Fixing the U-band photometry of Type Ia supernovae[1]

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ABSTRACT

We present previously unpublished photometry of supernovae 2003gs and 2003hv. Using spectroscopically-derived corrections to the U-band photometry, we reconcile U-band light curves made from imagery with the Cerro Tololo 0.9-m, 1.3-m and Las Campanas 1-m telescopes. Previously, such light curves showed a 0.4 mag spread at one month after maximum light. This gives us hope that a set of corrected ultraviolet light curves of nearby objects can contribute to the full utilization of rest frame U-band data of supernovae at redshift ∼0.3 to 0.8. As pointed out recently by Kessler et al. in the context of the Sloan Digital Sky Survey supernova search, if we take the published U-band photometry of nearby Type Ia supernovae at face value, there is a 0.12 mag U-band anomaly in the distance moduli of higher redshift objects. This anomaly led the Sloan survey to eliminate from their analyses all photometry obtained in the rest frame U-band. The Supernova Legacy Survey eliminated observer frame U-band photometry, which is to say nearby objects observed in the U-band, but they used photometry of high redshift objects no matter in which band the photons were emitted.

Subject headings: supernovae: individual (SN 2003gs), (SN 2003hv) — techniques: photometric

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1. Introduction

Type Ia supernovae (SNe) are very useful standardizable candles for extragalactic astronomy and observational cosmology. A Type Ia SN is often thought to be a carbon-oxygen white dwarf that approaches the Chandrasekhar limit of 1.4 $M_{\odot}$ owing to mass transfer from a close main sequence stellar companion or giant star (Whelan & Iben 1973; Livio 2000). Some Type Ia SNe might be mergers of two white dwarfs (Webbink 1984; Howell 2011; Schaefer & Pagnotta 2012). These supernovae provided the first observational evidence that the expansion of the universe is accelerating (Riess et al. 1998; Perlmutter et al. 1999); three members of the two key groups that carried out this work were awarded the Nobel Prize in Physics in 2011.

Three of the most important datasets containing U-band photometry of Type Ia SNe are the "CfA2 sample" of $UBVRI$ photometry of 44 objects by Jha et al. (2006), the "CfA3 sample" of 185 objects (Hicken et al. 2009), and the recent "CfA4 sample" of 94 objects (Hicken et al. 2012). The "CfA2 sample" was the first large dataset containing U-band light curves of Type Ia SNe. The "CfA4" sample contains U-band data of 14 objects and u' photometry 12 other objects. These datasets were produced by astronomers at the Harvard-Smithsonian Center for Astrophysics.

Of the Hicken et al. (2009) sample, 31 objects have U-band maxima, values of the decline rate parameter $\Delta m_{15}(B)$, and redshifts greater than $z = 0.01$. The U-band Hubble diagram shows a scatter of about $\pm$ 0.25 mag. Some of the scatter may be due to the asymmetric nature of some of these explosions, in which case what we see is a function of the viewing angle (Maeda et al. 2010). Some of the scatter may be due to incorrect extinction corrections for dust along the line of sight, or differences amongst the various U-band filters used. The larger scatter in the U-band Hubble diagram could also be due in part to spectroscopic differences that correlate with metallicity, galaxy type, and redshift. Foley et al. (2008a), Foley et al. (2012), and Maguire et al. (2012) have provided evidence that higher redshift Type Ia SNe have different spectral energy distributions in the ultraviolet than nearby objects.

By comparison, the scatter in the Hubble diagram is $\pm$ 0.15 mag or better for other optical or near-IR bands (Phillips et al. 1999; Folatelli et al. 2010; Kattner et al. 2012; Krisciunas 2012). If we observe Type Ia SNe beyond a redshift of $z \approx 0.03$, the effect of peculiar velocities diminishes, and the observed scatter of the absolute magnitudes is reduced to $\pm$ 0.12 mag in the near-IR J- and H-bands (Barone-Nugent et al. 2012). This corresponds to a $\pm$ 6 percent uncertainty in distance.

For an object at, say, redshift 0.7, the photons we observe in the R-band ($\lambda \approx 0.65\mu$m)were emitted at ultraviolet wavelengths. Medium deep SN surveys such as ESSENCE (Wood-Vasey et al.

2007), the Supernova Legacy Survey (SNLS, Conley et al. 2011), and the Sloan Digital Sky Survey (SDSS, Kessler et al. 2009) include a significant percentage of restframe ultraviolet observations. A tough problem arises. Kessler et al. (2009) show that if we include nearby objects observed in the U-band along with the higher redshift objects whose U-band light has been redshifted to longer wavelength passbands, there is a 0.12 mag shift in the distance moduli of the high-redshift sample, which leads to a 0.3 shift of the cosmic equation of state parameter w. This is a huge shift! SDSS-II decided to eliminate from analysis all photometry that originated in the rest-frame UV. SNLS, on the other hand, used photometry of high redshift objects even if the photons were emitted in the U-band, but eliminated U-band photometry of nearby objects. We note the 0.12 mag anomaly in the distance moduli may be due to a $\sim$0.05 mag shift in the U-band photometry of objects in the CfA2 sample (Kessler et al. 2009, p. 67); such a systematic error in the CfA2 U-band magnitudes is actually smaller than the typical rms scatter of fully corrected U-band light curves (see below). (Note that the CfA3 and CfA4 samples were published after the SDSS analysis.)

In §10.1.3 of their paper Kessler et al. (2009) list five possibilities to explain the U-band anomaly: 1) redshift dependent flux; 2) selection effects for the nearby sample; 3) problems with the lightcurve fitting model(s); 4) photometric calibration errors; and 5) differences in the UV spectral energy distributions of the supernovae. We remind the reader that most photometric calibration errors are of two kinds: 1) problems with the standard stars; or 2) insufficient knowledge of the effective passbands, leading effectively to multiple "systems". There appears to be unexplained variables in the CfA2 sample. The present paper primarily addresses the passband issue.

If we combine observations of a particular SN obtained with different cameras on different telescopes (or even the same camera on the same telescope, but with physically different filters), there can be significant systematic differences in the light curves, particularly in the U-band. Figure 1 shows that one month after maximum light the U-band data has spread out by 0.4 mag for two particular objects. This is the reason Krisciunas et al. (2009) did not publish the U-band photometry of SN 2003gs obtained with the Las Campanas Observatory (LCO) 1-m telescope. At that time we could not resolve the telescope to telescope differences. The one hopeful feature of the uncorrected U-band light curves of SNe 2003gs and 2003hv is that the CTIO 0.9-m and LCO 1-m photometry is offset from the CTIO 1.3-m photometry by about the same amounts for each object.

In this paper we show that spectroscopically-derived corrections to U-band photometry can effectively cure the problem that is so obvious in Figure 1. If appropriate S-corrections are applied to a specific set of $\sim$30 U-band light curves of nearby Type Ia SNe, we might be able to resolve the U-band anomaly that so affected the analysis of SDSS-II.

2. Photometric reduction and the method of S-corrections

On some given night the standardized magnitudes of Landolt (1992) standards may be related to instrumental magnitudes and instrumental colors as follows:

$$U = u - k_U X + ct_U(u - b) + zp_U \ , \tag{1}$$

$$B = b - k_B X + ct_B(b - v) + zp_b \ , \tag{2}$$

$$V = v - k_V X + ct_V(b - v) + zp_V \ , \tag{3}$$

$$R = r - k_R X + ct_R(v - r) + zp_R \ , \tag{4}$$

$$I = i - k_i X + ct_I(v - i) + zp_I \ , \tag{5}$$

where k's are atmospheric extinction coefficients, measured in magnitudes per airmass, X is the airmass (basically the secant of the zenith angle), ct's are color terms, and zp's are zero points. Typical extinction coefficients at Cerro Tololo or Las Campanas are $k_U = 0.51$, $k_B = 0.26$, $k_V = 0.15$, $k_r = 0.11$, and $k_i = 0.06$ magnitudes per airmass. The zero points and extinction vary from night to night, even if the nights are photometric, and the U-band parameters can even vary over the course of a single night.

In Equations 1 through 5 the particular instrumental color used should include the band which is being transformed to catalog magnitudes. For example, we use $v - r$ in Equation 4, but could have just as easily used $r - i$. It would not make sense to use either of these instrumental colors for Equation 1, however.

Mean color terms for the CTIO 1.3-m telescope and ANDICAM from August 2003 through October 2003 were $\mathrm{ct}_U = -0.109$, $\mathrm{ct}_B = +0.054$, $\mathrm{ct}_V = -0.040$, $\mathrm{ct}_R = +0.004$, $\mathrm{ct}_I = -0.067$, with uncertainties of $\pm$ 0.004. For the CTIO 0.9-m telescope $\mathrm{ct}_U = +0.119 \pm 0.007$, and for the LCO 1-m telescope $\mathrm{ct}_U = +0.185 \pm 0.011$ during this time.

The method of spectroscopically derived corrections to the photometry of SNe was first laid out by Stritzinger et al. (2002) and Krisciunas et al. (2003). Basically, we take the nominal filter profiles, determined in the lab or provided by a manufacturer, and multiply those by a number of other functions of wavelength to account for transmission of the light through the Earth's atmosphere, reflection off of aluminum coated mirrors, the effect of any field lenses or a dichroic beamsplitter, and the quantum efficiency of the chip. The nominal effective filter profile is then shifted arbitrarily in wavelength so that synthetic magnitudes of standard stars reproduce the photometric color terms that one measures directly doing photometry with a particular telescope and camera. Krisciunas et al. (2003) and Krisciunas et al. (2004) show the $BVRI$ S-corrections for the CTIO 1.3-m and 0.9-m telescopes. The numerical values of these corrections are added to appropriate standardized magnitudes of Equations 1 to 5 to correct the photometry to what we would have obtained, had we observed with the Bessell (1990) filters.

Figure 2 shows the effective filter profiles of the U-band filters of the CTIO 0.9-m, CTIO 1.3-m, LCO 1-m telescopes and the Bessell (1990) filter prescription (with appropriate atmospheric and CCD chip quantum effiiciencies accounted for). Note how blue the U-filter of the CTIO 1.3-m telescope camera (ANDICAM) is compared to those of the CTIO 0.9-m and LCO 1-m telescopes.

To calculate the U-band S-corrections we used spectra of 50 standard stars by Stritzinger et al. (2005) and calculated synthetic magnitudes using a script written by one of us (N. B.S.) which runs in the IRAF environment.[7] At the short wavelength end, if spectra do not extend to the short wavelength limit of a filter, the flux points are set to zero. This also holds for spectra that do not extend to the long wavelength limit of a filter. These standard star spectra were extended to $\lambda = 3100$ Å in the blue by means of Kurucz stellar atmosphere code, as modified by W. Vacca and P. Massey. See §3 of Stritzinger et al. (2005).

U-band S-corrections for four "normal" Type Ia SNe are shown in Figure 3. For subsequent purposes we adopt the low order polynomial fits to the individual points to correct U-band photometry. Typical uncertainties of the U-band S-corrections are ± 0.03 to 0.04 mag.

We should consider what systematic errors there may be in our synthetic magnitudes and S-corrections owing to SN spectra not extending to the short wavelength limits of the effective filter profiles. Using the Hsiao et al. (2007) SN template spectra truncated at 3200 Å (and not truncated) we can perform some experiments. Owing to truncation at the short wavlength end of the spectra, the systematic errors in the S-corrections are greatest for the ANDICAM U-band filter, as it is the bluest shown in Figure 2. Some of our U-band S-corrections at T(B_{max}) may be too negative by 0.06 mag, diminishing to 0.03 to 0.04 mag

[7]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation (NSF).

afterwards. For the CTIO 0.9-m and LCO 1-m, our S-corrections may be too positive by 0.01 to 0.02 mag. These systematic errors are noticeably smaller than the typical scatter of single-telescope U-band photometry of Type Ia SNe (typically $\pm$ 0.07 mag or greater).

In Figure 3 we also show some S-corrections calculated with the Hsiao templates. For this purpose the templates were warped to match the natural system magnitudes of SNe 1999ee (from the CTIO 0.9-m telescope) and 2002bo (from the Yale-AURA-Lisbon-Ohio telescope at CTIO). In the case of SN 1999ee the template spectra still have excess flux in the two humps at 3050 and 3450 Å relative to the double hump at 3900 to 4050 Å, leading to S-corrections that do not match the values based on actual spectra of SN 1999ee prior to t = 15 d. The agreement for SN 2002bo from $0 \leq t \leq 15$ d is good, however. We conclude that warped Hsiao et al. (2007) templates can be used in the U-band, but with caution.

For SN 1999ee we used spectra from Hamuy et al. (2002); the earliest spectrum extends to λ = 2965 Å while the others extend to 3260 Å. For SN 2001ay we used the "CfA set" of spectra reduced by T. Matheson; these are spectra obtained with the Fred L. Whipple Observatory 1.5-m telescope and the Multiple Mirror Telescope (Krisciunas et al. 2011). For SN 2001el we used spectra obtained by Peter Nugent with the *Hubble Space Telescope* and previously used by Krisciunas et al. (2003) to obtain $BVRI$ S-corrections; these spectra extend to 2950 Å and are shown and discussed by Foley, Filippenko, & Jha (2008b). For SN 2002bo we used the four spectra of Benetti et al. (2004) that extended to 3200 Å in the blue or beyond. For SN 2004S we used two of the spectra discussed by Krisciunas et al. (2007).

As found by Krisciunas et al. (2011) and Baron et al. (2012), SN 2001ay is an unusual object, and perhaps the prototype of a new subclass of Type Ia SNe. It is the most slowly declining Type Ia SN found to date, but it has a normal peak luminosity. Its photometric behavior can be understood in terms of a pulsating delayed detonation model, which gives a relatively rapid rise to maximum light and a very slow decline. These objects are undoubtedly very rare. In Figure 4 we show the U-band S-corrections of SN 2001ay, which are numerically quite different than the corrections based on spectra of four "normal" objects shown in Figure 3.

3. Newly published data

In Table 1 we give fully corrected U-band photometry of SN 2003gs obtained with the Las Campanas Observatory 1-m telescope. Previously, Krisciunas et al. (2009) published U-band photometry without S-corrections from observations with the CTIO 1.3- and 0.9-

m telescopes.[8] Figure 5 shows the fully corrected U-band light curve of SN 2003gs from observations made with these three telescopes. This is a significant improvement compared to the light curve shown in the upper panel of Figure 1. The rms scatter of the U-band photometry is $\pm$ 0.085 mag.

In Table 2 we give S-corrected photometry of SN 2003hv based on 15 nights of observations with the CTIO 1.3-m telescope and ANDICAM. In addition to the field stars used by Leloudas et al. (2009) we needed an extra secondary standard; it is located at right ascension α = 3:04:00.3, declination $\delta = -26$:08:43 (J2000). From observations on four photometric nights in September and October of 2003, we find U= 14.187, B = 14.124, V = 13.577, R = 13.234, I = 12.926 for this star, with internal random errors of $\pm$ 0.005 mag. Without this extra star, which is reasonably bright in the U-band, we could not have accurately calibrated the CTIO 1.3-m U-band data obtained on non-photometric nights.

Figure 6 shows the S-corrected light curves of SN 2003hv based on data from the LCO 1-m, CTIO 1.3- and 0.9-m telescopes. Leloudas et al. (2009) previously published data without the S-corrections. G. Leloudas kindly provided the $BVRI$ data with the S-corrections. Now the U-band light curve of SN 2003hv is greatly improved compared to the light curve shown in the lower panel of Figure 1. The rms scatter of the U-band photometry is $\pm$ 0.074 mag.

SNe 2003gs and 2003hv were reasonably fast decliners, with $\Delta m_{15}(B)$ = 1.83 and 1.61 mag, respectively. As a result, we would expect them to be subluminous in optical passbands and intrinsically red. Figure 7 shows the $U-B$ colors of SNe 2003gs and 2003hv. For SN 2003gs, E($U-B$) = 0.025 mag. This fast declining object clearly had much redder $U-B$ colors than SN 2003hv. SN 2003hv was unreddened in its host, and we have subtracted off a small amount of reddening due to Milky Way dust (E($U-B$) = 0.011 mag), based on the reddening maps of Schlegel, Finkbeiner, & Davis (1998), as corrected by Schlafly & Finkbeiner (2011).

We may compare the $U-B$ color curves of SNe 2003gs and 2003hv to loci shown in Figure 45 of Kessler et al. (2009). They show color curves for three values of the Multi-color Light Curve Shape parameter Δ.[9] Figure 45 of Kessler et al. (2009) also shows loci modified to reproduce the flux and color evolution of objects from the SNLS project. To help decide which light curve fitting model is best for fitting restframe U-band data of high redshift

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[8]Extensive optical spectra of SN 2003gs (Kotak et al., in preparation) were not available to us for the calculation of S-corrections.

[9]The MLCS parameter Δ is effectively the number of V-band magnitudes that a Type I SN at maximum light is brighter or fainter than an object of nominal decline rate. Slowly rising, slowly declining objects, which are overluminous, have $\Delta < 0$. Δ ranges from about -0.4 to $+1.4$.

objects we need the corrected photometry of a sample of nearby slow decliners. Magnitude limited surveys discover a high percentage of such Type Ia SNe.

In Figure 7 we show three loci from the nominal Multicolor Light Curve Shape model (MLCS2K2, Jha, Riess, & Kirshner 2007). Of the three loci shown in this figure the dereddened colors of SN 2003hv are best fit by the $\Delta = +0.4$ locus prior to $t = 20$ d.

4. Discussion

The future of ground based photometry of supernovae will involve end-to-end calibration of whole telescope-plus-camera systems. A review of the concerns involved is given by Stubbs & Tonry (2006). Stubbs et al. (2007) describe preliminary results with a tunable laser system used on the CTIO 4-m telescope. Rheault et al. (2010) describe a *monochromator* that measures the throughput of a filter in a camera on a telescope at a range of wavelengths simultaneously; this system works from short wavelength optical light into the near-IR. The purpose of these systems is to eliminate the guesswork involved in multiplying together the wavelength dependent atmospheric transmission, the optical reflection and transmission functions, and the quantum efficiency of the detector, in an attempt to determine the effective transmission profiles of a telescopic system.

Our U-band results presented here were not produced with a system that measures the filter transmission *in situ*. But it is clear from Figures 5 and 6 that the application of S-corrections done the traditional way gives greatly improved U-band light curves in the cases of SNe 2003gs and 2003hv. We found values of the rms scatter of the U-band photometry equal to $\pm$ 0.085 and 0.074 mag, respectively, for these two objects. This is comparable to the scatter ($\pm$ 0.077 mag) of S-corrected Sloan u-band photometry of Type Ia SNe observed with multiple telescopes (Mosher et al. 2012).

We can apply our S-corrections to the U-band light curves of two other normal objects, SNe 2001el and 2004S. SN 2001el was observed in the U-band at maximum light using the CTIO 0.9-m telescope and thereafter with the CTIO 1.5-m telescope using an essentially identical U-band filter. SN 2004S was observed in the U-band with the CTIO 1.3-m telescope and ANDICAM.

Krisciunas et al. (2007) found that SNe 2001el and 2004S were essentially clones of each other. These two objects suffered known small amounts of interstellar extinction from dust in the Milky Way, but SN 2001el suffered more host galaxy extinction. Figure 14 of Krisciunas et al. (2007) shows the *difference* of the broad band apparent magnitudes of the two objects, corrected for the effect of Milky Way dust. But the U-band point was anomalous. The corrected U-band point required a shift of 0.35 mag. Now all the points can be fit very well by a simple curve (see Figure 8). Such data allow us to show that a combination of optical and near-IR data gives us the most accurate values of R_V and A_V.[10]

Another possibility is that while the Cardelli, Clayton, & Mathis (1989) extinction law (CCM89) might work well to account for dust extinction in the Milky Way, it might actually not be the right extinction model to account for the extinction due to circumstellar dust and interstellar dust that affects the light of Type Ia SNe in other galaxies (Shappee & Jha, in preparation), at least in the UV. Our corrected U-band point in Fig. 8 is 1.8-σ different than what we would expect using a CCM89 extinction law with $R_V = 2.15$, the most robust value derived from $BVRIJHK$ photometry.

We note that the mean U-band S-correction for the CTIO 1.3-m telescope to convert the data to the Bessell (1990) filter prescription is $\Delta U \approx -0.21$ mag for four "normal" objects (after the elimination of two outlying points). For the CTIO 0.9-m the mean value is about +0.16 mag. For the LCO 1-m telescope the mean value is about +0.25 mag. While the determination of S-corrections is non-trivial, we note that the determination of the mean color term in Equation 1 is easily done with observations of a dozen or more standard stars covering a range of color, obtained on a number of photometric nights.

In Figure 9 we show a sparse empirical plot of the U-band S-correction at 3 days after B-band maximum vs. the U-band color term for the three telescope systems we are considering here. The bluest U-band filter (for the CTIO 1.3-m telescope) leads to the largest negative color term and the largest negative S-correction. The reddest U-band filter (for the LCO 1-m telescope) leads to the largest positive color term and the largest positive S-correction. It would certainly be worthwhile to use the effective U-band filter transmission curves from other systems to derive S-corrections to see to what extent the linear trend shown in Figure 9 holds.

We surmise that the resolution of the U-band anomaly will require multiple upgrades to the analysis: 1) improved effective filter profiles, allowing better standardization of the data; 2) adoption of a reddening law that differs from a CCM89-type extinction law tied to a specific value of R_V, at least in the UV; and 3) retraining the lightcurve fitters to account for evolution in the UV spectral energy distributions of Type Ia SNe as a function of redshift (Foley et al. 2012; Maguire et al. 2012). When it comes to determining the equation of state parameter of the universe, $w = P/(\rho c^2)$, we do not want attribute to the universe something

[10]Here $A_V = R_V\ E(B - V)$, where A_V is the V-band interstellar extinction, $E(B - V)$ is the color excess for $B - V$ colors, and R_V is a scale factor. See Cardelli, Clayton, & Mathis (1989) and Krisciunas et al. (2006).

that is in a subtle way an artifact of data analysis pushed to its limits.

5. Conclusions

Over the past dozen years we have published U-band photometry of quite a few Type Ia SNe, but we have never really done anything with the U-band data. It was obvious that there were systematic offsets from telescope to telescope. We previously opted not to publish U-band photometry of SN 2003gs from the LCO 1-m telescope (Krisciunas et al. 2009). Here we have worked out S-corrections for that telescope, along with corrections for the CTIO 0.9-m and 1.3-m telescopes. Even though we did not measure the effective U-band filter profiles using end-to-end calibration, our S-corrections provide a significant improvement to the analysis.

Kessler et al. (2009) discovered that if we anchor the absolute magnitudes of distant Type Ia SNe (redshift $z \gtrsim 0.3$) with U-band light curves of nearby objects, there is a 0.12 mag discrepancy in the distance moduli, which leads to a 0.3 shift in the equation of state parameter w. Using WMAP data, baryon acoustic oscillations and Type Ia supernovae, the random error of w from modern surveys is now about $\pm$ 0.06 (Komatsu et al. 2011), and within one standard deviation it appears that $w = -1$.[11] But a systematic error of 0.3 is so serious that it ruins the experiment.

Our experiments with traditional S-corrections presented in this paper should give us hope and motivate us to compile a set of S-corrected light curves of nearby objects that cover maximum light as well as possible. This should better enable the full use of restframe U-band photometry of higher redshift objects. We could use these corrected light curves to retrain the light curve fitters used for such projects as ESSENCE, SDSS, and SNLS and see if the U-band anomaly found by Kessler et al. (2009) is resolved. This may be time well spent while new projects such as the Dark Energy Survey begin operations.

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[11] If $w = -1$, then the Dark Energy is equivalent to Einstein's Cosmological Constant.

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Table 1. Fully Corrected U-Band Photometry of SN 2003gs

JD[a]	Epoch[b]	U
2850.80	+1.99	14.566 (0.018)
2851.80	+2.99	14.647 (0.018)
2870.80	+21.89	17.026 (0.018)
2888.90	+39.91	17.575 (0.018)
2890.80	+41.80	17.603 (0.018)
2905.70	+56.63	18.192 (0.020)
2906.80	+57.72	18.177 (0.023)
2907.80	+58.72	18.197 (0.019)
2908.80	+59.71	18.265 (0.021)
2914.80	+65.68	18.405 (0.040)

[a]Julian Date *minus* 2,450,000.

[b]Restframe days since T(B_{max}) = JD 2452848.8.

Table 2. Fully Corrected Optical Photometry of SN 2003hv[a]

JD[b]	Epoch[c]	U	B	V	R	I
2892.88	+1.17	11.976 (0.015)	12.416 (0.015)	12.480 (0.015)	12.425 (0.015)	12.756 (0.015)
2896.78	+5.05	12.512 (0.015)	12.674 (0.015)	12.607 (0.015)	12.612 (0.015)	12.998 (0.015)
2899.79	+8.04	12.967 (0.017)	13.011 (0.015)	12.798 (0.015)	12.908 (0.015)	13.273 (0.015)
2906.80	+15.02	14.184 (0.015)	14.012 (0.015)	13.299 (0.015)	13.181 (0.015)	13.116 (0.015)
2910.76	+18.95	14.677 (0.015)	14.577 (0.041)	13.573 (0.034)	13.317 (0.035)	13.016 (0.037)
2914.70	+22.87	15.054 (0.032)	15.024 (0.066)	13.954 (0.033)	13.621 (0.034)	13.191 (0.052)
2917.75	+25.90	15.233 (0.015)	15.180 (0.015)	14.141 (0.015)	13.825 (0.015)	13.427 (0.015)
2920.74	+28.88	15.408 (0.025)	15.290 (0.029)	14.363 (0.024)	14.065 (0.031)	13.708 (0.037)
2923.72	+31.84	15.501 (0.022)	15.403 (0.015)	14.493 (0.015)	14.220 (0.015)	13.895 (0.015)
2926.75	+34.85	15.609 (0.022)	15.507 (0.015)	14.626 (0.015)	14.367 (0.015)	14.078 (0.015)
2929.72	+37.81	15.755 (0.015)	15.579 (0.015)	14.729 (0.015)	14.453 (0.015)	14.210 (0.015)
2932.67	+40.74	15.810 (0.015)	15.656 (0.015)	14.821 (0.015)	14.595 (0.015)	14.385 (0.015)
2939.71	+47.74	16.042 (0.024)	15.827 (0.015)	15.044 (0.015)	14.851 (0.015)	14.726 (0.025)
2946.71	+54.70	16.197 (0.029)	15.957 (0.015)	15.236 (0.015)	15.102 (0.015)	15.033 (0.015)
2953.72	+61.67	16.301 (0.058)	16.105 (0.018)	15.435 (0.020)	15.343 (0.015)	15.336 (0.015)

[a]The photometry includes the usual color corrections derived from standard stars, and also the S-corrections. Magnitude uncertainties (1σ) are given in parentheses.

[b]Julian Date *minus* 2,450,000.

[c]Rest frame days since T(B_{max} = JD 2452891.7).

Fig. 1.— U-band photometry (without S-corrections) of SN 2003gs and SN 2003hv. Symbols: green circles = CTIO 1.3-m with ANDICAM; blue squares = CTIO 0.9-m; yellow triangles = LCO 1-m.

Fig. 2.— Effective U-band transmission functions of the cameras on the CTIO 1.3-m, CTIO 0.9-m, and LCO 1-m telescopes, along with the U-band filter specified by Bessell (1990).

Fig. 3.— U-band S-corrections for "spectroscopically normal objects". Symbols: red upward pointing triangles = SN 1999ee; blue squares = SN 2001el; green dots = SN 2002bo; orange downward pointing triangles = SN 2004S. The top panel shows corrections for the ANDICAM instrument on the CTIO 1.3-m telescope. The middle panel shows corrections for the CTIO 0.9-m reflector. The bottom panel shows corrections for the Las Campanas Observatory 1-m telescope. The solid lines are low order polynomial fits to these data. Connected by dashed lines we also show S-corrections based on Hsiao et al. (2007) templates warped to match the natural system magnitudes of SN 1999ee data from the CTIO 0.9-m telescope (cyan diamonds) and SN 2002bo data from ANDICAM when it was mounted on the Yale-AURA-Lisbon-Ohio (YALO) telescope at CTIO (yellow diamonds).

Fig. 4.— Similar to Figure 3, except these are U-band S-corrections for the unusal Type Ia SN 2001ay. The green dots correspond to corrections based on spectra with the Fred L. Whipple Observatory 1.5-m telescope. The blue squares correspond to corrections base on spectra with the MMT.

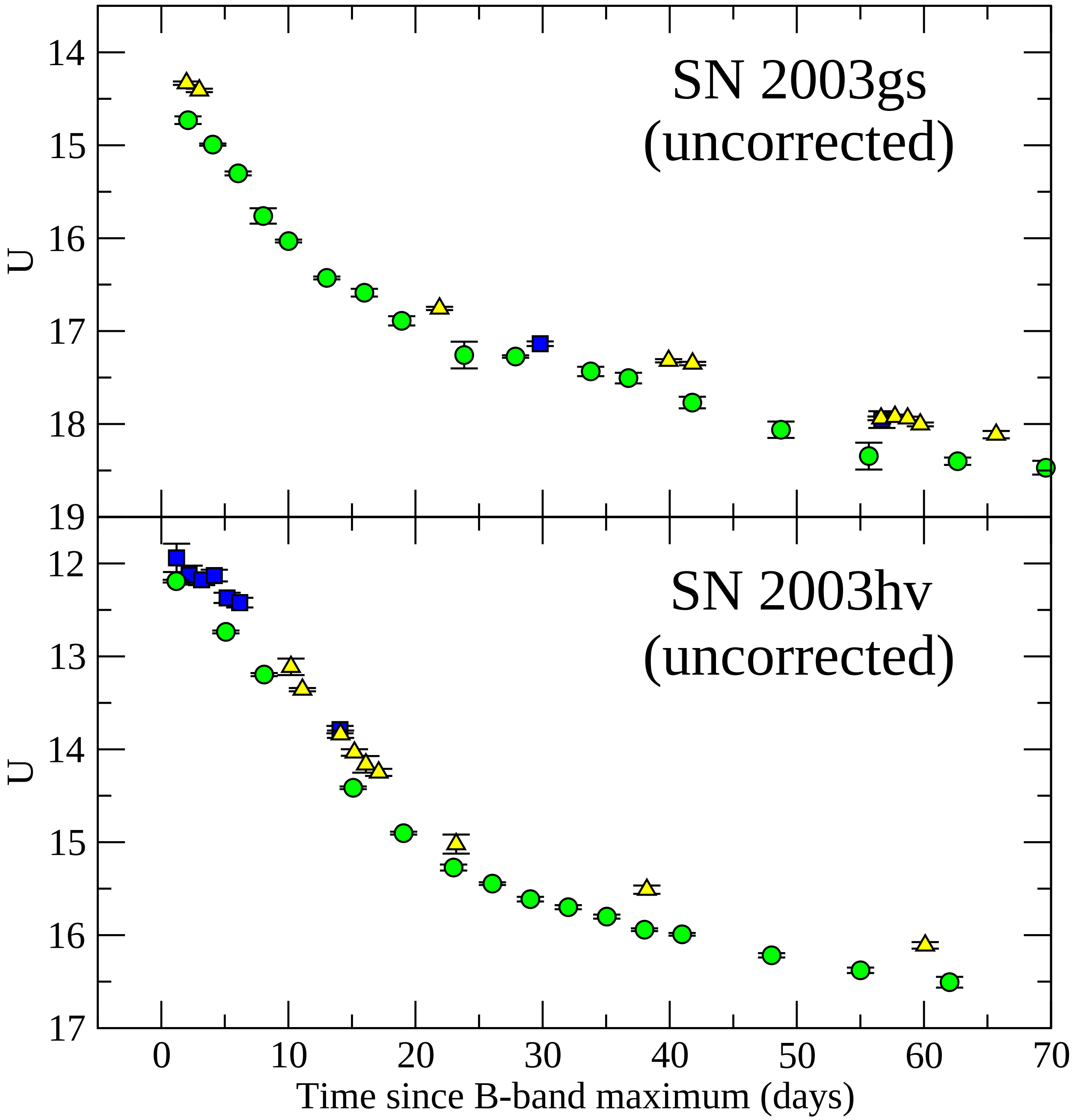
Fig. 5.— U-band photometry (with S-corrections) of SN 2003gs. There are now no significant systematic differences of photometry obtained with different telescopes.

Fig. 6.— $UBVRI$-band photometry (with S-corrections) of SN 2003hv. The CTIO 0.9-m and LCO 1-m $BVRI$ data (blue squares and yellow upward pointing triangles, respectively) are from Leloudas et al. (2009), with S-corrections provided by G. Leloudas. The CTIO 1.3-m data are plotted as green dots. We have excluded KAIT data and data from the Siding Spring Observatory 2.3-m.

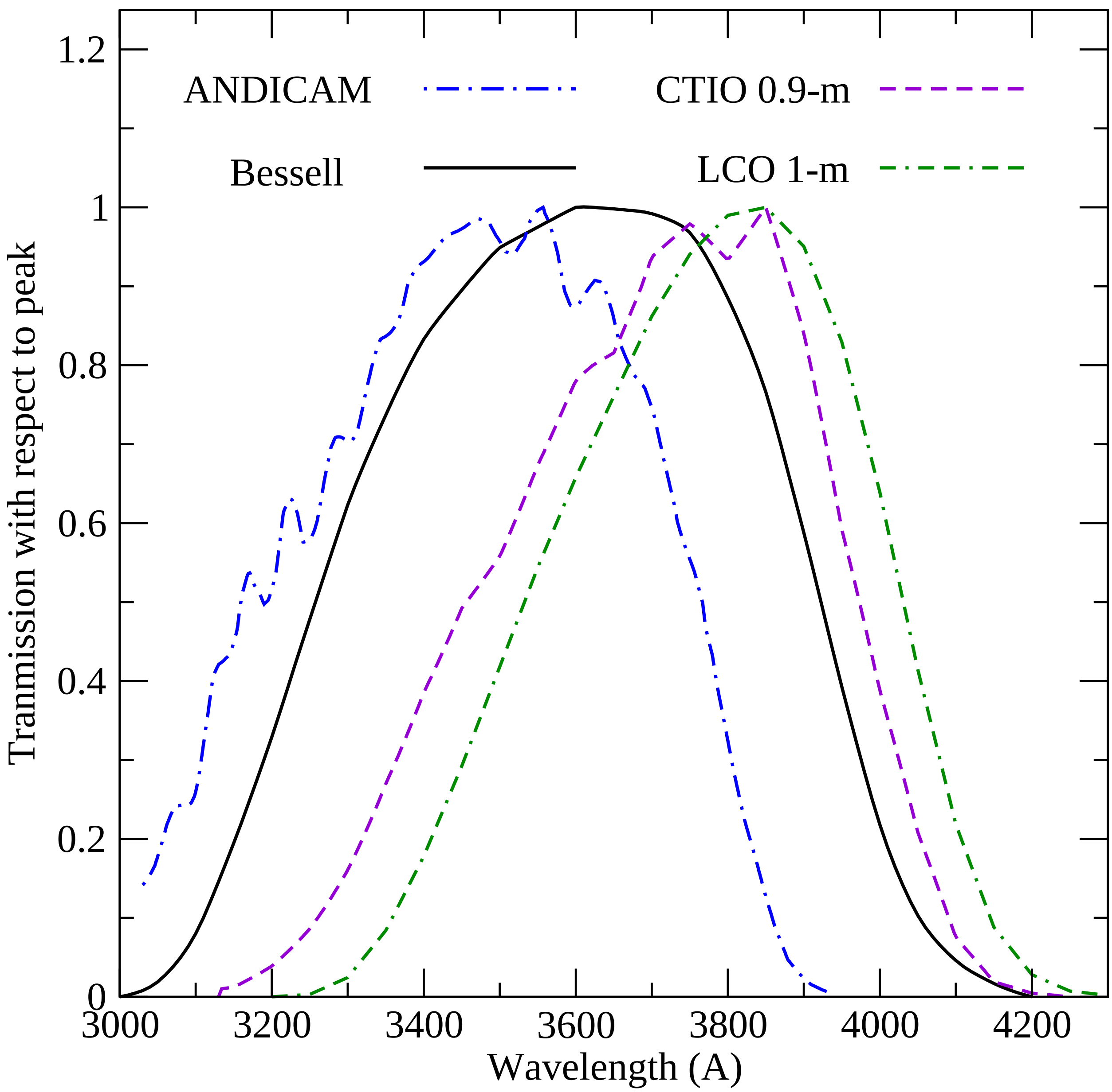
Fig. 7.— $U - B$ color curves of SNe 2003hv and SN 2003gs. The photometry of SN 2003hv has been S-corrected and corrected for a small amount of Milky Way reddening (E($U - B$) = 0.011). Symbols: green dots (CTIO 1.3-m), blue squares (CTIO 0.9-m), yellow upward pointing triangles (LCO 1-m). For SN 2003gs, E($U - B$) = 0.025 mag, which has been subtracted out. Symbols: red downward pointing triangles (CTIO 1.3-m), magenta diamonds (CTIO 0.9-m). The solid line is the MLCS2K2 locus for $\Delta = +0.4$. The dashed line is for $\Delta = 0.0$. The dot-dash line is for $\Delta = -0.4$.

Fig. 8.— Difference of apparent magnitudes of SNe 2001el and 2004S, following Figure 14 of Krisciunas et al. (2007). The U-band difference is now based on S-corrected photometry. The horizontal dashed line is the derived difference of the distance moduli. The solid line is a fourth order fit to the $UBVRIJHK$ points. The red dashed line is based on a distance modulus difference of 1.936 mag, $A_V = 0.472$ mag and scale factors A_λ/A_V from Table 6 of Krisciunas et al. (2007), using a CCM89 extinction law and $R_V = 2.15$.

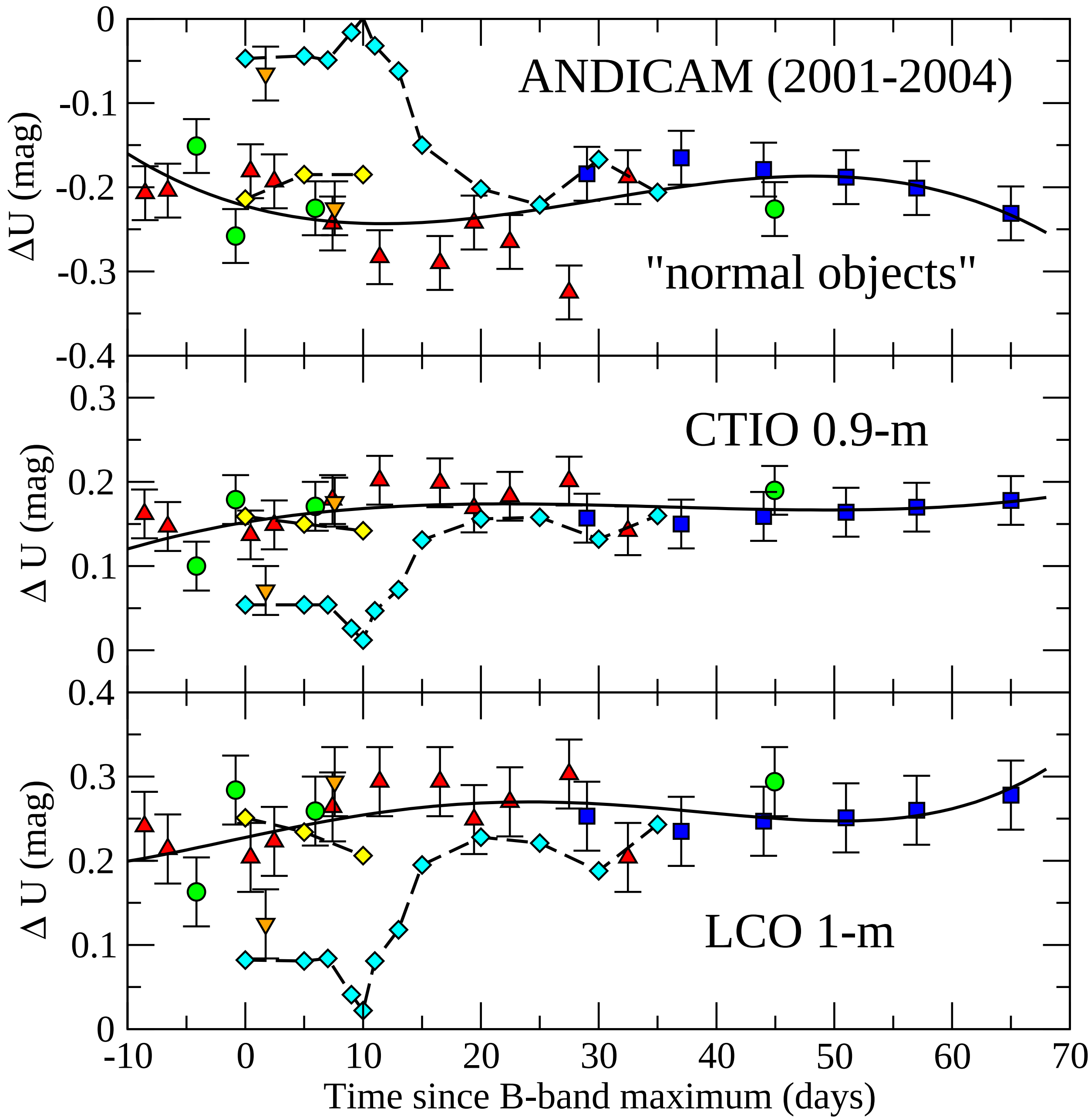
Fig. 9.— U-band S-correction as a function of U-band photometric color term.



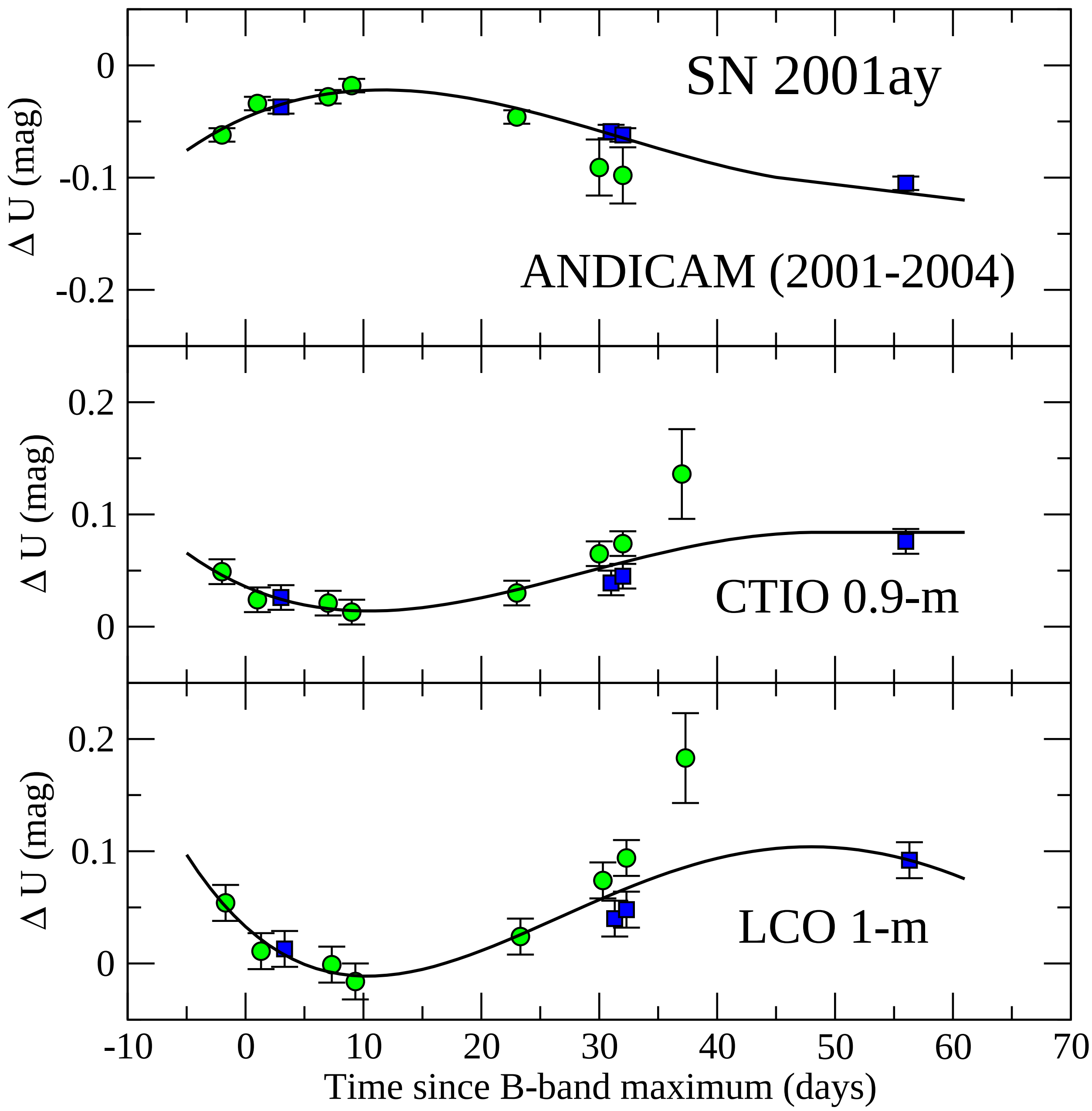
Krisciunas *et al.* Fig. 1



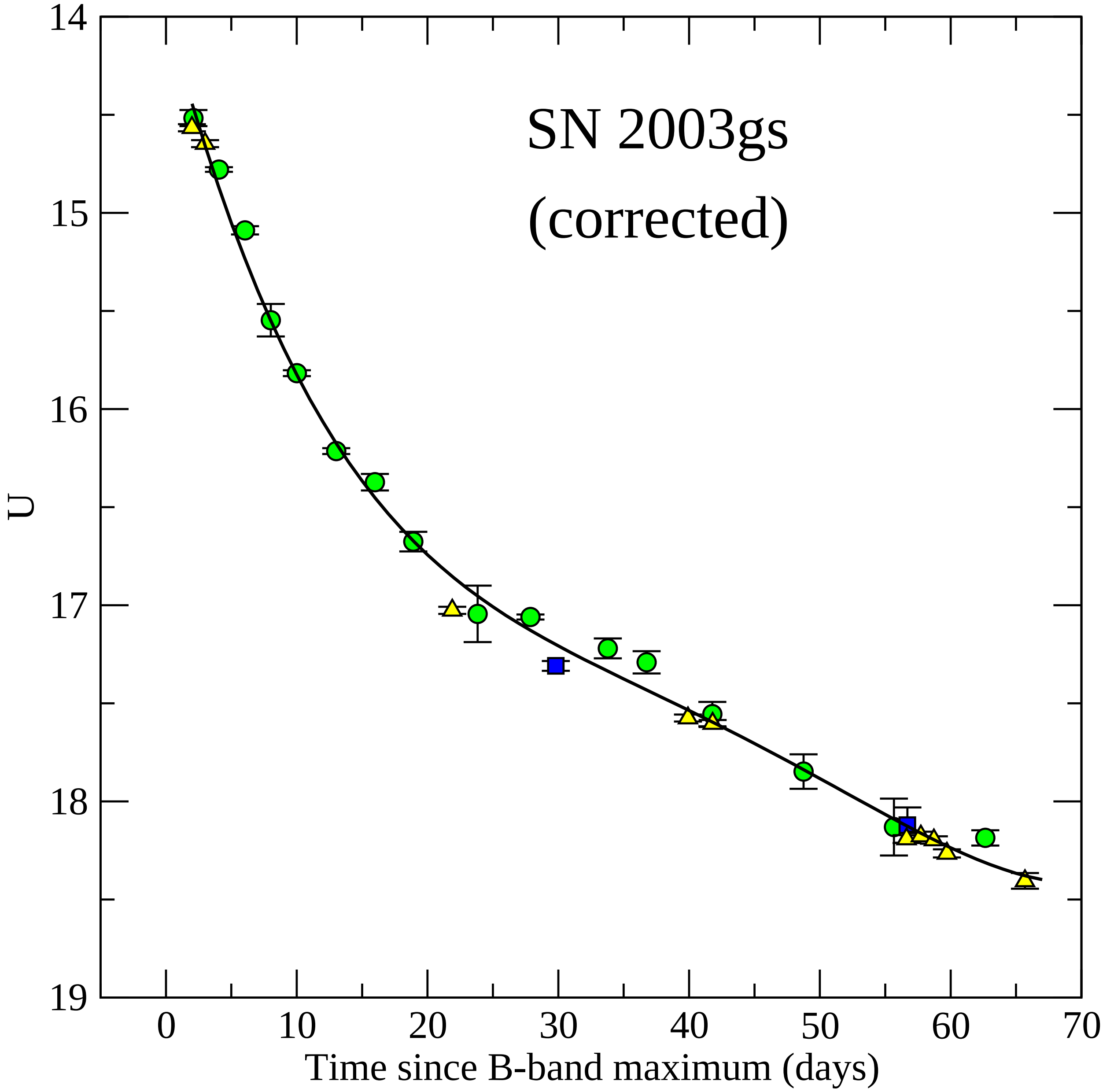
Krisciunas *et al.* Fig. 2



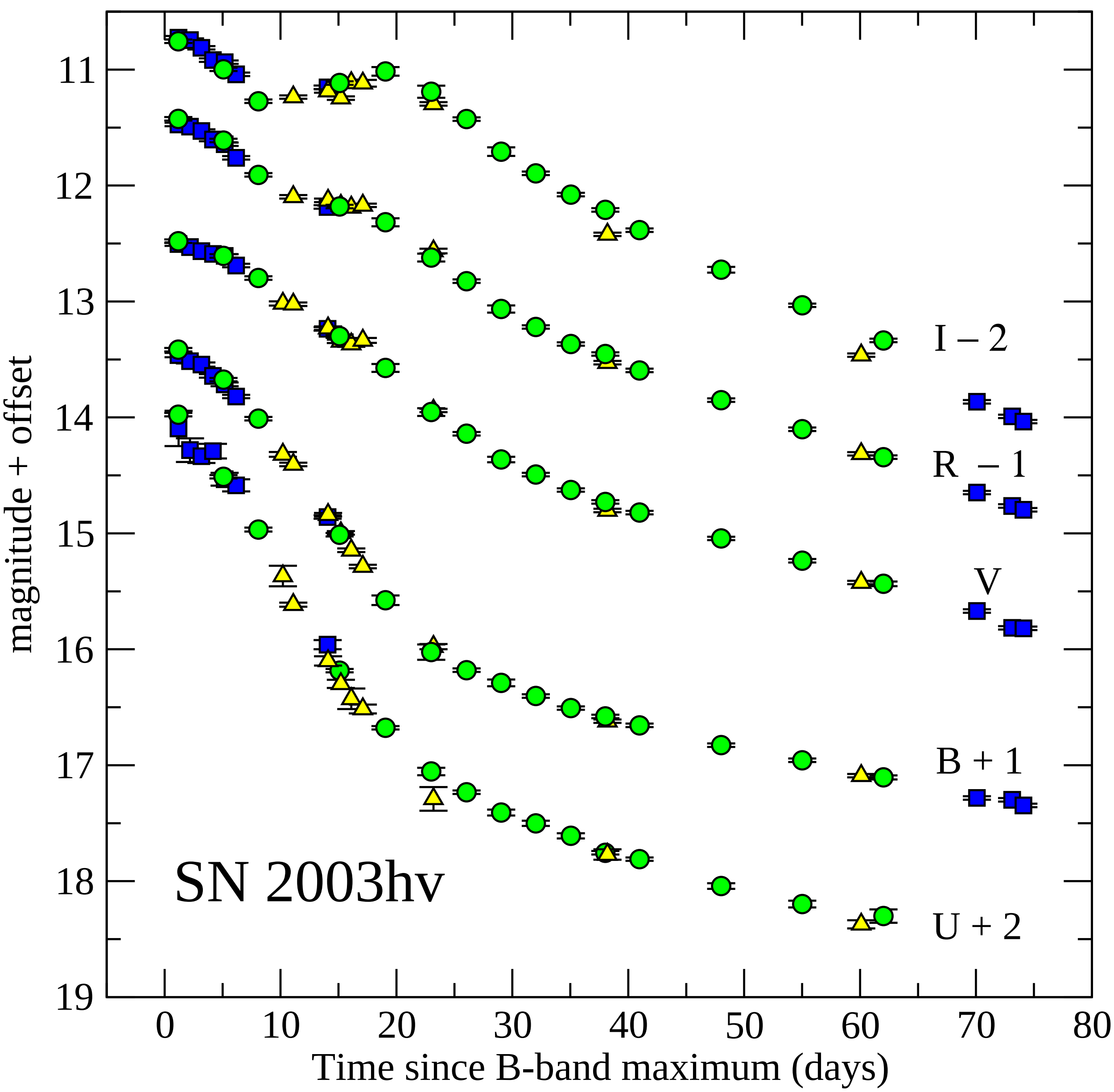
Krisciunas *et al.* Fig. 3



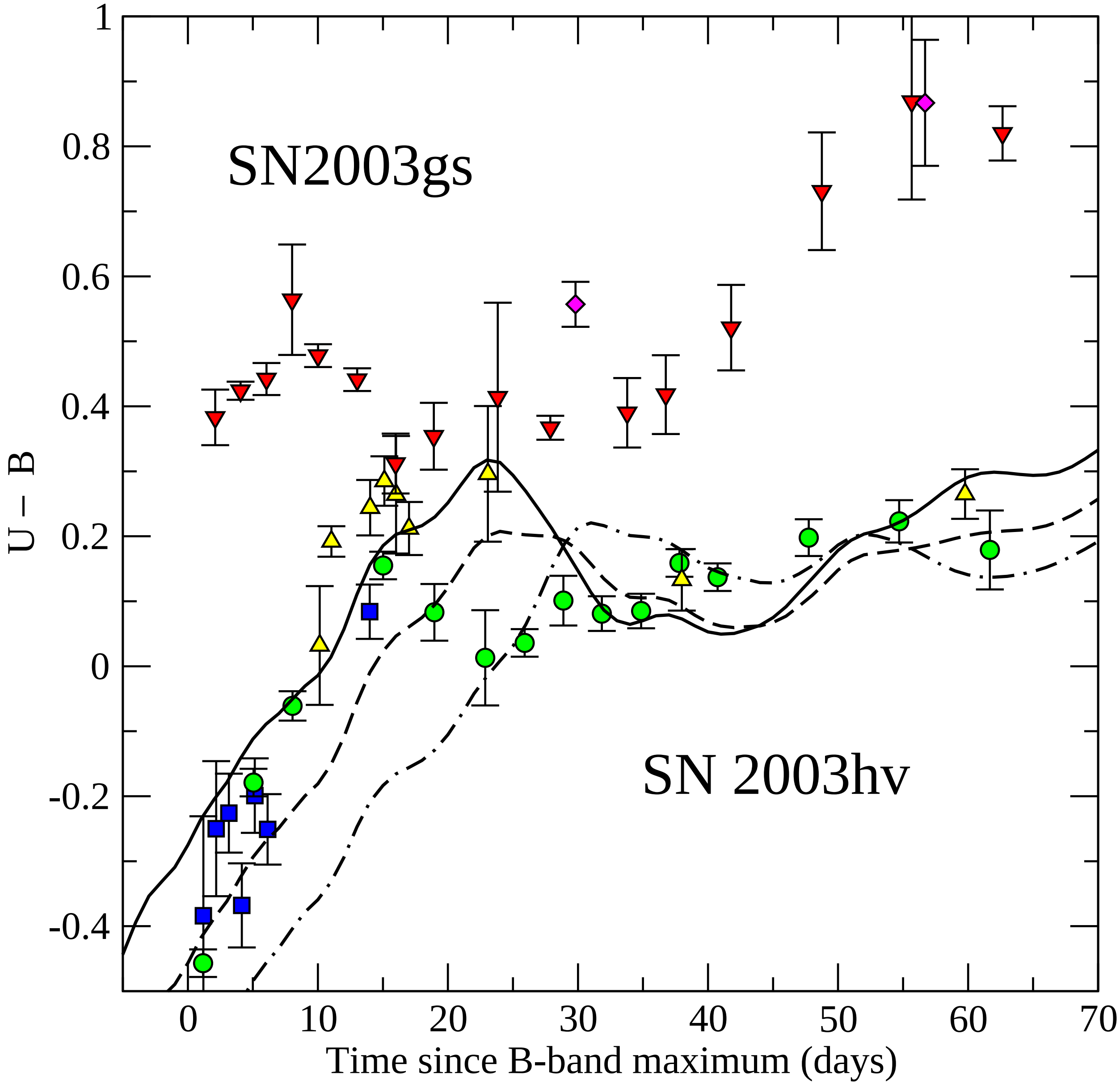
Krisciunas *et al.* Fig. 4



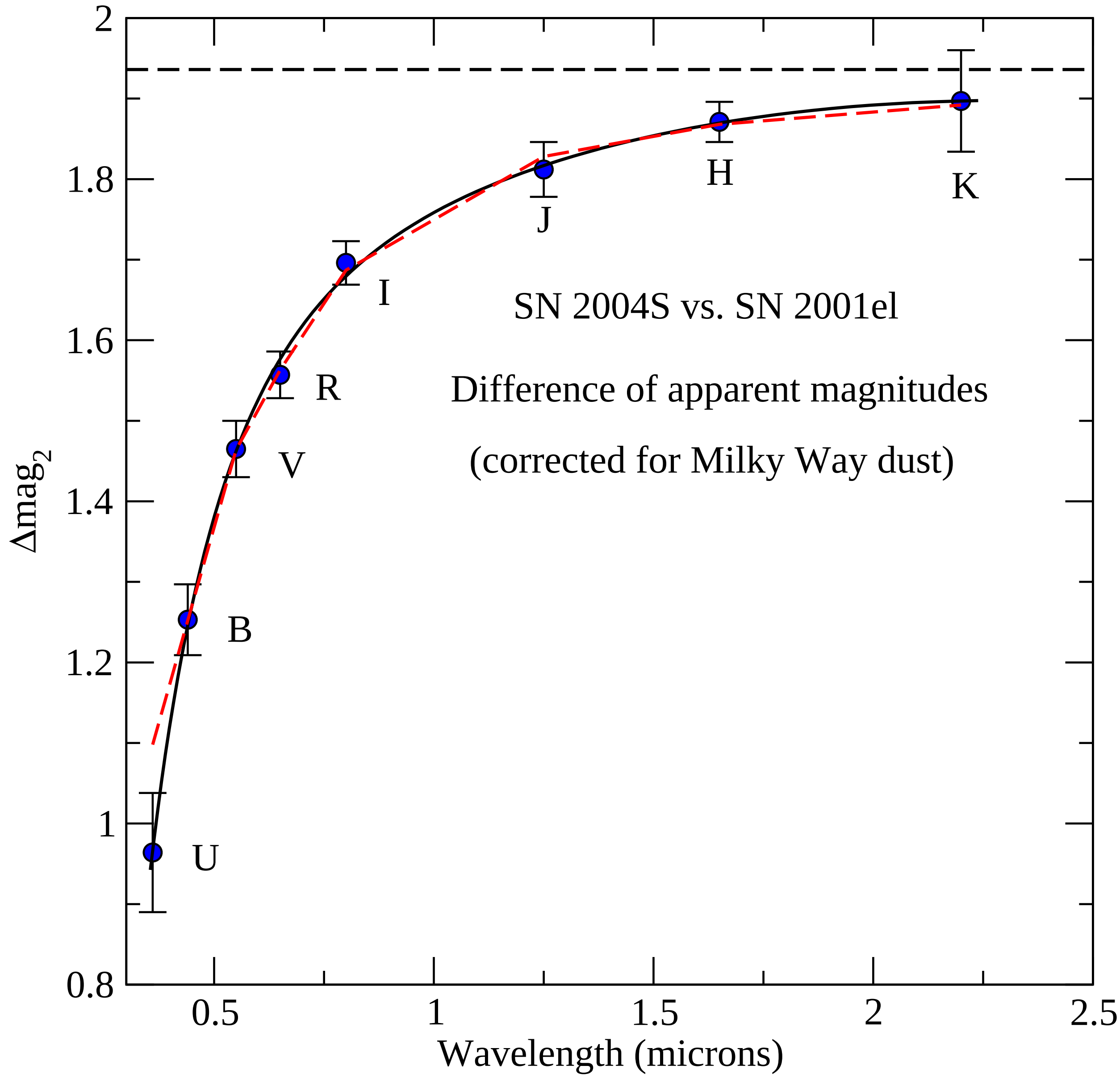
Krisciunas *et al.* Fig. 5



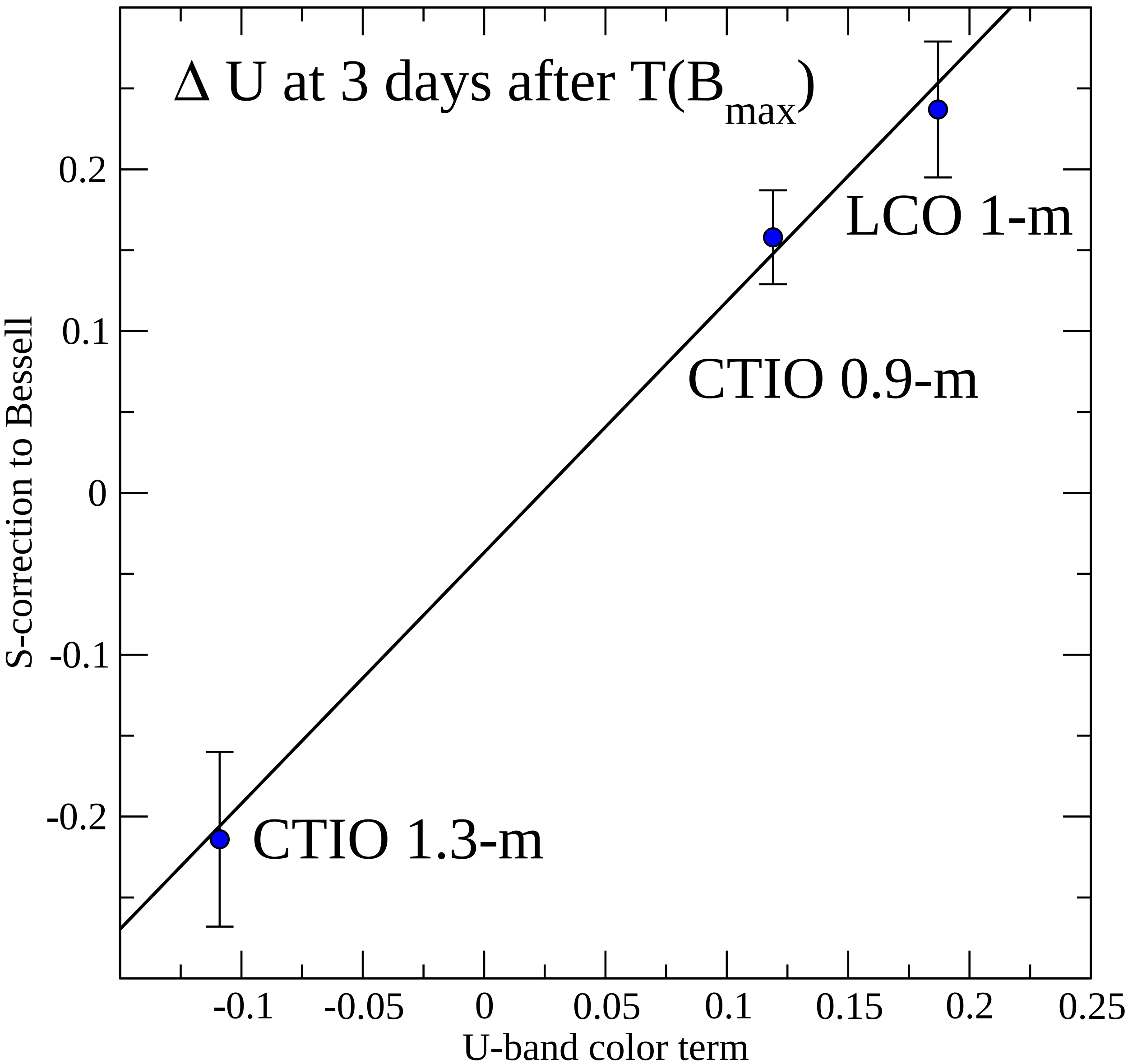
Krisciunas *et al.* Fig. 6



Krisciunas *et al.* Fig. 7



Krisciunas *et al.* Fig. 8



Krisciunas *et al.* Fig. 9