The Type Ia supernova 2004S, a clone of SN 2001el, and the optimal photometric bands for extinction estimation[1]

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ABSTRACT

We present optical (*UBVRI*) and near-infrared (*YJHK*) photometry of the normal Type Ia supernova 2004S. We also present eight optical spectra and one near-IR spectrum of SN 2004S. The light curves and spectra are nearly identical

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to those of SN 2001el. This is the first time we have seen optical *and* IR light curves of two Type Ia supernovae match so closely. Within the one parameter family of light curves for normal Type Ia supernovae, that two objects should have such similar light curves implies that they had identical intrinsic colors and produced similar amounts of ^{56}Ni. From the similarities of the light curve shapes we obtain a set of extinctions as a function of wavelength which allows a simultaneous solution for the distance modulus difference of the two objects, the difference of the host galaxy extinctions, and R_V. Since SN 2001el had roughly an order of magnitude more host galaxy extinction than SN 2004S, the value of $R_V = 2.15^{+0.24}_{-0.22}$ pertains primarily to dust in the host galaxy of SN 2001el. We have also shown via Monte Carlo simulations that adding rest frame J-band photometry to the complement of $BVRI$ photometry of Type Ia SNe decreases the uncertainty in the distance modulus by a factor of 2.7. A combination of rest frame optical and near-IR photometry clearly gives more accurate distances than using rest frame optical photometry alone.

Subject headings: supernovae: individual (SN 2004S) — supernovae: individual (SN 2001el) — techniques: photometric — extinction: interstellar

1. Introduction

A Type Ia supernova (SN, plural SNe) is widely believed to be a carbon-oxygen white dwarf which explodes when its mass reaches the Chandrasekhar limit owing to mass transfer from a nearby companion (Livio 2000, and references therein). The explosion produces several tenths of a solar mass of radioactive ^{56}Ni, which decays to ^{56}Co, and finally to stable iron (Stritzinger et al. 2006). Since the progenitors of Type Ia SNe have approximately the same mass ($M_{Ch} \approx 1.4$ $M_{\odot}$), the explosions have approximately the same brightness at maximum light. Phillips (1993) first demonstrated unambiguously that the peak brightness of a Type Ia SN is related to the decline rate of the light curve. Since the publication of Phillips' classic paper, the common measure of the decline rate has been the number of B-band magnitudes that a Type Ia SN fades in the first 15 days after maximum light (designated $\Delta m_{15}(B)$). A typical value is $\Delta m_{15}(B)$= 1.10 mag. Values range from $\sim$0.7 for SN 2001ay (Nugent et al. 2006, in preparation) to 1.93 for SN 1991bg (Filippenko et al. 1992; Leibundgut et al. 1993; Phillips et al. 1999).

In the past 13 years supernova researchers have noted various patterns in the light curves of Type Ia SNe. This has allowed the determination of the peak magnitudes, host galaxy extinction, and distances to these objects even if the data of a particular object are irregularly spaced in time and do not necessarily overlap the light curve maxima. The three most widely used systems for fitting optical light curves are the $\Delta m_{15}(B)$ system itself (Hamuy et al. 1996; Phillips et al. 1999; Germany et al. 2004; Prieto, Rest, & Suntzeff 2006), the "stretch method" (Perlmutter et al. 1997; Goldhaber et al. 2001; Knop et al. 2003), and the multi-color light curve shape (MLCS) method (Riess, Press & Kirshner 1996a; Riess et al. 1998; Jha, Riess, & Kirshner 2006b). There is also the hybrid magnitude-color system of Wang et al. (2003a).

Host galaxy extinction of Type Ia SNe is measured empirically by first determining reddening-free color loci, determining color excesses, and using empirically determined scale factors to convert color excesses to A_V or extinction in some other band. Lira (1995) found, from a small sample of Type Ia SNe unreddened in their hosts, that $B-V$ colors are uniform and evolve in the same way from 30 to 90 days after the time of V-band maximum. Nobili et al. (2003) investigated the optical colors of Type Ia SNe and found that all the colors except $V-I$ are consistent with zero intrinsic dispersion at 35 days after $T(B_{max})$. Wang et al. (2005) found that the $B-V$ colors at 12 days after $T(B_{max})$ provided the best method of determining the $B-V$ color excess. With MLCS2k2 Jha, Riess, & Kirshner (2006b) adopt an intrinsic color of $B-V = 1.054 \pm 0.049$ at $t = 35$ days and assume an exponential distribution of host galaxy reddening with scale length $E(B-V) = 0.138$ mag. They also adopt a Bayesian prior on the distribution of R_V, with a minimum value of 1.8. Then they marginalize over the optical photometry to obtain the best values of A_V and R_V.

The prime problem with using optical photometry to determine A_V along the line of sight to a Type Ia SN can be illustrated as follows. For normal dust in our Galaxy $R_V \equiv A_V \ / \ E(B-V) \approx 3.1$ (Cardelli, Clayton, & Mathis 1989). A small uncertainty in the $B-V$ color excess translates into a much larger uncertainty in A_V. The scale factor R_V is not necessarily equal to 3.1. The mean value most appropriate to galaxies that host Type Ia SNe is somewhere in the range 2.3 to 2.65 (Riess, Press, & Kirshner 1996b; Altavilla et al 2004; Reindl et al. 2005; Wang et al. 2006; Jha, Riess, & Kirshner 2006b). Some very low values have been measured. The Type Ia SN 1999cl was reddened by dust with $R_V = 1.55 \pm 0.08$ (Krisciunas et al. 2006). The dust in the host of SN 2003cg had $R_V = 1.80 \pm 0.19$ (Elias-Rosa et al. 2006). Our observations of SN 2006X are consistent with $R_V \approx 1.56$.[13] Perhaps these very low values of R_V associated with highly reddened objects are the result of an interaction of the SN ejecta and the surrounding circumstellar material (Wang 2005).

To account for non-standard reddening laws and to obtain the most robust value of the extinction towards a Type Ia SN, it is best to combine optical and IR photometry. Elias et al.

[13]See http://www.nd.edu/ kkrisciu/sn2006X.html.

(1985) first suggested that the $V-K$ colors of Type Ia SNe might be uniform and therefore very useful for determining extinction for these objects. Using the standard reddening law of Cardelli, Clayton, & Mathis (1989), $A_V \approx c_R$ E($V-K$), where $c_R = 1.13$ for Galactic ($R_V = 3.1$) dust, and $c_R = 1.07$ for the extreme case of $R_V = 1.55$ for SN 1999cl. Thus, if we can determine a $V-K$ color excess, it needs to be scaled only slightly to give us A_V. Using data of 8 Type Ia SNe, we determined zero-reddening $V-J$, $V-H$, and $V-K$ loci of Type Ia SNe with mid-range decline rates (Krisciunas et al. 2000). Subsequently, we determined that the corresponding loci of Type Ia SNe with slow decline rates ($\Delta m_{15}(B) \lesssim 1.0$) are roughly 0.24 mag bluer (Krisciunas et al. 2004b). We note that $V-J$ colors of Type Ia SNe are the least uniform of the three color indices. Also, our previous loci are valid for the time range $-9 \leq t \leq +27$ days, where t is measured with respect to the time of B-band maximum.

Since the Calán-Tololo SN survey in the early 1990's, extensive efforts have been devoted to discovering and following the light curves of Type Ia SNe, most notably the SN search carried out with the Katzman Automatic Imaging Telescope at Lick Observatory (Filippenko et al. 2001). Because of the time required to observe the SNe, obtain image subtraction templates for those objects that require templates, and to reduce the data for many objects, one recent trend has been to publish papers on individual objects which are unusual, such as SNe 2000cx (Li et al. 2001; Candia et al. 2003) and 2002cx (Li et al. 2003). The analogy is that pathologists can better understand how normal human organs work by studying organ malfunction and disease. In this paper we discuss the astronomical case of SN 2004S, a normal Type Ia SN, the light curves of which are essentially clones of another object, SN 2001el (Krisciunas et al. 2003).

SN 2004S was discovered using images taken on 2004 February 3.54 and 4.56 UT by Martin (2004). The supernova was located at RA = $06^h\ 45^m\ 43\overset{s}{.}5$, DEC $=-31^{\circ}\ 13'\ 52\overset{''}{.}5$ (J2000), some $47\overset{''}{.}2$ west and $2\overset{''}{.}5$ south of the core of the Sc galaxy MCG -05-16-021 (Biggs 2004). SN 2004S was confirmed to be a Type Ia supernova by Suntzeff et al. (2004) from a spectrum taken on 2004 Feb 6.1 UT with the CTIO 1.5-m telescope. In Fig. 1 we see the Suntzeff et al. (2004) spectrum, along with a spectrum of SN 2001el obtained by Wang et al. (2003b). Given the similarities of the optical and IR light curves and the spectra of these two objects, we feel fully justified in calling these two objects clones.

According to Theureau et al. (2005), the heliocentric radial velocity of MCG -05-16-021 is 2808 km s^{-1}. In the reference frame of the Cosmic Microwave Background (CMB) radiation the recession velocity is 2957 km s^{-1}. Assuming a Hubble constant of 72 km s^{-1} Mpc^{-1} (Freedman et al. 2001), the distance modulus of SN 2004S and its host is $m-M = 33.07 \pm 0.21$ mag, where the uncertainty corresponds to an assumed random velocity of 300 km s^{-1}.

The Galactic reddening along the line of sight to SN 2004S is E$(B-V) = 0.101 \pm 0.010$ mag (Schlegel, Finkbeiner & Davis 1998). Assuming R$_V$ = 3.1 for Galactic dust, there must be at least 0.313 ± 0.031 mag of V-band extinction toward SN 2004S. Given the offset of the SN from the core of its host (see Fig. 2), we expected the SN to be essentially unreddened by the host. An analysis of SN 2004S may thus provide useful information on the intrinsic colors of normal Type Ia SNe of mid-range decline rates.

In this paper we present optical and near-IR photometry of SN 2004S. Other optical photometry of the object has been published by Misra et al. (2005). These authors obtained a light curve solution using their own measurements plus our optical data from the CTIO 1.3-m published here. Important conclusions can be made about SN 2004S by using IR data as well. That the optical and IR light curves of SNe 2001el and 2004S are so similar sheds light on the uniformity of explosion models of normal Type Ia SNe and also allows us to investigate the interstellar dust content of the hosts of SNe 2001el and 2004S beyond what is possible from a study of either object on its own.

The paper is organized as follows. In §2 we present optical and infrared photometry of SN 2004S. In §3 we present optical and IR spectra of SN 2004S and compare them to several other Type Ia SNe. In §4 we consider the extinction suffered by SNe 2004S and 2001el as two separate problems and also as a joint exercise. Using information about the relative uncertainties of the filter by filter photometry from §4, in §5 we carry out Monte Carlo simulations of extinction and reddening for a general model of the effect of the dust on the uncertainty of distance measurements of Type Ia SNe. This is relevant for future ground-based and space-based SN surveys. Our conclusions are presented in §6.

2. Optical and Infrared Photometry

Most of our photometry was taken with the CTIO 1.3-m telescope and the optical/IR imager ANDICAM. ANDICAM contains standard Johnson UBV filters, Kron-Cousins R and I filters and standard Caltech/CTIO JHK filters. Read out in 2×2 binning mode, ANDICAM gives a plate scale on the 1.3-m telescope of $0\farcs369$ px^{-1} for optical imaging and $0\farcs274$ px^{-1} for IR imaging. The optical field of view was $6\farcm3$ by $6\farcm3$, while the IR field of view was $2\farcm34$ by $2\farcm34$.

ANDICAM also contains a 1.03 μm filter (known as Y). This new filter exploits a previously unused atmospheric window. For more information see Hillenbrand et al. (2002). However, there are problems with their calibration of standard stars. From synthetic photometry of Kurucz model spectra spanning a range of temperatures Hamuy et al. (2006, Appendix C) obtained a relationship between $Y-K_s$ colors and the published $J-K_s$ colors of Persson et al. (1998) standards. The resulting Y-band magnitudes for standard stars are typically accurate to better than 0.01 mag.

This paper also contains some optical photometry obtained with the Siding Spring 2.3-m telescope and the ESO 2.2-m telescope. One night of JHK photometry was obtained with the 3.58-m Telescopio Nazionale Galileo (TNG) at La Palma. Two epochs of late-time near-IR photometry were obtained with the number 1 Very Large Telescope (VLT) at Cerro Paranal, using ISAAC.

In Fig. 2 we show an optical finding chart of the field of SN 2004S. We calibrated the *UBVRI* magnitudes of some of the fields stars on 12 photometric nights using Landolt (1992) standards, in particular the Rubin 149 field. The optical field star magnitudes are to be found in Table 1. The near-IR magnitudes of some of these stars are to be found in Table 2. The IR calibration was carried out on 8 photometric nights with good seeing using the star P9123 from the list of Persson et al. (1998) standards. For P9123 we estimate $Y = 11.077 \pm 0.010$ from the fifth order polynomial of Hamuy et al. (2006). Our JHK photometry of the field stars is in very good agreement (often $\pm$ 0.01 mag) with values from the Two Micron All-Sky Survey (2MASS).

We present *UBVRI* photometry of SN 2004S in Table 3 and the $YJHK$ photometry in Table 4. The brightness and location of the SN did not require the use of host galaxy subtraction templates. Our CTIO 1.3-m photometry is based on aperture photometry using a typical aperture of radius 10 px. On nights of bad seeing a larger software aperture was used.

The 12 dates marked with an asterisk in Table 3 were photometric nights at CTIO. On those occasions we tied the SN 2004S photometry directly to the Landolt system using the Ru 149 field. Given that the SN 2004S field and Ru 149 were always observed at an airmass difference of less than 0.2, and given that the range of color of the Ru 149 standards was reasonably large ($-0.129 \leq B-V \leq 1.115$) we feel that the calibration of the field stars near SN 2004S must be quite robust. On other occasions we determined the photometric zeropoints using the field star photometry listed in Table 1. The color terms were determined from observations of the Landolt (1992) standards on photometric nights.

The *UBVRI* light curves of SN 2004S are shown in Fig. 3, and the $YJHK$ light curves of SN 2004S are shown in Fig. 4. The light curve templates shown in these figures are derived from the photometry of SN 2001el (Krisciunas et al. 2003). We simply adjusted the light curve templates in the Y-direction to minimize the χ^2 statistic of the fits to SN 2004S.[14]

We note that because the optical and IR photometry of SN 2001el was obtained with different telescopes and different filters, the *BV* photometry of Krisciunas et al. (2003) required correction to a uniform photometric system. We adopted the filter system of Bessell (1979, 1990). While the "method of S-corrections" is not perfect (Stritzinger et al. 2002), it resolves the systematic differences of ANDICAM *B* and *V* photometry compared to SN data obtained with the CTIO 0.9-m telescope. Graphical and tabular values of the S-corrections can be found in Krisciunas et al. (2003) and Krisciunas et al. (2004c). Officially, each SN should have its own set of S-corrections. While many Type Ia SNe have similar spectra, they are not identical, so applying the S-corrections adds scatter to the data. However, since the S-corrections we used were based on SNe 1999ee and 2001el, and SN 2001el is so similar photometrically to SN 2004S, correcting SN 2004S data in the same manner as we corrected data of SN 2001el may add only ± 0.01 mag of scatter.

Similary, we calculated IR S-corrections to place the ANDICAM *JHK* photometry on the system of Persson et al. (1998). We found that corrections to the *R*- and *I*-band photometry actually made the photometry of SN 2001el from different telescopes more discordant, not less. Here we use only the ANDICAM photometry of SN 2001el (without S-corrections) to produce *R*- and *I*-band templates for a direct comparison of photometry of SNe 2001el and 2004S.[15] The key point is that we have made the same corrections to the photometry of the two SNe in the same way, filter by filter, so that a direct comparsion of the light curves of the two objects is consistent.

The one exception is the *U*-band. On the one hand, the shapes of the *U*-band light curves of SNe 2001el and 2004S are quite similar. On the other hand, the *U*-band photometry of SN 2004S is "too faint", on average, compared to SN 2001el. We can use a single function to fit the *BVRIJHK* data sets (see Fig. 14 below), but the mean difference of the *U*-band data is discrepant by 0.26 ± 0.07 mag. Jha et al. (2006a, Fig. 9) have shown that normal Type Ia SNe at maximum light have $B - V \approx -0.1$, but that the $U - B$ colors of these objects range more than half a magnitude. They emphasize that "this is not an artifact

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[14]For *BVRI* we used cubic splines to fit the SN 2001el light curves. For *UJHK* we used polynomials. The *U*-band photometry of SN 2001el from 29 to 65 days after the time of *B*-band maximum was synthetic photometry based on *HST* spectra kindly made available by P. Nugent.

[15]In 2001 ANDICAM was used with the CTIO 1.0-m Yale-AURA-Lisbon-Ohio (YALO) telescope, while beginning in 2003 it has been used on the 1.3-m ex-2MASS telescope. We assume that the optics of the primary and secondary mirrors of the two telescopes are sufficiently similar that no serious photometric differences result. We also note that all of the *U*-band photometry of SN 2001el was obtained with the CTIO 0.9-m and 1.5-m telescopes, *not* with ANDICAM.

of the reddening correction, nor can it be explained by variation in the extinction law in these external galaxies." Their data imply that "there is a significant intrinsic dispersion in U-band peak brightness even after accounting for variations in light-curve shape." Since the ultraviolet portion of the spectra of Type Ia SNe contains many metallic lines, a significant fraction of the dispersion of U-band photometry from object to object must be due to the metallicity of the progenitors (Hoeflich, Wheeler, & Thielemann 1998; Podsiadlowski et al. 2006). Suffice it to say that a full understanding of the U-band photometry and deductions that may be made from it are beyond the scope of the present paper.

A visual inspection of Figs. 3 and 4 demonstrates the remarkable similarity of the light curves of SNe 2001el and 2004S. Any differences are more obvious if we plot the residuals of the fits, as shown in Figs. 5 and 6. Using SN 2001el templates, the reduced χ^2 values of the fits to the CTIO 1.3-m data of SN 2004S are 1.24, 1.67, 1.12, 1.50, and 3.45 for U, B, V, R, and I, respectively. For J, H, and K the reduced χ^2 values of the fits are 1.90, 5.62, and 0.99, respectively.

Very little Y-band photometry of SNe has been published so far. Previously, we published some Y-band data of SNe 1999ee and 2000bh (Krisciunas et al. 2004b) and noted that the second maximum of SN 2000bh was brighter than the first maximum. SN 2004S has shown the same behavior. Hamuy et al. (2006) indicate that many Type Ia SNe observed at Las Campanas Observatory as part of the Carnegie Supernova Project also show stronger second maxima in the Y-band compared to the first maxima.[16]

The origin of the secondary maximum in the light curves of Type Ia SNe has recently been discussed by Kasen (2006). His results derive from 1-D (spherically symmetric) modelling. The basic idea is that a mixture of 75 percent ^{56}Co, 24 percent iron, and 1 percent ^{56}Ni, has a near-IR emissivity that sharply peaks at a temperature of 7000 K. This corresponds to the composition and temperature of the ejecta of a Type Ia SN 40 days after explosion, or 20 days after T(B_{max}). (The exact composition is not critical, however, so long as we are considering iron group elements.) At this time the iron group elements undergo a transition from a state of double to single ionization. This in turn causes a redistribution of energy from optically thick shorter wavelengths to optically thin near-IR wavelengths. If the Y-band secondary maximum is brighter than the first maximum in most or all cases, the process which gives rise to the secondary maximum must be happening to the greatest degree at 1.03 μm.

Kasen (2006) also suggests that a transition from singly ionized iron group elements to neutral atoms, occurring some 80 days after T(B_{max}), may give rise to a *third* maximum.

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[16]Some preliminary light curves can be seen at http://csp1.lco.cl/ cspuser1/CSP.html.

In Figs. 4 and 7 we see evidence for this phenomenon in the light curves of SN 2004S, at the 2.8σ level in the J-band and up to 5.3σ in the H-band. There exist very few near-IR measurements of Type Ia SNe at these late epochs. We now have an extra movitation to observe these objects in the near-IR at late epochs − to check Kasen's prediction.

Using the light curve fitting code of Prieto, Rest, & Suntzeff (2006), which relies on $BVRI$ data, we find for SN 2004S that T(B_{max}) = JD 2,453,039.87 ± 0.25, $\Delta m_{15}(B)$= 1.14 ± 0.01, and $E(B-V)_{host} = 0.00 \pm 0.01$. The derived value of the decline rate is statistically equal to that of SN 2001el, $\Delta m_{15}(B)$= 1.13 ± 0.04 (Krisciunas et al. 2003).[17] The $\Delta m_{15}(B)$ solution confirms that SN 2004S had minimal host galaxy reddening, A_V(host) $\approx 0.00 \pm 0.03$. A more robust solution for the host galaxy extinction is obtained using the optical and IR data (see below). The $\Delta m_{15}(B)$ method gives a distance modulus of $m - M = 33.32 \pm 0.17$ mag on an $h = 0.72$ scale (Freedman et al. 2001).[18] This is to be compared with $m-M$ = 33.07 ± 0.21 mag from the recession velocity in the CMB frame.

Using the SN 2001el V-band template, we estimate that the V-band maximum of SN 2004S is $V_{max} = 14.48 \pm 0.03$. With A_V(tot) = 0.38 mag (see §4) and adopting a distance modulus of $m - M = 33.07 \pm 0.21$ mag from the radial velocity in the CMB frame and Hubble's Law, we obtain M_V(max) = −18.97 ± 0.22 mag. The expected value for a Type Ia SN of average decline rate is $M_V = -19.13$ on an $h = 0.72$ scale (Phillips et al. 1999). Thus, SN 2004S has an absolute V magnitude at maximum within 1-σ of the nominal value for its decline rate.

Using the SN 2001el templates, we estimate that the S-corrected, K-corrected apparent magnitudes at maximum light of SN 2004S were $J_{max} = 14.806$, $H_{max} = 14.975$, and $K_{max} = 14.766$, with uncertainties of ± 0.03 mag. The total extinction due to dust in our Galaxy and in the host of SN 2004S is $A_J = 0.107$, $A_H = 0.068$, and $A_K = 0.043$ mag, with uncertainties of ± 0.02 mag or less (see §4). Adopting a distance modulus of $m - M = 33.07 \pm 0.21$ mag from the radial velocity in the CMB frame and Hubble's Law, we obtain IR absolute magnitudes at maximum light of $M_J = -18.37$, $M_H = -18.16$, and $M_K = -18.35$, with uncertainties of ± 0.22 mag. These are to be compared with the mean values of more than 20 objects with $\Delta m_{15}(B) \lesssim 1.8$ of $M_J = -18.61$, $M_H = -18.28$, and $M_K = -18.44$ (Krisciunas et al. 2004c, Table 17). Taking the numbers at face value, SN 2004S is slightly underluminous in the IR, which contradicts the implication from MLCS2k2 analysis that

[17]In the context of the MLCS2k2 system Jha, Riess, & Kirshner (2006b) give $\Delta = -0.19 \pm 0.03$ mag for SN 2001el. Using a copy of that software we obtain $\Delta = -0.24 \pm 0.04$ mag for SN 2004S. $\Delta < 0$ is a measure of the overluminosity of these SNe compared to the fiducial object of the system.

[18]We define $h \equiv H_0$ / (100 km s^{-1} Mpc^{-1}).

the object is somewhat overluminous. In any case, the near-IR absolute magnitudes are still consistent with the notion that Type Ia SNe with $\Delta m_{15}(B) \lesssim 1.8$ are standard candles in the near-IR (Krisciunas, Phillips, & Suntzeff 2004a), with an intrinsic dispersion of roughly ± 0.15 mag.

For SN 2004S Misra et al. (2005) found $A_V(\mathrm{tot}) = 0.542 \pm 0.167$ mag. This implies host galaxy extinction of $A_V(\mathrm{host}) \approx 0.23$ mag, with a rather large uncertainty. These authors adopt a distance modulus of 32.94 mag on an $h = 0.65$ scale, equivalent to $m - M = 32.72$ mag on an $h = 0.72$ scale. They used a somewhat lower heliocentric redshift for the host galaxy (2730 km s^{-1}) and corrected for the Virgocentric infall of the Local Group, but do not quote a velocity in the CMB frame. One can also use the flow model of Tonry et al. (2000) to give an estimate of the distance to SN 2004S. Along a vector towards the direction of a galaxy in the sky, one determines the distance at which the flow model gives a radial velocity that matches the observed heliocentric velocity. For the host of SN 2004S that distance is 36.25 Mpc on an $h = 0.784$ scale, using the Theureau et al. (2005) heliocentric radial velocity of 2808 km s^{-1}. On an $h = 0.72$ scale the equivalent distance modulus is $m - M = 32.98$ mag, statistically in agreement with the value of 33.07 ± 0.21 mag from the CMB velocity and Hubble's Law.

Since SN 2001el is known as one of the few Type Ia SNe to exhibit measurable polarization, implying an asymmetrical explosion (Wang et al. 2003b), SN 2004S may also have exhibited the same effect. See Chornock et al. (2006) for a discussion.

A final topic to mention in this section is the late-time photometry given in Tables 3 and 4. As Sollerman et al. (2004) found in the case of SN 2000cx, six months to a year after $T(B_{max})$ SN 2004S continued to get fainter at optical wavelengths, but in the near-IR it reached a plateau and stayed constant. This confirms that at late times the near-IR flux of a Type Ia SN becomes a larger and larger fraction of the total flux (see Fig. 13 of Sollerman et al. 2004). We show in Fig. 7 our V- and H-band photometry of SN 2004S. The B-band photometry from 50 to 410 days after $T(B_{max})$ gives dm/dt $= 1.50 \pm 0.01$ mag per 100 days. The late-time photometry ($t > 196$ d) in the V, R and I bands gives dm/dt $= 1.42 \pm 0.04$, 1.55 ± 0.12, and 1.40 ± 0.10 mag per 100 days, respectively. Sollerman et al. (2004) found decline rates of $\sim$1.4 mag per 100 d for the optical light curves of SN 2000cx. Stritzinger & Sollerman (2007, in preparation) present late-time photometry of SN 2001el.

At late times the optical minus IR color of SN 2004S became very red. $V - H = +0.27 \pm 0.10$ at $t = 76$ d (see Figs. 12 and 13 below). At $t = 342$ d the $V - H$ color was one magnitude redder ($+1.27 \pm 0.20$), and at $t = 416$ d it was one magnitude redder still ($+2.27 \pm 0.20$).

3. Optical and Infrared Spectra of SN 2004S

In Table 5 we summarize some basic information about the spectra of SN 2004S presented here. The spectra were obtained with the CTIO 1.5-m telescope, the 3.58-m Telescopio Nazionale Galileo (TNG), the 2.56-m Nordic Optical Telescope (NOT), and the 10-m Keck telescope, and were reduced following the standard recipe for longslit spectroscopy. Spectropolarimetry of SN 2004S, obtained with the Keck telescope, and a comparison to SN 2001el, are also given by Chornock et al. (2006).

In Fig. 8 we show optical spectra of SN 2004S obtained between 1.7 and 42.5 days after T(B_{max}). In Fig. 9 we compare the optical spectra of SN 2004S at three epochs to several other normal Type Ia supernovae: SN 1996X (Salvo et al. 2001), SN 1998bu (Hernandez et al. 2000), SN 1999ee (Hamuy et al. 2002), SN 2001el (Wang et al. 2003b), and SN 2003du (Gerardy et al. 2004; Stanishev et al. 2006). Clearly, the spectral evolution of SN 2004S closely follows that of other normal Type Ia SNe. It is worth noting that the largest differences between the SNe are observed in the Ca II H&K and infra-red triplet lines. Otherwise, all the spectra are nearly identical.

In Fig. 1 one can see how remarkably similar SNe 2001el and 2004S are at maximum light. Branch et al. (2006) investigated the maximum-light spectra of 24 Type Ia SNe. Their "core-normal" group of 7 objects included SNe 1998bu and 2001el. They noted the high-velocity Ca II absorption of SN 2001el and also identified the three local minima in the spectrum between 4600 and 4900 Å as being due to high-velocity Fe II. Since SN 2004S shows the same features, the identification undoubtedly holds for SN 2004S as well. Branch et al. (2006) also noted that SN 2001el had the strongest high-velocity Fe II of all "core-normal" SNe. In Fig. 1 one can see that high-velocity Fe II features in SN 2004S are as strong as in SN 2001el, thus strengthening the similarity between the two SNe. Besides, the two SNe had equal Si II ratios, $\mathcal{R}(\mathrm{Si\,II}) \approx 0.3$, as defined by Nugent et al. (1995).

Despite the similarities between SNe 2001el and 2004S, there *are* a few spectroscopic differences. The depth of the Si II absorption observed at 6150 Å is weaker in SN 2004S. Part of the blend due to Fe II just blueward of 5000 Å is different in the two SNe. The greater dust extinction along the line of sight to SN 2001el produces some absorption due to the Na D lines at 5889/5896 Å. SN 2001el had a slight shoulder in its Ca II absorption at 7900 Å whereas SN 2004S did not.

Larger differences are observed in the Ca II infra-red triplet (Ca II IR3). The differences may be attributed to the presence of high-velocity features (HVFs) approximately centered at 20000 km s^{-1}. In Fig. 10 we see a comparison of the velocity profiles of the Ca II IR3 in SNe 1999ee, 2001el, and 2004S. The line profiles are normalized to a local pseudo-continuum, approximated by a straight line in a way similar to the definition of the Si II ratio (see Nugent et al. 1995). Around T(B_{max}) the Ca II HVFs in SNe 2001el and 2004S have equal strength, but at the later epochs they are stronger in SN 2004S. At the same time the photospheric Ca II line is stronger in SN 2001el. The HVFs in SN 1999ee at the time of maximum light are weaker than in SNe 2001el and 2004S, but are stronger 20 days after. Note, however, that while SN 1999ee also had high-velocity Ca II, it was placed by Branch et al. (2006) in their "shallow-silicon" category; it had weaker Si II and S II features than SN 2001el. We note that SN 1999ee had a much slower decline rate ($\Delta m_{15}(B)$= 0.94 ± 0.06; Stritzinger et al. 2002), which, along with the shallower absorption lines of singly ionized species, is consistent with it having been a hotter explosion than SNe 2001el and 2004S.

Another difference emerges when comparing the velocity inferred from the minimum of the Si II λ6355 line. Around T(B_{max}) SN 2004S had a velocity of $\sim$ 9300 km s^{-1}, while in SN 2001el it was $\sim$ 10200 km s^{-1}. Analyzing the spectrophotometric properties of a sample of Type Ia SNe, Benetti et al. (2005) found that they can be statistically divided into three groups mainly on the behavior of the rate of decrease of the expansion velocity of the Si II λ6355 absorption after the time of maximum light, $\langle \dot{v} \rangle$ ('velocity gradient'), and also according to the velocity of the Si II λ6355 at T(B_{max}), v_{max}(Si II). Respectively, the groups have been called high velocity gradient (HVG; $\langle \dot{v} \rangle = 97 \pm 16$ km s^{-1}d^{-1}, v_{max}(Si II) = 12200±1100), low velocity gradient (LVG; $\langle \dot{v} \rangle = 37 \pm 18$ km s^{-1}d^{-1}, v_{max}(Si II) = 10300±300), and FAINT ($\langle \dot{v} \rangle = 87 \pm 20$ km s^{-1}d^{-1}, v_{max}(Si II) = 9200±600). The FAINT group includes SNe that are intrinsically dim, on average $\sim$ 2 mag fainter than SNe belonging to the other two groups. SN 2001el had $\dot{v} = 31 \pm 5$ km s^{-1}d^{-1}, and Benetti et al. (2005) placed it in the LVG group. For SN 2004S, however, we measure $\dot{v} = 69 \pm 5$ km s^{-1}d^{-1}, which is in between the LVG group on one hand, and HVG and FAINT groups on the other. Along with the relatively low velocity at the time of maximum light, this suggests that SN 2004S may be an intermediate object in the context of the analysis of the Si II λ6355 line velocity evolution.

A single IR spectrum of SN 2004S was obtained 15 days after T(B_{max}) using the Near-Infrared Camera and Spectrograph at the TNG. An Amici prism was used as a disperser, providing the whole near-IR spectral range in one exposure but with very low resolving power of $\sim$ 100. In Fig. 11 we compare the near-IR spectra of SNe 2004S, 1999ee, and 1998bu; the near-IR spectra of these three objects are dominated by the same singly ionized species, mostly of iron group elements. Marion et al. (2003) showed that the abrupt change of the flux near 1.52 μm (rest wavelength $\sim$ 1.57μm) observed in many Type Ia SNe defines the transition from partial to complete silicon burning. In SN 2004S we measure a velocity of $\sim$ 11000 km s^{-1}, which is consistent with the measurements of other SNe and the model predictions for a normal-bright Type Ia SNe (Marion et al. 2003).

4. Considerations of reddening and extinction of SNe 2001el and 2004S

The $V-J$, $V-H$, and $V-K$ color curves of SN 2004S are shown in Fig. 12. Using our zero-reddening loci for Type Ia SNe with mid-range decline rates, we find total color excesses (i.e. due to Galactic dust and host galaxy dust) of E$(V-J)$ = 0.324 ± 0.060, E$(V-H)$ = 0.371 ± 0.056, and E$(V-K)$ = 0.316 ± 0.030 mag. We note that the $V-K$ curve is by far the best match as to shape. To scale the color excesses to estimates of A_V, the appropriate coefficients are 1.394 ± 0.110, 1.217 ± 0.058, and 1.130 ± 0.029, respectively. These coefficients differ slightly from the values in Eqs. 2, 3, and 4 of Krisciunas et al. (2004b). The Cardelli, Clayton, & Mathis (1989) values of A_λ/A_V are appropriate for determining extinction of stars with normal spectra. Since SNe have such different spectra we used the values in Table 8 of Krisciunas et al. (2006), which are based on spectra of SN 1999ee at maximum light. The uncertainites assigned to these coefficients correspond to a 20 percent uncertainty in A_λ/A_V. For SN 2004S we obtain three estimates of A_V, namely 0.452 ± 0.090, 0.452 ± 0.071, and 0.357 ± 0.035 mag. The weighted mean is A_V(tot) = 0.384 ± 0.030 mag, of which 0.313 ± 0.031 mag is due to dust in our Galaxy. It follows that A_V(host) = 0.071 ± 0.043 mag, implying a finite but small amount of host galaxy extinction. This is consistent with the host galaxy extinction derived using the $\Delta m_{15}(B)$ method.

Since we have already demonstrated that the optical and IR light curves of SNe 2001el and 2004S are so similar, it is no suprise that the shapes of the photometric color curves of the two objects are also nearly identical. By adjusting a color template from SN 2001el to the corresponding color curve of SN 2004S we can determine the difference of the colors and therefore the difference of the color excesses. In Fig. 13 we show the same SN 2004S data as in Fig. 12 but with the color templates derived from data of SN 2001el, adjusted to minimize the χ^2 statistic. We find that we need to shift the SN 2001el templates by $\Delta(V-J)$ = −0.144 ± 0.044, $\Delta(V-H)$ = −0.175 ± 0.035, and $\Delta(V-K)$ = −0.187 ± 0.068 mag.

We may next correct for the effect of Galactic dust. SN 2001el has E$(B-V)_{Gal}$ = 0.014, while SN 2004S has E$(B-V)_{Gal}$ = 0.101 (Schlegel, Finkbeiner & Davis 1998). Thus, the difference of the Galactic components of V-band extinction toward these two objects is (0.101 − 0.014) times R_V of 3.1, or 0.270 ± 0.027 mag. The differences of the color excesses due to dust in our Galaxy are: ΔE$(V-J)_{Gal}$ = 0.270 / 1.394 = 0.194 ± 0.019, ΔE$(V-H)_{Gal}$ = 0.270 / 1.217 = 0.222 ± 0.022, and ΔE$(V-K)_{Gal}$ = 0.270 / 1.130 = 0.239 ± 0.024 mag. We find that the host galaxy dust of NGC 1448 reddened SN 2001el more than the host galaxy dust of MCG -05-16-021 reddened SN 2004S by these amounts: ΔE$(V-J)_{host}$ = 0.194 + 0.144 = 0.338 ± 0.048, ΔE$(V-H)_{host}$ = 0.222 + 0.175 = 0.397 ± 0.041, and ΔE$(V-K)_{host}$ = 0.239 + 0.187 = 0.426 ± 0.072 mag. To obtain the difference of host galaxy V-band extinction, we need to scale these values by coefficients appropriate to the dust in the two host galaxies. Krisciunas et al. (2003) found $A_V(\mathrm{tot}) = 0.57 \pm 0.05$ for SN 2001el. With $A_V(\mathrm{Gal}) \approx 0.043$ towards SN 2001el, $A_V(\mathrm{host}) \approx 0.53$ mag. Thus, SN 2001el suffered approximately an order of magnitude ($0.53/0.07 \approx 7.6$) more host galaxy extinction compared to SN 2004S. For SN 2001el Wang et al. (2003b) give $R_V = 2.88 \pm 0.15$ from the peak wavelength of the interstellar polarization.[19] Jha, Riess, & Kirshner (2006b) give $R_V = 2.40 \pm 0.19$ for the host galaxy dust of SN 2001el. Using the values in Table 8 of Krisciunas et al. (2006) and this range of values of R_V, we find that the difference of host galaxy V-band extinction of the two SNe is $A_V = 0.471 \pm 0.027$ mag. Adding this to the magnitude difference of the V-band light curves, corrected for Galactic extinction (column 5 of Table 6 below), the implied difference of the distance moduli of the two objects is 1.936 $\pm$ 0.044 mag.

It is not absolutely necessary to make any a priori assumptions about the parameters of interest here. In Table 6 we lay out a spread sheet relating to the implied dust extinction in the hosts of SNe 2001el and 2004S. In column 2 we give the magnitude offsets necessary to minimize the χ^2 statistic of fitting the SN 2001el light curve templates to SN 2004S. In column 5 of Table 6 we have corrected the values of column 2 for the extinction due to Galactic dust.

In Fig. 14 we show the values from column 5 of Table 6 vs. the wavelengths of the photometric filters. As the wavelength tends to infinity, the effect of the dust in the two host galaxies becomes negligible. In other words, in the absence of host galaxy dust extinction, all the points (excepting U) would lie along some horizontal line near the top of the graph. This is most directly interpreted as the difference of the distance moduli ($\equiv \Delta\mu$) of the two objects.[20]

We have carried out a multi-dimensional χ^2 minimization, to find the values of R_V, A_V and $\Delta\mu$ that give the best match to the values in column 5 of Table 6. See Table 7 and Fig. 15. We find $R_V = 2.15^{+0.24}_{-0.22}$, $A_V = 0.472 \pm 0.025$ mag, and $\Delta\mu = 1.936$ mag. Note the close agreement of A_V and $\Delta\mu$ with the values obtained from a consideration of the $V-[JHK]$ color curves of SNe 2001el and 2004S.

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[19] In our view the polarization curve shown in Fig. 8 of Wang et al. (2003b) does not have a well constrained maximum, so their value of R_V should probably be assigned a larger numerical uncertainty.

[20] Because Type Ia SNe exhibit an intrinsic dispersion at any given decline rate of $\pm$ 0.15 mag, two objects with identical explosion mechanisms, or at least producing the same amount of ^{56}Ni, would not necessarily give the exact same extinction-corrected absolute magnitudes. And even if the two objects produced the same number of ergs per second, the explosions could be asymmetric. One elongated fireball might be observed end-on, while the other could be observed side-on, giving different apparent brightnesses.

Using only $BVRI$ data we find $R_V = 2.51^{+0.50}_{-0.36}$. This is statistically in agreement with the values of Jha, Riess, & Kirshner (2006b) and Wang et al. (2003b) for the host galaxy dust of SN 2001el. However, our value derived from $BVRIJHK$ data is considerably smaller than that of Wang et al. (2003b), derived from polarization data. Our "best" value implies that the dust in the host of SN 2001el had an R_V value considerably less than the canonical Galactic value of 3.1.

In Fig. 15 we show the 1-σ contours of our extinction solutions using 4, 5, and 7 filter photometry. As the number of filters and the wavelength range of the filters increase, the contours become smaller and rounder. In Table 7 one can see how the uncertainties decrease as the number of filters increases from 4 to 6. Adding the K-band data changed the solution only slightly. This is undoubtedly due to the larger uncertainty of the magnitude shift necessary to fit the SN 2004S K-band data with the corresponding SN 2001el template.

We can estimate the total V-band extinction of SN 2001el as follows. The extinction due to Galactic dust along the line of sight is $A_V(\mathrm{Gal}) = 0.043 \pm 0.004$ mag. The host galaxy V-band extinction of SN 2001el is 0.472 ± 0.025 mag (difference of SNe 2001el and 2004S) plus the host galaxy extinction of SN 2004S (0.071 ± 0.043 mag from $VJHK$ data, but possibly zero if we rely on the $\Delta m_{15}(B)$ solution using $BVRI$ data). For SN 2001el $A_V(\mathrm{tot}) = 0.586 \pm 0.050$ mag. This compares very well with our previously published value of 0.57 ± 0.05 mag (Krisciunas et al. 2003).

5. Modelling distance uncertainty and dust

For Type Ia SNe to be useful as accurate probes for cosmology it is important that systematic errors be minimized. Future probes of Dark Energy properties will need to control systematic uncertainties to better than a few percent to provide useful constraints (Miknaitis et al. 2006, in preparation). For a typical $E(B-V) \approx 0.10$ mag, a systematic error of 0.2 in R_V leads to a systematic error of 0.02 mag in the distance modulus. The range of extinction properties seen in nearby supernovae, such as SN 2004S, suggests that it is important to measure the extinction law to avoid making a systematic error in distance determination. But our photometry of SN 2004S shows how difficult it is to precisely constrain R_V using just four optical filter bands.

To better understand how well dust extinction can be corrected in a sample of well-observed Type Ia SNe, we have simulated the process used to recover R_V, A_V and $\Delta\mu$ for SN 2004S. In the simulation we have assumed the following:

- Supernovae have a probability distribution for A_V like that found by Jha, Riess, & Kirshner (2006b). This is an exponential probability distribution function (pdf) peaking at zero extinction and having a scale factor of 0.4 mag.

- R_V has a Gaussian pdf with a mean value of 2.4 and standard deviation of 0.4.
- The extinction as a function of bandpass is given by $\mathrm{A}_i/\mathrm{A}_V = a_i + b_i/\mathrm{R}_V$ where i corresponds to one of the $BVRIJHK$ bands and the coefficients a_i and b_i are given in Table 8 of Krisciunas et al. (2006).

We then did a Monte Carlo simulation selecting pseduo-random values of R_V and A_V which define the extinctions in the $BVRIJHK$ bands. How accurately these input parameters can be recovered depends on two factors: the number of filters used in the observations and the signal-to-noise ratio of the observations. The simulations were done assuming observations in four bands ($BVRI$), five bands ($BVRIJ$), and all seven filters ($BVRIJHK$). The signal-to-noise ratio in each band was simulated by setting a variance, σ^2_{phot}, about the true extinction. Each realization of the Monte Carlo simulation selected a random value that had a Gaussian distribution with that variance and centered on the true bandpass extinction.

The resulting simulated measurements were then fit with three free parameters, R_V, A_V, and $\Delta\mu$, using a χ^2 minimization technique. $\Delta\mu$ is the offset in the recovered distance modulus and the measure for how well the various filter set and photometric uncertainties perform.

A sample result for 30,000 events with a photometric error of 0.02 mag and recovery in $BVRIJ$ bands is shown in Fig. 16. The difference between the input A_V and recovered A_V (i.e. the A_V error) is plotted along with the corresponding R_V error to show the correlation between these parameters. Note that on average the recovered values of R_V and A_V have no significant systematic error.

In Fig. 17 we explore how adding IR bands improves the distance estimation. As expected, the use of $BVRIJHK$ comes closest to the optimal recovery of the distance modulus. The use of only $BVRI$ bands means that the recovered distance uncertainty rises sharply with photometric error. For $BVRI$, photometric errors of only 0.03 mag result in distance uncertainites of 0.2 mag, which is the same order as the intrinsic scatter in the luminosities of Type Ia SNe. We note that our simulation was quite simple and assumes that the true color distribution for unextincted Type Ia SNe at all decline rates is known with perfect precision.

The addition of the rest frame J-band to the filter complement decreases the distance uncertainty by a factor of 2.7. The use of rest frame J-band observations greatly improves the precision in estimating the distance modulus when independently fitting a two-parameter

(R_V, A_V) extinction law. Adding H and K further improves the uncertainty of the distance modulus, but only by an additional 30 percent.

Any future SN survey to be carried out with a satellite-borne telescope would wisely observe Type Ia SNe in rest frame optical and IR bands. To determine the cosmic equation of state parameter (w) to within 10 percent requires controlling photometric systematic errors at the 0.01 to 0.02 mag level (Miknaitis et al., 2006, in preparation). At minimum we must know the appropriate mean value of R_V for high redshift SNe. Better still would be the option to determine R_V accurately for a large fraction of those yet-to-be discovered objects.

6. Conclusions

In this paper we provided optical and IR photometry of the normal Type Ia SN 2004S. Using optical and near-IR data, it was found to have minimal host galaxy extinction, with $\mathrm{A}_V(\mathrm{host}) = 0.07 \pm 0.04$ mag.

There are remarkable similarities of the shapes of the optical and IR light curves of SNe 2004S and 2001el. This is the first time we have seen two objects exhibit such similar JHK light curves at the time of maximum light until 65 days afterwards. We might assume that the two objects had identical explosion mechanisms, or at least produced the same amount of ^{56}Ni. Given that Type Ia SNe exhibit an intrinsic dispersion of roughly ± 0.15 mag at any given decline rate, SNe 2001el and 2004S could have produced identically shaped filter-by-filter light curves, yet could have had absolute magnitudes that differ by 0.15 mag or more. For our purposes it is reasonable to interpret the difference of their extinction-corrected magnitudes in any band (except U) as a measure of the difference of their distance moduli. More generally, we may assume that they had identical extinction-corrected colors.

SNe 2001el and 2004S not only had similar light curves, but very similar optical and near-IR spectra, exhibiting high-velocity absorption due to singly ionized Ca and Fe. Except for the high velocity features in their ejecta prior to $t \approx +14$ d, they can be considered spectroscopically normal (Branch et al. 2006).

The similarities of the light curves of SNe 2001el and 2004S allow us to use the photometry, filter by filter, to derive the *difference* of the host galaxy extinctions without making any a priori assumptions about the unreddened colors of Type Ia SNe, values of R_V, or the reddening law between the K-band and infinite wavelength. Since SN 2001el had roughly an order of magnitude more host galaxy extinction compared to SN 2004S, our multi-dimensional χ^2 minimization primarily tells us something about the dust in the host of SN 2001el. For this object we find $\mathrm{R}_V = 2.15^{+0.24}_{-0.22}$ and $\mathrm{A}_V(\mathrm{tot}) \approx 0.59 \pm 0.05$ mag. Because of the advantages of combining optical and IR photometry to determine extinction, it is important that we know the shapes and zeropoints of the color curves of Type Ia SNe. Our analysis gives us unreddened solutions for SNe 2001el and 2004S.

The $V-K$ color curves of SNe 2001el and 2004S have the same shape as our template based on the not-so-well sampled light curves of 8 mid-range decliners. Our $V-J$ and $V-H$ templates do not have quite the same shapes as the color curves of SNe 2001el and 2004S. In the near future it should be possible to construct more robust color curves from a larger database of objects, which will reflect more realistically the inherent scatter exhibited by Type Ia SNe.

We find that SN 2004S had $VJHK$ absolute magnitudes at maximum light within 1-σ of the mean of other Type Ia SNe of comparable decline rate. Any systematic differences may only be due to the unknown peculiar velocity of the host galaxy. The JHK absolute magnitudes at maximum of SN 2004S are consistent with the notion that in the near-IR Type Ia SNe (excepting the fastest decliners) are standard candles.

We can derive host galaxy extinction much more accurately using optical and IR photometry than using optical photometry alone, as we have shown graphically and quantitatively. Our Monte Carlo simulations indicate that rest frame $BVRIJ$ photometry gives distance uncertainties 2.7 times smaller than just using rest frame $BVRI$ photometry. Assuming a fixed value of R_V for high-redshift SNe runs the risk of systematic errors if the fixed value is far from the true mean. Here we showed that adding one additional rest frame band in the near-IR substantially improves the resulting uncertainty of determining the distance moduli of Type Ia SNe. Rest frame J-band corresponds to 3.6 μm in the observer frame at $z \sim 2$, which is observable with space-based telescopes. Having rest frame optical and near-IR data for Type Ia SNe will lead to stricter constraints on models of Dark Energy.

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Table 1. Optical Photometric Sequence near SN 2004S[a]

Star ID[b]	*U*	*B*	*V*	*R*	*I*
1	16.841 (0.011)	16.442 (0.008)	15.612 (0.006)	15.140 (0.006)	14.727 (0.005)
2	19.282 (0.066)	18.504 (0.012)	17.441 (0.010)	16.777 (0.015)	16.222 (0.008)
3	18.134 (0.026)	18.157 (0.014)	17.609 (0.010)	17.257 (0.011)	16.884 (0.015)
4	19.081 (0.054)	17.897 (0.011)	16.527 (0.007)	15.642 (0.005)	14.845 (0.006)
5	19.255 (0.051)	18.556 (0.017)	17.509 (0.009)	16.875 (0.006)	16.325 (0.007)
6	16.377 (0.008)	16.282 (0.008)	15.590 (0.005)	15.175 (0.006)	14.771 (0.006)
7	18.206 (0.042)	17.848 (0.010)	16.996 (0.007)	16.501 (0.008)	16.056 (0.006)

[a]The numbers in parentheses are 1-σ uncertainties (mean errors of the mean).

[b]The identifications are the same as in Fig. 2.

Table 2. Infrared Photometric Sequence near SN 2004S[a]

Star ID[b]	*Y*	*J*	*H*	*K*
1	14.450 (0.005)	14.166 (0.009)	13.794 (0.009)	13.682 (0.017)
2	15.828 (0.010)	15.448 (0.010)	14.879 (0.009)	14.751 (0.039)
3	16.595 (0.019)	16.441 (0.023)	16.117 (0.024)	···
4	14.340 (0.005)	13.918 (0.008)	13.273 (0.009)	13.100 (0.017)

[a]The numbers in parentheses are 1-σ uncertainties (mean errors of the mean).

[b]The identifications are the same as those in Table 1 and Fig. 2.

Table 3. *UBVRI* Photometry of SN 2004S[a]

JD−2,450,000	U	B	V	R	I	Telescope[b]
3042.72*	14.645 (0.053)	14.554 (0.024)	14.447 (0.024)	14.385 (0.022)	14.762 (0.021)	1
3045.75*	14.965 (0.060)	14.723 (0.023)	14.491 (0.019)	14.446 (0.025)	14.839 (0.022)	1
3048.76	15.317 (0.085)	14.948 (0.029)	14.592 (0.034)	14.596 (0.015)	15.015 (0.024)	1
3052.72*	15.865 (0.061)	15.335 (0.026)	14.805 (0.024)	14.823 (0.023)	15.246 (0.023)	1
3056.68*	16.452 (0.051)	15.799 (0.025)	15.050 (0.022)	14.962 (0.021)	15.228 (0.023)	1
3060.59	16.886 (0.054)	16.231 (0.025)	15.256 (0.022)	15.040 (0.032)	15.128 (0.022)	1
3066.67*	17.406 (0.061)	16.744 (0.026)	15.546 (0.028)	15.161 (0.026)	14.993 (0.022)	1
3070.60*	17.729 (0.080)	17.093 (0.031)	15.808 (0.022)	15.415 (0.022)	15.125 (0.028)	1
3074.57*	17.881 (0.066)	17.357 (0.026)	16.103 (0.025)	15.723 (0.023)	15.394 (0.022)	1
3081.64*	18.094 (0.063)	17.600 (0.023)	16.377 (0.033)	16.035 (0.022)	15.750 (0.023)	1
3087.60	18.330 (0.087)	17.806 (0.019)	16.602 (0.015)	16.306 (0.011)	16.105 (0.019)	1
3090.55*	18.445 (0.047)	17.841 (0.023)	16.693 (0.022)	16.402 (0.021)	16.247 (0.020)	1
3092.94	18.301 (0.104)	17.858 (0.046)	16.806 (0.037)	16.473 (0.067)	16.333 (0.053)	2
3096.54	18.528 (0.104)	17.901 (0.052)	16.856 (0.050)	16.614 (0.028)	16.452 (0.025)	1
3102.55*	18.581 (0.147)	17.964 (0.039)	16.967 (0.027)	16.709 (0.027)	16.711 (0.034)	1
3109.51	18.786 (0.066)	18.101 (0.026)	17.177 (0.020)	16.967 (0.021)	16.954 (0.061)	1
3116.50	18.834 (0.061)	18.162 (0.022)	17.325 (0.019)	17.190 (0.014)	17.203 (0.052)	1
3122.48*	···	18.368 (0.066)	17.573 (0.032)	17.407 (0.044)	17.299 (0.045)	1
3130.51*	18.790 (0.321)	18.259 (0.067)	17.685 (0.033)	17.638 (0.044)	17.667 (0.053)	1
3137.47	19.014 (0.228)	18.438 (0.045)	17.811 (0.022)	17.799 (0.018)	17.894 (0.040)	1
3151.47	···	18.619 (0.038)	18.122 (0.034)	18.214 (0.098)	18.194 (0.036)	1
3238.31	···	···	19.778 (0.058)	20.369 (0.090)	19.489 (0.089)	2
3267.26	···	···	20.394 (0.049)	21.034 (0.080)	20.547 (0.151)	2
3357.75	···	21.731 (0.035)	21.471 (0.041)	22.271 (0.123)	21.306 (0.102)	3
3361.14	···	···	21.689 (0.094)	22.292 (0.247)	21.217 (0.126)	2
3453.51	···	23.198 (0.140)	23.084 (0.117)	···	···	3

[a]The nights marked by an asterisk were photometric at CTIO. On these occasions the SN 2004S photometry was tied directly to the Landolt (1992) system using the stars in Ru 149. The numbers in parentheses are 1-σ errors (mean errors of the mean) and include the RMS error of the photometric calibration from the standards and the scatter of the multiple measurements of SN 2004S with respect to their mean.

[b]1 = CTIO 1.3-m. 2 = Siding Spring 2.3-m. 3 = La Silla 2.2-m.

Table 4. Near Infrared Photometry of SN 2004S[a]

JD−2,450,000	Y	J	H	K	Telescope[b]
3042.72	15.170 (0.026)	14.945 (0.021)	15.064 (0.022)	14.874 (0.059)	1
3045.75	15.340 (0.026)	15.238 (0.024)	15.090 (0.021)	14.976 (0.060)	1
3048.76	15.472 (0.026)	15.641 (0.029)	15.228 (0.026)	15.116 (0.066)	1
3052.72	15.499 (0.026)	16.156 (0.036)	15.160 (0.021)	15.042 (0.063)	1
3053.43	···	16.124 (0.010)	15.151 (0.012)	14.946 (0.019)	2
3056.68	15.299 (0.025)	16.258 (0.040)	15.107 (0.021)	14.886 (0.048)	1
3060.59	15.181 (0.023)	16.227 (0.040)	15.041 (0.021)	14.957 (0.054)	1
3070.60	14.750 (0.020)	15.866 (0.036)	15.050 (0.024)	15.007 (0.055)	1
3074.57	14.782 (0.020)	15.932 (0.035)	15.260 (0.027)	15.204 (0.060)	1
3087.60	15.544 (0.037)	17.013 (0.093)	16.017 (0.046)	16.017 (0.148)	1
3090.55	15.727 (0.031)	17.233 (0.099)	16.221 (0.056)	16.065 (0.153)	1
3096.54	16.059 (0.055)	···	···	···	1
3102.55	16.293 (0.043)	18.200 (0.267)	16.779 (0.085)	16.561 (0.254)	1
3109.51	···	18.587 (0.259)	16.851 (0.077)	···	1
3116.50	···	18.652 (0.231)	17.030 (0.099)	···	1
3130.51	···	···	18.407 (0.320)	···	1
3341.81	···	···	20.57 (0.18)	···	3
3342.80	···	21.35 (0.06)	···	···	3
3414.71	···	21.27 (0.13)	···	···	3
3415.62	···	···	20.63 (0.18)	···	3

[a]The numbers in parentheses are 1-σ uncertainties (mean errors of the mean).

[b]1 = CTIO 1.3-m. 2 = TNG. 3 = VLT number 1.

Table 5. Spectra of SN 2004S

UT Date	Telescope[a]	JD−2,450,000	Phase[b]	Range (Å)	Resolution (Å)	Exptime (sec)
Feb06.10	1	3041.60	1.7	3100-9650	17	900
Feb11.96	2	3047.46	7.6	3230-10400	25	900
Feb17.00	3	3052.50	12.6	4880-7940	20	2x600
Feb17.85	3	3053.35	13.5	3260-9050	20	2x600
Feb18.45	4	3053.95	14.1	3360-10380	10-12	2x180
Feb22.92	3	3058.42	18.5	3190-9050	20	2x600
Mar11.88	3	3076.38	36.5	3200-9040	20	2x900
Mar17.85	3	3082.35	42.5	3210-9060	15	2x900

[a]1 = CTIO 1.5-m. 2 = 3.58-m Telescopio Nazionale Galileo. 3 = 2.56-m Nordic Optical Telescope. 4 = Keck 10-m, using LRIS.

[b]Days since T(B_{max}) = JD 2,453,039.87.

Table 6. Adjusting SN 2001el templates to the light curves of SN 2004S

Filter	Δmag_1[a]	A_λ/A_V[b]	A_{Gal}[c]	Δmag_2[d]
U	1.725 (0.062)	1.5288	0.413 (0.041)	1.312 (0.074)
B	1.608 (0.025)	1.3147	0.355 (0.036)	1.253 (0.044)
V	1.735 (0.022)	1.0000	0.270 (0.027)	1.465 (0.035)
R	1.781 (0.019)	0.8299	0.224 (0.022)	1.557 (0.029)
I	1.859 (0.022)	0.6050	0.163 (0.016)	1.696 (0.027)
J	1.888 (0.033)	0.2828	0.076 (0.008)	1.812 (0.034)
H	1.919 (0.024)	0.1785	0.048 (0.005)	1.871 (0.025)
K	1.928 (0.063)	0.1154	0.031 (0.003)	1.897 (0.063)

[a]Number of magnitudes the SN 2001el templates must be shifted to produce the best fits to the SN 2004S data.

[b]From column 4 of Table 8 of Krisciunas et al. (2006).

[c]Adjustments for Galactic extinction, equal to 0.270 mag times the coefficients of column 3. We assumed R_V = 3.1 for Galactic dust and uncertainties of 10 percent.

[d]Values of column 2 minus those in column 4. These are the equivalent light curve template shifts after correcting for the effects of Galactic extinction.

Table 7. Extinction solutions[a]

Filters	R_V	A_V[b]	$\Delta\mu$[c]
$BVRI$	2.51 (+0.50,−0.36)	0.534 (+0.075,−0.057)	1.994
$BVRIJ$	2.02 (+0.30,−0.28)	0.451 (+0.041,−0.043)	1.916
$BVRIJH$	2.14 (+0.24,−0.22)	0.470 (+0.027,−0.026)	1.934
$BVRIJHK$	2.15 (+0.24,−0.22)	0.472 (+0.025,−0.025)	1.936

[a]Numbers in parentheses are upper and lower 1-σ errors.

[b]Difference of V-band extinction of SNe 2001el and 2004S, in magnitudes.

[c]Implied difference of distance moduli of SNe 2001el and 2004S, in magnitudes.

Fig. 1.— Maximum light spectra of SN 2001el (2001 October 1), obtained with the VLT + FORS1, and SN 2004S (2004 February 6), obtained with the CTIO 1.5-m. The SN 2004S spectrum is shifted by an artibrary amount for display purposes.

Fig. 2.— MCG -05-16-021, SN 2004S, and the field stars nearby. This 3.′1 by 3.′1 finder was made from a V-band exposure obtained with the CTIO 1.3-m telescope on 2004 February 17 UT. (Note: a different figure will appear in the AJ version of this paper.)

Fig. 3.— *UBVRI* photometry of SN 2004S from 3 to 110 days after T(B_{max}). The circles are data obtained with the CTIO 1.3-m telescope, while the triangles are data obtained with the Siding Spring 2.3-m telescope. The templates are based on the light curves of SN 2001el and have been adjusted in the Y-direction to minimize the χ^2 statistic of the fits to the data of SN 2004S obtained with the CTIO 1.3-m.

Fig. 4.— $YJHK$ photometry of SN 2004S to 90 days after maximum light. The circles are data obtained with the CTIO 1.3-m telescope, while the triangles are data from one night with the 3.58-m TNG. The solid black lines are fits to the data of SN 2001el, adjusted in the Y-direction to minimize the χ^2 statistic of the fits to the CTIO 1.3-m data. The dashed blue lines are estimates of a linear decline of the light curves. At t = 69 and 76 days the H-band data are 4.3σ and 5.3σ above the dashed line. At t = 76 days the J-band datum is 2.8σ above the dashed line. This late time photometry is evidence that SN 2004S exhibited a third hump in its light curve, in agreement with the prediction of Kasen (2006).

Fig. 5.— Residuals of the *UBVRI* data of SN 2004S and the light curve templates based on fits to the data of SN 2001el. "Δ" is in the sense "data minus templates".

Fig. 6.— Residuals of the JHK data of SN 2004S and the light curve templates based on fits to the data of SN 2001el. "Δ" is in the sense "data minus templates".

Fig. 7.— All of our V- and H-band of SN 2004S from Tables 3 and 4. The photometric errors are smaller than or equal to the size of the points.

Fig. 8.— Optical spectra of SN 2004S from 1.7 to 42.5 rest frame days after the time of maximum light. The number of days since B-band maximum is given at the right hand side.

Fig. 9.— Comparison of optical spectra of various Type Ia SNe and SN 2004S.

Fig. 10.— Evolution of the high-velocity blue shifted Ca absorption from 1 to 18 days after the time of maximum light of SNe 1999ee, 2001el, and 2004S.

Fig. 11.— Comparison of near-IR spectra of the Type Ia SNe 2004S, 1999ee, and 1998bu at 15 days after maximum light.

Fig. 12.— $V - J$, $V - H$, and $V - K$ color curves of SN 2004S. The solid lines are the zero-reddening loci based on eight Type Ia SNe of Krisciunas et al. (2000), adjusted by the corresponding color excesses to minimize χ^2.

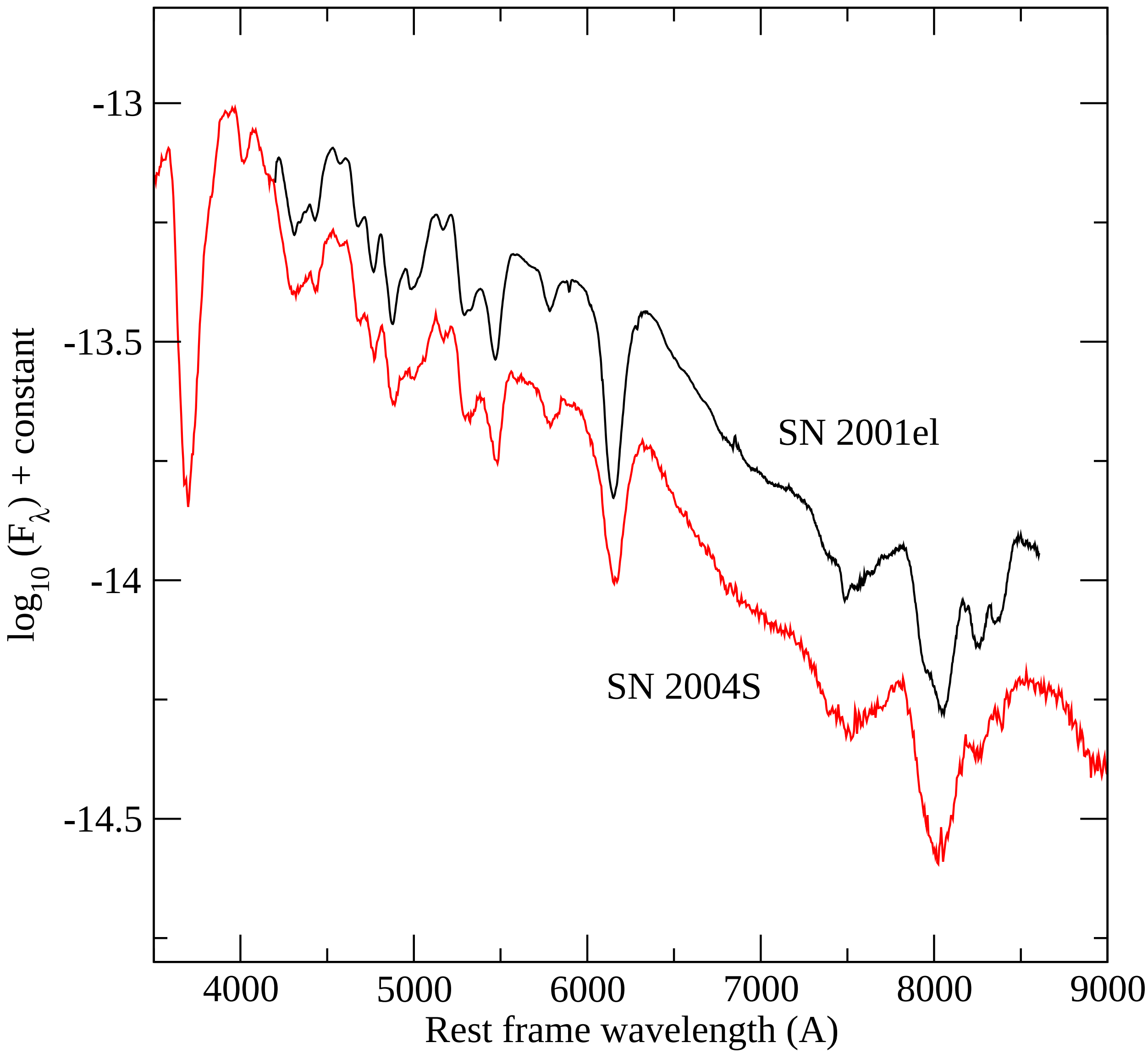
Fig. 13.— $V - J$, $V - H$, and $V - K$ color curves of SN 2004S. The solid lines are fits to the corresponding data of SN 2001el and adjusted in the Y-direction to minimize the χ^2 statistic.

Fig. 14.— Values from column 5 of Table 6 vs. the wavelengths of the photometric bands. In the limit as the wavelength tends to infinity we obtain a measure of the difference of the distance moduli of SNe 2001el and 2004S (the horizontal dashed line). The (red) solid line is the (R_V = 2.15) solution that minimizes the χ^2 statistic of the fit. The (blue) dashed line shows that normal Galactic dust with R_V = 3.1 does not fit the data points as well.

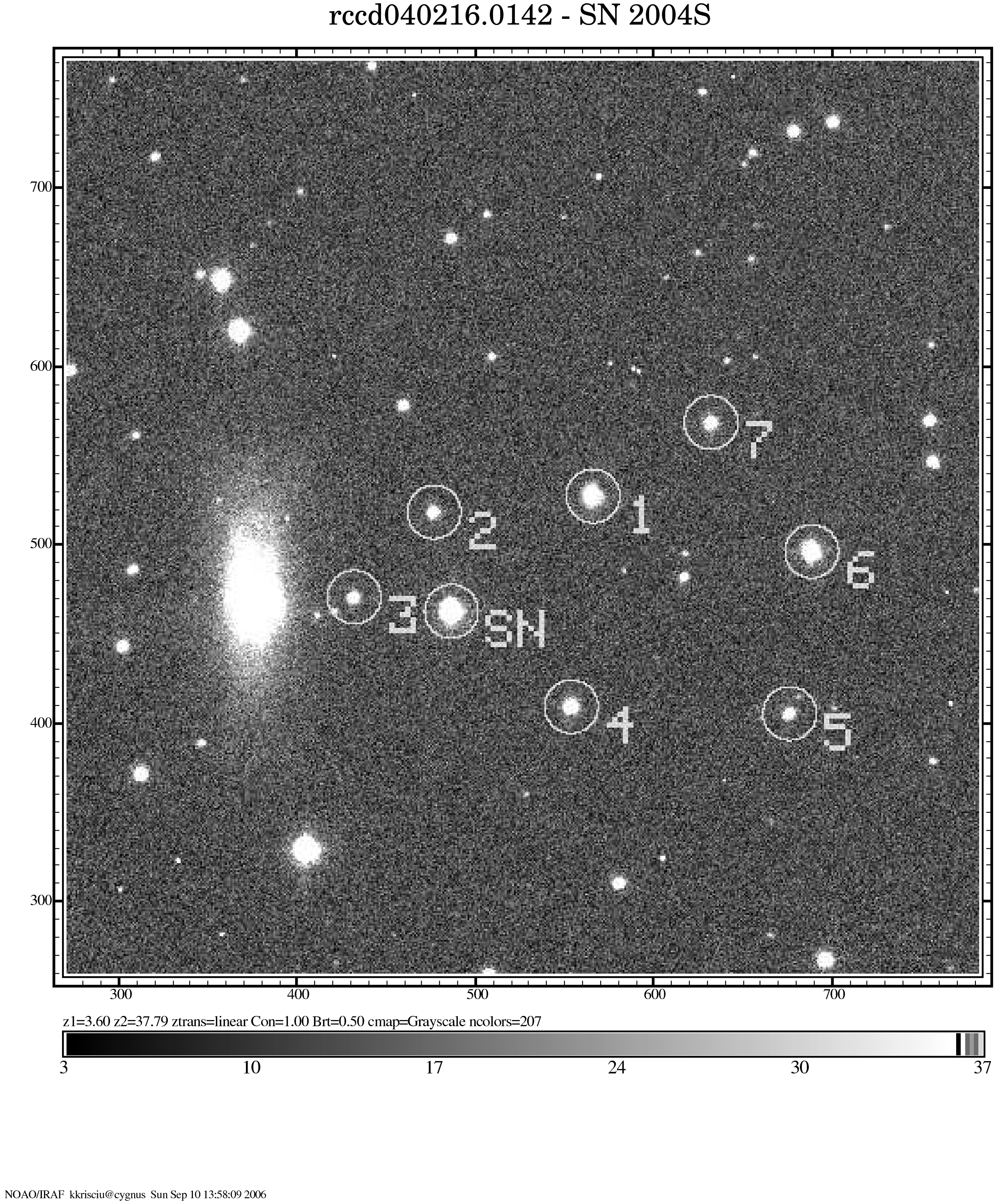
Fig. 15.— Contours in the A_V-R_V plane. The X-axis represents possible values of the *difference* of the host galaxy V-band extinction of SN 2001el vs. SN 2004S. The Y-axis represents the value of R_V pertaining primarily to the dust in the host of SN 2001el. We plot the 68 percent contour levels for three solutions, using 4, 5, and 7 filter photometry, respectively.

Fig. 16.— Correlation of uncertainty in R_V vs. uncertainty in A_V. We have simulated the recovery of the host galaxy extinction for 30,000 SNe. For this simulation we picked at random values of R_V and A_V, then recovered them using $BVRIJ$ photometry. Here we assumed a V-band photometric accuracy of ± 0.02 mag. Other bands had correspondingly larger or smaller errors on the basis of our actual SN 2001el and SN 2004S data.

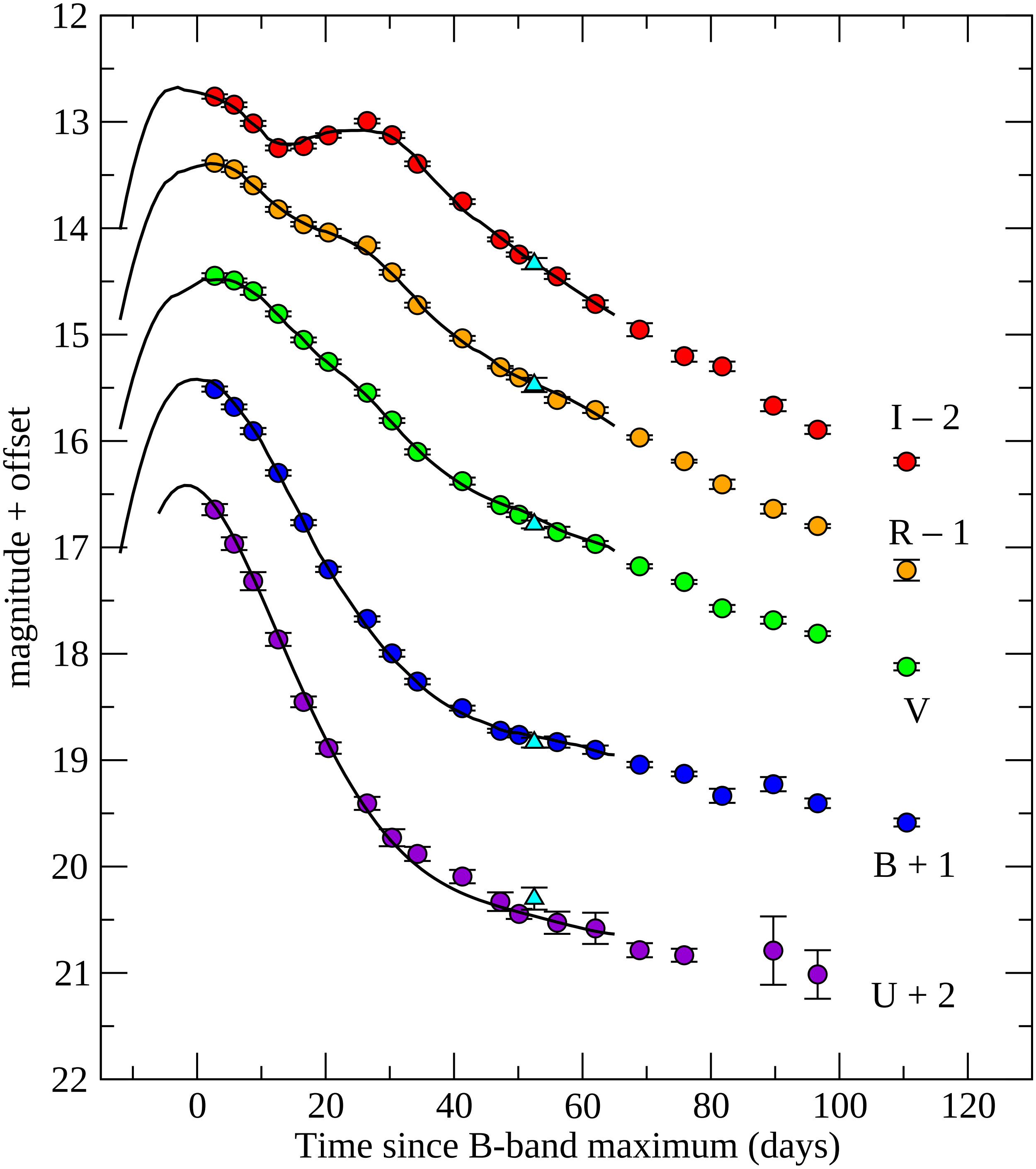
Fig. 17.— The uncertainty in the distance modulus for Type Ia SNe as a function of the photometric accuracy and the number of filters used to determine the photometric solution. The dotted line corresponds to the photometric accuracy. It is not possible to recover a distance modulus more accurately than the level of accuracy of the photometry.



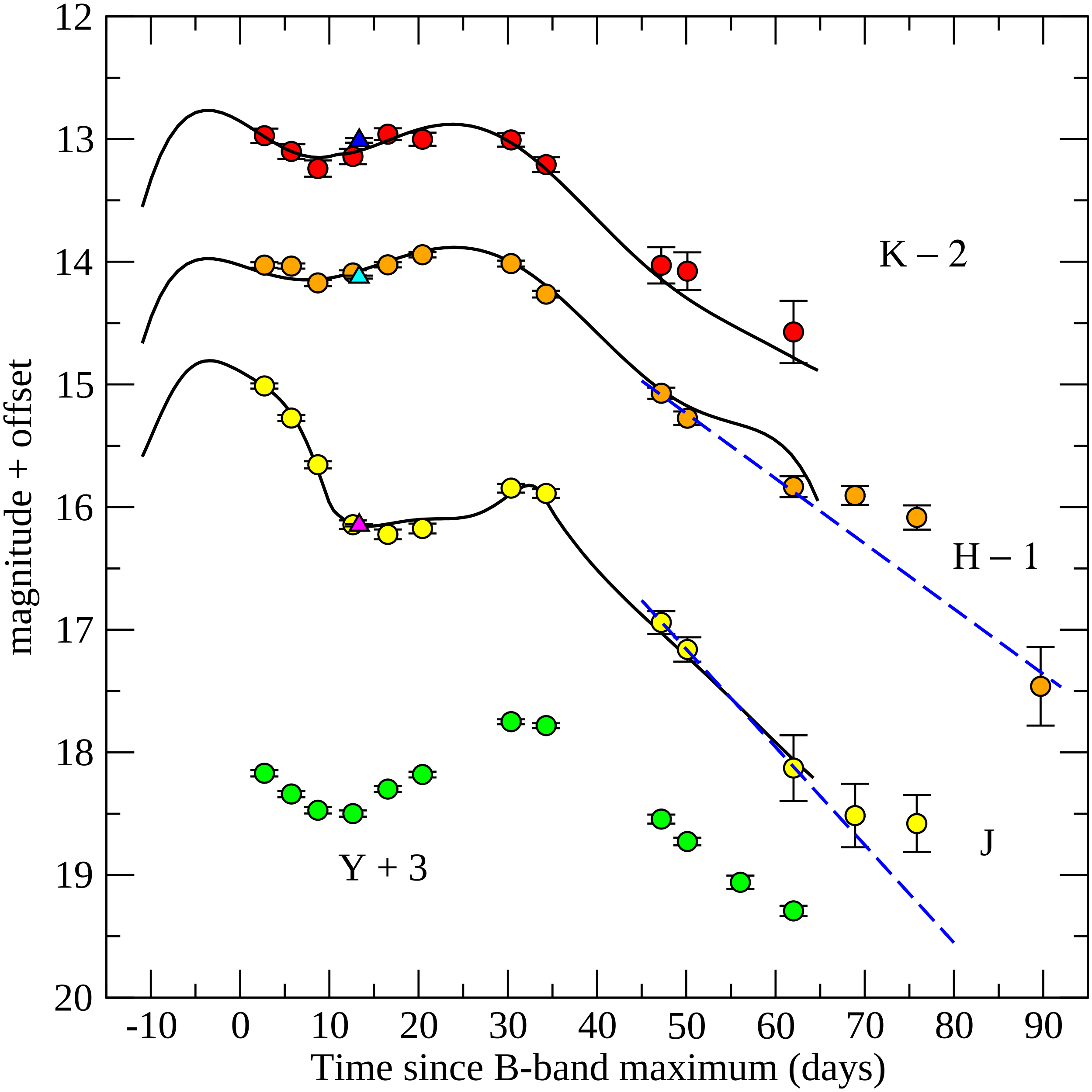
Krisciunas *et al.* Fig. 1



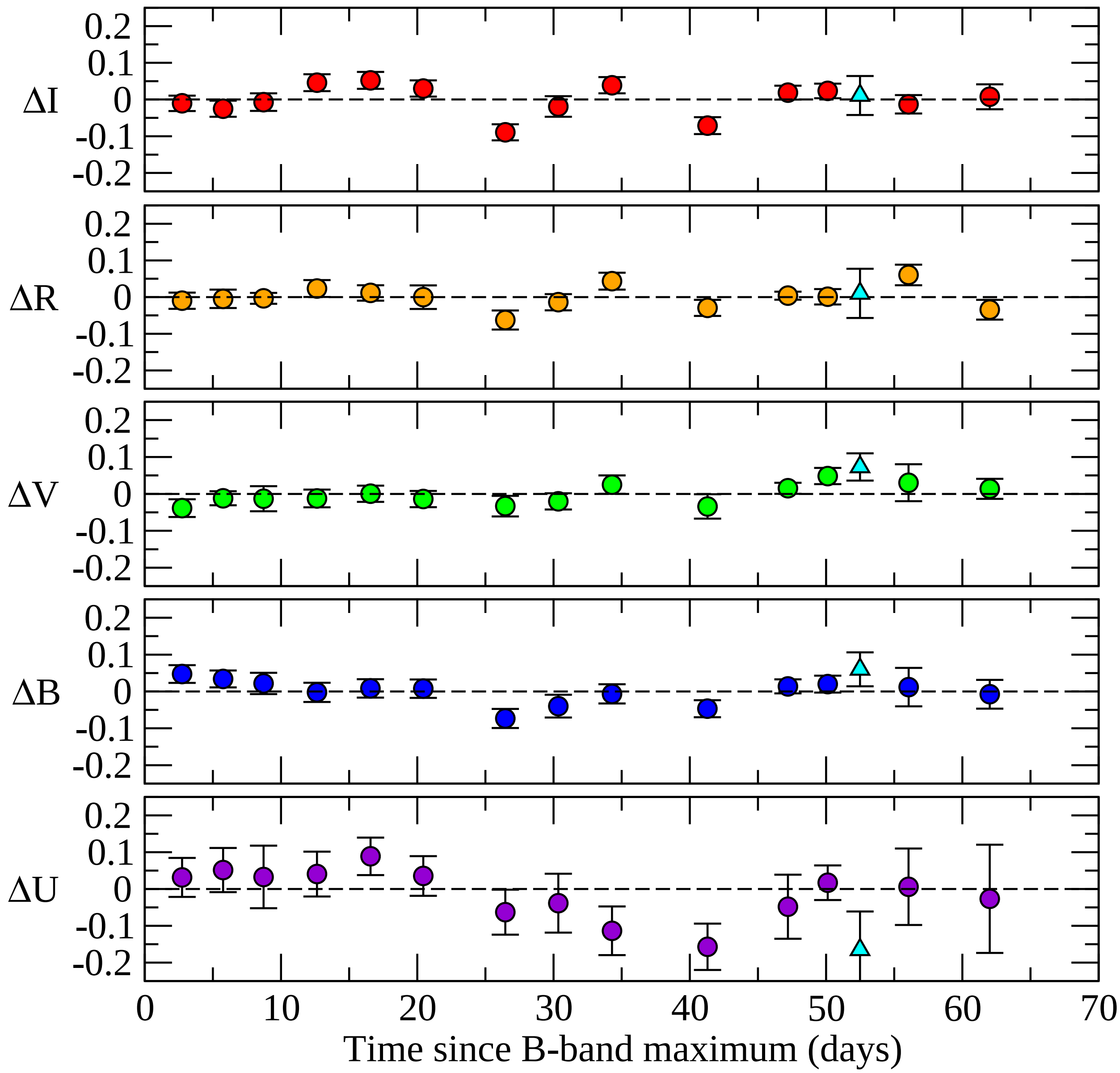
Krisciunas *et al.* Fig. 2



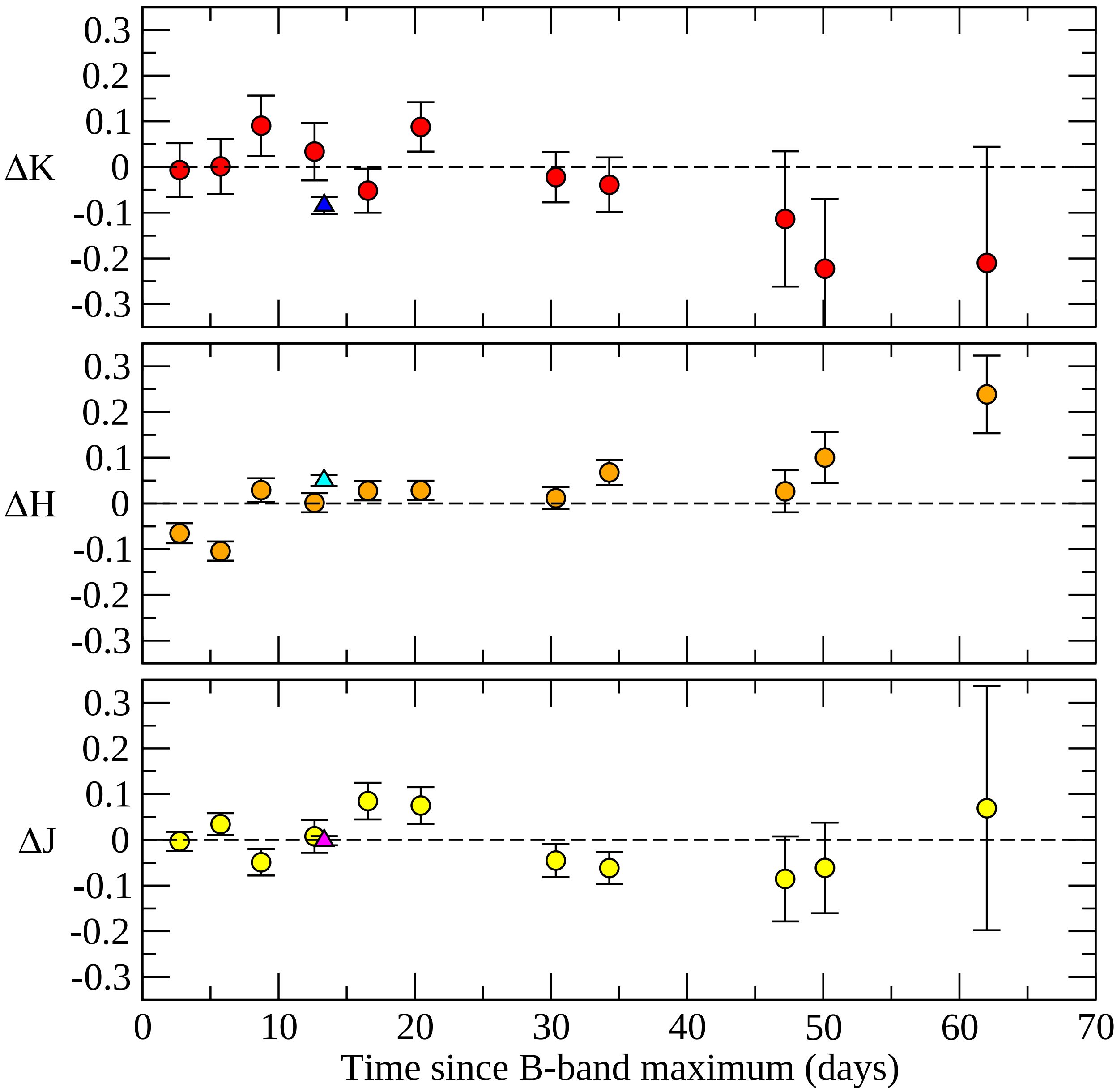
Krisciunas *et al.* Fig. 3



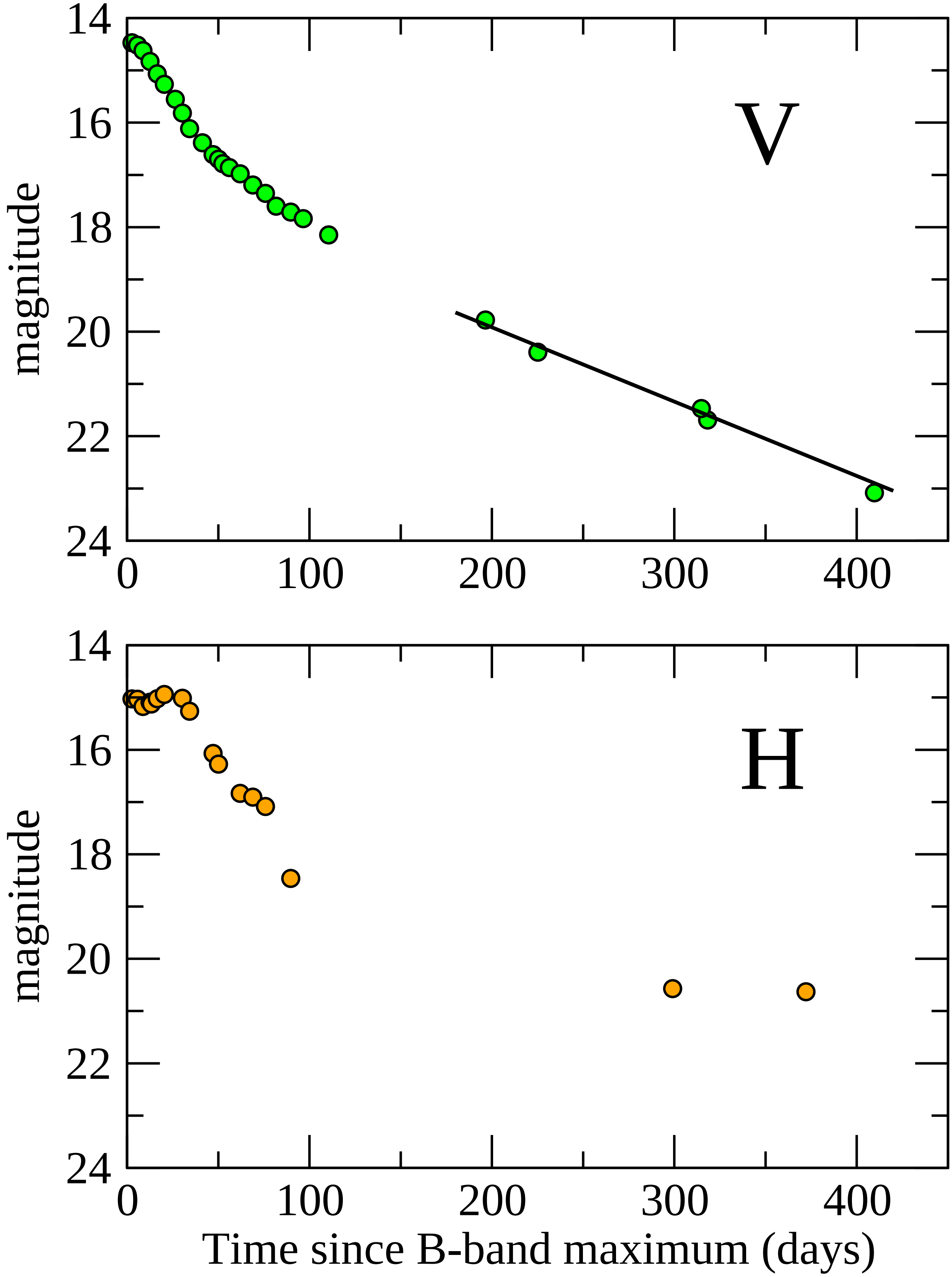
Krisciunas *et al.* Fig. 4



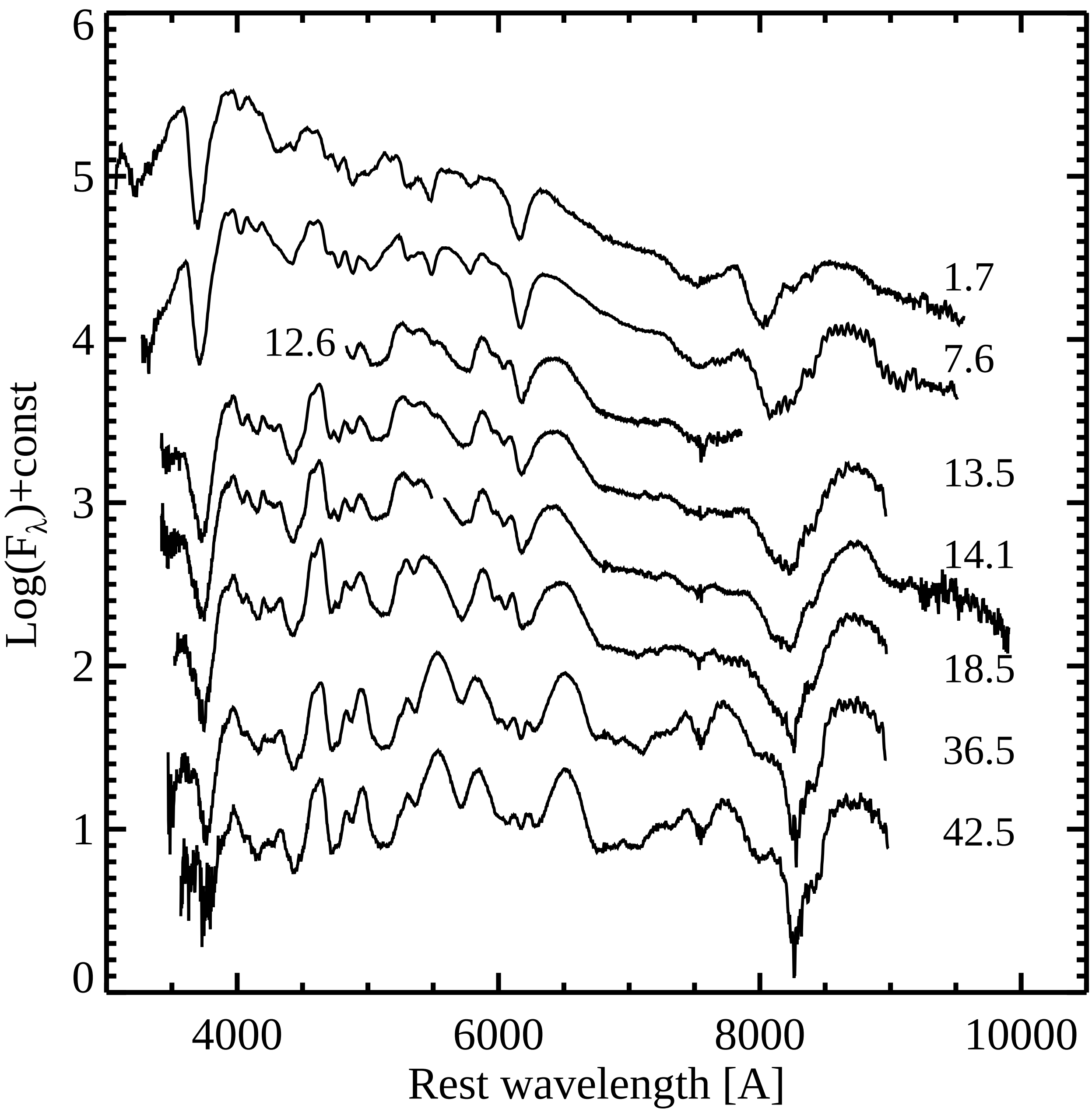
Krisciunas *et al.* Fig. 5



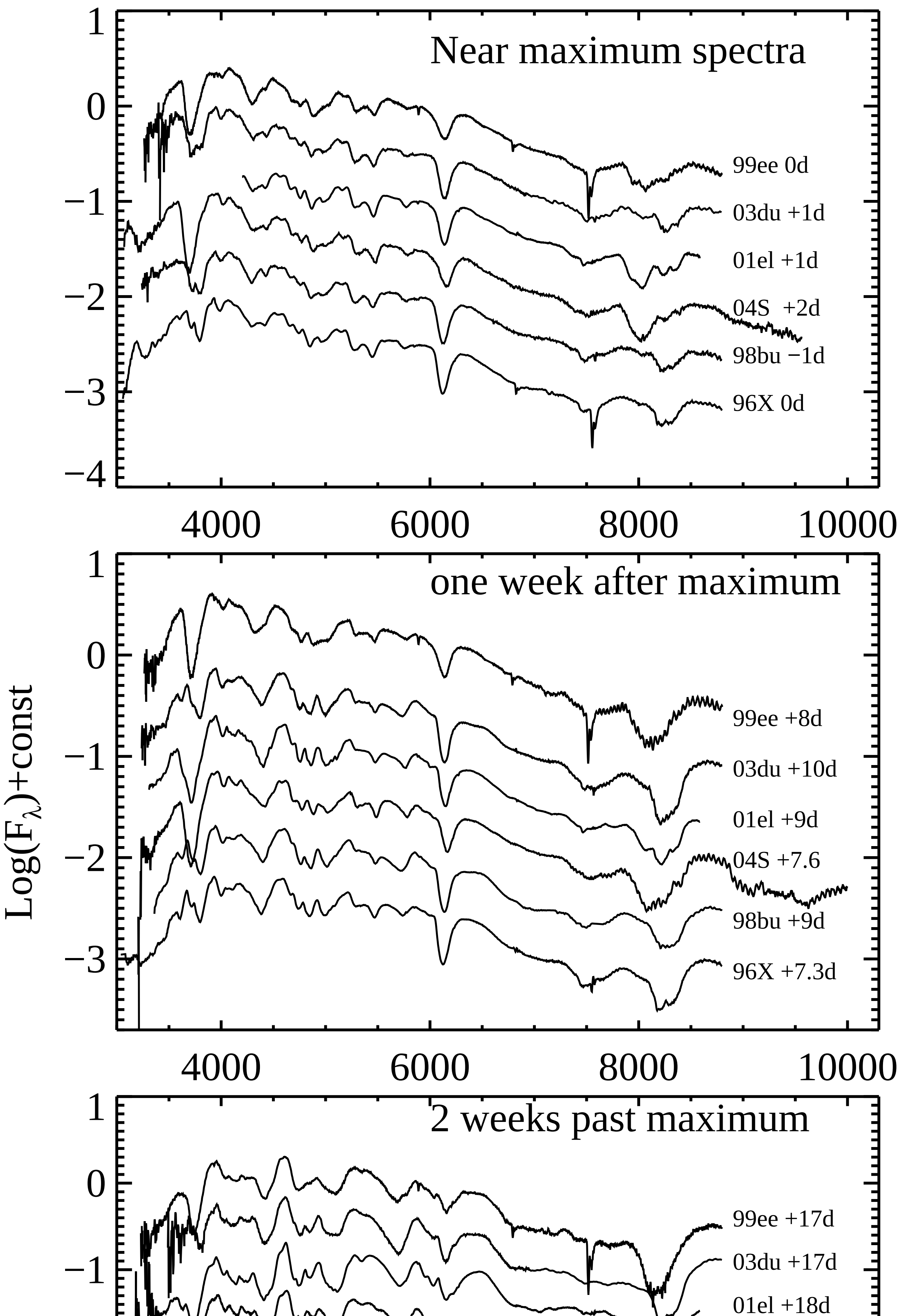
Krisciunas *et al.* Fig. 6



Krisciunas *et al.* Fig. 7



Krisciunas *et al.* Fig. 8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01el +1d
04S +2d
98bu −1d
96X 0d
one week after maximum
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03du +10d
01el +9d
04S +7.6
98bu +9d
96X +7.3d
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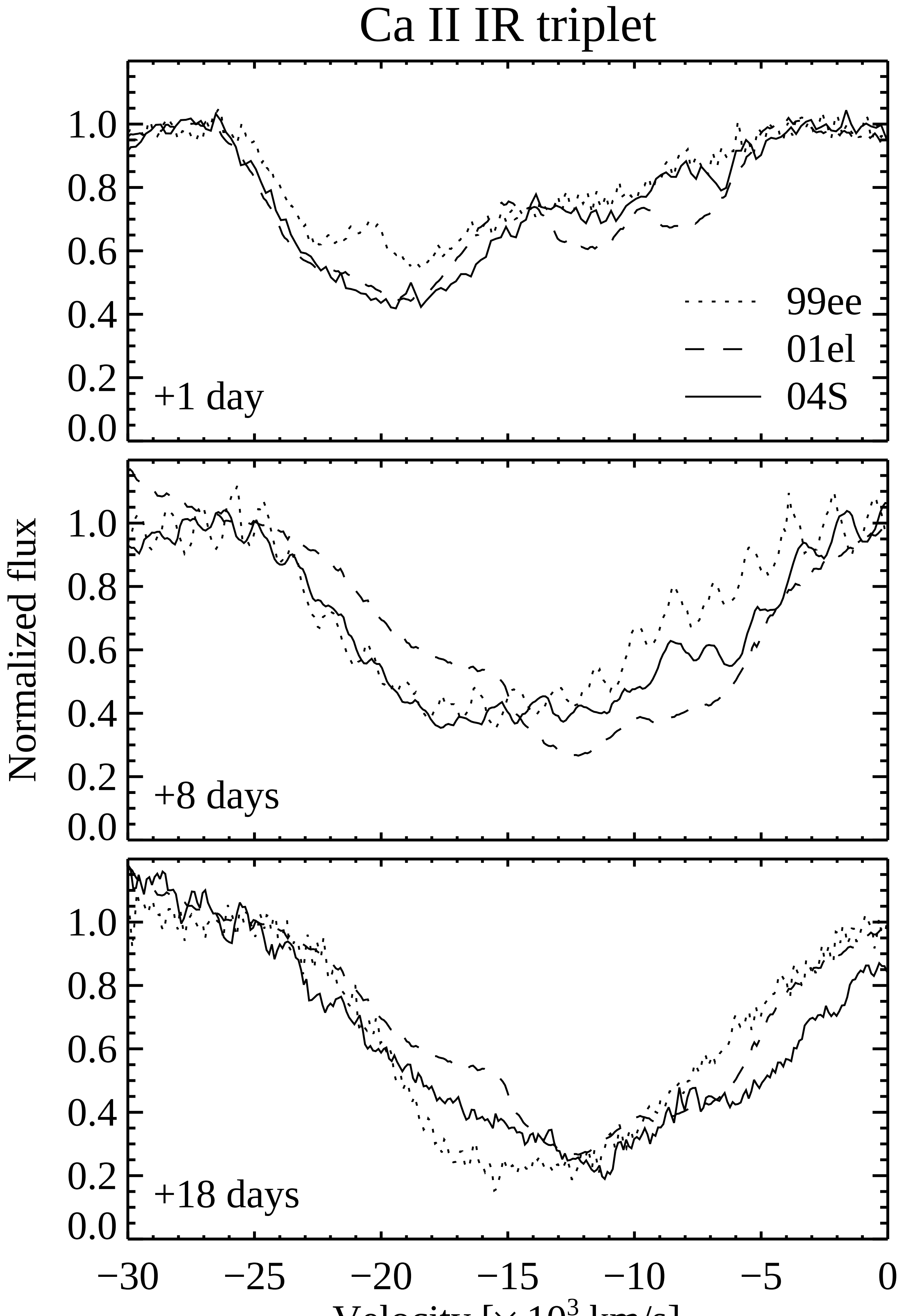
6000
8000
10000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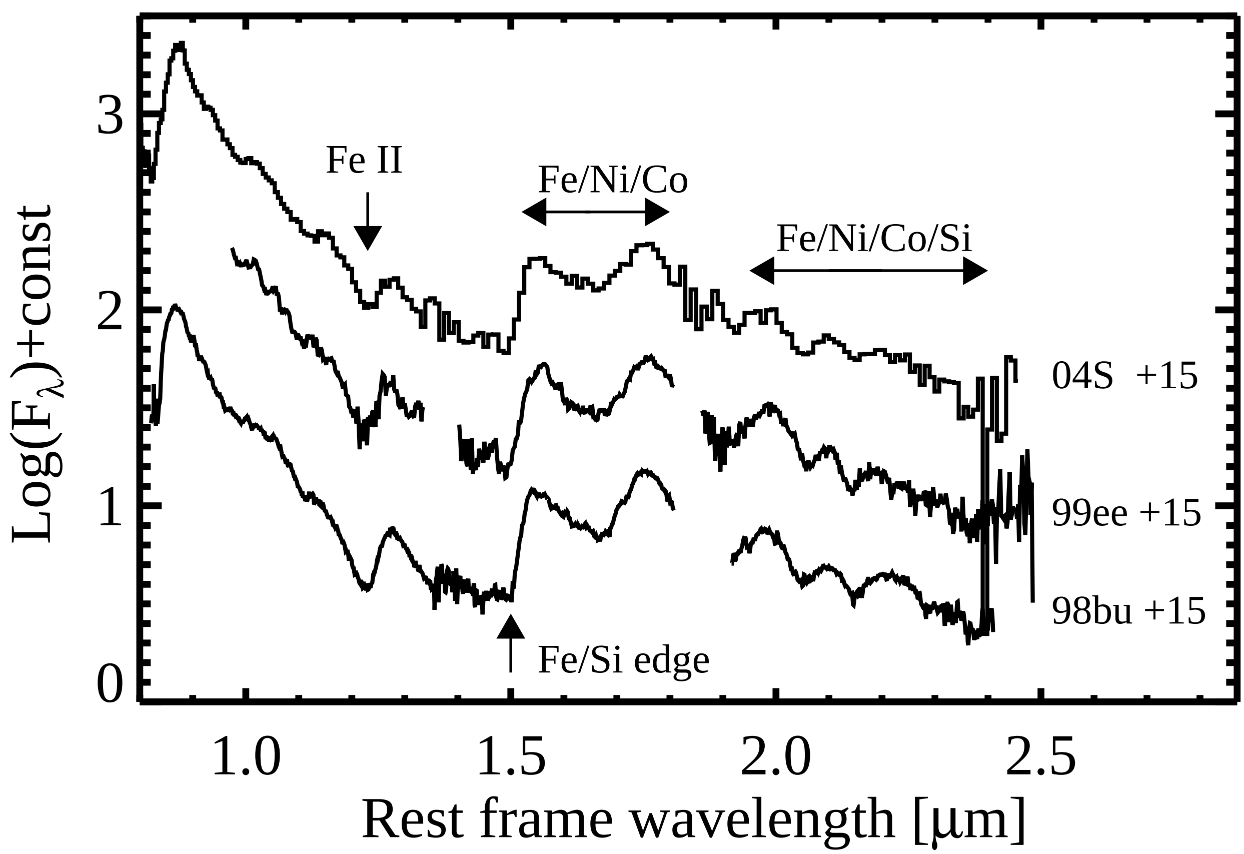
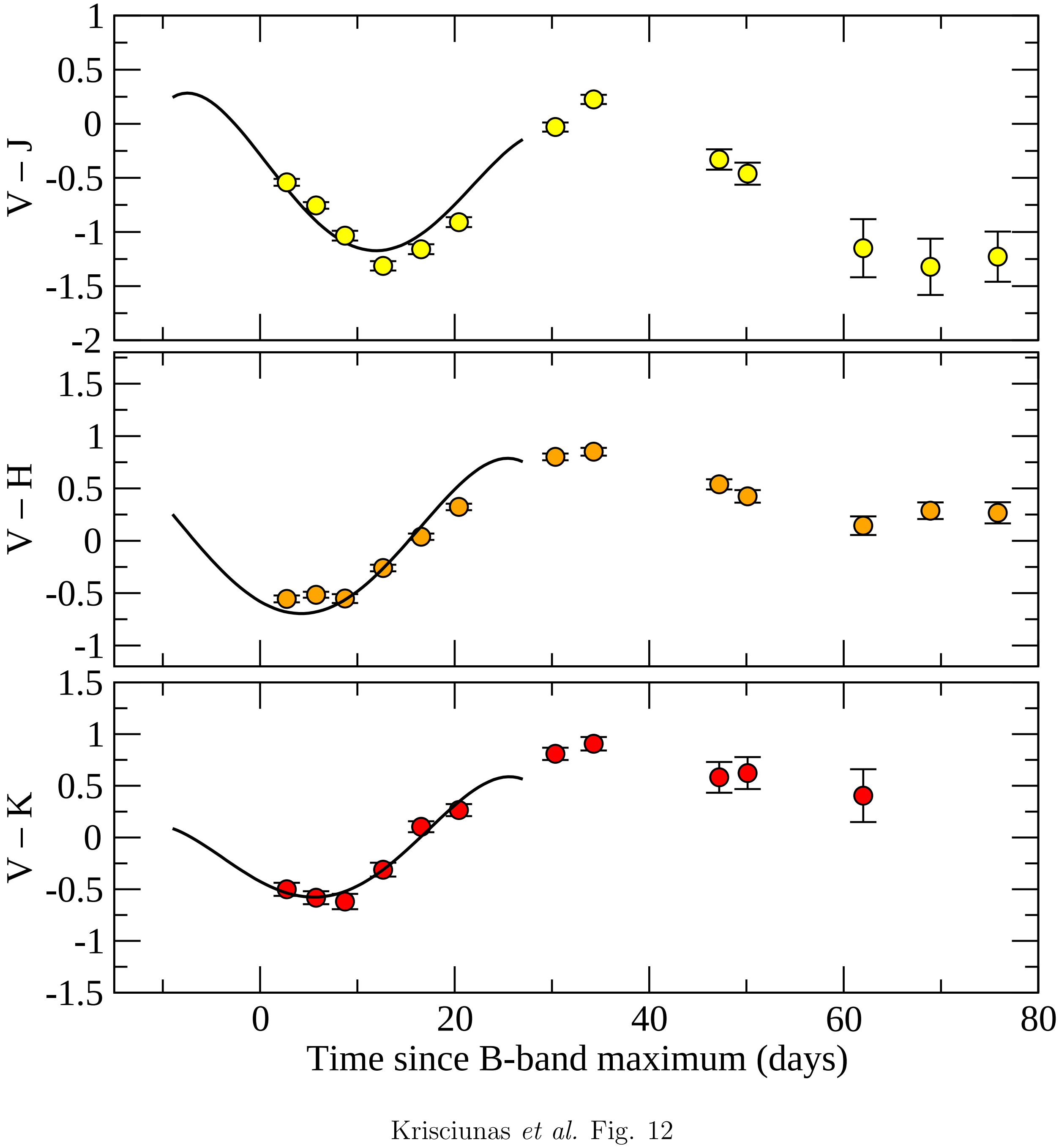
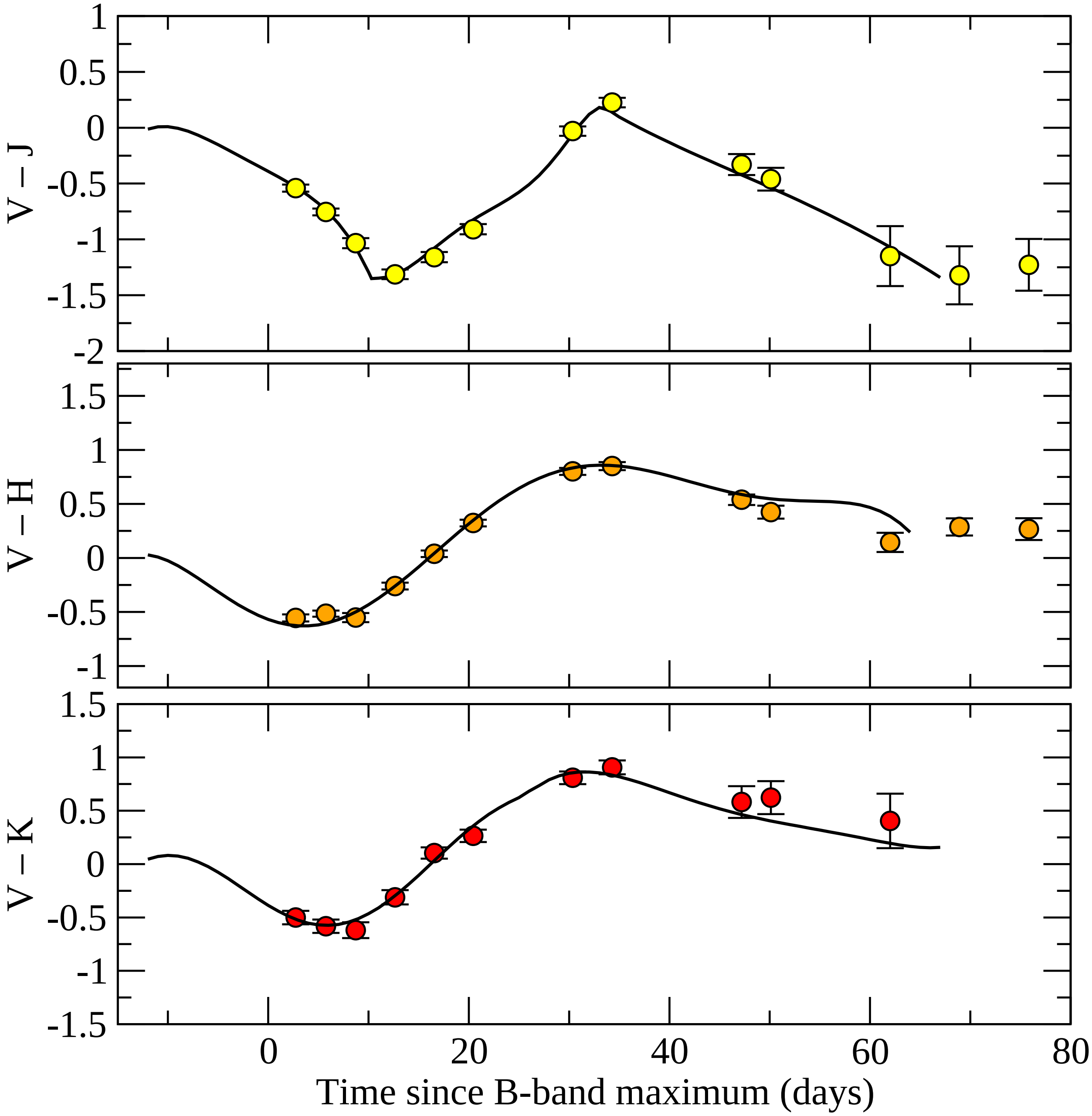


Krisciunas *et al.* Fig. 11



Krisciunas *et al.* Fig. 12



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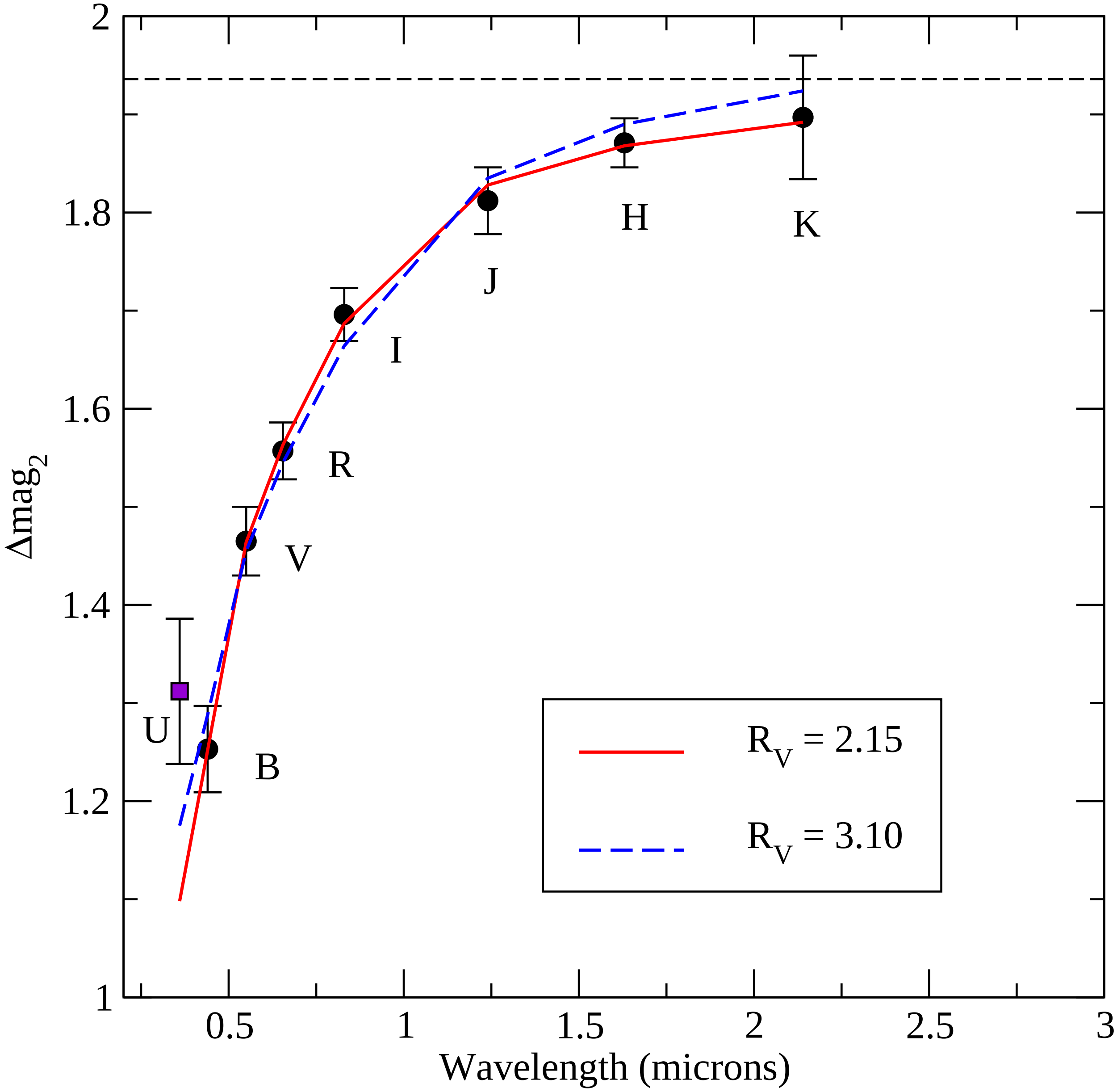
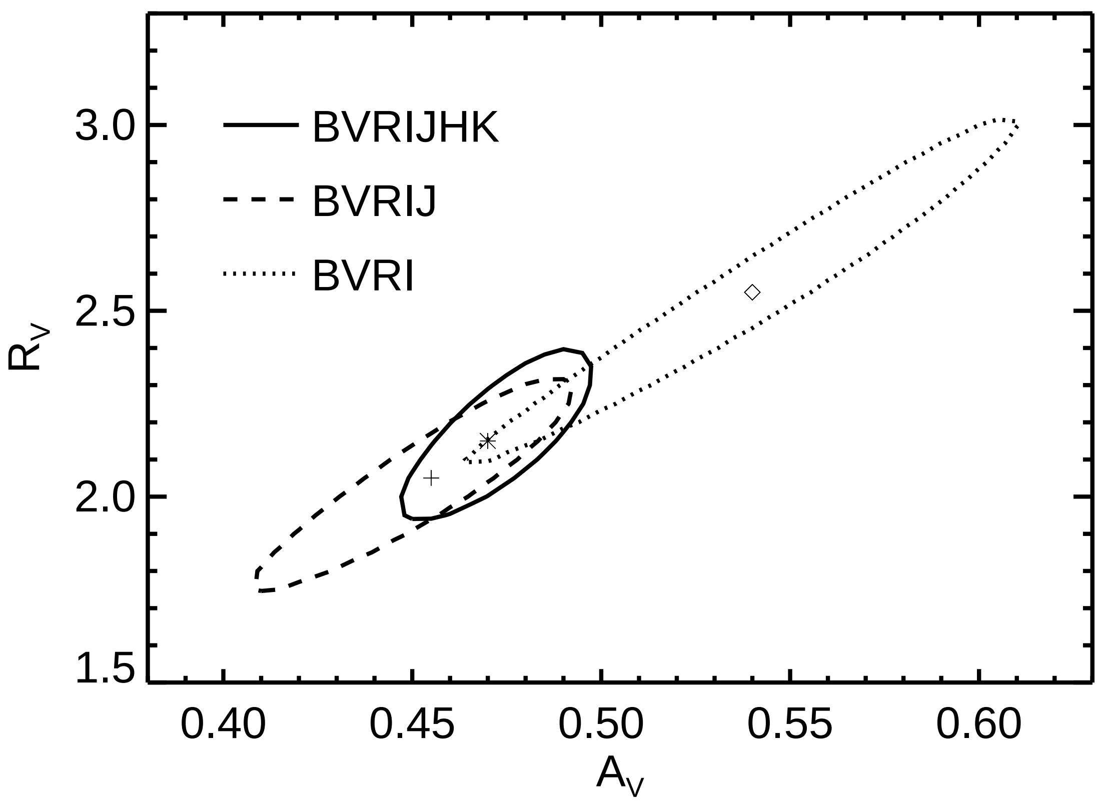
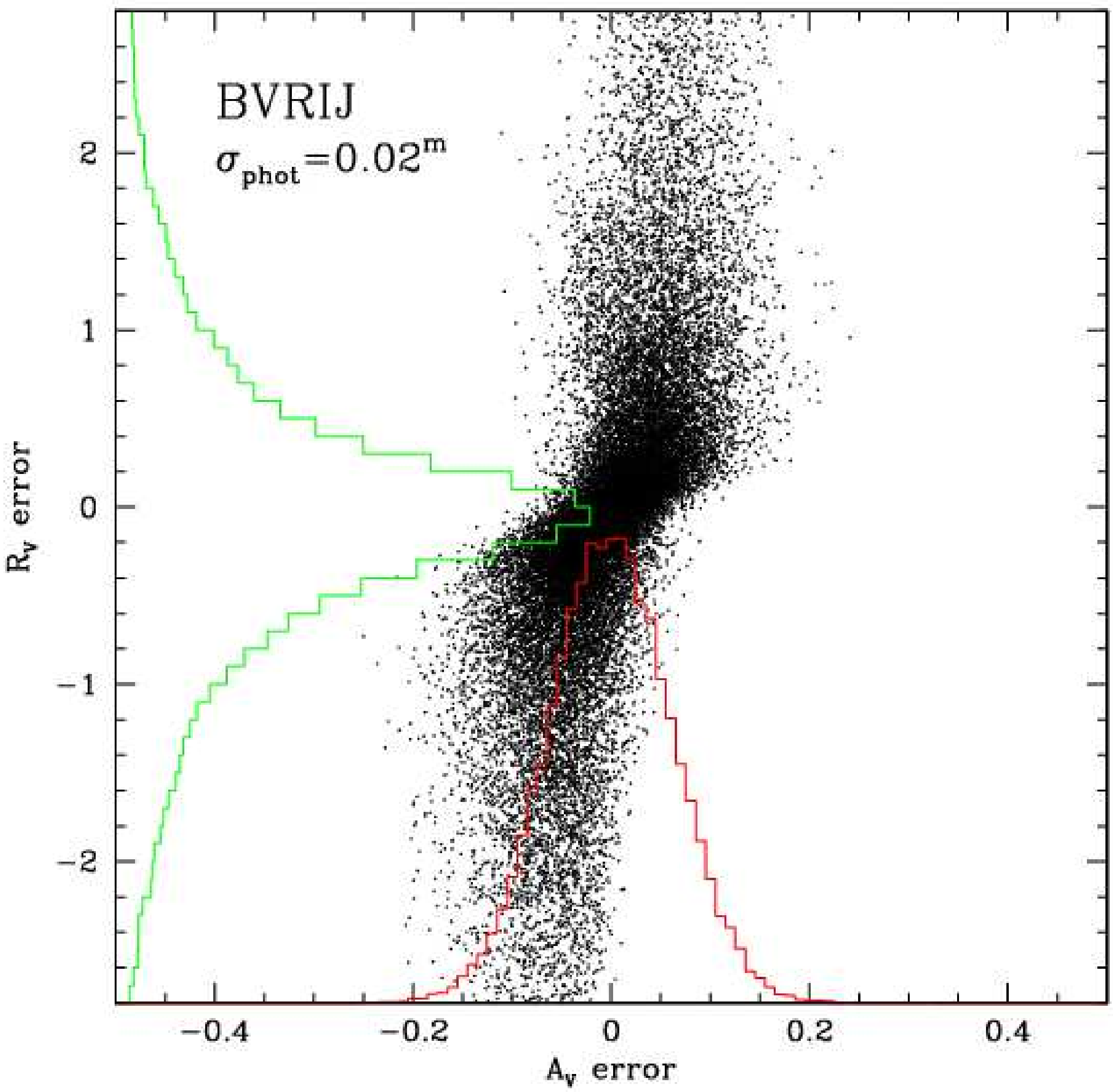


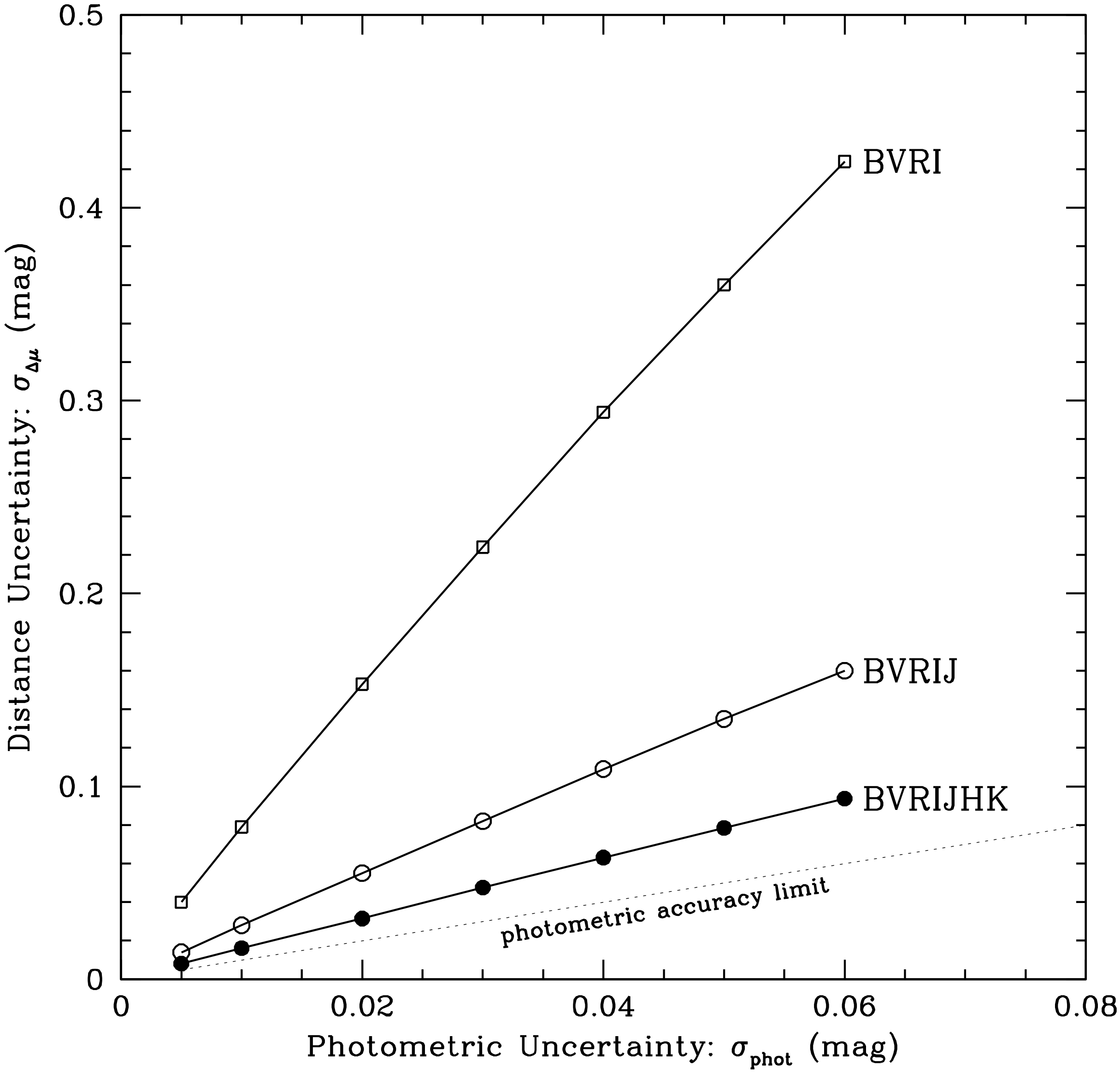
Krisciunas *et al.* Fig. 14



Krisciunas *et al.* Fig. 15



Krisciunas *et al.* Fig. 16



Krisciunas *et al.* Fig. 17