Infant-phase reddening by surface Fe-peak elements in a normal type Ia supernova

Yuan Qi Ni1, Dae-Sik Moon6, Maria R. Drout1, Abigail Polin2,3, David J. Sand4, Santiago González-Gaitán5, Sang Chul Kim6,7, Youngdae Lee6,8, Hong Soo Park6,7, D. Andrew Howell9,10, Peter E. Nugent11,12, Anthony L. Piro2, Peter J. Brown13,14, Luís Galbany15,16, Jamison Burke9,10, Daichi Hiramatsu9,10,17,18, Griffin Hosseinzadeh19, Stefano Valenti19, Niloufar Afsariardchi1, Jennifer E. Andrews4, John Antoniadis20,21,22, Iair Arcavi4, Samuel Wyatt4 and Sheng Yang23,24,25

Type Ia supernovae are thermonuclear explosions of white dwarf stars. They play a central role in the chemical evolution of the Universe and are an important measure of cosmological distances. However, outstanding questions remain about their origins. Despite extensive efforts to obtain natal information from their earliest signals, observations have thus far failed to identify how the majority of them explode. Here, we present infant-phase detections of SN 2018aoz from a very low brightness of $-10.5$ AB magnitude, revealing a hitherto unseen plateau in the $B$ band that results in a rapid redward colour evolution between 1.0 and 12.4 hours after the estimated epoch of first light. The missing $B$-band flux is best explained by line-blanket absorption from Fe-peak elements in the outer 1% of the ejected mass. The observed $B-V$ colour evolution of the supernova also matches the prediction from an over-density of Fe-peak elements in the same outer 1% of the ejected mass, whereas bluer colours are expected from a purely monotonic distribution of Fe-peak elements. The presence of excess nucleosynthetic material in the extreme outer layers of the ejecta points to enhanced surface nuclear burning or extended subsonic mixing processes in some normal type Ia SN explosions.

Type Ia supernovae (SNe) are the main source of Fe-peak elements in the Universe1, and their use in measuring extragalactic distances led to the discovery of accelerated cosmological expansion and dark energy2,3. Despite their fundamental importance, the explosion mechanisms of type Ia SNe remain a matter of extensive debate4, particularly for the ‘normal’ events, which comprise ~70% of their population5. Normal type Ia SNe may be ignited by nuclear burning in a white dwarf when binary accretion or merger causes its mass to reach the critical Chandrasekhar limit ($\sim 1.4 M_\odot$). Alternatively, recent studies have shown that they may also arise from sub-Chandrasekhar-mass white dwarfs via a helium-shell double detonation (He-shell DDet), in which the detonation of a thin helium layer on the surface of the white dwarf subsequently ignites carbon in the core6–8. Normal type Ia SNe may arise from multiple explosion channels, and it is uncertain what fraction of them are produced by different explosion channels. It has been suggested that He-shell DDets can potentially account for up to ~40% of them9.

Historically, most type Ia SNe are discovered and monitored around the peak of their light curves 2–3 weeks post-explosion, when their emission is dominated by the decay of $^{56}$Ni concentrated in the centre of their ejecta. However, multiple explosion processes, such as subsonic mixing10 and surface He burning11, predict over-densities of Fe-peak elements in the shallow outer layers of the ejecta, leading to excess emission and short-lived spectroscopic features in the faint and elusive ‘infant’ phase within a few days post-explosion. Excess red emission identified between 1 and 5 days in at least two spectroscopically peculiar events was interpreted to be from the ashes of a He-shell detonation15,20. For the vast majority of type Ia SNe observed between 1 and 5 days, the rising parts of their light curves match simple power-law profiles21–26, consistent with a centrally concentrated and monotonic distribution of $^{56}$Ni under the ejecta surface. Overall, observations to date have tightened constraints on the distribution of nucleosynthetic elements in normal type Ia SNe, but how they explode remains uncertain13. Deep multicolour observations covering the infant phase within ~1 day post-explosion can shed new light on this longstanding problem.

**Discovery and follow-up observations of SN 2018aoz**

SN 2018aoz was first detected at 00h 54 m on 29 March 2018 Universal Time (UT) in a $B$-band image taken by the Korea Microlensing Telescope Network (KMTNet)27,28 of a field containing...
the elliptical galaxy NGC 3923 (ref. 29) at redshift \( z = 0.00580 \) (Table 1). Unlike in previous studies of type Ia SNe, our observations were obtained in three bands (\( B, V \) and \( I \)) from the moment of first detection, at an average cadence of 4.7 h. The first detections in the \( V \) and \( I \) bands followed 2 min and 2.4 h later, respectively, whereas it was not detected in images from the previous night. The source was also identified by the Distance Less Than 40 Mpc survey (DLT40)\(^{30}\) 1.1 days after the first KMTNet detection, reported to the Transient Name Server at 07 h 25 m on 2 April 2018 UT, and classified as a normal type Ia SN with a spectrum obtained by the Las Cumbres Observatory\(^{11} \) at 09 h 25 m on 2 April 2018 UT. The discovery triggered an extensive follow-up campaign in which ultraviolet, optical and near-infrared imaging and spectroscopy were performed.

Figure 1 compares part of our high-cadence \( UBVri \) light curves of SN 2018aoz (see Supplementary Information for the full ultraviolet to near-infrared light curves) with early light curves of other normal type Ia SNe after Galactic extinction correction (Methods). Note that the KMTNet \( BVI \)-band observations are calibrated to the nearest AAVSO (American Association of Variable Star Observers) standard filters (\( BVI \); see Methods). The \( B \)-band light curve peak absolute magnitude, \( M_{\text{abs}}(B) = -19.32 \text{ mag} \), and decline rate over the first 15 days post-peak, \( \Delta M_{\text{B}}(B) = 1.12 \text{ mag} \)—two parameters commonly used to classify type Ia SNe\(^{31,32} \)—identify SN 2018aoz as a normal type Ia. The early light curves of SN 2018aoz rise faster than most normal events such as SNe 2011fe\(^{21,33} \), 2018oh\(^{17} \), and a normal type Ia. The early light curves of SN 2018aoz rise faster than most normal events such as SNe 2011fe\(^{21,33} \), 2018oh\(^{17} \), and 2017cbv\(^{24} \), which have \( M_{\text{abs}}(B) \) and \( \Delta M_{\text{B}}(B) \) values similar to those of SN 2018aoz, although the total rest-frame rise time of SN 2018aoz from its onset to \( B \)-band maximum (15.32 days) is consistent with events near the lower extreme of the rise time distribution of the normal population (15–22 days)\(^{33} \).

### Earliest observations: \( B \)-band plateau and excess emission

The onset of the light curve (or ‘epoch of first light’) is estimated to be 23 h 54 m on 28 March 2018 UT (modified Julian date (MJD) 58205.9958), or 1.0 ± 0.5 h before the first detection (see below), making it one of the earliest 3d detections for any type Ia SN. Figure 1 (inset) compares the earliest observations of SN 2018aoz to those of other normal type Ia SNe in filters nearest to the \( B \) band. The observations of SN 2018aoz over the first ~0.5 days constitute some of the lowest luminosity signals ever detected from an early type Ia SN—up to a factor of 3 below the first detected luminosity of SN 2011fe\(^{31} \). In this unexplored ‘infant’ phase and depth, the \( B \)-band fluxes are nearly constant (the \( B \)-band plateau) whereas the \( V \) and \( i \) bands rise rapidly at a rate of ~2 mag per day, resulting in an abrupt redward evolution of the \( B \)–\( V \) colour by 1.5 mag between 1.0 h and 12.4 h after first light (Fig. 2). These features have not yet been identified in other type Ia SNe.

To estimate the epoch of first light, we fit a power-law model to the rising light curves of SN 2018aoz (Supplementary Section 1), as typically adopted in the analysis of type Ia SNe\(^{11,17,21-26,35} \). The \( B \)-band light curve during 0–0.5 days was omitted from the fitting to avoid the uncertainty associated with the \( B \)-band plateau. Figure 3 (left panels) compares the best-fit power-law to the observed light curves of the SN over the fitting interval (0–7 days). In the infant phase of 0–0.5 days, faint excess emission over the simple power-law fit is evident in the \( V \) and \( i \) bands, simultaneous with the \( B \)-band plateau. In subsequent epochs, the power-law provides an acceptable fit to the rising light curves, consistent with the vast majority of type Ia SNe such as 2011fe (Fig. 1), whereas there is no evidence for excess emission in SN 2018aoz at the brightness level of the excess emission observed in SNe 2018oh and 2017cbv during 1–5 days.

### Origin of infant-phase emission in the extreme outer ejecta

The appearance of a short-duration \( B \)-band plateau and simultaneous excess emission over the power-law emission almost immediately following the SN explosion would localize the mechanisms responsible for these features to the extreme outer ejecta where the optical depth is lower. However, the short 15.3-day rise time of SN 2018aoz compared to the 18.9-day average for normal type Ia SNe could, in principle, indicate a long ‘dark phase’ between the epochs of explosion and first light due to the time delay for radioactive photons to diffuse out of the ejecta\(^{10} \). To examine the presence of such a dark phase in SN 2018aoz, we estimate the explosion epoch, \( t_{\text{exp}} \), by fitting its photospheric velocity evolution traced by the \( Si\text{\(\nu\)} \) absorption feature with a power-law model that has provided a good fit to other type Ia SNe\(^{10,37} \) (Supplementary Section 2). From the power-law fit to the \( Si\text{\(\nu\)} \) velocity evolution (Supplementary Section 2), we estimate the explosion epoch, \( t_{\text{exp}} = MJD 58205.56 ± 0.7 \) (0.4 days prior to first light). As this method is independent of the distribution of radioactive photons, it is also dark-phase-independent. The difference between the epochs of explosion and first light constrains the dark phase in SN 2018aoz to be \( \lesssim 1 \) day, disfavouring the dark phase explanation for its short rise time among normal events. Instead, the shorter rise time can be attributed to a smaller effective ejecta mass along the line of sight, or a smaller total ejecta mass assuming spherically symmetric ejecta (Supplementary Section 4).

### Table 1 | Properties of SN 2018aoz

| Parameter | Value\(^a\) |
|-----------|------------|
| Sky coordinates (RA, dec.) | (11h 51 m 01.80 s, –28° 44′ 38.48″) |
| Redshift of host galaxy NGC 3923 (ref. 29) | 0.00580 ± 0.00003 |
| First detection (UT, MJD) | 00 h 54 m on 29 March 2018, MJD 58206.03779 |
| Observed peak apparent magnitudes of \( BVI \)-band light curves | 12.81 mag (B), 12.80 mag (V), 13.26 mag (I) |
| Observed peak epochs of \( BVI \)-band light curves | MJD 58221.41 (B), 58221.30 (V), 58218.29 (I) |
| Power-law indices of first light (\( \alpha \)) | 2.24 ± 0.02 (B), 1.99 ± 0.02 (V), 2.26 ± 0.01 (I) |
| Epoch of first light (\( t_{\text{exp}} \)) | MJD 58206.00 ± 0.02 |
| Difference between epochs of first light and first detection | 1.0 ± 0.5 h |
| Post-peak decline rate (\( \Delta M_{\text{B}}(B) \)) | 1.17 ± 0.015 mag |
| Colour stretch parameter (\( s_{\text{sys}} \)) | 0.797 ± 0.019 |
| Peak absolute magnitudes (\( M_{\text{abs}} \)) | -19.32 mag (B), -19.23 mag (V), -18.61 mag (I) |
| Peak \( Si\text{\(\nu\)} \) velocity (\( v_{\text{exp}} \)) | (11.43 ± 0.12) \( \times 10^3 \) km s\(^{-1} \) |
| Explosion epoch (\( t_{\text{exp}} \)) | MJD 58205.6 ± 0.7 |
| Peak luminosity of bolometric light curve (\( L_{\text{peak}} \)) | \( 1.42 \times 10^{45} \) erg s\(^{-1} \) |
| Peak epoch of bolometric light curve (\( L_{\text{exp}} \)) | -1.16 days |
| \( ^{25}Ni \) mass (\( M_{\text{Ni}} \)) | 0.509 ± 0.006 \( M_{\odot} \) |
| \( r_{\text{exp}} \) parameter | 9.51 ± 0.26 days |
| Ejecta mass (\( M_{\text{ej}} \)) | ~ 0.8–1.0 \( M_{\odot} \) |
| Ejecta kinetic energy (\( E_{\text{kin}} \)) | \( -0.6–0.8 \) \( \times 10^{45} \) erg |

\(^{a} \) All time and date values are given in the observer frame. \(^{b} \) From the power-law fit to the \( BVI \)-band early light curves (Supplementary Section 1). \(^{c} \) For the rest-frame \( BVI \)-band light curves (Methods). \(^{d} \) See Supplementary Section 2. \(^{e} \) From the power-law fit to the \( Si\text{\(\nu\)} \) velocity evolution (Supplementary Section 2). \(^{f} \) See Supplementary Section 3. \(^{g} \) From modelling the bolometric luminosity (Supplementary Section 4).
via the following equation derived from a polytropic \((n=3)\) ejecta profile expected for an exploding white dwarf undergoing homologous expansion\(^{36}\):

\[
\frac{\Delta M}{M_{ej}} \approx 2 \times 10^{-2} \left( \frac{\kappa \rho_{ej}}{0.1 \text{ cm}^2 \text{ g}^{-1}} \right)^{-0.88} \left( \frac{M_{ej}}{1.1 \odot} \right)^{0.32} \left( \frac{E_{ej}}{10^{51} \text{ erg}} \right)^{0.44} \left( \frac{t_{exp}}{1 \text{ day}} \right)^{1.76} \odot, \tag{1}
\]

where \(M_{ej}\) and \(E_{ej}\) are the mass and kinetic energy of the SN ejecta, respectively, and \(\kappa \approx 0.1 \text{ cm}^2 \text{ g}^{-1}\) is expected for \(^{56}\)Ni-dominated opacity\(^{36}\). The equation can be rewritten compactly in terms of the parameter \(\tau_{ns}\), the geometric mean of the diffusion and expansion timescales:

\[
\frac{\Delta M}{M_{ej}} \approx 1.3 \left( \frac{t - t_{exp}}{\tau_{ns}} \right)^{1.76} \odot, \quad \tau_{ns} = \left( \frac{\kappa}{13.8} \right)^{1/2} \left( \frac{6M_{ej}}{5E_{ej}} \right)^{1/4}. \tag{2}
\]

Adopting \(\tau_{ns} \approx 9.5\) days from modelling the observed bolometric luminosity of the SN (Sections 3 and 4), this locates the origin of the infant-phase features of SN 2018aoz visible \(\lesssim 1\) day post-explosion within the outer \(\sim 2\)% of the SN-ejected mass along the line of sight.

**Origin of the infant-phase B-band plateau and red B \(\rightarrow\) V colour**

We examine whether the infant-phase B-band plateau and redward B \(\rightarrow\) V colour evolution are consistent with blackbody emission from cooling shock interactions that can be readily expected in early type Ia SNe (for example, ejecta collision with a companion\(^{35}\)). Figure 4 compares the observed spectral energy distribution (SED) of SN 2018aoz in B\(V\) filters at 0.5 days, when the B \(\rightarrow\) V colour peaks, to those of various blackbodies. Clearly, it is impossible to fit all three B\(V\) bands at this epoch with a single blackbody distribution. The V\(i\)-band fluxes alone are consistent with a 13,000 \(\pm\) 5,000 \(K\) blackbody, which is within the expectations for shock-heated SN ejecta\(^{35,40}\). However, accommodating the low B\(V\) flux level requires either unreasonably cold temperatures for early type Ia SNe or a break in the spectrum between the B and V bands (\(\sim 5,000 \text{ K}\)) with \(\geq 70\%\) flux suppression beyondwards of the break (Supplementary Section 6). This indicates that although the underlying emission may be thermal in origin, a suppression of the B\(V\) flux relative to the blackbody distribution is required to reproduce the observed SED of SN 2018aoz during the infant phase. Note that continuous extinction (for example, by circumstellar dust) is unable to explain the suppressions, even for the case of extreme dust extinction (Supplementary Section 6). For a photospheric radius of 2.5 \(\times 10^{14}\) cm at 0.9 days post-explosion—estimated by adopting a polytropic \((n=3)\) ejecta profile\(^{36}\) with \(\tau_{ns} \approx 9.5\) days and the observed Si\(i\) velocity near peak (Table 1) as the characteristic ejecta velocity—the amount of B\(V\) flux suppression needed to explain the observed SED at
Distribution of Fe-peak elements in the extreme outer ejecta

To understand the origin of Fe-peak elements near the ejecta surface in SN 2018aoz, we investigate whether the elements are part of the centrally concentrated and monotonic main distribution of $^{56}$Ni in the ejecta or whether they constitute a distinct radial over-density in a shell (or clump, depending on the three-dimensional distribution). We find that the early light curves of the SN accommodate the presence of a radioactive shell or clump as follows. Figure 3 compares the observed early light curves to those predicted by blackbody models powered by four $^{56}$Ni distributions: a logistic function37 fitted at the ejecta core fitted to the SN light curves during 0–10 days (Supplementary Section 5), representing the main $^{56}$Ni distribution, and the same function with total $^{56}$Ni mass in the outer 0.31% of the SN ejected mass increased to (0.9, 1.8, and 3.6) $\times 10^{-4} M_\odot$. During 1–7 days, the logistic model follows rising behaviour similar to that of the SN luminosity, confirming that the $^{56}$Ni distribution is mainly centrally concentrated and monotonic under the ejecta surface. In the infant phase between 0 and 1 days, however, the pure logistic model underpredicts the observed luminosity in all three $BVI$ bands. Excess radioactive materials is one possible explanation for the luminosity difference, as shown by the models with increased $^{56}$Ni fractions.

The stratification of Fe-peak elements in the ejecta also affects the $B-V$ colour of the SN$^{41,42}$ as their absorption features (Fig. 4) evolve over time. Figure 2 shows that the $B-V$ colour evolution of SN 2018aoz is best explained if the ejecta possesses an over-density of surface Fe-peak elements in addition to a centrally concentrated and monotonic $^{56}$Ni distribution. The observed colour curve is compared to those predicted by radiative transfer calculations of two different ejecta profiles: a purely logistic $^{56}$Ni distribution37 fitted to the light curves of SN 2018aoz during 1–10 days (Supplementary Section 7.2), and a logistic-like $^{56}$Ni distribution with a shell of Fe-peak elements in the outer 1% of the ejected mass from the best-fit He-shell DDet simulation (see below). The model with an Fe-shell peak provides a much better fit to the observed colour evolution from the infant phase to later epochs than the one with a logistic distribution alone, although both models are consistent with the observed colour evolution after ~2 days.

Nature of SN 2018aoz and implications for type Ia SN origins

The presence of an Fe-shell peak or clump near the ejecta surface, as found in SN 2018aoz, has critical implications for the normal type Ia explosion mechanism. Simulations of type Ia SNe have shown that over-densities of Fe-peak elements in the extreme outer ejecta can result from either mixing during a subsonic explosion process or surface nuclear burning during the explosion. The former is predicted by some Chandrasekhar-mass explosion models, in which a white dwarf initially deflagrates subsonically before transitioning into a detonation4. When the explosion is spherically symmetric, the deflagration phase is usually limited to the inner ejecta, whereas a detonation is required to traverse the low-density outer ejecta4, a process that is not expected to produce surface Fe-peak clumps45. However, some simulations have found that asymmetric explosions resulting from off-centre deflagrations can produce surface Fe-peak clumps that are visible from a limited set of favourable viewing angles$^{46,47}$, which could be one possible explanation for the distribution of Fe-peak elements in SN 2018aoz. Separately, a gravitationally confined detonation, where the off-centre deflagration plume rises buoyantly to the progenitor surface, is another scenario that produces a spherical shell of Fe-peak elements near the ejecta surface, although recent simulations have shown that this produces peculiar explosions that are incompatible with normal type Ia SNe48.

Sub-Chandrasekhar-mass He-shell DDets offer another way to produce Fe-peak elements in the outer ejecta. In the case of the spectroskopically peculiar type Ia SN MUSSE1604D$^{19}$, the detonation of a 0.054 $M_\odot$ He-shell was invoked to explain its redward colour
evolution during 1–2 days post-explosion (Fig. 2). To investigate whether this scenario can explain a redward colour evolution with a much shorter timescale and larger amplitude, as observed in SN 2018aoz, we perform a grid of He-shell Det type Ia SN simulations with a range of white dwarf and He-shell masses (Supplementary Section 7.1), fitting the observed light curves during 0–8 days. We obtain the best fit with a small He-shell mass of 0.01 M⊙ on a 1.05 M⊙ white dwarf, which also provides the best match to the near-peak BV I light curves and spectroscopic features. As shown above, this model can indeed explain the B-band suppression (Fig. 4, magenta spectrum) and B−V colour evolution (Fig. 2, magenta curve) of SN 2018aoz. If He-shell Det is the origin of surface Fe-peak elements in SN 2018aoz, it would imply that detonations of He shells as thin as ~0.01 M⊙ can successfully initiate normal type Ia SNe, consistent with the predictions of our simulations and other recent simulations. In our best-fit He-shell Det model for SN 2018aoz, 12.9% of the outer 1% of the ejecta by mass is composed of 56Ni, 52Fe and 48Cr. Although this is comparable to the amount of radioactive material needed to reproduce the infant-phase excess emission in SN 2018aoz (see ‘Distribution of Fe-peak elements in the extreme outer ejecta’), the He-shell Det model underpredicts the emission in the <0.5 day time period (Supplementary Section 7.1), indicating that either the current He-shell Det models do not fully capture radioactive heating at early times or another source of emission is also required (for example, ejecta collision with a companion). Future modelling is necessary to ascertain how the inclusion of more detailed effects would influence the inferred mass of surface Fe-peak elements in SN 2018aoz.

No other type Ia SN has been detected in multiple bands at early enough epochs and sufficient depth to identify the remarkable B-band plateau and extreme redward B−V colour evolution observed during the first ~1 day post-explosion in SN 2018aoz. Thus, such features could be present in many normal type Ia SNe, but likely not all of them. Observationally, based on the colour evolution in later epochs (2–5 days; see Fig. 2), SN 2018aoz appears to belong to the ‘early red’ population of type Ia SNe, which comprises just over half of the normal events, although whether the reported ‘early red/blue’ dichotomy of type Ia SNe truly represents separate populations is still uncertain. Theoretically, we note that two of the three type Ia SN explosion mechanisms described above that can accommodate the presence of surface Fe-peak elements can account for only some fractions of the entire normal type Ia population in current models: He-shell DDets leave almost no unburnt carbon, incompatible with >40% of type Ia SNe, and the strong asymmetry of the gravitationally confined detonation scenario leaves only a small (if existent) set of compatible viewing angles for normal events. SN 2018aoz provides evidence that surface Fe-peak elements are required in at least a fraction of normal type Ia SN explosions.

Methods

Discovery and photometric observations of SN 2018aoz. SN 2018aoz was identified by both the KSP and the DLT40. KSP uses the three 1.6 m telescopes of the KMTNet in Chile, South Africa and Australia to conduct a survey optimized for detecting and continuously monitoring infant SNe in multiple colours. Each telescope of the network is equipped with an identical wide-field charge-coupled device (WFCCD) camera with a field of view over four square degrees and with multiple filters. Between February and July 2018, we conducted high-cadence monitoring of a 2°×2° field containing the nearby elliptical galaxy NGC 3923. We obtained ~700 images of the field with 60 s exposure times at a mean cadence of 4.7 h in each of the BV I bands. (Note that the I-band observations are calibrated to AAVSO I-band magnitudes as described in ‘Photometric calibration’ below.) The typical limiting magnitude for a point source in these images is 21.2−22 mag at a signal-to-noise ratio (S/N) of 5. DLT40 uses the 0.4 m PROMPT telescope at Cerro Tololo Observatory in Chile to conduct a daily cadence survey of nearby galaxies, also optimized for detecting SNe at an early phase. The survey observations are unfiltered with a typical single-epoch depth of ~19–20 mag.

The earliest detections (S/N > 3) of SN 2018aoz were made by KSP at 09h54 m on 29 March 2018 UT (MJD 58206.0738) in the B and V bands obtained with the Chilean KMTNet telescope at the coordinate (RA, dec.) = (11h51 m 01.80 s, −28°44′38.5″) (2000), 3.72 away from the centre of NGC 3923 in the northern direction. Supplementary Fig. 1 (column 2) shows the first BV I-band images, taken within 4 min of each other, obtaining S/N values of 3.5, 4.3 and 1.9, respectively, at the source position. The apparent magnitudes of the source in the images were measured to be 21.57 ± 0.44 mag, 21.26 ± 0.25 mag and 21.97 ± 0.58 mag, respectively, where the error includes contributions from background noise at the source position, from photometric calibration and from B-band S-correction (see below). The source was not detected in B−V−I bands obtained 1.1 days before the first detected source. DLT40 detected the source 1.1 days later and made the discovery report at 07h25 m on 2 April 2018 UT (MJD 58210.4158)−46.

In addition to observations made by KSP and DLT40, we conducted optical photometric observations of SN 2018aoz using 1 m telescopes of the Las Cumbres Observatory (LCO) network of robotic telescopes in conjunction with the Global SN Project between 4.4 and 64 days since first light. These observations are supplemented by ultraviolet observations acquired by the Neil Gehrels Swift Observatory53 Ultra-Violet Optical Telescope (UVOT) and by near-infrared observations from the ANDICAM59 instrument on the SMARTS 1.3 m telescope at Cerro Tololo Observatory. The Swift-UVOT and ANDICAM observations were carried out during the periods of 5.5–59 and 9.1−110 days since first light, respectively.

Photometric calibration. Point-spread function (PSF) photometry of SN 2018aoz on KSP images was performed using the SuperNova Analysis Package (SNAP), a custom python-based pipeline for SN photometry and analysis. A local PSF was obtained by fitting a Moffat function to nearby reference stars and...
simultaneously fitting sky background emission with a first-order polynomial function. The fluxes of SN 2018aoz were obtained by fitting the local PSF near the source location, and the detection S/N is equal to the best-fit flux divided by its uncertainty. The fluxes of SN 2018aoz were performed against 6–9 standard reference stars within 10’ of the source from the AAVSO Photometric All-Sky Survey (APASS) database whose apparent magnitudes are in the range of 15–16 mag; the observations in the BVJ KMTNet filters were calibrated against reference stars in the nearest AAVSO filters (Johnson BV and Sloan i, r, or BVI). The KSP instrumental magnitudes for the AAVSO reference stars were transformed to standard magnitudes using the photometric transformations in our data. Supplementary Fig. 1 provides the measured S/N at the SN position in the bottom-right corner of each stamp image, showing the robust (S/N > 5) detection of the SN in all three bands at 0.11 days, 0.18 days and 0.51 days during its B-band plateau and reddward B – V colour evolution. We confirm the detection of the infant-phase B-band suppression as follows. Supplementary Fig. 1 (column 5) shows stamp images of the SN at 0.51 days, when its B-band flux was lowest compared to the V and i bands and when its B – V colour reached maximum. The images were obtained by binning 2–3 adjacent images within 1.5 h of each other for higher S/N. Each of the BV, V- and i-band images robustly detected the SN with S/N > 7. In these images, we measured the magnitudes of 21.78 ± 0.1 m for the SN, 20.33 ± 0.08 mag, respectively, corresponding to a B-band flux that is 3.7 ± 0.7 times lower than the average of the V and i bands, after applying extinction correction. The detection of the B-band suppression is also confirmed with synchronous BVι fluxes of the SN at 0.5 days (Fig. 5, yellow stars) obtained via Gaussian process light curve interpolation (see below), which show a B-band flux that is 4.4 ± 1.2 times lower than the average of the V and i bands. We note that it is impossible to reconcile this difference with a modification to the flux of the background source located ~0.8” from the position of SN 2018aoz. The background source is 18 times dimmer than the SN at this epoch in B band and incapable of affecting the SN brightness. Consequently, the brightness of the background source relative to the SN would have to increase by factors of 31 and 5.5 in the V and i bands, respectively, relative to its brightness in our deep stacked images, without a corresponding increase in the B band, to lower the inferred V- and i-band fluxes of the SN at this epoch to that of the B band. This is not supported by the centroids of the V- and i-band SN detections at this epoch, which are aligned with the SN position (<0.04” away). With this in mind, we conclude that the inferred suppression of the B-band flux relative to that of the V and i bands is robust.

**Spectroscopy of SN 2018aoz.** We obtained 25 low-resolution optical spectra of SN 2018aoz spanning 4–136.3 days since first light with a combination of the Gemini Multi-Object Spectrograph (GMOS) on the 8.1 m Gemini South telescope, the WFCCD on the 2.5 m du Pont telescope at Las Campanas Observatory, and the FLOYDS spectrographs located on the 2 m Faulkes telescopes of the Las Cumbres Observatory in Siding Spring and Haleakala. Two moderate-resolution spectra were obtained near maximum light in the region around Na I D with the Blue Channel Spectrograph on the MMT telescope. The spectroscopic observations are summarized in Supplementary Table 1.

Spectra from the du Pont and MMT telescopes were reduced using standard tasks within IRAF. Bias and flat-field corrections were performed on the two-dimensional frames, one-dimensional spectra were extracted and wavelength calibration was performed using calibration lamps taken immediately after target exposures. Flux calibrations and telluric corrections were performed with a set of custom IDL scripts using spectrophotometric standards observed on the night. GMOS spectra were reduced in a similar manner, but using the custom ‘gmos’ suite of IRAF tasks. Initial flux calibration for GMOS spectra was performed using the IRAF tasks ‘standard’ and ‘calibrate’, and final scaling was performed based on matching to observed host galaxy fluxes.

A selection of our best low-resolution spectra are presented in Supplementary Fig. 4 (left panel), as well as the two moderate-resolution spectra. (The full set of spectra obtained will be available on the Open SN Catalog and WISEREP.). As seen in the figure, the spectra of SN 2018aoz are dominated by high-velocity absorption features of Ca ii, Fe i/ii, Ni ii and Ti ii at early times. In particular, the presence of silicon features and the absence of hydrogen features confirm its type Ia SN nature. Supplementary Fig. 4 (top-right panel) shows that the spectrum of the SN near peak is nearly identical to normal type Ia SN 1994D and 2002dj.

**Host, distance and extinction.** The host galaxy of SN 2018aoz is NGC 3923, approximately 150 Mpc away. The Swift UVOT and GMOS spectra were reduced in a similar manner, but using the custom ‘gmos’ suite of IRAF tasks. Initial flux calibration for GMOS spectra was performed using the IRAF tasks ‘standard’ and ‘calibrate’, and final scaling was performed based on matching to observed host galaxy fluxes. A selection of our best low-resolution spectra are presented in Supplementary Fig. 4 (left panel), as well as the two moderate-resolution spectra. (The full set of spectra obtained will be available on the Open SN Catalog and WISEREP.). As seen in the figure, the spectra of SN 2018aoz are dominated by high-velocity absorption features of Ca ii, Fe i/ii, Ni ii and Ti ii at early times. In particular, the presence of silicon features and the absence of hydrogen features confirm its type Ia SN nature. Supplementary Fig. 4 (top-right panel) shows that the spectrum of the SN near peak is nearly identical to normal type Ia SN 1994D and 2002dj.

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to extinction corrections of 0.40 mag, 0.29 mag and 0.18 mag for the B, V and I bands, respectively, for an $R_v=3.1$ Fitzpatrick reddening law. The spectra and spectral energy distribution of the SN (Supplementary Information), we adopted Galactic extinction corrections based on the updated reddening law of Fitzpatrick & Massa, which is slightly better than the ultraviolet regime. Given the halo environment of SN 2018aoz, we used our Galactic extinction table for the observer frame using a Voigt doublet profile in each of the two MMT spectra. The mean of the measurements is $E(B-V) = 0.07 \pm 0.01$ mag, consistent with the value from Schlafly & Finkbeiner. The non-detection of NaN in the rest frame of the SN in these spectra constrains the host galaxy extinction to be substantially below the value. Voigt profiles of the Galactic Voigt NaN D to the MMT spectra at $z = 0.0058$, we estimate a 3$\sigma$ upper limit on the equivalent width of NaN D of 0.11 Å, corresponding to $E(B-V) < 0.02$ for the host galaxy, assuming a Milky-Way-like correlation between NaN D and dust extinction. The nature of the background source located $0.8^\circ$ northeast and underlying the position of SN 2018aoz in KSP images (Supplementary Fig. 2) is uncertain, although we consider several possibilities. It can be a source at the redshift of the SN, in which case the low $V$-band luminosity ($-7.7$ mag) and red $V - I$ colour ($-1.6$ mag) of the source are consistent with it being a dwarf galaxy or globular cluster in NGC 3923 (refs. 8, 79). The projected distance of ~86 pc between the SN and the galaxy suggests that the type Ia SN is associated. However, for associated sources, two, although the source apparently does not provide a dusty host environment, as evidenced by the lack of NaN D lines in the rest frame (see above). Alternatively, the source can be a spatially coincident foreground star or background galaxy. Additional observations with higher spatial resolution are required to determine whether the source is separated from the SN or truly underlying it.

**Light curve parameters.** The light curves of SN 2018aoz (Supplementary Fig. 3) display two post-peak decay timescales, consistent with SNe powered by $^{56}$Ni and $^{56}$Co radioactive decay. As typically found in normal type Ia SNe, each of the near-infrared $JHK$-band light curves reaches a primary peak before the $B$ and $V$ bands, followed by a secondary peak associated with the recombination of iron group elements in the ejecta. The light curves of normal type Ia SNe in the photospheric phase from ~10 to 15 days since peak are also known to form a family of functions parameterized by the Phillips parameter, $\Delta M_{B}(B)$, which measures the post-peak decline rate in the $B$-band light curve. To effectively include some peculiar type Ia SNe, such as the rapidly evolving 91bg-like subtype, the colour stretch parameter, $\gamma_{0}$ has been used as an alternative to $\Delta M_{B}(B)$; it is defined by $\gamma_{0} = \Delta M_{B}(30\text{ days})$, where $\Delta M_{B}$ is the time from the $B$-band peak to the maximum post-peak $B - V$ colour. We used SNooPyPy to fit the $BVI$-band light curves of SN 2018aoz with a normal type Ia SN template based on ref. 92, where the fitted parameters are stretch, time, of $B$-band peak ($t_{p}$) and DM. In the fitting process, we applied $K$-correction between the observer and rest-frame filter response functions for each filter (see below) and corrected for Galactic extinction. The best-fit template (Supplementary Fig. 3) provides a good comparison to our observed light curves with $t_{p}$ and DM of 58222.27 $\pm$ 0.02 (MJD) and 31.75 $\pm$ 0.08 mag, respectively. The stretch parameter of the best-fit template is $\gamma_{0} = 0.87$. We give rest-frame magnitudes for SN 2018aoz light-curve fitting the DM and $K$-corrections from the best-fit template and Galactic extinction correction. The $K$-corrections are insubstantial ($<0.02$ mag) given the relatively small redshift of the SN. With rest-frame light curves for the SN and with polynomial fitting, we measured the peak absolute magnitudes of each BN/Vi light-band curve to be $-19.319 \pm 0.009$ mag, $-19.226 \pm 0.009$ mag and $-18.614 \pm 0.012$ mag, respectively. The corrected BN/Vi band light curves each attained their peaks at ~0.86 days, ~0.97 days and ~3.98 days (in the observer frame) prior to $t_{p}$ obtained from the template fitting, respectively. We also measured the Phillips parameter and colour stretch parameter to be $\Delta M_{B}(B) = 1.117 \pm 0.013$ mag and $\gamma_{0} = 0.797 \pm 0.019$, respectively. These parameters are close to the average of normal type Ia SNe, whereas they are inconsistent with subluminous (91bg-like) and luminous (91T-like) events, confirming the classification of SN 2018aoz as a normal type Ia SN.

**Data availability** Source data for Fig. 1 during 0–1 days since first light are provided with this paper, whereas data for the entire single-epoch ultraviolet to near-infrared light curves are provided in the Supplementary Information. All photometric and spectroscopic data are also available from the Open Supernova Catalog and WISEREP. The modelled light curves and spectra of our He-shell DDet simulations are available at https://github.com/miyuaoq/99064I.

**Code availability** We performed light curve template fitting in the post-infant phase using SNooPyPy, available at https://cas.obs.carnegiescience.edu/data/snp/snpyn. Our He-shell DDet models, hydrodynamics and nucleosynthesis simulations were conducted using Castro and the radioactive transfer calculations were conducted using Sedona. The code used to measure the KMTNet light curves of SN 2018aoz, construct the bolometric light curves and generate the analytic $^{56}$Ni-powered light curve models are available at https://github.com/miyuaoq/SNP. IREF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
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Author contributions

Y.Q.N. conducted most of the analyses under the supervision of D.-S.M. and M.R.D. D.-S.M. is the principal investigator of the KSP that detected the infant-phase features of SN 2018aoz and wrote the KSP pipeline. M.R.D. led the collaboration between the KSP and other partners. Y.Q.N., D.-S.M. and M.R.D. co-drafted the manuscript. A.P. conducted the He-shell DDT simulations under the supervision of P.N. D.-S.M., M.R.D., Y.Q.N., N.A., S.G.-G., S.C.K., Y.L., H.S.P., J.A., A.G.-Y., S.B.C., G.P. and S.D.R. are members of the KSP. N.A., D.-S.M., M.R.D., R.G.C. and C.D.M. are members of the Canadian Gemini South observing programme for the KSP. H.S.P., D.-S.M., S.C.K. and Y.L. are members of the Korean Gemini South observing programme for the KSP. A.L.P. performed the shock breakout modelling. P.I.B. led the Swift program for ultraviolet observations with help from S.B.C. L.G. and G.P. obtained the ANDICAM near-infrared observations. D.I.S. and S.V. co-led the DLT40 programme. J.H., D.E.B., Y.K. and S.W. contributed to the operation of the DLT40 programme. S.Y. built the machine-learning implementation for the DLT40 survey. K.A.B., Y.D., J.E.A. and N.S. are members of the DLT40 team who obtained the Keck and MMT spectra. S.-M.C. and Y.L. helped operate the KMTNet. D.A.H., C.M., I.A., J.B., D.H. and G.H. contributed to the LCO photometry, and the FLOYDS spectroscopy. M.R.D., R.L.B., T.W.-S.H., S.D.M., N.M. and J.R. contributed to the du Pont WFCCD and Magellan spectra. All of the authors contributed to the discussion.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Dae-Sik Moon.

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