Spectroscopy of the first resolved strongly lensed Type Ia supernova iPTF16geu

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ABSTRACT

We report the results from spectroscopic observations of the multiple images of the strongly lensed Type Ia supernova (SN Ia), iPTF16geu, obtained with ground based telescopes and the Hubble Space Telescope (HST). From a single epoch of slitless spectroscopy with HST, we can resolve spectra of individual lensed supernova images for the first time. This allows us to perform an independent measurement of the time-delay between the two brightest images, \( \Delta t = 1.4 \pm 0.5 \) days, which is consistent with the time-delay measured from the light-curves.

We also present measurements of narrow emission and absorption lines characterizing the interstellar medium in the SN Ia host galaxy at \( z = 0.4087 \), as well as in the foreground lensing galaxy at \( z = 0.2163 \). We detect strong Na i\( \alpha \) absorption in the host galaxy, indicating that iPTF16geu belongs to a subclass of SNe Ia displaying "anomalously" large Na i\( \alpha \) column densities in comparison to the amount of dust extinction derived from their light curves. For the deflecting galaxy, we refine the measurement of the velocity dispersion, \( \sigma = 129 \pm 4 \) km s\(^{-1}\), which significantly constrains the lens model.

Since the time-delay between the SN images is negligible, we can use unresolved ground based spectroscopy, boosted by a factor \( \sim 70 \) from lensing magnification, to study the properties of a high-z SN Ia with unprecedented signal-to-noise ratio. The spectral properties of the supernova, such as pseudo-Equivalent widths of several absorption features and velocities of the Si ii-line indicate that iPTF16geu, besides being lensed, is a normal SN Ia, indistinguishable from well-studied ones in the local universe, providing support for the use of SNe Ia in precision cosmology. We do not detect any significant deviations of the SN spectral energy distribution from microlensing of the SN photosphere by stars and compact objects in the lensing galaxy.

Key words: gravitational lensing: strong, supernovae: general, supernova: individual (iPTF16geu)

1 INTRODUCTION

More than half a century has passed since Refsdal (1964) proposed to measure the expansion rate of the universe, the Hubble parameter,
2 Observations

The main focus of this paper is the analysis of the ground- and space-based spectroscopic observations of iPTF16geu. In order to accurately account for the lens and host galaxy contribution to the observed SN spectra, we will use the HST and ground-based photometry described in Goobar et al. (2017) and Dhawan et al. (2020).

Figures 1 and 2 illustrate the observations used in this work. Figure 1 shows the ground-based P48, rP60, and HST F625W light-curves of the four SN images summed over all four images (black lines). The epochs of spectroscopic observations are indicated by black, vertical lines.

2.1 Photometry

Dhawan et al. (2020) present HST photometry of the four resolved SN images, and fit the individual light-curves together with the summed photometry from ground based telescopes. For Image 1 (the brightest image, see Fig. 3), they find $T_{\text{max},1} = 57652.80 \pm 0.33$ (MJD, which we will refer to as the time of maximum light) and a stretch $s = 0.99 \pm 0.01$. The measured time delays between the four images are consistent with being less than 1 day and the four lines of sight through the host and lensing galaxy experience differential extinction. Furthermore, the lensing analyses in More et al. (2017) and Mörtsell et al. (2019) indicate that iPTF16geu, especially the brightest image (Image 1), is likely affected by additional "microlensing" from sub-structures in the lens galaxy halo.

We make use of the resolved HST and ground-based SN photometry presented in Goobar et al. (2017) and Dhawan et al. (2020). In Sec. 3, we also use of pre- and post-SN photometry of the lens and host galaxy system from the SDSS, PS1 and 2MASS surveys as well as the HST reference images.

2.2 Spectroscopy

A summary of our spectroscopic observations are listed in Table 1 and the time series of spectra are shown in Fig. 2. In addition to the previously unpublished spectra presented here, we also analyse the early spectra from Goobar et al. (2017) and the GTC+OSIRIS and VLT+XSHOOTER spectra from Cano et al. (2018). All our spectra are available from the WISEREP archive.

The long-slit spectra presented here were reduced in a standard fashion using IRAF routines. To reduce and extract the P200+DBSP

References

Goobar et al. (2017); Suyu et al. (2020). We refer to Oguri (2019) for an excellent review of the field of lensing of explosive transients.

The first case of a spatially resolved SN Ia is iPTF16geu (Goobar et al. 2017), a four-image gravitational lens system and the subject of this work. In accompanying papers (Dhawan et al. 2020; Mörtsell et al. 2019) we report on the photometric measurements of time-delays, extinction and magnification of iPTF16geu as well as the lens model. In addition to the time-delay estimates from photometric measurements, the well known temporal spectral evolution of SNe Ia (Hsiao et al. 2007) can also be used to constrain the time-delay between images, through spatially resolved spectroscopy. We have obtained HST data for this purpose.

The high lensing amplification, $\mu \sim 70$, allows us to obtain very high signal-to-noise ratio spectroscopic observations that can be used to test the "standard candle" nature of SNe Ia, as done previously for PS1-10afx by Petrukhin et al. (2017). Furthermore, the amplification allows for spectroscopy with high spectral resolution, otherwise unfeasible for high-redshift SNe. These observations allow us also to scrutinize the host and lens galaxy properties. The large difference in the relative magnification between the four SN images, in spite of the spatial symmetry, suggests that milli- or micro-lensing by substructures in the lensing galaxy is significant (see e.g., More et al. 2017; Yahalomi et al. 2017; Foxley-Marrable et al. 2018; Mörtsell et al. 2019). The impact of microlensing of strongly lensed SNe has been quantified by Dobler & Keeton (2006) and, more recently, Goldstein et al. (2018); Huber et al. (2019); Pierel & Rodney (2019) carried out simulations including the effect of an expanding SN photosphere to show that microlensing often induces chromatic effects on the supernova spectrum, most noticeable starting about a month after the explosion. Here we explore this possibility using a time series of iPTF16geu spectra.

The paper is organized as follows: First, in Sect. 2 we describe the photometric and spectroscopic data that we will use in our analysis. Then, in Section 3 we construct a model spectral energy distribution (SED) of the lens and host galaxy, that we can subtract from our observed spectra. We also analyse emission and absorption lines in our highest resolution spectra, probing the velocity dispersion of the lens and the interstellar medium of the host galaxy of iPTF16geu. In Sect. 4 we analyse the time-evolution of the SN features, measuring their pseudo-equivalent widths and expansion velocities. In Sect. 5 we analyse our single epoch of slitless spectroscopy with HST, and perform an independent measurement of the time-delay between the brightest SN images. We conclude with a discussion, summary and future outlook in Sect. 6 and 7.
Figure 2. Time series of all spectra of iPTF16geu. The spectra (red lines) have been corrected for lens and host galaxy contamination. Blue lines are reddened Hsiao template SEDs at the same epochs.

Table 1. Log of spectroscopic observations of iPTF16geu used in this analysis.

| UT date      | MJD  | Phase (days) | Telescope+Instrument | Source |
|--------------|------|--------------|----------------------|--------|
| 2016-10-02.23| 57663.23| +7.4         | P60+SEDM             | 1      |
| 2016-10-04.22| 57665.22| +8.8         | P200+DBSP            | 1      |
| 2016-10-06.13| 57667.13| +10.2        | P200+DBSP            | 1      |
| 2016-10-09.20| 57670.70| +12.8        | NOT+ALFOSC           | 1      |
| 2016-10-15.87| 57676.87| +17.1        | GTC+OSIRIS           | 2      |
| 2016-10-18.00| 57679.00| +18.6        | VLT+XSHOOTER         | 2      |
| 2016-10-22.34| 57681.34| +20.3        | DCT+DeVeny           | 3      |
| 2016-10-25.33| 57686.33| +23.8        | Keck+DEIMOS          | 3      |
| 2016-10-26.19| 57687.10| +24.3        | P200+DBSP            | 3      |
| 2016-10-30.01| 57691.01| +27.1        | VLT+XSHOOTER         | 2      |
| 2016-11-02.24| 57694.24| +29.4        | Keck+LRIS            | 3      |
| 2016-11-06.27| 57694.27| +29.4        | HST+WFC3/IR          | 3      |
| 2016-11-16.86| 57710.86| +41.2        | GTC+OSIRIS           | 2      |
| 2016-11-28.21| 57720.21| +47.9        | Keck+LRIS            | 3      |
| 2016-11-30.82| 57722.82| +49.7        | GTC+OSIRIS           | 2      |
| 2016-12-15.81| 57737.81| +60.3        | GTC+OSIRIS           | 2      |
| 2019-05-24.46| 58627.46| -            | P200+DBSP            | 3      |
| 2019-06-26.46| 58660.46| -            | P200+DBSP            | 3      |

1: Goobar et al. (2017), 2: Cano et al. (2018), 3: This work

WFC3/IR GRISMS/G102. The grism spectra were reduced using GRIZLI (see Wang et al. 2018, Brammer 20194), a tool to reduce, model, and extract slitless spectra. GRIZLI first performs raw processing of direct F105W and G102 exposures, makes a composite F105W image, and constructs a source catalog and segmentation map (with various individual internal steps performed with AstroDrizzle and Source Extractor; Bertin & Arnouts 1996). Individual grism exposures are then corrected for contamination from the other sources using iterative contamination modeling, using the masked F105W image of each source as the spatial profile (e.g., as in Abramson et al. 2019).

Composite 2D grism spectra for each source are then constructed from these contamination-corrected individual exposures (see Fig. 4). Finally, we extract optimally-weighted 1D spectra (Horne 1986) for each source from the composite 2D spectra, adopting the collapsed composite masked F105W image trace as the optimal spatial profile. In this analysis, the F105W image and G102 grism spectra are split into two parts, where we extract two separate spectra: the first corresponding to a blend of Images 1, 3, and 4 (Image 1 being the dominant), and a second being Image 2 (the second brightest, south east image).

3 THE IPTF16GEU LENS AND HOST GALAXIES

Unlike the case of e.g. strongly lensed quasars, we are able to separately observe the lens and host galaxy system before and after the SN was active. Besides allowing us to study the lens and host galaxy properties, we can use pre- and post SN data to remove the lens and host galaxy contribution from the observed SN spectra.

Two years after the SN explosion, we obtained a low signal-to-noise spectrum of the lens and host galaxy system combining two epochs of P200+DBSP observations with 900 and 1800 seconds
Figure 3. Left panel: HST template images of the lens and host galaxies obtained after the SN faded. We note that the lens galaxy has a faint, diffuse blue halo. Middle panel: A difference image between the template and SN images (from 2016-10-25). Right panel shows the $F625W - F814W$ color of the lens and host galaxy system from template HST images (zoomed in on the central $1'' \times 1''$). The red contour lines show the brightness distribution in $F814W$, indicating that the bright lens galaxy center has an observed color $F625W - F814W \approx 0.8$ mag, whereas the lensed host galaxy ring has a color that varies between $F625W - F814W = 0.9 - 1.3$ mag.

Figure 4. HST $F105W$ direct imaging (left column), resolved HST $G102$ grism spectra (center), and collapsed $F105W$ trace used for optimal 1D extraction (right) for the lens and host galaxies (top row). Grism spectra for Images 1, 3, and 4 (middle row) and Image 2 (bottom) are separately extracted. The 1D spectra of the image groupings are extracted from the contamination-subtracted grism spectra (center) using the masked $F105W$ trace (right) as the optimal extraction profile (solid black line; other trace shown as dashed grey line).
Figure 5. SED of lens and host galaxies. Purple symbols show broad-band GALEX, SDSS (ugriz), Pan-Starrs (grizy), 2MASS (JHK) and HST photometry of the lens and host galaxies. The blue line is the lensing galaxy at $z = 0.2163$ (reddened by galactic extinction, $E(B-V)_{\text{MW}} = 0.073$ mag), the red line is the host galaxy at $z = 0.4087$ (reddened by extinction in the MW and the lensing galaxy, $E(B-V)_{\text{host}} = 0.30$ mag). The purple line is the sum of both galaxy template spectra. The black line is a P200+DBSP spectrum, observed in 2019 after the SN faded.

exposure time, covering 3500 - 10000 Å (black line in Fig. 5). To further disentangle the contributions from the lens and host galaxies to the total flux over a wider wavelength range, we construct a model spectral template of the combined lens and host galaxies. To do this, we use broad band photometric data of the lens+host system from the SDSS (ugriz filters), Pan-Starrs (grizy filters) and 2MASS (JHK filters) surveys predating the SN, as well as our HST template images ($F390W, F475W, F625W, F814W, F110W$ and $F160W$ filters, observed after the SN faded). We then use the models of the lens and host galaxy light in Dhawan et al. (2020) to compute the fractional fluxes of the lens and host galaxies (blue and red symbols in Fig. 5, respectively) within a 1” diameter aperture for all filters. We then fit for a combination of two galaxy template SEDs (Elliptical/00/Sa/Sb or Sc) from Mannucci et al. (2001) at the lens and host redshifts. Fig. 5 shows the best-fit lens and host galaxy SED (blue and red lines in Fig. 5, respectively) and the total lens+host SED (purple symbols and line).

While we have little information on the morphology of the lens and host galaxy, we note that the fitted Sérsic indices of the central lens galaxy core (within 0.3”) from HST and Keck AO images range between 0.8 - 1.6, which is consistent with that of an Elliptical or a Bulge galaxy. As seen in Fig. 3, there is a faint extended blue halo (possibly spiral arms) around the bright lens galaxy core, and weak emission lines from $H_{\alpha}$, $[N\,\alpha]$ and $[O\,\alpha]$ at the lens rest-frame on top of broader absorption features. Similarly, weak emission lines from $H_{\beta}$, $[N\,\beta]$ and $[O\,\beta]$ are also seen at the host redshift.

Dhawan et al. (2020) used the SN images to measure the differential extinction along the line-of-sight towards the four point-like SN images. To verify the assumptions on the global dust extinction of the host galaxy by the lens, we investigate the color of the lensed host galaxy ring. The $F625W - F814W$ color of a Elliptical (Sa) galaxy template is 0.89 (0.81) mag. Along the galaxy ring, we measure $F625W - F814W = 0.9-1.3$ mag, while the brightest host galaxy spot has a color of $F625W - F814W \approx 1.1$ mag (right panel in Fig. 3). This motivates us to redden the host galaxy SED by $E(B-V) = 0.3$ mag.

3.1 Redshift and velocity dispersion of the lens

In the SN and galaxy spectra we see narrow emission lines from the $[O\,\alpha]$ 13727 doublet, $H_{\alpha}$, $[N\,\alpha]$ (and weak emission from of $[S\,\alpha]$) at the lens galaxy redshift, indicating a low level of star formation.

Goobar et al. (2017) analyzed the emission lines visible in the early, low-resolution, SN spectra and measured the lens galaxy redshift ($z_{\text{lens}} = 0.216$), and gave a first estimate of line-of-sight velocity dispersion, $\sigma_v = 163^{+31}_{-22}$ km s$^{-1}$, of the lensing galaxy from the combined widths of the $H_{\alpha}$ and $[N\,\alpha]$ lines.

Here, we use our highest resolution spectra (two VLT+XSHOOTER spectra) and fit gaussian profiles to the emission lines. We do this after normalizing the spectra, fitting low-order polynomials to the continuum level around the regions of interest. The most prominent emission lines are shown in Fig. 6 for the lens galaxy (top panels) and host galaxy (bottom panels). From these lines we determine the redshift of the lens, $z_{\text{lens}} = 0.2163 \pm 0.0001$.

In the VLT+XSHOOTER spectra, we note that the lens galaxy $H_{\alpha}$ emission line is affected by Balmer absorption from stellar atmospheres (seen from extrapolating the stellar continuum fit, shown as a blue dashed line in the upper right panel of Fig. 6) and hence the true strength is underestimated.

For the lensing galaxy, we measure the equivalent widths (EW) of the Ca $\alpha$ H&K and Na $\Dag$ absorption features to be 11.5 Å and 2.3 Å, respectively. Both features are centered at the lens rest-frame redshift (see Figures 6 and 7).

In order to estimate the velocity dispersion of the lens galaxy, we perform stellar continuum fitting with pPXF (Cappellari & Emselfelt 2004; Cappellari 2017). pPXF models a galaxy spectrum $G$ as a convolution between template spectra $T$ and the line of sight velocity distribution (LOSVD) of the stars $L$:

$$G_{\text{mod}}(x) = T(x) \ast L(x),$$

where $x = \ln \lambda$.

For the VLT+XSHOOTER ($R \approx 5400$) and Keck+DEIMOS ($R \approx 2000$) spectra, we use the high resolution PEGASE models (Le Borgne et al. 2004), spanning the wavelength range 3900 - 6800 Å at a FWHM ~ 0.55 Å and having ages and metallicities in the range $t = 1 - 2 \times 10^4$ Myr and $Z = 0.0004 - 0.1$. We mask the $[O\,\alpha]$ line from the host, and use the restframe wavelength range 3900-4550 Å (to avoid Ca $\alpha$ H&K from the host) in the XSHOOTER spectrum, giving a best-fit velocity dispersion $\sigma_v = 129 \pm 4$ km s$^{-1}$. The data and fit are shown in Fig. 7. This measured velocity dispersion is lower than the previous estimate (Goobar et al. 2017), and matches the expected velocity dispersion $\sigma_{\text{mod}} = 132^{+7}_{-5}$ km s$^{-1}$ from the lens modelling in Mörtsell et al. (2019).

As a consistency check, we also fit our low-resolution Keck+LRIS and post-SN P200+DBSP spectra using the UV-extended MILES templates (eMILES; Vazdekis et al. 2016). These single-age, single-metallicity stellar population spectra and have a resolution of 2.51 Å (FWHM) in the range 3540 – 8950 Å. These spectra yield similar best-fit values of the velocity dispersion, but with larger errorbars (~ 25 km s$^{-1}$).

3.2 The host galaxy of iPTF16geu

Thanks to the high lensing magnification we are able to study the structure and time evolution of interstellar absorption lines for
SNe Ia at cosmological distances, at a level previously only possible by a small subset of very nearby SNe Ia (e.g. Goobar et al. 2014; Ferretti et al. 2016, 2017).

Similar to the lens galaxy, we also detect narrow emission lines from [O ii] λ3727, Hα, [N ii] at the host galaxy redshift. From these lines we determine the and host galaxy redshift, $z_{\text{host}} = 0.4087 \pm 0.0001$ (see right, bottom panel of Fig. 6).

For Na i D, we resolve three distinct, narrow components (FWHM $\sim 44 - 79$ km s$^{-1}$, see left, bottom panel of Fig. 6) at $v_1 = -61$, $v_2 = 23$, $v_3 = 139$ km s$^{-1}$, with respect to the galaxy rest-frame (defined by the emission lines). For the first XSHOOTER epoch at +18.6 days we measure a total Na i EW = 3.9 Å, and for the second epoch EW = 3.3 Å at +27.1 days. The EWs are listed in Table 2.

The equivalent width of the Na i lines is a commonly used proxy for dust reddening, $E(B-V)$ (see e.g. Munari & Zwitter 1997; Poznanski et al. 2011, 2012). It should be noted that these relations are typically well-defined for EW $< 1.0$ Å and that the theoretical relation is between EW and optical depth, $\tau \sim A_V$, rather than the color excess $E(B-V)$. Nonetheless, applying these relations using and $EW_{\text{host}} = 3.9$ Å yields $E(B-V)_{\text{host}} \sim 0.6 - 1.9$ mag. The light-curve fits (Dhawan et al. 2020) indicate that the host extinction is $E(B-V)_{\text{host}} = 0.17 - 0.29$ mag (depending whether the total-to-selective absorption ratio is fixed to $R_V = 2.0$, 3.1 or as a treated as a free parameter). iPTF16geu therefore seems to be another case of a SN Ia displaying "anomalously" strong Na i absorption (Phillips et al. 2013).

We do not detect any absorption lines from Diffuse Interstellar
4 SUPERNOVA FEATURES AND THEIR TIME-EVOLUTION

Cano et al. (2018) found that iPTF16geu can be classified as a high-velocity ($v_{\text{Si II} 6355} = 11950 \pm 140 \ \text{km s}^{-1}$), high-velocity gradient ($v = -110.3 \pm 10.0 \ \text{km s}^{-1}$) and "core-normal" SN Ia. The strength of various features (measured through their pseudo-equivalent widths) argue against SN iPTF16geu being a faint, broad-lined, cool or shallow-silicon SN Ia.

Using more data, and a refined lens and host galaxy template spectrum, we will measure the pseudo-equivalent widths (pEWs) and Si ii line expansion velocities. As demonstrated in Cano et al. (2018), accurate removal of the lens- and host galaxy contribution is crucial in order to measure the intrinsic SN pEWs. For our purposes, we subtract both our observed and model template spectrum from the observations, where the former allows us to measure pEW1 and pEW8. We first subtract the lens and host galaxy contamination from the observed spectra, scaling the observed spectra with a constant factor, so that the subtracted spectra match the template subtracted photometry (this scaling typically varies between 0.8 - 1.2, accounting for imperfect flux calibration, varying degrees of host galaxy removal in the different reduction procedures, etc.). While the spectra could in practice also suffer from wavelength-dependent calibration offsets (due to slit-losses, atmospheric dispersion etc.), we do not attempt to correct for this, since this might erase any chromatic micro-lensing signatures. Furthermore, we de-redden the summed spectra with the best fit lens and host galaxy extinction parameters found by Dhawan et al. (2020), using $E(B-V)_{\text{host}} = 0.18$ mag with $R_{\text{V}}^{\text{host}} = 2.0$, $E(B-V)_{\text{env}} = 0.26$ mag with $R_{\text{env}}^{\text{V}} = 1.8$ (since the ground-based spectra are dominated by the light from Image 1) and $E(B-V)_{\text{MW}} = 0.073$ mag.

To compute the pseudo-equivalent widths (pEWs) and Si ii line expansion velocities, we use the spextractor code (Papadogian-nakis et al., in prep. 5). Instead of fitting a series of gaussians to the absorption features, spextractor measure the pEWs and absorption minima through model-independent gaussian processes.

In our spectra, ranging between +7 to +60 days from peak brightness, we can measure pEW1 (Ca ii H&K), pEW3 (Mg ii), pEW4 (Fe ii), pEW7 (Si ii 6355) and pEW8 (Ca ii IR) (following the conventions in Garavini et al. 2007; Folatelli 2004; Folatelli et al. 2013). Figure 8 shows an example of a lens and host galaxy subtracted, de-reddened VLT+XSHOOTER spectrum from 2016 Oct. 18. It includes the smoothed spectrum (red line), the pEW features and absorption line minima fitted by spextractor.

We measure the Si ii 6355 line expansion velocities for all our spectra. Using data between +7 and +20 days after maximum (although the clear identification with Si ii 6355 is only valid until day ∼+10), we find a linear slope of the Si ii expansion velocity, $v = -82 \pm 13 \ \text{km s}^{-1}$, which is slower than what Cano et al. (2018) reports for the same data ($v = -110 \pm 10 \ \text{km s}^{-1}$, see Fig. 9). Hence, the velocity gradient for iPTF16geu is more comparable to the normal sub-class in Folatelli et al. (2013) ($v = -86 \pm 14 \ \text{km s}^{-1}$), rather than the high-velocity gradient subclass. However, from the linear fit we extrapolate the velocity at $t_{\text{g,max}}$ to be $v_{B,\text{g,max}} = 12100 \pm 220 \ \text{km s}^{-1}$, which would make iPTF16geu a high-velocity SN Ia (following the definitions in Wang et al. 2009; Folatelli et al. 2013). We note that our velocities are systematically higher (by ∼ 400 km/s) than in Cano et al. (2018).

Turning to the pEW measurements, we do not see any significant deviations from the time-evolution of SNe Ia in Folatelli et al. (2013). In Figure 9, the black points show the pEW measurements of iPTF16geu compared to all (red points) or "normal" (blue points and blue shaded region) SNe Ia in Folatelli et al. (2013). However, we note that some measurements are outside the $1\sigma$ range, e.g. late time pEW1 (likely due to improper lens and host galaxy removal), pEW3 and pEW7 (where the telluric corrections are imperfect).

5 TIME-DELAY MEASUREMENTS FROM RESOLVED SPECTRA

In our single epoch of HST spectroscopy, we can resolve two spectra: one spectrum corresponding to Image 2 and one spectrum corresponding to Images 1, 3 and 4. However, Images 3 and 4 are subdominant, contributing with 7% and 5% to the total flux in $F814W$ at this epoch, respectively. Hence, we will treat this spectrum as stemming from Image 1. By comparing the time evolution of spectral features between the spectra, we can in principle provide an independent measurement of the time delays between the SN images. However, in our case we are limited by the coarse spectral resolution. To complicate things further, at the epoch (+29 days) the Si ii absorption feature is no longer well-defined, displaying two or more local minima.

We construct a simple $\chi^2$-statistic, fitting Hsiao template spectra (Hsiao et al. 2007) at different phases to the resolved spectra. We simultaneously fit for residual lens and host galaxy contamination using our template spectrum, and subtract a fraction of that flux (0.80 ± 0.03 and 0.19 ± 0.02 for Images 1 and 2, respectively) from the resolved SN spectra, so that the subtracted SN spectra and Hsiao templates at each phase match the host subtracted $F814W$ photometry.

The best fit phases for the Hsiao templates are $+30.0^{+2.5}_{-2.2}$.
Table 2. Measured pseudo-equivalent widths (pEW) and Si ii λ6355 line velocities for iPTF16geu. Last two columns list the total Na id equivalent widths for the lens and host galaxies from our highest-resolution spectra.

| Phase (days) | pEW1 (Å) | pEW3 (Å) | pEW4 (Å) | pEW7 (Å) | pEW8 (Å) | vSi ii,6355 (10^3 km/s) | Lens Na id EW (Å) | Host Na id EW (Å) |
|--------------|----------|----------|----------|----------|----------|--------------------------|------------------|------------------|
| 7.4          | 103 (19) | 157 (35) | 92 (34)  |          |          | 11.66 (0.47)             |                  |                  |
| 8.8          | 101 (18) | 167 (35) | 117 (32) |          |          | 11.38 (0.53)             |                  |                  |
| 10.2         | 70 (9)   | 177 (25) | 212 (23) | 153 (20) |          | 11.22 (0.97)             |                  |                  |
| 12.8         | 75 (15)  | 256 (38) | 271 (39) | 80 (24)  |          | 11.07 (0.73)             |                  |                  |
| 14.1         | 79 (12)  | 295 (26) | 320 (26) | 95 (15)  |          | 10.85 (0.36)             |          2.4 (0.1)  | 3.9 (0.1)        |
| 16.6         | 64 (14)  | 277 (31) | 291 (30) | 224 (31) | 451 (38) | 11.07 (0.53)             |          2.3 (0.2)  | 3.5 (0.2)        |
| 18.8         | 108 (16) | 283 (28) | 368 (36) | 186 (24) |          | 11.38 (0.53)             |          2.3 (0.1)  | 3.3 (0.1)        |
| 20.2         | 164 (18) | 200 (25) | 370 (40) | 241 (32) |          | 11.22 (0.97)             |          2.3 (0.2)  | 3.5 (0.2)        |
| 21.4         | 129 (37) | 131 (57) | 273 (93) | 230 (73) |          | 11.07 (0.73)             |          2.3 (0.1)  | 3.3 (0.1)        |
| 22.6         | 164 (18) | 200 (25) | 370 (40) | 241 (32) |          | 11.22 (0.97)             |          2.3 (0.2)  | 3.5 (0.2)        |
| 23.8         | 108 (16) | 283 (28) | 368 (36) | 186 (24) |          | 11.38 (0.53)             |          2.3 (0.1)  | 3.3 (0.1)        |
| 25.0         | 129 (37) | 131 (57) | 273 (93) | 230 (73) |          | 11.07 (0.73)             |          2.3 (0.1)  | 3.3 (0.1)        |
| 26.2         | 164 (18) | 200 (25) | 370 (40) | 241 (32) |          | 11.22 (0.97)             |          2.3 (0.2)  | 3.5 (0.2)        |
| 27.4         | 129 (37) | 131 (57) | 273 (93) | 230 (73) |          | 11.07 (0.73)             |          2.3 (0.1)  | 3.3 (0.1)        |

Figure 9. Time evolution of the pEWs for features 1,3,4,7 and 8 together with the Si ii expansion velocity evolution (bottom right panel). Black circles are the measured pEWs after lens- and host galaxy subtraction and de-reddening. Transparent points and shaded bands are individual measurements and the binned mean (±1σ) of low-redshift SNe from Folatelli et al. (2013), for all (red) and “Normal” (blue) SNe Ia in their sample. The black and red dashed lines shows the pEW and velocity evolution of the Hsiao template and SN 2007le, respectively.
Spectroscopy of iPTF16geu

We do note a small dip in the F625W light-curve of Image 1 (∆m = ~0.3 mag, also seen in the summed photometry in Fig. 1) around 50 days after peak brightness. This dip is only seen for Image 1 in two F625W epochs (2016 Nov. 10 and Nov. 15), and is not seen for the other images nor in the other HST filters. Unfortunately, there are no spectroscopic observations during this dip. However, we do see a small decrease in pEW3 just before the onset of the dip.

While the pEW evolution could be a useful tool to detect or constrain chromatic lensing effects, it is difficult to quantify. For example, the pEWs are at all times consistent with the binned mean of the sample of normal SNe Ia in Fiolatelli et al. (2013), while if we compare the pEW evolution to an individual SN, the deviations as a function of wavelength and time can be larger or smaller depending on which SN we choose. Using SNID (Blondin & Tonry 2007) to cross-correlate the iPTF16geu spectra with a library of well studied SNe Ia, SN 2007le (Simon et al. 2009) appears among the top matches. In Figure 9, we show the pEWs and Si ejecta expansion velocity as function of time for iPTF16geu (black symbols) which closely follows the values for SN 2007le (crosses and red dashed lines).

Turning to the strong Na absorption features in the host galaxy of iPTF16geu, it is interesting to note that the deepest absorption feature is the most redshifted, placing iPTF16geu in the “blueshifted subclass” as defined in Sternberg et al. (2011). Phillips et al. (2013) studied a large sample of SNe Ia with high-resolution spectra, and found that all events with anomalously large Na column densities (in comparison to the derived dust extinction from their colors) belonged to this “blueshifted subclass”. We also see a significant decrease of the total Na ID EW in our highest resolution spectra: the Na ID EW goes from 3.9 to 3.3 Å between VLT+XSHOOTER epochs at +18 and +27 days (EW = 3.5 Å in the Keck+DEIMOS spectrum at +24 days).

These facts also make a strong link to SN 2007le (Simon et al. 2009) which also showed strong, blueshifted and time-variable Na absorption (EW ~ 1.6 Å) but was not highly reddened (E(B − V) = 0.27 mag). It has been speculated that these SNe Ia, with strong, blueshifted absorption may belong to a distinct subpopulation of SNe: having systematically higher ejecta velocities and redder colors at maximum brightness, preferentially residing in late-type galaxies (Foley et al. 2012; Maguire et al. 2013). High-resolution spectroscopy of gravitationally lensed SNe thus offer us a way to study the progenitor systems and the explosion properties of high-redshift SNe Ia.

6 DISCUSSION

Much attention has recently been given to microlensing effects, especially how chromatic distortion of the supernova spectra affect light-curve and time-delay measurements (Suyu et al. 2020). While the light-curve analysis and lens modelling indicate that Image 1 (and possibly Image 2) are affected by microlensing, we do not see any clear spectroscopic signs of chromatic effects.
SN images, the time delays can be measured to roughly one day precision (given that e.g. the expansion velocities of absorption lines of the SN is observed at early phases, when the expansion velocity gradient is higher). Since the typical expansion velocity decreases as $v_{\text{exp}}(t) \propto t^{-0.22}$ (Piro & Nakar 2014), spectra at even earlier phases would allow time-delays measurements with precision better than one day.

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