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The Late-Time Light Curve of SN 1998bw Associated with GRB 980425

ERIC H. MCKENZIE[1] AND BRADLEY E. SCHAEFER[2]
Department of Physics, Yale University, 260 Whitney Avenue, JWG 463, New Haven, CT 06520-8120
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ABSTRACT. We report 139 photometric observations through the *B*, *V*, and *I* filters of the supernova SN 1998bw, an object which is associated with the gamma-ray burst GRB 980425. Detailed light curves of this unique supernova can be compared with theoretical models, so we report here our light curve for 123 days between 1998 June 27 and 1998 October 28. The light curve of SN 1998bw is consistent with those of the Type Ic class. We find that the magnitude versus time relation for this supernova is linear to within 0.05 mag in all colors over the entire duration of our study. Our measured uniform decline rates are 0.0141 ± 0.0002, 0.0184 ± 0.0003, and 0.0181 ± 0.0003 mag per day in the *B*, *V*, and *I* bands. The linear decline and the rate of that decline suggest that the late-time light curve is powered by the radioactive decay of cobalt with some leakage of the gamma rays.

1. INTRODUCTION

In their search for an optical counterpart for the gamma-ray burst GRB 980425, Galama et al. (1998) detected SN 1998bw in the galactic arm of ESO 184-G82 (EOP 184-82), which Tinney et al. (1998) determined to have a redshift of 0.0085 ± 0.0002. The supernova's light curves rose sharply after the burst, and its spatial coordinates were well within the burst's error box, strongly suggesting a connection between the two events. The probability of their independence was estimated by Galama et al. (1998) at 1.1×10^{-4}. However, *BeppoSAX* also detected a fading X-ray source (generally thought to be the hallmark of the burst counterpart) at a position inconsistent with SN 1998bw (Pian et al. 1998a, 1998b, 1998c, 1999; Piro et al. 1998), so the relationship between SN 1998bw and GRB 980425 is unclear. Further observations showed that SN 1998bw is positionally coincident with a second *BeppoSAX* X-ray source which has faded by a factor of 2 in brightness from 1999 April 26 to November 10, which is consistent with X-ray emission from a supernova plus the galaxy (Pian et al. 1999).

SN 1998bw has peculiar and unique properties other than a possible association with a gamma-ray burst. Its spectrum is unique (although two Type Ic supernovae have somewhat similar spectra; see Iwamoto et al. 1998) and displays ejection velocities measured from the blue wings of the Ca II line as high as 60,000 km s^{-1} (Kulkarni et al. 1998). Its emissions at radio wavelengths increased much more quickly than other supernovae, and it is also the most luminous supernova to date at radio wavelengths (Kulkarni et al. 1998). These coincidences of unusual properties greatly strengthen the connections between GRB 980425 and SN 1998bw. In general, a consensus has emerged that the burst is related to the supernova, and this has inspired much research detailing connections between the two phenomena.

Because of the unique and pivotal nature of SN 1998bw, it is imperative that the light curve be tracked in a wide range of optical bands as long as possible. Galama et al. (1998) tracked the *U*, *B*, *V*, *R*, and *I* light curves for 58 days after the burst, and these showed a typical peak as generally seen for supernovae of many types. In the interests of recording as much data as possible for such an unprecedented event, we followed up on their results with further observations in the *B*, *V*, and *I* filters.

2. OBSERVATIONS

The data were obtained using the Yale 1 m telescope, at the Cerro Tololo Inter-American Observatory in Chile, from 1998 June 27 through October 28. Our series of observations commenced as soon as the refurbishing of the Yale 1 m telescope had been completed and the CCD camera installed. The images' pixel size was 0″.30, with a field of view of 10′.2 × 10′.2. Our exposure times were always 300 s per image, using *B*, *V*, and *I* filters. Our typical seeing had an FWHM of 1″.2. We obtained 139 measures of the brightness of SN 1998bw.

[1] eric.mckenzie@yale.edu.

[2] schaefer@grb2.physics.yale.edu.

The images were first processed with the normal procedure for overscan correction, bias subtraction, and flat-fielding. Our photometric analyses were made with IRAF's program APPHOT. We used apertures of only 3 pixel radius to minimize interference from the parent galaxy, which was a sufficient size because of the high signal-to-noise ratio. Our background annuli were constructed with inner and outer radii of 30 and 40 pixels centered on the star, with the sky background taken as the mode within this annulus. The deduced sky background for the supernova is close to that deduced for isolated stars.

For each image, observed magnitudes were recorded for SN 1998bw and for five comparison stars. We used the updated magnitudes provided by T. Galama et al.,[3] choosing numbers 4, 6, 7, 9, and 10 because they were relatively bright. Comparison star 2 was excluded because its data were just erratic enough to arouse suspicion that it might be a small-amplitude variable star, although it is was not definitively identified as such.

We were able to estimate our magnitude uncertainties by comparing the standard stars with each other in a variety of images. These errors were determined to be substantially dependent on the apparent magnitudes of the stars due to the normal Poisson variations, which is why we used the brightest ones for our data analysis. Monitoring the differences between the standard stars in each image also enables us to catch photometric problems with the standard stars (due to cosmic rays, bad columns, etc.). A few nights had large uncertainty due to clouds or bad seeing. Our results are that in general we have systematic uncertainty of 0.02 mag added in quadrature with the statistical errors reported by IRAF. For the supernova, the statistical errors are generally substantially smaller than our systematic errors in the early portions of our light curve. The comparison stars are fainter than the supernova, yet our use of the average of five stars as our "standard" improves the accuracy of this "standard" to $\sim$0.01 mag. In all, the uncertainties in our supernova magnitudes typically range from 0.02 to 0.04 mag.

SN 1998bw appears in the spiral arm of its host galaxy, so we must consider the effects of the galaxy light in our photometry. Fortunately, the supernova was quite bright during the entire duration of our study, and the contribution of light from the spiral arm is minimal. To be quantitative, we have measured the surface brightness of the center of the spiral arm on both sides of the supernova and compared this with the total brightness within our photometric aperture centered on the supernova. Images of the galaxy from before the supernova show the brightness along the spiral arm to be uniform along the position of the supernova, so we know that there are no significant knots or stars at the supernova position. At the beginning of our light curve, the contamination from galaxy light in our photometry aperture varied from 0.5% to 0.8% for the three filters. So we have a systematic error which is smaller than our quoted uncertainties that will make the supernova slightly fainter than tabulated. Ideally, we should wait several years for the transient to fade to invisibility, then get further images with our same equipment and subtract off the galaxy light; but in the meantime the systematic error is known to be small.

For each image, we compared the instrumental magnitude of the supernova to the average instrumental magnitude of the five standard stars. This difference was then applied to the average of the standard stars' actual magnitudes taken from the Galama et al. Finding Chart to determine the actual magnitude of SN 1998bw. Our results are plotted in Figure 1 (along with Galama's earlier results) and tabulated in Table 1.

We are impressed with the remarkable linearity of our portion of the light curves. The best-fit lines to our data are displayed in Figure 1, and we see no significant systematic deviation from perfect lines at any time or in any color. Our limits on systematic deviations are less than 0.05 for our entire 123 day observation time. In the *B* filter, the light is declining at 0.0141 ± 0.0002 mag per day, which corresponds to a radioactive half-life of 53.4 ± 0.8 days. For *V*, these figures are 0.0194 ± 0.0003 mag per day, with a corresponding radioactive half-life of 40.9 ± 0.7 days. For *I*, the figures are 0.0181 ± 0.0003 mag per day and a half-life of 41.6 ± 0.7 days.

The *B* light curve has a somewhat slower decay than in the *V* and *I* bands. For an extinction of $A_v = 0.2$ (Galama et al. 1998), the supernova's $B-V$ was 0.82 mag at the beginning of our observation period and around 0.3 mag toward the end. The extinction-corrected $V-I$ rose by a small amount, from 0.53 to 0.60 mag, during the same time period.

With our *B*, *V*, and *I* light curves, we can approximate the bolometric light curve for radiation from the ultraviolet to the infrared. We have done this by first correcting for galactic extinction ($A_v = 0.20$), converting our magnitudes into f_v, adopting a power-law spectrum from *B* to *V* and from *V* to *I*, adopting a Rayleigh-Jeans spectrum for lower frequencies than *I*, adopting a Wien spectrum for higher frequencies than *B*, and integrating the spectrum. For JD 2,450,996 (68 days after the burst) we get a bolometric flux of 1.1×10^{-11} ergs cm^{-2} s^{-1} or a bolometric luminosity of 2.0×10^{42} ergs s^{-1}. For JD 2,451,098 (170 days after the burst) we get a bolometric flux of 2.1×10^{-12} ergs cm^{-2} s^{-1} or a bolometric luminosity of 3.9×10^{41} ergs s^{-1}. For the conversion to luminosity, we adopted a velocity of 2550 km s^{-1} and a Hubble constant of 65 km s^{-1} Mpc^{-1}, for a distance of 39 Mpc. These calculated luminosities have significant uncertainties arising from the extinction ($\sim$10%),

[3] See their 1998 Finding Chart for GRB 980425/SN 1998bw (http://www.astro.uva.nl/~titus/grb980425/grb980425chart.html), hereafter Galama et al. Finding Chart.

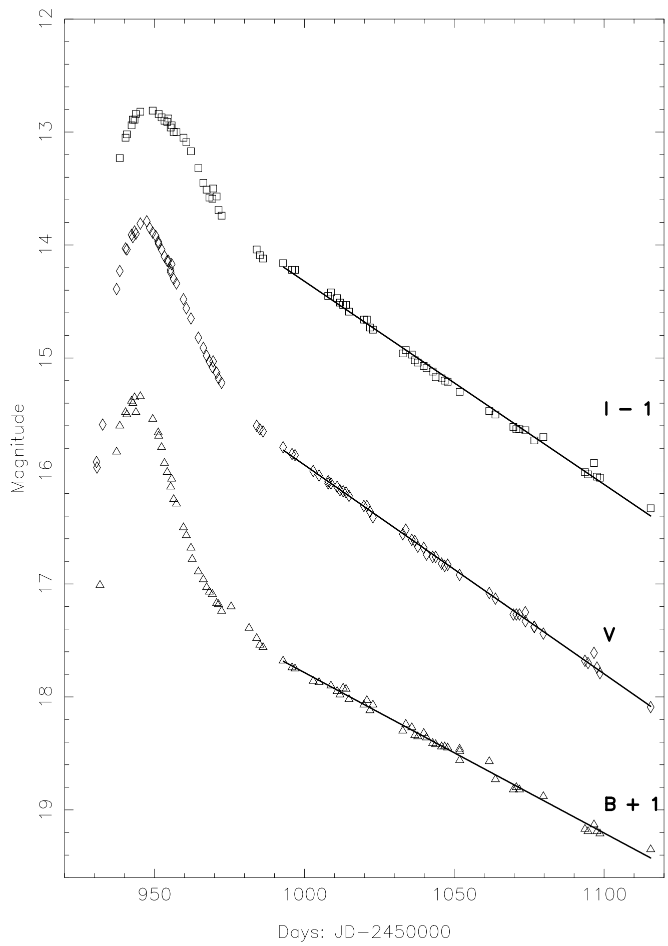

FIG. 1.—*B*, *V*, and *I* light curves for SN 1998bw. Galama et al. (1998) data are all from before day 986 (JD 2,450,986) while ours begin on day 992 (JD 2,450,992). The best-fit lines show a remarkably good fit to our measured late-time observations with no significant deviations at any time or in any color. The corresponding decay half-lives are 53.4 ± 0.8, 40.9 ± 0.7, and 41.6 ± 0.7 days in *B*, *V*, and *I*, respectively. The closeness of the magnitude vs. time relation to a line and the similarity of the decline rates with those for Type Ia supernovae are suggestive that the decay of radioactive cobalt might be the source powering the tail with leakage of gamma radiation. The overall light curve shape is similar to those of Type Ia, Ib, Ic, and IIL supernovae. Our measurements with greater than 0.1 mag are not represented in this chart (see Table 1).

bolometric correction ($\sim$30%), and distance ($\sim$20%), so that overall errors perhaps as large as $\sim$50% might be present. The effective half-life for this decline is 44 days.

3. COMPARISON WITH OTHER SUPERNOVA

SN 1998bw has many unique and extreme properties, however, at first look, its light curve appears to be that of a normal supernova. Is the light curve unique? We will compare our light curve with those of Type Ia, Ib, Ic, and II supernovae in turn.

For the majority of Type Ia events, the *B* light curve fades

TABLE 1

SN 1998bw LIGHT CURVE

JD − 2,450,000	*B*	*V*	*I*
992.89	16.68 ± 0.03	15.79 ± 0.02	15.16 ± 0.03
995.88	16.74 ± 0.03	15.85 ± 0.02	15.22 ± 0.02
996.88	16.75 ± 0.03	15.86 ± 0.02	15.22 ± 0.02
1002.92	16.86 ± 0.03	16.00 ± 0.03	...
1004.88	16.87 ± 0.03	16.04 ± 0.03	...
1007.93	...	16.09 ± 0.03	15.45 ± 0.03
1007.94	...	16.11 ± 0.03	...
1008.87	16.90 ± 0.04	16.11 ± 0.03	15.42 ± 0.04
1010.90	16.95 ± 0.03	16.14 ± 0.03	15.47 ± 0.03
1011.88	16.98 ± 0.04	16.17 ± 0.02	15.51 ± 0.03
1012.92	16.92 ± 0.03	16.18 ± 0.03	15.53 ± 0.03
1013.90	16.93 ± 0.03	16.19 ± 0.03	15.53 ± 0.03
1014.90	17.02 ± 0.03	16.22 ± 0.02	15.59 ± 0.03
1019.87	17.07 ± 0.03	16.31 ± 0.02	15.66 ± 0.03
1020.86	17.03 ± 0.03	16.31 ± 0.03	15.66 ± 0.03
1021.86	17.12 ± 0.03	16.36 ± 0.02	15.73 ± 0.03
1022.86	17.07 ± 0.03	16.41 ± 0.03	15.75 ± 0.03
1032.84	17.30 ± 0.05	16.56 ± 0.03	15.96 ± 0.03
1033.84	17.24 ± 0.07	16.52 ± 0.04	15.93 ± 0.04
1035.84	17.27 ± 0.04	16.61 ± 0.03	15.97 ± 0.03
1036.84	17.34 ± 0.03	16.62 ± 0.03	16.02 ± 0.03
1037.83	17.35 ± 0.03	16.67 ± 0.02	16.04 ± 0.03
1039.82	17.32 ± 0.03	16.68 ± 0.02	16.07 ± 0.03
1040.77	17.36 ± 0.03	16.74 ± 0.02	16.09 ± 0.03
1041.80	...	16.75 ± 0.02	...
1041.84	17.39 ± 0.03	16.84 ± 0.04	...
1042.82	17.41 ± 0.03	16.76 ± 0.02	16.12 ± 0.03
1043.81	17.42 ± 0.03	16.76 ± 0.02	16.17 ± 0.03
1045.80	17.44 ± 0.03	16.82 ± 0.02	16.18 ± 0.03
1046.79	17.43 ± 0.03	...	...
1046.80	17.44 ± 0.03	16.84 ± 0.02	16.20 ± 0.03
1047.81	17.45 ± 0.03	16.83 ± 0.02	16.21 ± 0.03
1051.79	17.46 ± 0.03	16.92 ± 0.02	...
1051.80	17.48 ± 0.03	...	...
1051.80	17.56 ± 0.03	...	16.30 ± 0.03
1061.70	17.57 ± 0.06	17.08 ± 0.04	16.47 ± 0.03
1062.76	17.57 ± 0.15	16.85 ± 0.15	...
1062.76	...	16.92 ± 0.15	...
1063.75	17.73 ± 0.04	17.13 ± 0.03	16.50 ± 0.03
1064.76	17.61 ± 0.13	17.28 ± 0.18	16.75 ± 0.27
1069.73	17.82 ± 0.03	17.27 ± 0.02	16.61 ± 0.03
1070.73	17.80 ± 0.03	17.27 ± 0.02	16.63 ± 0.03
1071.76	17.82 ± 0.04	17.27 ± 0.03	16.63 ± 0.03
1073.72	...	17.25 ± 0.03	...
1073.73	...	17.33 ± 0.03	16.64 ± 0.03
1076.70	...	17.38 ± 0.03	...
1076.71	...	17.38 ± 0.03	16.73 ± 0.03
1079.73	17.88 ± 0.03	17.44 ± 0.03	16.70 ± 0.03
1093.62	18.17 ± 0.04	17.68 ± 0.03	17.01 ± 0.03
1094.63	18.19 ± 0.04	17.70 ± 0.03	17.03 ± 0.03
1096.63	18.13 ± 0.05	17.61 ± 0.04	16.93 ± 0.05
1097.63	18.19 ± 0.03	17.74 ± 0.03	17.05 ± 0.03
1098.62	18.21 ± 0.03	17.79 ± 0.03	17.06 ± 0.03
1115.55	18.35 ± 0.06	18.09 ± 0.05	17.33 ± 0.06

by 1.1 mag in the first 15 days after peak (Hamuy 1996a), while SN 1998bw has the same drop. The usual slope of the late-time B light curve is 0.01516 ± 0.00024 mag day^{-1} for Type Ia events (Barbon et al. 1984) and is easily compatible with that of SN 1998bw. However, the decline rates in V and I differ substantially between most of the Type Ia events and SN 1998bw (0.0184 vs. 0.024 and 0.0181 vs. 0.041 mag per day, respectively) from 70–80 days after peak. A second important difference is that almost all Type Ia events display a prominent bump in the I-band light curves from 20 to 50 days after peak (Hamuy et al. 1996a; Riess et al. 1999), while SN 1998bw does not show any sign of such a bump. A third difference is that SN 1998bw has a peak absolute magnitude of -18.88 ± 0.05 (Galama et al. 1998) whereas the majority of Type Ia events have peak absolute magnitudes of -19.26 (Hamuy et al. 1996b). However, uncertainties in distance and extinction can perhaps be as large as a third of a magnitude, so this third difference may not be significant. A fourth difference is that the extinction-corrected color at peak of SN 1998bw is $B-V = 0.47 \pm 0.07$ mag (Galama et al. 1998) while the usual value for Type Ia events is 0.00 mag (Hamuy et al. 1996b). So, in all, the light curve of SN 1998bw looks similar to that of Type Ia events, yet detailed parameters are quantitatively different.

Perhaps a closer match can be found with the anomalous Type Ia SN 1991bg (Leibundgut et al. 1993; Filippenko et al. 1992). This event had a substantially redder peak color ($B-V \sim 0.8$), a much lower peak absolute magnitude ($M_B = -16.62$), and no bump in the I-band light curves. While the detailed light curve (and spectrum) of SN 1991bg is still different from that SN 1998bw, we note that many of the properties are more like those of SN 1991bg than of normal Type Ia events.

Type Ib and Ic light curves have not been characterized as closely as those of Type Ia supernovae. Nevertheless, enough is known (see, e.g., Uomoto & Kirshner 1986; Ensman & Woosley 1988; Clocchiatti et al. 1997) to find similarities and differences with SN 1998bw. The overall light curve of Type Ib and Ic events is the same for SN 1998bw with similar decline rates over the first 15 days. The late-time decline rate of Type Ic events vary, apparently with two classes, as slow and fast decliners. The 60–180 day decline rates of roughly 0.016 mag per day are seen for the Type Ic events SN 1983N and SN 1983V (Clocchiatti et al. 1997) which is comparable to that for SN 1998bw. The color evolution for Type Ic events is similar to that of SN 1998bw, both at peak and at late times. The peak absolute magnitude of Type Ic events vary about $M_B \sim -17.5$, yet are all significantly fainter than SN 1998bw. However, with the few well-measured Type Ic events having a wide scatter, the luminosity of SN 1998bw may not be unusual. In all, SN 1998bw appears to have a light curve within the class of Type Ic events.

Type II supernovae vary greatly in their light curve shape and color (Patat et al. 1993). The colors, peak absolute magnitudes, decline rate of SN 1998bw from peak, and late-time decline rate are all within the normal range for the IIL subclass. Nevertheless, there are some subtle distinctions, such as a total lack of any indication of a plateau in the I band and the switch to the late-time decline rate only ~ 30 days after peak.

In all, the light curve of SN 1998bw is fully consistent with those of Type Ic supernovae, in keeping with the spectral classification and physical models.

4. COMPARISON WITH MODELS

The decay rate of the tail is so close to an exponential that we suggest that this is no coincidence. In addition, the measured decline rate corresponds to that expected from the decay of radio active cobalt (with a half-life of 78.5 days) as modified by the effects due to the expansion of the shell (Colgate & McKee 1969). Hence, it is reasonable to take our light curve as strong evidence that the late-time light curve of SN 1998bw is being powered by the decay of cobalt, with the difference in slope caused by the leakage of gamma radiation from the shell.

Three detailed models have been presented seeking to explain the light curve of SN 1998bw. Iwamoto et al. (1998) and Iwamoto (1999) model the event as an extremely energetic explosion of a massive star stripped down to its carbon/oxygen core. Woosley, Eastman, & Schmidt (1998) independently present a similar model with similar results. Höflich, Wheeler, & Wang (1998) and Wheeler, Höflich, & Wang (1999) present a model with an aspherical explosion in the nondegenerate C/O core of a massive star. An asymmetric event can account for the observed polarization. All three models account for the early light curve, the early colors, and the early spectrum with generally acceptable accuracy.

Iwamoto et al. (1998) and Iwamoto (1999) present predictions for the late-time V light curve of SN 1998bw (see Fig. 1 of Iwamoto 1999) as a perfectly straight line in a log-log plot of flux versus time since the burst, for a predicted power law with slope -2.75. This power-law prediction does not agree with the observed exponential decline. However, K. Nomoto (1999, private communication) has presented a more detailed light curve prediction which shows a more complicated shape (neither a power law nor an exponential) than presented in Iwamoto (1999). The model V magnitude declines by 2.80 mag from June 27 to October 28 with deviations from a simple exponential curve defined by the endpoints of up to 0.22 mag. For comparison, our data shows a decline of 2.26 mag over this same time and maximum departures from a simple exponential decline of less than 0.05 mag.

One way to distinguish the three models is by the explosion energy and the ejected ^{56}Ni mass. The spherically symmetric models have energies and nickel masses of around 3×10^{52} ergs and 0.7 $M_{\odot}$, while the aspherical models have 2×10^{51} ergs and 0.2 $M_{\odot}$. Wheeler, Höflich, & Wang point out that if the late-time light curve tracks the radioactive decay line, then the ejected nickel mass can be determined, and that this might prove the simplest discriminant between models.

One possible method to measure the nickel mass from our light curve is to scale the luminosity in the tail from another supernova of known late-time luminosity and nickel mass. The best case for comparison might be SN 1987A, which has a well-measured light curve (Hamuy et al. 1988), a well-known distance (50 kpc; McCray 1993), and a well-known nickel mass (0.069 ± 0.003 $M_{\odot}$; McCray 1993). On day 170 after the core collapse, SN 1998bw had an extinction-corrected V magnitude of 17.60, while SN 1987A had an extinction-corrected magnitude of 4.39. If SN 1987A were placed at 39 Mpc, then its V magnitude should appear 1.25 mag fainter than we observed for SN 1998bw. This implies a nickel mass 3.2 times larger, or that SN 1998bw has 0.22 $M_{\odot}$. The dominant uncertainty arises from the distance to SN 1998bw, for which peculiar velocities of up to 400 km s^{-1} and uncertainties in the Hubble constant of up to 10 km s^{-1} Mpc^{-1} yield nickel mass uncertainties of 0.09 $M_{\odot}$.

The procedure in the previous paragraph can be only approximate, in particular, since there might be substantial leakage of the gamma rays from the expanding nebula. Such leakage could explain why our observed decline is steeper than that associated with ^{56}Co decay (Clocchiatti & Wheeler 1997). Such leakage would lower the late-time luminosity and lower the deduced nickel mass. The V light curve of SN 1987A declined with the ^{56}Co rate, whereas the V light curve of SN 1998bw declined at roughly twice the rate. The effect of leakage on our previous derived nickel mass can be estimated only within specific models, yet it is likely that our 0.22 ± 0.09 $M_{\odot}$ value must be regarded as a lower limit.

We expect that our late-time light curve will provide a set of observations useful for refining and constraining individual models of the unique SN 1998bw. In particular, our data might constrain the quantity of ejected ^{56}Ni so as to decide between symmetric and asymmetric models. Another challenge to models is to explain the near perfect exponential shape of the light curve even though the slope is not that of the ^{56}Co decay.

We will continue to monitor the brightness of SN 1998bw in 1999. However, the background light from its host galaxy is increasingly a problem for exact photometry.

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