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SUPERNOVAE AS A STANDARD CANDLE FOR COSMOLOGY

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ABSTRACT

Supernovae can perhaps be found at $Z \approx 1$ using the Space Telescope and the Focal Plane Camera (cryogenic charge coupled devices) at a rate of approximately four per week using 3 hours per week of viewing time. If Type II supernovae are used as a self-calibrating candle at $Z \ll 1$, then Type I's can be calibrated from Type II's as a secondary standard candle (2 mag brighter) and used instead of Type II's for a less difficult determination of q_0. This assumes all Type I's are the same independent of Z whereas each Type II is self-calibrated. Adequate statistics of supernovae in nearby galaxies $Z \lesssim 1$ can further verify the uniqueness of Type I's. Three-color wide-band photometry performed over the period of the maximum luminosity of a Type I gives the time dilation $\propto (1 + Z)^{-1}$, color shift $\propto (1 + Z)^{-1}$, and apparent luminosity $\propto Z^{-2}[1 + 0.5(1 + q_0)Z + O(Z)]^{-2}(1 + Z)^{-2}$. A Type I supernova at maximum and $Z = 1$, $H_0 = 50$, should give rise to a statistically meaningful maximum single pixel signal of ~ 250 photoelectrons compared to an average galaxy center background of ~ 25 photoelectrons for an 80 s integration time. An average of ~ 100 large galaxies ($10^{10}\ L_\odot$) per field allows $\sim 10^4$ galaxies to be monitored using 3 hours of viewing time. Z can be determined by time dilation and color shift sufficiently accurately that the determination of q_0 will have twice the error of the calibration of Type I as a standard candle.

Subject headings: cosmology — stars: supernovae

I. INTRODUCTION

The motivation for finding distant supernovae (SN) has been discussed by Wagoner (1977), who showed that the concept of a self-calibrated candle (Kirshner and Kwan 1974; Branch and Patchett 1973) leads to a definitive measurement of H_0 and q_0 if supernovae can be found and measured at reasonably large redshifts ($Z \geq 0.3$). We point out how a small fraction of the Space Telescope time might be used both for such a search and for the simultaneous determination of H_0 and q_0. We also suggest that Type I SN are most likely so similar to one another than they can and should be calibrated by comparison to Type II SN at $Z \lesssim 0.1$ for use as a secondary standard candle that is brighter than Type II's and also has smaller dispersion than Type II's.

In the work cited above it is assumed that Type II SN are a candle that can be self-calibrated. The means of doing this is to measure the temperature assuming a blackbody spectrum and then to measure the expansion velocity from the line profiles. The line profiles calibrate whatever mass fraction constitutes the immediate photosphere. Then, provided the velocity of every mass fraction is constant and *if* the zero time is known, the radius of the expanding photosphere can be calculated and hence the absolute luminosity. The time-dependent behavior of the observed luminosity and color shift (temperature) then gives H_0 directly at small Z, and SN at larger values of Z give q_0.

We find several relative disadvantages to using Type II SN for this purpose compared to using Type I's as a precalibrated candle. These are:

1. Type I's are 2 mag brighter at maximum (Kowal 1968).
2. Type II's occur primarily in spiral arms of Sc and Sb galaxies (Moore 1973; Maza and van den Bergh 1976) with a resulting dispersion in luminosity consistent with a variable absorption of 0.65 mag (Tammann 1978).
3. The use of either Type I's or Type II's as a standard candle requires a measurement of a fiducial time. The observation of light maximum in a Type I at 5–6 days has been observed several times (Barbon, Ciatti, and Rosino 1973), but the light maximum of Type II's is only poorly known (Kirshner *et al.* 1973) and its relation to zero time is not yet defined.
4. Observations of the maximum luminosity of Type I SN gave a dispersion of 0.4 when observed in E galaxies, but are consistent with no dispersion (Tammann 1978). This is qualitatively consistent with a highly specific selection process and mechanism. Currently the most likely evolution of a Type I progenitor involves mass transfer in a binary system (Whelan and Iben 1973). A white dwarf accretes mass until it exceeds the Chandrasekhar limit, hence leading to identical progenitors.
5. Type I's occur in elliptical galaxies and in spirals at roughly equal rates so that a search can take advantage of the increased density of elliptical galaxies in rich clusters.

Type I: $M_p \approx -19.0$
no or weak Balmer lines
Lichtkurven gleichartig

Type II: $M_p \sim -17$
kräftige Balmer linien
[illegible]

II. SUPERNOVA CALIBRATION

The calibration procedure assumes that SN Type II's have an intrinsic dispersion ($\sim$0.6 mag, Kowal 1968) and that they can be self-calibrated. If this dispersion is due to variable absorption in the parent galaxy as argued by Tammann (1978), then the self-calibration procedure cannot reduce the apparent dispersion except by color reconstruction of the absorption. This can be done only with significantly better statistics of Type II SN light curves than currently available. On the other hand, Type I SN with little or no hydrogen in their envelopes and a higher probability of occurrence in old stellar populations are more likely to have a small intrinsic dispersion and less absorption in the parent galaxy. This view that Type I SN have negligible intrinsic dispersion has recently been strongly reinforced by Tammann (1978) who points out that Type I SN observed in E galaxies have indeed the expected smaller dispersion (0.4) as compared to observations of Type I's in Sc and Sb galaxies. The evolution of the presupernova star is inadequately understood, but the occurrence of SN in old populations most likely requires a slow evolution to the critical presupernova state, e.g., by binary mass transfer (Whelan and Iben 1973; Warner 1974). The difficulty of modeling SN would indicate that the structure of the presupernova core should be a near unique one (Paczyński 1970). It is likely, then, that all Type I SN are more nearly identical than even the small dispersion (0.4) observed in E galaxies suggests.

III. TWO POSSIBLE CLASSES OF TYPE I SUPERNOVAE

On the other hand, Barbon, Ciatti, and Rosino (1973) argue for two distinct classes of Type I SN, viz., "fast" ($32^{\rm d}$) and "slow" ($38^{\rm d}$), characterized by a 16% difference in initial decay rates and roughly $\frac{3}{4}$ mag differences at the inflection of the light curve. If this indeed were the case, this would add additional uncertainty for their use as a standard candle; however, the methods for selecting these two classes has been questioned (Tammann 1978). All Type I SN data were plotted and the average curve drawn through the points. The SN lying above the line are considered as a class separate from those lying below the average curve. This *a priori* selection necessarily creates two classes of different characteristics. Subsequent Type I supernovae found in the Coma cluster do not fall into these distinct classes, and thus this observation substantiates the single class hypothesis (Tammann 1978). If, despite this evidence to the contrary, there should prove to be two classes of Type I's, then the correlation of peak luminosity with decay rate and color should still allow the use of Type I SN as a standard candle since Z is overdetermined by both apparent decay rate and apparent color.

IV. LIGHT CURVES

The light curves of Type I SN are not uniquely understood. Kirshner claims only that the very early phase near maximum could be explained as a Planck spectrum, and we agree. In view of the lack of hydrogen observed in Type I's (Kirshner *et al.* 1973) and the persistently tantalizing but as yet not fully explained late time exponential behavior of the light curve (Colgate and McKee 1969; Morrison and Sartori 1969; Colgate 1972; Van Hise 1974; Lasher 1975; Karp *et al.* 1977; Arnett and Falk 1976; Falk and Arnett 1977; Meyerott 1978) we feel that a late time blackbody assumption may be misleading. In particular the late time mechanism of optical emission is best explained by excitation of a restricted set of lines, the Fe II blend (Branch and Patchett 1973; Kirshner *et al.* 1973; Assousa *et al.* 1976), so that interpreting the late time broad-band photometry measurements as a Planck spectrum will give an erroneous result. This does not apply to Type II SN where hydrogen and Ca lines, a blackbody spectrum, and typical P Cygni lines have been identified.

We propose doing very broad-band photometry (UV to near-IR) of Type I's at very early time before maximum, at maximum, and down to approximately 1 *e*-folding time below maximum where, we believe, it is most likely that blackbody conditions exist and where hydrodynamics and radiation diffusion give a very good account of the time, intensity, and width of the luminosity peak (Colgate and McKee 1969). This avoids the complicated question of late time emission mechanisms, e.g., Fe II band fluorescence, radioactivity, and/or He fluorescence. It is likely but not yet certain that these complications could explain the question of the two different early decay rates if they exist. Finally, it would appear that the maximum luminosity is negatively correlated with fast or slow type so that the total emitted energy is more nearly constant than the possible dispersion in decay rate. Furthermore, the fast type has not yet been seen in E galaxies whereas three of the slow types have been seen. We hope to use only E galaxy Type I's so that the remaining uncertainty concerning the existence of slow or fast types, the possible additional correlation of rise time and color, the selection by galaxy type, and finally the ratio of luminosity to the knee all point toward the probable exclusion of this variable. If Type I's are a unique restricted class, then their advantage as a standard candle is still greater.[1]

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[1] We need to measure on each night for several weeks the spectra of a dozen Type I SN at $Z \lesssim 0.1$, occurring in E galaxies and within 5 days of zero time—i.e., well before maximum, so that temperature, time, and luminosity can be determined. To find these SN would require an observing program lasting for a year that would have to monitor 10^{-3} of full sky to 20th magnitude assuming one-fourth of the SN occur in E galaxies. This requires processing approximately 3×10^{10}, $2'' \times 2''$ (pixels) per 5 nights for a blind survey that does not select E galaxies. Instead, if large ellipticals are selected, then with an estimated Type I SN rate of 1 per 100 years, 7000 galaxies must be monitored each 5 nights to 17th magnitude and fewer than 2×10^7 pixels need be processed each night. Similarly if large spiral galaxies are selected, a similar number of Type II's can be found with comparable effort, where the reduced luminosity is counterbalanced by the somewhat higher rate.

V. THE METHOD FOR DETERMINING THE COSMOLOGY

As Wagoner (1977) has pointed out, as soon as we determine an absolute luminosity in the rest frame L_*, the observed luminosity L is related by

$$L = L_*(1 + Z)^{-2} \times \frac{(c/H_0)^2}{4\pi\{cH_0^{-1}[Z - 0.5(1 + q_0)Z^2 + O(Z^3)]\}^2} . \qquad (1)$$

It is worthwhile noting that one factor of $(1 + Z)^{-1}$ comes from the time dilation of the relativistic expansion and the second factor of $(1 + Z)^{-1}$ is derived from the color shift. These two separable observational factors allow a dual determination of Z, that is, by color and by time. It therefore becomes important to know the effective temperature (color) and time history of our standard-candle SN, in which case we can presumably determine Z by a combination of the time history and "three-color photometry."[2] If indeed this can be done from the Space Telescope, then there is a major advantage compared to taking spectra because the combined photoefficiency and light path losses favor the accumulation of signal statistics by the solid state CCD focal plane detector over the signal rate of the faint-object spectrograph by a factor of 30 or greater. We propose doing three-band photometry to 2% repeatedly (10 to 20 samples over the light curve), and this should establish $1 + Z$ and the apparent luminosity to $\sim 1\%$. The determination of $1 + Z$ separately from both time and color allows a reconstruction of L_* and hence a check on the SN type. A Type I SN that has become slower by $1 + Z$ and reddened by the same factor may appear as a Type II SN. The background galaxy, if it can be recognized, can be used to select Type I's. The early light curves ($t \lesssim 3$ days) of Type I's and Type II's should be different. The slow rise (5 days) of Type I's over ~ 6 mag (Zwicky 1964 [SN Ophiuchi 1604, Kepler's SN]) is inconsistent with an extended envelope. If Type I's are initially compact as we have proposed (Colgate and McKee 1969), then the X-ray signal will be very much smaller (Colgate and Petschek 1979) and this should be determined by the time of the Space Telescope. The extended envelope of Type II's, on the other hand, should give rise to a more rapid rise to maximum (hours to a few days) and a larger X-ray pulse (Falk and Arnett 1977; Klein and Chevalier 1977).

VI. SPACE TELESCOPE OBSERVATIONS

The Focal Plane Camera (FPC) in either of two modes ($0''.1$ per pixel or $0''.043$ per pixel, Westphal 1977) is the optimum Space Telescope instrument for a supernova search. There are predicted to be enough galaxies per average field of view for $Z \approx 1$ that several SN per week could be found using less than 1% of the observing time. The FPC will have 1600 lines and readout noise of ~ 12 electrons per pixel. The quantum efficiency in the visible is greater than 50%, leading to an average overall efficiency of a photon entering the telescope to a photoelectron in the detector of $\sim 30\%$ (Gunn 1978). The minimum useful integration time of 80 seconds is limited by the data transmission rate. Slewing to an adjacent field (3′) may take 10–20 s, provided a new guide star does not have to be acquired.

VII. SUPERNOVA STATISTICS

We can either estimate the number of galaxies to a given redshift and the mean rate of supernovae per galaxy or simply take the supernova rate per unit volume of space. The latter is more direct, but it is worthwhile to compare this to a rate per galaxy for completeness. Tammann (1976) calculates that, within 100 Mpc (m_v Type I ≈ 15), 270 SN occur per year. This is the potential set of SN that might be easily found and hence is of interest. One obtains this number by assuming that the search within 20 Mpc has been reasonably complete. In the last 35 years 77 SN have been found. Corrections for SN missed because of the inclination of some galaxies, the Milky Way, and those missed in the southern sky just about balance the extra concentration of galaxies within the nearby supercluster, resulting in the above rate. We estimate the SN frequency per galaxy by assuming a standard large galaxy of $10^{10}\,L_\odot$ and noting that the observed mean luminosity of extragalactic space is $3 \times 10^8\,(H_0/100)^3\,L_\odot\,\mathrm{Mpc}^{-3}$ (Peebles 1971). Then the number of galaxies within 100 Mpc is such that the SN rate per average galaxy becomes 1 per 440 $(H_0/100)^3$ years. The number of SN per second within $Z \leq 1$ with no cosmological corrections then becomes $\sim 2\ \mathrm{s}^{-1}$ for $H_0 = 50$. If we take the simplest cosmological correction, just the dilation time so that the rate

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[2] We must emphasize that we have in mind a broader definition of three-color photometry than the classical ground-based interpretation. The transparency of our atmosphere and the limitations of past detectors has limited the useful wavelength region of the *UBV* system to roughly 3150–6000 Å. With the Space Telescope and CCD detector this will be extended from 1150 Å to 11,000 Å at the 5% quantum efficiency level. The CCD detectors can be divided into three detectors for photometry and each one fed a separate band by a combination of mirrors and filters. Since these filters and mirrors can transmit or reflect finite bands with near unity efficiency, we will assume for the purposes of this discussion that the incident photon flux can be divided into three bands of near optimum width, spacing, and unity efficiency. Since we will be measuring a spectrum redshifted from $\sim 10{,}000$ K temperature to 5,000 K, this will place one band centered at ~ 5000 Å, a near-IR band longward of ~ 6000 Å, and a blue band shortward of ~ 4000 Å. The bands should be chosen such that, inclusive of the detector sensitivity, roughly equal counting rates exist in each band. Since the approximate width of a Planck intensity spectrum (full width at half-maximum) is roughly equal to the frequency of maximum intensity, the sensitivity of an optimized three-band photometry is roughly

$$\frac{\Delta[(m_1 - m_2) - (m_2 - m_3)]}{\log_{2.5}(\Delta T/T)} \approx 2 ,$$

where m_1, m_2, and m_3 are the respective magnitudes in the three bands and T the redshifted source temperature. The problem is to select the proper filters without knowing beforehand the true value of T. We imagine an optimized strategy would comprise several-step photometry where the first look with $\times 2$ broader band filters would establish T to, say, 30%, and subsequent higher accuracy measurements would use optimized narrower bands.

of SN per galaxy decreases as $(Z + 1)^{-1}$ with no galactic evolution, then the SN rate $(Z \leq 1) \approx 1\ \mathrm{s}^{-1}$. Galaxy evolution may increase or decrease this rate; clustering may allow selected fields to present twice the galaxy density (Groth and Peebles 1977), and cosmological curvature depending upon q_0 may significantly change the observed rate. A first order expansion of the volume element gives (Weinberg 1972)

$$N(<Z) = (4/3)\pi n_0 Z^3 (c/H_0)^3 \times [1 - (3/2)(1 + q_0)Z + O(Z^2)]\,, \quad (2)$$

so that for $q_0 = -1$, the first order correction is zero and becomes increasingly severe as q_0 increases. The steady state model corresponds to $q_0 = -1$. In the limit that the cosmological k term is 0 (Weinberg 1972) the equation can be integrated exactly, giving

$$N(<Z) = (4/3)\pi n_0 Z^3 (c/H_0)^3 \times 4\left[1 - \frac{1}{(1+Z)^{3/2}} + \frac{3}{1+Z} - \frac{3}{(1+Z)^{1/2}}\right] = 0.1 \times (4/3)\pi n_0 (c/H_0)^2 \quad \text{at} \quad Z = 1\,.$$

Hence there is considerable variation of the expected SN rate dependent upon cosmology, but we will neglect this correction in a first order estimate of detectability.

VIII. SUPERNOVA DISCOVERY

Thus for a supernova rate $(Z \leq 1) = 1\ \mathrm{s}^{-1}$ and a detector solid angle of 4.8×10^{-8} (1600^2, $0''.1$ pixels) the SN rate per FPC field per 10^6 s (this is 5×5^5 s or the type I SN rise time in the star frame at $Z = 1$) becomes 0.048 per field. The expected photon rate is such that we would expect to utilize the ST in the fastest framing mode. This corresponds to 80 s per frame. If one allows 20 s to slew to an adjacent field ($2'.7$) and assumes the same guide star, this allows a frame per 100 s so that 100 frames can be taken in a reasonable time of 3 hours or an expected rate of 1.7 SN per hour of search time.

IX. PHOTOELECTRON STATISTICS

The detection of a point image depends upon the photoelectron shot noise of the signal and background. The mean radius for one-half the luminosity of spirals is approximately 3 kpc (Freeman 1970; Schechter 1976) so that a galaxy center image subtends a circle of $0''.2$ diameter, two pixels, or with overlap roughly five pixel area at $Z = 1$, $H_0 = 50$. The SN image should be smaller than a pixel so that the light will be distributed in roughly three pixels. There is also 50% probability that a SN will occur outside this area, in which case the background from the galaxy will be negligible. The luminosity of our standard galaxy is equal to $10^{10}\,L_\odot = 4 \times 10^{43}$ ergs s^{-1} whereas that of a Type I SN at maximum is $M_{\mathrm{bol}} = 20.1$ or 3×10^{43} ergs s^{-1} (Kowal 1968), so the galaxy background in five pixels will be $0.16\,(100/H_0)^2$ of the SN at maximum. The redshift, color correction strongly favors the higher temperature SN spectrum depending upon the filter by an additional factor of at least 4 at $Z = 1$ so that, as a first approximation, the galaxy background will be small, $\lesssim 10\%$, with the FPC resolution. Then since $L_{\max} \approx 3 \times 10^{43}$ ergs s^{-1}, the number of photons per second emitted at $\langle h\nu \rangle = 3$ eV collected at $\langle h\nu \rangle = 1.5$ eV by a 2.4 m mirror at $Z = 1$ becomes

$$n(h\nu) = \frac{L_{\max} A}{(1 + Z) 4\pi R^2} = 33\ \mathrm{s}^{-1} \quad \text{at} \quad H_0 = 50\,.$$

This neglects an absorption due to the galaxy of $0.25 \csc\theta$, which is within the error of the estimate of the photon to photoelectron efficiency. These photons will be redshifted from a number peak at ~3500 Å to 7000 Å, so they will be at the maximum response of the FPC–CCD detector. An estimate of the photoefficiency of the combined telescope detector system (Gunn 1978) is 30% including optical losses, so an 80 s integration will produce 800 photoelectrons. On the average some one pixel contains slightly less than about one-third the signal, or ~250 photoelectrons. We expect to difference two pictures with a computer determined registration error of ± 1 pixel and a background noise ~12 photoelectrons per pixel. Therefore a simple peak detecting scan of the digital picture at ~50 photoelectron level has a small false alarm rate but ensures the detection of SN with a signal to noise ratio $\gtrsim 10$. Local integration of the pixels around any peak determines a statistically more meaningful signal. Once a supernova is found, one would expect to do three-band photometry on a more frequent basis to determine Z by both time and color shift.

The color ratios are needed to remove the variation in quantum efficiency as a function of wavelength in order to determine the true apparent luminosity as well as the redshift Z. To determine the color temperature to, say, 10% requires ~10% statistics in each of three bands, presumably each of approximately equal counting rate. Then a supernova at half-maximum results in roughly 1.5 counts s^{-1} in each band, and less than 80 s is required to reach 10% statistics. Thus, photometry can be carried on simultaneously for several supernovae as well as the search function for new ones. If 20 measurements are distributed over the SN peak of 10 days, a 2% measurement of Z and absolute luminosity should result. The limitations for cosmology will then depend primarily upon the calibration of Type I SN at small Z (but already, for an uncertainty in Type I SN luminosity of 20%, q_0 could be determined to ~40%).

X. CONCLUSION

We have suggested that a coordinated program to use supernovae and particularly Type I supernovae from the Space Telescope has the potential for determining the cosmological constant with greater accuracy—free of potential evolutionary and aperture corrections—than other standard candles.

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REFERENCES

Arnett, W. D., and Falk, S. W. 1976, *Ap. J.*, **210**, 733.
Assousa, G. E., Peterson, D. J., Rubin, V. C., and Ford, W. K. 1976, *Pub. A.S.P.*, **88**, 828.
Barbon, R., Ciatti, F., and Rosino, L. 1973, *Astr. Ap.*, **25**, 241.
Branch, D. R., and Patchett, B. 1973, *M.N.R.A.S.*, **161**, 71.
Colgate, S. A. 1972, *Ap. J.*, **174**, 377.
Colgate, S. A., and McKee, C. 1969, *Ap. J.*, **157**, 623.
Colgate, S. A., and Petschek, A. G. 1979, *Ap. J.*, in press.
Falk, S. W., and Arnett, W. D. 1977, *Ap. J. Suppl.*, **33**, No. 4, 515.
Freeman, K. C. 1970, *Ap. J.*, **160**, 811.
Groth, E. J., and Peebles, P. J. E. 1977, *Ap. J.*, **217**, 385.
Gunn, J. E. 1978, private communication; see Westphal 1977.
Karp, A. H., Lasher, G., Chan, K. L., and Salpeter, E. E. 1977, *Ap. J.*, **214**, 161.
Kirshner, R. P., and Kwan, J. 1974, *Ap. J.*, **193**, 27.
Kirshner, R. P., Oke, J. B., Penston, M., and Searle, L. 1973, *Ap. J.*, **185**, 303.
Klein, R., and Chevalier, R. 1978, *Ap. J. (Letters)*, **223**, L109.
Kowal, C. T. 1968, *A.J.*, **73**, 1021.
Lasher, G. 1975, *Ap. J.*, **201**, 195.
Maza, J., and van der Bergh, S. 1976, *Ap. J.*, **204**, 519.
Meyerott, R. E. 1978, *Ap. J.*, **221**, 975.
Moore, E. 1973, *Pub. A.S.P.*, **85**, 564.
Morrison, P., and Sartori, L. 1969, *Ap. J.*, **158**, 541.
Paczyński, B. 1970, *Acta Astr.*, **20**, 47.
Peebles, P. J. E. 1971, *Physical Cosmology* (Princeton: Princeton University Press).
Schechter, P. 1976, *Ap. J.*, **203**, 297.
Tammann, G. 1976, report presented at the Eighth Texas Symposium on Relativistic Astrophysics.
———. 1978, report presented at the Erice Workshop on Supernovae and Supernova Remnants May 16–27, 1978, Erice, Italy.
Van Hise, J. R. 1974, *Ap. J.*, **193**, 657.
Wagoner, R. V. 1977, *Ap. J.*, **214**, L5.
Warner, B. 1974, *M.N.R.A.S.*, **167**, 61P.
Weinberg, S. 1972, *Gravitation and Cosmology, Principles, and Application of the General Theory of Relativity* (New York: Wiley).
Westphal, J. 1977, Summary Section Investigation Definition Team, Wide Field/Planetary Camera for Space Telescope, Cal tech, Pasadena, CA.
Whelan, J., and Iben, I. 1973, *Ap. J.*, **186**, 1007.
Zwicky, F. 1964, Report to Committee for Research on Supernovae, IAU Commission 28.

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