Subaru Late Time Spectroscopy of Extremely Luminous SN 2006gy

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Abstract

Supernova (SN) 2006gy is an extremely luminous Type IIn SN characterized by the bright peak magnitude M_R ~–22 mag and its long duration. The mechanism giving rise to its huge luminosity is still unclear. We performed optical spectroscopy and photometry of SN 2006gy at late time, ~400 days after the explosion, with the Subaru/FOCAS. We found that the SN faded by ~3 mag from ~200 to ~400 days after the explosion (i.e., by ~5 mag from peak to ~400 days) in R band. The overall light curve is marginally consistent with the 56Ni heating model, although the flattening around 200 days suggests the optical flux declined more steeply between ~200 and ~400 days. The late time spectrum was quite peculiar among all types of SNe. It showed many intermediate width (~2000 km s^{-1} FWHM) emission lines, e.g., [Fe II], [Ca II], and Ca II. The absence of the broad [O I] 6300, 6364 line and weakness of [Fe II] and [Ca II] lines compared with Ca II IR triplet would be explained by a moderately high electron density in the line emitting region. This high-density assumption seems to be consistent with the large amount of ejecta and low expansion velocity of SN 2006gy. The Hα line luminosity was as small as ~1×10^{39} erg s^{-1}, being comparable with those of normal Type II SNe at similar epochs. Our observation indicates that the strong circumstellar medium interaction had almost finished by ~400 days. If the late time optical flux is purely powered by radioactive decay, at least M(^{56}Ni) ~ 3 $M_\odot$ should be produced at the SN explosion. In the late phase spectrum, there were several unusual emission lines at 7400 Å-8800 Å and some of them might be due to Ti or Ni synthesized at the explosion.

1. Introduction

SN 2006gy (Fig. 1):

Extremely luminous (Ofek+ 2007, Smith+ 2007)
LC evolved very slowly
Extremely high total radiation energy ~10^{51}ergs

Suggested models:

- Interaction between CSM and SN ejecta, analog with SNe IIn/IIa (Ofek+ 2007)
- Radioactive decay of ^{56}Ni (> 10$M_\odot$) is primal heating source (e.g., Smith+ 2007)
- Both CSM interaction and radioactive decay contributed (Agnoletto+ 2009)
- Pair-instability SN at extremely massive star (Smith+ 2007)
- Core-collapse SNe is also plausible (Umeda & Nomoto 2007)
- Shell collisions in pulsational pair-instability activity in a ~90$M_\odot$ star (Woosley+ 2007)
- Merging of two massive stars (Portegies+ 2007)

→ **Explore the origin of this unusual SN by optically-thin phase observation**

2. Observation and Data Reduction

Subaru 8.2m telescope + FOCAS:

2006 Dec 25.4 (127 d) and 2007 Jan 24.4 (157 d)
R~3600 spec with VPH650 grism, 1200sec exp. + VR imaging

2007 Sep 18.5 (394 d)
R~660 spec with B300 grism, 1200sec exp. + VR imaging
Underlying galaxy component is carefully subtracted.

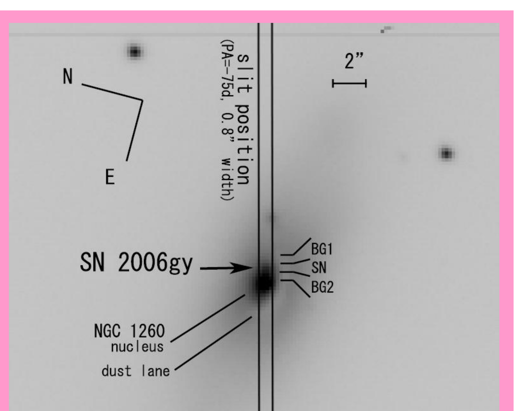

Fig. 1 Subaru R-band image of SN 2006gy at t=394 days

3. Light curve Analysis

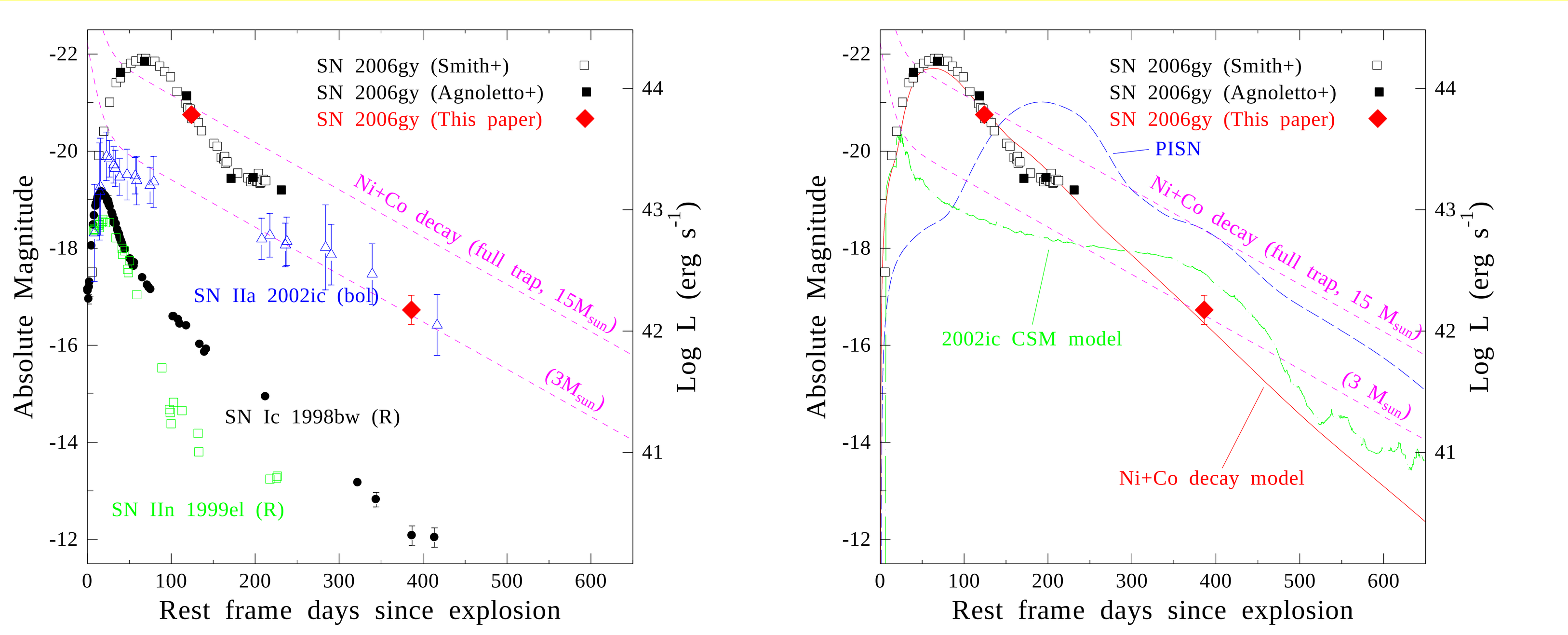

Fig 2. (Upper) Absolute R-band light curve of SN 2006gy compared with compared with bright type Ic SN 1998bw, SNe IIa 2002ic and 1999el (Patat+ 2001; Deng+ 2004; Di Carlo+ 2002). **(Lower)** Compared with core-collapse SN and pair-instability SN LC models.

In Fig.2 we plot LC of SN 2006gy. Decline rate between 200d and 400d is faster than that of SN 2002ic and ^{56}Co decay (full trap) line, while it is comparable to LC of SN 1998bw. The extremely bright maximum magnitude and its slow evolution is atypical.

From comparison with model LCs (Fig. 2, lower), the ^{56}Ni-^{56}Co decay model with M_{ej}=53$M_\odot$, kinetic energy=64×10^{51}erg and M_{Ni}=15$M_\odot$ reasonably explains the overall LC of SN 2006gy. Woosely et al (2007) also gives a good agreement in LC with their PPI model. Diffusion model by Smith & McCray (2007) is inconsistent in the decline rate at late phase.

Decline rate at late phase seems almost consistent with the radioactive heating models, but we cannot exclude some kinds of CSM interaction models like SNe IIa/IIn from our sparse LC.

4. Spectral Analysis

In Figs. 3, we show observed spectra. The early phase (127d, 157d) spectra are characterized by structured H-alpha emission line (accompanied with broad blue absorption ranging up to ~-4000 km s^{-1}, which might be a SN blast wave component; Fig. 4) as well as FeII, He I and Na I D lines. At 394d the H-alpha emission line has been narrowed (<500km s^{-1}). Na I D line still has a broad absorption with a Doppler shift of ~3000 km s^{-1}.

In the late phase spectra (394 d), we can see several emission lines in red wavelength, including [Ca II] 7291, 7323 (7302 in average), Ca II IR triplet and [Fe II] 7155. The blue spectrum is likely to be dominated by continuum component and/or heavily blended emission lines. **Additionally, there is a possible Hα emission component having an intermediate width, ~1000 km s^{-1} (Fig. 4). Its line flux is estimated as ~1×10^{39} erg s^{-1}.**

In Fig. 5, the late time spectrum is compared with those of various classes of SNe. Unlike other slowly declining SNe IIn/IIa, **Hα emission line in SN 2006gy is neither strong nor wide**. Some unidentified emission lines are seen in red region (marked by blue vertical dashed lines in Fig. 3), which are unusual for any type of SNe.

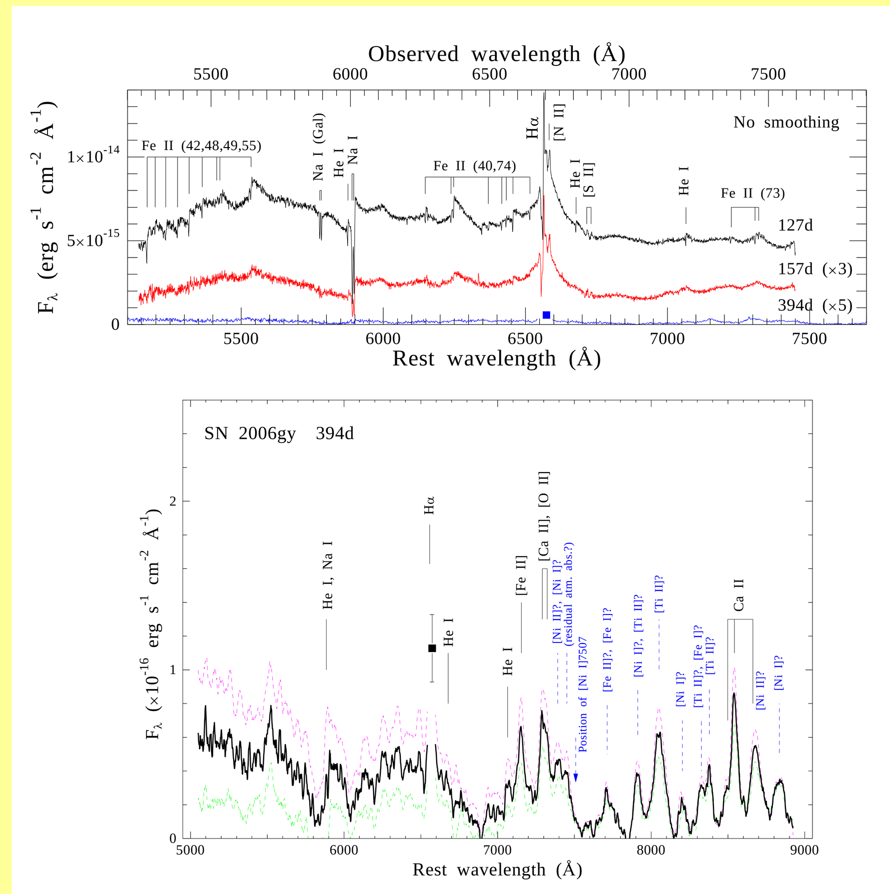

Fig 3 (upper): Higher resolution spectra on t = 127d an 157d.which is characterized by many lines with P Cyg type profiles. **(Lower)** Late phase (394d) spectrum. Since the Hα emission line was contaminated by background H II region component, we plotted the Hα component estimated from the interline flux between Hα and [N II] 6584.

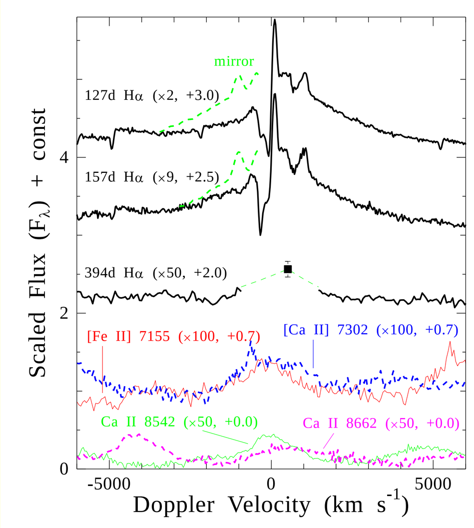

Fig 4: Line profiles of Hα plotted against Doppler velocity. The green dashed line is the reflected red-side profile across v = 0 km s^{-1}. lower four lines are Fe and Ca lines at t=394 d.

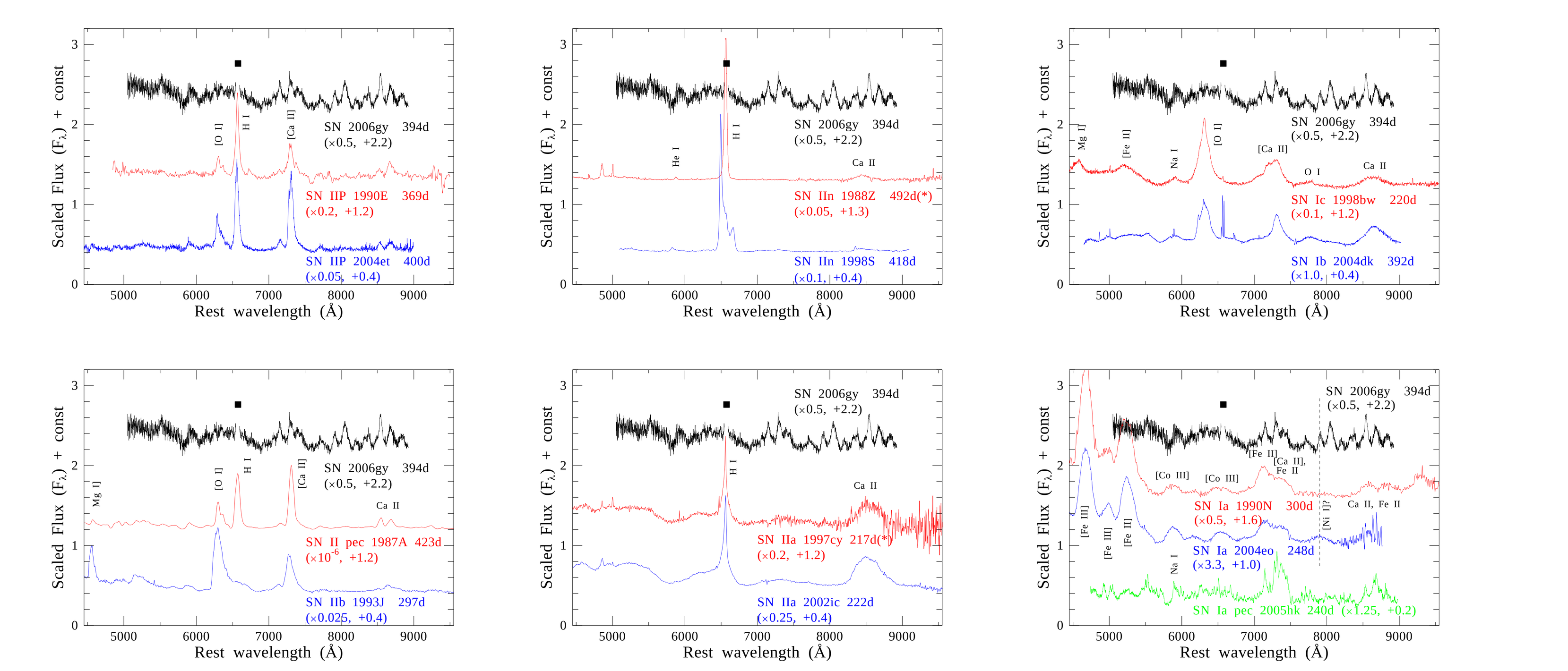

Fig 5: Late spectrum comparison with (upper left) SNe IIP, (lower left) peculiar II 1987A and SN IIb 1993J, (upper mid) SNe IIn, (lower mid) SNe IIa, (upper right) SNe Ib/c, and (lower right) SNe Ia (Gomez & Lopez 2000; Sahu+ 2006; Pun+ 1995; Barbon+ 1995; Turatto+ 1993; Pozzo+ 2004; Germany+ 2000; Turatto+ 2000; Patat+ 2001; Maeda+ 2008; Deng+2004).

5. Discussion

Which is main heating source, CSM Interaction or Radioactive Decay?

Although SN 2006gy is classified as Type IIn from earlier spectra, the late time spectrum is quite atypical for Type IIn/Iia SNe as seen in Fig. 5. The Hα emission at 394 days (1×10^{39} erg s^{-1}) is considerably smaller than those of other Type IIn/IIa SNe at similar phases (10^{40}-10^{41} erg s^{-1}) and rather consistent with that of a typical Type II SN. **Thus, we do not need any strong CSM interaction at t=394 days.**

However, pure radioactive decay model also have an inconsistency. Core-collapse SNe generally show [O I] 6300,6364 line at late time except for Type IIn/Iia SNe, while SN 2006gy showed little or no [O I]. As for Fe line, in Type Ic SN 1998bw, a blend of [Fe II] around 5200Å and [Fe II] 7155 line are strong, while only [Fe II] 7155 is seen in SN 2006gy. The LC of SN 1998bw is fully explained by the heating of ~0.4 $M_\odot$ of ^{56}Ni (Maeda+ 2006). If the peak luminosity of SN 2006gy is powered by the decay of ^{56}Ni, the required mass of ^{56}Ni is > 10 $M_\odot$, more than 20 times larger than that of SN 1998bw. This would result in stronger Fe lines in SN 2006gy. **Thus, the weakness of [O I] and [Fe II] lines seem against the ^{56}Ni heating scenario.**

Moderately High Density of Line Emitting Region

The line flux ratio F(7302)/F(IR triplet) of SN 2006gy is only ~0.5, while It is >1 in SNe of other types. The value of F(7302)/F(IR triplet) ~0.5 suggests an electron density of the emitting region N_e~10^8-10^9 cm^{-3}. (Ferland & Persson 1989; Fransson & Chevalier 1989). This is consistent with the existence of the [Fe II] 7155 (critical N_e ~a few times 10^8 cm^{-3}) and also with the absence of [O I] (critical N_e ~10^6 cm^{-3}**). N_e~10^8-10^9 cm^{-3}.of SN 2006gy would be less than those of Type IIn/IIa SNe and more than other Type II and Ib/c SNe**.

The unidentified emission lines at 7400-8800Å might be from [Ni II], [Ni I] or [Ti II] lines in the innermost ejecta. The moderately high density assumption (N_e~10^8-10^9 cm^{-3}) is not against that the ejecta is transparent. However, these identifications are still tentative.