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THE ULTIMATE LIGHT CURVE OF SN 1998bw/GRB 980425

Alejandro Clocchiatti[1], Nicholas B. Suntzeff[2,5], Ricardo Covarrubias[3,5], and Pablo Candia[4,5]
[1] Departamento de Astronomía y Astrofísica, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 22, Chile; aclocchi@astro.puc.cl
[2] Department of Physics & Astronomy, Mitchell Institute for Fundamental Physics & Astronomy, Texas A&M University, College Station, TX 77843, USA; nsuntzeff@tamu.edu
[3] Australian Astronomical Observatory, P.O. Box 296, Epping, NSW 1710, Australia; ricardo@aao.gov.au
[4] Gemini Observatory, Casilla 603, La Serena, Chile; pcandia@gemini.edu
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ABSTRACT

We present multicolor light curves of SN 1998bw which appeared in ESO184-G82 in close temporal and spatial association with GRB 980425. The light curves are based on observations conducted at Cerro Tololo Inter-American Observatory (CTIO) and data from the literature. The CTIO photometry reaches ∼86 days after the gamma-ray burst (GRB) in U and ∼160 days after the GRB in $BV(RI)_C$. The observations in U extend the previously known coverage by about 30 days and determine the slope of the early exponential tail. We calibrate a large set of local standards in common with those of previous studies and use them to transform published observations of the supernova (SN) to our realization of the standard photometric system. We show that the photometry from different sources merges smoothly and we provide a unified set of 300 observations of the SN in five bands. Using the extensive set of spectra in the public domain, we compute extinction and K-corrections and build quasi-bolometric unreddened rest-frame light curves. We provide low-degree piecewise spline fits to these light curves with daily sampling. They reach ∼86 rest-frame days after the GRB with U-band coverage and ∼498 rest-frame days after the GRB without U.

Key words: gamma-ray burst: general – supernovae: general – supernovae: individual (SN 1998bw)

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

Stripped envelope core-collapse supernovae (SNe) remain one of the open frontiers for basic observational work on SNe. Without the appeal of Type Ia and Type II SNe which, through different techniques, can be used as distance estimators, their follow-up is typically neglected when they are discovered in SN searches, unless they are particularly bright or display puzzling peculiarities. As a consequence, progress in this area occurs at a slower pace.

After a peak in activity during 1993–1995, which resulted mainly from the impact of the bright and well-observed SNe 1993J and 1994I, the field of study of these "exotic" SNe entered a time of slower productivity. In 1998, however, a long-duration gamma-ray burst (GRB) provided new insight into core-collapse SNe and gave new incentives to justify their follow-up. The association of long-duration, soft-spectrum GRBs with SNe has been explored in many publications (Woosley & Bloom 2006; Hartmann 2010; Wheeler & Akiyama 2010). It is now considered that most long-duration soft-spectrum GRBs are accompanied by massive stellar explosions.

One of the events that made a significant contribution to establish the connection of GRB–SNe was SN 1998bw/GRB 980425 (Galama et al. 1998). It was the target of extensive coverage both in terms of wavelength range and time span, and was the subject of many theoretical studies conducted to understand the nature of the progenitor and uncover details of the asymmetric explosion.

SN 1998bw was discovered after a search triggered by GRB 980425, 1.6 arcminute away from the center of the 8 arcminute error box of the Wide Field Camera of *BeppoSAX* (Galama et al. 1998). After some initial confusion, it was recognized as a peculiar Type Ib/c SN (Saddler et al. 1998). It appeared superimposed on a complicated background, as became clear with the exquisite resolution of the *Hubble Space Telescope* (*HST*; Patat et al. 2001). Hence, while simple aperture photometry and point-spread function (PSF) fitting photometry were reasonable approaches to use when the SN was bright, more sophisticated techniques became necessary when it was fading. Galama et al. (1998) presented the first set of observations in the optical and near-infrared passbands. Their light curves start as early as ∼17 hr after the GRB, in V and R_C, and extend up to ∼57 days after the GRB with $UBV(RI)_C$ coverage. They use simple aperture photometry to estimate the SN brightness. McKenzie & Schaefer (1999) present BVI_C photometry, from ∼64 up to ∼187 days after the GRB. Patat et al. (2001) present an extensive set of observations, including spectroscopy, spectropolarimetry, and photometry. The last of these spans the range from 323 up to 426 days after the GRB, and the brightness is measured with PSF-fitting photometry using a software specifically designed for analyzing point sources superimposed on bright, spatially variable, backgrounds. Sollerman et al. (2002) present $BV(RI)_C$ photometry that extends from 140 up to more than 500 days after the GRB and includes data from a reanalysis of the images used by Patat et al. (2001). They estimate the SN brightness by performing PSF-fitting photometry on images where the background light of the galaxy had been removed using very late, high quality images. Finally, Fynbo et al. (2000) analyze very late *HST* images of ESO184-G82 taken through non-standard passbands and provide estimates of the SN brightness more than 750 days after the GRB.

[5] Staff astronomers, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, under contract with the National Science Foundation.

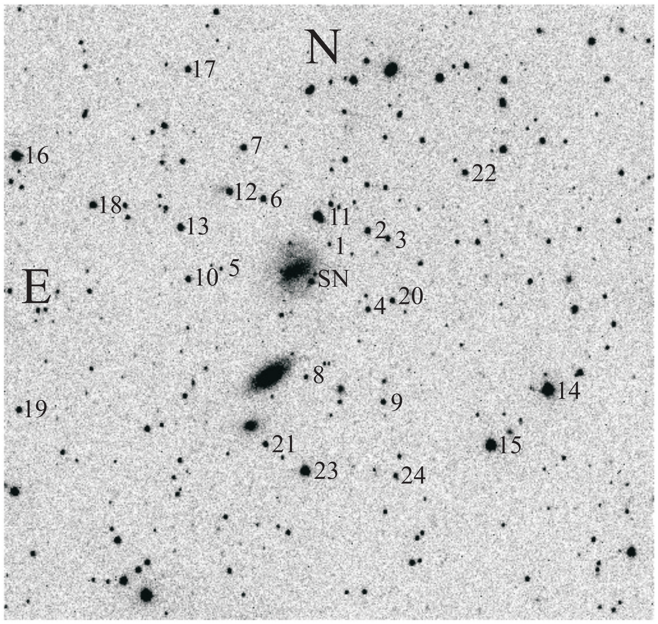

Figure 1. Local standard sequence for SN 1998bw. The image was taken with the CTIO 0.9 m telescope on 1998 October 2, using the I_C passband. Exposure time was 600 s. North is up and east is left. The width of the field in the east–west direction is approximately 6.6 arcminute. Star numbers 1–15 are the same local sequence of Galama et al. (1998).

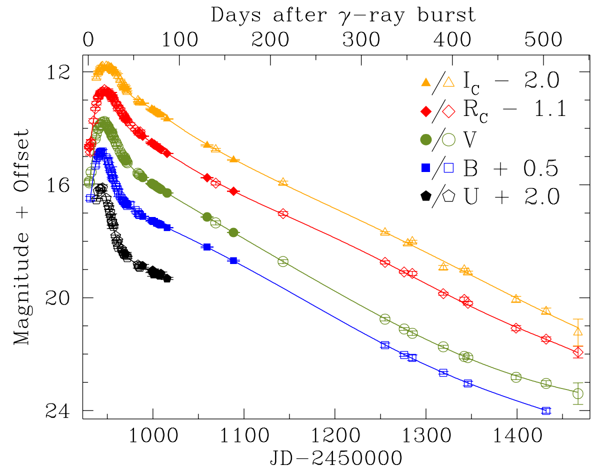

Figure 2. Complete light curves of SN 1998bw. Open symbols display the earlier observations of Galama et al. (1998) and later observations of Sollerman et al. (2002). Solid symbols bridging the two sets are the CTIO observations presented here. All the observations were transformed to the photometric system defined by the local standards in Table 1. The solid lines are the fits used to build the intrinsic light curves given in Table 3.

(A color version of this figure is available in the online journal.)

The main purpose of this paper is to present an independent set of photometric observations conducted at Cerro Tololo Inter-American Observatory (CTIO) between 1998 June and October, from ∼40 up to 160 days after the GRB. The CTIO observations overlap most of the data sets mentioned above, and our *U*-band observations reach about 30 days later than those published so far.

We purposely calibrated our photometry with the same set of local standards used by Galama et al. (1998) for the early light curve and Sollerman et al. (2002) for the very late light curve. Therefore, if *S*-corrections (Pignata et al. 2004) between the different realizations of the passbands are not large, these data sets could be straightforwardly merged which provides a secondary goal for this paper. We merge our data with the earlier set of Galama et al. (1998) and the later set of Sollerman et al. (2002) providing an ensemble of 300 $UBV(RI)_C$ observations, spanning from about 15 days before up to more than 500 days after maximum light, consistently calibrated with the sequence of local standards as defined by the CTIO realization of the standard photometric system. Finally, by having this photometry available, it is possible to obtain multicolor, unreddened, rest-frame light curves as well as quasi-bolometric light curves. We do so providing fits to the photometry that extend more than ∼80 days after the GRB with $UBV(RI)_C$ coverage and close to 500 days after the GRB with only $BV(RI)_C$.

In Section 2, we present our observations, in Section 3 we describe the comparison and merging of our data with those already published, and the computing of *K* and extinction corrections to obtain the rest-frame unreddened light curve of SN 1998bw, which we present interpolated with low-degree piecewise splines. Finally, in Section 4 we summarize our work.

2. OBSERVATIONS

The CTIO observations started ∼40 days after the GRB (about a month after maximum light). The 0.9 m telescope with a direct CCD camera attached was used. The detector was a TEK 2048 CCD, with a pixel size of 24 μm, providing a scale of 0.396 arcsec pixel^{-1}. The passbands routinely used were the standard $UBV(RI)_C$ of the Johnson–Kron–Cousins photometric system (Kron & Smith 1951; Johnson 1955; Cousins 1976). $BV(RI)_C$ images were taken on 15 nights while *U* images were taken on 12. Five of those nights appeared to be photometric, and extensive sets of standards from the lists of Landolt (1992) were observed as well, to fit color terms for the instrument and extinction coefficients for the nights.

Reduction of the images was done in the usual manner within the IRAF[6] environment. Briefly, images were trimmed, bias corrected, and flat fielded. A sequence of isolated stars with good signal-to-noise ratio was located and used to build a variable PSF for each image using the package DAOPhot (Stetson 1987). The PSF is later fitted to all the stars of the local photometric sequence indicated in Figure 1, and the SN, to estimate their instrumental magnitudes. Using the instrumental magnitudes, the $UBV(RI)_C$ magnitudes for the local sequence and the color terms for the instrument that had been measured in the photometric nights, we transformed the instrumental PSF magnitudes of the SN into calibrated magnitudes.

After reduction, two of the five supposedly photometric nights gave larger than expected residuals for the photometric fits. Then, they were used in the fitting of color terms, but not in the absolute calibration of the sequence of local standards. The magnitudes of the local sequence of standards are given in Table 1. The photometry of SN 1998bw is given in Table 2, under reference code (2), and plotted in Figure 2.

3. LIGHT CURVES

3.1. Merged Photometry

The photometry presented above can be joined with data published elsewhere to build a well-sampled and extended multicolor light curve of SN 1998bw. After comparing our raw observations with those of Galama et al. (1998), McKenzie &

[6] The Image Reduction and Analysis Facility is developed and maintained by NOAO, which is operated by AURA, Inc. under cooperative agreement with the National Science Foundation.

Table 1
Local Standard Sequence for SN 1998bw

ID[a]	V	$B-V$	$U-B$	$V-R_C$	$V-I_C$
1	18.503 ± 0.032	0.422 ± 0.053	−0.208 ± 0.053	0.293 ± 0.050	0.576 ± 0.043
2	17.696 ± 0.006	1.161 ± 0.044	0.964 ± 0.179	0.717 ± 0.010	1.309 ± 0.007
3	18.072 ± 0.008	0.864 ± 0.031	0.570 ± 0.041	0.495 ± 0.023	0.972 ± 0.012
4	17.792 ± 0.022	0.696 ± 0.024	0.085 ± 0.039	0.399 ± 0.023	0.780 ± 0.025
5	19.403 ± 0.021	0.772 ± 0.030	...	0.435 ± 0.029	0.855 ± 0.041
6	17.215 ± 0.014	0.641 ± 0.016	0.022 ± 0.013	0.397 ± 0.016	0.761 ± 0.016
7	17.489 ± 0.021	0.831 ± 0.022	0.315 ± 0.016	0.524 ± 0.022	1.024 ± 0.021
8	18.572 ± 0.018	0.622 ± 0.021	−0.025 ± 0.034	0.394 ± 0.051	0.753 ± 0.029
9	17.983 ± 0.017	0.909 ± 0.029	0.560 ± 0.034	0.524 ± 0.018	0.983 ± 0.027
10	17.496 ± 0.021	0.840 ± 0.038	0.410 ± 0.034	0.484 ± 0.024	0.911 ± 0.022
11	15.561 ± 0.002	0.999 ± 0.013	0.556 ± 0.019	0.550 ± 0.007	1.059 ± 0.002
12	16.740 ± 0.035	0.599 ± 0.039	0.009 ± 0.017	0.370 ± 0.045	0.746 ± 0.036
13	16.676 ± 0.004	0.762 ± 0.008	0.317 ± 0.030	0.444 ± 0.007	0.826 ± 0.005
14	14.070 ± 0.012	0.755 ± 0.019	0.335 ± 0.018	0.429 ± 0.023	0.833 ± 0.019
15	14.515 ± 0.014	0.665 ± 0.021	0.151 ± 0.019	0.380 ± 0.025	0.752 ± 0.021
16	15.204 ± 0.004	0.845 ± 0.006	0.533 ± 0.020	0.457 ± 0.005	0.846 ± 0.005
17	17.190 ± 0.005	0.849 ± 0.011	0.418 ± 0.027	0.482 ± 0.006	0.931 ± 0.006
18	16.701 ± 0.005	0.640 ± 0.006	0.014 ± 0.020	0.403 ± 0.005	0.811 ± 0.006
19	17.569 ± 0.007	0.952 ± 0.014	0.624 ± 0.039	0.572 ± 0.009	1.081 ± 0.007
20	17.886 ± 0.007	1.052 ± 0.013	0.818 ± 0.035	0.575 ± 0.009	1.059 ± 0.008
21	17.516 ± 0.005	0.669 ± 0.008	0.130 ± 0.022	0.381 ± 0.006	0.755 ± 0.009
22	17.710 ± 0.008	0.998 ± 0.010	0.712 ± 0.028	0.586 ± 0.009	1.101 ± 0.008
23	16.046 ± 0.005	1.349 ± 0.006	1.244 ± 0.023	0.866 ± 0.005	1.688 ± 0.005
24	17.973 ± 0.007	0.654 ± 0.009	0.007 ± 0.024	0.394 ± 0.008	0.759 ± 0.011
25[b]	18.007 ± 0.007	0.925 ± 0.014	0.734 ± 0.035	0.535 ± 0.009	0.999 ± 0.018

Notes.
[a] Star numbers 1–15 are the same as those of Galama et al. (1998).
[b] Star number 25 falls outside the finding chart of Figure 1. It is located 23.1 arcsec north and 20.6 arcsec east from star number 19.

Schaefer (1999), and Sollerman et al. (2002), we decided to join our data with those of Galama et al. (1998) and Sollerman et al. (2002). At early times, the data of Galama et al. (1998) are unique and must be considered. At late times, the data of Sollerman et al. (2002) include a reanalysis of the images used by Patat et al. (2001) and correspond to PSF photometry on images with the background subtracted. An additional consideration is that Galama et al. (1998) and Sollerman et al. (2002) calibrate the photometry using a common set of 15 local standards while McKenzie & Schaefer (1999) use a different local sequence.

After a careful comparison, we found phase-dependent systematic differences between our photometry and that of McKenzie & Schaefer (1999). They are probably the result of slightly different realizations of the photometric passbands combined with the non-stellar character of the spectrum of SN 1998bw, the different set of local standards used, and the different technique applied to estimate the SN brightness (aperture versus PSF photometry). The effects of bandpass differences causing large systematic errors in SN photometry have been known for quite a while (Suntzeff et al. 1988). Since our earlier data are coincident in time with those of McKenzie & Schaefer (1999), and at late times our data already merge with those of Sollerman et al. (2002) we decided not to use the observations of the former in our combined light curve.

We also found small systematic differences between our photometry and that of Galama et al. (1998) and Sollerman et al. (2002) as well. Within the uncertainties, however, the differences were constant with SN phase. We took this as an indication of negligible *S*-corrections between our photometry and those of either Galama et al. (1998) or Sollerman et al. (2002). Since the three studies had a sequence of 15 local standards in common, it was possible to fit zero points and relative color terms between the two sets and transform all the observations to the system defined by the magnitudes of the local standard set given in Table 1. The transformed magnitudes merge very well. The transformed photometry from different sources is consistent within the uncertainties. It is particularly reassuring that they merge very well at our latest times in the passbands R_C and I_C, which are those where the effect of the *S*-corrections is expected to be strongest (see Figure 3). Since Sollerman et al. (2002), who obtained the very late time photometry shown in the figure, did correct the observations for background light contamination and we did not, this means, in addition, that as late as ∼160 days after the GRB, contamination by background light was not critically important, and that our PSF-fitted photometry is not biased.

The transformed photometry is given in Table 2 under reference codes (1) and (3) and plotted in Figure 2 together with the new data presented here. In addition to providing a consistently calibrated bridge between the photometry of Galama et al. (1998) and that of Sollerman et al. (2002), the CTIO observations define the slope of the early exponential tail in *U*, which was not known.

3.2. The Unreddened Rest-frame Light Curves

To compute the intrinsic light curve of SN 1998bw, it is necessary to correct the photometry for the effect of extinction by foreground material and apply *K*-corrections to transform it to the rest frame of ESO184-G82. It is always a challenge to compute the extinction toward an object of exotic type, like SN 1998bw, because the intrinsic colors are not known. All the

Table 2
Photometry of SN 1998bw Transformed to CTIO System

JD[a]	U	B	V	R_C	I_C	Ref.[b]
930.13	...	...	15.88 ± 0.08	15.74 ± 0.07	...	(1)
930.25	...	...	...	15.77 ± 0.06	...	(1)
930.31	...	...	15.93 ± 0.08	15.74 ± 0.07	...	(1)
931.30	...	15.98 ± 0.07	...	15.94 ± 0.11	...	(1)
931.92	...	...	...	15.69 ± 0.06	...	(1)
932.19	...	...	15.55 ± 0.08	15.59 ± 0.07	...	(1)
932.22	...	...	...	15.59 ± 0.09	...	(1)
934.83	...	...	...	14.84 ± 0.08	...	(1)
936.84	...	14.81 ± 0.06	14.36 ± 0.05	14.41 ± 0.05	...	(1)
937.91	14.53 ± 0.05	14.57 ± 0.08	14.19 ± 0.06	14.21 ± 0.06	14.21 ± 0.04	(1)
939.83	14.23 ± 0.26	14.46 ± 0.06	14.00 ± 0.05	14.02 ± 0.05	14.03 ± 0.04	(1)
940.28	...	14.48 ± 0.07	14.01 ± 0.06	13.98 ± 0.06	14.00 ± 0.04	(1)
941.83	14.16 ± 0.05	14.36 ± 0.05	13.88 ± 0.05	13.90 ± 0.05	13.92 ± 0.03	(1)
942.27	...	14.38 ± 0.08	13.90 ± 0.07	13.85 ± 0.07	13.87 ± 0.05	(1)
942.83	14.15 ± 0.04	14.33 ± 0.05	13.85 ± 0.05	13.86 ± 0.05	13.87 ± 0.03	(1)
943.29	...	14.36 ± 0.11	13.87 ± 0.08	13.82 ± 0.07	13.82 ± 0.05	(1)
944.76	14.11 ± 0.11	14.32 ± 0.07	13.78 ± 0.08	13.79 ± 0.08	13.80 ± 0.04	(1)
946.90	...	...	13.76 ± 0.13	13.73 ± 0.07	...	(1)
947.90	...	...	13.82 ± 0.06	...	...	(1)
948.90	14.48 ± 0.07	14.53 ± 0.06	13.87 ± 0.06	13.78 ± 0.05	13.79 ± 0.05	(1)
949.88	...	...	13.90 ± 0.06	...	...	(1)
950.72	...	14.65 ± 0.12	13.95 ± 0.08	13.82 ± 0.12	...	(1)
950.89	14.71 ± 0.05	14.68 ± 0.10	13.97 ± 0.08	13.82 ± 0.08	13.81 ± 0.05	(1)
951.85	14.81 ± 0.07	14.79 ± 0.08	14.03 ± 0.07	13.85 ± 0.07	13.84 ± 0.04	(1)
952.81	14.98 ± 0.10	14.93 ± 0.07	14.09 ± 0.06	13.89 ± 0.07	13.87 ± 0.04	(1)
953.74	15.10 ± 0.05	15.01 ± 0.06	14.13 ± 0.06	13.92 ± 0.06	13.88 ± 0.04	(1)
954.10	...	...	14.13 ± 0.06	13.96 ± 0.06	13.85 ± 0.04	(1)
954.85	...	...	14.21 ± 0.06	13.97 ± 0.06	...	(1)
954.88	15.33 ± 0.10	15.15 ± 0.08	14.24 ± 0.06	13.94 ± 0.12	13.93 ± 0.08	(1)
955.20	15.29 ± 0.26	15.08 ± 0.22	14.17 ± 0.14	13.97 ± 0.13	13.91 ± 0.07	(1)
955.86	...	...	...	14.03 ± 0.12	...	(1)
955.88	15.40 ± 0.04	15.26 ± 0.09	14.30 ± 0.07	14.02 ± 0.07	13.97 ± 0.04	(1)
956.80	15.47 ± 0.06	15.30 ± 0.07	14.34 ± 0.06	14.07 ± 0.07	13.97 ± 0.05	(1)
959.17	15.82 ± 0.04	15.51 ± 0.05	14.48 ± 0.05	14.19 ± 0.05	14.02 ± 0.05	(1)
960.13	16.02 ± 0.05	15.58 ± 0.06	14.56 ± 0.07	14.24 ± 0.06	14.06 ± 0.04	(1)
961.66	15.98 ± 0.04	15.69 ± 0.05	14.65 ± 0.06	14.40 ± 0.08	14.14 ± 0.08	(1)
962.08	16.22 ± 0.04	15.79 ± 0.13	...	14.33 ± 0.05	...	(1)
964.12	...	15.91 ± 0.05	14.83 ± 0.05	14.42 ± 0.05	14.29 ± 0.03	(1)
965.80	16.28 ± 0.05	15.98 ± 0.05	14.92 ± 0.05	14.54 ± 0.05	14.42 ± 0.04	(1)
966.87	16.36 ± 0.04	16.05 ± 0.05	14.99 ± 0.05	14.60 ± 0.05	14.48 ± 0.03	(1)
967.82	16.44 ± 0.04	16.08 ± 0.05	15.03 ± 0.05	14.63 ± 0.05	14.55 ± 0.03	(1)
968.81	16.46 ± 0.05	16.10 ± 0.05	15.08 ± 0.05	14.70 ± 0.05	14.56 ± 0.03	(1)
969.06	...	...	15.03 ± 0.05	14.72 ± 0.05	14.47 ± 0.03	(1)
969.76	16.44 ± 0.05	16.17 ± 0.02	15.14 ± 0.01	14.76 ± 0.01	14.58 ± 0.01	(2)
970.22	...	16.18 ± 0.09	15.13 ± 0.07	14.77 ± 0.06	14.54 ± 0.04	(1)
970.87	16.51 ± 0.04	16.19 ± 0.05	15.18 ± 0.05	14.80 ± 0.05	14.66 ± 0.04	(1)
971.89	16.58 ± 0.04	16.25 ± 0.05	15.22 ± 0.05	14.84 ± 0.05	14.71 ± 0.04	(1)
975.06	...	16.21 ± 0.10	...	14.95 ± 0.05	...	(1)
981.04	...	16.40 ± 0.05	...	15.14 ± 0.05	...	(1)
983.58	16.84 ± 0.11	16.48 ± 0.07	15.59 ± 0.06	15.22 ± 0.06	15.01 ± 0.04	(1)
984.63	16.89 ± 0.07	16.55 ± 0.08	15.63 ± 0.06	15.28 ± 0.06	15.06 ± 0.08	(1)
985.69	16.92 ± 0.04	16.57 ± 0.05	15.65 ± 0.05	15.29 ± 0.05	15.09 ± 0.03	(1)
986.04	...	...	...	15.22 ± 0.06	...	(1)
988.83	16.87 ± 0.05	16.62 ± 0.01	15.74 ± 0.00	15.38 ± 0.01	15.11 ± 0.01	(2)
998.74	17.06 ± 0.05	16.77 ± 0.02	15.95 ± 0.01	15.60 ± 0.02	15.31 ± 0.02	(2)
999.73	17.03 ± 0.05	16.78 ± 0.01	15.98 ± 0.01	15.64 ± 0.01	15.34 ± 0.01	(2)
1000.76	17.18 ± 0.06	16.81 ± 0.03	16.00 ± 0.02	15.67 ± 0.02	15.37 ± 0.02	(2)
1001.70	...	16.80 ± 0.02	16.00 ± 0.02	15.66 ± 0.02	15.35 ± 0.02	(2)
1003.69	17.13 ± 0.05	16.85 ± 0.02	16.06 ± 0.01	15.73 ± 0.01	15.42 ± 0.01	(2)
1004.80	17.14 ± 0.05	16.87 ± 0.01	16.08 ± 0.01	15.75 ± 0.01	15.45 ± 0.01	(2)
1005.70	17.16 ± 0.05	16.87 ± 0.02	16.10 ± 0.01	15.78 ± 0.01	15.46 ± 0.01	(2)
1006.72	17.19 ± 0.05	16.89 ± 0.01	16.12 ± 0.01	15.80 ± 0.01	15.49 ± 0.01	(2)
1007.60	17.22 ± 0.04	16.90 ± 0.01	16.14 ± 0.01	15.82 ± 0.01	15.51 ± 0.01	(2)
1008.72	17.14 ± 0.05	16.92 ± 0.01	16.16 ± 0.01	15.84 ± 0.01	15.53 ± 0.01	(2)
1015.57	17.32 ± 0.04	17.02 ± 0.01	16.29 ± 0.01	15.99 ± 0.01	15.67 ± 0.01	(2)
1059.57	...	17.71 ± 0.02	17.14 ± 0.01	16.85 ± 0.01	16.60 ± 0.02	(2)

Table 2
(Continued)

JD[a]	U	B	V	R_C	I_C	Ref.[b]
1069.00	...	...	17.35 ± 0.07	17.04 ± 0.07	16.75 ± 0.04	(3)
1088.55	...	18.19 ± 0.02	17.69 ± 0.01	17.33 ± 0.01	17.12 ± 0.02	(2)
1143.00	...	...	18.72 ± 0.07	18.12 ± 0.07	17.93 ± 0.06	(3)
1255.00	...	21.18 ± 0.08	20.76 ± 0.06	19.85 ± 0.06	19.70 ± 0.04	(3)
1276.00	...	21.53 ± 0.05	21.11 ± 0.05	20.19 ± 0.04	...	(3)
1280.00	...	...	...	...	20.08 ± 0.05	(3)
1285.00	...	21.63 ± 0.10	21.26 ± 0.08	20.24 ± 0.07	20.01 ± 0.05	(3)
1319.00	...	22.16 ± 0.05	21.74 ± 0.05	20.96 ± 0.05	20.93 ± 0.07	(3)
1342.00	...	...	22.08 ± 0.08	21.16 ± 0.08	21.01 ± 0.05	(3)
1346.00	...	22.54 ± 0.08	22.12 ± 0.07	21.30 ± 0.07	21.11 ± 0.05	(3)
1399.00	...	...	22.82 ± 0.09	22.18 ± 0.09	22.06 ± 0.11	(3)
1432.00	...	23.51 ± 0.09	23.04 ± 0.10	22.57 ± 0.08	22.48 ± 0.11	(3)
1467.00	...	...	23.40 ± 0.38	23.03 ± 0.21	23.23 ± 0.48	(3)

Notes.
[a] Mean Julian Date −2450000.
[b] References for photometry are (1) Galama et al. 1998; (2) this work; (3) Sollerman et al. 2002.

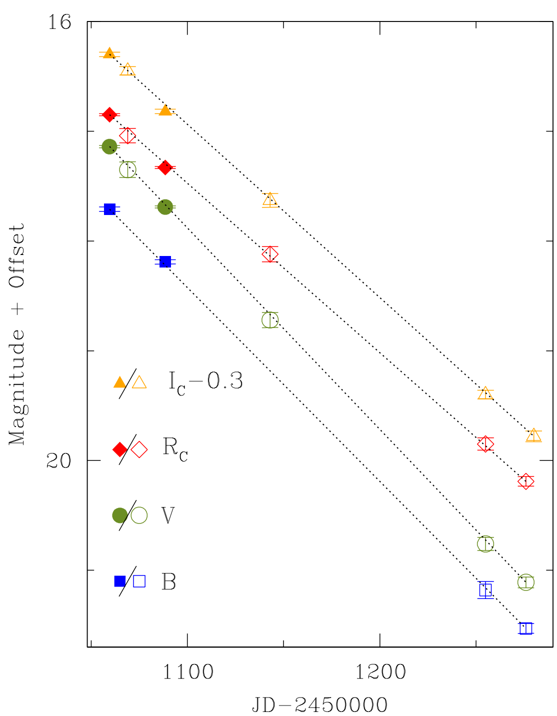

Figure 3. Expanded view of the region of overlap between the CTIO observations and those of Sollerman et al. (2002). Solid symbols correspond to the last epochs of CTIO photometry (Table 2 under reference number (2)); open symbols correspond to the first epochs observed by Sollerman et al. (2002). For each passband, dotted straight lines connect the first and last observation plotted.

(A color version of this figure is available in the online journal.)

indications, however, suggest that the amount of foreground matte between us and the SN is small. The Galactic dust toward ESO184-G82 contributes $A_V \sim 0.2$, according to Schlegel et al. (1998), which is an increase from the earlier value of $A_V \sim 0.05$ given by Burstein & Heiles (1982). Patat et al. (2001) obtained high-resolution spectra of SN 1998bw near maximum light. They did not find Na D absorption lines at either the redshift of ESO184-G82 or at zero and set upper limits to the extinction which are consistent even with the higher estimate of Schlegel et al. (1998).

The peculiarities of the spectrum of SN 1998bw and the fact that it evolves in time prompted us to compute a time-dependent extinction in each passband using the excellent series of spectra of Patat et al. (2001), which is publicly available. We took the transmittance of the $BV(RI)_C$ passbands given by Bessell (1990), transformed them from energy-based to photon-based units, convolved them with a typical CCD quantum efficiency, the spectral response of two aluminum coated surfaces, and a typical response of the sky telluric absorption bands, and used this combined sensitivity curve to compute the difference in magnitudes between the unreddened and reddened spectra of SN 1998bw. The differences between the extinction computed in this way and a constant are small but they vary with time, allowing for small systematic changes in the trends of the light curves.

The extinction law for GRBs has received some attention (see Liang & Li 2010, and references therein). It has been found that, in some cases, the extinction estimated from the GRB spectrum is different from that of the Milky Way or Magellanic Clouds. When there are differences, however, they are typically marked in the UV, at wavelengths below ∼2500 Å, and modest at longer wavelengths. This, together with the low estimate of the extinction toward SN 1998bw, makes it reasonable to assume a typical Milky Way extinction law to unredden the lights curves presented here. We take as a model the extinction curve of Cardelli et al. (1989) with $R_V = 3.1$.

Similar considerations apply to the *K*-corrections, which, at the redshift of ESO184-G82 ($z = 0.0087$; Foley et al. 2006), are expected to be small, but still variable in time. We used the passbands of Bessell (1990), prepared as stated above, and the spectra of Patat et al. (2001) to compute the time-dependent *K*-corrections of SN 1998bw.

Using the computed reddening and *K*-corrections unreddened and transformed to the rest frame, the photometry of SN 1998bw is given in Table 2. The results, fitted with low-degree piecewise polynomial and/or spline fits to provide daily sampling, are presented in Table 3. The uncertainties given in the table are the result of combining the uncertainties of photometry, reddening, and *K*-corrections in quadrature.

With the multicolor rest-frame photometry, it is possible to convert the observed single-bandpass light curves into monochromatic fluxes at the effective wavelengths of the passbands, integrate them over frequency, and obtain

Table 3
Intrinsic Light Curve of SN 1998bw

JD[a]	Phase[b]	U_0	B_0	V_0	R_C	I_C	$F_{UBV(RI)_C}$[c]	$F_{BV(RI)_C}$[c]
938	8.5	14.20 ± 0.04	14.36 ± 0.12	13.98 ± 0.08	14.03 ± 0.08	14.05 ± 0.01	520.973 ± 39.134	403.065 ± 29.406
941	11.5	13.83 ± 0.02	14.10 ± 0.01	13.67 ± 0.01	13.72 ± 0.02	13.80 ± 0.01	683.884 ± 6.995	528.501 ± 5.135
943	13.5	13.75 ± 0.04	14.02 ± 0.01	13.56 ± 0.03	13.59 ± 0.02	13.70 ± 0.01	749.795 ± 12.392	583.606 ± 9.806
945	15.5	13.79 ± 0.03	14.03 ± 0.01	13.51 ± 0.01	13.52 ± 0.02	13.65 ± 0.01	772.324 ± 8.626	608.760 ± 6.209
948	18.4	14.02 ± 0.02	14.16 ± 0.01	13.55 ± 0.01	13.50 ± 0.02	13.63 ± 0.01	732.902 ± 8.147	592.157 ± 6.288
950	20.4	14.25 ± 0.01	14.31 ± 0.02	13.63 ± 0.02	13.53 ± 0.03	13.64 ± 0.01	674.712 ± 11.467	555.124 ± 9.836
955	25.4	14.95 ± 0.03	14.81 ± 0.02	13.95 ± 0.01	13.73 ± 0.02	13.75 ± 0.01	499.760 ± 7.093	428.436 ± 5.743
965	35.3	15.93 ± 0.02	15.64 ± 0.01	14.63 ± 0.01	14.27 ± 0.03	14.19 ± 0.02	276.104 ± 3.807	244.144 ± 3.467
970	40.3	16.14 ± 0.04	15.84 ± 0.04	14.87 ± 0.01	14.51 ± 0.03	14.44 ± 0.03	222.657 ± 5.377	196.032 ± 4.304
975	45.2	16.28 ± 0.01	15.97 ± 0.06	15.07 ± 0.01	14.72 ± 0.01	14.64 ± 0.01	187.186 ± 2.876	163.734 ± 1.791
1016	85.9	16.95 ± 0.02	16.71 ± 0.01	16.03 ± 0.01	15.77 ± 0.01	15.52 ± 0.01	80.130 ± 0.311	68.060 ± 0.222
1090	159.3	...	17.92 ± 0.01	17.45 ± 0.01	17.15 ± 0.01	16.89 ± 0.03	...	19.382 ± 0.133
1232	300.1	...	20.47 ± 0.01	20.08 ± 0.01	19.29 ± 0.01	19.07 ± 0.01	...	2.204 ± 0.017
1332	399.2	...	22.02 ± 0.01	21.69 ± 0.02	20.94 ± 0.67	20.70 ± 0.07	...	0.495 ± 0.131
1432	498.4	...	23.18 ± 0.01	22.82 ± 0.04	22.38 ± 0.01	22.33 ± 0.06	...	0.145 ± 0.004

Notes.
[a] Mean Julian Date −2450000.
[b] Rest-frame days after GRB.
[c] Units are 10^{40} erg cm^{-2} s^{-1}. Uncertainty does not include the ∼7% uncertainty in the distance.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

quasi-bolometric light curves that include the energy output in all the observed bands (Suntzeff & Bouchet 1990). We used the zero points of Bessell (2000) and integrated the monochromatic fluxes using a trapezoid rule. We did not extrapolate the flux beyond the limits of the U (or B) and I_C passbands. The distance to ESO 184-G082 was taken to be 37.3 ± 2.6 Mpc, as computed by the NED database[7] from the redshift measured by Foley et al. (2006), a Hubble constant of 74.2 km s^{-1} Mpc^{-1} (Riess et al. 2009), and a model of the local velocity field given by Mould et al. (2000). The $UBV(RI)_C$ and $BV(RI)_C$ luminosities have been included in Table 3.

4. CONCLUSIONS

We present 72 new photometric observations of SN 1998bw in the $UBV(RI)_C$ bands, spanning from ∼40 up to ∼60 days after the GRB. Our U data extend the previously known coverage by about 30 days and sample the early exponential tail.

We collect previously published photometry and transform it to our realization of the standard system using relative zero points and color terms measured from the common local standard sequence. We show that data from different sources merge smoothly, providing a homogeneous set of 300 observations covering about 500 days since the explosion.

Finally, we use the extensive series of spectra in the public domain to compute time-dependent reddening and K-corrections and compute the unreddened rest-frame multicolor and quasi-bolometric light curves. We fit them with low-degree piecewise splines to provide daily sampling and present the results as a table.

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