The Peculiar SN 2005hk

Do Some Type Ia Supernovae Explode as Deflagrations?

M.M. Phillips

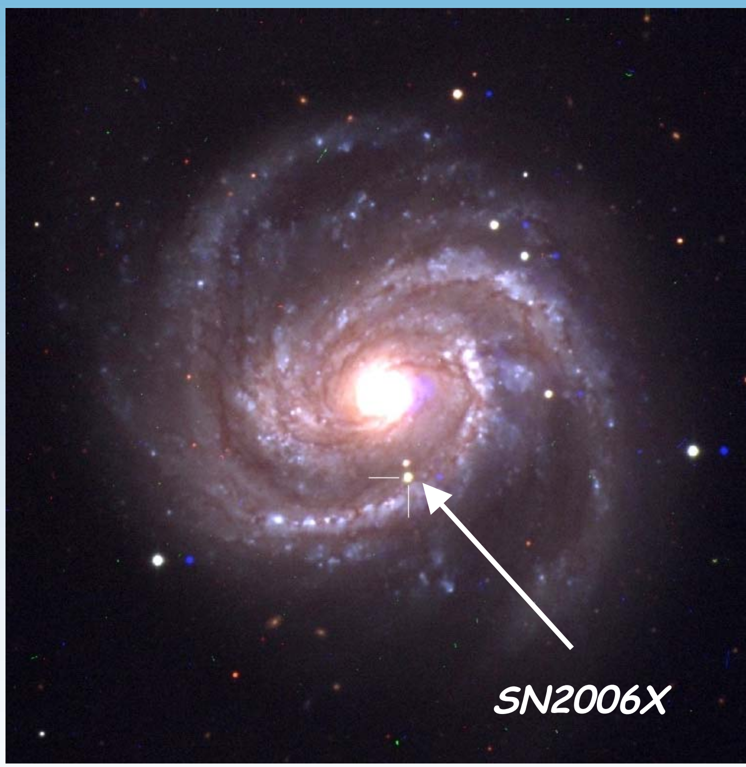
Carnegie Observatories

Carnegie Supernova Project (CSP)

in collaboration with the Lick, SDSS II, & Swift groups

The Carnegie Supernova Program (CSP)

Las Campanas Observatory, Chile



Swope 1 m

duPont 2.5 m

Magellan 6.5 m telescopes

Low-z CSP Goals

- A 5-year program to obtain high-quality, gap-free u'BVg'r'i'YJHK light curves and optical spectra of:
  - ≥100 nearby ($z<0.07$) **Type Ia** supernovae
  - ≥100 nearby ($z<0.05$) **Type II** supernovae
  - ≥20 nearby ($z<0.05$) **Type Ibc** supernovae
- Establish and refine methods for obtaining distances to **Type Ia** and **Type II** supernovae
- Provide a new fundamental reference for observations of high-z supernovae
- **Gain insight into the progenitors and explosion mechanisms of supernovae**

High-z CSP Goals

- Obtain rest system I light curves of ~100 SNe Ia at $0.2 < z < 0.7$
- Provide an independent estimate of the dark energy contribution to the total energy density of the Universe
- The CSP High-z effort differs from other projects undertaken to date in focusing on the I band
    - Effect of dust extinction is 2-3 times less than in U and B bands
    - Slope of peak luminosity vs. decline rate relation is less in I band

CSP People

Chile

Mark Phillips (OCIW/LCO) P.I. Low-z
Miguel Roth (OCIW/LCO)
Gastón Folatelli (postdoc)
Mario Hamuy (U. Chile)
Nidia Morrell (OCIW/LCO)
Wojtek Krzeminski (OCIW/LCO retired)
Sergio Gonzalez (research assistant)
Carlos Contreras (research assistant)
Luis Boldt (research assistant)

OCIW

Wendy Freedman P.I. High-z
Eric Persson
Barry Madore
Chris Burns (postdoc)
Pamela Wyatt (research assistant)
David Murphy

Texas A&M

Nick Suntzeff
Kevin Krisciunas
Lifan Wang

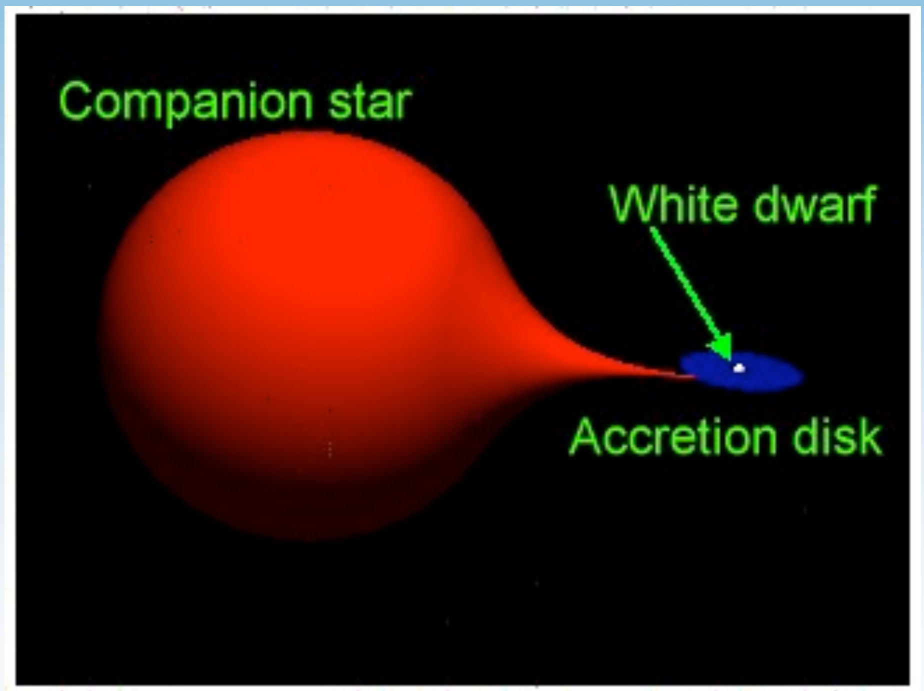
Other collaborators

Alex Filippenko (UC Berkeley)
Weidong Li (UC Berkeley)
Ray Carlberg (Univ. Toronto)
Josh Frieman (Chicago/Fermi Lab.)
Darren Depoy (Ohio St.)
Jose Luis Prieto (Ohio St.)

Papers Published or in Preparation

- **Low-z:**
  - The Carnegie Supernova Project: The Low-Redshift Survey (Hamuy et al. 2006)
  - SN 2005bf: A Possible Transition Event between Type Ib/Ic Supernovae and GRBs (Folatelli et al. 2006)
  - The Peculiar SN 2005hk: Do Some Type Ia Supernovae Explode as Deflagrations (Phillips et al. 2007)
  - K-Corrections and Spectral Templates of Type Ia Supernovae (Hsiao et al. 2007)
  - Collaboration with SDSS II on SN 2005gj (a 2002ic-like object) (Prieto et al.)
  - Collaboration with Swift group on SN 2005ke (a fast-declining SN Ia with a possible CSM interaction (Milne et al.)
  - Optical/NIR light curves for 32 SNe Ia observed during first 1.5 campaigns (Contreras et al.)
  - Analysis of the above data (Folatelli et al.)
- **High-z:**
  - Observations/analysis of first batch of rest frame I-band light curves

How Do SNe Ia Explode?



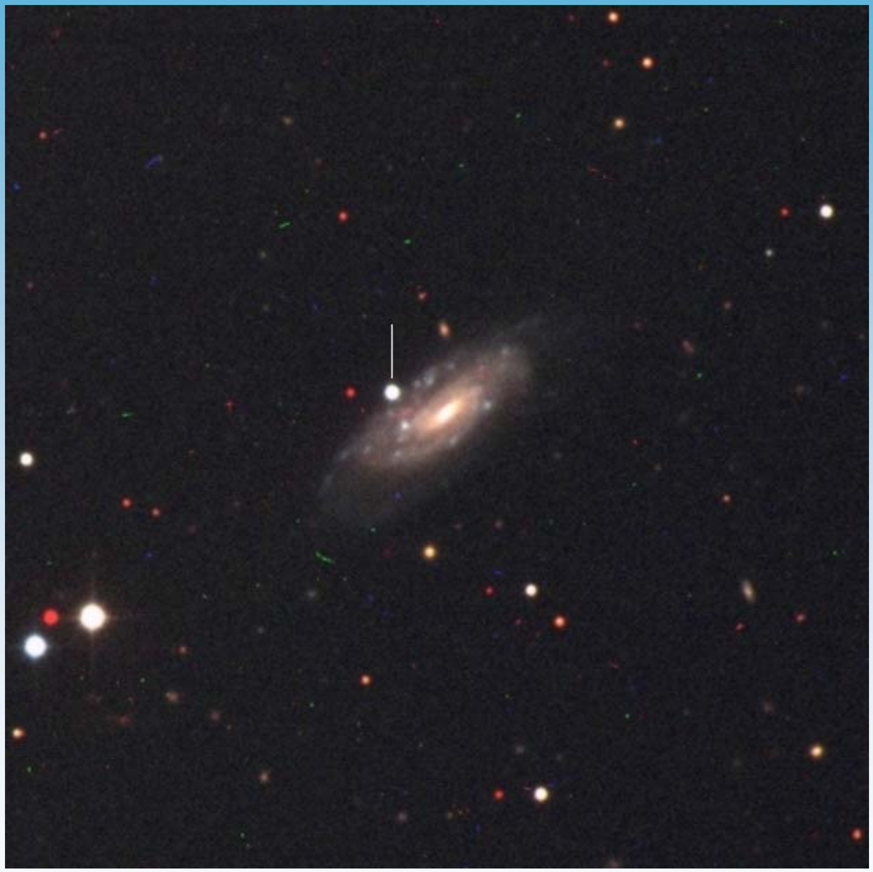
- The most popular model is an accreting C-O white dwarf approaching the Chandrasekhar mass limit in a binary system
- At some point, carbon ignition occurs producing a sub-sonic burning front called a “deflagration”
- The flame may eventually transition from a deflagration to a sonic or super-sonic detonation — this is called a “delayed detonation”
- In either case, the white dwarf is completely incinerated in seconds, with most of the C and O being burned to Fe-peak elements

Deflagrations vs. Delayed Detonations

- Results in recent years from 3D calculations of **pure deflagrations** suggest that these models fail to match observations of "normal" SNe Ia in several ways:
  - Not enough ^{56}Ni or kinetic energy produced
  - ^{56}Ni is too mixed
  - Too much unburned carbon and oxygen
- Delayed detonation models do not appear to suffer these problems, although this is still to be confirmed by 3D calculations

Are there any SNe Ia that match pure deflagration models?

SN 2005hk in UGC 272



- Discovered independently by the Lick Observatory and SDSS-II supernova searches on 2005 Oct. 28
- Maximum in *B* occurred 2 weeks after discovery
- Initially classified as 1991T-like SN Ia (high ionization pre-max spectrum)
- Closer analysis by the Lick and CSP groups revealed that it actually was a **2002cx-like** event

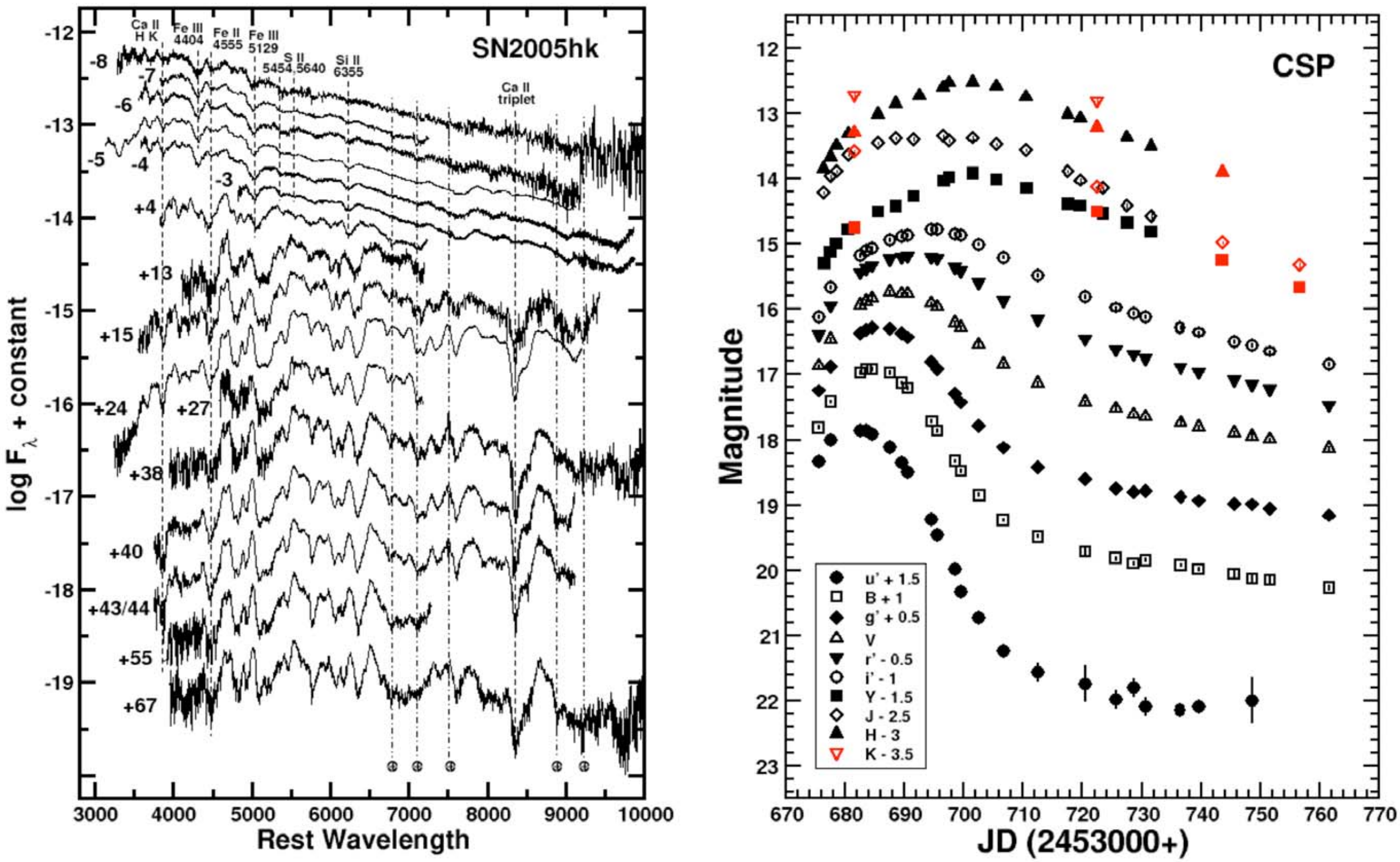
What are 2002cx-Like Events?

SN 2002cx-like events are SNe Ia which display the following peculiarities:

- A 1991T-like spectrum dominated by a blue continuum and Fe III absorption features at pre-maximum epochs
- Unusually-low expansion velocities at all epochs
- Absence of secondary maximum in *I* band
- Low peak luminosity

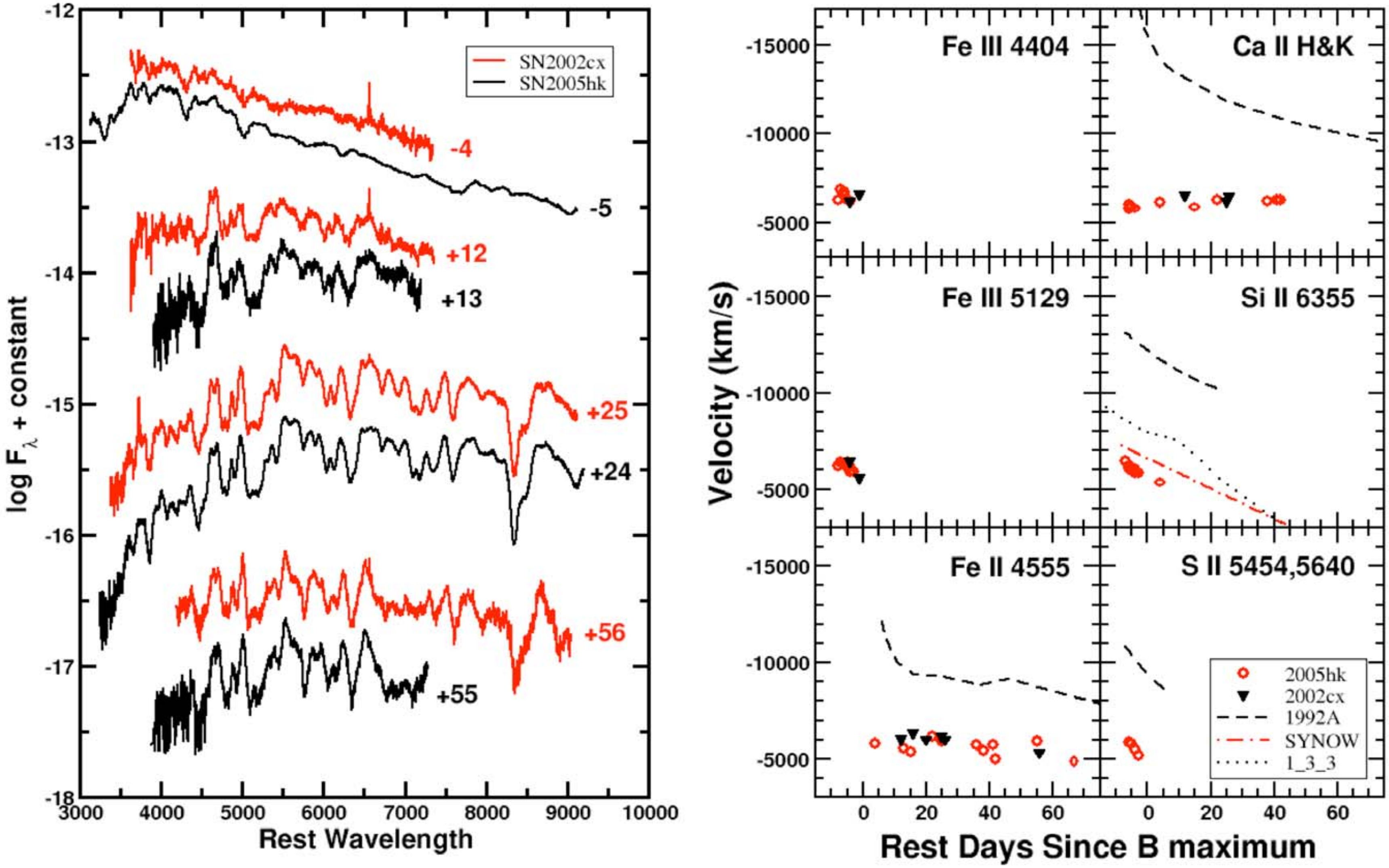
The prototype of this subclass, SN 2002cx, has been called "the most peculiar known Type Ia supernova" (Li et al. 2003)

CSP Observations of SN 2005hk

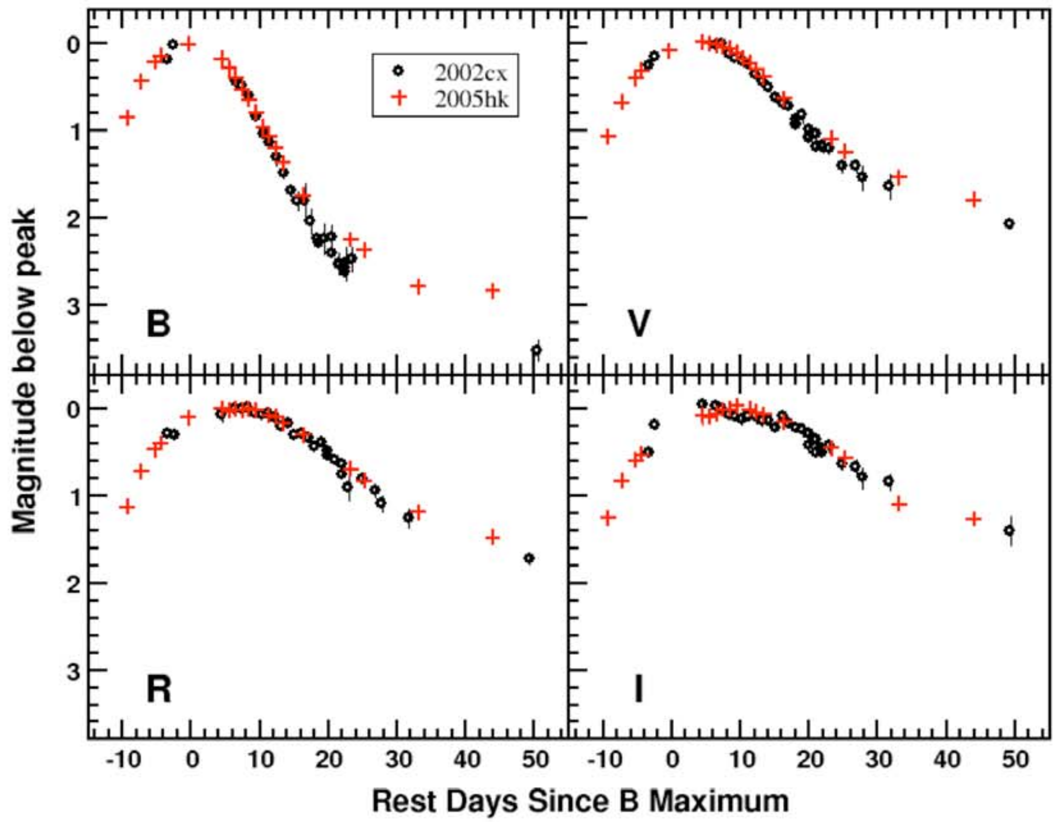


Paths to Exploding Stars, KITP, Mar 2007

Comparison with SN 2002cx

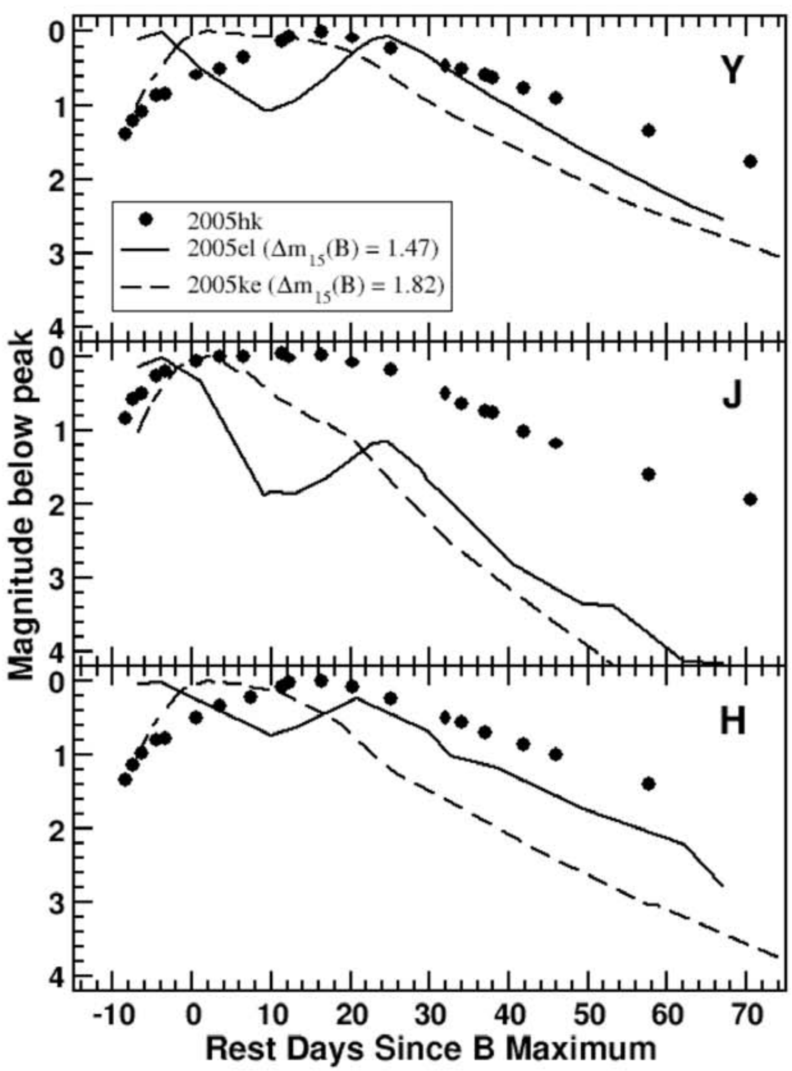


Comparison with SN 2002cx

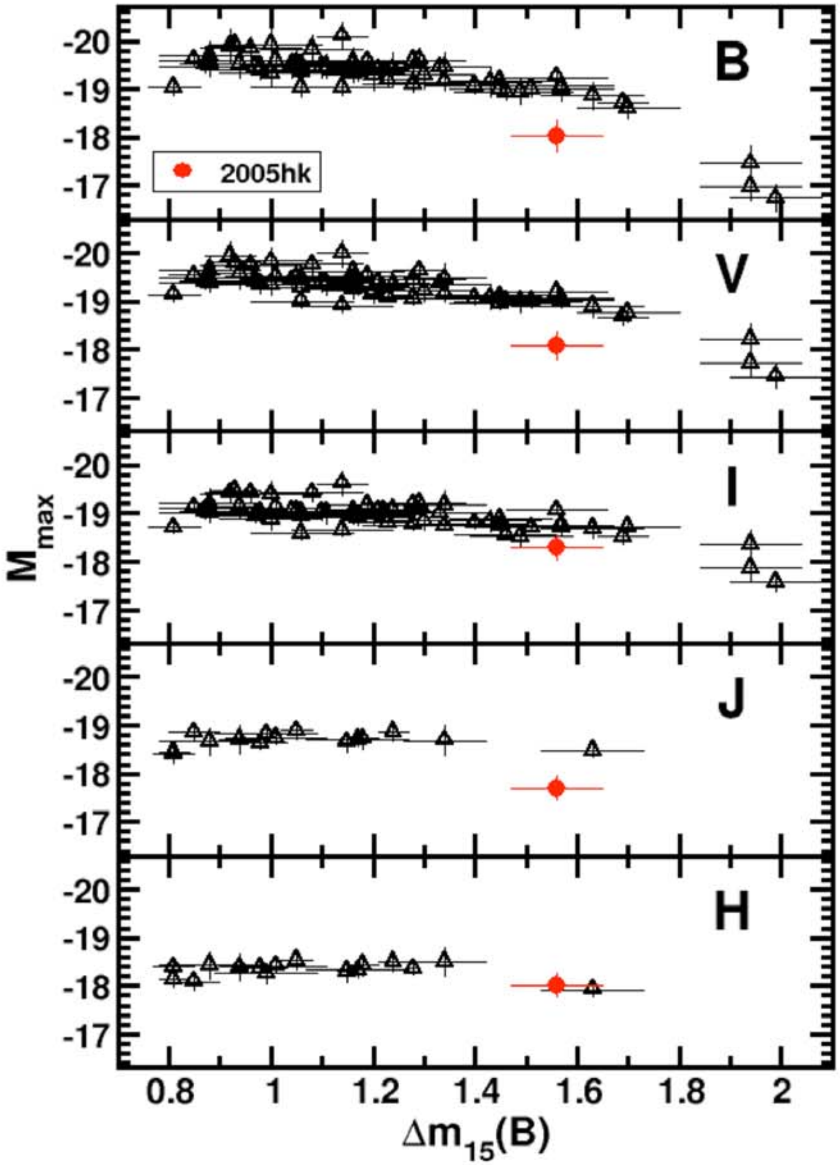


SN	M_B^{max}	M_V^{max}	M_R^{max}	M_I^{max}
2002cx	-17.53(26)	-17.49(22)	-17.60(20)	-17.73(18)
2005hk	-18.02(32)	-18.08(29)	-18.20(27)	-18.28(26)

Near-IR Light Curves of SN 2005hk



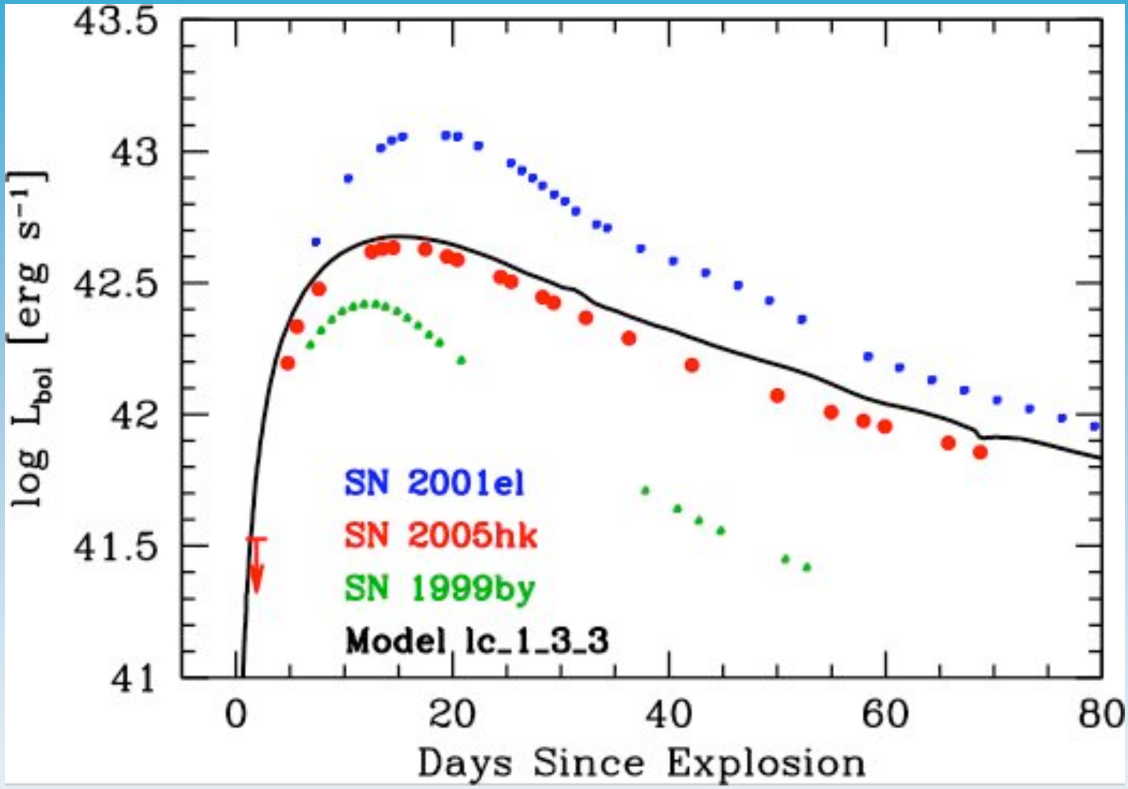
- Note absence of secondary maxima
- This behavior is observed only in the very fastest-declining, lowest luminosity SNe Ia
- The strength of the secondary maximum is a good indicator of the amount of mixing of ^{56}Ni in the ejecta (Kasen 2006)
- The absence of secondary maxima in a moderate decline rate SN Ia such as 2005hk is indicative of complete mixing of ^{56}Ni



Absolute Magnitudes of SN 2005hk

- SN 2005hk and SN 2002cx were notably sub-luminous compared to other SNe Ia with comparable decline rates
- Nevertheless, in the H band, the luminosity of SN 2005hk was essentially normal

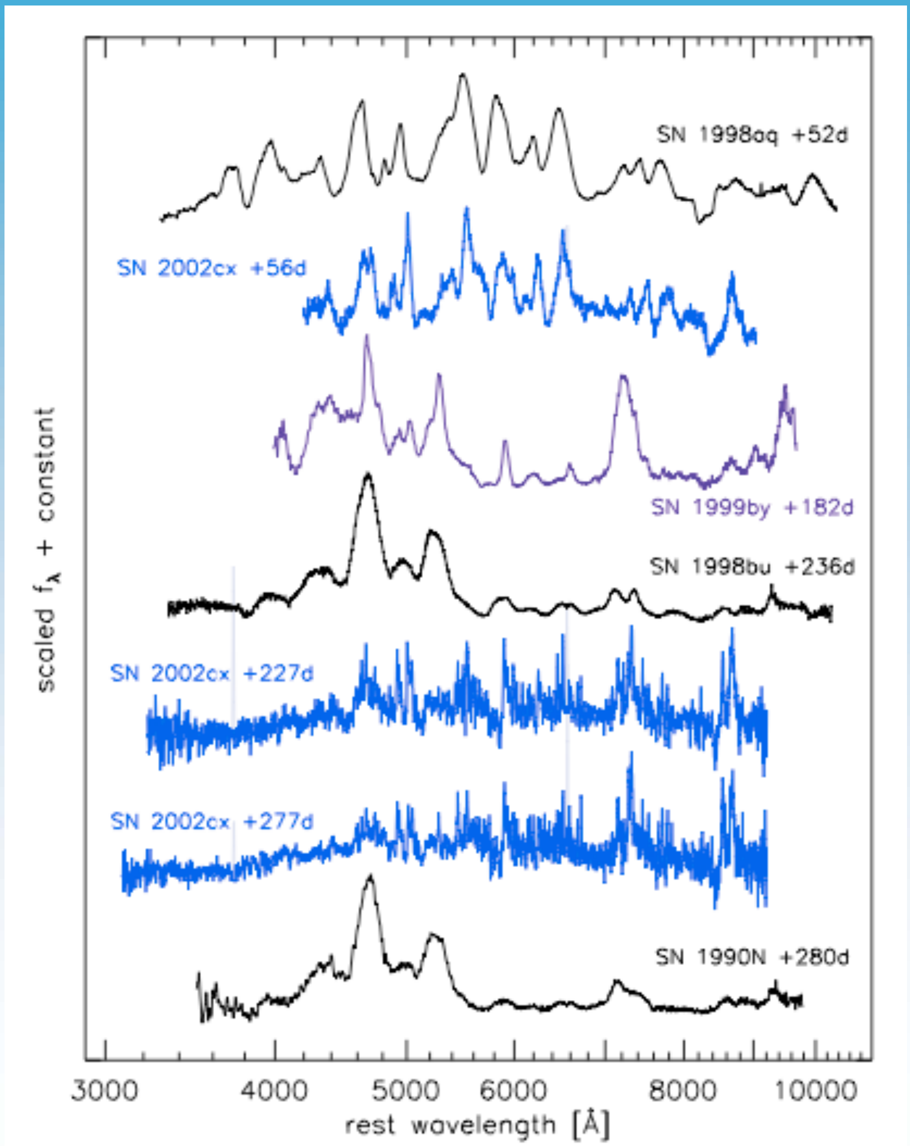
Bolometric Light Curve of SN 2005hk



• CSP u′Bg′Vr′i′YJHK photometry was combined with Swift satellite data to calculate the bolometric light curve of SN 2005hk covering the wavelength range from 1100 Å to infinity

• Not only was SN 2005hk **sub-luminous**, but the decline rate at later epochs was **slower** than that of normal SNe Ia

Late-Epoch Spectra of SN 2002cx

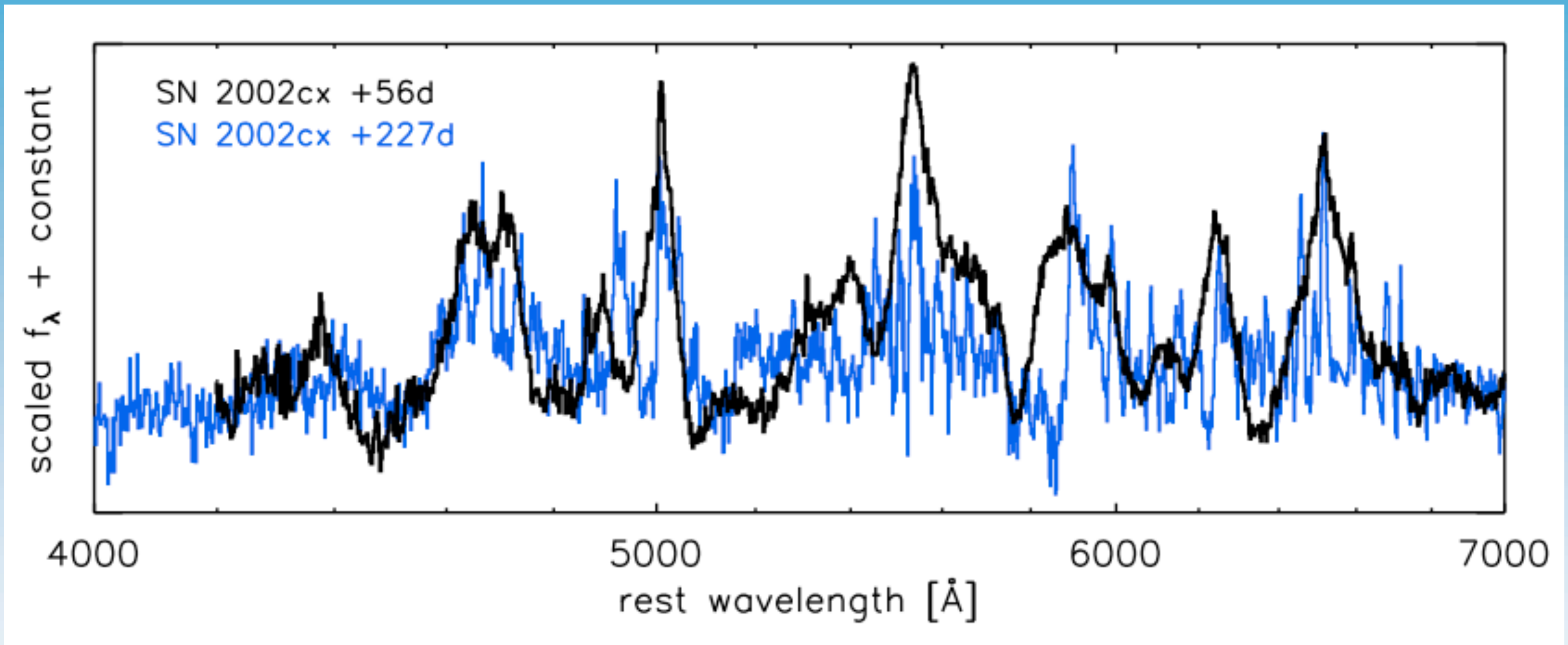


Jha et al. (2006)

- Jha et al. (2006) obtained late-epoch spectra of SN 2002cx
- At +56 days, the spectrum of SN 2002cx resembles that of a typical SN Ia, expect for the narrower line profiles
- However, at 8-9 months past maximum, the spectra of SN 2002cx bear little resemblance to the late-epoch spectra of normal SNe Ia which are dominated by [Fe II] and [Fe III]
- At these late-epochs, the spectrum of SN 2002cx continues to resemble that obtained at +56 days

Late-Epoch Spectra of SN 2002cx

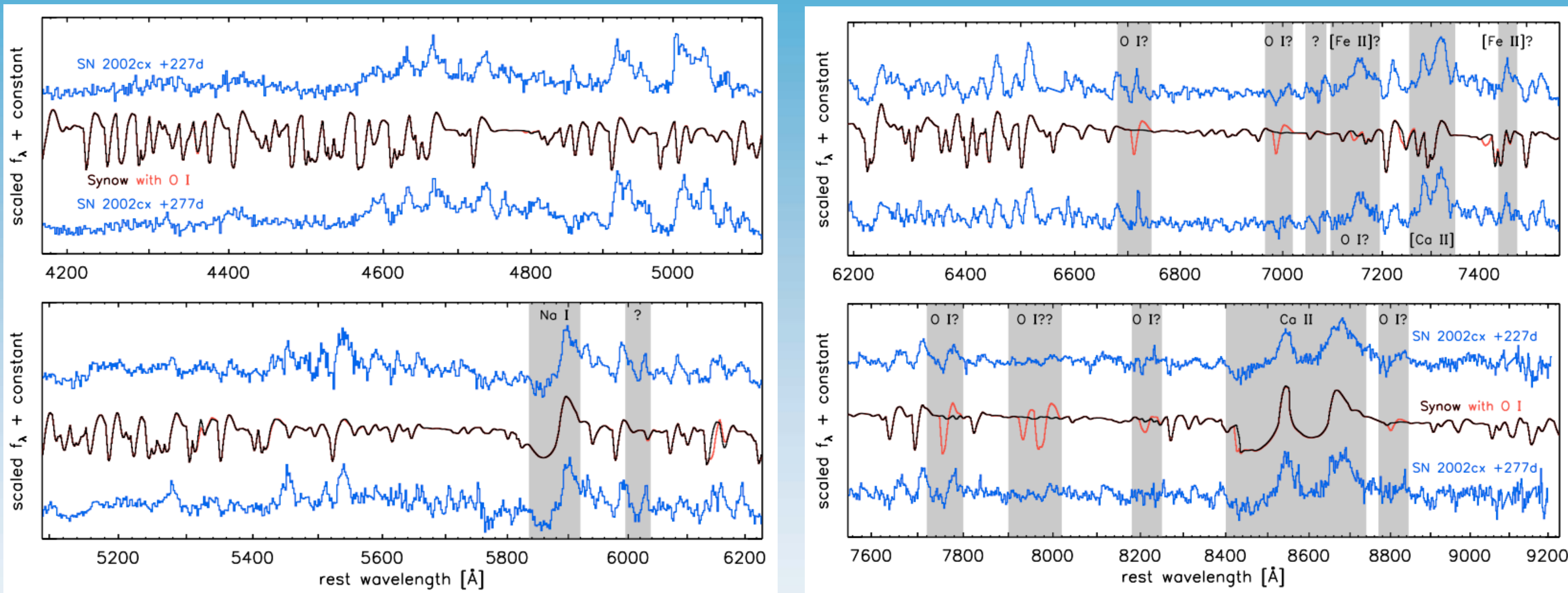
Jha et al. (2006)



The close resemblence of these spectra (apart from the line widths) suggested to Jha et al. (2006) that the majority of the emission was due to permitted lines of Fe II

Late-Epoch Spectra of SN 2002cx

Jha et al. (2006)



Note, also, the presence of Na I, Ca II, and certain Fe II lines with clear P Cygni profiles! ➔ **continuum or pseudo-continuum flux at late times** (when the spectra of normal SNe Ia are purely nebular)

Summary of the Peculiar Properties of 2002cx-Like Events

• High-ionization (1991T-like) spectrum prior to maximum

➔ **^{56}Ni mixed to surface?**

• Absence of secondary maxima in near-IR / Fe features in spectra at all epochs

➔ **Fully-burned material present at all layers of ejecta**

• Features due to metals lighter than Fe at all epochs

➔ **Partially-burned material present at layers of ejecta**

• Low expansion velocities

➔ **Low kinetic energy of ejecta**

Summary of the Peculiar Properties of 2002cx-Like Events

- Low peak luminosity

  ➔ **≤ 0.25 solar masses of ^{56}Ni produced in explosion**

- Slowly declining UVOIR bolometric light curve at late times

  ➔ **Relatively large ejected mass**

- Permitted Fe II lines and continuum or pseudo-continuum at late epochs (Jha et al. 2006)

  ➔ **High density and large mass at low velocity**

- Low level of continuum polarization (Chornock et al. 2006)

  ➔ **Peculiarities are not likely to be explained by large asymmetries**

Was SN 2005hk a Pure Deflagration?

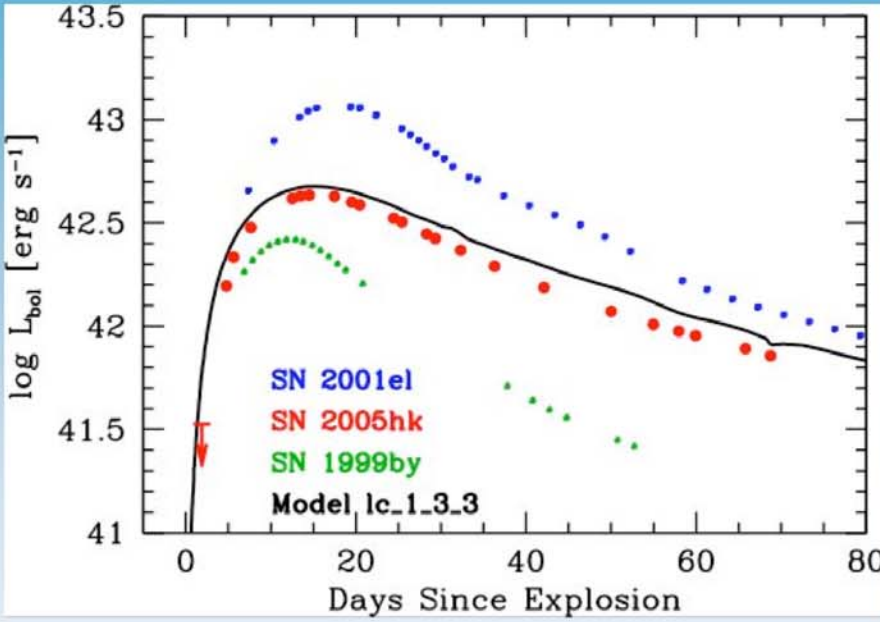
- Branch et al. (2004) and Jha et al. (2006) have suggested that the subset of 2002cx-like SNe Ia can be understood in terms of the pure deflagration of a C-O white dwarf

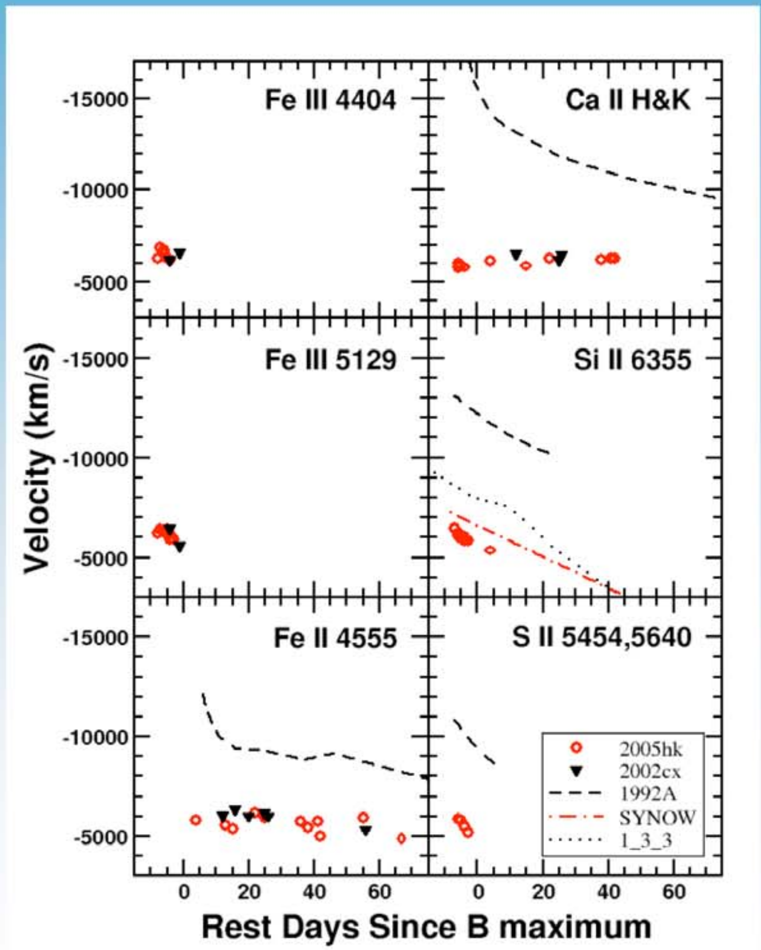
- In particular, **a deflagration naturally produces the strong mixing and low ^{56}Ni mass and kinetic energy that characterized SN 2005hk**

- A potentially serious discrepancy remains in the large amount of unburned oxygen and carbon at low expansion velocities predicted by 3D deflagration models

- Such material was not clearly visible in spectra of SN 2002cx obtained 7-9 months after maximum -- although densities were probably too high to reveal the expected forbidden emission lines

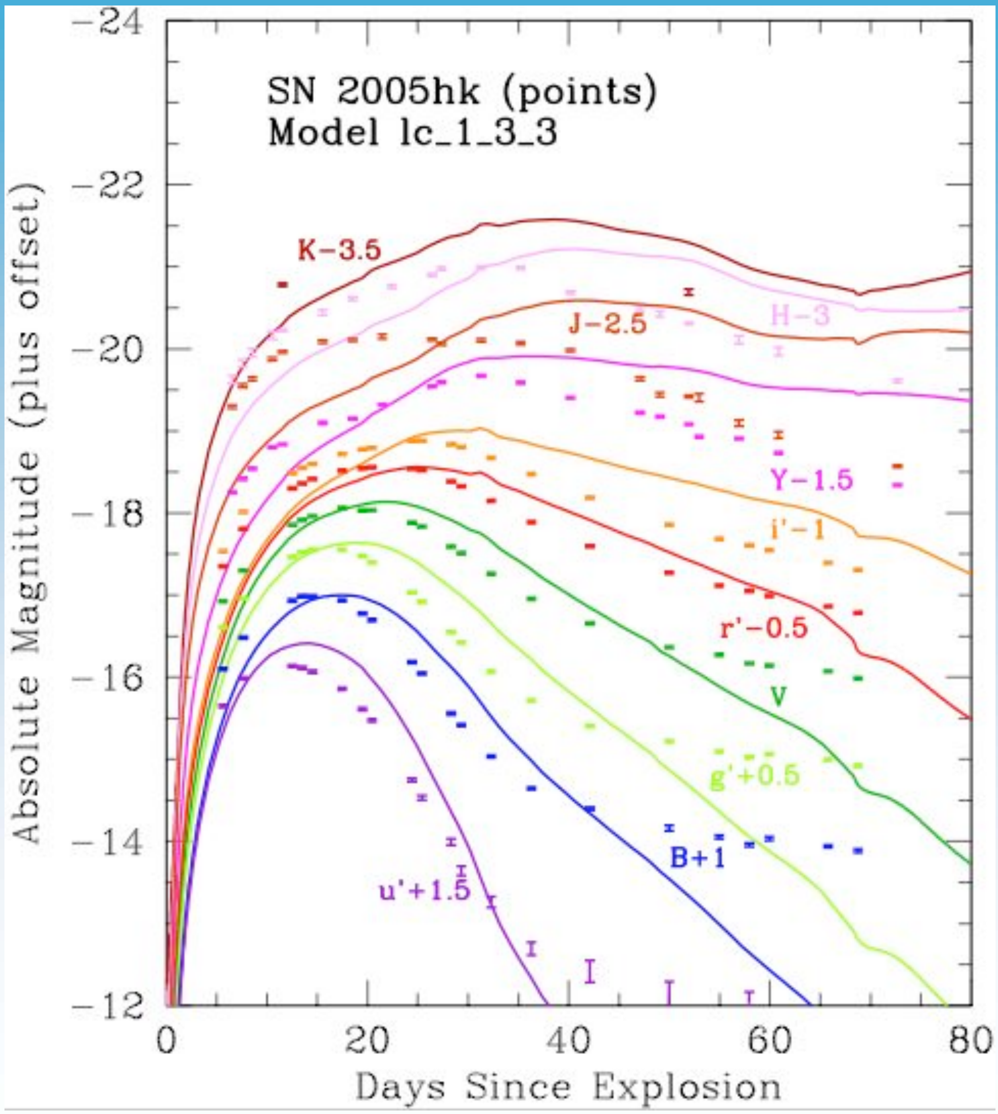
Bolometric Light Curve & Ejecta Velocities of SN 2005hk





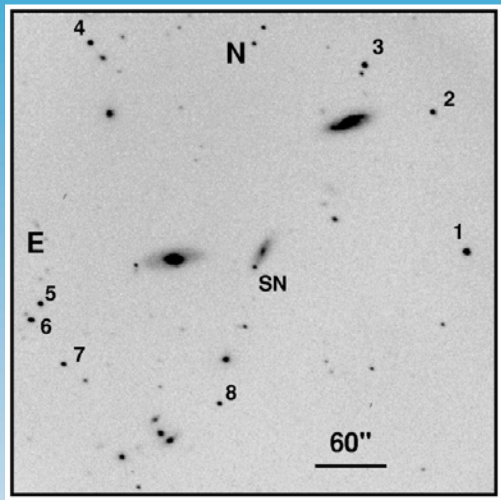
The bolometric light curve and low expansion velocities of SN 2005hk are remarkably well matched by 3D models of a deflagration of a 0.25 solar mass white dwarf

Bolometric Light Curve of SN 2005hk

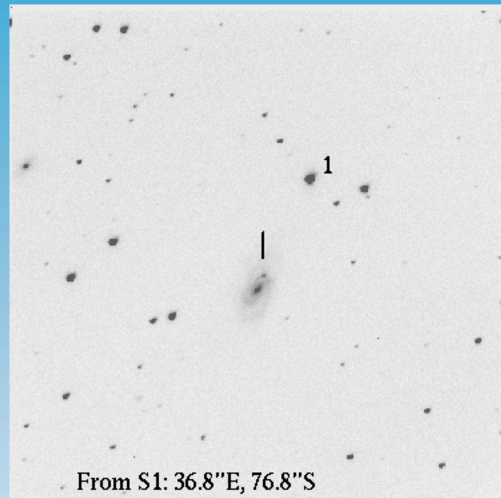


- Blinnikov et al. (2006) have calculated optical and near-IR light curves for the same 3D deflagration model
- These provide a reasonable match to the optical data over the first 30 days after explosion
- At later epochs, the model does poorly due to the finite number of lines included in the code and/or non-LTE effects
- The near-IR light data are qualitatively similar, but do not provide good fits; more lines need to be included in the code

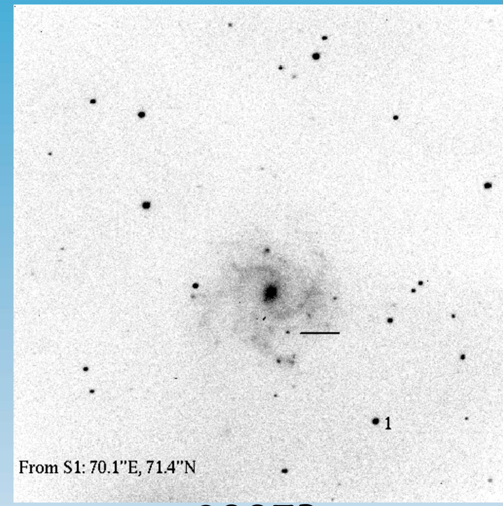
A Gallery of SN 2002cx-like Events



2002cx



2003gq



2005P

2005cc

2005hk

- All have occurred in disk galaxies with evidence of recent star formation
- Are the conditions for pure deflagrations produced only in a younger stellar population??

Are SN 2002cx-like and SN 1991T-like Events Physically Related?

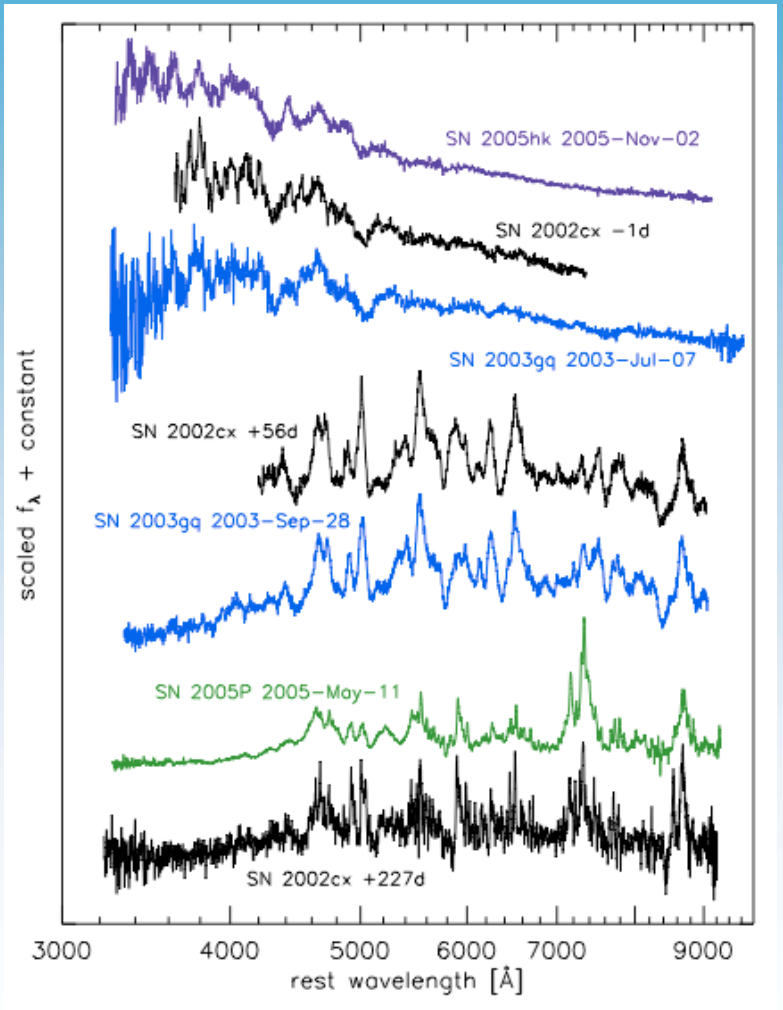
- The similarity of the pre-maxima spectra is striking
- Both types of events occur preferentially in star-forming disk galaxies

However,

- SN 1991T was slow-declining & luminous; SN 2002cx was faster-declining & sub-luminous
- Ejecta of SN 1991T displayed high initial expansion velocities; expansion velocities of SN 2002cx were nearly 2x lower
- SN 1991T had a normal late-time spectrum; spectrum of SN 2002cx at late epochs was dominated by Fe II
- I-band light curve of SN 1991T displayed typical secondary maximum; SN 2002cx did not

A Few Final Questions

Jha et al. (2006)



- How homogeneous is this sub-class of SNe Ia?

    ➔ The handfull of members identified to date are remarkably similar, but we don't yet know if this is coincidental

- How common are SN 2002cx-like events ?

    ➔ In the local universe, SN 2002cx-like objects appear to account for ~5% of all SNe Ia

Conclusions

• SNe 2002cx and 2005hk represent a distinct sub-class of SNe Ia

• The general properties of these objects are remarkably well matched by 3D models of the pure deflagration of a white dwarf

• An alternative explosion mechanism (e.g., a delayed detonation) appears to be required to explain the majority of normal SNe Ia

(See the poster on SN 2005hk by Stanishev et al.)