

Signatures of anti-social mass loss in the ordinary Type II SN 2024bch

A non-interacting supernova with early high-ionisation features

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Received 24 September 2024 / Accepted 12 September 2025

ABSTRACT

In this paper we analyse the spectro-photometric properties of the Type II supernova SN 2024bch, which exploded in NGC 3206 at a distance of 19.9 Mpc. Its early spectra are characterised by narrow high-ionisation emission lines, which are often interpreted as signatures of ongoing interaction between rapidly expanding ejecta and a confined dense circumstellar medium. However, we provide a model for the bolometric light curve of the transient that does not require sources of energy other than radioactive decays and H recombination. Our model can reproduce the bolometric light curve of SN 2024bch if we adopt an ejected mass of $M_{\text{bulk}} \approx 5 M_{\odot}$ surrounded by an extended envelope of only $0.2 M_{\odot}$ with an outer radius $R_{\text{env}} = 7.0 \times 10^{13}$ cm. Accurate modelling focused on the radioactive part of the light curve, which accounts for incomplete γ -ray trapping, gives a ^{56}Ni mass of $0.048 M_{\odot}$. We propose that narrow lines are powered by Bowen fluorescence that is induced by scattering of He II Ly α photons. Simple light travel time calculations based on the maximum phase of the narrow emission lines place the inner radius of the H-rich, un-shocked shell at a radius $\approx 4.4 \times 10^{15}$ cm, consistent with no interaction occurring between the ejecta and the surrounding circumstellar material during the initial weeks of evolution. Possible signatures of interaction appear only ~ 69 days after the explosion, although the resulting conversion of kinetic energy into radiation does not seem to contribute significantly to the total luminosity of the transient.

Key words. circumstellar matter – supernovae: general – supernovae: individual: SN 2024bch

1. Introduction

Core-collapse supernovae (CC SNe) are the endpoint of the evolution of massive stars ($M \gtrsim 8\text{--}9 M_{\odot}$; Heger et al. 2003). Hydrogen-rich CC SNe (called ‘Type II’ SNe) are the most common kind of explosion, with a further classification based on their photometric evolution, which either shows a ‘plateau’ (Type IIP) or a ‘linear’ (Type IIL) decline after maximum light (Hillier & Dessart 2019). It has been suggested that linearly evolving Type II SNe arise from stars that are partially depleted of their outer H layer, with relatively large radii ($\sim 10^3 R_{\odot}$; Blinnikov & Bartunov 1993) compared to the more compact red supergiant (RSG) progenitors associated with Type IIP SNe (see e.g. Smartt 2009).

Narrow emission lines (full-width-at-half-maximum – FWHM – $10^2\text{--}10^3 \text{ km s}^{-1}$) are generally associated with SNe that explode within an extended circumstellar medium (CSM), where such features dominate the observed spectra throughout the entire evolution of the transients, as in the case of the H-rich Type IIn (e.g. Schlegel 1990; Chevalier & Fransson 1994) and He-rich Type Ibn SNe (e.g. Pastorello et al. 2016; see also

Smith 2017 and Blinnikov 2017 for more recent reviews). The collision of the rapidly expanding SN ejecta ($\sim 10^4 \text{ km s}^{-1}$) with the surrounding medium and the subsequent efficient conversion of kinetic energy into radiation may also contribute significantly to the energy output of these transients and produce slow-evolving transients (see e.g. Taddia et al. 2013; Fransson et al. 2014; Tartaglia et al. 2020; Taddia et al. 2020).

Early observations (from a few hours to a few days after the explosion; see e.g. Tartaglia et al. 2021, and references therein) of CC SNe may also show narrow, high-ionisation lines (e.g. He II, N III and, occasionally, C III/IV and N IV/V, O IV/V; see Gal-Yam et al. 2014; Yaron et al. 2017; Bruch et al. 2023). These features are believed to arise from shells that are expelled during the very last evolutionary stages of the progenitors and hence may reflect physical and chemical properties of their outer layers. In this scenario, early narrow features would be the result of photo-ionisation from the SN shock breakout (the first electromagnetic signal from a SN; e.g. Ensman & Burrows 1992; Tominaga et al. 2011). The presence of a surrounding shell may drastically extend the duration of the shock breakout signal, which, in Type II SNe, is expected to have a timescale $\gtrsim 100$ s at most (see e.g. Moriya et al. 2015, and references therein), depending on the radius of the progenitor star. An extension of

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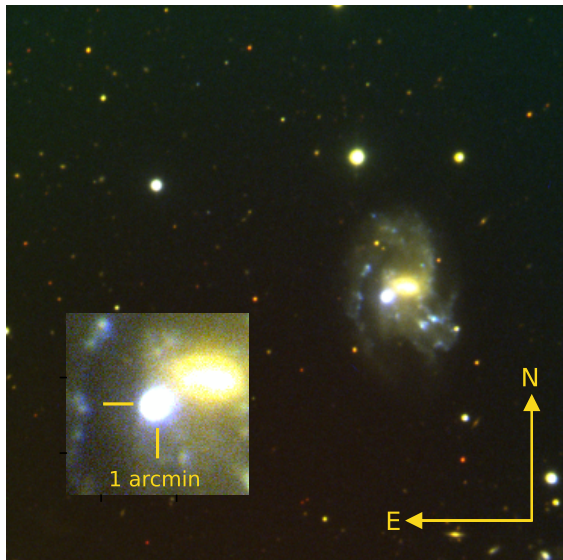


Fig. 1. Colour image of SN 2024bch and its host galaxy NGC 3206, obtained combining u -, g -, r -, and i -band data obtained on 2024 February 5 with the 1.82 m Copernico telescope with AFOSC. The transient is the bright source in the middle of the inset.

a few days may have different explanations, including photon diffusion in a dense CSM (e.g. Balberg & Loeb 2011) and an aspherical explosion (e.g. Suzuki & Shigeyama 2010). Energetic photons produced in shocked regions may also help to increase the lifespan of narrow lines, until the emitting shell is reached and swept away by the expanding SN ejecta. This scenario, on the other hand, should also result in a drastic change in the profiles of narrow features, which is typically not observed. Inflated envelopes have also been invoked to explain the relatively long duration of the shock breakout signal of the Type Ib SN 2008D (Soderberg et al. 2008; Modjaz et al. 2009). Moriya et al. (2015) argued that such an extension may also affect the early spectroscopic evolution of SNe that arise from H-rich progenitors.

High-ionisation features were observed in early spectra of Type II SNe, including SNe 1983K (Niemela et al. 1985; Phillips et al. 1990), 1998S (Leonard et al. 2000; Shivvers et al. 2015), 2006bp (Quimby et al. 2007), PTF11iqb (Smith et al. 2015), LSQ13fn (Polshaw et al. 2016), 2013fs (Yaron et al. 2017), 2014G (Terreran et al. 2016), 2016bkv (Hosseinzadeh et al. 2018), 2017ahn (Tartaglia et al. 2021), 2020pni (Terreran et al. 2022), and 2020tlf (Jacobson-Galán et al. 2022). More recent and well-studied transients that show similar early features include SN 2022jox (Andrews et al. 2024) and the nearby 2023ixf (e.g. Jacobson-Galán et al. 2023; Smith et al. 2023) and thanks to modern dedicated surveys, such as Distance Less Than 40 Mpc (DLT40; Tartaglia et al. 2018) and Zwicky Transient Facility (ZTF; Graham et al. 2019; Bellm et al. 2019; Masci et al. 2019), the number of discoveries has increased dramatically in recent years. Bruch et al. (2023) claim that the rate of SNe that show such features is expected to be relatively high (>30% at 95% confidence level).

Here we report the results of our analysis of the UV to Optical data of SN 2024bch, which were obtained soon after discovery and cover up to the early nebular phases (corresponding to the first seasonal gap). Analysis of later data will be performed and presented in a forthcoming paper once SN 2024bch is again observable using ground-based facilities. The transient

was discovered on 2024 January 29.27 UT (Wiggins 2024) in the nearby SB(s)cd NGC 3206 (de Vaucouleurs et al. 1991), at $\alpha = 10:21:49.740$, $\delta = +56:55:40.51$ [J2000] (see Fig. 1), which, at a distance of 19.9 ± 4.1 Mpc (Tully et al. 2016) and adopting an inclination of $61^\circ 1'$ (as reported in the HyperLeda database¹; Makarov et al. 2014) corresponds to a de-projected distance of 3.9 kpc from the host centre. The SN was confirmed by ongoing transient surveys² such as the Gravitational-wave Optical Transient Observer (GOTO; Steeghs et al. 2022), the Asteroid impact early warning system (ATLAS; Smith et al. 2020), ZTF, and the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS; Chambers et al. 2016) within the Young Supernova Experiment (YSE; Jones et al. 2021); it was assigned the internal names GOTO24hm, ATLAS24bmx, ZTF24aaghpeh, and PS24aap, respectively. Additional photometric points were later provided by the Mobile Astronomical System of Telescope-Robots (MASTER; Lipunov et al. 2004) and by the ESA Gaia Photometric Science Alerts Team³, who further labelled the transient MASTER OT J102149.74+565540.4 and Gaia24bdk. Low-resolution spectroscopy was used to classify SN 2024bch as a young SN with high-ionisation features (Balcon 2024; Mujortova et al. 2024). We then started our UV to optical follow-up campaign detailed in Sect 2, which revealed a spectro-photometric evolution consistent with that of a Type II SN, with narrow features that disappeared a few days after discovery and little or no contribution from a source of energy in addition to the ‘canonical’ H recombination and radioactive decays, as we discuss in Sect. 3. A summary of our main results is reported in Sect. 4.

2. Observations and data reduction

The follow-up campaign of SN 2024bch started soon after discovery (corresponding to 2024 January 29.29 UT; Wiggins 2024), with early photometry obtained on 2024 January 29.92 UT and low-resolution spectroscopy on 2024 January 29.95 UT (see Table 1). Optical observations were mostly carried out with facilities of the Istituto Nazionale di Astrofisica (INAF) – Osservatorio Astronomico di Padova (i.e., the 1.82 m Copernico with the Asiago Faint Object Spectrograph and Camera – AFOSC – and the 69/92 cm Schmidt with a G4-16000LC Moravian camera, both located in Asiago). Additional *ugriz* photometry were provided by the Wide-field Optical Telescope (WOT), a 67/91 cm Schmidt telescope equipped with an Apogee Aspen CG16M camera located at the Campo Imperatore observatory in l’Aquila (Italy). These data were reduced using the dedicated pipeline SuperNOva Photometry (SNOOPY⁴) fitting the point spread function (PSF) computed on selected non-saturated stars in the field and zero-point calibration using stars from the Sloan Digital Sky Survey (SDSS) catalogue (Data Release 17 – DDR17; Abdurro’uf et al. 2022). Further details on the reduction steps within SNOOPY are available in Tartaglia (2016).

Near ultra-violet (NUV) observations were carried out using the 0.3 m Ultra-Violet Optical Telescope (UVOT) on board the Swift Gamma Ray Burst Explorer (Gehrels & Swift 2004). These were reduced using HEASOFT v. 6.33 (Nasa High Energy Astrophysics Science Archive Research Center (Heasarc) 2014) on pre-processed images

¹ <http://leda.univ-lyon1.fr>

² <https://www.wis-tns.org/object/2024bch>

³ <http://gsaweb.ast.cam.ac.uk/alerts>

⁴ <https://graspa.oapd.inaf.it/ecsnoopy.html>

Table 1. Log of the spectroscopic observations of SN 2024bch.

Date	JD	Phase (days)	Telescope+Instrument	Grism/grating	Range Å	Resolution ($\lambda/\Delta\lambda$)	Exposure (s)
20240129	2460339.45	+1.40	Ekar182+AFOSC	Gr04	3600 – 8200	310	1200
20240129	2460339.47	+1.42	Ekar182+AFOSC	VPH6+VPH7	3600 – 9200	380 + 420	900 + 900
20240130	2460340.48	+2.44	Ekar182+AFOSC	VPH6+VPH7	3600 – 9200	380 + 420	1800 + 1800
20240201	2460341.50	+3.45	Ekar182+AFOSC	VPH6+VPH7	3300 – 8800	380 + 420	2 × (1200 + 1200)
20240201	2460341.56	+3.51	Ekar182+AFOSC	VPH4	6300 – 7000	3500	2 × 1800
20240204	2460345.33	+7	T122+B&C	300tr	3300 – 7400	740	3 × 1800
20240205	2460346.38	+8	Ekar182+AFOSC	VPH6+VPH7	3300 – 8800	380 + 420	1200 + 1200
20240213	2460354.46	+16	T122+B&C	600tr	5000 – 7400	1900	3 × 1800
20240310	2460380.34	+42	Ekar182+AFOSC	VPH7	3600 – 7200	420	900
20240317	2460386.51	+48	TNG+DOLOres	LRB+LRR	3600 – 9200	580 + 710	900 + 900
20240406	2460407.45	+69	Ekar182+AFOSC	VPH7	3800 – 7200	250	900
20240412	2460413.49	+75	Ekar182+AFOSC	VPHD1 (blue+red)	3600 – 9200	1200 + 730	2700
20240515	2460445.83	+107	TNG+DOLOres	LRB	3600 – 8100	380	1800
20240515	2460446.47	+108	TNG+DOLOres	VHRV+VHRR	4800 – 7800	1530 + 2510	2700 + 2700
20240616	2460476.40	+138	TNG+DOLOres	LRB+LRR	3600 – 9200	580 + 710	1200 + 1200
20240630	2460492.42	+154	TNG+DOLOres	LRB	3600 – 8100	580	2700

Notes. Ekar182: 1.82 m Copernico telescope at the Asiago observatory (Mount Ekar) with the ‘Asiago Faint Object Spectrograph and Camera’ (AFOSC); T122: 1.22 m Galileo telescope at the Osservatorio Astrofisico di Asiago; TNG: 3.58 m Telescopio Nazionale Galileo at La Palma (Canary Islands, Spain) with the ‘Device Optimised for the Low Resolution’ (DOLOres) camera. Phases refer to the estimated epoch of the SN explosion.

retrieved from the Swift archive⁵, following the prescription of Brown et al. (2009). The field of SN 2024bch was also monitored by ZTF and we later used its forced-photometry service (Masci et al. 2019) to collect extra *g*- and *r*-band epochs that spanned a period of approximately 4 years prior discovery. UV and *UBV* photometry were both calibrated in the Vega photometric system, while *ugriz* magnitudes were referred to the AB system. Optical spectroscopy was reduced using the FOSCGUI pipeline⁶ designed for the reduction of AFOSC data and performing standard IRAF (Tody 1986, 1993) reduction steps through PYRAF (Science Software Branch at STScI 2012).

3. Analysis and modelling

3.1. Photometric evolution

The photometric monitoring of SN 2024bch started soon after its discovery (≈ 0.4 days after the report by Wiggins 2024, see Section 1). The GOTO collaboration later provided an earlier discovery on 2024 January 29.05 UT (~ 0.5 days earlier), with a non-detection on 2024 January 28.04 UT, which corresponds to JD = 2460337.5. If we take the midpoint between the GOTO reported epochs, we then assume the explosion occurred on JD = 2460338.0 \pm 0.5 and refer phases to this epoch. Forced photometry on archival ZTF images (Masci et al. 2019) did not show evidence of variability down to limiting magnitudes of $g > 20.5$, $r > 20.6$ mag approximately 4 years prior to discovery, which rules out pre-SN outbursts with an absolute peak magnitude brighter than ≈ -11 mag.

Details on the instruments used and data reduction can be found in Sect. 2 while light curves are shown in Figure 2. The early evolution is fast, with rise times that span from ≈ 4.4 to ≈ 16.3 days, in the *u*- and *z*-band, respectively, which were estimated using fifth order polynomials to the early light curve and

adopting the explosion epoch reported above. Within the first ~ 1.6 days after explosion, optical magnitudes rise at an average rate of 3 mag day⁻¹, which confirms that SN 2024bch was discovered very soon after explosion.

By following Anderson et al. (2014) (see also Gutiérrez et al. 2014), we inferred *V*-band photometric quantities to be compared with those available in the literature (see Table 2). These included the end of the initial steeper decline of the plateau phase, t_{tran} , the mid-point of the plateau to linear decline transition, t_{PT} , the end of the plateau phase, t_{end} , and the corresponding absolute magnitude, M_{end} (see e.g. Fig. 1 in Anderson et al. 2014). We could identify the two distinct phases of the decline after maximum, which consist of a fast steeper decline, followed by the slower plateau phase with slopes s_1 and s_2 , respectively, while in agreement with Anderson et al. (2014), we referred to the slope of the radioactive tail using the s_3 parameter. We computed t_{tran} , t_{end} , and t_{TP} using the mid-points between the last and first epochs of adjacent phases and we estimated their errors adding uncertainties on the explosion epoch and those due to gaps in the light curves (i.e., semi-amplitudes among adjacent phases) in quadrature. When we adopted the most recent redshift-independent distance for NGC 3206 (19.9 ± 4.1 Mpc, which corresponds to a distance modulus $\mu = 31.49 \pm 0.45$ mag; Tully et al. 2016), we inferred a *V*-band peak absolute magnitude -17.71 ± 0.03 mag (where the uncertainty on the distance modulus of 0.45 mag was not included), with the maximum light occurring at +7.7 days. After maximum, at $t < t_{\text{tran}} = +44.4 \pm 2.0$ days, we inferred $s_1 = 3.41 \pm 0.18$ mag/100 days by performing 10^4 Monte Carlo simulations. Mean values and standard deviations of the resulting distributions were taken for s_1 , s_2 , and s_3 and their uncertainties. At later phases, the light curve evolves more slowly, with a slope $s_2 = 1.83 \pm 0.18$ mag/100 days, up to $t_{\text{end}} = 67.5 \pm 1.1$ days, which results in a length of the optically thick phase (‘plateau duration’) of $Pd = 77.2 \pm 4.6$ days. Both s_1 and s_2 are higher than the mean values inferred by Gutiérrez et al. (2014) for their sample of 52 Type II SNe. The

⁵ <https://swift.gsfc.nasa.gov/archive/>

⁶ <https://sngroup.oapd.inaf.it/foscgui.html>

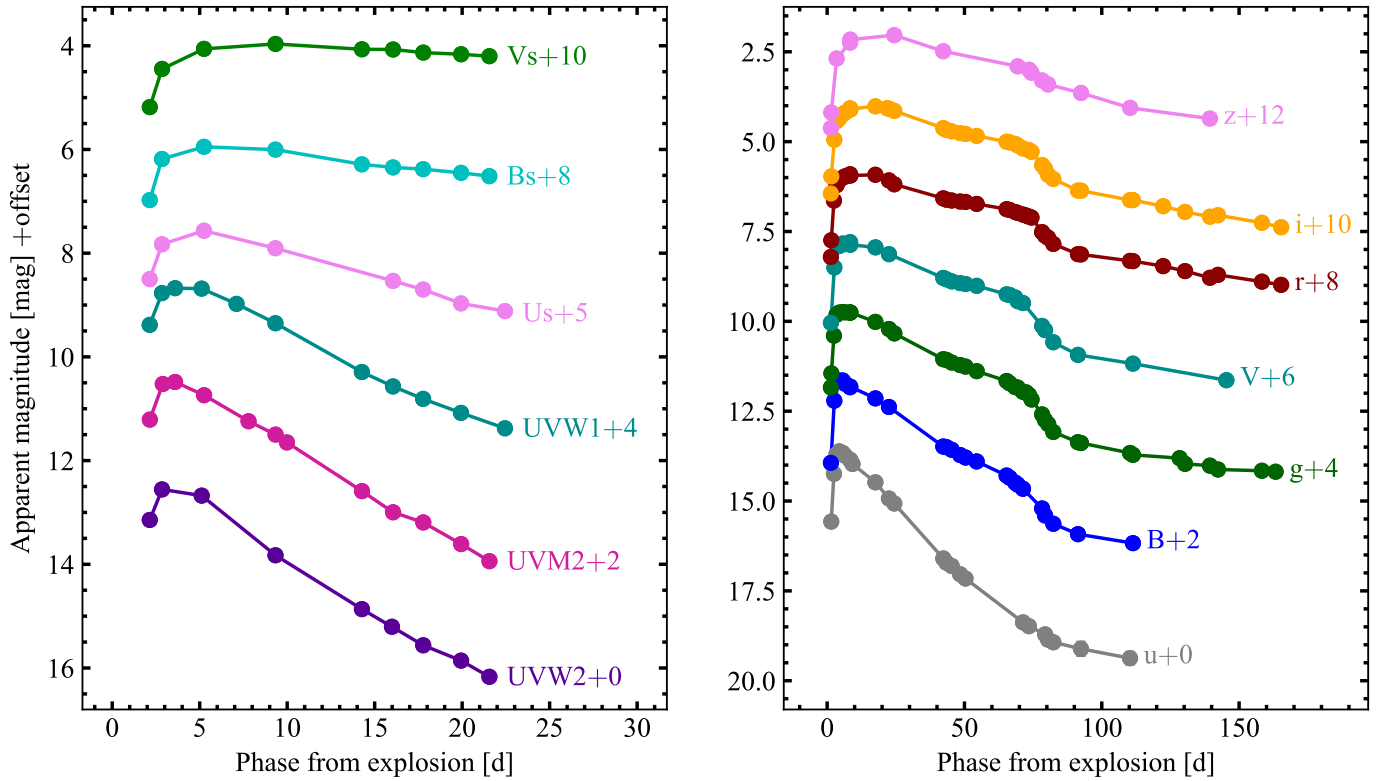


Fig. 2. UltraViolet Optical Telescope (UVOT) (*w2, m2 w1 u b v*; **left**) and (**right**) optical *ugBVriz* light curves of SN 2024bch. Magnitudes were not corrected for extinction. UV and *BV* magnitudes were calibrated in the Vega and *griz* magnitudes in the AB photometric systems.

derived s_2 value is also relatively large if compared to samples of well-studied SNe II (see Arcavi et al. 2012; Sanders et al. 2015; Valenti et al. 2016), in particular to those of Faran et al. (2014a) and Faran et al. (2014b), who set the maximum slope for the plateau phase of Type IIP SNe to ≈ 0.25 mag/100 days. This suggests that SN 2024bch belongs to the linearly declining Type II SNe class. At $t \geq +67.5$ days the light curve rapidly drops, with a decline of ≈ 1.7 mag within the following ≈ 25 days. At $t \geq 91$ days, the *V*-band light curve settles on the radioactive tail, with a slope $s_3 \approx 1.3$ mag/100 days.

In Fig. 3, we compare the photometric evolution of SN 2024bch to those of a sub-sample of Type II SNe that show high-ionisation lines in their early spectra. Among these, SNe 1998S, 2014G, 2017ahn, 2020pni, 2022jox, and 2023ixf are those that show similar early features over a comparable period after estimated explosion epochs. While the different temperature evolution is highlighted by the $u - g$ colours, we note a remarkable similarity among the $g - r$ and $B - V$ light curves. In addition, the early $u - g$ evolution shows a rapid evolution from relatively red to blue colours within approximately the first 3 days after explosion in all selected objects (see the inset in Fig. 3).

3.2. Modelling of the bolometric light curve

The bolometric light curve was inferred by fitting a blackbody to the spectral energy distribution (SED) computed at each epoch, which provided estimates of the photospheric radius, temperature, and corresponding luminosity. At early epochs with available UV data ($t < +25$ days), we interpolated light curves at the epochs of the UV photometry, while at later times the interpo-

Table 2. *V*-band light curve parameters of SN 2024bch.

Parameter	Value (err)
t_0	60337.5(0.5)
M_V	-17.71(0.03) mag
M_{end}	-16.26(0.03) mag
M_{tail}	-14.60(0.09) mag
t_{M_V}	60345.2(0.5)
s_1	3.41(0.18) mag/100 days
s_2	1.83(0.18) mag/100 days
s_3	1.31(0.23) mag/100 days
t_{tran}	44.4(2.0) days
t_{end}	67.46(1.14) days
Pd	77.2(4.6) days

Notes. Reported epochs are modified Julian dates: MJDs.

lation was performed with respect to the *r*-band light curve (the best sampled one). To avoid extrapolation, UV fluxes beyond +25 days were excluded; however, UV fluxes estimated from the blackbody fit were incorporated into luminosity calculations via the Stefan-Boltzmann law. The SEDs were inferred by adopting zero points and λ_{eff} reported in the Spanish Virtual Observatory (SVO⁷; Rodrigo et al. 2012; Rodrigo & Solano 2020) database, which refers to values in the AB or Vega systems, according to the calibration adopted for each filter (see Section 2). The resulting photometry was corrected for a Galactic reddening $E(B - V) = 0.013$ mag (Schlafly & Finkbeiner 2011), consid-

⁷ <http://svo2.cab.inta-csic.es/theory/fps/>

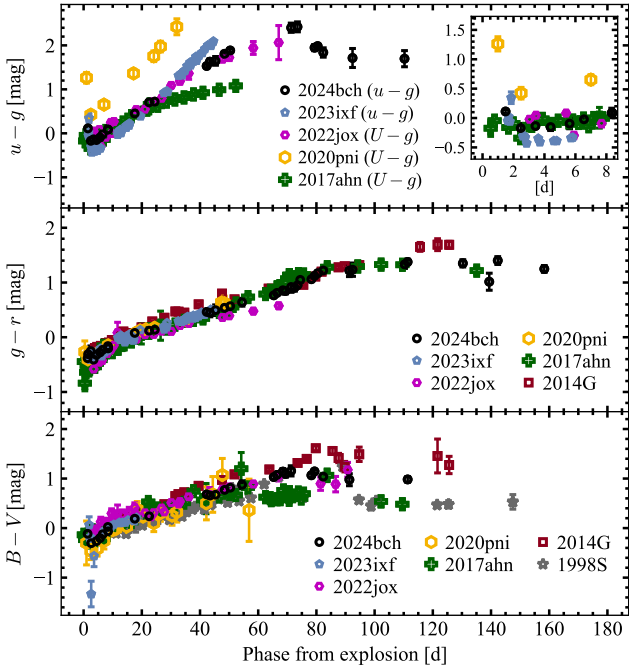


Fig. 3. Colour evolution of SN 2024bch compared to those of selected transients that show high-ionisation features in their early spectra. Objects were selected from those with a similar evolution in their main features (including the duration of the narrow features and SN type) with data available in the literature. In the upper panel, the evolution of the $U - g$ colours for SNe 2017ahn, 2020pni, and 2022jox was included, since u -band photometry for these objects was not available. U -band magnitudes for these objects were converted in the AB photometric system adopting the Vega – AB magnitude conversions reported in Blanton & Roweis (2007). In the same panel, the inset includes a zoom-in of the $u/U - g$ early evolution, which shows a rapid decrease in the colours within approximately the first 3 days after explosion for all the selected objects (see the main text). Phases refer to the estimated explosion epochs reported in the literature. Light curves of SN 2023ixf were collected from Li et al. (2024) and Zimmerman et al. (2024).

ering a negligible contribution of the local environment to the total reddening, as we did not detect Na I D absorption features at the host redshift in the SN spectra. The resulting evolution of temperature, radius, and bolometric luminosity assuming a distance of 19.9 ± 4.1 Mpc is reported in Table 3. The evolution of both the photospheric temperature and radius already suggests the presence of a relatively low-mass ejected shell that rapidly cools down, and little or no contribution from alternative sources of energy, such as efficient conversion of kinetic energy into radiation through shocks (see Fig. 4). To explore this scenario, we tried to reproduce the bolometric light curve of SN 2024bch using the model provided by Nagy & Vinkó (2016). In this model, the light curve results from the contribution of two distinct regions: a massive ‘bulk’ of ejecta surrounded by a less massive envelope (see also Salmaso et al. 2023). The model assumes homologous expansion of the ejecta, spherical symmetry, and constant opacity ($0.34, \text{cm}^2, \text{g}^{-1}$ for a H-rich medium with solar composition; Rybicki & Lightman 1986; Lodders 2019). Radiation transport is treated using the diffusion approximation, and the bolometric luminosity is only powered by radiation generated from ^{56}Ni radioactive decay, energy released during gas expansion and cooling, and H recombination (see Arnett & Fu 1989; Nagy et al. 2014). Nagy & Vinkó

Table 3. Parameters of the blackbody fit to the SEDs of SN 2024bch.

Phase (days)	T_{ph} (err) (K)	R_{ph} (err) (10^{14} cm)	L_{bol} (err) (10^{42} erg s^{-1})
+2.2	16289(75)	2.506(0.026)	3.15(0.10)
+2.9	15163(88)	3.658(0.041)	5.04(0.16)
+3.6	13663(73)	4.59(0.10)	5.24(0.17)
+5.3	11993(47)	5.92(0.10)	5.17(0.13)
+7.8	10338(40)	7.49(0.10)	4.56(0.12)
+9.3	9601(31)	8.24(0.10)	4.11(0.10)
+10.0	9308(31)	8.59(0.10)	3.95(0.10)
+14.3	7789(23)	10.66(0.11)	2.98(0.12)
+16.1	7299(21)	11.62(0.12)	2.73(0.13)
+17.8	6941(19)	12.37(0.13)	2.53(0.15)

Notes. Evolution of the photospheric temperature and radius and the corresponding bolometric luminosity of SN 2024bch. Errors are the 1σ uncertainties derived by CURVE_FIT (see the main text). Phases refer to the estimated epoch of the SN explosion. The table is published in its entirety in a machine-readable format, available at the CDS. A portion is shown here for guidance regarding its form and content.

(2016) further assume a density structure for the supernova ejecta that consists of an inner region with constant density up to a dimensionless radius x_0 , and an outer region characterised by either an exponential or power-law density profile. Furthermore, they report that a constant density profile for the outer H-rich envelope is particularly effective in fitting the plateau phase of many Type II SNe, which is consistent with the prescription of Arnett & Fu (1989). For our analysis, we employed both a flat (constant) density profile and a power-law profile ($\rho \propto r^{-2}$) for the outer region (see e.g. Moriya et al. 2011), noting that this choice minimally affects the overall fit and only influences the derived envelope mass. Following the formalism reported in Chatzopoulos et al. (2012) (see their Eq. 4), we also introduced an additional diffusion time term (t_{CSM}), which simulates the presence of an optically thick CSM along the line of sight. Although observational evidence suggests the need for a ‘detached’ CSM (e.g. early high-ionisation features and the observed rise in the bolometric light curve), we note that this component does not add a further powering mechanism (see also Valerin et al. 2025): no extra energy is provided by ejecta-CSM interaction. We found that the early, sharp peak of SN 2024bch is compatible with the energy radiated by a $0.2 M_{\odot}$ cooling envelope characterised by a low diffusion time. The longer-lasting plateau phase is well constrained if we adopt $5 M_{\odot}$ of ejecta containing $4.3 \times 10^{-2} M_{\odot}$ of ^{56}Ni . Although this value does not take into account incomplete γ -ray trapping, it is comparable to the one discussed later in this section that results from a more accurate analysis of the late light curve. This is also similar to the mean value of $0.037 \pm 0.005 M_{\odot}$ found by Rodríguez et al. (2021) for their sample of 109 Type II SNe. The velocities adopted for both the bulk and the envelope are $\approx 7500 \text{ km s}^{-1}$, which is comparable to the ejecta velocities derived from the spectral analysis (see Section 3.3). This is of paramount importance given the partial degeneracy between the model parameters (e.g. a larger v_{ej} would give a larger M_{ej}). Velocity measurements from the minima of the P-Cygni features allow us to constrain the characteristic velocity of the gas, thereby enabling a more reliable estimate of the ejected mass. In Fig. 5, the resulting model is compared to the observed bolometric luminosity of SN 2024bch, while the parameters used are reported in Table 4. The best model was obtained by generating a grid of over 50 models and selecting

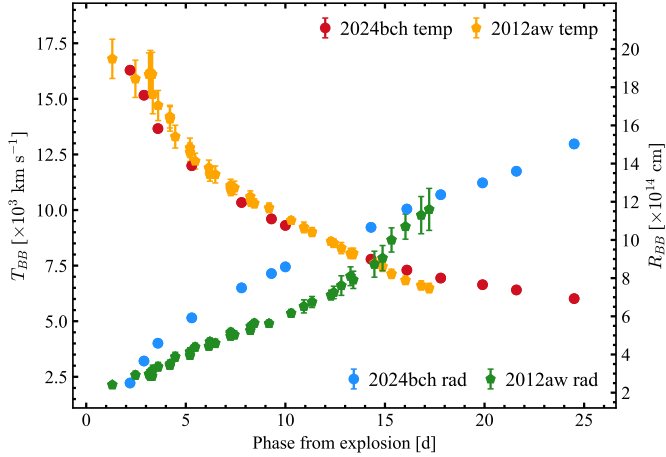


Fig. 4. Evolution of the radius and temperature inferred from the blackbody fit to the early SED of SN 2024bch compared to those of SN 2012aw (Dall’Ora et al. 2014) computed using the same approach.

the one with the lowest root mean square error with respect to the observed data.

At $t \gtrsim +85$ days the bolometric light curve settles on the radioactive tail, where the luminosity output is dominated by deposition and re-emission of the γ -rays produced in the reaction chain $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$. With an e-folding time of 8.8 days, the ^{56}Ni to ^{56}Co decay releases energy during the early phase of the light curve. Its luminosity contribution is delayed by the diffusion time within the bulk of the ejecta and mixed with the emission of the surrounding cooling gas. Instead, ^{56}Co has a much longer lifetime (111.4 days; Nadyozhin 1994; Junde 1999), and the last part of the radioactive chain is therefore expected to shape the late light curves of CC SNe, after the end of the recombination-dominated phase. The predicted luminosity output during the ^{56}Co -decay phase is given by

$$L = 9.92 \times 10^{41} \frac{M_{^{56}\text{Ni}}}{0.07 M_{\odot}} \left(e^{-t/111.4\text{d}} - e^{-t/8.8\text{d}} \right) \text{ erg s}^{-1}. \quad (1)$$

Equation (1) assumes full trapping of the γ -rays produced during the decays and instantaneous re-emission of the deposited energy (Jerkstrand et al. 2012). The late evolution of SN 2024bch, on the other hand, slightly deviates from that expected by Eq. (1) and seems to evolve faster (see Fig. 6). A similar behaviour was observed in the stripped-envelope (SE) SNe 1983N, 1983V, and 1993J (Clocchiatti et al. 1996, 1997; Richmond et al. 1994) and, more recently, in the linearly declining Type II SNe 2014G and 2017ahn (Terreran et al. 2016; Tartaglia et al. 2021, both show a spectro-photometric evolution similar to SN 2024bch) and attributed to incomplete trapping of γ -rays produced in radioactive decays. Following Clocchiatti & Wheeler (1997), we then included the additional term

$$L(t) = L_0 \left(1 - e^{-\tau_0/t^2} \right), \quad (2)$$

where L_0 is given by Eq. (1) and τ_0 is a full-trapping characteristic timescale that can be expressed as

$$\tau_0 = \left(C \kappa_{\gamma} \frac{M_{ej}^2}{E_k} \right)^{1/2}, \quad (3)$$

with M_{ej} and E_k being the mass and kinetic energy of the SN ejecta, respectively, κ_{γ} γ -ray opacity, and C a constant that can

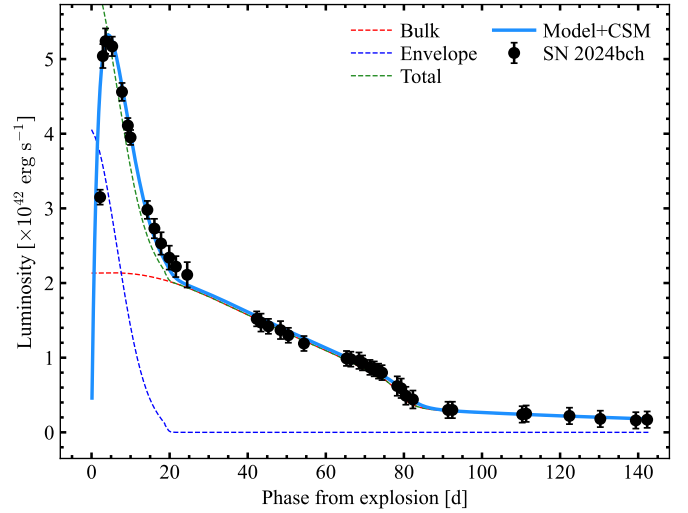


Fig. 5. Evolution of the bolometric luminosity of SN 2024bch along with the model used to reproduce the observed data. Dashed lines represent the luminosity contribution from both the envelope and the bulk of the ejecta. The solid green line is the sum of the two components, while the solid light blue line shows the contribution of the extra diffusion time introduced by the CSM.

be expressed analytically by $C = (\delta - 3)^2 [8\pi(\delta - 1)(\delta - 5)]^{-1}$ for a radioactive medium with a density profile $\rho(r, t) \propto r^{\delta}(t)$. Fitting Eq. (2) to the late light curve of SN 2024bch, we inferred a ^{56}Ni mass of $0.048 \pm 0.003 M_{\odot}$ and $\tau_0 = 200 \pm 50$ days, where values and uncertainties were obtained by performing 10^4 Monte Carlo simulations. Assuming a typical E_k of 10^{51} erg, $\kappa_{\gamma} = 0.06 \text{ cm}^2 \text{ g}^{-1}$ (Morozova et al. 2015) and $\delta = 0$, including $\tau_0 \simeq 200$ days in Eq. (3) then gives a $M_{ej} \simeq 4.5 M_{\odot}$. Both $M_{^{56}\text{Ni}}$ and M_{ej} are in agreement with the masses predicted by our simple model described above (0.043 and $5.2 M_{\odot}$; see Table 4). The derived ^{56}Ni mass, in particular, is very similar to the Ni mass found for the Type II SN 2022jox ($0.04 M_{\odot}$; Andrews et al. 2024) and is consistent with mean values inferred by statistical studies on CC SNe (see the discussion above).

3.3. Spectroscopic evolution

Early spectra ($t \gtrsim +1.4$ days; see Fig. 7) show narrow emission lines over a blue continuum ($T \gtrsim 1.8 \times 10^4$ K), similar to those observed in H-rich interacting SNe (SNe IIn; Schlegel 1990; Smith 2017), with broad wings due to electron scattering occurring in a dense, relatively slow-moving CSM (see Chugai 2001; Huang & Chevalier 2018). The most prominent features are H Balmer lines ($H\alpha$, $H\beta$, $H\gamma$, and $H\delta$), He II $\lambda 4686$, N III $\lambda 4641$, as well as the CIV doublet $\lambda\lambda 5801, 5812$. The presence of N III $\lambda 4641$ also suggests that $\lambda 4103$ likely contaminates the flux of $H\gamma$. At +2.4 days we also identify a faint feature that corresponds to He II $\lambda 5412$. This is the only transition of the He II Pickering-Fowler series (Osterbrock & Ferland 2006) that does not form a blend with H Balmer lines, which suggests that He II $\lambda 6560$, $\lambda 4859$, and $\lambda 4339$ also contribute to the fluxes of $H\alpha$, $H\beta$ and $H\gamma$, respectively. The signal-to-noise ratio (S/N) of spectra obtained at +1.40 and +1.42 days is not sufficient to rule out the presence of this feature at earlier phases as well.

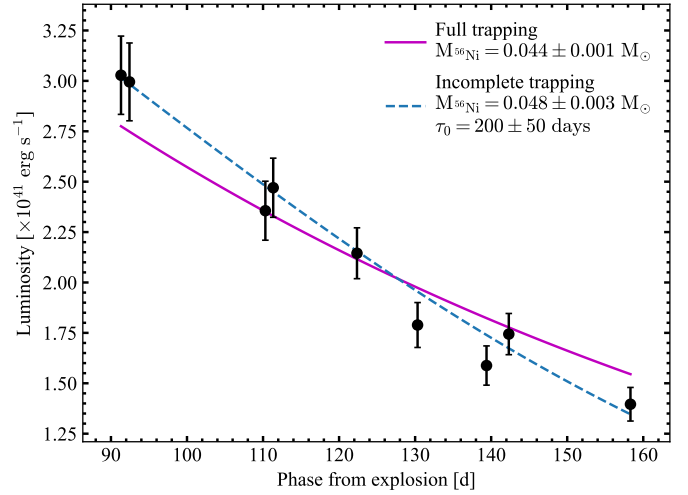
In Fig. 8, we also compare the $H\alpha$ region in the medium resolution spectrum of SN 2024bch ($R \sim 3500$) obtained at +3.51 days with the one obtained at a similar epoch for

Table 4. Parameters used in the models displayed in Fig. 5.

^{56}Ni (M_{\odot})	$M(\text{bulk})$ (M_{\odot})	$E_k(\text{bulk})$ (erg)	$E_{\text{th}}(\text{bulk})$ (erg)	$R(\text{bulk})$ (cm)	$M(\text{env})$ (M_{\odot})	$E_k(\text{env})$ (erg)	$E_{\text{th}}(\text{env})$ (erg)	$R(\text{env})$ (cm)	t_{CSM} (days)
4.3×10^{-2}	5.0	1.65×10^{51}	5.0×10^{50}	3.5×10^{13}	0.2	7×10^{49}	1.9×10^{49}	7.0×10^{13}	1.4

SN 1998S (Shivvers et al. 2015). SN 2024bch shows a similar profile, with broad wings due to electron scattering in the unshocked circumstellar material, which also emits other narrow high-ionisation features visible up to $\approx +8$ days. Although broad wings in relatively narrow emission lines (as in the case of Type IIn SNe) have often been interpreted as an additional emission component from underlying fast-moving SN ejecta or shocked regions (see e.g. Turatto et al. 1993), Chugai (2001) showed that multiple scattering of photons by free electrons is able to reproduce the whole line profile in SN 1998S without invoking additional components (see also Huang & Chevalier 2018, for a more recent discussion on the process), adopting a Thomson optical depth of the shell of at least $\tau \sim 3-4$ at this epoch (for an electron temperature $T_e \approx (2.5-3.0) \times 10^4$ K). Based on the remarkable similarities between the two objects, we can therefore assume a similar optical depth for the circumstellar environment of SN 2024bch. To further investigate the similarities between the two transients, we compare their spectroscopic evolution up to ≈ 140 days in Fig. 9. SN 2024bch exhibits a more rapid evolution, with high-ionisation features disappearing within the first ≈ 8 days. The spectro-photometric evolution of SN 1998S was successfully reproduced by Dessart et al. (2016) through radiation hydrodynamics and radiative transfer modelling, based on a scenario where the explosion occurred within a dense medium and a significant fraction of the SN luminosity is powered by ejecta-CSM interaction. In their ‘model A’, typical SN ejecta ($\sim 10 M_{\odot}$, with an $E_k = 10^{51}$ erg) collide with an outer dense shell formed through a wind expanding at $v_w = 10^2$ km s $^{-1}$, characterised by a mass loss rate of $0.1 M_{\odot} \text{ yr}^{-1}$. This intense mass loss episode lasted 3.5 yr and ended ~ 3 yr before the SN explosion, producing a shell with an inner radius of 1.0×10^{15} cm extending out to 2.1×10^{15} cm, where its density drops sharply, a configuration similar to that proposed by Chugai et al. (2004) for the Type IIn SN 1994W. Figures 9 and 10 show that, although this model is able to reproduce the spectroscopic evolution of both transients (with SN 2024bch showing a faster spectroscopic evolution), it fails to match both the rise and the peak luminosity of SN 2024bch. The faster rise time and fainter bolometric light curve of SN 2024bch reinforce our claim that interaction makes only a marginal, if any, contribution to its luminosity output.

Narrow high-ionisation lines in early spectra are often attributed to a confined shell of gas expelled during the very late evolutionary stages of the progenitor, which is rapidly overtaken by the expanding SN ejecta. The engine that provides the energetic photons responsible for the ionisation of this gas is typically identified as the conversion of ejecta kinetic energy into radiation, as happens in interacting transients (see Chevalier & Fransson 2003, and references therein). The early evolution of SN 2024bch, on the other hand, does not show clear signatures of ongoing ejecta-CSM interaction, with a rapidly evolving SED that is consistent with a freely expanding photosphere where the contribution of an extra source of energy is not required to model its early bolometric light curve (see Section 3.1). In addition, while in most cases the strength of narrow features progressively declines, in SN 2024bch we note a rapid increase in their integrated luminosity up to $\sim +2.44$ days

**Fig. 6.** Evolution of the late bolometric luminosity of SN 2024bch with respect to the r -band light curve (see the main text), including the fit on the radioactive tail. The fit assuming full γ -ray trapping is also reported.

(except for $H\alpha$, where the maximum occurs at $+3.40$ days, which suggests a larger radius for the H-rich region). After maximum, the luminosity of narrow features rapidly declines until $t \approx +7$ days, when they fade below the continuum level. As discussed in Sect. 3.1, the increase in the flux of narrow lines does not correspond to a similar evolution of the pseudo-continuum temperature, although optical spectra do show an apparent increase in their slope at $\lambda < 5000$ Å. The same effect was observed in the early spectra of SN 1998S (see Leonard et al. 2000) and explained by invoking a non-standard extinction law or the presence of dust ‘echoing’ the SN light from earlier epochs. As for SN 1998S, a single blackbody cannot reproduce the spectral continuum at $+2.4$ days, which would suggest a similar interpretation for SN 2024bch. While a non-standard extinction law seems implausible due to the negligible reddening along the line of sight of SN 2024bch, a light echo may be supported by the peculiar evolution of the narrow lines, as discussed below. We note, on the other hand, that the SED of SN 2024bch is well reproduced by a blackbody if we include fluxes obtained from UV photometry, which rules out the need for a hotter source of energy or a non-standard extinction law. This also highlights the importance of UV data when the peak of the emission is at bluer, or much bluer wavelengths than those covered by optical spectra.

We note all narrow lines are blueshifted, with peaks progressively shifting towards their rest wavelengths. In $H\alpha$ (the most prominent line) the shift decreases from ≈ 240 to ≈ 30 km s $^{-1}$ up to $+3.4$ days and similar values are measured from the other emission lines, although these may be affected by the lower S/N and the contamination of other emission features, as discussed above. This is not the expected evolution for an ionised CSM accelerated by SN radiation. Radiative acceleration has already

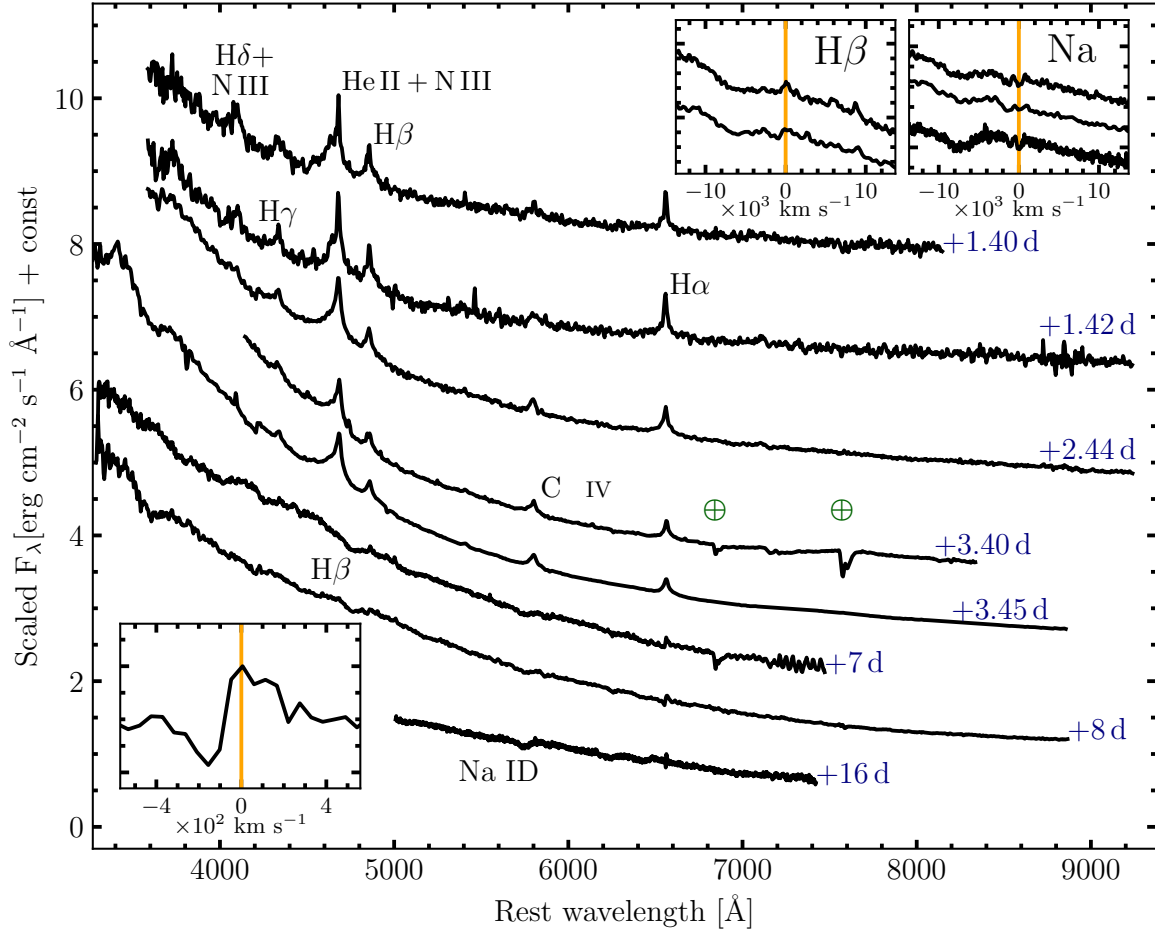


Fig. 7. Early spectroscopic evolution of SN 2024bch (up to +16 days). Spectra were not corrected for Galactic extinction along the line of sight. The circle with cross, \oplus , symbols mark the position of the main telluric features. Zoom-in panels show the H β and He I/Na ID regions (at +7 and +8 days for H β , and +7, +8, and +16 days for Na ID) and H α , with expansion velocities referred to the rest-frame wavelengths marked with vertical yellow lines. Rest-frame phases refer to the estimated explosion epoch.

been discussed for other objects (e.g. SNe 2010jl, 2015da and 2023ixf Fransson et al. 2014; Tartaglia et al. 2020; Smith et al. 2023; Zimmerman et al. 2024) and it can be recognised by a progressive increase in the blueshift of the line peaks. Since in SN 2024bch we see the opposite, we can assume a negligible acceleration of the CSM by the SN radiation field. The radius at which radiative acceleration does not efficiently affect the CSM velocity ($\sim 10^{15}$ cm for SN 2024bch) may provide a lower limit for the inner CSM radius. In gas shells of this size, light travel time and light echoes become both relevant in shaping the observed spectral features. The evolution of narrow peaks towards their rest wavelengths in SN 2024bch may then be interpreted as the contribution of emitting regions with progressively smaller velocity components along the line of sight. In a CSM geometry similar to that presented by Miller et al. (2010, see e.g. their Fig. 6), at early phases one would detect narrow features emitted by the region closest to Earth, blueshifted by ≈ 240 km s $^{-1}$ due to its motion towards the observer. As time progresses, the observer would be reached by photons emitted by more distant regions, with a progressively smaller velocity component along the line of sight. Consequently, at later phases, the emission peaks would be blueshifted by only ≈ 30 km s $^{-1}$. This scenario would also explain the luminosity evolution of narrow lines due to the progressive increase in the emitting

volume. The luminosity peak would in fact be expected when the emission is dominated by light from the inner shell layers on the opposite side with respect to the observer. This is because we expect the inner part of the shell to be the most affected by the SN light, hence the luminosity of narrow features is likely dominated by photons emitted in this region. In this context, the epoch at which narrow features reach their maximum luminosity can also be used to infer an independent estimate of the inner CSM radius through the light travel time ($R_{\text{in}} \simeq c \times t/2$). Adopting $t_{\text{max}} = 3.4$ days (the maximum luminosity measured for H α), we obtained $R_{\text{in}} \simeq 4.4 \times 10^{15}$ cm, in agreement with the lower limit derived above. Typical SN ejecta (i.e. with $v_{ej} = 10^4$ km s $^{-1}$) would then reach R_{in} not earlier than $t_{\text{reach}} \simeq +51$ days, +68 days assuming $v_{ej} \simeq 7500$ km s $^{-1}$ adopted for the bulk of the ejecta in our model (see Section 3.2). These phases are in agreement with the later spectroscopic evolution of SN 2024bch, which at $t \simeq +69$ days shows possible signature ejecta-CSM interaction in terms of a blue boxy component in the H α profile (see the discussion below and in Section 4). This analysis points towards a distant CSM, reached by the SN ejecta only several weeks after explosion, and highlights the need for a source of ionising photons different from interaction for the early narrow features observed in SN 2024bch.

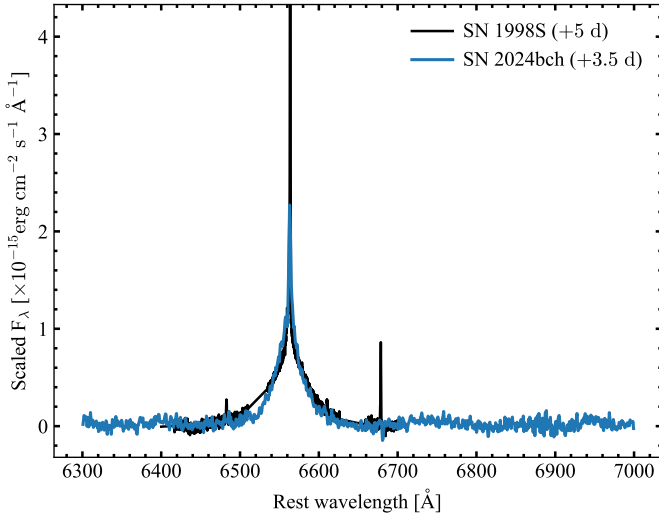


Fig. 8. Comparison of the higher-resolution spectrum available ($R \sim 3500$) for SN 2024bch obtained $\approx +3.5$ days with AFOSC with the one of SN 1998S (published by Shivvers et al. 2015) at a similar phase (adopting JD = 2450872.5 as reported by Fassia et al. 2000).

The Bowen fluorescence mechanism (Bowen 1934, 1935) may explain the presence of high-ionisation lines without involving a significant contribution of ejecta-CSM interaction. This mechanism relies on a fortuitous coincidence in wavelengths that allows the He II $\lambda 303.783$ resonance line to populate the O III $2p3d^3P_2$ level, followed by the emission of O III $\lambda 303.799$ (O I process; see Osterbrock & Ferland 2006). The excited O III can then emit several Bowen lines, including prominent ones at $\lambda 3444$, $\lambda 3133$, $\lambda 3341$, $\lambda 3312$, $\lambda 3047$, and $\lambda 3760$, as well as other extreme ultraviolet lines (see the Grotrian diagrams reported in Kallman & McCray 1980; Selvelli et al. 2007). Notably, O III $\lambda 374.436$ can further excite nitrogen through a resonance doublet at $\lambda 374.434$ and $\lambda 374.441$, populating the N III $3d^2D_{3/2,5/2}$ levels, subsequently decaying to $3p^2P^o_{3/2}$ and $3p^2D^o_{1/2}$ emitting N III $\lambda 4641$, $\lambda 4641$, and $\lambda 4642$, respectively, and to the $3s^2S_{1/2}$ level emitting N III $\lambda 4097$ and $\lambda 4103$ (see Fig. 13 and the discussion in Selvelli et al. 2007). This mechanism was invoked to explain N III lines in a variety of gaseous nebulae, including planetary nebulae, X-ray binaries, symbiotic stars and novae in the early nebular stages (see Kastner & Bhatia 1996), and, more recently, in the tidal disruption events (TDEs) iPTF15af (Blagorodnova et al. 2019) and iPTF16fnl (Onori et al. 2019), and it may be a viable excitation mechanism for SN 2024bch as well. Fransson et al. (2002) used near-UV spectra to quantify the contribution of the Bowen mechanism in the Type II SN 1995N through O III $\lambda 3047$, $\lambda 3133$, $\lambda 3340$, and $\lambda 3444$ lines, as well as the $I(\text{O III } \lambda 3132)/I(\text{He II } \lambda 4686)$ ratio to estimate the Bowen yield for He II $\lambda 304$. Unfortunately, our early spectra do not extend below ~ 3600 Å (see Table 1 and Fig. 7) and we cannot quantify the Bowen yield using O III $\lambda 3132$. While early spectra of SN 2024bch lack O III $\lambda 3444$ (a key diagnostic of the Bowen mechanism in planetary nebulae as well; see e.g. Weymann & Williams 1969; Liu & Danziger 1993), the presence of N III $\lambda 4641$ and He II $\lambda 4686$ in our observations aligns with Galactic X-ray sources (e.g. McClintock et al. 1975). Although these lines can also arise via dielectronic recombination (Mihalas & Hummer 1973), theoretical (e.g. Hatchett et al. 1976) and observational (e.g. Margon & Cohen 1978) evidence

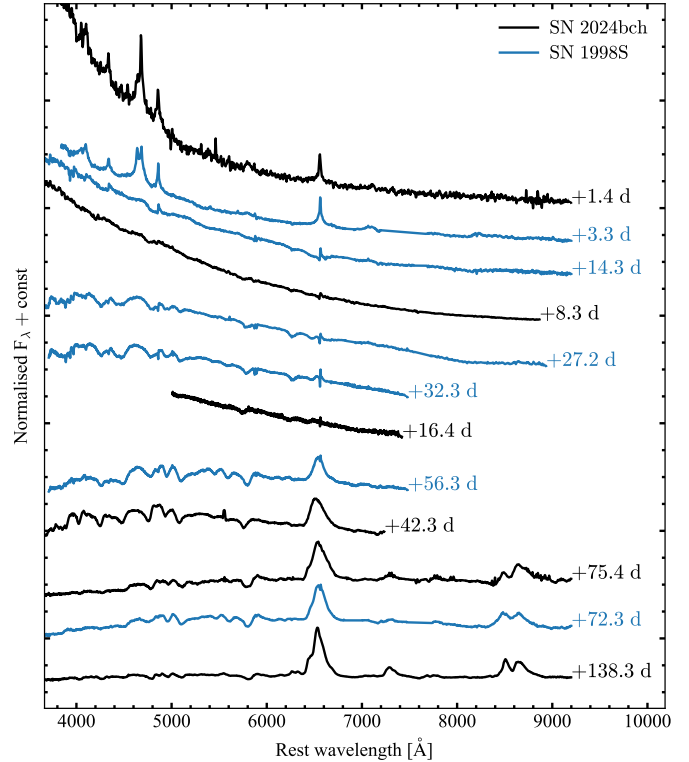


Fig. 9. Comparison between the spectroscopic evolution of SN 2024bch and SN 1998S up to $\sim +140$ days (spectra from Leonard et al. 2000; Fassia et al. 2001).

strongly supports Bowen fluorescence as the dominant mechanism for amplifying N III emission. Thus, despite the absence of direct UV diagnostics, the observed spectral features suggest that Bowen fluorescence remains a viable explanation for SN 2024bch.

At $t > +7$ days, spectra are dominated by a blue ($T \approx 1.3 \times 10^4$ K), almost featureless continuum typically observed during the early phases of Type II SNe. The persistence of a narrow H α line with an absorption component visible at +7 and up to +16 days, on the other hand, suggests the presence of a H-rich unshocked shell with a blue-velocity-at-zero-intensity (BVZI) ≈ 300 km s $^{-1}$ and a photospheric velocity ≈ 150 km s $^{-1}$ (as measured from the highest resolution spectrum available at these phases, obtained at +16 days); see the inset in Figure 7. Adopting the R_{in} derived above and BVZI for the expansion velocity of the CSM, this would date the mass-loss event producing the outer shell to approximately 5 years before the SN explosion.

At +42 days, spectra show a significant metamorphosis, as broad P Cygni features begin to shape the spectral continuum. We identify broad absorption features that correspond to H Balmer lines (H β , H γ and H δ), He I/Na ID and O I (from +48 days; see Fig. 11). The blue part of the continuum is also shaped by several features that correspond to the Fe-group elements, such as Fe II (multiplet 42), Sc II (multiplets 28 and 29), and Ba II $\lambda 6142$, where multiplets numbers are given following the notation reported in Moore (1945). At +48 days, we also identify broad features that correspond to the Ca II near infrared 8498, 8542, 8662 Å triplet, O I $\lambda 8446$, and O I 7772 – 7775, although we cannot rule out their presence at earlier phases due to the limited spectral coverage of previous data. From the minima of H β and Na ID at +42 days, we estimate

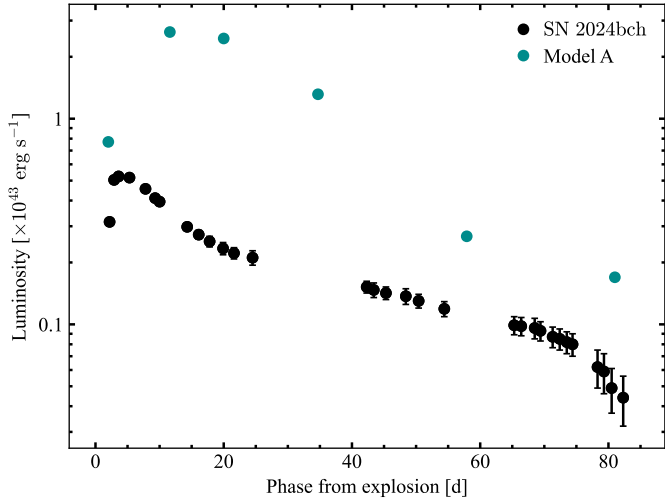


Fig. 10. Comparison between the bolometric light curve of SN 2024bch and ‘Model A’ from Dessart et al. (2016), which was built to explain the luminosity evolution of SN 1998S. The model fails to reproduce both the fast rise and the overall luminosity of SN 2024bch, which suggests that ejecta-CSM interaction does not play a role in powering its light curve.

photospheric expansion velocities for the outer ejecta layers of $6745 \pm 760 \text{ km s}^{-1}$ and $6830 \pm 740 \text{ km s}^{-1}$, respectively, with uncertainties computed as in Gutiérrez et al. (2017). Both values are higher than those typically observed in Type II SNe at similar phases (see Gutiérrez et al. 2017). At +108 days the estimated expansion velocities are 3440 ± 750 and $4600 \pm 250 \text{ km s}^{-1}$ for H β and Na ID, respectively, still above the average values inferred by Gutiérrez et al. (2017). During the same period, emission peaks (e.g. H α , H β) progressively shift towards the corresponding rest wavelengths (see panels 2 and 3 in Figure 11). As it is believed to form closer to the SN photosphere, another estimate of the photospheric expansion velocity can be inferred from the P Cygni profiles of the Fe II 42 multiplet, in particular the relatively isolated $\lambda 5169$ line (see e.g. the discussion in Dessart & Hillier 2006). This gives an expansion velocity of $5210 \pm 740 \text{ km s}^{-1}$ at +42 days, which declines to $3900 \pm 300 \text{ km s}^{-1}$ at +108 days. These are both significantly above the mean velocities inferred by Gutiérrez et al. (2017) for their sample of Type II SNe at similar phases ($3760 \pm 1045 \text{ km s}^{-1}$ at $t \approx +42$ days and $2625 \pm 457 \text{ km s}^{-1}$ at $t \approx +108$ days).

3.4. Early nebular spectra

Forbidden [Ca II] $\lambda\lambda 7291, 7324$ emerge at $t \gtrsim 75$ days, although we cannot rule out their presence at earlier phases due to the limited wavelength coverage of the +69 days spectrum. Several forbidden lines may contribute to the flux in the 7000–7600 Å spectral region, including [Fe II] and stable [Ni II]. At +154 days, [Ca II] $\lambda\lambda 7291, 7323$ shows a strongly asymmetric profile where [Fe II] $\lambda 7155$ likely contributes to the blue part of the emission, while [Ni II] $\lambda 7378$ and $\lambda 7412$ and [Fe II] $\lambda 7453$ shape the red tail of the emission feature. Jerkstrand et al. (2015) and Terreran et al. (2016) modelled the similar feature observed in SNe 2012ec and 2014G by adopting a multi-Gaussian fit to the entire region, and considered the contribution of [Ca II] $\lambda\lambda 7291, 7323$, [Fe II] $\lambda 7155, \lambda 7172, \lambda 7388, \lambda 7453$, and [Ni II] $\lambda 7378$ and $\lambda 7412$ to the overall profile. Since we were unable to reproduce

the overall spectral feature using the aforementioned lines, even letting the line ratios vary within reasonable ranges, we had to include two additional emissions around ~ 7050 and ~ 7450 Å. Although we tentatively identified the blue excess as He I $\lambda 7065$, we could not find a reasonable identification for the red feature. We therefore fixed the wavelength of the blue component and allowed the red one to vary within our fitting procedure. In addition, to minimise the number of free parameters, we also ignored the contributions of [Fe II] $\lambda 7172$ and $\lambda 7388$, which are relatively faint with respect to the other components in the reference model ($L_{7172}/L_{7155} = 0.24$ and $L_{7388}/L_{7172} = 0.74$; see Jerkstrand et al. 2014, 2015). Our ‘best-fit’ model is shown in Fig. 12, where we found the red extra component to be centred at $\lambda 7471$ with a luminosity $(2.03 \pm 0.84) \times 10^{38} \text{ erg s}^{-1}$, while for He I $\lambda 7065$ we derived $(3.0 \pm 1.2) \times 10^{38} \text{ erg s}^{-1}$, which corresponds to $L_{7471}/L_{7155} \approx 0.6$ and $L_{7065}/L_{7155} \approx 0.8$. Following Jerkstrand et al. (2014), we fixed the luminosity ratios of lines coming from the same levels, such as $L_{7453}/L_{7155} = 0.31$, and, as in Jerkstrand et al. (2015), we also assumed $L_{7412}/L_{7378} = 0.31$. When we allowed the blueshift and FWHM of the emission lines to vary (while forcing it to the same value for all lines), we inferred: $L_{7155} = (3.4 \pm 1.4) \times 10^{38} \text{ erg s}^{-1}$, $L_{7453} = (1.05 \pm 0.43) \times 10^{38} \text{ erg s}^{-1}$, $L_{7378} = (6.0 \pm 2.5) \times 10^{38} \text{ erg s}^{-1}$, and $L_{7412} = (1.87 \pm 0.77) \times 10^{37} \text{ erg s}^{-1}$, assuming $L_{7291} = L_{7323} = (1.15 \pm 0.47) \times 10^{39} \text{ erg s}^{-1}$, where we considered a distance of $19.9 \pm 4.1 \text{ Mpc}$ and errors are dominated by its uncertainty ($\sim 50\%$ of the total uncertainty). The fitting procedure also provided a rigid shift $\Delta\lambda = 20.10 \pm 0.52 \text{ Å}$ ($\approx 830 \text{ km s}^{-1}$ with respect to 7250 Å , the centre of the spectral region considered) and a FWHM velocity of $3332 \pm 45 \text{ km s}^{-1}$, both assumed to be constant for all lines (as in Terreran et al. 2016).

Although the reference model was specifically designed for SN 2012aw (see Jerkstrand et al. 2014, for details) and assumes local thermodynamic equilibrium (LTE) and that all lines are optically thin, it is capable of reproducing the observed spectral region between 6900 and 7600 Å of SN 2024bch as well, although we had to include two additional features (He I $\lambda 7065$ and $\lambda 7471$). On the other hand, we note that a red excess with respect to the same model was also observed in the [Ca II] region of SNe 2012ec and 2014G (Jerkstrand et al. 2015; Terreran et al. 2016, respectively), so the red feature we find at $\lambda 7471$ is likely to be real. The luminosity ratio of the [Ni II] $\lambda 7378$ and [Fe II] $\lambda 7155$ lines can be used to estimate iron and nickel abundances, which, in LTE and assuming optically thin emission, can be expressed as

$$\frac{L_{7378}}{L_{7155}} = 4.9 \frac{n_{\text{Ni II}}}{n_{\text{Fe II}}} \exp\left(\frac{3250 \text{ K}}{T}\right), \quad (4)$$

where we used a ratio between partition functions $Z_{\text{Ni II}}/Z_{\text{Fe II}} = 0.25$, statistical weights $g_{4s2SF7/2}^{\text{Ni II}} = 8$ and $g_{3d7a2G9/2}^{\text{Fe II}} = 10$, and transition probabilities $A_{7378} = 0.23 \text{ s}^{-1}$ and $A_{7155} = 0.146 \text{ s}^{-1}$, as in Jerkstrand et al. (2015). Although we lack evidence that supports LTE at these phases, this ratio is relatively insensitive to temperature and density, which implies that deviations from LTE would similarly affect both lines. However, we note that the fit of the [Ca II] region accurately reproduces the overall shape of its spectral region, which suggests that large deviations from LTE are unlikely. In addition, as shown by Jerkstrand et al. (2017), modelling of commonly observed SN lines suggests that the assumption of LTE may hold for [Ca II] $\lambda\lambda 7291, 7324$, [Fe II] $\lambda 7155$, and [Ni II] $\lambda 7378$ up to ~ 280 – 350 days after explosion. Moreover, the assumption of optically thin emission may be reasonable at +154 days (e.g. see the typical t_{thin} reported there

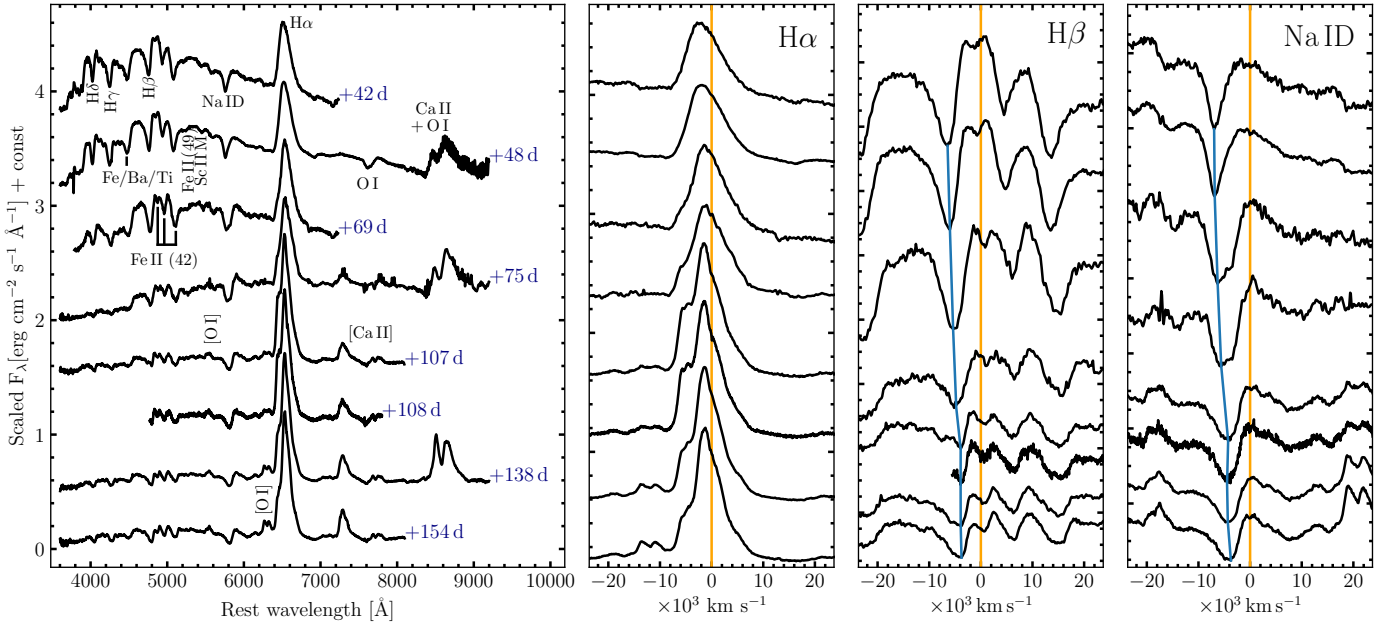


Fig. 11. From left to right: Optical spectroscopic evolution of SN 2024bch at $t \geq +42$ days (**Panel 1**; along with the identification of the most prominent spectral features), evolution of the H α profile (**panel 2**), H β (**panel 3**), and Na I D (**Panel 4**) features in the velocity plane at the same epochs. Yellow lines correspond to the rest-frame wavelengths, while blue lines mark the evolution of the P Cygni absorption minima. Phases refer to the estimated explosion epoch.

for [Ni II]). Assuming $\text{Ni II}/\text{Fe II} \approx \text{Ni}/\text{Fe}$, Eq. (4) then gives the Ni/Fe production rate as a function of temperature. If all ^{56}Ni decayed and most of ^{56}Co decayed into ^{56}Fe ($\approx 65\%$ at +154 days, assuming e-folding times of 8.8 and 111.4 days for ^{56}Ni and ^{56}Co , respectively), the Fe-zone temperature can be determined comparing the measured $L_{7155}/M_{^{56}\text{Ni}}$ to the theoretical value

$$\frac{L_{7155}}{M_{^{56}\text{Ni}}} = \frac{A_{7155} h \nu g_{3d7a2G9/2}^{\text{Fe II}}}{56 m_u Z_{\text{Fe II}}(T)} \exp\left(\frac{-22745 \text{ K}}{T}\right), \quad (5)$$

where we adopted a partition function $Z_{\text{Fe II}} = 15 + 0.006T$ as in Jerkstrand et al. (2015). The resulting temperature is 3946_{-80}^{+85} K, where, in comparing the two sides of Eq. (5), we took into account the uncertainties on the derived L_{7155} and $M_{^{56}\text{Ni}}$ (see Sect. 3.1), but we did not consider possible contamination by primordial Fe and Ni (see e.g. Maguire et al. 2012), which may lead to an underestimation of the derived Ni II/Fe II ratio. This temperature gives a $\text{Ni II}/\text{Fe II} = 0.16 \pm 0.06$, ≤ 3 times higher than the solar value of 0.056 (Lodders 2003), which is in agreement with the values found for SNe 2012ec (0.19 ± 0.07) and 2014G (0.18 ± 0.02) by Jerkstrand et al. (2015) and Terreran et al. (2016), respectively. This is also higher than typical values found for other CC SNe, although the number of objects with estimated Ni II/Fe II is still relatively small (see Rank et al. 1988; MacAlpine et al. 1989, 2007; Wooden et al. 1993; Jerkstrand et al. 2012, 2015).

At $t \geq 107$ days, [O I] $\lambda\lambda 6300, 6364$ and 5577 emerge, progressively increasing their strength with respect to the local continuum. At +154 days, the total luminosity of the $\lambda\lambda 6300, 6364$ doublet is $\approx 1.4 \times 10^{39}$ erg s $^{-1}$, while the luminosity ratio is ~ 1 , which suggests optically thick emission. While both lines are clearly visible, a fit to the overall profile is complicated by the complex region around the doublet, where the level of the continuum cannot be determined easily. [O I] $\lambda 5577$ is usually weak

in CC SNe, although we clearly detect the line in the early nebular phase of SN 2024bch. In order to avoid contamination from nearby emission features, Jerkstrand et al. (2014) fit the overall profile including the contribution of [Fe II] $\lambda 5528$. Following the same approach, we found a two-component Gaussian fit is able to reproduce the entire emission feature at +154 days, corresponding to [Fe II] $\lambda 5528$ and [O I] $\lambda 5577$ both with a blueshift comparable to the one measured from the multi-Gaussian fit to the 7000–7600 spectral region (20.10 ± 0.52 Å; see above). The derived luminosity $L_{5577} \approx 3.0 \times 10^{38}$ erg s $^{-1}$ can be used, along with the estimate of $L_{6300,6364}$ mentioned above, to derive the temperature of the emitting region. In LTE,

$$\frac{L_{5577}}{L_{6300,6364}} = 38 \exp\left(\frac{-25790 \text{ K}}{T}\right) \frac{\beta_{5577}}{\beta_{6300,6364}}, \quad (6)$$

where β_{5577} and $\beta_{6300,6364}$ are the photon escape probabilities in the Sobolev approximation ($\beta_\lambda = (1 - e^{-\tau_\lambda})/\tau_\lambda$; Sobolev 1957). When the [O I] doublet transitions to optically thin conditions, the relative intensities approach their intrinsic ratio of 3:1 since both transitions share the same upper energy level. In approaching the optically thin regime (i.e. $\tau \lesssim 1$ and [O I] $\lambda 6300$ stronger than [O I] $\lambda 6364$), $\beta_{6300,6364}$ becomes ≥ 0.6 . This is not the case for SN 2024bch at +154 days, where the doublet is still in the optically thick regime. On the other hand, if we assume similar temperatures for the Fe- and O-rich zones (≈ 3946 K, as derived above), we can use Eq. (6) to estimate the escape probabilities ratio, resulting in $\beta_{5577}/\beta_{6300,6364} \approx 3.85$. The dependence of the O mass on the photon escape probabilities is represented in Fig. 13.

The oxygen yield of the explosion can be derived using

$$M_{\text{O I}} = \frac{L_{6300,6364} \beta_{6300,6364}^{-1}}{9.7 \times 10^{41} \text{ erg s}^{-1}} \exp\left(\frac{22720 \text{ K}}{T}\right) M_\odot, \quad (7)$$

where we adopted the atomic constants reported in Jerkstrand et al. (2014). Substituting the measured $L_{6300,6364}$

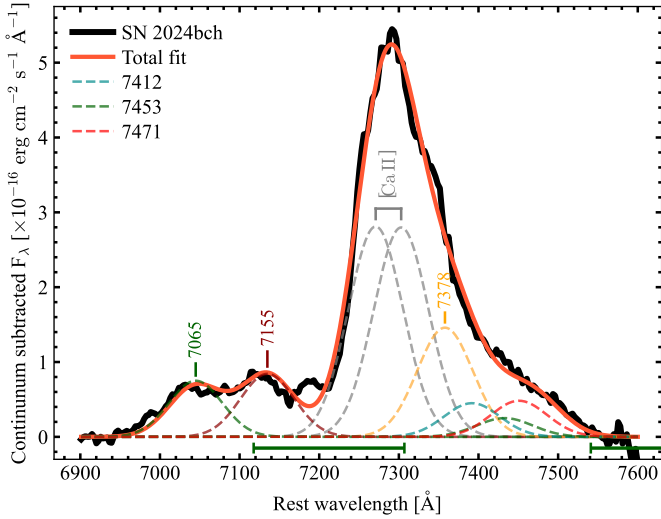


Fig. 12. Multi-Gaussian fit to the spectral region around [Ca II] $\lambda\lambda 7291, 7324$, following the prescriptions of [Jerkstrand et al. \(2015\)](#) and [Terreran et al. \(2016\)](#). The fit was performed on the spectrum obtained at +154 days.

in Eq. (7) gives $M_{O1} = 0.46\beta_{6300,6364}^{-1}$ assuming a similar temperature for the Fe- and O-rich zones. As an example, the photospheric temperature at +158 days inferred in Sect. 3.1 (i.e. if we consider the O-rich zone to be closer to the photosphere than the Fe-rich zone), would give $M_{O1} = 0.27\beta_{6300,6364}^{-1}$. Assuming $\beta_{6300,6364} = 0.32$ (equivalent to $\tau_{6300,6364} \approx 3$) would give $M_{O1} \approx 0.8\text{--}1.4 M_{\odot}$, consistent with a $M_{ZAMS} = 15\text{--}20 M_{\odot}$ according to [Nomoto et al. \(1997\)](#) and [Rauscher et al. \(2002\)](#). However, these estimates are heavily affected by the assumptions made, including the temperature of the emitting region, the value of $\beta_{6300,6364}$, and the optical thickness of the [O I] $\lambda\lambda 6300, 6364$ doublet at +154 days. One of the most important sources of uncertainty is the assumed temperature of the O-rich region, reflected in Equation 7, which, in our case, is supported by neither observational nor theoretical considerations. As seen in Sect. 3.4, an uncertainty of only ~ 400 K (the difference between T_{Fe} and T_{ph} at +158 days) translates to roughly a factor of two uncertainty in the derived oxygen mass, spanning from $0.27\beta_{6300,6364}^{-1}$ to $0.46\beta_{6300,6364}^{-1}$. Later spectra (e.g. when the transition to the optically thin regime occurs; see Valerin et al. in preparation) will provide more precise constraints and enable a comparison with these preliminary estimates.

4. Summary and conclusions

In the previous sections we have detailed our analysis of the photometric (Sect. 3.1) and spectroscopic (Sect. 3.3) evolution of the Type II SN 2024bch. Early spectra ($t \lesssim +7$ days) are dominated by narrow emission lines such as He II, N III, and C IV in addition to those of the H Balmer series (from H α to H δ). These show broad wings due to Thomson scattering by free electrons in a dense CSM (see e.g. [Chugai 2001](#); [Huang & Chevalier 2018](#), and the comparison with the H α profile of SN 1998S at sufficiently high resolution in Fig. 8) with an integrated luminosity that increases up to a maximum occurring $\approx 2\text{--}3$ days after explosion for all narrow lines. As narrow lines increase in strength, their peaks progressively shift towards their rest wave-

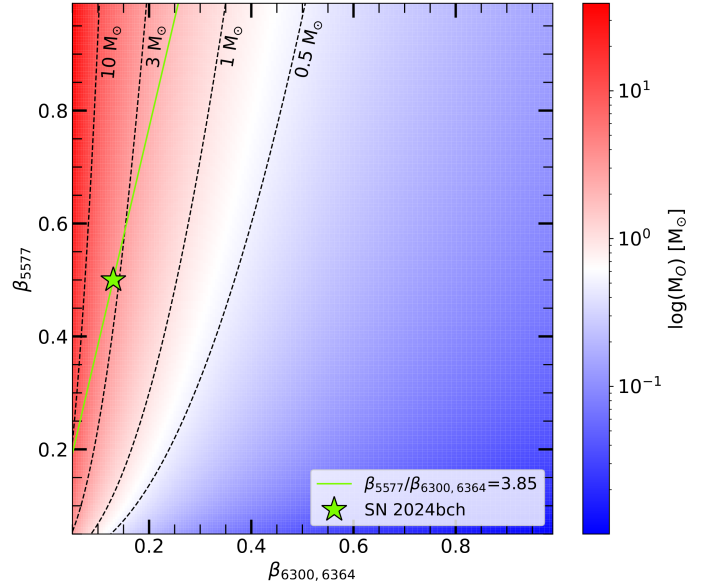


Fig. 13. Colour map showing the dependence of the O mass on the escape probabilities $\beta_{6300,6364}$ and β_{5577} , according to Eqs. (6) and (7). Dashed black lines trace the location of some relevant O mass values. The solid green line displays the constant $\beta_{5577}/\beta_{6300,6364}$ ratio found through Eq. (6). The position of SN 2024bch in this plane, based on the measurements performed on the spectrum at +154 days, is marked with a green star.

lengths. We interpreted this evolution as a geometrical effect of the emitting region, in a similar fashion to a light echo (see the geometry described for SN 2006gy in Fig. 6 by [Miller et al. 2010](#), and Figure 14). At the time of the H α maximum luminosity ($\approx +3.4$ days), we inferred the inner radius of the H-rich circumstellar shell by only considering the light travel time, which resulted in an inner radius $R_{in} \approx 4.4 \times 10^{15}$ cm. This can be reached by typical SN ejecta (with $v_{ej} \approx 10^4$ km s $^{-1}$; consistent with the BVZI measured from the H β P Cygni profile) not earlier than $t_{reach} \approx 51$ days, which corresponds to the appearance of a blue shoulder in the H α line profile, occurring at $t \gtrsim +69$ days. It is therefore unlikely that the disappearance of narrow high-ionisation emission lines at $\approx +7$ days (see Fig 7) is due to the CSM being swept away by the SN ejecta. In addition, the contribution of CSM-ejecta interaction to the luminosity output of the transient could be marginal and it is not necessary to reproduce the observed data of SN 2024bch, as shown by the modelling of its bolometric light curve (see Sect. 3.1 and Figure 5). Our ‘best-fit’ model is able to reproduce the entire evolution of the bolometric luminosity invoking the contribution of two regions: a bulk of relatively massive ejecta ($M_{bulk} = 5 M_{\odot}$), whose emission accounts for the plateau luminosity, and an extended envelope ($M_{env} = 0.2 M_{\odot}$) with an outer radius $R_{env} = 7 \times 10^{13}$ cm, which is responsible for the early luminosity peak due to its short diffusion time. This challenges the most common scenario invoked for SNe displaying ‘flash spectroscopy features’ ([Gal-Yam et al. 2014](#)), where shocks are the main source of ionising photons behind high-ionisation features.

Narrow high-ionisation features may instead be the result of fluorescence due to efficient absorption of extreme early UV radiation and subsequent resonance due to the nearly coincident wavelengths of He II, O III, and N III transitions. H Balmer (and possibly He II $\lambda 4686$ and C IV) lines may instead be interpreted as recombination features following the photo-ionisation

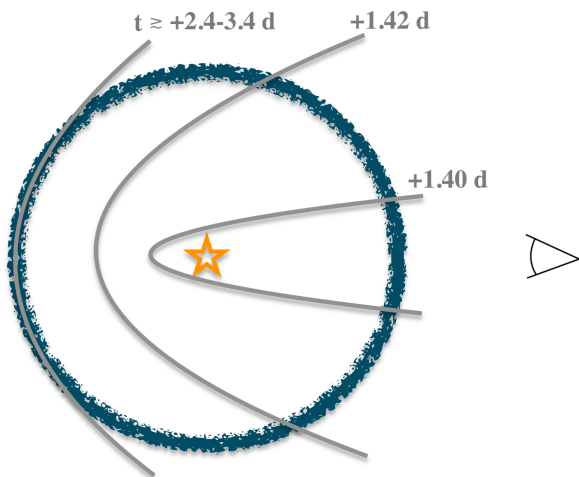


Fig. 14. Schematic view, not to scale, of the preferred geometrical configuration for the CSM of SN 2024bch. An outer shell with $R_{\text{in}} \gtrsim 4.4 \cdot 10^{15}$ cm is reached by radiation at different times and emits high-ionisation features through the Bowen fluorescence mechanism. This scenario can simultaneously explain the evolution of the luminosities and redshifts of narrow features without the need for ejecta-CSM interaction as an additional source of energy.

of the CSM by the SN shock breakout, possibly extended by the presence of an inflated envelope (see e.g. [Moriya et al. 2015](#)). All these features are typically observed in a significant fraction of CC SNe with sufficiently early spectra (see [Bruch et al. 2021](#)) and this alternative scenario may be relevant in interpreting their early evolution. In this context, narrow emission lines in SN spectra only prove the presence of an outer CSM and are not related to ‘efficient’ interaction (see e.g. [Salmaso et al. 2023](#), for a definition of ‘strongly interacting’ SNe). This also has important implications for multi-messenger astronomy, as strongly interacting SNe may provide a viable source of neutrinos in an energy range comparable to those detected by IceCube (up to 1 Pev; see [Fang et al. 2020](#); [Pitík et al. 2023](#)). A lack of ‘early interaction’ may also explain the non-detection of some SNe II with high-ionisation features at radio wavelengths at early times (see e.g. [Tartaglia et al. 2021](#)).

Possible signatures of CSM interaction appear at $t \gtrsim +69$ days, in terms of a blue ‘shoulder’ visible in the $H\alpha$ emission profile (see Figure 11). However, according to the photometric analysis, this neither contributes significantly to the total energy output of the transient, nor causes a significant change in the ionisation state of the emitting region. Alternatively, a flat-topped boxy profile may be produced by a recombining H-rich inner shell visible at later times after the SN photosphere recedes (see e.g. [Wagenblast et al. 1983](#); [Bertout & Magnan 1987](#), for an analytical discussion on possible line profiles emitted by expanding spherical shells). This shell should contain a relatively small mass of H in order to account for the shape of the light curve, which at +85 days already settles on the radioactive decay tail. In any case, the interaction of fast SN ejecta with the pre-existing CSM, if present at all, does not seem to contribute significantly to the total energy output of the transient at any phase. While the negligible contribution of interaction at early phases can be explained invoking Bowen fluorescence powering narrow lines at $t \lesssim +7$ days, which shows that the lack of a significant extra source of energy at later

phases is non-trivial and may involve a complex geometry or CSM structure. The presence of a ‘clumpy’ CSM was discussed by [Chugai & Danziger \(1994\)](#) to explain the multi-component emission lines observed in SN 1988Z and similar and/or asymmetric structures seem to be common in eruptive and explosive transients (see e.g. [Smith et al. 2001](#); [Kamiński et al. 2021](#)), while a peculiar geometry was invoked to explain ‘hidden interaction’ in PTF11iqb, iPTF14hls, and SN 2020faa (see e.g. [Smith et al. 2015](#); [Salmaso et al. 2023](#)). The dataset collected so far does not allow us to further constrain the physical and geometrical properties of the SN explosion and its circumstellar environment.

Modelling of the radioactive tail (i.e. at $t \gtrsim +90$ days; see Fig. 6) reveals a non-complete trapping of the γ -rays produced in the $^{56}\text{Ni} \rightarrow ^{56}\text{Fe}$ decay and results in a mass of radioactive Ni produced in the explosion of $\approx 0.048 M_{\odot}$. If we include information provided by early nebular emission features and assume $\tau \approx 3$ for the O-rich region, this results in a mass of synthesised O of $0.8\text{--}1.4 M_{\odot}$, which, according to the nucleosynthesis yields computed by [Nomoto et al. \(1997\)](#) and [Rauscher et al. \(2002\)](#), corresponds to a $M_{\text{ZAMS}} = 15\text{--}20 M_{\odot}$ progenitor. This estimate is strongly limited by the estimated temperature of the O-rich region and the optical thickness of the [O I] $\lambda\lambda 6300, 6364$ doublet at +154 days, which is the last available spectroscopic epoch before the end of the transient visibility window and will be refined with proper spectroscopic data once the transient is visible again.

Modelling of the bolometric light curve along with our analysis of spectroscopic data suggest that SN 2024bch exploded and expelled a moderate amount of H-rich gas ($\lesssim 6 M_{\odot}$) within an extended ($R_{\text{in}} \approx 4.4 \times 10^{15}$ cm) and likely massive shell of CSM. The presence of this outer CSM, along with the estimated M_{ZAMS} for the progenitor and ejected mass from our modelling, support the claim that fast-evolving Type II SNe are produced by massive stars that lose a significant fraction of their outer H-rich layers before explosion.

Data Availability

Table 3 and data shown in Figures 2, 7, 8 and 11 are available at the CDS via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/703/A177>

Acknowledgements. We thank Elena Mason for the useful and lively discussions. G. V., A. P., I. S., S. B. L. Tom. and P. O. acknowledge support from the PRIN-INAF 2022 project “Shedding light on the nature of gap transients: from the observations to the model”. F. O. acknowledges support from MIUR, PRIN 2020 (grant 2020KB33TP) “Multimessenger astronomy in the Einstein Telescope Era (METE)” and from INAF-MINIGRANT (2023): “SeaTiDe - Searching for Tidal Disruption Events with ZTF: the Tidal Disruption Event population in the era of wide field surveys”. A. R. also acknowledges financial support from the GRAWITA Large Program Grant (PI P. D’Avanzo). This research made use of the Spanish Virtual Observatory (<https://svo.cab.inta-csic.es>) project, funded by MCIN/AEI/10.13039/501100011033/through grant PID2020-112949GB-I00, the NASA/IPAC Extragalactic Database (NED), funded by the National Aeronautics and Space Administration and operated by the California Institute of Technology and the HyperLeda database (<http://leda.univ-lyon1.fr>). The ZTF forced-photometry service was funded under the Heising-Simons Foundation grant #12540303 (PI: Graham). Based on observations collected with the Copernico and Schmidt telescopes (Asiago, Italy) of the INAF – Osservatorio Astronomico di Padova and the Wide-field Optical Telescope (WOT), a 67/91 cm Schmidt telescope equipped with an Apogee Aspen CG16M camera located at the Campo Imperatore observatory in l’Aquila (Italy) of the INAF – Osservatorio Astronomico d’Abruzzo. This article is also based on observations made in the Observatorios de Canarias del IAC with the Telescopio Nazionale Galileo, operated on the island of La Palma by

INAF at the Observatorio del Roque de los Muchachos under the A47TAC_37 (PI: G. Valerin) and A49TAC_64 (PI: L. Tartaglia) programmes.

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