The Peculiar Broad-Lined Type Ic Supernova 2009bb

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On behave of the MCSS + CSP collaboration

Introduction

The Millennium Center for Supernova Studies (MCSS) is obtaining systematic photometric, spectroscopic and polarimetric observations of nearby, extremely young SNe to study their physics. To discovery such kind of objects MCSS is carrying out a supernova search named CHASE (Chilean Automatic Supernova sEarch). CHASE observes a sample of nearby galaxies every day which allow us to discover a SN soon after the explosion. In the following we report, as an example, the case of SN 2009bb. For this SN we have negative detection (limiting mag *< 19.2)* two days prior to the discovery. This allowed us to tight constraint the explosion date and start a very early intensive observation follow-up (See fig 1 and Fig 4)

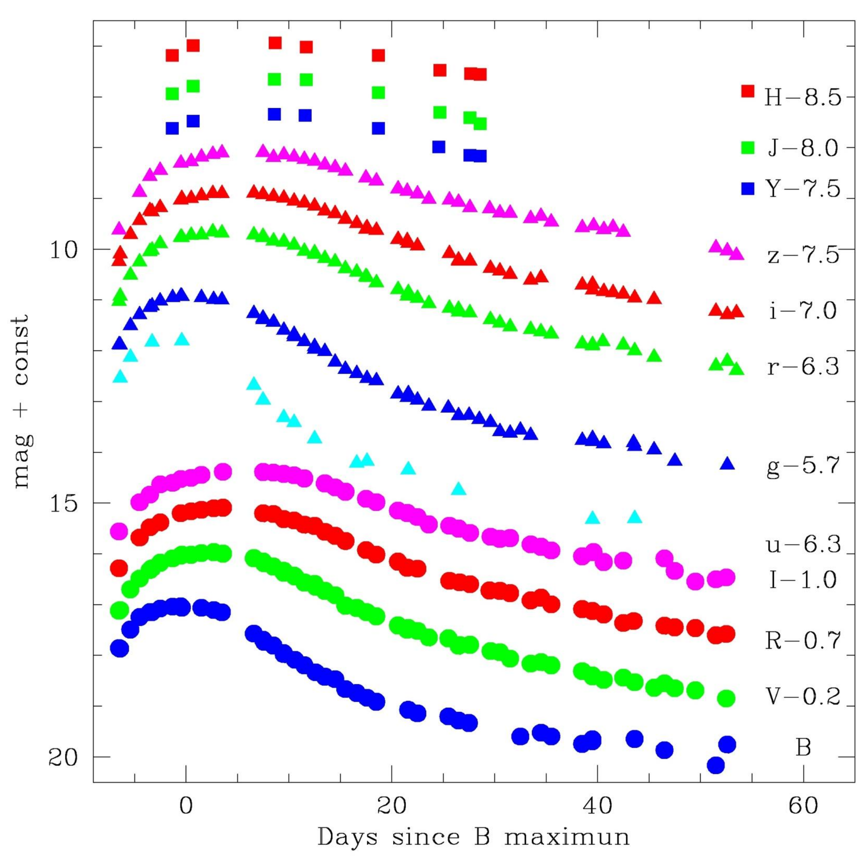

Fig. 1: BVRI ugrizYHK light curves of SN 2009bb

SN 2009bb physical parameters

To estimate the ^{56}Ni content and the ejected mass, we integrated the flux of SN 2009bb contained within the *u'BV RIJH* bands. Also included was a K band correction based on the SN 2002ap light curves. The resulting pseudo-bolometric light curve (see Fig. 2) was then modeled making use of an analytical description for the peak of the light curve (Arnett 1982).

$$L(t) = M_{Ni}\epsilon_{Ni}e^{-x^2}\int_0^x 2ze^{-2xy+z^2}dz$$

where ϵ_{Ni} is the energy produced in 1 second by 1 gram of ^{56}Ni, x=t/τm and $y=\tau_m/2\tau_{Ni}$ with τ_{Ni} being the e-folding time of the ^{56}Ni decay and τ_m effective diffusion time, which determines the width of the bolometric light curve.

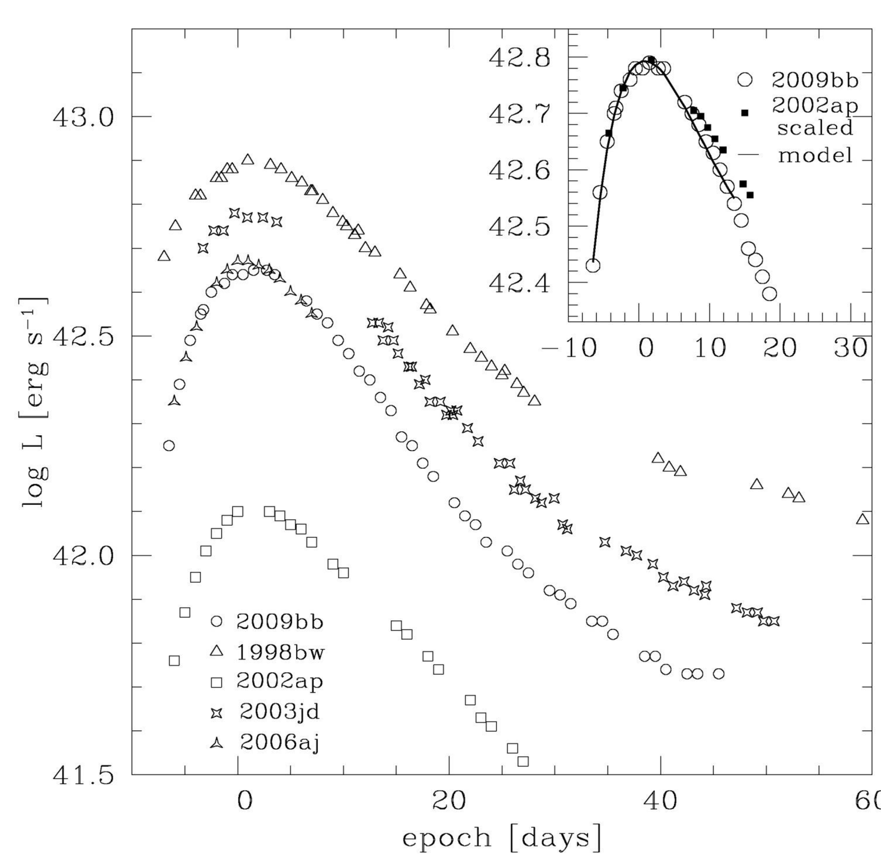

Fig 2: Bolometric light curve of SN 2009bb

In the insert of Fig. 2 we show the resulting model from which we obtain M_{ni} = 0.22 ± 0.06 $M_{\odot}$, M_{ej} = 4.1 ±1.7 $M_{\odot}$ and E_{kin} = 1.8 ± 6 ·10^{52} erg for SN 2009bb. As can be seen in Figure 3, these values of the ^{56}Ni mass and kinetic energy locate SN 2009bb close to SN 1997ef in an intermediate position between SN 2002ap and broad-lined SNe Ic associated with GRBs. "Normal" SNe Ic and the X-ray flash (XRF) SN 2006aj seem to lie out of this linear correlation, following a different trend. A detailed modelling of SN 2009bb and other "normal" SNe Ic spectra will refine these possible correlations.

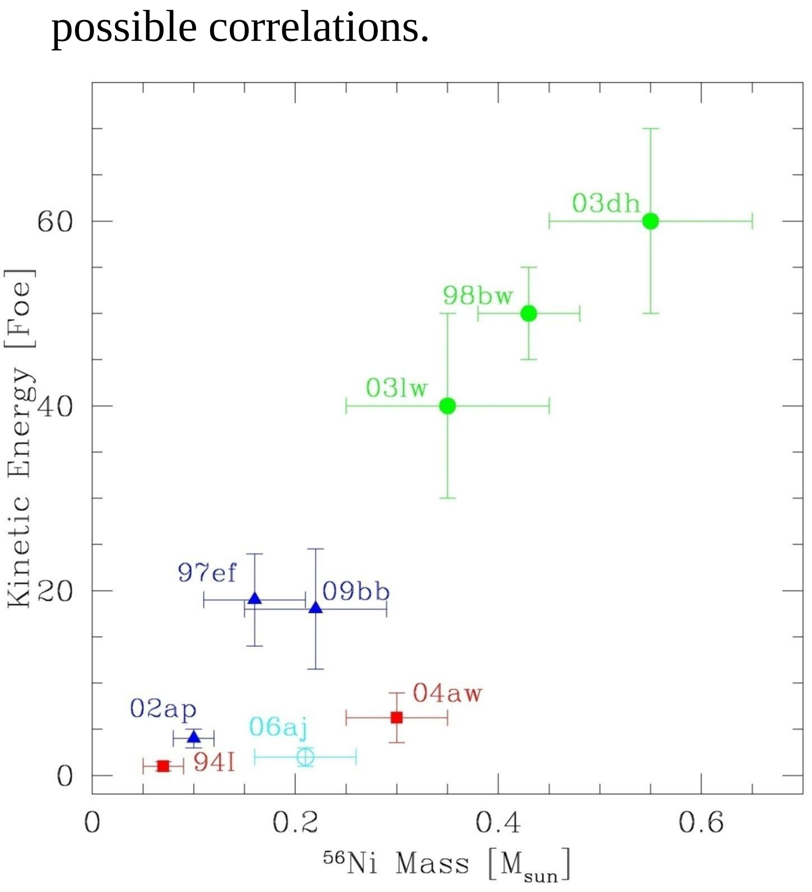

Fig.3: Relation between 56Ni and kinetic energy for "normal" SN Ic (red squares), broad lined SN Ic without GRB (blue triangles), broad lined SN Ic with GRB (green filled circles), and broad-lined SN Ic with XRF (light blue open circle).

Evidence for a central engine

Radio observations of SN 2009bb revealed evidence for an extraordinarily luminous, long-wavelength counterpart, with $L_\nu \sim 5\cdot 10^{28}$ erg s^{-1} (Soderberg et al. 2010). In comparison to the other 150 nearby SNe Ibc observed in the radio band on a similar timescale, SN 2009bb is a factor of 10 to 10^3 more luminous, rivaling the radio afterglow luminosities of the nearest GRB-SNe. Just as in the case of SN 1998bw, the high brightness temperature of the SN 2009bb radio counterpart required an unusually large emitting region and, in turn, a trans-relativistic blast-wave velocity, v ~ 0.9c. Moreover, the high radio luminosity implied a copious energy coupled to the fastest ejecta, E ~ 10^{49} erg. Analytic solutions for the distribution of ejecta in Type Ibc SNe predict a steep coupling of energy and velocity within the homologously-expanding materia.

$$E(v) \approx 3.7\cdot 10^{47}\,(E_{SN}/10^{51})^{3.59}\,(M_{ej}/M_{\odot})^{-2.59}\,(v/0.1c)^{-5.18}\ \text{erg}$$

Taking into account the previously computed values of E_{kin} and M_{ej}, within the homologous outflow, we therefore expect the ejecta traveling at v ~ 0.9c to carry a kinetic energy of $E_{kin} \sim 3.5\ 10^{45}$ erg. This is at least three orders of magnitude below the energy budget required to power the trans-relativistic radio emitting ejecta. We conclude that the luminous synchrotron emission from SN 2009bb cannot be explained in the framework of a homologous SN explosion and another energy reservoir (i.e. a central engine) is required to explain the distribution of ejecta within this GRB-like SN.

The helium detection

The clearest evidence of the presence of helium in the SN 2009bb ejecta is found in the first two spectra taken 2 and 1 days before B maximum brightness, respectively. A striking feature in these two spectra is the absorption around 5400 Å. As visible in Fig. 5, this line is not visible in the other SNe spectra, and we suggest that it corresponds to He I λ 5876. Fitting the line profile with SYNOW, we obtain a good match for a velocity in the line forming region of 28000 km s^{-1} and 27500 km s^{-1} in the first and second spectra, respectively. A similar velocity is also obtained by fitting the absorption around 4800 Å with Fe II λλ4924, 5018, 5169 and also provides a good match with Si II λ6355 for the absorption located at 5800 Å. The expected positions of the He I λ7065 absorption is also marked. In both the -2 and - 1 day spectra, features are present at this wavelength, but they are very weak. Looking to Fig. 5 (right side) the SN 2009bb spectrum taken at 4 days after B maximum, between 5000 and 6000 Å our SN still clearly differs compared to the other broad-lined SNe Ic. Attributing this absorption to detached He I at 25000 km s^{-1}, we obtain a reasonable fit of the observed feature. As for the previous spectra the expected positions of the other He I features for the assumed detached velocity (25000 km s^{-1}) are indicated in Fig. 7. Indeed, an absorption corresponding to He I λ6678 appears to be present and helps to fit the boxy profile of the Si II line

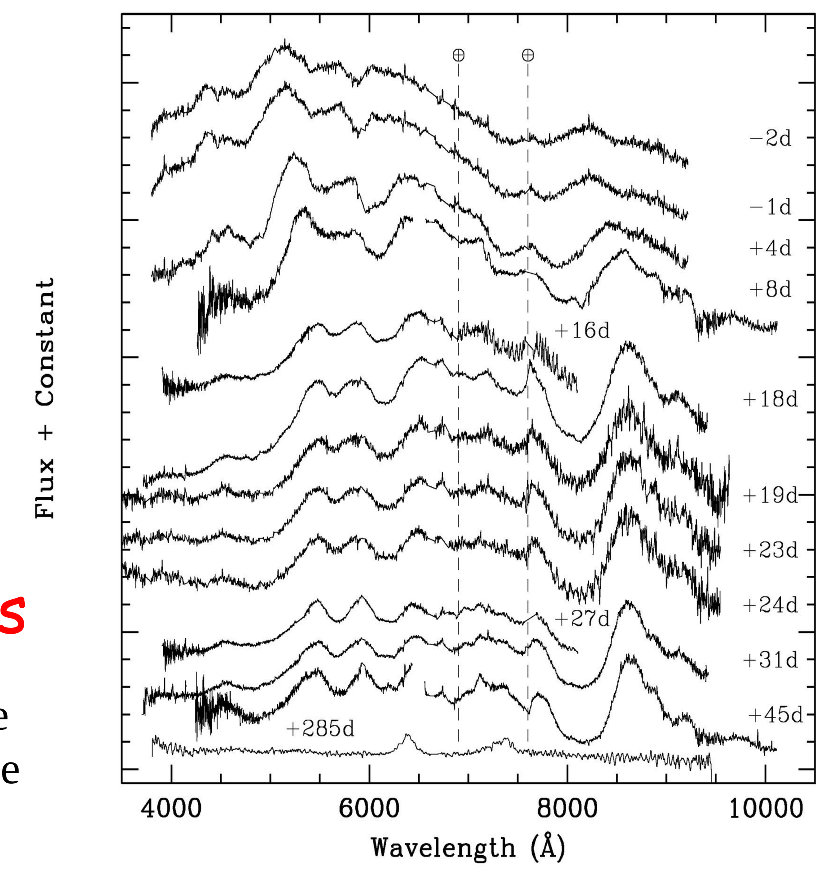

Fig. 4: Spectral evolution of SN 2009bb

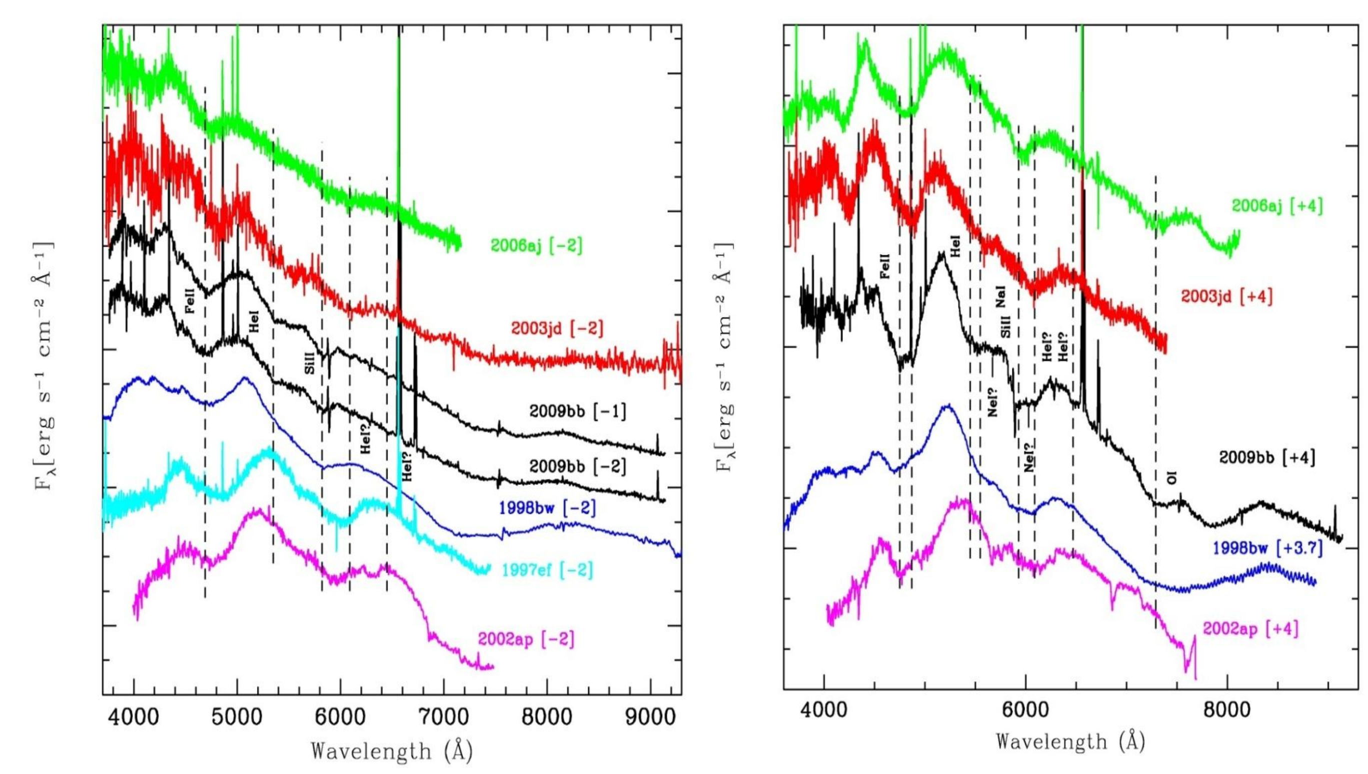

Fig 5: SN 2009bb spectra taken at -1 and -2 days (left side plor) and at +4 days (right side plot)

The helium disappearance

As visible in Fig. 6 in the SN 2009bb spectra taken on *+33 and +44* spectra of, there also is no clear signature of the He I *λ6678 and λ7065 features*. The latter evolution is odd compared to what is normally observed in SNe Ib where the He I features are stronger at these later epochs than at maximum (e.g. Matheson et al. 2001). A possible explanation for the lack of strengthening of the He I absorption features in the case of SN is that, due to the higher expansion velocity of broad-lined SNe Ic together with a less massive helium shell, the density of helium in the line forming region at these later epochs is likely much lower than in normal SNe Ib.

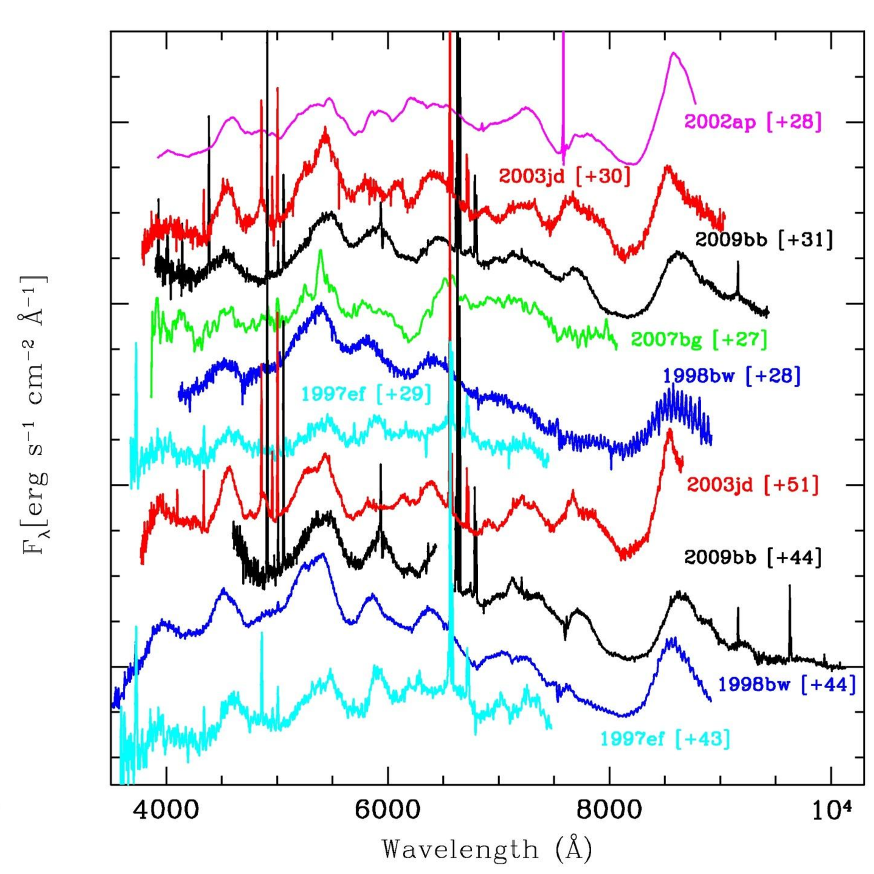

Fig. 6: SN 2009bb spectra taken at +33 and +44 days

The nebular spectrum

In Fig. 7 We compare the nebular spectrum of SN 2009bb with that of other broad lined SNe Ic. It is immediately clear that the calcium to oxygen ratio is much larger in SN 2009bb than in all the other comparison SNe. It is also evident, when compared to the spectra of SNe 2003jd and SN 1998bw, that the profile of the [O I] *λλ6300, 6354 emission* in SN 2009bb is more similar to that of SN 1998bw than that of SN 2003jd (see Fig. 8). In Fig. 7 is also reported a synthetic spectrum fitting the SN 2009bb observed spectrum. The model requires an outer velocity of 5500 km s^{-1}. *This velocity appears to be* adequate to fit all lines. This could be taken as an argument that SN 2009bb was not significantly aspherical. In models where more energy is released in a polar direction, leading to the synthesis of ^{56}Ni and possibly to the production of a GRB, the [Fe II] lines are broader than the [O I] line if the event is viewed close to the polar axis (Maeda et al 2003). Otherwise, the [Fe II] lines are narrower than the [O I] line, which shows a characteristic double-peaked profile, as in SN 2003jd. Nevertheless, the strongest evidence for asphericity in SN 1998bw was seen in nebular spectra obtained 200 days after maximum (Mazzali et al. 2001), while the difference between the iron and oxygen lines width was smaller at epochs of 340 days, which is closer to the epoch of the only nebular spectrum available for SN 2009bb. Therefore, while from this spectrum only we do not infer major asphericities in SN 2009bb, we cannot rule out that the signature of asphericity might have been seen in earlier nebular data.

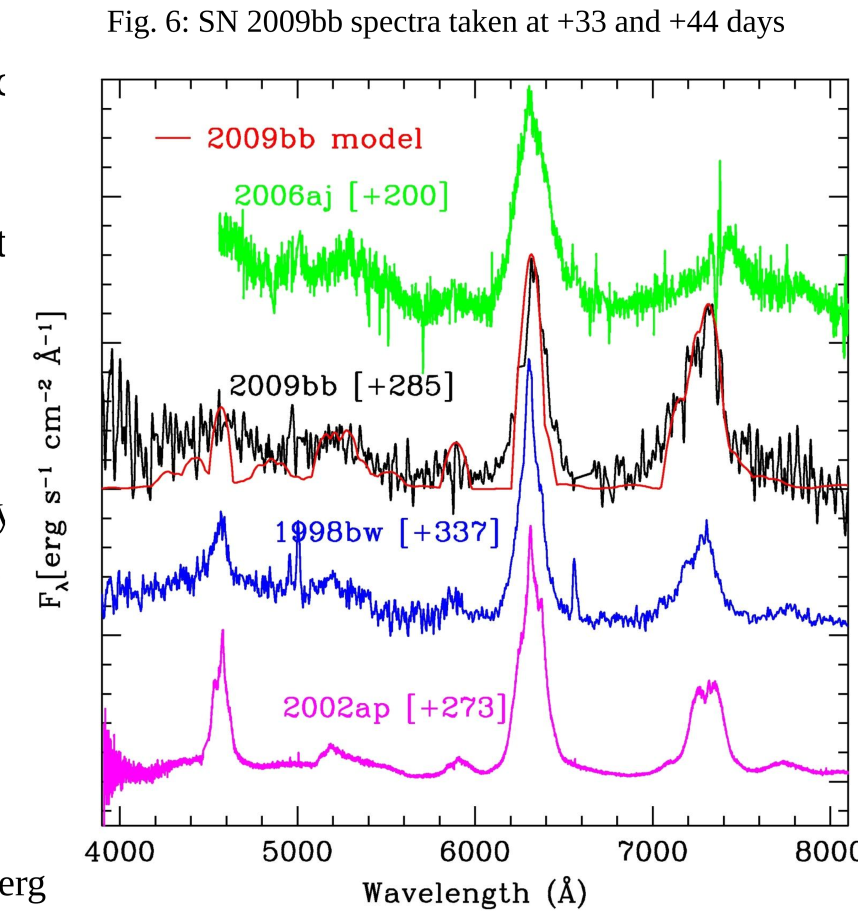

Fig. 7: Nebular spectrum of SN 2009bb

Conclusion

Without a detected GRB counterpart, SN 2009bb represents the first engine-driven, relativistic supernova ever discovered by its optical emission alone. The presence of a relatively massive helium layer may have played a role on the failed GRB detection, but a quantitative description of the helium shell is necessary to verify this hypothesis.

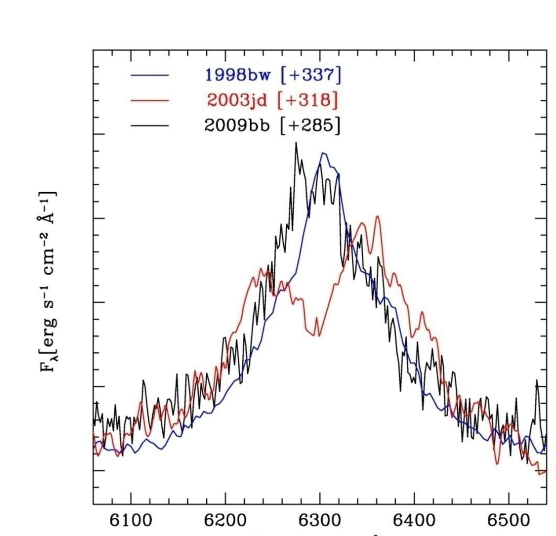

Fig. 9: zoom on the [O I] *λλ6300, 6354*

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