al. 2015 and Marion et al. 2015).

We do not have UV data to directly compare the UV excess so we investigated the \(B - V\) colour evolution. We do this to investigate the early phase UV excess. We notice that the \(B - V\) colour evolution of iPTF14atg shows a pre-maximum value around \(-1.5\) and \(-1\) around 10 d and it then sharply increases above 0 around maximum. SN 2012cg shows a different \(B - V\) colour evolution, being constant around 0 until maximum and smoothly reaching a value \(-1\) at 20 d. The LSQ14efd \(B - V\) evolution shows a different behaviour with respect to iPTF14atg, while shows a qualitative similar trend with respect to...
SN 2012cg but redder, since it differs of \~0.5 at all epochs. Instead, the $B - V$ colour evolution of SN 2008D in pre-maximum phases is similar to that of LSQ14efd.

### 3.2.2 Late evolution

The photometric evolution of LSQ14efd in the $BVRI$ and in the $g'r'i'$ filter systems is shown in Fig. 4. The SN was discovered 14 d before maximum in the $B$ band. The epoch of the B-maximum ($\text{MJD} = 56895.72$) was obtained with a polynomial fit performed using the first 20 d of data. All subsequent epochs referred to this work, unless specified, will refer to this date as the epoch zero.

The $B$-band light curve reaches a peak magnitude of $m_B = 19.47$ mag and has a decline rate of $5.61 \pm 0.78$ mag per 100 d, in the interval 5–30 d past B-maximum. This interval was assumed to measure the decline rate also for all other bands. The $V$-band light curve reaches the peak $\sim 5$ d after with a magnitude of $m_V = 18.97$ mag and a decline rate of $4.48 \pm 0.45$ mag per 100 d. In the $R$ band, the light curve peaks around 7 d with a value of $m_R = 18.84$ mag and a decline rate of $3.28 \pm 0.33$ mag per 100 d. In the $I$ band, the light curve peak appears around 8 d with a magnitude of $m_I = 18.66$ mag and a decline rate of $2.28 \pm 0.23$ mag per 100 d. In the $g'$ we see the peak after around 5 d with a magnitude of $m_{g'} = 19.11$ mag and a decline rate of $5.96 \pm 0.72$ mag per 100 d. The $r'$ band shows a peak after $\sim 5$ d with a magnitude of $m_{r'} = 18.87$ mag and a decline rate of $2.78 \pm 0.28$ mag per 100 d. The peak in the $i'$ band appears after around 5 d showing a magnitude of $m_{i'} = 18.96$ mag. The decline rate is $1.64 \pm 0.16$ mag per 100 d. We also note that the blue bands show narrower light curves compared to those of the red bands.

A comparison of the light curves of LSQ14efd with SN 2004aw (Taubenberger et al. 2006) shows that the shift of the maximum in the different bands is compatible, within the errors, with the ones estimated for SN 2004aw, except for the maximum in the $V$ filter, which is reached after $\sim 3$ d for SN 2004aw and after 5 d for LSQ14efd (see Table 3). A comparison of the decline rate, in the range 5–30 d, shows good agreement between the two SNe. However in the $B$ band the decline rate measured for SN 2004aw
The pre-explosion limit is represented with the arrow. is 6.96 ± 0.16 mag per 100 d and 5.61 ± 0.78 mag per 100 d for LSQ14efd (see Fig. 2 in Taubenberger et al. 2006). This decline rate is slower than of SN 1994I which shows a faster evolution and a decline rate of ∼9 mag per 100 d in the B band (Elmhamdi et al. 2006).

As it will be shown later, the spectroscopic evolution of LSQ14efd shows some similarities with type Iax SNe, therefore it is useful to compare its photometric evolution with Iax and peculiar type Ia SNe to determine if there are any similarities. In Fig. 5, we present the absolute I magnitude light curve of LSQ14efd compared with SNe 1999ac (normal Ia), SN 2008A (SN-Iax) and SN 2004aw (SN-Ic as discussed above). LSQ14efd does not show a secondary I-band peak as we see normal SN-Ia and it has a wider peak and a slower post-maximum decline when compared to the type Iax SN 2008A. It bears most similarities with SN 2004aw, although the comparison is qualitative. The measure of the Δm15 for LSQ14efd is reported in Table 3. We have applied the values of Δm15 of the Phillip’s relation (Phillips 1993) for type Ia SNe to LSQ14efd and found an implied $M_B = -19.3 ± 0.3$ mag. This differs by ∼1.26 mag from the measured B-band peak of SN (see Table 3) which implies that LSQ14efd does not satisfy the SN-Ia relation and does not comfortably fit with this physical explanation. We stress that the type Iax SNe also do not satisfy the Phillipps relation.

We then compared the light curves of LSQ14efd with those of a sample of SNe-Ib/c. In particular, the evolution of the light curve in the R and V bands of LSQ14efd was compared with the templates by Drout et al. 2011 (Fig. 6). Those template are the result of the interpolation over the normalized V and R light curve of 10 well-sampled literature SNe-Ib/c. The weighted mean flux density was then extracted over the time interval −20 to 40 d. We notice that the evolution of the V band of LSQ14efd follows the decline post-maximum of the template within 1σ while the pre-maximum evolution differs significantly from the template showing that the light curve of LSQ14efd is broader than the ones in the sample. Instead, the R-band evolution of LSQ14efd follows nicely the template but we note that in the R band we are missing data at early phases when the most significant deviation is observed in the V band.

The dereddened $B - V$, $V - R$, $B - R$ and $B - I$ colour evolution are shown in Fig 7. We measure a $B - V$ colour of 0.4 mag at ∼10 d before B-maximum. It then increases to about 1 mag at ∼5 d and stays more or less constant around this value. The $V - R$ colour increases from ∼0 mag to around 0.5 mag within 15 d after B-maximum and settles at around this value for the subsequent days. The $B - R$ colour steadily increases from ∼0.3 mag to about 1.4 mag within ∼20 d after B-maximum. The $B - I$ colour increases from ∼0.5 mag to around 1.7 mag at ∼20 d after B-maximum.
**Figure 4.** Left-hand panel: photometric evolution of LSQ14efd in the Johnson-Cousins BVRI filters, reported in the Vega magnitude. Right-hand panel: photometric evolution of LSQ14efd in the g’i’′ filters, in the AB magnitude. The pre-explosion limit in the V band is represented with the arrow. Phases refer to the date of explosion. A shift has been applied for clarity.

**Table 3.** Comparison of LSQ14efd some photometric parameters with those of SN 2004aw.

|                         | B        | V        | R        | I        |
|-------------------------|----------|----------|----------|----------|
| Apparent magnitude at maximum | LSQ14efd | 19.47 ± 0.11 | 18.97 ± 0.15 | 18.84 ± 0.19 | 18.66 ± 0.15 |
|                         | SN 2004aw | 18.06 ± 0.04 | 17.30 ± 0.03 | 16.90 ± 0.03 | 16.53 ± 0.03 |
| Absolute magnitude at maximum | LSQ14efd | −18.04 ± 0.18 | −18.50 ± 0.21 | −18.60 ± 0.24 | −18.75 ± 0.21 |
|                         | SN 2004aw | −17.63 ± 0.48 | −18.02 ± 0.39 | −18.14 ± 0.34 | −18.18 ± 0.28 |
| Epoch of maximum | LSQ14efd | 0.0 | +5.0 ± 0.5 | +7.0 ± 0.5 | +8.0 ± 0.6 |
|                         | SN 2004aw | 0.0 | +2.7 ± 0.6 | +6.6 ± 0.6 | +8.9 ± 0.9 |
| Decline rate | LSQ14efd | 5.61 ± 0.78 | 4.48 ± 0.45 | 3.28 ± 0.33 | 2.28 ± 0.23 |
|                         | SN 2004aw | 6.96 ± 0.16 | 4.64 ± 0.12 | 3.20 ± 0.12 | 2.16 ± 0.12 |
| ∆m15 | LSQ14efd | 0.9 ± 0.3 | 0.3 ± 0.1 | 0.1 ± 0.1 | 0.02 ± 0.02 |

The dereddened colour evolution has been compared with those of some type Ic SNe (2004aw, Taubenberger et al. 2006, 2003jd Valenti et al. 2008a, 2007gr Valenti et al. 2008b; Hunter et al. 2009 and 1998bw Patat et al. 2001), to those of some type Ia SNe (1999ac Phillips et al. 2006, 1997br Li et al. 1999) and to those of some type Iax SNe (2008A Foley et al. 2013 and 2005hk Phillips et al. 2007).

The colour evolutions of type Ic SNe are well defined in the B − V, V − R and B − I colours (see Fig. 7, upper panel). In the V − R and B − I evolution we can see that SN 1998bw shows a slightly different trend after ~15 d, with a flattening in the evolution that is shown only ~10 d after in the other SNe of this sample. The trend of the B − R evolution is also quite similar for all the SNe of this sample. We notice that the colour evolution of LSQ14efd is very similar to those of type Ic SNe. They show fairly similar trends in the rising part of curves and they all subsequently flatten to comparable values. The similarity between dereddened colours of LSQ14efd and those of the type Ic comparison sample supports the hypothesis of no extinction within LSQ14efd host galaxy (Section 2).

The B − V, B − R and B − I colour evolutions of type Ia and Iax SNe also show a broadly similar trend. The V − R colour evolution is the most diverse among the objects of the sample (see Fig. 7, lower panel). In V − R, the colour evolution of LSQ14efd is similar to that of SN 2005hk while SN 2008A appears to diverge from the broad trends of the set. The B − V, B − R and B − I colour evolutions of LSQ14efd seems to be bluer at early phases and around maximum with respect to those of SNe 2005hk and 1999ac. In the B − R and B − I colour evolutions we point out that the curves are steeper for Ia and Iax SNe with respect to those of LSQ14efd.

### 3.3 Quasi-bolometric light curve

A quasi-bolometric light curve has been calculated by integrating the observed optical flux over wavelength. The estimated Bg Vr R′ I′ apparent magnitudes were converted into monochromatic fluxes at the effective wavelength for each filter. After correcting for Galactic extinction (Section 2), the resulting spectral energy distribution (SED) has been integrated over the full observed wavelength range, assuming, at limits, a zero flux. The flux was estimated at the phases in which the V band observations were available. For the other bands for which photometry was not available, the magnitudes were calculated by interpolation of the values from the photometry on nearby nights. Finally, using the redshift-based distance of the galaxy (Section 2), the integrated fluxes were converted into luminosity. We note that the first point was excluded when building the quasi-bolometric light curve. The quasi-bolometric light curve of LSQ14efd is shown in Fig. 8 together with some other type Ia and Ic SNe.
The luminosity at the peak is $L = 3.9 \times 10^{42}$ erg s$^{-1}$. This has to be considered as a lower limit since we constructed the quasi-bolometric light curve only across the wavelength limits sampled by the observed filter set, namely the $Bg'Vr'RI$ bands. Lyman, Bersier & James (2014) developed a method to estimate the bolometric correction from data which are limited in wavelength. The value of the peak bolometric luminosity estimated with this method is $L \sim 5 \times 10^{42}$ erg s$^{-1}$.

In Fig 8, we can notice that the post-maximum slope of the light curve of LSQ14efd compares well with those of type Ic SNe 1998bw, 2003jd, iPTF15dtg and 2004aw, while its peak luminosity is intermediate between 2003jd and 2004aw. It is significantly less luminous than the SN-Ic-BL 1998bw, but with a similar width. LSQ14efd shows a different behaviour from type Ic SNe 1994I and 2007gr, being more luminous and showing a broader bolometric curve. Instead, iPTF15dtg has a comparable luminosity with respect to LSQ14efd but is much wider and shows a slower decay. We note that type Ia SN 1999ac shows an evident double peak in the curve, which is not present in the light curves of the other SNe plotted. Also the peak luminosity of type Ia SN 1999ac is much brighter than LSQ14efd. SN-Ia 1997gr has a comparable light-curve shape with respect to LSQ14efd, but it is more luminous at every epoch. The peak luminosity of LSQ14efd is not far from that of the type Iax SN 2008A, but it shows a wider peak and a slower decay. We can conclude from this comparison that the photometric evolution of LSQ14efd is consistent with those of the known population of type Ic SNe but also similar to peculiar type Iax SNe.

4 SPECTROSCOPIC EVOLUTION

4.1 Data sample and reduction

We performed a spectroscopic monitoring campaign of LSQ14efd at the ESO NTT at La Silla, Chile. Eight epochs of optical spectra were acquired with EFOSC2 from 8 d before B-maximum until 37 d after B-maximum. Details of the spectroscopic observations and the characteristics of the employed instrumentation are listed in Table 4.

The pre-reduction of the spectra (trimming, overscan, bias and flat-field correction) was performed using the PESSTO pipeline (Smartt et al. 2015), which is based on the standard IRAF tasks. Comparison spectra of arc lamps, obtained in the same instrumental configuration of the SN observations, were used for the wavelength calibration. Observations of spectrophotometric standard stars were used for the flux calibration. Atmospheric extinction corrections were applied using tabulated extinction coefficients of each telescope site. We note that the data presented and analysed in this paper were custom re-reduced, and differ somewhat from those in
Figure 7. Top panel: colour evolution of LSQ14efd compared to those of SNe-Ic, 2004aw (Taubenberger et al. 2006), 2003jd (Valenti et al. 2008a), 2007gr (Valenti et al. 2008b) and 1998bw (Patat et al. 2001). Bottom panel: colour evolution of LSQ14efd compared to those type Ia SNe, 1999ac (Phillips et al. 2006), 1997br (Li et al. 1999) and type Iax SN 2008A (Foley et al. 2013) and 2005hk (Phillips et al. 2007). Epochs refer to the B-maximum.
Figure 8. Upper panel: Quasi-bolometric light curve of LSQ14efd compared with type Ia SNe 1999ac (Phillips et al. 2006) and 1997br (Li et al. 1999) and with type Iax SN 2008A (McCully et al. 2014). Lower panel: Quasi-bolometric light curve of LSQ14efd compared with type Ic SNe 2007gr (UBVRI, Valenti et al. 2008b), 2004aw (UBVRI, Taubenberger et al. 2006), 1994I (UBVRI, Richmond et al. 1996), 2003jd (BVRI, Valenti et al. 2008a), iPTF15dtg (gri, Taddia et al. 2016) and 1998bw (UBVRI, Patat et al. 2001). Phases are respect to the B-maximum of each SN.

formal public release of the PESSTO Spectral data products. We obtained some better quality results with more tailored and manual reductions, particularly with manual fringing corrections for the fainter spectra. In this case, the reduction of the spectra followed the standard procedure, with particular attention to the flat-field, considering just a few columns (100) next to the target, such to improve the removing of the fringing in the red bands. Also the background has been optimized, considering also an adjacent area, to minimize the contamination of the host galaxy. An example of the difference

5 The spectra will be available on WISEREP public data base (Yaron & Gal-Yam 2012), at http://wiserep.weizmann.ac.il. All other data can be accessed also from the ESO Phase 3 archive, with all details on www.pessto.org

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in the data quality from the manual reduction and the pipeline is shown in Fig. 9.

A comparison of synthetic BV and r photometry obtained from the spectra, through the IRAF task CALCPHOT, with the observed photometry at similar epochs was performed to check the quality of the flux calibration. These spectra were dereddened for the total extinction and corrected for the estimated redshift.

### 4.2 Data analysis

The time evolution of the optical spectra of LSQ14efd, obtained from −8 to 37 d with respect to B-maximum and covering the whole photospheric phase, is shown in Fig. 10. Corresponding line identifications are presented in Fig. 11.

Spectra obtained one week before maximum show a blue continuum with some features due to Fe II lines ($\lambda\lambda 4555, 5169, 5535$). A feature very likely due to the Si II ($\lambda 6355$) appears around phase $-5$. Branch et al. (2002) pointed out the possibility of a misleading identification of the Si II in type Ib and Ic SNe as the Hα line (see also Parrent et al. 2015) at high velocities (or ‘detached hydrogen’). As shown below in this section, the estimated velocities of Si II and Fe II are in agreement, within the errors, which suggests to us that identification as Si II is the more plausible explanation. There is no evidence of narrow interstellar medium NaD absorption in the spectra, leading us to conclude the absorption due to the host galaxy is negligible, or at least not measurable with the data available. During the evolution of the photospheric phase, the spectra obtained close to maximum light show that the intensity of the blue continuum decreases significantly. It’s also possible to see prominent features due to Fe II ($\lambda\lambda 4555, 5169, 5535$) and the Si II line ($\lambda 6355$). A possible feature due to Ca II ($\lambda 8542$) starts to appear. Late spectra show a continuum dominated by the iron-group elements, we find Fe II ($\lambda\lambda 4555, 4924$) and Fe II ($\lambda\lambda 5169, 5535$) while Si II lines ($\lambda 6355$) are still barely visible. There is no evidence of forbidden lines arising in the last spectrum, leading us to conclude that the LSQ14efd is still in the photospheric phase.

A comparison with other type Ic SNe is shown is Fig. 12. The earliest LSQ14efd spectrum resembles the featureless continuum of SNe 2007gr, iPTF15dgt and 2004aw (admittedly having low S/N). The spectrum around B-maximum does not show any major differences with those of SNe 2004aw and iPTF15dgt. SN 2007gr shows a generally good agreement, but with the presence of extra features around 4000 Å and 5000 Å.

The feature at around 8200 Å is possibly due to Ca II, as the comparison with SN 2004aw seems to suggest. At the later stages, about 1 m past maximum, the spectrum of LSQ14efd exhibits similarities with iPTF15dgt, while there is a good agreement with SNe 2007gr and 2004aw, though they exhibit stronger Ca II and O I lines.

Fig. 13 shows the early spectrum of LSQ14efd (a few days before B-maximum) compared with pre-maximum spectra of type Ia SN 1999ac and type Iax SN 2008A. In the blue part of the spectrum, LSQ14efd has lower S/N than that of SNe 1999ac and 2008A, while the rest resembles an almost featureless continuum. The LSQ14efd spectrum around maximum differs, from that of SNe 1999ac and 2008A, mainly in the blue part. The late spectrum of LSQ14efd is again similar to that of SNe 1999ac and 2008A, though the intensity of the Si II feature is weaker for LSQ14efd. A comparison with SNe-Ic and SNe-Ic-BL templates (Modjaz et al. 2014; Liu et al. 2016) remarks a quite good similarity with SNe-Ic for the early spectra, considering the width of the lines present in both, LSQ14efd and the template (Fig. 14). We then note a significant deviation for the late ones since the strength and the width of emission line of LSQ14efd differ from those of the template. A similar comparison of LSQ14efd spectra with the template for SNe-Ic-BL seems to show also a good agreement at all epochs. This strengthens the peculiarity of LSQ14efd.

The ejecta velocities produced by the two different physical explosion mechanisms can be different. For comparison, ejecta velocities can be estimated from a Gaussian fit of the absorption profile of the P-Cygni features (after correction for the redshift of the host galaxy). The uncertainties on the estimated velocities are a result of the error propagation on the uncertainties obtained from the measurement. This was confirmed by several repeated tests. For LSQ14efd, the ~−7 spectrum indicates a Si II velocity of $v_{\text{ej}} \sim 12\,300$ km s$^{-1}$. At maximum, this fit to the same line gives $v_{\text{ej}} \sim 10\,000$ km s$^{-1}$, which decreases to ~8000 km s$^{-1}$ after 10 d. At around 20 d, we measure the Si II velocity to drop to ~5000 km s$^{-1}$ and also estimate the Fe II lines to show an outflow of ~3000 km s$^{-1}$. A comparison with SN 2004aw shows that the Si II velocity, goes from ~12700 km s$^{-1}$ around maximum to ~9300 km s$^{-1}$ after 10 d, which are comparable with those estimated for of LSQ14efd, within the errors. In the same temporal range, the Fe II velocity decreases from ~12000 km s$^{-1}$ to ~8100 km s$^{-1}$. At around 20 d, SN 2004aw shows a Si II velocity of

| Telescope   | Instrument | Grism | Range (Å) | Resolution (Å) | # of epochs |
|-------------|------------|-------|-----------|----------------|-------------|
| NTT (3.58 m)| EFOC2      | Gr13  | 3985–9315 | 18             | 7           |
| NTT (3.58 m)| EFOC2      | Gr11  | 3380–7520 | 12             | 1           |

*Note.* NTT = New Technology Telescope with the optical camera ESO Faint Object Spectrograph and Camera EFOSC2.
~6000 km s\(^{-1}\), in agreement with the value of Si\(\ii\) for LSQ14efd, within the errors.

We then compared the spectroscopic characteristics of LSQ14efd with those observed for sample of SNe-Ic (Modjaz et al. 2015; Liu et al. 2016). In particular, the evolution of the Fe\(\ii\) (5169Å) line velocities of LSQ14efd have been compared with the trends found by Modjaz et al. (2015) for SNe-Ic and SNe-Ic-BL, see Fig. 15. We can notice that LSQ14efd shows an initial Fe\(\ii\) velocity slightly higher with respect to SNe-Ic trend but quite in agreement within the uncertainties.

Following the comparison done for the light curve of LSQ14efd with type Iax SNe we then proceed to study the Si\(\ii\) velocity evolution.

Fig. 16 shows the evolution of the Si\(\ii\) velocities of LSQ14efd compared with other type Ic SNe (SN 2004aw Taubenberger et al. 2006, SN 2003jd Valenti et al. 2008a, SN 1994I Sauer et al. 2006, SN 2007gr Valenti et al. 2008b, and SN 1998bw Patat et al. 2001) other type Ia SNe (1999ac Garavini et al. 2005, 1991T Phillips et al. 1992, 1997br Li et al. 1999 and SN 2003du Stanishev et al. 2007) and type Iax 2008A Foley et al. (2013).

Benetti et al. (2005) found that in type Ia SNe there is a trend for the Si\(\ii\) velocity to reach a value of ~6000 km s\(^{-1}\) at ~30 d. Type Iax SNe, instead, are characterized by low-velocities of Si\(\ii\).

Foley et al. (2013) show, in their fig. 19, the typical range of velocities for type Iax SNe to be 5000 – 8000 km s\(^{-1}\), around maximum. Although we can note that SN 2008A displays higher velocities than almost all the objects in this class (~8000 km s\(^{-1}\)). Type Ic SNe, instead, show a wide diversity in ejecta velocities, varying from ~30000 km s\(^{-1}\) to ~10000 km s\(^{-1}\) around maximum. In summary, LSQ14efd shows a velocity evolution (traced by Si\(\ii\) and Fe\(\ii\)), which is quantitatively similar to that of SN 2004aw. We find that the velocities are compatible, within the errors, at almost all epoch. LSQ14efd velocities are significantly slower than those of the SN-Ic BL 2003jd at all epochs, but are faster than those of SN 2007gr. iPTF15dtg shows a higher pre-maximum velocity of Si\(\ii\) with respect to LSQ14efd, but starting from B-maximum they become comparable. The trend is also very similar to that of LSQ14efd.

The comparison with type Iax SN 2008A shows that the estimated Si\(\ii\) velocities for LSQ14efd have a similar slope but a higher value than the typical Iax SNe but they are low compared to that of type Ia SN. We also note there is a clear difference in the slope of the Si\(\ii\) evolution between type Ia SNe and type Ic; the former have slower decrease. The slope of the velocity decrease for LSQ14efd is more similar to those of type Ic SNe.
5 $^{56}\text{Ni}$ AND EJECTED MASS

The light-curve model developed by Arnett (1982) gives an analytical description of light curve of type I SNe. The original paper by Arnett (1982) contains a typographical error in the numerical factor of Arnett’s equation (54), which is discussed in Lyman et al. (2016) and that has been corrected in equation (3). The analysis performed at the peak of the light curve can lead to a rough estimate of the total mass of the SN ejecta ($M_{\text{ej}}$), the nickel mass ($M_{\text{Ni}}$) and the kinetic energy ($E_{\text{kin}}$). The main assumptions of the model are: a homologous expansion; spherical symmetry; a constant optical opacity; no mixing of $^{56}\text{Ni}$; and radiation-pressure dominance. Furthermore, it considers also the diffusion approximation for photons, which can reasonably be applied in the early phases when the ejecta is optically thick, due to the high density. The time evolution of the SN luminosity is given by

$$L(t) = \epsilon_{\text{Ni}} e^{-x^2} \int_0^x 2z e^{-2y+z^2} \, dz$$

where $x \equiv t/\tau_{\text{eff}}$, $y \equiv \tau_{\text{eff}}/2\tau_{\text{Ni}}$ and $\epsilon_{\text{Ni}} = Q_{\text{Ni}}/(M_{\text{Ni}} \tau_{\text{Ni}})$; $Q_{\text{Ni}}$ is the energy release for $^{56}\text{Ni}$ decay and $\tau_{\text{Ni}}$ is the $e$–folding time of the $^{56}\text{Ni}$ decay. The width of the peak of the bolometric is related to the effective diffusion time and it is given by

$$\tau_{\text{in}} = \left( \frac{2}{\beta c} \frac{k_{\text{opt}} M_{\text{ej}}}{v_{\text{sc}}} \right)^{1/2} \propto k_{\text{opt}}^{1/2} M_{\text{ej}}^{3/4} E_{\text{kin}}^{-1/4}$$

where $v_{\text{sc}}$ is the velocity scale of the expansion, $k_{\text{opt}}$ is the optical opacity and $\beta$ is an integration constant. Furthermore, assuming a homogeneous density of the ejecta, it is possible to relate the kinetic energy to the photospheric velocity ($v_{\text{ph}}$) at maximum through the relation (Arnett 1982)

$$v_{\text{ph}}^2 \approx \frac{10 E_{\text{kin}}}{3 M_{\text{ej}}}.$$  

We first estimate the width of the light curve of LSQ14efd, $\tau \sim 20$ d, following the prescription in Lyman et al. (2016) so the estimate of the light-curve width is the numbers of days required to reach the same magnitude the SN had 10 d prior maximum, then, assuming $k_{\text{opt}} = 0.06 \text{cm}^2 \text{g}^{-1}$ (Lyman et al. 2016) in equation (2) and considering the previously estimated Fe II velocity, we estimated $M_{\text{ej}} = 6.3 \pm 0.5 M_{\odot}$.

We then estimate the nickel mass synthesized through the equation (1), evaluated at the time of the bolometric peak when we have reliable measurement. We estimate a $M_{\text{ej}} = 0.25 \pm 0.06 M_{\odot}$. Finally, through equation (3), we obtained an estimate for the...
kinetic energy, $E_{\text{kin}} = 5.6 \pm 0.5 \times 10^{51}$ erg. We note that since the $M_{\text{Ni}}$ depends on the peak luminosity and has been estimated from a quasi-bolometric light curve, we should consider this value as a lower limit. Considering the peak luminosity inferred from the method developed by Lyman et al. (2014), the nickel mass could increase up to $\sim 0.32 M_\odot$. The estimated physical parameters are generally higher than other SNe-Ic, except for the nickel mass which is close to that estimated for SNe 2004aw (Taubenberger et al. 2006) and 2003jd (Valenti et al. 2008a). We note that a recent work from Mazzali et al. 2017 revisited the explosion parameters for SN 2004aw but they are still in agreement, within the error, with the ones from Taubenberger et al. 2006 and 2003jd (Valenti et al. 2008a). As expected, from the empirical comparison of the light curves, the ejecta mass and $^{56}\text{Ni}$ mass are larger than those found for type Ic SN 1994I (Nomoto et al. 1994), and somewhat comparable with the higher value for broad-lined type Ic such as SN 1998bw (Galama et al. 1998, Nakamura et al. 2000). iPTF15dtg is less energetic but has a more massive envelope and more nickel mass than LSQ14efd. Table 5 contains a quantitative comparison. A comparison of the explosion parameters with the average value found by Lyman et al. (2016) is also shown in Table 5. We note how LSQ14efd has generally a higher value than the average found for normal SNe-Ic, but somewhat similar to that found for SNe-Ic-BL. We also note that the LSQ14efd velocity is higher than the average value found for SNe-Ic, but still lower than those of SNe-Ic-BL. We point out that the kinetic energy estimated has to be considered as an upper limit since spherical symmetry was adopted for the explosion model for all these SNe in Table 5. Instead, Taubenberger et al. (2009) show that more than half of all stripped-envelope CC-SNe explosions may be significantly aspherical.

As a consistency check, we have also estimated the explosion parameters assuming that LSQ14efd is a possible type Ia SN using the same model but different assumptions for the physical constants, which are more appropriate for an exploding CO-WD. In this case we considered $k_{\text{opt}} = 0.3$ g cm$^{-2}$ s$^{-2}$ (Stritzinger et al. 2006) and therefore obtained a different ejecta mass of $M_{\text{ej}} = 1.0 \pm 0.2 M_\odot$ and $E_{\text{kin}} = 0.6 \pm 0.2 \times 10^{51}$ erg. The estimated nickel mass still remains at $0.25 \pm 0.06 M_\odot$. As expected, the difference in the values of the $M_{\text{ej}}$ and $E_{\text{kin}}$ under the two assumptions is simply due to the different values of $k_{\text{opt}}$, while the $M_{\text{Ni}}$ remains the same as it depends on the peak luminosity. We compared these results also with those of type Iax SN as reported in Magee et al. 2017, where the $M_{\text{Ni}}$ for SNe-Iax ranges in $\sim 0.03 - 0.6 M_\odot$. The estimated $M_{\text{Ni}}$ for LSQ14efd falls in this interval and it’s not possible to use this
parameter to discriminate among the two possible scenarios. We then compared the results obtained for LSQ14efd with those of a sample of SNe-Ic (Drout et al. 2011). In particular, the Ni mass with respect to the absolute magnitude in the R band $M_R$ of LSQ14efd was compared with the trend found by Drout et al. (2011) for SNe-Ic and SNe-Ic-BL (Fig. 17). Drout et al. (2011) derived the $^{56}$Ni mass through the light-curve models from Valenti et al. (2008a), which are based on Arnett (1982) formalism. We can notice that LSQ14efd follows the trend and it is in agreement with the best-fit evolution, within the uncertainties.

6 CONCLUSION

We have presented the photometric and spectroscopic follow-up of LSQ14efd within the PESSTO survey, which covered a period of $\sim 100$ d. LSQ14efd exploded in an anonymous galaxy at a distance modulus $\mu = 37.35 \pm 0.15$ mag and does not appear to suffer of strong reddening ($E(B-V) = 0.0376 \pm 0.0015$ mag).

Early photometric observations show the probable detection of the cooling of the shock break-out event in the light curve of LSQ14efd. A comparison with other CC-SNe shows a similarity in the cooling of the shock break-out detection of LSQ14efd and SN 2008D (see Fig. 3). The well sampled colour evolution was studied to investigate the possibility that LSQ14efd is a SN-Ia with an indication of interaction of its ejecta with either a companion or nearby circumstellar medium, such as SN 2012cg and iPTF14atg (see Section 3.2).

We want to stress that this early emission can have also different interpretation for CC-SNe as the presence of an extended envelope previously ejected by the progenitor or it can be due to some outwardly mixed $^{56}$Ni. But with only a single data point and in a single band it is actually quite difficult to definitely distinguish the source of this early emission and then discriminate among different possible progenitor scenarios, either CC-SNe or SNe-Iax.

We presented an analysis of the main photometric features of this SN including multicolour light curves, colour evolution and bolometric light curves, [see Figs 3 (right-hand panel), 7 and 8].

The colour evolutions of LSQ14efd (Fig. 7) resemble those of type Ic SNe, but do not differ much from SNe Iax as well. The quasi-bolometric light curve (Fig. 8) is similar to those of type Ic SNe.

Figure 13. Comparison of spectra of LSQ14efd with type Ia SN 1999ac (Garavini et al. 2005), type Iax SN 2008A (Blondin et al. 2012), at different epochs.
SNe 2004aw and 2003jd but also comparable with type Iax SN 2008A.

We also perform a comparison of some observables of LSQ14efd with the trend found for sample of SNe-Ic (Drout et al. 2011; Modjaz et al. 2015; Liu et al. 2016). In particular LSQ14efd $R$ band follows the template evolution found in Drout et al. (2011), while the $V$ band instead differs significantly in the pre-maximum evolution, showing that LSQ14efd has a broader light curve than average SN-Ib/c (Fig. 6). LSQ14efd follows the $^{56}$Ni mass versus $M_V$ correlation found by Drout et al. (2011).

The spectroscopic evolution of LSQ14efd shows Si II, Fe II lines and a likely Ca II feature and it is similar to that of SN 2004aw at epochs that are consistent with the light-curve evolution. The evolution of LSQ14efd Si II velocities (see Fig. 16) from B-maximum ($\sim 10,000$ km s$^{-1}$) until 20 d after (5000 km s$^{-1}$) is very similar to that of SN 2004aw, which is intermediate between ‘standard’ SNe-Ic and the very energetic ones, like SN 1998bw. Recently, it has also been proposed that SN 2004aw is a ‘fast-lined’ SN rather than a BL-SN (Mazzali et al. 2017), strengthening the peculiarity of this SN. However the spectra of this object present some similarities with peculiar type Ia and Iax SNe, in particular in the late phase (see Figs 13 and 12) and based on spectra only, we cannot determine whether this is a peculiar SN-Ia or a Ic. A comparison with SNe-Ic and SNe-Ic-BL templates (Modjaz et al. 2014; Liu et al. 2016) remarks a quite good similarity with SNe-Ic for the early spectra, but a significant deviation for the late ones but a better agreement

Figure 14. Comparison of the spectra of LSQ14efd at different epochs with the templates (Modjaz et al. 2014; Liu et al. 2016) for SNe-Ic (dashed red line) and SNe-Ic-BL (red solid line). The epochs refer to the V-maximum. Spectra have been flattened through the Supernova Identification package (Blondin & Tonry 2007) for the comparison with the templates.

Figure 15. Comparison of Fe II $\lambda 5169$ velocity of LSQ14efd with the general trend for SNe-Ic and SNe-Ic-BL found in Modjaz et al. 2015. Epochs refer to the V-maximum.
Table 5. Comparison of the physical parameters of some type Ic SNe and average values from Lyman et al. (2016): photospheric velocity; nickel mass; mass of the ejecta; and kinetic energy.

| SN     | $M_B$ (mag) | $v_{ph}^{\infty}$ (10$^3$ km s$^{-1}$) | $M_{Ni}$ ($M_{\odot}$) | $M_{ej}$ ($M_{\odot}$) | $E_{kin}$ ($10^{51}$ erg) |
|--------|-------------|----------------------------------------|------------------------|------------------------|-------------------------|
| 1994I  | 17.7        | 11                                      | 0.07                   | 0.9                    | 1                       |
| 2007gr | 17.3        | 11                                      | 0.07–0.1               | 1.5–3                  | 1.5–3                   |
| 2004aw | 18.14       | 14                                      | 0.25–0.35              | 3.5–8.0                | 3.5–9.0                 |
| iPTF15drg | 18.51    | 6                                       | 0.41–0.43              | 9.7–10.9               | 2.1–2.3                 |
| LSQ14efd | 18.6      | 12.2                                    | 0.25                   | 6.3                    | 5.3                     |
| 2003jd | 19          | 13                                      | 0.36                   | 3.0                    | 5–10                    |
| 1998bw | 19.14       | 18                                      | 0.7                    | 10                     | 30                      |
| Average Ic |          | 10.4                                    | 0.22                   | 3.0                    | 1.9                     |
| Average Ic-BL | | 19.1      | 0.32                                   | 2.9                    | 6.0                     |

Note. *At the B-maximum.

Figure 16. Si II velocity evolution of LSQ14efd compared with type Ic SNe 2004aw (Taubenberger et al. 2006), 2003jd (Valenti et al. 2008a), iPTF15drg (Taddia et al. 2016) and with type Ia SNe 1999ac (Garavini et al. 2005), 1991T (Phillips et al. 1992), 1997br (Li et al. 1999), SN 2003du (Stanishev et al. 2007) and type Iax 2008A (Foley et al. 2013). Epochs refer to the B-maximum.

with the templates for SNe-Ic-BL at all epochs. This strengthens the peculiarity of LSQ14efd.

The Fe II evolution of LSQ14efd was compared with the average trend for SNe-Ic found by Modjaz et al. 2015 for SNe-Ic and it shows a comparable behaviour at early epochs. Instead LSQ14efd shows a pretty different Si II evolution with respect of SNe-Ia and Iax.

Considering the overall properties shown by LSQ14efd we favour a core-collapse origin for LSQ14efd.

We applied a simple model for CC-SNe to the quasi-bolometric light curve to calculate the physical parameters of LSQ14efd. We obtained a synthesized $M_{Ni} = 0.25 \pm 0.06 M_{\odot}$, an ejected mass of $6.3 M_{\odot}$ and a kinetic energy of $5.6 \times 10^{51}$ erg. A comparison of the explosion parameters with the average values found by Lyman et al. (2016) shows that LSQ14efd seems to have values closer to that found for SNe-Ic-BL rather than those for normal SNe-Ic. No evident association with a GRB was identified.

The increasing number of discoveries of peculiar SNe-Ic, which represent a link between energetic Ic events, which are not connected with GRBs (as SN 2003jd) and those which show a clear association with GRBs (as GRB 980425/SN 1998bw) gives support to the idea of an existing continuum of properties between broad-lined Ic and ‘standard’ SNe-Ic events rather than suggesting the existence of clearly ‘separated’ classes of SNe-Ic. LSQ14efd is more energetic than standard SNe-Ic, it is not as energetic as SNe-Ic-BL which are often associated with GRBs. This again shows a diversity of the type Ic SNe class, which was already pointed out by Taubenberger et al. (2006).

LSQ14efd confirms the existence of an unresolved ambiguity in SN classification, particularly when the classification in SN types relies only on the photometric evolution and/or early stages spectra.

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