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H_0, WHY THE DIFFERENCES?

Sidney van den Bergh
Dominion Astrophysical Observatory, National Research Council, Canada

The researches of many commentators have already thrown much darkness on this subject, and it is probable that, if they continue, we shall soon know nothing at all about it.

Mark Twain

RESUMEN

Se presenta una revisión actualizada de la situación del problema de la escala de distancia. Se encuentra que el valor local ($v_0 < 10\,000$ km s^{-1}) del parámetro de Hubble es $H_0 = 83 \pm 6$ km s^{-1} Mpc^{-1}. Se deriva un valor global ($v_0 > 10\,000$ km s^{-1}) de $H_0 = 76 \pm 9$ km s^{-1} Mpc^{-1}. Se discuten las razones de algunos resultados discrepantes obtenidos recientemente por otros autores. Los principales culpables parecen ser (1) la suposición que las SNeIa son buenas lámparas estándar con colores uniformes y (2) la creencia que los diámetros de las galaxias ScI son buenos patrones de distancia.

ABSTRACT

An up-to-date review of the present status of the distance scale problem is given. The local ($v_0 < 10\,000$ km s^{-1}) value of the Hubble parameter is found to be $H_0 = 83 \pm 6$ km s^{-1} Mpc^{-1}. A global ($v_0 > 10\,000$ km s^{-1}) $H_0 = 76 \pm 9$ km s^{-1} Mpc^{-1} is derived. The reasons for some deviant results recently obtained by others are discussed. The main culprits appear to be (1) the assumption that SNeIa are good standard candles with uniform colors, and (2) the belief that the diameters of ScI galaxies are good yardsticks.

Key words: **ISM: DISTANCE SCALE**

1. INTRODUCTION

Determination of the extragalactic distance scale is among the most difficult enterprises in observational astronomy. This is so because galaxies are exceedingly distant. As a result standard candles are dim, and some standard yardsticks have dimensions that only barely exceed the size of the stellar seeing disk. In addition to such observational problems there is also a psychological difficulty that may be due to the fact that cosmology and religion have, for the last fifty centuries, been closely interwoven in the minds of men. Finally determinations of H_0 are affected by differences in methodology and, in particular, by the weights assigned to results obtained by various observational techniques.

During the oral presentation of the present paper in Viña del Mar I gave an up-to-date discussion of attempts to determine the numerical value of the Hubble parameter. A long and very detailed report on this work has recently been published in the *PASP* (van den Bergh 1992a). A somewhat more popular account is given in *Science* (van den Bergh 1992b). These results are in excellent agreement with those derived in a recent review by Jacoby et al. (1992), but are in complete disagreement with the values $H_0 = 45 \pm 9$ km s^{-1} Mpc^{-1} obtained by Sandage et al. (1992) and $H_0 = 43 \pm 11$ km s^{-1} Mpc^{-1} derived by Sandage (1993).

In order to minimize the effects of systematic errors I have chosen to use means of as many different observational techniques for distance determination as possible. Furthermore I have adopted the *unweighted* average of all but one of the values so obtained. This approach is least likely to bias the final result because it does not allow one to assign low weights to those techniques that give values that disagree with the particular value of H_0 that might be favored by any particular author. The only technique that was rejected outright was that based on SNeIa. It is feared that these objects will only add noise to the data, because they are "standard candles" of uncertain intrinsic color that have an *observed* luminosity range of 33× (3.8 mag) in blue light!

An unweighted average of eight distinct technique yields a Hubble parameter, based on the distance ladder out to the distance of the Coma cluster (v_0 = 7210 km s^{-1}), of $\langle H_0(\text{local})\rangle$ = 83 ± 6 km s^{-1} Mpc^{-1} . Available evidence on the relative distances and redshifts of rich clusters of galaxies gives no evidence for a statistically significant difference between the local (v_0 < 10 000 km s^{-1}) and the global (v_0 > 10 000 km s^{-1}) values of H_0 . From four nearby and 21 distant rich clusters one obtains H_0 (global)/H_0 (local) = 0.92 ± 0.08 km s^{-1} Mpc^{-1} . (Throughout this paper 1σ errors are used). Adopting this ratio one gets H_0 (global) = 76 ± 9 km s^{-1} Mpc^{-1}.

2. SUPERNOVAE OF TYPE IA AS STANDARD CANDLES

In a recent paper Sandage et al. (1992) have used observations of Cepheid variables in IC 4182, which were obtained with the Hubble Space Telescope, to derive a distance modulus $(m-M)_V$ = 28.47 ± 0.05 for this galaxy. Using V(max) = 8.55 for the type Ia supernova 1937C these authors obtain M_V(max) = −19.92 for this supernova. Adopting $(B-V)_{max}$ = −0.18 then yields M_B(max) = −20.1 ± 0.2. Combining this value with the Hubble diagram for SNeIa Sandage et al. (1992) get a Hubble parameter H_0 = 45 ± 9 km s^{-1} Mpc^{-1}. This seemingly straight forward procedure involves the following four assumptions: (1) supernovae of type Ia are good standard candles with a small luminosity dispersion, (2) $(B-V)_{max}$ = −0.18 for all SNIa, (3) the Hubble flow can be derived in a straight forward and unambiguous fashion from the Hubble diagram of SNeIa and (4) the mean reddening of Cepheids in IC 4182 is identical to that of SN 1937C. The latter point is presently being investigated by Jacoby & Pierce and will not be discussed further in the present paper. A final caveat is that the value V(max) = 8.55 for SN 1937C was obtained by extrapolating the actual observations of this supernova by fitting of a standard template (Leibundgut et al. 1991), which fits many [but not all (Leibundgut 1993)] SNIa lightcurves, to the post-maximum V observations.

Standard candles have to be identical, or at a minimum, should exhibit only a very small luminosity dispersion. In recent years it has become increasingly clear that SNeIa are *not* all identical and that some of them have luminosities that deviate significantly from the mean. Branch, Drucker & Jeffrey (1988) have shown that SNeIa exhibit a wide range of expansion velocities. Some SNeIa, such as SN 1986G (Frogel et al. 1987, Phillips et al. 1987), show deviant color evolution. Furthermore the recent observations of SN 1991T (Phillips et al. 1992, Filippenko et al. 1992a) and of SN 1991bg (Filippenko et al. 1992b, Leibundgut et al. 1993) have demonstrated that some SNIa exhibit very peculiar spectra at maximum light. Finally SN 1991bg was indubitably subluminous at maximum. It is not yet clear if it might eventually be possible to isolate spectroscopically a subsample of SNIa that are, indeed, identical standard candles. The present status of this problem is, perhaps, best summarized by Filippenko et al. (1992b), who write: "*However, it remains to be demonstrated that a majority of SNeIa really are homogeneous; peculiar examples seem to have been common among the nearest SNeIa observed during the last decade*". The situation is best illustrated by the SNeI in the Virgo cluster. After applying small corrections for absorption the brightest of seven SNeIa in Virgo, that have well-observed maxima, is observed to have been 33 times more luminous than the faintest Virgo SNIa. Strong confirmation of the large luminosity dispersion among SNIa is provided by a comparison of SN 1957B and SN 1991bg, which both occurred in the elliptical galaxy NGC 4374(=M 84). These two supernovae had a luminosity difference ΔB(max) ≃ 2.4 mag. On the other hand SN 1980N and SN 1981D, which both occurred in NGC 1316, had ΔB(max) ≃0.1 mag. (Hamuy et al. 1991). From these data it is not yet clear whether (1) the bulk of SNIa are standard candles, with a few mavericks like SN 1991bg or if (2) supernovae of type Ia exhibit a broad range in their luminosities, colors and spectra. Until this question is settled it seems rather hazardous, and at best premature, to use any particular SNIa, such as SN 1937C, as a standard candle to determine H_0 .

A recent investigation by van den Bergh (1993) shows that the discovery probability for subluminous objects like SN 1991bg is an order of magnitude lower than it is for SNIa of more nearby normal luminosity. This suggests that SN 1991bg-like objects might actually be quite common in volume-limited supernova samples. SN 1992K may be another example of such an object.

Additional evidence for the diversity of SNeIa comes from the wide range in their observed expansion rates (Branch, Drucker & Jeffery 1988, Barbon et al. 1990). The observed expansion velocity for the most rapidly expanding SNIa, SN 1983G, was almost twice as large as that of SN 1961H and SN 1970J. It is noted in passing that the two most slowly expanding SNeI are also the *only* two objects in the sample of 28 objects listed by

Branch, Drucker & Jeffery (1988) and Barbon et al. (1990) that occurred in elliptical galaxies. The expansion velocity of SN 1991bg (Leibundgut 1993), which also occurred in an elliptical, is also unusually low. This low expansion velocity of SNeIa in elliptical galaxies has also been noted by Filippenko (1989). *If confirmed by a larger sample this result would indicate that there is a physical difference between* (presumably old) *SNeI in elliptical galaxies and the* (probably younger) *SNeIa in spiral galaxies.* Such differences suggest the possibility that the luminosities and intrinsic colors of SNeIa in elliptical and spiral galaxies could also be systematically different.

It might, of course, be speculated that the observed range in expansion velocities of SNeIa is due to standard, but asymmetrical, explosions seen from different directions. However, this will not make SNeIa standard candles because the luminosity of prolate (or oblate) supernovae would now depend on viewing angle.

3. INTRINSIC COLORS OF SNEIA

The intrinsic colors adopted for SNeIa enter into the distance scale calibration in a critical way. Mainly on the basis of *photographic* lightcurves Cadonau, Sandage & Tammann (1985) adopted an intrinsic color $(B-V)^0_{max} = -0.27$ for SNeIa at maximum blue light. This differs substantially from the value $(B-V)^0_{max} = +0.01$ that Hamuy et al. (1991) obtain from *photoelectric* photometry of the (presumably unreddened) supernova 1980N, which occurred in the outer envelope of the cD-like galaxy NGC 1316. For a standard ratio of total-to-selective absorption of $R_B = A_B/E(B-V) = 4.2$ (Mathis 1990) this yields a systematic *difference* of 1.18 mag in the A_B values for SNeIa. (This corresponds to a change of 72% in the numerical value of the Hubble parameter!) An additional complication is provided by the observation (Filippenko et al. 1992b) that SN 1991bg was anomalously red at maximum light. This suggests that the possibility that the colors and the luminosities of SNeIa at maximum light might be correlated.

The importance of intrinsic color to the distance scale problem has been discussed in considerable detail by van den Bergh & Pierce (1992) and van den Bergh & Pazder (1992). In a recent review Branch & Tammann (1992) adopt a rather blue intrinsic color $(B-V)^0_{max} = -0.15$ for SNeIa at blue maximum. With this value they find that "A value of $R_B = 4$ would drastically increase the scatter about the Hubble line. Using 14 field SNeIa with color information, Leibundgut & Tammann (1992) have found from a least-squares solution $R = 0.7 \pm 0.1$ (which is unphysical), whereas the 17 SNeIa from the sample of Miller & Branch (1990) give $R = 1.3 \pm 0.1$". These unphysically low values for the ratio of total-to-selection absorption suggest that the intrinsic supernova colors adopted by Branch & Tammann (1992) are too blue, resulting in reddening values that are too large, and R_B values that are too small.

From a study of the lightcurves of SNeIa in ellipticals Filippenko (1989) concludes that such objects might have a smaller dispersion in their lightcurve characteristics than do SNeIa in spirals. Such differences could be due to the fact that all SNeIa in ellipticals have old progenitors, whereas those in spirals and irregulars might have both old and intermediate-age progenitors (van den Bergh 1990). *If* this speculation is correct then SNeIa in ellipticals might be better (more uniform) calibrators of the extragalactic distance scale than are the supernovae of type Ia in spirals. Unfortunately, the deviant photometric and spectroscopic characteristics of SN1991bg, which occurred in the normal E1 galaxy M 84, now make this speculation less attractive.

4. HUBBLE DIAGRAM FOR SUPERNOVAE OF TYPE Ia

Supernovae are often discovered serendipitously. As a result most SNe do not have good photometry near maximum. To determine the intrinsic luminosity dispersion of SNeIa at maximum light it is therefore essential to restrict the sample to those objects having the most accurate photometry. In a recent paper van den Bergh & Pierce (1992) give a list of the 23 SNeI for which maximum magnitudes, with estimated errors ≤ 0.5 mag, were available in the literature on 1992 January 1. A Hubble diagram for these data is plotted in Fig. 1. Also shown in this figure are the more recent supernovae 1991T and 1991bg. Assuming $H_0 = 75$ km s^{-1} Mpc^{-1}, a Virgocentric infall model with a retardation of 300 km s^{-1}, a Virgo cluster distance of 17 Mpc and $(B-V)^0_{max} = 0.0$ for SNeIa yields $\langle M_B(\max)\rangle = \langle M_V(\max)\rangle = -19.01 \pm 0.12$, with a dispersion $\sigma_M = 0.58$ mag. On the one hand the true luminosity dispersion will be smaller than this value because both observational errors and deviations from a smooth Hubble flow contribute to the apparent luminosity dispersion. However, on the other hand, the true luminosity dispersion among SNeIa will be underestimated because the database on SNeIa is strongly biased against the discovery of subluminous objects such as SN 1991bg. Including SN 1991T (Filippenko et al. 1992a, Phillips et al. 1992) and SN 1991bg (Filippenko et al. 1992b, Leibundgut et al. 1993), for which published data were not yet available to van den Bergh and Pierce (1992), yields $M_V(\max) =$

–19.00 ± 0.14, with σ_M = 0.71 mag and M_B(max) = –18.94 ± 0.17, with σ_M = 0.83 mag. It is concluded from Fig. 1 and from the σ_M values quoted above that it is by no means certain that the luminosity dispersion of supernovae of type Ia is as small as it was believed to be by Branch & Tammann (1992). Van den Bergh (1993) shows that the sample of actually discovered supernovae is strongly biased against very subluminous objects. He finds that the faint end of the magnitude distribution of SNeIa will be depressed by a factor of ~ 10 at 2 magnitudes below the peak in the luminosity distribution. Furthermore, since most SNeIa have been discovered at redshifts $\leq$ 1500 km s^{-1}, large-scale deviations from a smooth Hubble flow (or from a simple Virgocentric infall model) may significantly affect the M_V(max) values that are derived from the data.

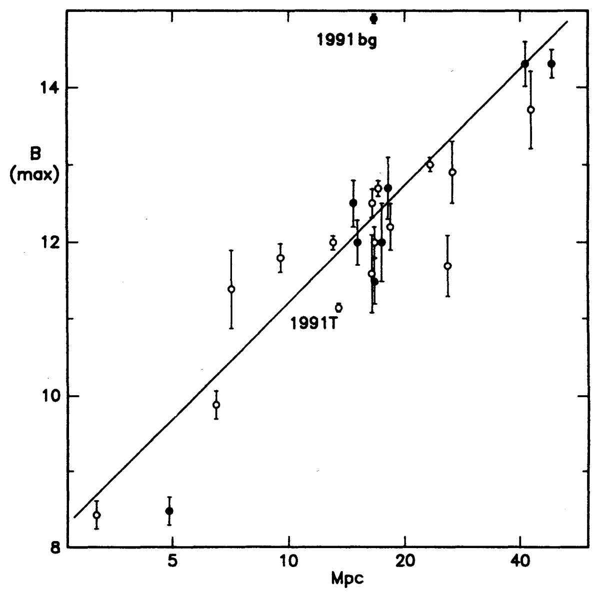

Figure 1. Hubble diagram for SNIa for which the errors of B(max) are smaller than (or approximately equal to) 0.5 mag. Values of B(max) (except in E and S0 galaxies) have been corrected for absorption by assuming $(B-V)_{max}$ = 0.0. Filled circles are objects in E or S0 galaxies. Distances of galaxies were derived from a Virgocentric infall model with a local retardation of 300 km s^{-1} and H_0 = 75 km s^{-1} Mpc^{-1} .

Assuming the Hubble relation for SNIa to have a slope of 0.2 one can derive values of M_0, which is defined by the relation

$$M_B(\max) = M_0 + 5\log(H_0/75). \quad (1)$$

In a pioneering investigation of SNeI in E and S0 galaxies Sandage & Tammann (1982) found M_0 = –18.86 ± 0.24. Neglecting the effects of internal absorption in galaxies Tammann & Leibundgut (1990) and Miller & Branch (1990) obtained even fainter values M_0 = –18.75 and M_0 = –18.68, respectively. Recent determinations of M_0, which do take into account internal absorption, are listed in Table 1. Note that all of the investigations used in compiling this table employed supernova distances that were derived using Tully's (1988) Virgocentric infall model. The data in Table 1 show that values of M_0 that take absorption into account are significantly more luminous than those that do not. Furthermore the bluest intrinsic colors yield the largest absorption values and therefore the highest supernova luminosities.

Substituting the value M_B(max) = –20.1 ± 0.2 (Sandage et al. 1992) into Eqn.(1) yields H_0 = 45 km s^{-1} Mpc^{-1} (34 < H_0 < 61) for $(B-V)^0_{max}$ = 0.00 and H_0 = 62 km s^{-1} Mpc^{-1} (44 < H_0 < 89) for $(B-V)^0_{max}$ = –0.25, in which the extreme limits of H_0 were obtained by adding ε, the uncertainty in the mean of M_0, the magnitude dispersion σ_M and the uncertainty in M_B(max) of SN 1937C in quadrature. This result again serves to emphasize the extreme sensitivity of the values of the Hubble constant that are derived for SNIa on their assumed intrinsic colors.

The effect of intrinsic color on the Hubble parameter, the luminosities of SNeIa, etc. may be summarized as follows:

If $(B-V)^0_{max} \approx 0.0$, as seems to be indicated by the photometry of Hamuy et al. (1991), then the Hubble diagram for SNeIa gives $M_B(max) = -19.01 \pm 0.12 + 5 \log (H_0/75)$. In conjunction with the results of Sandage et al. (1992) for SN 1937C this yields $34 < H_0$ (km s^{-1} Mpc^{-1}) < 61. Furthermore SNeIa in ellipticals and spirals have the same luminosities and the ratio of total-to-selective absorption $R_B \approx 4$.

If $(B-V)^0_{max} \approx -0.25$, as is indicated by the (mainly photographic) observations reviewed by Cadonau, Sandage & Tammann (1985), then $M_B(max) = -19.69 \pm 0.16 + 5 \log (H_0/75)$. When combined with the data of Sandage et al. (1992) on SN 1937C this yields $44 < H_0$ (km s^{-1} Mpc^{-1}) < 89. Furthermore SNeIa in spirals become ~ 1 mag brighter than those in ellipticals (van den Bergh & Pazder 1992) and the value of R_B becomes unphysically low. A third (and perhaps more attractive) alternative is that old, slowly expanding, SNeIa in elliptical galaxies are systematically less luminous (and intrinsically redder) than are the younger, more rapidly expanding SNeIa in spiral galaxies.

5. THE DIAMETERS OF SPIRALS

In a recent paper Sandage (1993) has argued that luminous ScI galaxies are good standard metric rods "which, when calibrated, can be used to determine a system of geometric distances, and therefore the Hubble constant". This assumption flies in the face of observations (Block 1984) which unambiguously show that supergiant spirals of type ScI exhibit a large range in their linear diameters. For example, Fig. 4 of van den Bergh (1992a) shows that the ScI galaxy NGC 309 has a linear diameter which is ~3 times greater than that of NGC 4321 (=M 100), which is the largest ScI galaxy in the Virgo clusters. [Both galaxies were photographed at the prime focus of the KPNO 4-m telescope.]

From a comparison of the diameters of the relatively nearby ScI galaxies M 101 and M 100 Sandage (1993) derives $H_0 = 41 \pm 4$ km s^{-1} Mpc^{-1}. This value, and its small quoted uncertainty, ignore both the large intrinsic dispersion in the diameters of ScI galaxies and the observation that M 100 and M 101, although both of type Sc I, actually have quite different morphologies. This difference is also reflected in the fact that the blue surface brightness (Holmberg 1958) of M 100 is 54% greater than that of M 101.

Another example of the dangers of employing galaxy diameter as distance indicators is provided by M 31 (Sb I-II) and M 33 (Sc II-III). Comparison of the diameters of these objects with those of the galaxies with the most accurate DDO classifications (van den Bergh, Pierce & Tully 1990) in the Virgo and Ursa Major clusters yields cluster distances of $17.1^{+3.1}_{-2.3}$ Mpc (estimated errors) from M 31 and $10.6^{+3.2}_{-2.0}$ Mpc from M 33. The corresponding values of H_0 are 76 ± 12 km s^{-1} Mpc^{-1} from M 31 and 123 ± 28 km s^{-1} Mpc^{-1} from M 33. Both the large estimated errors, and the difference between these two distance estimates, shows that galaxy diameters are not suitable for use as precision distance indicators.

TABLE 1. Recent luminosity[a] determinations for SNIa

M_0	ε	σ_M	$(B-V)^o_{max}$	Reference
−19.24	± 0.18	...	−0.16	Della Valle & Panagia(1992)
−19.01	0.12	0.58	0.00	van den Bergh & Pierce (1992)
−19.69	0.16	0.75	−0.25	van den Bergh & Pierce (1992)

[a] $H_0 = 75$ km s^{-1} Mpc^{-1} assumed

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Sidney van den Bergh: Dominion Astrophysical Observatory, National Research Council, 5071 West Saanich Road, Victoria, British Columbia, V8X 4M6, Canada.