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THE ABSOLUTE MAGNITUDES OF TYPE Ia SUPERNOVAE

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ABSTRACT

Absolute magnitudes in the B, V, and I bands are derived for nine well-observed Type Ia supernovae using host galaxy distances estimated via the surface brightness fluctuations or Tully-Fisher methods. These data indicate that there is a significant intrinsic dispersion in the absolute magnitudes at maximum light of Type Ia supernovae, amounting to ± 0.8 mag in B, ± 0.6 mag in V, and ± 0.5 mag in I. Moreover, the absolute magnitudes appear to be tightly correlated with the initial rate of decline of the B light curve, with the slope of the correlation being steepest in B and becoming progressively flatter in the V and I bands. This implies that the intrinsic $B-V$ colors of Type Ia supernovae at maximum light are not identical, with the fastest declining light curves corresponding to the intrinsically reddest events. Certain spectroscopic properties may also be correlated with the initial decline rate. These results are most simply interpreted as evidence for a range of progenitor masses, although variations in the explosion mechanism are also possible. Considerable care must be exercised in employing Type Ia supernovae as cosmological standard candles, particularly at large redshifts where Malmquist bias could be an important effect.

Subject headings: distance scale — supernovae: general

1. INTRODUCTION

One of the remarkable properties of Type Ia supernovae (SN Ia's) is their apparent homogeneous nature. This characteristic has been interpreted as the observable consequence of a model where the progenitors of these events are C-O white dwarfs which have been pushed over the Chandrasekhar limit through mass transfer in a binary system. The uniformity of the light curves of SN Ia's has attracted considerable attention to the potential utility of these objects as cosmological standard candles. In a recent review, Tammann (1993) argues that SN Ia's have peak luminosities which scatter by <0.2 mag and concludes that they are unrivaled standard candles. Nevertheless, observations of a few "peculiar" events in recent years have raised questions about the uniformity of SN Ia's. The most disturbing object to date is SN 1991bg, which was discovered in the elliptical galaxy NGC 4374 and reached a peak brightness that was ~ 2.5 mag fainter in B than that of the Type Ia SN 1957B *which occurred in the same galaxy*. The light curves of SN 1991bg declined unusually fast following maximum, and the optical spectral evolution was distinctly peculiar (Filippenko et al. 1992b; Leibundgut et al. 1993; Porter et al. 1993).

SN 1991bg is one of five SN Ia's identified by Branch & Miller (1993, hereafter B&M) as intrinsically subluminous. Interestingly, all five were fast-declining events, which would appear consistent with the peak luminosity–initial decline rate correlation claimed a number of years ago by Pskovskii (1977, 1984). However, the validity of this relation has been called into question by Boisseau & Wheeler (1991) who argued that contamination of the supernova photometry by the underlying light of the host galaxy would naturally introduce such a correlation into the data.

This controversy highlights the fact that the vast majority of published photometry for supernovae is generally of poor and nonuniform quality. Fortunately, the introduction of CCD digital photometry techniques into the field in recent years has significantly increased the number of SN Ia events for which precise and well-sampled light curves are now available. In this *Letter*, these well-observed objects, whose light curves should be free of systematic errors, are used to test whether the true dispersion in the absolute magnitudes of SN Ia's really is as small as ± 0.2 mag and to reexamine the reality of the Pskovskii peak luminosity–initial decline rate relation.

2. THE SAMPLE

The sample of SN Ia's employed for this study was selected using the following three criteria:

1. *Precise Optical Photometry.*—Only events observed with CCDs or photoelectric photometers were considered for inclusion. Photoelectric data were employed where the background light of the host galaxy was judged to be insufficient to affect the measurements. Photographic photometry was *not* utilized except in the case of one supernova, SN 1971I, for which the available photoelectric and spectrophotometric data confirm the general accuracy of the photographic measurements.
2. *Well-sampled Light Curves.*—The photometry must have started *before or at maximum* and must have continued for at least 20 days after maximum. The light curve must also have been sufficiently well sampled to allow measurement of the decline rate without large interpolations.
3. *Accurate Relative Distance.*—An accurate relative distance must have been measured for the host galaxy via the surface brightness fluctuations (SBF) or Tully-Fisher (T-F) methods. The SBF technique works best for early-type galaxies and yields distances which appear to be exceptionally precise (see Jacoby et al. 1992). For spirals, the T-F method must be used which gives distances that are consistent with the zero point of the SBF scale, but with a larger associated error

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TABLE 1

SAMPLE OF WELL-OBSERVED TYPE Ia SUPERNOVAE

SN	Host Galaxy	Distance Modulus	Method	Distance Modulus References[a]	Δm_{15}(B)	$E(B-V)$	M_B	M_V	M_I	Photometry References[b]
1971I	NGC 5055	29.3(0.3)	T-F	1	1.64(0.15)	0.00(0.02)	−17.20(0.35)	−17.52(0.34)	...	1, 2
1980N	NGC 1316	31.02(0.12)	SBF	2	1.28(0.05)	0.00(0.02)	−18.53(0.15)	−18.58(0.14)	−18.32(0.14)	3
1981B	NGC 4536	30.5(0.3)	T-F	1	1.10(0.07)	0.00(0.02)	−18.47(0.31)	−18.54(0.31)	...	4
1986G	NGC 5128	27.71(0.08)	SBF	3	1.73(0.07)	0.60(0.10)	−17.72(0.42)	−18.12(0.32)	−18.21(0.23)	5
1989B	NGC 3627	29.4(0.3)	T-F	1	1.31(0.07)	0.35(0.03)	−18.50(0.33)	−18.50(0.32)	−18.30(0.31)	6
1990N	NGC 4639	31.4(0.3)	T-F	1	1.01(0.10)	0.01(0.02)	−18.74(0.31)	−18.82(0.31)	...	7
1991T	NGC 4527	30.6(0.3)	T-F	1	0.94(0.07)	0.00(0.02)	−18.96(0.31)	−19.10(0.31)	−19.04(0.30)	8, 9
1991bg	NGC 4374	31.08(0.08)	SBF	4	1.88(0.10)	0.00(0.02)	−16.38(0.15)	−17.13(0.10)	−17.57(0.10)	10, 11
1992A	NGC 1380	30.65(0.11)	SBF	5	1.33(0.04)	0.00(0.02)	−18.05(0.14)	−18.10(0.13)	−17.85(0.12)	12

[a] REFERENCES.—(1) Pierce 1993; (2) Tonry 1993; (3) Tonry & Schechter 1990, revised per Tonry 1991 calibration; (4) Tonry et al. 1990, revised per Tonry 1991 calibration; (5) Tonry 1991.

[b] REFERENCES.—(1) Deming et al. 1973; (2) Barbon et al. 1973; (3) Hamuy et al. 1991; (4) Buta & Turner 1983; (5) Phillips et al. 1987; (6) Wells et al. 1993; (7) Leibundgut et al. 1991; (8) Phillips et al. 1992; (9) L. A. Wells et al., unpublished; (10) Filippenko et al. 1992b; (11) Leibundgut et al. 1993; (12) Suntzeff et al. 1993.

(typically ± 0.3 mag) for any single measurement (Jacoby et al. 1992).[2]

These three criteria are satisfied by only nine of the historical SN Ia's. Data for these events are listed in Table 1.

As a measure of the initial decline rate of the light curve, Pskovskii (1984) employed a slope parameter, β, defined as the mean rate of decline of the B light curve between maximum light and the bend which typically occurs 25–30 days later. Unfortunately, in practice β is difficult to measure precisely in even the best observed supernovae (see Hamuy et al. 1991). Rather than trying to determine the *slope*, a simpler and more robust procedure is to measure the *total amount* in magnitudes that the light curve decays from its peak brightness during some specified period following maximum light. After some experimenting, a time interval of 15 days was found to provide the greatest discrimination. Measurements of this new decline rate parameter, $\Delta m_{15}(B)$, are included in Table 1.

Except for SNs 1986G and 1989B, the reddenings listed in Table 1 are the Burstein & Heiles (1984) values for interstellar dust in our own Galaxy. Most of the supernovae were located far from the centers of their host galaxies and were unlikely to have suffered significant additional extinction. Weak Na I D absorption due to gas in the host galaxies was observed in SN 1981B (Branch et al. 1983) and SN 1991T (Meyer & Roth 1991), so the absolute magnitudes listed in Table 1 for these events are actually lower limits (although the corrections are probably small). In contrast, strong redshifted interstellar lines were observed for both SN 1986G (Phillips et al. 1987) and SN 1989B (Bolte et al. 1990) indicating that the dust absorption produced by the host galaxies of these supernovae was considerable. For SN 1989B, the value of $E(B-V) = 0.35 \pm 0.03$ derived by Wells et al. (1993) from a comparison of the *UBVRIJHK* light curves with the photometrically similar SN 1980B was adopted. Likewise, the color excess of SN 1986G given in Table 1 was derived with respect to its apparent "close cousin," SN 1971I (see Phillips et al. 1987; Frogel et al. 1987; Filippenko et al. 1992b).[3] Note that in all cases where extinction corrections were made, a standard reddening curve was assumed with $R = A_V/E(B-V) = 3.1$.

3. RESULTS

Absolute magnitudes in B, V, and I for the sample of nine SN Ia's are plotted versus the decline rate parameter $\Delta m_{15}(B)$ in Figure 1. The points for SN 1986G and SN 1971I are joined by a dotted line to indicate that the reddening for SN 1986G was determined by assuming that its light curves and colors were a close match to those of SN 1971I; the points for SN 1989B and SN 1980N are similarly connected, although they lie so close in the figure that the dotted line is not apparent. The fact that the reddenings were derived in this fashion does *not* guarantee that the absolute magnitudes will be similar; hence, the close agreement seen in Figure 1 reinforces the idea that these pairs of supernovae closely resembled each other.

The major implications of Figure 1 are obvious. First, and most important, the data provide striking evidence for the existence of a significant intrinsic dispersion in the absolute magnitudes of SN Ia's. The scatter in absolute magnitude amounts to ±0.79 mag in the B band, decreasing up ±0.59 mag in V and ±0.46 mag in I. Even in the I band, the dispersion is significantly greater than the combined errors associated with the photometry and host galaxy distances. This increased scatter could conceivably be due to inaccurate reddening corrections and/or relative distances, but this cannot explain the second major result of Figure 1—namely that the peak luminosities and initial decline rates of SN Ia's are highly correlated, with the slope of the correlation being steepest in B and becoming progressively flatter in the V and I bands. Spearman rank-order correlation coefficients calculated for the B and V data

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[2] Absolute magnitudes calculated using SBF and T-F distances reflect the "short" distance scale ($H_0 \approx 85$ km s^{-1} Mpc^{-1}). Recently, Sandage et al. (1992) derived $M_V = -19.76 \pm 0.13$ for the Type Ia SN 1937C based on a distance to the host galaxy, IC 4182, derived from Cepheid variables. The decline rate of the V light curve of SN 1937C appears to have been fairly typical of a Type Ia event such as SN 1980N which, according to Table 1, had $M_V = -18.58 \pm 0.11$. This suggests that the zero point of the SBF and T-F distance scales is incorrect, although the calibration of these methods is also based on Cepheid variables. Alternatively, if the distances for IC 4182 and the galaxies in Table 1 are correct, then SN 1937C was an unusually luminous Ia event. In any case, this problem does not affect the conclusions of the present paper which are dependent on relative—not absolute—distances

[3] The reddening of SN 1986G is controversial. The value of $E(B-V) = 0.60 \pm 0.10$ listed in Table 1 is very similar to the reddening of 0.63 ± 0.11 found by di Serego Alighieri & Ponz (1987) from an analysis of the diffuse interstellar bands observed in the spectrum, but differs substantially from the amount $E(B-V) = 0.88 \pm 0.1$ inferred by Rich (1987) from the column densities of the interstellar Na I D lines and is even more at odds with the value of 1.09 ± 0.02, deduced by Ruiz-Lapuente & Lucy (1992) from modeling of the late-epoch nebular spectrum. If the latter value were assumed, then an absolute magnitude of $M_B = -19.45 \pm 0.10$ is implied, which would make SN 1986G the *most luminous* event in this sample.

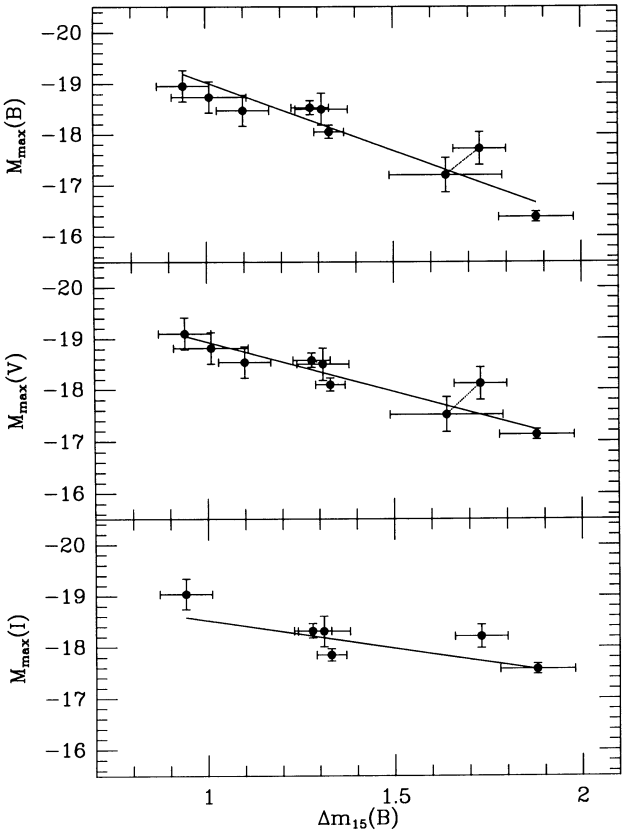

FIG. 1.—Decline rate–peak luminosity relation for the nine best-observed SN Ia's. Absolute magnitudes in *B*, *V*, and *I* are plotted vs. $\Delta m_{15}(B)$, which measures the amount in magnitudes that the *B* light curve drops during the first 15 days following maximum.

are 0.980 and 0.992, respectively. Eliminating SN 1986G and SN 1989B from the sample on the grounds that the reddening corrections for these events are uncertain yields correlation coefficients in *B* and *V* of 0.961 and 0.984, consistent in both cases with rejection of the null hypothesis at the 1% level of significance.

Linear regression fits to the data in Figure 1 are given in Table 2. Interestingly, the sense of the correlation in *B* is the same as that claimed by Pskovskii (1977, 1984)—i.e., the lowest luminosity SN Ia's have the fastest decline rates. Unfortunately, since only two of the nine events overlap with the SN Ia's studied by Pskovskii, a detailed comparison with his findings is not possible. However, the criticisms of Boisseau & Wheeler (1991) are compelling, and so the general agreement of the data in Figure 1 with Pskovskii's conclusions may be fortuitous.

Are there other properties of SN Ia's which correlate with decline rate? The different slopes of the *B*, *V*, and *I* relationships in Figure 1 imply that the intrinsic colors of SN Ia's at maximum are a function of the decline rate of the *B* light curve, with the reddest events corresponding to the intrinsically faintest. Spectroscopic peculiarity may also be related to the decline rate. The two events in this sample with the most pronounced spectroscopic peculiarities are SN 1991bg (the fastest decliner) and SN 1991T (the slowest). At maximum light, SN 1991bg showed a deep "trough" of absorption between 4000 and 4500 Å which Filippenko et al. (1992b) identified with a blend of Ti II lines. In addition, the Si II λ5979 absorption was unusually strong compared to the Si II λ6355 line. SN 1991T, on the other hand, displayed a spectrum at maximum which was dominated by absorption features due to iron-group elements instead of the normally strong lines of Si, Ca, and S (Filippenko et al. 1992a; Phillips et al. 1992). The supernova in this sample with the second-highest decline rate, SN 1986G, displayed optical spectroscopic peculiarities which were similar to those of SN 1991bg, although less pronounced (see Filippenko et al. 1992b; Leibundgut et al. 1993). Likewise, near maximum light, the Si II λ6355 absorption in the spectrum of SN 1990N (the event with the second lowest decline rate) was intermediate in strength between that of SN 1991T and the more spectroscopically normal event SN 1989B (see Phillips et al. 1992).

Pskovskii (1977, 1984) and Branch (1981) claimed that the velocity of the Si II λ6355 absorption near maximum light was correlated with the value of Pskovskii's β parameter. Although no such relationship is apparent in the data for the nine SN Ia's in the present sample, there is a suggestion that the velocity of the Ca II H and K minimum may be a function of $\Delta m_{15}(B)$ (see Wells et al. 1993). Interestingly, the *rate of decrease* of the Si II λ6355 velocity during the first weeks following maximum light may depend on the decline rate. For the slowest declining supernovae (SN 1991T and SN 1990N), the expansion velocity of the Si II line changed only very slowly during the first month following maximum, while for the supernovae with steep light curves (SN 1991bg and SN 1986G), the Si II velocity displayed the fastest decrease with time (see Fig. 9 of Leibundgut et al. 1993). This apparent correlation suggests that the decline rate of the light curve is closely related to the density gradient of the ejecta.

TABLE 2

LEAST-SQUARES FITS

	$M_{max} = a + b\Delta m_{15}(B)$		
BANDPASS	*a*	*b*	σ (mag)
B	−21.726(0.498)	2.698(0.359)	0.36
V	−20.883(0.417)	1.949(0.292)	0.28
I	−19.591(0.415)	1.076(0.273)	0.38

4. DISCUSSION AND CONCLUSIONS

The large dispersion in the absolute *B* magnitudes implied in Figure 1 is in apparent conflict with the results of B&M, who derived $\sigma(M_B) \leq 0.36$ mag for a larger sample of SN Ia's. However, B&M eliminated SN 1971I, SN 1986G, and SN 1991bg from their sample due to their "peculiar" nature. If these objects are deleted from Figure 1, the remaining "luminous" SN Ia's yield dispersions of ∼0.3 mag in both *B* and *V*. B&M noted that more than half of the supernovae in their sample occurred at large distances where intrinsically faint events such as SN 1971I and SN 1991bg would not have been detected. If we limit the B&M sample to supernovae at the distances of the Virgo and Fornax clusters or closer, and include the two events that were clearly intrinsically faint (SN 1971I and SN 1991bg), a dispersion of $\sigma(M_B) \sim 0.7$ mag results. Hence, the large dispersions derived in the present *Letter* are likely to be more representative of the SN Ia class *as a whole*. Nevertheless, an alternative interpretation of Figure 1 is that there are two physically distinct classes of SN Ia's—one corresponding to the "luminous" events, and the other consisting of the three intrinsically faint objects. The main arguments against this point of view are (1) the correlation of spectroscopic peculiarity with $\Delta m_{15}(B)$ and (2) the evidence for a peak luminosity–decline rate relationship even among the subset of six "luminous" SN Ia's (see Fig. 1). Clearly, however, more observations are needed to settle this question.

A basic assumption of most models of SN Ia's is that the progenitors of these events are 1.4 $M_\odot$ white dwarfs. However, the existence of a significant dispersion in maximum-light luminosities implies that the progenitor masses may not all be the same. Recently, Shigeyama et al. (1992) and Woosley & Weaver (1993) have proposed mechanisms which might lead to the explosion of lower mass (0.6–1.0 $M_\odot$) white dwarfs. These new models may explain the low-luminosity events in Figure 1, or perhaps even the entire range of observed magnitudes and decline rates. Naively, one would expect low-mass progenitors to eject less mass, allowing the γ-rays produced by ^{56}Ni and ^{56}Co to escape more easily and leading to a faster declining light curve (see, however, Woosley & Weaver 1993). Even if the progenitors of SN Ia's are 1.4 $M_\odot$ white dwarfs, variations in the explosion mechanism could conceivably produce a dispersion in absolute magnitudes similar to that observed (e.g., see Khokhlov, Müller, & Höflich 1993).

The existence of a decline rate–absolute magnitude dependence for SN Ia's has significant implications for the use of these objects as cosmological standard candles. Low-luminosity events may be common in a volume-limited sample (B&M; van den Bergh 1993). Although an object like SN 1991bg is easily recognized due to its obvious spectroscopic peculiarities, less extreme low-luminosity events may not be so readily identified. B&M argued that the existence of subluminous events does not seriously compromise the use of SN Ia's as distance indicators since, at large distances, these events are strongly selected against. Conversely, however, searches for distant SN Ia's will clearly favor the discovery of superluminous events. B&M concluded that there is no evidence for such objects among the historical SN Ia's; nevertheless, even if superluminous SN Ia's were 100 times rarer than "normal" events, they could still introduce a significant Malmquist bias in surveys of distant ($z = 0.2$–0.4) SN Ia's.

If the decline rate–absolute magnitude relationship is confirmed by further observations, it should in principle be possible to correct the Hubble diagram of SN Ia's for this effect. Alternatively, it may be more fruitful to concentrate observations in the *I* band, or in the near-infrared, where the intrinsic dispersion in peak brightness appears to be smaller. Photometry of SN 1991bg [$\Delta m_{15}(B) \sim 1.9$] recently presented by Porter et al. (1993) indicates that the apparent magnitude in the *H* band of this object at *B* maximum was nearly exactly the same as that observed for SN 1980N [$\Delta m_{15}(B) \sim 1.3$]. Since the host galaxies for these two supernovae lie at comparable distances (see Table 1), this implies that the absolute magnitudes at *H* were very similar, in contrast to the ~2 mag difference observed in the blue.

I am indebted to George Jacoby for suggesting the $\Delta m_{15}(B)$ parameter as an alternative to Pskovskii's β and for presenting in my absence a preliminary version of these results at the Aspen distance scale meeting. Helpful discussions with George, Bob Schommer, Mario Hamuy, Nick Suntzeff, Brian Schmidt, Bruno Leibundgut, Sidney van den Bergh, and Allan Sandage are gratefully acknowledged. Thanks to John Tonry for sending me his SBF distance for NGC 1316 in advance of publication, and to Nick Suntzeff and Pat Sietzer for providing the software to calculate the linear regressions.

REFERENCES

Barbon, R., Ciatti, F., & Rosino, L. 1973, Mem. Soc. Astron. Ital., 44, 65
Boisseau, J. R., & Wheeler, J. C. 1991, AJ, 101, 1281
Bolte, M., Saddlemyer, L., Mendes de Oliveira, C., & Hodder, P. 1989, PASP, 101, 921
Branch, D. 1981, ApJ, 248, 1076
Branch, D., Lacy, C. H., McCall, M. L., Sutherland, P. G., Uomoto, A., Wheeler, J. C., & Wills, B. J. 1983, ApJ, 270, 123
Branch, D., & Miller, D. L. 1993, ApJ, 405, L5 (B&M)
Burstein, D., & Heiles, C. 1984, ApJS, 54, 33
Buta, R. J., & Turner, A. 1983, PASP, 95, 72
Deming, D., Rust, B., & Olson, E. 1973, PASP, 85, 321
di Serego Alighieri, S., & Ponz, J. D. 1987, in ESO Workshop on SN 1987A, ed. I. J. Danziger (Garching: ESO), 545
Filippenko, A. V., et al. 1992a, ApJ, 384, L15
Filippenko, A. V., et al. 1992b, AJ, 104, 1543
Frogel, J. A., Gregory, B., Kawara, K., Laney, D., Phillips, M. M., Terndrup, D., Vrba, F., & Whitford, A. E. 1987, ApJ, 315, L129
Hamuy, M., Phillips, M. M., Maza, J., Wischnjewsky, M., Uomoto, A., Landolt, A. U., & Khatwani, R. 1991, AJ, 102, 208
Jacoby, G. H., et al. 1992, PASP, 104, 599
Khokhlov, A., Müller, E., & Höflich, P. 1993, A&A, 270, 223
Leibundgut, B., Kirshner, R. P., Filippenko, A. V., Shields, J. C., Foltz, C. B., Phillips, M. M., & Sonneborn, G. 1991, ApJ, 371, L23
Leibundgut, B., et al. 1993, AJ, 105, 301
Meyer, D. M., & Roth, K. C. 1991, ApJ, 383, L41
Phillips, M. M., et al. 1987, PASP, 99, 592
Phillips, M. M., Wells, L. A., Suntzeff, N. B., Hamuy, M., Leibundgut, B., Kirshner, R. P., & Foltz, C. B. 1992, AJ, 103, 1632
Pierce, M. J. 1993, ApJ, in press
Porter, A. C., Dickinson, M., Stanford, S. A., Lada, E. A., Fuller, G. A., & Myers, P. C. 1993, BAAS, 24, 1244
Pskovskii, Y. P. 1977, Soviet Astron., 21, 675
———. 1984, Soviet Astron., 28, 658
Rich, R. M. 1987, AJ, 94, 651
Ruiz-Lapuente, P., & Lucy, L. B. 1992, ApJ, 400, 127
Sandage, A., Saha, A., Tammann, G. A., Panagia, N., & Macchetto, D. 1992, ApJ, 401, L7
Shigeyama, T., Nomoto, K., Yamaoka, H., & Thielemann, F.-K. 1992, ApJ, 386, L13
Suntzeff, N. B., et al. 1993, in preparation
Tammann, G. A. 1993, in International Symposium on Origin and Evolution of the Elements, Institute of Nuclear Study, University of Tokyo, in press
Tonry, J. L. 1991, ApJ, 373, L1
———. 1993, in preparation
Tonry, J. L., Ajhar, E. A., & Luppino, G. A. 1990, AJ, 100, 1416
Tonry, J. L., & Schechter, P. L. 1990, AJ, 100, 1794
van den Bergh, S. 1993, in Proceedings of the VII IAU Latin American Regional Meeting, in press
Wells, L. A., et al. 1993, in preparation
Woosley, S. E., & Weaver, T. A. 1993, ApJ, submitted