An optical photometric and spectroscopic analysis of the slowly-evolving type IIn supernova SN 2007rt is presented, covering a duration of 481 days after discovery. Its earliest spectrum, taken approximately 100 days after the explosion epoch, indicates the presence of a dense circumstellar medium, with which the supernova ejecta is interacting. This is supported by the slowly-evolving light curve. A notable feature in the spectrum of SN 2007rt is the presence of a broad Hα P-Cygni profile, the absorption component of which has a width of 128 km s\(^{-1}\). This slow velocity suggests that the progenitor of SN 2007rt recently underwent mass-loss with wind speeds comparable to the lower limits of those detected in luminous blue variables. Asymmetries in the line profiles of H and He at early phases bear some resemblance to double-peaked features observed in a number of Ib/c spectra. These asymmetries may be indicative of an asymmetric or bipolar outflow or alternatively dust formation in the fast expanding ejecta. In addition, the late time spectrum, at over 240 days post-explosion, shows clear evidence for the presence of newly formed dust.

Key words. supernovae: individual: SN 2007rt – stars: circumstellar matter – stars: evolution – stars: winds, outflows – stars: supernovae: general
The ambiguities surrounding type IIn progenitors leads us to tread carefully whilst discussing this group of supernovae, and warrants further investigation. The presence of CSM provides a unique insight into the mass-loss history of the progenitor prior to core-collapse. However, there remains an element of ambiguity over the ionisation forbidden emission lines and they refer to this as a pseudo-continuum. This verified earlier speculation by Stathakis & Sadler and Turatto et al. that the source of the blue spectral re-

gion in SN 1988Z was a strong interaction with the surrounding circumstellar material.

The presence of CSM provides a unique insight into the mass-loss history of the progenitor prior to core-collapse. However, there remains an element of ambiguity over the progenitors of type IIn supernovae. Recent work has indicated that some of these objects may be connected to luminous blue variables (LBVs) or at least have undergone LBV-like behaviour shortly before core-collapse (see Kotak & Vink 2006; Gal-Yam et al. 2007; Gal-Yam & Leonard 2008; Smith et al. 2007; Trundle et al. 2008; Smith et al. 2008a; Agnoletto et al. 2009). Another group, the hybrid type Ia/IIn, are thought to be a type Ia disguised as a type IIn, due to the strong narrow H$_\alpha$ emission in their spectra and the possible presence of the S II and Si II features typical of type Ia (viz. SN 2002ic; see Hamuy et al. 2003; Aldering et al. 2006; Kotak et al. 2004). However, this is largely under debate within the community (Benetti et al. 2006; Trundle et al. 2008). There are also a number of so-called “transitional” objects, where the presence of varying degrees of narrow hydrogen and helium lines in their spectra place them in a classification scheme between type IIn and type IIf objects (such as SN 2005ia and the type IIn, SN 2006jc Pastorello et al. 2007; Foley et al. 2007; Pastorello et al. 2008a,b; Smith et al. 2008b). In follow-up spectra we identified a broad helium feature, which is not detected in SN 1998S or many other type IIn SNe, and hence warrants further investigation.

2. Observations

Photometric and spectroscopic data of SN 2007rt were collected from November 2007 to March 2009. The details of these observations are logged in Table 1 and are outlined below.

2.1. Photometry

Our collaboration obtained optical photometry of SN 2007rt with the Telescopio Nazionale Galileo (TNG) and Nordic Optical Telescope (NOT) in La Palma (Canary Islands, Spain), the 1.82 m Copernicus telescope of the Asiago Observatory (Italy), the 1.52 m telescope of the Loiano Observatory (Italy), and the 2.2 m Calar Alto telescope (Spain). In addition four data points provided by amateur astronomers were used. In total this gives a coverage from 4 to 481 days after discovery (see Fig. 1). The images were trimmed, de-biased and flatfielded. Since template images of the host galaxy were not available, the SN magnitudes were measured using a point spread function (PSF) fitting technique in the Image Reduction and Analysis Facility (IRAF). Zero-points were defined making use of standard Landolt fields observed on the same night as the SN. The

1 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Table 2. Optical photometry of SN 2007rt.

<table>
<thead>
<tr>
<th>Date</th>
<th>Phase(days)</th>
<th>U</th>
<th>(U_{\text{err}})</th>
<th>B</th>
<th>(B_{\text{err}})</th>
<th>V</th>
<th>(V_{\text{err}})</th>
<th>R</th>
<th>(R_{\text{err}})</th>
<th>I</th>
<th>(I_{\text{err}})</th>
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<tr>
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<td>17.600</td>
<td>0.388</td>
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<td>02–12–2007</td>
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<td>17.263</td>
<td>0.186</td>
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<td>16.935</td>
<td>0.273</td>
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<td></td>
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<tr>
<td>09–12–2007</td>
<td>96</td>
<td>17.617</td>
<td>0.222</td>
<td>16.977</td>
<td>0.201</td>
<td>16.803</td>
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<td>17.191</td>
<td>0.027</td>
<td>17.670</td>
<td>0.019</td>
<td>17.327</td>
<td>0.025</td>
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<td>19–12–2007</td>
<td>106</td>
<td>17.648</td>
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<td>0.023</td>
<td>16.943</td>
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<tr>
<td>13–01–2008</td>
<td>131</td>
<td>17.541</td>
<td>0.026</td>
<td>17.885</td>
<td>0.018</td>
<td>17.490</td>
<td>0.021</td>
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<tr>
<td>11–02–2008</td>
<td>160</td>
<td>17.623</td>
<td>0.039</td>
<td>17.968</td>
<td>0.020</td>
<td>17.602</td>
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<td>29–03–2008</td>
<td>207</td>
<td>18.166</td>
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<td>17.882</td>
<td>0.090</td>
<td>17.171</td>
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<tr>
<td>30–03–2008</td>
<td>208</td>
<td>18.708</td>
<td>0.041</td>
<td>18.160</td>
<td>0.039</td>
<td>17.881</td>
<td>0.097</td>
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<td>01–05–2008</td>
<td>240</td>
<td>18.289</td>
<td>0.028</td>
<td>18.001</td>
<td>0.045</td>
<td>17.339</td>
<td>0.047</td>
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<tr>
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<td>18.059</td>
<td>0.073</td>
<td>18.335</td>
<td>0.034</td>
<td>18.200</td>
<td>0.047</td>
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<td>07–07–2008</td>
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<td>18.206</td>
<td>0.051</td>
<td>18.601</td>
<td>0.049</td>
<td>18.433</td>
<td>0.082</td>
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<tr>
<td>05–12–2008</td>
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<td>18.565</td>
<td>0.070</td>
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<td>22–12–2008</td>
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<td>0.102</td>
<td>19.948</td>
<td>0.082</td>
<td>18.622</td>
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<td>13–01–2009</td>
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<td>19.088</td>
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<tr>
<td>20–01–2009</td>
<td>506</td>
<td>18.866</td>
<td>0.148</td>
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<tr>
<td>23–01–2009</td>
<td>507</td>
<td>19.675</td>
<td>0.071</td>
<td>20.543</td>
<td>0.079</td>
<td>20.250</td>
<td>0.149</td>
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<tr>
<td>19–03–2009</td>
<td>562</td>
<td>21.179</td>
<td>0.103</td>
<td>21.012</td>
<td>0.095</td>
<td>19.610</td>
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</table>

The phase is given relative to the explosion date, believed to be 81 days prior to the discovery date on 24th November 2007.

Fig. 1. UBVRI light curves of SN 2007rt up to 481 days after discovery. From top to bottom the points are \(I, R, V, B,\) and \(U\) with offsets of \(-1, -0.3, 0, +0.5\) and \(+1.7\) mag. respectively. The discovery magnitudes reported by Li (2007) are also included here.

The spectroscopic data have been corrected for the redshift of the host galaxy, UGC 06109 \((z = 0.02365 \pm 0.00080)\) as published in the updated Zwicky catalog (Falco et al. 1999). The blue continuum plus absence of Na I D lines in the spectra of SN 2007rt suggest that there is a negligible effect due to extinction on the observed spectral energy distribution. Thus we have only corrected the spectra by the small Galactic extinction contribution as suggested by Schlegel et al. (1998). Along the line of sight of SN 2007rt the Galactic extinction is \(E(B-V) = 0.02\).

3. Light curve evolution

Figure 1 shows the UBVRI light curves of SN 2007rt. Over the first 130 days after discovery, the light curve of SN 2007rt evolves slowly (at a rate of \(0.003 \text{ mag d}^{-1}\)) and it is clear the supernova has not been caught at maximum (see Sect. 4). Following this there is a gradual decline in the light curve, which steepens at late phases (0.01 mag d\(^{-1}\) from 458–562 days post-explosion). It was reported by Li (2007) that on a KAIT image taken almost seven months prior to discovery, on 8th May 2007, nothing was detected at the position of the supernova. Since this supernova has been discovered quite late on in its evolution, as suggested by the non-detection of a maximum in the light curve, it is difficult to determine the explosion epoch. However we obtained an estimate of the explosion date of SN 2007rt indirectly...
using the spectra and light-curve of an interacting type IIn SN, SN 2005ip.

3.1. Age of SN 2007rt

The light-curve of SN 2005ip declined rapidly after discovery, suggesting SN 2005ip was discovered close to maximum (Smith et al. 2009a). Many core collapse SNe, for which the rise time to peak was observed, have rise times of 3 weeks or less. Few SNe type IIn have been detected during this rise phase, and those that have, give rise times of 20–50 days (see SN 2006gy and SN 2005gj in Fig. 2). The fact that type IIn are rarely detected before maximum, suggests that the rise time is quite fast. Based on this, it is reasonable to assume that SN 2005ip was detected within a couple of weeks from explosion. Hence we adopt an explosion date for SN 2005ip of JD = 2453673, which is 7 days prior to its detection (Fig. 2). This is consistent with the findings of Smith et al., however we cannot ignore that there is a large degree of uncertainty in this. The assumption of a short rise time of SN2005ip is also supported by the rapid change in the spectra after discovery. The first spectrum shows an almost featureless and very blue spectrum (Smith et al. 2009a) and over the following days the broad features and continuum evolve rapidly (from unpublished spectra, Trundle et al. in prep).

At 95 days after its discovery, the spectrum of SN 2005ip best fits the broad features and slope of our first SN 2007rt spectrum (see Sect. 5.1). Assuming the similarity of the spectra of SN 2005ip and SN 2007rt indicates that these supernovae are of similar age, the age estimate of the first spectral epoch of SN 2007rt can be refined to approximately 102 ± 40 days after explosion, and thus the explosion date is set to JD = 2454349 ± 40. Before adopting this age, for the following discussions, we will attempt to qualify our assumption that these two objects are close to or of a similar age at these epochs. The spectra of SN 2007rt at discovery and SN 2005ip at 95 days are heavily dominated by the CSM interaction. So although there is evidence for spectral similarity the properties of the CSM may mask the true epoch. However a very young age can be ruled out for SN 2007rt. Firstly, the first spectrum was obtained 21 days post-discovery and hence SN 2007rt must be at least 21 days old. Secondly, in an early epoch (<40 days) type IIn, a strong blue continuum would be expected which evolves rapidly along with the broad features (viz. SN 2005ip, SN 2005gj; Smith et al. 2009a; Aldering et al. 2006). However the blue continuum and broad features in SN 2007rt, do not evolve rapidly over a 60 day period between our first and fifth spectrum (see further discussion on continuum Sect. 4). Similarly a large amount of CSM, prolonging the interaction duration of SN 2007rt could lead to an underestimate of its age. In spite of this, uncertainties of a few weeks in our estimates will not substantially alter our findings. From this point forward we adopt the explosion date of JD = 2454349 ± 40, implying the observations of SN 2007rt were taken between 85 to 562 days post-explosion\(^2\).

The light curve of SN 2007rt is compared to those of a range of SNe types in Fig. 2. At approximately 100 days past maximum, SN 2007rt is more luminous than the fast-declining type IIn SN 1999el, but fainter than some of the most luminous type IIn objects, SN 2006gy and SN 2005gj. Despite the similarity in the spectra of SN 2007rt and SN 2005ip at early times, there is a significant difference in the absolute luminosity of their light curves. This may be caused by differing densities and distributions of circumstellar matter surrounding the two SNe. The early time light-curve evolution of SN 2007rt is very slow, declining by 0.003 mag d\(^{-1}\). This is considerably slower than SN 2005ip which has a decline rate for a similar period of 0.015 mag d\(^{-1}\) (Smith et al. 2009a).

\(^2\) All dates in the rest of this article refer to the adopted explosion epoch, unless otherwise stated.
4. Spectral evolution

The spectra of SN 2007rt, displayed in Fig. 3, have been corrected for a Galactic reddening of $E(B-V) = 0.02$ mag as discussed in Sect. 2.2. There is a blue excess present in the spectra in the early epochs, which flattens after more than 300 days post-explosion. We fit a blackbody to the spectrum of SN 2007rt, and obtain a temperature of $\approx 7500$ K for the first epoch. This fit in itself was poor and as the SN evolved it became increasingly difficult to simultaneously reconcile the flat red spectral region and the blue excess with a single blackbody. Smith et al. (2009a) showed that, in the case of SN 2005ip, spectra taken some 200 days after maximum revealed a blue pseudo-continuum composed of a forest of narrow emission lines, rather than a real thermal continuum with a blackbody like behaviour. This indicated that for SN 2005ip the blue pseudo-continuum at late times arose from the interaction with circumstellar material, and was not a real thermal continuum. This had previously been speculated by Stathakis & Sadler (1991) and Turatto et al. (1993) for the case of SN 1988Z. The low velocity of the CSM in SN 2005ip allowed the detection of the separate components of the emission line spectrum in the blue which formed the pseudo-continuum at late-stages. It therefore may be possible that the temperature derived by fitting a blackbody to the spectrum of SN 2007rt is not meaningful. This will be discussed further in Sect. 5.1.

Prominent features in the spectra of SN 2007rt are the narrow and broad Hα features, the intermediate velocity Hβ line and broad Ca II infrared triplet. There are also a number of narrow emission features associated with He and heavier metals in the spectra. However, possibly the most peculiar spectral feature is the broad, relatively flat topped He i 5875 Å emission line. In Fig. 3 these main features are identified. At all phases the H and He lines are asymmetric. At late times the Hα and He i 5875 Å lines have a pronounced blueshift, and a significant lack of redshifted emission in the broad component. There is also a hint of a narrow component of He i 5875 and 7065 Å in the early epochs (see Fig. 4), suggesting there is a certain amount of helium in the CSM. The narrow He i 5875 Å line diminishes from the first spectra (102 days post-explosion), and disappears by day 208. In the later epochs, from day 475, an intermediate velocity component appears. This suggests that there is interaction between the ejecta and the He in the CSM. In addition, a strong permitted O i 8446 Å line develops from day 273, which has velocities comparable to the intermediate H component.

To determine the properties of the spectral features we have fit Gaussians to their profiles. Each Gaussian was parameterized by three quantities, the central wavelength, full-width-half-maximum (FWHM) and peak height. These parameters were freely fit by the fitting routine. In a small number of cases, the central wavelengths of the narrow lines were fixed, as the low intensity of the line relative to the continuum prohibited the detection of its peak. The resulting wavelengths, velocities and intensities of the lines are presented in Tables 3–5. All FWHM given in the aforementioned tables and the discussions below are corrected for the instrumental resolution. In interacting supernovae the flux calibration is subject to large uncertainties due to the presence of strong emission lines. Errors on the measured intensities of the lines are therefore on the order of 20%, whereas the FWHM uncertainties are 10%. The narrow lines which were detected and fitted in the spectrum had FWHM velocities that were not fully resolved by the low resolution spectra (these are discussed further in Sect. 4.4). As a guide to the properties of these lines, their parameters as determined from the TNG spectrum taken on the 11th February are presented in Table 5. In addition a number of the lines were resolved in the intermediate resolution WHT spectrum taken on the 4th February, and these are also presented in the aforementioned table.

In the case of Hα and He i 5875 Å, multiple Gaussian fits were employed (see Sect. 4.2) due to the asymmetry of the observed profiles. As discussed in more detail below, Hα was first fit with a broad, intermediate and narrow Gaussian whilst the
He I 5875 Å line was fit with a broad and narrow component for the early epochs, and a broad and intermediate component for the latest epochs. The parameters of the broad and intermediate components from these fits are shown in Table 3. However these initial fits were poor, and hence we refit the profiles with up to four Gaussians; an intermediate component, two broad components, and where appropriate a narrow component. The parameters of the broad and intermediate components of the latter fits are presented in Table 4.

4.1. Narrow Hα P-Cygni profile

Figure 4 shows the time-series of the Hα line. From day 102 to day 208 there is a narrow emission component present which decreases in strength over time. The luminosity of this narrow component decreases by more than a factor of 2 between our first epoch of data and that taken 58 days later. It has disappeared completely 138 days after our first spectrum. This feature is not fully resolved by the low resolution spectra which makes up most of our dataset. However, we can place an upper limit on the FWHM velocity of ≤200 km s$^{-1}$ (see Table 5).

To resolve this narrow Hα feature we obtained intermediate resolution spectra of SN 2007rt on the 4th February 2008 with ISIS on the WHT. This revealed a previously unresolved P-Cygni profile (see Fig. 5). The FWHM of the emission and absorption feature are 84 and 54 km s$^{-1}$, respectively (Table 5). The blue wing of the absorption profile extends out to 128 km s$^{-1}$. If we assume that the narrow feature is representative of unshocked CSM, this edge velocity of 128 km s$^{-1}$ corresponds to the terminal velocity of the wind of the progenitor star (see Sect. 5.3 for more discussion on the progenitor).

4.2. Hα and He i evolution

From the Hα profiles in the first panel of Fig. 4, we can see that the line is highly asymmetric and consists of multiple components. Typically, the Hα profile of type II supernovae can be decomposed into three parts: broad, intermediate and narrow. These are normally attributed to shocked (intermediate) and unshocked (narrow) circumstellar matter and emission from the underlying supernova ejecta (broad). In SN 2007rt, the red wing of the broad feature appears to be less extended than the blue wing, and both the broad and intermediate features show some asymmetry. The extent of the blue and red wings decrease rapidly with time, showing a reduction in the FWHM of the broad component, and hence a change in the asymmetry. The extent of the blue and red wings decrease rapidly with time, showing a reduction in the FWHM of the broad component, and hence a change in the asymmetry.

In the first instance the complex profile of Hα in SN 2007rt was fit with three Gaussian profiles allowing all parameters to be freely fit. In the early epochs, the He i 5875 Å line did not require an intermediate component and hence was fit only with components representing the broad and narrow features. An additional narrow component was added to account for the contribution to the profile from [N II] 5755 Å. In the case of He i 5875 Å the central wavelength of the narrow component was fixed. The narrow line is no longer present in either the H or He lines after 208 days, and hence the profiles at these epochs were fit with only two Gaussians (see Fig. 6). From day 475, two Gaussians were fit to the He i 5875 Å line representing the broad and intermediate components. The top panel of Fig. 6 shows a typical fit to Hα for one epoch. The parameters determined from this process for the intermediate and broad components

Fig. 4. Observed Hα, Hβ, He i 5875 Å and He i 7065 Å profiles in SN 2007rt from 102 to 507 days since the explosion date. The flux of each spectrum is arbitrarily offset for clarity. Note the blue-shift in the later epochs of Hα and the asymmetry in its red wing. In the last two panels, the flux has been magnified by a factor of 4 for an easier view of the weak narrow helium features. Note under magnification there appears to be a weak broad helium component at 7065 Å.
are reported in Table 3, those of the narrow components are presented separately. Uncertainties in the central wavelengths, FWHM, and intensities of the fits are ±5 Å, 10%, and 20%, respectively. The intermediate component has a FWHM velocity range of ~2900–1800 km s⁻¹ over the first 192 days from discovery. There is a gradual reduction in the FWHM of the broad components of the two lines over the observed period. In the first spectrum the broad component has a FWHM velocity of ~10000 km s⁻¹, decreasing to 6000 km s⁻¹ 171 days later (see upper panel of Fig. 7). The fact that there is nearly a 40% 

### Table 3. Initial parameters for the intermediate and broad Gaussian fits to spectral lines in SN 2007rt.

<table>
<thead>
<tr>
<th>Line</th>
<th>Day</th>
<th>Å</th>
<th>( \lambda )</th>
<th>FWHM</th>
<th>Intensity</th>
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<td>5875</td>
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<td>5876</td>
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### Table 4. Parameters of the multiple Gaussian fits to the He II 5875 Å lines, using four Gaussian profiles (2 broad, 1 intermediate & 1 narrow).

<table>
<thead>
<tr>
<th>Line</th>
<th>Day</th>
<th>Å</th>
<th>( \lambda )</th>
<th>FWHM</th>
<th>Intensity</th>
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<td>5875</td>
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<td>10^{-15} erg s^{-1} cm^{-2}</td>
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<td>Broad Blue</td>
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<td>10^{-15} erg s^{-1} cm^{-2}</td>
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</table>

* An intermediate He I 5875 Å line was detected at 475 & 507 days. Prior to that only weak narrow and broad components were present.
reduction in the width of the line clearly shows that this broad component is related to the ejecta. Nevertheless, the high velocity of 10 000 km s\(^{-1}\) detected over three months after explosion is inconsistent with non-interacting CCSNe and requires an extremely energetic explosion. We note here that the high expansion velocities are only inconsistent if the age of SN 2007rt is greater than a month or two. However as discussed in Sect. 3.1 we cannot provide an accurate age estimate of the SN, the implications of these assumptions will be discussed further in Sect. 5.4.

Careful inspection of Fig. 6 reveals that the combination of the three Gaussian profiles does not provide a suitable fit to the red wing of the H\(_{\alpha}\) profile. In addition, the peculiarly flat-topped He I mentioned in Sect. 4 is not consistent with a single broad component. An enhanced fit to both lines was found by fitting up to four Gaussian profiles: an intermediate component, broader blue and red-shifted components, and where appropriate, a narrow component (see Fig. 6). The significance of these fits will be discussed in more detail in Sect. 5, but briefly the two components at rest represent the shocked and unshocked circumstellar material. The other two components represent blobs of higher velocity material moving away from the supernova, one in the direction of the observer and one opposite to this. To produce these fits, the H\(_{\alpha}\) line was fit with multiple components, fixing the central wavelengths of the blue and red-shifted broad components in an iterative manner, whilst the other parameters were set free. For the helium line, the FWHM and separation of the broad and intermediate components determined for the H\(_{\alpha}\) line, were used to fix their counterparts in the He I feature. The lower panels of Fig. 6 show the resultant fits to H\(_{\alpha}\) and He I 5875 Å. (Fits to the spectra for additional epochs can be seen in Fig. B.2, which is only available online). The parameters for the intermediate and broad components are presented in Table 4.

In the first epoch the intermediate component in both profiles has a FWHM of \(\sim 2700\) km s\(^{-1}\), whilst the blue and red-shifted broader components are at \(\sim 5800\) and 6700 km s\(^{-1}\), respectively (see Table 4 and lower panel of Fig. 7). Over the first six months of the observational period of SN 2007rt, the broad component shows a 40% reduction in FWHM, whereas the intermediate component does not experience any noticeable change. It is therefore clear that the broader components are related to the ejecta, whilst the intermediate component is consistent with shocked material. In the last epochs taken a further 6 months later, only two components (a blue-shifted broad and intermediate component) were used to fit the data due to a lack of emission in the red wing of the lines.
The FWHM presented in parentheses are not corrected for resolution, all other values are: c- emission, a- absorption.

4.3. Hγ

A strong intermediate component of Hγ is detected in SN 2007rt, with some indication of a weak narrow component in the earliest epochs (see second panel of Fig. 4). Unlike Hα, the higher order Balmer lines, Hβγ, do not appear to have a broad component. For Hγ this is clearer, as it has a higher intensity relative to the strong blue continuum, but the behaviour of these lines are similar. The line profile of Hγ has an emission peak with a FWHM of ~4000 km s\(^{-1}\) in the first epoch of data. This corresponds to the intermediate component seen in H\(\alpha\), and changes at a similar rate (see Fig. 7). In SN 1988Z, similar differences in the H\(\alpha\) and Hγ profiles were observed, with no broad component detected in the latter (Turatto et al. 1993). Blended with the H\(\delta\) line is an absorption trough or depression in the continuum. Whilst there may be some contribution from hydrogen, the FWHM is twice the width of the emission in H\(\delta\), and it is unlikely to be due to hydrogen alone.

4.4. Narrow emission lines

Besides the prototypical narrow H\(\alpha\) feature, a number of other narrow emission features, many of which are identified in the low resolution spectra of SN 2007rt. These narrow lines have been identified as He I 5875, 7065 Å, [O III] 4363, 4959, 5007 Å, [N II] 5755 Å, [Ne III] 3866 Å, and very weak [Fe III] 5270 Å and [Fe VII] 6086 Å. There is also a possible detection of [Fe XI] 7891, although fringing in that part of the spectrum makes this identification marginal. Unfortunately the narrow lines were not resolved in our low resolution spectra. In the highest resolution spectrum in this low resolution group, taken on the 11th February 2008 the FWHM of the lines are typically a few 100 km s\(^{-1}\) (see Table 5). The [O III] lines have velocities of ~200 km s\(^{-1}\), which compares well with the narrow emission component of H\(\alpha\), suggesting they are produced in the same region of the CSM. An intermediate resolution spectrum of the H\(\alpha\) region of SN 2007rt was obtained on the 4th February 2008 with ISIS/WHT and revealed additional narrow features of [O I] 6300, 6363 Å, [N II] 6548, 6583 Å and the high ionisation line [Fe X] 6374 Å. The [Fe VII] 6086 line was also clearly detected in this spectrum. In Table 5 the parameters of the Gaussian fits to the narrow lines detected in the TNG spectrum on 11th February 2008 (day 160) and the ISIS/WHT spectrum (day 153) are presented as a guide to their parameters. Note that the velocities of the lines from the ISIS/WHT spectrum are significantly lower than derived from the lines in the spectrum taken seven days later, on the 11th February. This is due to the differences in the spectral resolution, as the lines in the low resolution spectra are unresolved. We note here that as the lines are unresolved there may be some unidentified contribution to these narrow emission lines from underlying H\(\alpha\) regions.

5. Discussion

In the introduction we mentioned the ambiguity surrounding the progenitors of type IIn SNe and the debate over the mechanism for the SN 2002ic-like supernovae. The strong interaction in these so-called hybrid type Ia/IIn objects makes it difficult to definitively conclude whether these are type Ia or core-collapse supernovae. However in the case of SN 2007rt the presence of He in the ejecta, indicated by the broad He I 5875 Å line and the lack of broad forbidden Fe features at late phases, which are prominent in type Ia SNe, suggests that SN 2007rt is a core-collapse supernova.

5.1. Comparison with other interacting SNe

In Sect. 3 we noted the similarity between SN 2007rt and another type IIn supernova, SN 2005ip. At early stages this SN displayed a weak series of both low and high ionisation, narrow features (Smith et al. 2009a, see their Fig. 2), as detected here in SN 2007rt. SN 2005ip bears a strong resemblance to the prototype for the type IIn class, 1988Z, which also had a narrow, forbidden, emission line spectrum (Stathakis & Sadler 1991; Turatto et al. 1993). In SN 2005ip and 1988Z there is a strong
Fig. 8. Comparison of SN 2007rt, SN 2005ip, the type IIn prototype, SN 1988Z, and an additional type IIn, SN 1997eg. Note the likeness of the underlying broad features of SN 2007rt, & SN 2005ip, suggesting that these two supernovae are of the same age at the given epoch. The data for SN 2005ip and SN 1997eg are unpublished spectra from the Padova-Asiago Supernova Archive, and that of SN 1988Z is from Turatto et al. (1993).

narrow He i feature, with SN 2005ip developing an intermediate feature over time (Smith et al. 2009a, see their Fig. 8). SN 2007rt also has narrow He i 5875 and 7065 Å lines, which indicate the presence of helium in the circumstellar medium. However the main spectral difference between these two SNe is the presence of a broad He i 5875 Å feature in SN 2007rt.

This broad helium line is not usually detected in type IIn spectra but is present in SN 2007rt from the first spectrum taken ~102 days post-explosion and narrows with time. A supernova with striking similarities to SN 2007rt is the type IIn SN 1997eg (Salamanca et al. 2002; Hoffman et al. 2008). In Fig. 8 these two supernovae are compared along with SN 2005ip and SN 1988Z. SN 1997eg has strong broad He i 5875 and 7065 Å lines with velocities comparable to the broad Hα profile. Hoffman et al. suggest that the high He/H ratio in the ejecta of SN 1997eg, indicates that the progenitor star must have shed a significant amount of its hydrogen shell, possibly through an episode of mass-loss prior to the supernova explosion. This mass-loss episode would rid the star of a large quantity of its hydrogen shell and deposit the hydrogen rich material into its immediate environment, thus a helium rich atmosphere would be left behind in the progenitor star to be revealed in the supernova ejecta. We suggest that this is also a likely scenario for SN 2007rt. However, it should be noted that strong lines can be formed not just by a high abundance but are dependent on the temperature and density conditions of the material. Comparing the spectra of the four supernovae mentioned above, it is clear that there are varying degrees of He line strengths in these objects, with SN 2007rt being intermediate between SN 2005ip/ SN 1988Z and SN 1997eg. One interpretation of this, is that there is varying degrees of H and He in the ejecta of these SNe. In addition to the high helium abundance, Hoffman et al. remarked that the peaked He profiles are suggestive of ejecta interacting with an asymmetric circumstellar medium, and this is substantiated by spectropolarimetry results.

At early times these type IIn supernovae have strong blue continua, with flatter red spectra. In the case of SN 2005ip a blackbody of 7300 K (Smith et al. 2009a) was required to fit the data. Our earliest spectrum of SN 2007rt, at 102 days post-explosion, was poorly fit by a blackbody with ~7550 K. Over time the blue excess decreased, and the red part of the spectrum flattened, making it difficult to fit a single blackbody. Smith et al. reported a similar effect in SN 2005ip. However, in this case the late time data resolved this continuum into a forest of high-ionisation (mainly Fe) emission lines. They suggest these lines are ionised by X-rays formed in the shocked material of a slow wind, and refer to a pseudo-continuum. This provides support for the suggestion that the blue excess in type IIn supernovae is related to the interaction of the ejecta with the CSM. Smith et al. suggest that the blue excess in SN 2006jc is a result of a similar effect, but the wind of the progenitor (likely a WR star) was faster, and hence the blue pseudo-continuum consisted of a blend of broader emission lines. If confirmed, this highlights the role the density and geometrical configuration of the progenitors wind plays in the evolution of these interacting SNe.

In the case of SN 2007rt the narrow Hα line suggests that the progenitors wind has a velocity similar to that of SN 2005ip (~100 km s^{-1}). The partially resolved features of O III at 200 km s^{-1} suggest we should be able to at least partially resolve a forest of narrow emission lines, if present. Nevertheless even at 507 days post-explosion we do not see this forest of narrow emission lines in the blue, despite the broad features in the continua of the two SNe being similar. The lack of evidence for this forest in our spectrum may be due to the continuum in SN 2007rt consisting of intermediate width emission lines, possibly of permitted/forbidden iron lines, formed in the shocked region. In Sect. 4.3 we noted the depression in the continuum to the blue of the Hβ line. There is another such feature to the red of the [O III 5007] Å line (see Fig. 9). These features are detected in many interacting supernovae such as 1997eg, 1995G,
2005la (Salamanca et al. 2002; Hoffman et al. 2008; Pastorello et al. 2002, 2008b, see their Fig. 4), and coincide well with the broad Fe II absorption features from multiplet 42 (4924, 5018, 5169 Å) present in type Ib/c spectra. However a comparison of late time spectra of SN 2007rt and SN 2005ip, as in Fig. 9, shows convincing evidence that in the spectra of interacting SNe this is due to a lack of emission lines amongst a dense forest, rather than an absorption trough. This is also thought to be the case for SN 2006jc (Pastorello et al. 2007). The non-blackbody like continuum, similarity in the broad features in the blue part of the spectrum with those of many interacting supernovae, and the clear case of a pseudo-continuum in SN 2005ip leads us to believe that SN 2007rt also has a pseudo-continuum. However we can not rule out that a real thermal continuum contributes wholly or partially to the early time spectra of SN 2007rt.

5.2. Properties of the CSM

The CSM electron density and temperature can be inferred from the narrow forbidden lines in the spectrum of SN 2007rt. Coronal lines, such as [FeX] 6374 Å, as well as low ionisation [O III] lines are present, suggesting that there are regions of the CSM with different temperatures and densities. This is not unexpected in the complex environment of the CSM, and the detection of high ionisation Fe lines indicates that X-rays are produced in the shocked region. The presence of [Fe VII] 6086 Å and [Fe X] 6374 Å combined with the absence of [Fe VI] suggests that these lines are formed in a region of the CSM with an electron temperature between 2.5 and 8 x 10^5 K (Bryans, et al. 2008). The [O III] lines, however, are expected to form in cooler regions with electron temperatures of ~1 x 10^5 K (Bryans, et al. 2008). Using the relationship between the [O III] lines and electron density by Osterbrock (1989), as cited in Salamanca et al. (2002), we can determine the density of the CSM. Thus using the temperature range implied above, with the [O III] line intensity ratio (I_{5007}/I_{4959}) of 2.93 the density of the CSM, where the [O III] lines form, is 4.6 x 10^7 cm^-3.

The narrow H_p component is present in the early spectra of SN 2007rt but has completely disappeared in the spectrum taken on 1st May 2008. If we assume that this is due to the ejecta having swept up the entire CSM, we can determine the extent of the CSM. Assuming the explosion date discussed in Sect. 3 and an ejecta velocity of 10000 km s^-1, the unshocked region extends out to a maximum of 2.13 x 10^16 cm. Material ejected from a star at a wind speed of ~100 km s^-1 would take ~70 years to reach such a distance, hence the mass-loss must have occurred on this timescale. However, given the high densities of the CSM, as implied above from the O III lines, it is possible that this narrow H_p feature disappears due to recombination. This explanation has been given for the disappearance of such features in SN 1994aj and SN 1996L (Benetti et al. 1998, 1999).

5.3. Nature of the progenitor star

In Sect. 4.1 we discussed the very narrow P-Cygni feature detected in SN 2007rt, the absorption component of which has a FWHM of 54 km s^-1, and extends out to 128 km s^-1. Narrow P-Cygni profiles have been detected in a number of type II In SNe. However, they appear to fall into two different categories; those with very narrow profiles with the blue edge of the absorption profile extending out to <200 km s^-1 and those with velocities in the range 600–1000 km s^-1. Some supernovae which fall into the latter category are SNe 1994aj, 1994W, 1995G, and 1996L, while those with lower velocities are SNe 1997ab, 1997eg, 2005gj (Chugai & Danziger 1994; Sollerman et al. 1998; Benetti et al. 1998, 1999; Pastorello et al. 2002; Salamanca et al. 1998, 2002; Trundle et al. 2008). As mentioned in Sect. 4.1 these P-Cygni profiles provide insight into the stellar wind velocity of the progenitor star. The high velocities observed in SN 1994W and others are consistent with the wind velocities observed in WR stars (Crowther 2007). Luminous blue variables (LBVs) have slower wind velocities in the range 100–500 km s^-1 (Stahl et al. 2001, 2003; Smith et al. 2007), which may explain some of the
objects in the low velocity category, such as in the case of SN 1997ab. Typically red supergiants have velocities of approximately 10 km s\(^{-1}\) but there are a few cases for which 30–40 km s\(^{-1}\) edge velocities have been detected (viz. VV CMa see Smith et al. 2009b, and references therein). Therefore it cannot be ruled out that the wind velocities of some of these lower velocity objects may be consistent with extreme red supergiants. The expansion velocity of ~128 km s\(^{-1}\) is on the lower extreme of the LBV range, comparable to quiescent LBVs such as HD160529 (Stahl et al. 2003), and is quite high for red supergiants.

Type II spectra show no indication of He spectral lines at optical wavelengths, except for at very early stages (~1 week) when the high temperatures in the ejecta allow for their formation. Type Ib are the only SNe which have He and H present in their spectra, with possibly type Ib showing a trace of H accompanied by He. If the interpretation that the broad He I 5875 Å line in SN 2007rt is formed by a high helium abundance is valid, it suggests that the atmosphere of SN 2007rt’s progenitor has a higher He/H ratio than that of many type II SNe progenitors. This places the progenitor of SN 2007rt as a transitional object between those of normal type IIP’s and those of hydrogen stripped core collapse SNe. The combination of H and He in the ejecta would suggest either the progenitor passed through an LBV phase and has lost a significant amount of its H shell through its previous mass-loss history or that the progenitor is in a more evolved WN or WNH phase, i.e. mass-loss via stellar winds has revealed H-burning products at the stars surface but not He-burning products as would be the case in WC stars. However, the very low (LBV-like) wind velocity of the unshocked material is not consistent with a WR wind, as velocities in such stars are typically greater than 500 km s\(^{-1}\) (Crowther 2007, and references therein). If the progenitor is a WR star, the CSM detected by the narrow H components could be the result of an LBV outburst, which occurred prior to the progenitor entering a WN phase. In this case the progenitor would need to be in a very early stage of the WN phase, as otherwise the LBV wind would be swept up by the WN wind (van Marle et al. 2007). However we should note that there is no clear distinction between quiescent LBVs and WNH stars, as many of the latter are known to be quiescent LBVs (viz. AG Car, see Smith & Conti 2008, and references therein).

5.4. Explanation of the H and He I asymmetries

As discussed in Sect. 4.2, the H\(_{\alpha}\) and He I 5875 Å profiles in the spectra of SN 2007rt are peculiar. An asymmetry is present in these lines from the first spectrum onwards (see Fig. 4). In the last few epochs of our spectral dataset, from 240 days, a blueshift is detected.

5.4.1. Late phase evolution: ~240–507 days post-explosion

Once the temperature in the ejecta has dropped below the threshold for dust grains to condense, dust can form. The presence of dust grains causes a net blueshift due to the absorption of redshifted light. Hence, asymmetric and blueshifted profiles formed as the ejecta expands and cools, can be explained by dust forming in the ejecta. In Fig. 4 it can be seen that the asymmetry of the H\(_{\alpha}\) profile in SN 2007rt increases with time and at late phases become blueshifted with significant absorption of the redshifted light. This behaviour appears to be consistent with the presence of newly formed dust. In addition there is an increasing asymmetry in the He I line. Evidence of such behavior due to dust has been seen in a number of type II SNe, viz. 1987A (Danziger et al. 1989; Lucy et al. 1989). In SN 2007rt this blueshift is first detected in the spectrum taken on day 240 and becomes more pronounced by day 273. At even later epochs (475–507 days) the H\(_{\alpha}\) and He I 5875 Å lines show significant absorption of the redshifted light. Additionally, there is a significant decrease in SN 2007rt’s magnitude during this late phase. The R-band magnitude declines at a rate of 0.01 mag d\(^{-1}\) from 458 to 562 days post-maximum. In the case of type II SN 1987A a clear rise in the IR magnitudes was detected and is accompanied by a decline in the optical band at over 450 days post-explosion, indicating the formation of dust (0.016 mag d\(^{-1}\) at 467–562 days, Whitelock et al. 1989). Hence the formation of dust is the most probable justification for the decline in SN 2007rt’s lightcurve in these latter points.

5.4.2. Early phase evolution: ~102–240 days post-explosion

The explanation of asymmetries in the H and He profiles in the earliest SN 2007rt spectra is uncertain, due in part to the uncertainty in its age. Here we outline two possible scenarios: (1) the object is young and can form dust in the fast expanding ejecta; (2) the broad components are inconsistent with the SNe’s age and it has an asymmetric or bipolar outflow.

As mentioned above the reduced emission in the red wing of line profiles are suggestive of dust formation, however most dust detections have been made in late-time (~300 days) SNe spectra. The asymmetry in the first spectrum, taken approximately 102 days post-explosion, would appear to be inconsistent with the late-time formation of dust. Additionally if dust is invoked to explain the asymmetry in the profiles, an explanation for high ejecta velocities of 10,000 km s\(^{-1}\) at approximately 102 days after explosion is required due to the high energetic explosions implied by such velocities. Typically non-interacting core collapse supernovae have velocities of 10,000 km s\(^{-1}\) and greater only within 30 days of the explosion (Pataet al. 2001, see Fig. 5). At 100 days post-explosion, 7000–5000 km s\(^{-1}\) are more typical expansion velocities. Whilst the age of SN 2007rt is uncertain it is unlikely to be less than one month old, as the SN was first observed 21 days after discovery, was caught post-maximum, and in an interacting SNe such as this the spectrum is expected to be significantly bluer than detected (see Sect. 3.1).

Nevertheless assuming that SN 2007rt has an age significantly less than or equal to 100 days, it is difficult to form dust at an early epoch. Unlike the case of the peculiar Ibn SN 2006jc (Sakon et al. 2007; Mattila et al. 2008; Smith et al. 2008b; Di Carlo et al. 2008; Nozawa et al. 2008), the dust must have formed in the ejecta not in a post-shock region as the asymmetries observed are in the broad rather than the intermediate component. The only other object, for which dust has been invoked to explain early-time fading of the broad component, is SN 2005ip (Smith et al. 2009a). Smith et al. suggest that the dust forms in the fast expanding ejecta, however it is unclear what mechanism would allow for dust formation in the high temperature gas of the ejecta. A possible added support to dust formation at a young age is the detection of IR excess by Fox et al. (2009) from NIR photometry of SN 2005ip from 50–200 days post-discovery.

An alternative scenario requires the presence of an aspherical or bipolar outflow. This scenario does not require such high expansion velocities as is the case above and hence is more consistent with our adopted explosion epoch. It also provides fits to the H\(_{\alpha}\) and He I 5875 Å lines, which are more consistent with their profiles. The profile fit in this case requires a blue and red-shifted
component at velocities in the range 6000–7000 km s\(^{-1}\) with an additional intermediate and narrow component (see Fig. 6). The blue and red-shifted components represent high velocity material moving away from the SN, which may be indicative of an asymmetric outflow of material from the SNe. The profiles seen in SN 2007rt are reminiscent of the double-peaked profiles seen in type Ib/c, viz. the broad-lined Ic, SN 2003jd, and the type Iib, SN 2006T (Maeda et al. 2008; Valenti et al. 2008; Taubenberger et al. 2009). In the case of these latter objects the profile shapes can be explained by aspherical jet-like explosions viewed nearly sideways on (Mazzali et al. 2005; Maeda et al. 2008). Mazzali et al. and Maeda et al. suggest that these double-peaked features can be detected if viewed from angles of 60–90 degrees to the jet axis. For SN 2007rt, there is still a significant amount of H in the shell and any model would need to account for this.

6. Conclusions

We have presented a photometric and spectroscopic analysis of the type IIn supernova SN 2007rt over more than 1 year after discovery. At 102 days post-explosion, SN 2007rt bears a striking resemblance to the type IIn supernovae SN 1988Z, SN 1997eg and SN 2005ip (Stathakis & Sadler 1991; Turatto et al. 1993; Aretxaga et al. 1999; Salamanca et al. 2002; Hoffman et al. 2008; Smith et al. 2009a), with strong narrow/intermediate/broad H\(\alpha\) emission lines, a strong blue continuum, as well as weak narrow emission lines from neutral to highly ionised states (viz. H\(\alpha\), [O III], N \(\pi\), [Fe VII], [Fe X]).

The narrow H\(\alpha\) lines indicate the presence of a H-rich CSM surrounding the SN. An intermediate resolution spectrum of the H\(\alpha\) region resolved the narrow emission feature into a P-Cygni profile with an edge velocity of 128 km s\(^{-1}\). This suggests the SN progenitor underwent mass-loss with velocities at the low end of those detected in LBV winds. The first spectrum contains a strong intermediate H\(\alpha\) component suggesting the ejecta had already begun to interact with the CSM. This is supported by the light curve of SN 2007rt, as it evolves very slowly over the early epochs of our data, declining at a rate of 0.003 mag d\(^{-1}\). By day 240 the narrow H\(\alpha\) component has disappeared and provides an estimate of the maximum extension of 2.13 x 10\(^{16}\) cm for the unshocked CSM shell. Furthermore, a blue shift in the broad H\(\alpha\) feature at this late stage suggests that dust has begun to form in the ejecta.

A broad He I 5875 Å component was also present in SN 2007rt. This is not a typical feature of SNe type IIn, and may be indicative of ejecta with a higher He/H ratio than generally observed in type IIn SNe. It is therefore possible that its progenitor is transitional between those of normal type II’s and hydrogen stripped core-collapse SNe, which as a result of its previous mass-loss history has lost a large amount of its hydrogen shell. There is also a hint of He present in the CSM, and hence the progenitor may be a WNH star in an early stage of evolution or an LBV which has lost a significant amount of H in previous mass-loss events. Throughout the spectral observations, the H\(\alpha\) profiles show a strong asymmetry that increases over time, the red wing being dampened compared to the blue wing. The presence of dust in the ejecta beyond 240 days is clear, however what causes the asymmetry in the earlier spectra is less certain. Two possible scenarios are presented to account for this which cannot be distinguished by our current dataset: (1) the supernova is significantly younger than estimated and dust is formed through some unknown mechanism in the fast expanding ejecta or; (2) an asymmetric or bipolar outflow viewed nearly side on accounts for the asymmetry in the early epochs. The first scenario is similar to that invoked for SN 2005ip by Smith et al. (2009a), however the mechanism for forming dust in the fast expanding ejecta is unclear. The second scenario relies on the SNe being older than one or two months and that the expansion velocity behaves like normal non-interacting core-collapse supernovae.

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Appendix A: Sequence stars in local region of SN 20007rt

The sequence stars used to estimate the SN magnitudes are identified in Fig. A.1 and their magnitudes are presented in Table A.1.

![Fig. A.1](http://www.martin-nicholson.info/1/1a.htm). In addition we are grateful for the support from Aretxaga/Martín-Canas at the TNG, La Palma. C.T. acknowledges financial support from the STFC. F.P.K. is grateful to AWE Aldermaston for the award of a William Penney Fellowship. This paper is based on observations from a number of telescopes: 2.2-m Calar telescope at the German-Spanish Astronomical Center at Calar Alto operated jointly by the Max-Planck-Institut für Astronomie (MPIA) and the Instituto de Astrofísica de Andalucía (CSIC), 1.82-m Copernico telescope at Asiago Observatory operated by Padova Observatory, ALFOSC owned by the Instituto de Astrofísica de Andalucía (IAA) and operated at the Nordic Optical Telescope under agreement between IAA and the NBI/AFG of the Astronomical Observatory of Copenhagen, WHT and the Italian Telescopio Nazionale Galileo (TNG) operated by the Isaac Newton Group, and the Fundació Niv Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) on the island of La Palma at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. Observations were also carried on with the 0.35-m SLOOH telescope at the Teide Observatory (Canary Islands, Spain). SLOOH (http://www.slooh.com) is a subscription-based website enabling affordable, user-friendly control of observatories in Teide, Chile, and Australia.

![Fig. A.1](http://www.martin-nicholson.info/1/1a.htm)
**Table A.1. UBVRI magnitudes of the sequence stars in the field of SN 2007rt.**

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<th>U err</th>
<th>B</th>
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**References**

Blondin, S. 2007, CBET, 1156
Appendix B: Gaussian profile fits to H\textsubscript{\alpha} and He I 5875 Å

Fig. B.1. H\textsubscript{\alpha} profile from each epoch (102, 131, 160, 208, 240, 273, 475, and 497 days after explosion going left-right from top to bottom). The profiles are decomposed into 2 or more components representing the broad, intermediate and narrow velocity components. Note that in the later spectra only the broad and intermediate components are observed. The parameters of these fits are presented in Table 3.
Fig. B.2. Hα profile from each epoch (102, 131, 160, 208, 475, 497, and 507 days after explosion going left-right from top to bottom) decomposed into 3 or more components representing the two broad, the intermediate and narrow velocity components. In the later spectra, only the broad and intermediate components are observed. Parameters for these fits are presented in Table 4.
Fig. B.3. \( \text{He} \ i \ 5875 \ \AA \) profile from each epoch (102, 131, 160, 208, 240, 475, 497, and 507 days after explosion going left-right from top to bottom) decomposed into 3 or more components representing the two broad, the intermediate and narrow velocity components. In the later spectra, only the broad and intermediate components are observed. Parameters for these fits are presented in Table 4.