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SUPPLEMENTARY INFORMATION

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A hybrid envelope-stripping mechanism for massive stars from supernova nebular spectroscopy

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Supplementary Information for the manuscript entitled "A Hybrid Envelope-Stripping Mechanism for Massive Stars from Supernova Nebular Spectroscopy"

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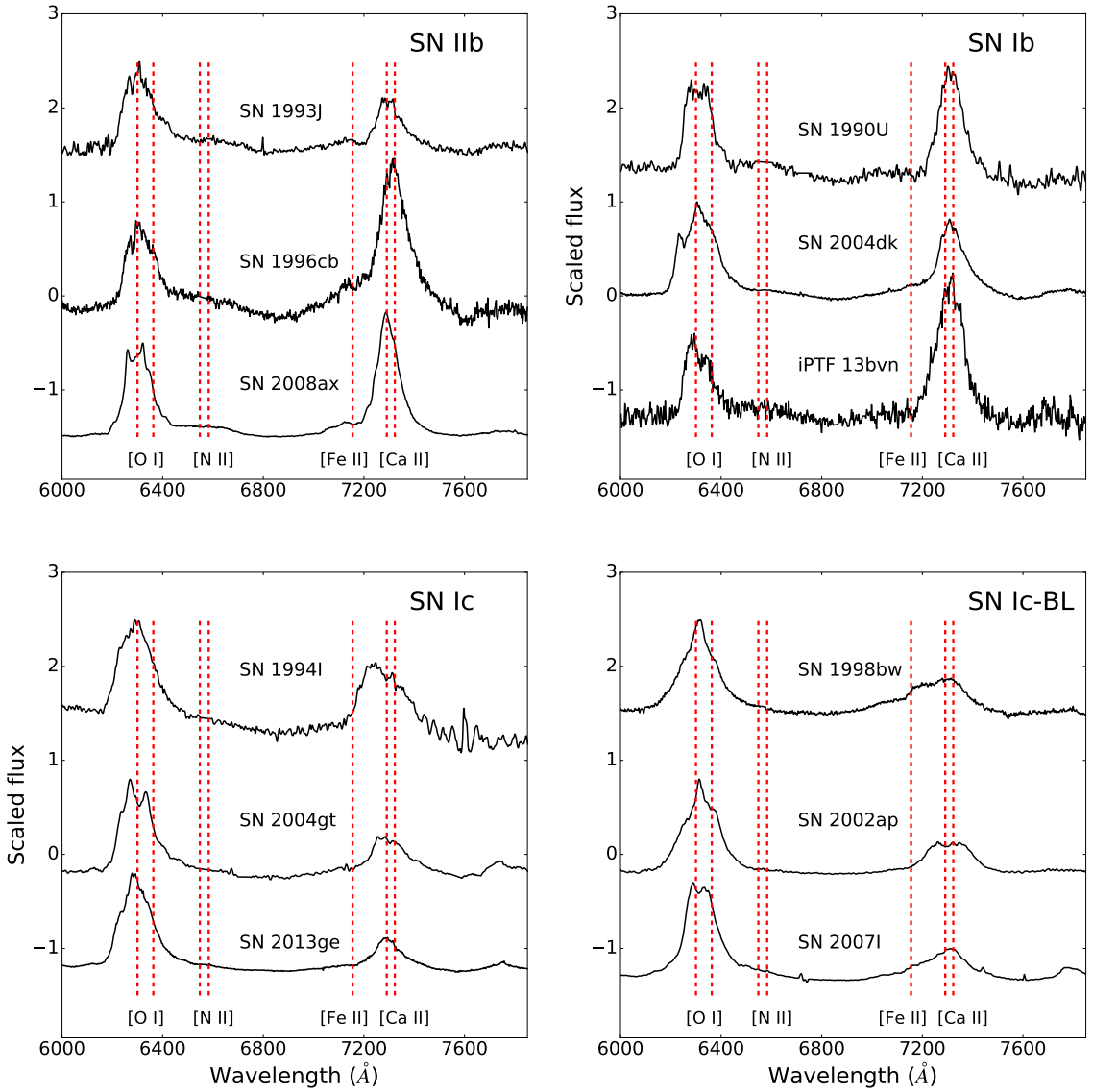
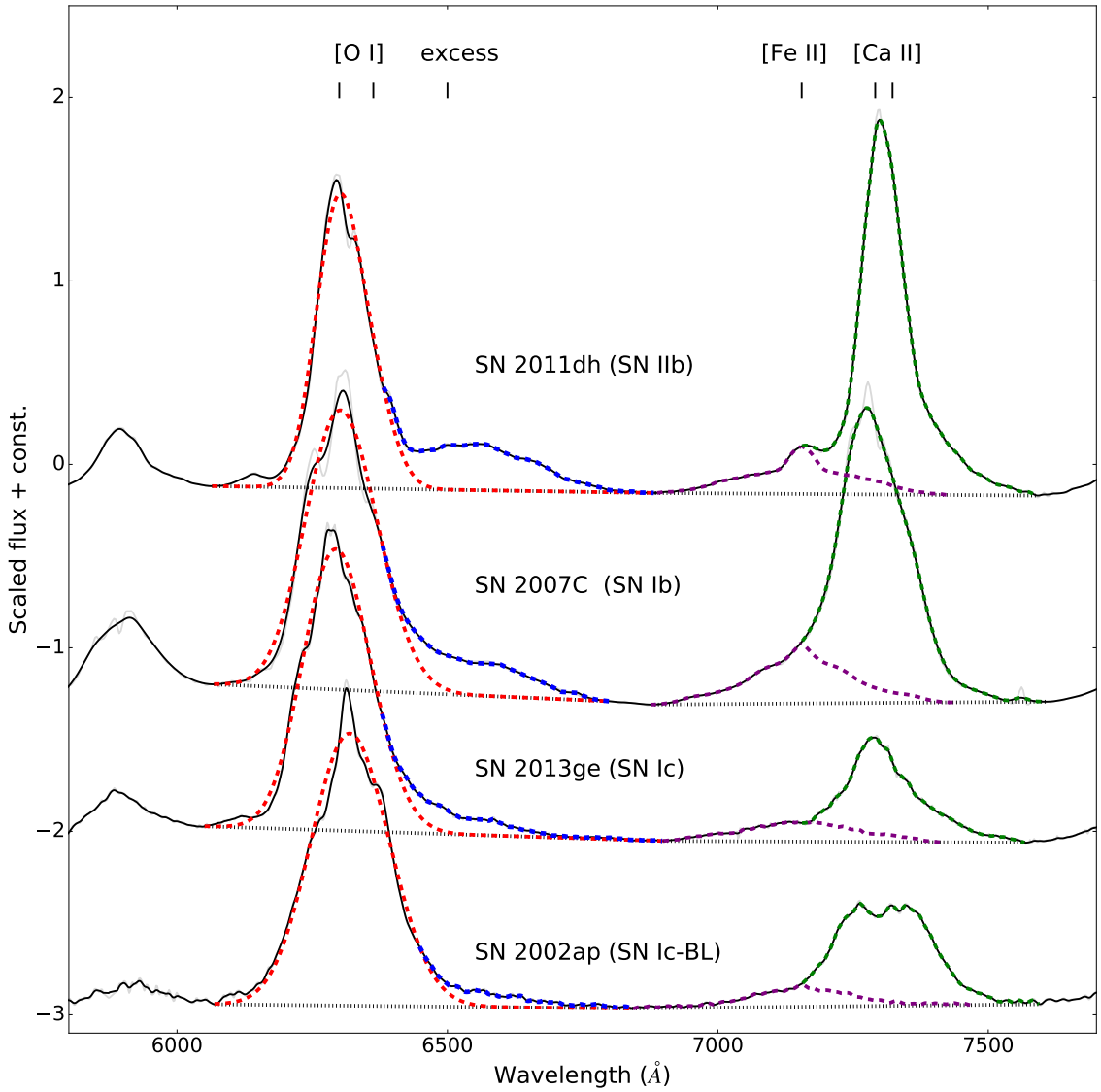
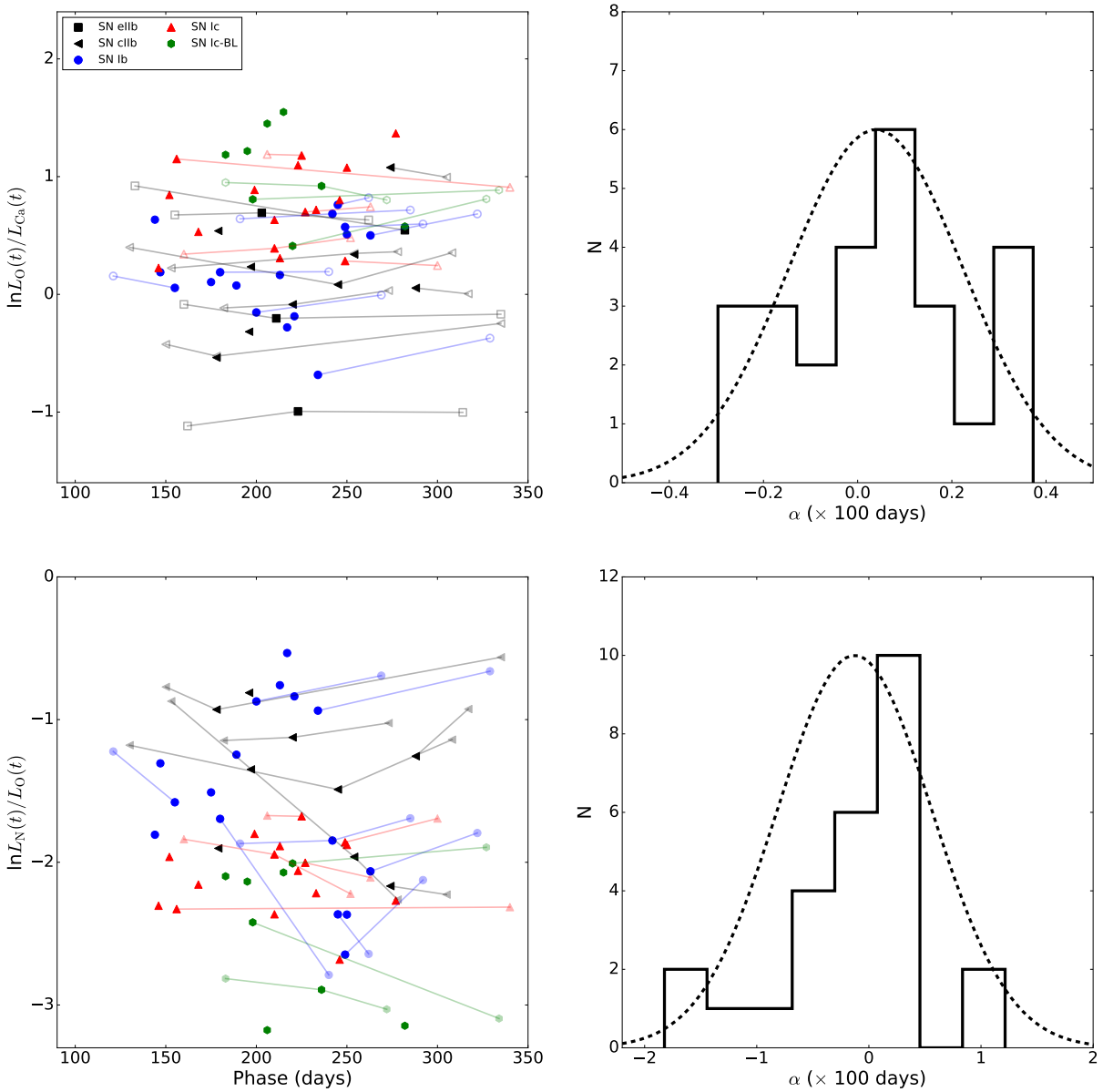


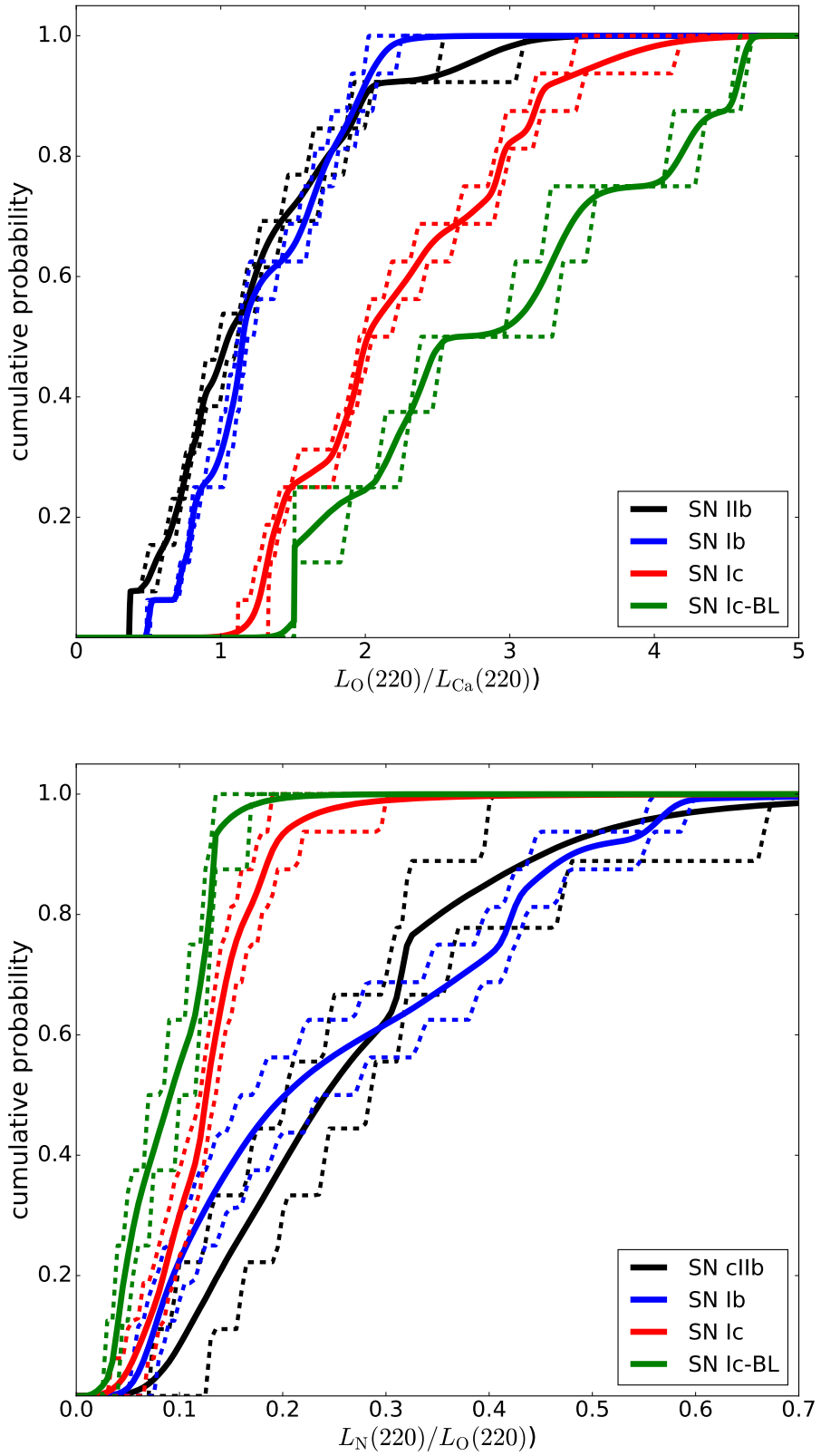
Supplementary Figure. 1: **An illustration of SNe of different subtypes in this work.** The spectra are corrected for host redshifts and the flux is scaled for demonstration purpose. The red vertical lines are emission lines of interest. From left to right: [O I] $\lambda\lambda$6300, 6363; [N II] $\lambda\lambda$6548, 6583; [Fe II] λ7155; [Ca II] $\lambda\lambda$7291, 7323.



Supplementary Figure. 2: **Examples of the line decomposition for SNe of different subtypes.** All spectra are corrected for redshift and extinction. The black dotted line is background emission and the red dashed line is the best-fitted double Gaussian profile of the [O I] doublet. The excess flux ([N II]) is illustrated by blue dashed line. Purple dashed line defines the blue wing of [Fe II], together with its mirror image relative to 7155 Å . The green dashed line is the [Ca II] doublet.



Supplementary Figure. 3: **Effect of line evolution.** The left panels show evolution of the line ratios in a logarithmic scale. The upper left panel is for [O I]/[Ca II] and the lower left panel is for [N II]/[O I]. SNe of different subtypes are labeled by different colors and symbols. The solid points are the line ratios adopted in the main text and the transparent points are line ratios at other spectral phases. Points for the same object at different phases are connected by a line. Since SNe eIIb contain additional contribution from Hα in the '[N II] feature', they are omitted in the lower panels. The right panels show distributions in the speed of the evolution for these two line ratios, characterized by α (see text for details). The dashed lines are Gaussian functions (which are adopted in the Monte-Carlo simulations), with the same mean values and standard distributions as the observed distribution.



Supplementary Figure. 4: **The distribution of the line ratios of different SNe subtypes from 10^4 Monte-Carlo simulations.** Solid lines are average values and dashed lines are 1σ deviations. SNe of different subtypes are labeled by different colors.

Supplementary Table. 1: **SN IIb in this work.**

SN name	date[a]	phase[b]	$E(B-V)$[c]	References
SN 1993J	1993/09/20	155	0.19	22, 49
	1993/11/07	203		
	1994/01/05	262		
SN 1996cb	1997/06/03	150	0.03	50
	1997/07/01	178		
	1997/12/05	335		
SN 2001ig	**2002/10/08**	274	0.10	51, 52
	2002/11/08	305		
SN 2003bg	2003/08/20	153	0.02	53
	2003/11/29	254		
	2003/12/23	278		
SN 2006T	**2006/11/26**	288	0.08	54, 55, 56
	2006/12/25	317		
SN 2008ax	2008/08/01	130	0.40	56, 57
	2008/11/25	245		
	2009/01/25	305		
SN 2008bo	**2008/10/27**	197	0.08[d]	33
SN 2011dh	2011/12/18	182	0.07	58, 59, 60
	2012/01/25	220		
	2012/03/18	273		
SN 2011fu	2012/02/22	133	0.10	61
	2012/07/20	282		
SN 2011hs	2012/03/18	160	0.17	62
	2012/06/21	211		
	2012/10/22	334		
SN 2012P	**2012/08/08**	197	0.29	63
(PTF 12os)				
SN 2013ak	**2013/09/12**	179	0.39[e]	31
SN 2013df	2013/12/05	162	0.10	64, 65
	2014/02/04	223		
	2014/05/06	314		

a. From Supplementary Table 1 to 4, the spectra labeled by bold face is used for analyses in the main text.

b. Phase relative to the light curve maximum in most cases. However, the light curves are not available for all objects. The phase of an object, whose light curve is not available, relies on the literatures or IAUC reports by comparing thrie early spectra with those of reference SNe. This will introduce uncertainty in the phase determination. However, this will not have significant effect on the main conclusion of this work given the small uncertainty in the spectral phase determination as compared to the phase of the spectra used in this study.

c. From Supplementary Tables 1 to 4, objects labeled by (+) indicate the case where its extinction can not be calculated from light curve or Na I D absorption. The average $E(B-V)$ of SN Ib/c (0.36 mag) is adopted [40] for this case.

d. Calculated from Na I D absorption of spectra taken on 2008/04/17 ($t = +4$ days) [33].

e. Calculated from Na I D absorption of spectra taken on 2013/04/01 ($t = +15$ days) [31].

Supplementary Table. 2: **SN Ib in this work.**

SN name	date	phase	$E(B-V)$	References
SN 1990U	**1991/01/06**	189	0.52	56, 66, 67
SN 1990W	**1991/02/21**	180	0.36(+)	68, 69, 70
	1991/04/21	239		
SN 2004ao	**2004/11/14**	250	0.12	33, 75
SN 2004dk	**2005/05/11**	263	0.34	40, 56, 71, 72
	2005/07/09	322		
SN 2004gn	**2005/07/06**	217	0.36(+)	33, 54
SN 2004gq	**2005/08/26**	249	0.25	40, 54, 56, 71
	2005/10/08	292		
SN 2004gv	2005-07-06	191	0.25[a]	54, 56, 71
	2005/08/26	242		
	2005/10/08	285		
SN 2005bf	**2005/12/11**	213	0.14	56, 73
SN 2006F	**2006/06/30**	175	0.54	40, 54, 74
SN 2006gi	**2007/02/10**	144	0.38	69, 75
SN 2007C	2007/05/17	121	0.64	40, 56, 69
	2007/06/20	155		
SN 2007Y	**2007/09/22**	200	0.11	76
	2007/11/30	269		
SN 2009jf	**2010/06/19**	245	0.12	56, 77, 78
	2010/07/08	264		
iPTF13 bnv	**2014/02/21**	234	0.07	63
	2014/05/28	330		
SN 2014C	**2014/08/25**	221	0.75	33, 79
ps 15bgt	**2015/12/17**	147	0.23[b]	33

a. Calculated from Na I D absorption of spectra taken on 2005/01/11 ($t = +15$ days) [56].
b. Calculated from Na I D absorption of spectra taken on 2015/07/23 ($t = +1$ day) [33].

Supplementary Table. 3: **SN Ic in this work.**

SN name	date	phase	$E(B-V)$	References
SN 1991N	**1992/01/09**	277	0.12[a]	54, 67, 80
SN 1994I	**1994/09/02**	146	0.45	56, 81, 82
SN 1996D	**1996/09/10**	199	0.36(+)	69, 83
SN 1996aq	1997/02/11	160	0.36(+)	69, 84
	1997/04/02	210		
	1997/05/14	252		
SN 1997dq	1998/05/30	206	0.11[b]	56, 67
	1998/06/18	225		69, 85
SN 2004aw	**2004/11/14**	233	0.37	56, 86
SN 2004fe	**2005/07/06**	249	0.32	40, 54, 56
	2005/08/26	300		
SN 2004gk	**2005/07/10**	223	0.47	54, 56, 75
SN 2004gt	**2005/05/24**	152	0.10	56, 69, 87
SN 2005kl	**2006/06/30**	213	0.29[c]	40, 54, 56
SN 2006ck	**2007/01/24**	246	0.36(+)	54, 56, 88
SN 2007gr	**2008/02/12**	170	0.09	33, 40
SN 2011bm	**2011/12/17**	227	0.06	89
	2012/01/22	263		
SN 2013ge	**2014/04/28**	156	0.07	90
	2014/10/23	334		
SN 2014eh	**2015/06/16**	210	0.36(+)	33

a. Calculated from Na I D absorption of spectra taken on 1991/04/07 (t = +0 days)[67].
b. Calculated from Na I D absorption of spectra taken on 1997/11/08 (t = +3 days)[67].
c. Calculated from Na I D absorption of spectra taken on 2005/11/25 (t = -4 days)[56].

Supplementary Table. 4: **SN Ic-BL in this work.**

SN name	date	phase[a]	$E(B-V)$	References
SN 1997ef	**1998/09/21**	282	0.00	56, 67, 91, 92
SN 1998bw	**1998/11/26**	198	0.06	93, 94, 95
	1999/04/12	335		
SN 2002ap	2002/08/09	183	0.08	94, 96, 97, 98
	2002/10/01	236		
	2002/11/06	272		
SN 2005kz	2005/06/30	215	0.46	40, 54, 99
SN 2005nb	2006/06/30	183	0.36(+)	54, 56, 100
SN 2006aj	2006/09/21	206	0.15	56, 94, 101
SN 2007I	2007/07/15	195	0.36(+)	56, 69, 102
SN 2012ap	2012/09/21	272	0.45	103
	2012/11/16	328		

Supplementary Table. 5: **Early parameters of SNe in this work.**

SN name	type[a]	Δm_{15}	$v_{\rm ph}$ (km s^{-1})[b]	references
SN 1993J	IIb	$0.971^{+0.052}_{-0.078}$	8000^{+1000}_{-1000}	14, 49
SN 1994I	Ic	$1.745^{+0.091}_{-0.140}$	11500^{+1000}_{-1400}	14, 82
SN 1996cb	IIb	$0.764^{+0.059}_{-0.072}$	8500^{+1300}_{-1000}	14, 50
SN 1997ef	Ic-BL	$0.331^{+0.025}_{-0.050}$	13000^{+5000}_{-5000}	91
SN 1998bw	Ic-BL	$0.782^{+0.065}_{-0.079}$	19500^{+1700}_{-1000}	14, 93
SN 2002ap	Ic-BL	$0.983^{+0.045}_{-0.071}$	13000^{+2000}_{-1000}	14, 96
SN 2003bg	IIb	$0.520^{+0.101}_{-0.122}$	8000^{+1000}_{-1000}	14, 53
SN 2004aw	Ic	$0.564^{+0.047}_{-0.056}$	11000^{+1000}_{-1900}	14, 86
SN 2004dk	Ib	$0.468^{+0.041}_{-0.049}$	9200^{+1400}_{-1000}	14, 40, 104
SN 2004fe	Ic	$1.110^{+0.078}_{-0.100}$	11000^{+1000}_{-1000}	14, 105
SN 2004gq	Ib	$0.876^{+0.066}_{-0.082}$	13000^{+1000}_{-1500}	14, 40
SN 2004gt	Ic	$0.634^{+0.058}_{-0.068}$	$10400^{+1200}_{-1200}(+)$	105
SN 2004gv	Ib	$0.777^{+0.058}_{-0.072}$	$9900^{+1400}_{-1400}(+)$	105
SN 2005bf	Ib	$0.433^{+0.057}_{-0.058}$	7500^{+1800}_{-1000}	14, 73
SN 2005kl	Ic	$0.835^{+0.087}_{-0.095}$	$10400^{+1200}_{-1200}(+)$	106
SN 2006aj	Ic-BL	$1.367^{+0.095}_{-0.127}$	18000^{+1000}_{-1000}	14, 106
SN 2006T	IIb	$0.951^{+0.071}_{-0.090}$	7500^{+1000}_{-1000}	14, 105
SN 2007C	Ib	$0.966^{+0.062}_{-0.084}$	11000^{+1000}_{-1400}	14, 40
SN 2007Y	Ib	$1.012^{+0.052}_{-0.080}$	9000^{+1000}_{-1700}	14, 76
SN 2007gr	Ic	$0.940^{+0.072}_{-0.089}$	10000^{+1000}_{-1000}	14, 107
SN 2008ax	Ib	$1.041^{+0.061}_{-0.087}$	7500^{+2100}_{-1000}	14, 57, 108
SN 2008bo	IIb	$1.228^{+0.061}_{-0.093}$	$9900^{+1400}_{-1400}(+)$	14, 106
SN 2009jf	Ib	$0.476^{+0.080}_{-0.026}$	9500^{+2100}_{-1000}	14, 77
SN 2011bm	Ic	$0.172^{+0.016}_{-0.018}$	9000^{+1000}_{-1000}	14, 89
SN 2011dh	IIb	$0.923^{+0.071}_{-0.088}$	7000^{+1000}_{-1000}	14, 59
SN 2011fu	IIb	$0.816^{+0.039}_{-0.063}$	$8300^{+750}_{-750}(+)$	61
SN 2011hs	IIb	$1.252^{+0.067}_{-0.101}$	8000^{+1000}_{-1000}	14, 62
SN 2012P[c] (PTF12os)	IIb	$0.786^{+0.073}_{-0.084}$	7500^{+1750}_{-1750}	63
SN 2012ap	Ic-BL	$0.908^{+0.070}_{-0.087}$	$19100^{+5000}_{-5000}(+)$	103
SN 2013ak	IIb	$0.961^{+0.081}_{-0.099}$	8000^{+1000}_{-1000}	109
SN 2013df	IIb	$1.059^{+0.035}_{-0.052}$	8450^{+1000}_{-1000}	65, 110
SN 2013ge	Ic	$0.732^{+0.061}_{-0.074}$	$10400^{+1200}_{-1200}(+)$	90
iPTF13bvn	Ib	$1.170^{+0.069}_{-0.088}$	8000^{+1000}_{-1000}	14, 63

a. See Supplementary Table 1 to 4 for references.

b. Object with marker (+) means that its photometric velocity is taken as the average value of SN subtype reported in the leterature [14].

c. PTF12os does not have a reported $V-$band light curve. The absolute flux scales of early phase spectra are anchored by $r-$band photometric data [63] and $V-$band light curve is calculated from the calibrated early phase spectra.

Supplementary Table. 6: **KS coefficients of line ratios after phase is corrected.**

Group	IIb/Ib	IIb/Ic	IIb/Ic-BL	Ib/Ic	Ib/Ic-BL	Ic/Ic-BL
[N II]/[O I][a]	$0.541^{+0.338}_{-0.228}$	$0.006^{+0.035}_{-0.008}$	$0.005^{+0.019}_{-0.004}$	$0.023^{+0.042}_{-0.021}$	$0.006^{+0.030}_{-0.004}$	$0.191^{+0.163}_{-0.150}$
[O I]/[Ca II]	$0.863^{+0.087}_{-0.214}$	$0.004^{+0.010}_{-0.001}$	$0.008^{+0.}_{-0.006}$	$0.007^{+0.}_{-0.005}$	$0.002^{+0.004}_{-0.}$	$0.354^{+0.233}_{-0.163}$

a. When comparing [N II]/[O I], SNe eIIb are excluded from the SNe IIb sample, since their '[N II]' flux may be contaminated by Hα. For [O I]/[Ca II], SNe eIIb are included in the KS test.

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