

The Peculiar Type Ia Supernova 2005hk

V. Stanishev^{*}, S. Taubenberger[†], G. Blanc^{**}, G.C. Anupama[‡], S. Benetti[§],
E. Cappellaro[§], N. Elias-Rosa[§], C. Féron[¶], A. Goobar^{*}, K. Krisciunas^{||}, A.
Pastorello^{†,††}, D.K. Sahu[‡], M. E. Salvo^{‡‡}, B. P. Schmidt^{‡‡}, J. Sollerman^{¶,§§},
C. C. Thöne[¶], M. Turatto[§] and W. Hillebrandt[†]

^{*}*Physics Department, Stockholm University, AlbaNova University Center, 106 91 Stockholm, Sweden*

[†]*Max-Planck-Institut für Astrophysik, PO Box 1317, 85741 Garching, Germany*

^{**}*Laboratoire Astroparticules et Cosmologie, Université Paris 7, 2 place Jussieu, 75005 Paris, France*

[‡]*Indian Institute of Astrophysics, Koramangala, Bangalore 560 034, India*

[§]*INAF, Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, 35122 Padova, Italy*

[¶]*DARK Cosmology Center, Niels Bohr Institute, Copenhagen University Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark*

^{||}*Department of Physics, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, IN 46556-5670*

^{††}*Department of Physics & Astronomy, Queen's University, Belfast, BT7 1NN, Northern Ireland, UK*

^{‡‡}*Research School of Astronomy and Astrophysics, Australian National University, Mt Stromlo Observatory, via Cotter Road, Weston Creek PO 2611, Australia*

^{§§}*Department of Astronomy, Stockholm University, AlbaNova University Center, 106 91 Stockholm, Sweden*

Abstract. We present a preliminary analysis of an extensive set of optical observations of the Type Ia SN 2005hk. We show that the evolution of SN 2005hk closely follows that of the peculiar SN 2002cx. SN 2005hk is more luminous than SN 2002cx, while still under-luminous compared to normal Type Ia supernovae. The spectrum at 9 days before maximum is dominated by conspicuous Fe III and Ni III lines, and the Si II 6355 line is also clearly visible. All these features have low velocity (~ 6000 km/s). The near maximum spectra show lines of Si II, S II, Fe II-III, as well as other intermediate mass and iron group elements. Analysis with the code for synthetic spectra SYNOW indicates that all these spectral lines have similar velocities.

Keywords: supernovae, spectroscopy, photometry

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INTRODUCTION

Type Ia Supernovae (SNe Ia) form a fairly homogeneous class of objects [see, e.g. 1]. Most of them fall into the so-called "Branch-normal" group [2]. However, spectroscopically peculiar SNe have also been found, and their fraction might be non-negligible [2, 3]. The peculiar SNe Ia are classically divided into two groups – 1991bg-like and 1991T-like [see 3]. Recently, some objects that do not fit in any of these categories have been discovered [see, e.g. 4] and included into a group with SN 2002cx as prototype [5].

SN 2005hk was discovered on Oct. 30.25 UT in UGC 272 by Burket and Li [6]. We obtained two spectra of SN 2005hk on Oct. 31st. The spectral features were similar to

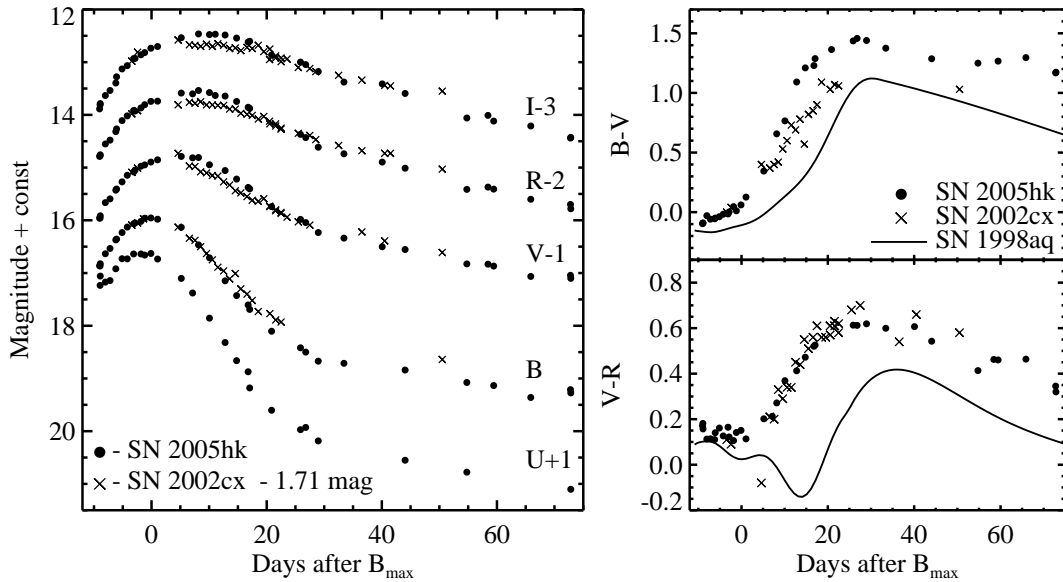


FIGURE 1. The *UBVRI* light curves of SN 2005hk (left), and the $B - V$ and $V - R$ color indexes of SN 2005hk (right) compared to those of SN 2002cx and the normal SN Ia 1998aq [7].

those observed in the 1991T-like events, about 10 days before maximum light. After this, an observational campaign was started by the European Supernova Collaboration (ESC) and an extensive set of data was obtained using a number of telescopes. A more thorough study of the early spectra, however, revealed that SN 2005hk was more similar to SN 2002cx. Thus, SN 2005hk became the best observed 2002cx-like event so far. In this work we present a preliminary analysis of a significant part of our data.

RESULTS

After the standard bias and flat field corrections, the magnitudes of SN 2005hk were measured with the point-spread function (PSF) fitting technique. The instrumental magnitudes were transformed to Johnson-Cousins standard magnitudes using field stars whose magnitudes were calibrated on two photometric nights at CTIO. The photometry was calibrated using linear equations derived from observations of Landolt [8] stars. The *UBVRI* light curves, and the $B - V$ and $V - R$ color indexes are shown in Fig. 1. The light curves show well-defined single maxima in all bands. SN 2005hk reaches the *B*-band maximum light $B_{\max} = 15.96$ mag on Nov. 9th (JD 2453684.5 \pm 0.5) and $\Delta M_{15}(B) \simeq 1.5$ was estimated. The *UVRI* peak magnitudes of 15.62, 15.80, 15.57 and 15.46 mag were reached -1.6 , $+2.2$, $+7.5$ and $+10$ days from the *B* maximum, i.e. the light curve maxima occur progressively later from *U* to *I*-band. The peak magnitudes are uncertain to ~ 0.02 mag and the epochs of the maxima to ~ 0.5 days. The light curves of SN 2002cx [4] are also shown in Fig. 1, shifted by 1.71 mag to match the *B* band peak magnitude of SN 2005hk. The light curves of the two SNe are very similar; however, a few differences are noticeable. The *R* and *I* band maxima of SN 2002cx are flatter than those of

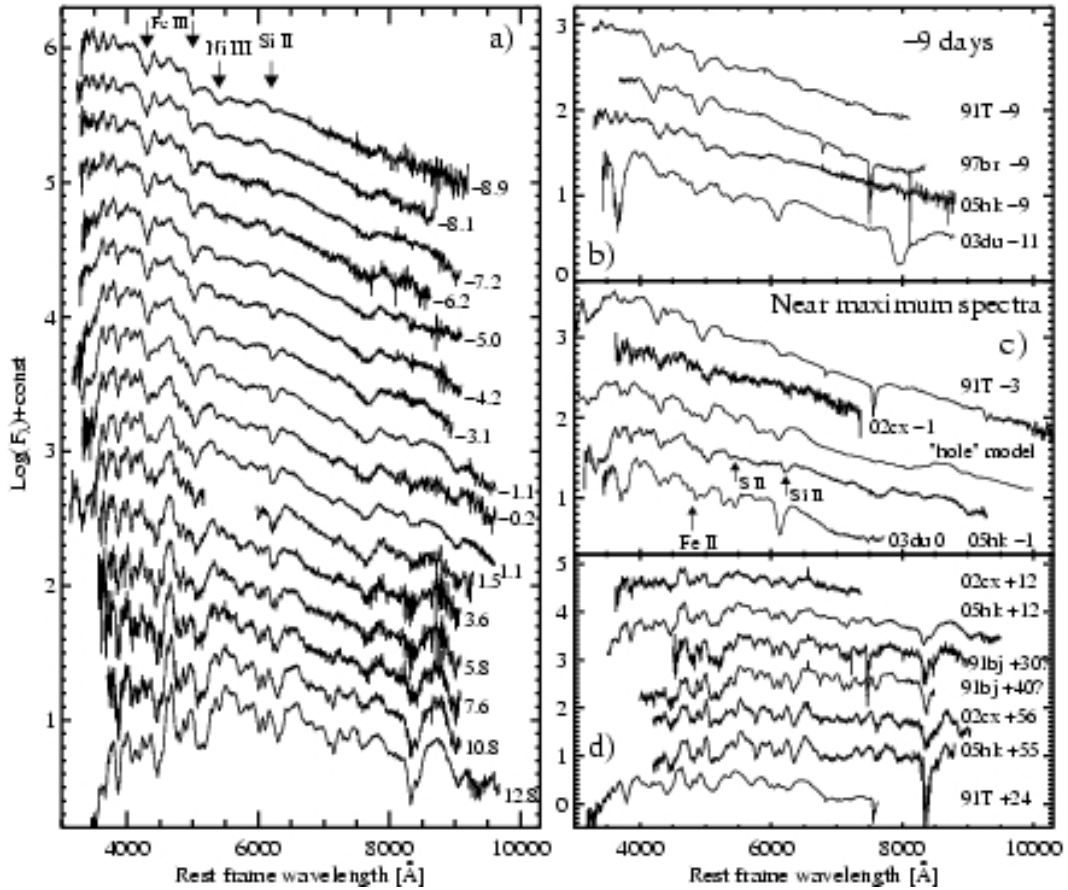


FIGURE 2. (a) Early-time spectral evolution of SN2005hk and (b-d) comparison with spectra of SN 1991T [9, 10], 1997br [11], 2003du [12], 1991bj [13, 14] at different epochs. A "hole" model [15] (see text) is also shown in (c) panel.

SN 2005hk. The color indexes of the two SNe are similar, and generally much redder than those of normal SNe Ia.

The early-time spectral evolution of SN 2005hk is shown in Fig. 2a. The -9 days spectrum is dominated by Fe III and Ni III lines, and only weak Ca II H&K and Si II 6355 lines are visible. The spectrum is very similar to the 91T-like SNe Ia (Fig. 2b), suggesting a rather high temperature, while the line velocities are anomalously low, only ~ 6000 km/s. With time, lines of intermediate mass elements start to emerge and by the time of maximum Si II, S II, Mg II and Ca II are clearly detected together with the Fe III lines. Fe II lines around 4800-5200 Å are also prominent (Fig. 2c). In general, around maximum the spectrum of SN 2005hk is not much different from that of a normal SN Ia (e.g. SN 2003du), but the lines of intermediate mass elements are considerably weaker. After maximum, the spectral evolution of SN 2005hk closely follows SN 2002cx (Fig. 2d), which is different from all other SNe Ia sub-types. According to Branch et al. [16], the post-maximum spectra of SN 2002cx are dominated mostly by Fe II absorption lines. In addition, in Fig. 2d we show two spectra of SN 1991bj [13, 14], which we have identified as a 2002cx-like discovered approximately a month after maximum.

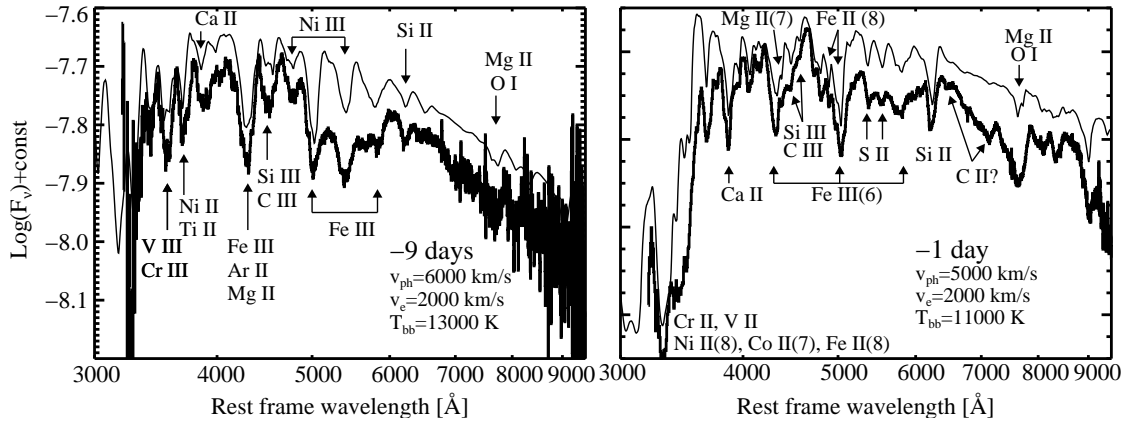


FIGURE 3. The -9 and -1 days spectra of SN 2005hk compared with SYNOW synthetic spectra (for clarity, the model spectra are shifted up by 0.05 dex). The SYNOW global parameters and the species contributing to the absorption features are indicated. The numbers reported in brackets after the name of the ions is the velocity (in units of 1000 km/s) at which the corresponding ion is detached.

We used the supernova spectral synthesis code SYNOW [for details see, e.g. 17] to give more insights to the properties of SN 2005hk spectra. We modeled spectra at two epochs, 9 and 1 days before the B maximum. The synthetic spectra (for clarity shifted up by 0.05 dex) and the adopted parameters are shown in Fig. 3. The adopted excitation temperature was 10000 K for the singly and 15000 K for the doubly ionized species. Note that besides the great simplifications assumed by SYNOW, some of the derived parameters are correlated, e.g. the photospheric v_{ph} and the e-folding velocity v_e .

The species contributing to the strongest features in the spectra are labeled in Fig. 3. In the -9 days spectrum we consider the presence of Fe III, Ni III and Si II lines as definite, and Ca II as likely. The feature around 4500Å is best reproduced with Si III and C III. The features in the blue part of the spectrum are due to singly and doubly ionized Fe-group elements. Most notably, the strong feature around 3600Å is better fitted with V III and Cr III. It was also found that Ar II improves the fit of the strong 4300Å feature; the absorption is too shallow if only Fe III is used. Although the synthetic spectrum reproduces fairly well most of the observed features, there are wavelength intervals which are not well fitted. For example, the absorption near 3900Å is too broad to be attributed to Ca II H&K only. The observed flux level between 5000Å and 6000Å cannot be reproduced and the synthetic spectrum gives too much flux.

Most of the observed absorption features in the -1 day spectrum are well reproduced by the synthetic spectrum. The photospheric velocity used is 5000 km/s, but it was found that many of the lines should be detached. In addition to the species used to model the -9 days spectrum, for the -1 day synthetic spectrum S II, Fe II, Cr II, V II and Co II were added, and no Ni III, Cr III or V III was used. The line around 7200Å could be due to C II; however, as discussed by Chornock et al. [18] if this was the case, there should be a stronger feature around 6400Å which is not visible in the observed spectrum. It should also be noted that Ar and V are typically not considered in the analyzes of SN Ia spectra and their presence in SN 2005hk is not certain.

DISCUSSION

The recession velocity of UGC 272 corrected for the Local Group in-fall onto Virgo is 3863 km/s (from the LEDA database¹), providing a distance modulus of $\mu = 33.65$ mag (assuming $H_0 = 72$ km/s/Mpc). The observed $B_{\max} = 15.96$ mag of SN 2005hk thus implies an absolute magnitude $M_B \simeq -17.7$. The Milky Way reddening in the direction to SN 2005hk is only $E(B - V) = 0.023$ [19] and the host galaxy reddening is $E(B - V) = 0.091$ [18]. The total dimming by dust in the B band is thus 0.47 mag (with $R_B = 4.1$). SN 2005hk is therefore significantly sub-luminous compared to the normal SNe Ia with $\Delta M_{15}(B) \sim 1.5$, whose expected absolute magnitude is $M_B \simeq -19$ [e.g., 20]. Li et al. [4] estimated that SN 2002cx had $M_B \simeq -17.55$ and $\Delta M_{15}(B) \simeq 1.3^2$. With $M_B \simeq -18.2$, SN 2005hk is thus more luminous than SN 2002cx.

The $UBVRI$ magnitudes were transformed to fluxes using the absolute calibration of Bessell et al. [21] and then integrated in order to estimate the *uvoir* bolometric luminosity of SN 2005hk. A correction for the flux emitted in the near-infrared part of the spectrum was also applied. This correction, $\sim 10\%$ at maximum and $\sim 42\%$ one month after, was derived integrating the combined optical and near-infrared spectra at five epochs during the first month after B band maximum. The *uvoir* bolometric maximum of 4.24×10^{42} erg/s occurred ~ 3 days after the B -band maximum.

With its low luminosity and peculiar light-curve morphology with single maxima occurring progressively later in the red bands, SN 2005hk is more similar to Type Ic SNe rather than SNe Ia. The time evolution of the color indexes of SN 2005hk is also quite similar to SNe Ic [see e.g., 22]. While the broadband colors evolved similarly to SNe Ic, the spectral features' evolution was closer to SNe Ia and suggests that SN 2005hk was likely a thermonuclear event. In favor of this is the clear detection of Si and S lines in the near maximum spectra. We have also obtained a late-time spectrum of SN 2005hk, which is quite similar to the spectrum of SN 2002cx at a similar epoch [5]. According to [5] the late-time spectrum is dominated by Fe absorption lines [5], which also suggests a thermonuclear explosion. In contrast, late-time spectra of SNe Ic are dominated by forbidden emission lines of O, Ca and Mg.

The studies of SNe 2002cx and 2005hk [4, 16, 5, 18] point out that no existing SN model accounts for the peculiar properties of the 2002cx-like SNe. In particular, it is difficult to explain the combination of hot early-time spectra, and low luminosity and expansion velocities. The observed polarization of SN 2005hk is relatively low [18] and models involving large asymmetry are unlikely. The explosion simulations of Marietta et al. [23] show that the interaction with a companion star may leave a hole of the ejecta. Kasen et al. [15] computed flux and polarization spectra, and the luminosities of such a model with different orientations of the hole. They suggested that SN 2002cx might be a 1991bg-like, but seen straight down the hole. This allows to see into the deep hot layers and the synthetic spectra resemble the early-time spectra of the 1991T-like SNe, but have low expansion velocity and luminosity. Moreover, when looking straight down the hole the polarization will be small. In Fig. 2c we compare the near-maximum spectrum

¹ <http://leda.univ-lyon1.fr>

² $\Delta M_{15}(B)$ of SN 2002cx might actually be $\simeq 1.6$ according to Li et al. [4]

of SN 2005hk with a synthetic spectrum from [15] when looking directly into the ejecta hole. Although, the two spectra are similar, recent studies cast doubts on this scenario [5, 18].

The late-time spectra of 2002cx-like SNe are completely different from all other supernova types, which let [5] to suggest that radically different models may be needed. Our Fig. 2d and Fig. 5 in Jha et al. [5] clearly demonstrate the spectral homogeneity within this group and strengthen the hypothesis that these objects belong to a different SN type.

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