THE SUPERNOVA Ia 2011fe IN M101, ITS TIP OF THE RED-GIANT BRANCH (TRGB) DISTANCE, AND THE VALUE OF H0

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Abstract

The light curve parameters of the normal type Ia SN 2011fe are derived from the rich archive of the AAVSO. This leads, together with the TRGB distance modulus of \((m-M) = 29.39 \pm 0.05\) of the parent galaxy M101, to maximum magnitudes of the unreddened SN of \(M_B = -19.45 \pm 0.08\), \(M_V = -19.46 \pm 0.08\), and \(M_I = -19.25 \pm 0.06\) (for the standard decline rate of \(\Delta m_{15} = 1.1\)). When these values are inserted into the Hubble line defined by 62 SNe Ia with \(3000 < v < 20,000\) km s\(^{-1}\) — and considering also four other SNe Ia with TRGB distances — one obtains a large-scale value of the Hubble constant of \(H_0 = 64.3 \pm 1.9 \pm 3.2\). This value can be much improved in the future by using only TRGB distances of SNe Ia.

Subject headings: cosmological parameters — distance scale — galaxies: distances and redshifts — galaxies: individual (M101) — supernovae: individual (SN 2011fe)

1. Introduction

A single SN Ia with a reliable distance can be important for the luminosity calibration of SNe Ia as a class and hence for the determination of the cosmic value of \(H_0\). The Hubble diagram of SNe Ia out to \(20,000\) km s\(^{-1}\) (Reindl et al. 2005, in the following RTS 05) shows that their intrinsic luminosity dispersion is 0.14 mag — after corrections for internal absorption, the decline rate, and if necessary for the \(z\)-dependent \(K\)-effect. From this follows that the luminosity of only one SN Ia determines the distances of all SNe Ia — and hence the value of \(H_0\) — to within a statistical error of 0.14 mag or 7% in linear distance.

The SN Ia 2011fe occurred in the outer region of M101. Since the Cepheid distance of this galaxy is rather ambiguous (see Section 3 below), we rely on the tip of the red-giant branch (TRGB) as the most secure distance indicator for this galaxy. Attempts to calibrate other SNe Ia with TRGBs have been made before (Tammann et al. 2008a; see also Mould & Sakai 2009b). SN 2011fe is particularly favorable for the purpose because its light curve parameters are well determined and its internal absorption is close to zero.

The method of the TRGB seems problem-free if applied to old halo populations. The absolute magnitude \(M_I^*\) of the TRGB is well determined through 22 galaxies with RR Lyr star distances. The result of \(M_I^* = -4.05 \pm 0.02, \sigma = 0.08\) (Tammann et al. 2008a), agrees exactly with two earlier, independent determinations by Sakai et al. (2004) and Rizzi et al. (2007). The color/metallicity dependence of the TRGB has been discussed several times with contradictory results. But in the relevant color range around \((V-I)^* = 1.6\) the variation is not larger than 0.05 mag (Tammann et al. 2008a) and is neglected in the following. Also internal absorption poses a minimum problem in the halo fields. The most severe problem of the TRGB are very red stars like young AGBs, that can become brighter than the TRGB in dense fields of mixed populations. In that case the TRGB may get drowned by contaminating stars, as further discussed in Section 3. This always leads to an underestimate of the distance. TRGB distances are so far restricted to \(\sim 22\) Mpc (Schweizer et al. 2008), but M101 lies well within the reach.

2. The Supernova 2011fe

The SN 2011fe was discovered in M101 by the Transient Palomar Factory on August 24, 2011, and classified as a normal type Ia (Nugent et al. 2011). The American Association of Variable Star Observers (AAVSO) has collected 190 \(B, 4143\ V\), and 252 \(I\) magnitudes until November 10, 2011, from 48 different sources. They establish the exceptionally well defined light curves shown in Figure 1. Overplotted are the well fitting standard light curves in \(B\) and \(V\) for SNe Ia with a decline rate of \(\Delta m_{15} = 1.1\) (Leibundgut 1988). The relevant light curve parameters are shown in Table 1.

The reddenings in Table 1 are the differences between the SN 2011fe and its internal absorption is close to zero. This leads, together with the TRGB distance modulus of \((m-M) = 29.39 \pm 0.05\) of the parent galaxy M101, to maximum magnitudes of the unreddened SN of \(M_B = -19.45 \pm 0.08\), \(M_V = -19.46 \pm 0.08\), and \(M_I = -19.25 \pm 0.06\) (for the standard decline rate of \(\Delta m_{15} = 1.1\)). When these values are inserted into the Hubble line defined by 62 SNe Ia with \(3000 < v < 20,000\) km s\(^{-1}\) — and considering also four other SNe Ia with TRGB distances — one obtains a large-scale value of the Hubble constant of \(H_0 = 64.3 \pm 1.9 \pm 3.2\). This value can be much improved in the future by using only TRGB distances of SNe Ia.

3. The Distance of M101

The TRGB of M101 has been detected in an outlying field at \(I^* = 25.39 \pm 0.04\) (Sakai et al. 2004). Rizzi et al. (2007)
found $I^* = 25.30 \pm 0.08$. (The magnitudes are corrected throughout for Galactic absorption following Schlegel et al. (1998)). The mean value of $I^* = 25.35 \pm 0.04$ gives together with the calibration from above a true distance modulus of M101 of $(m-M) = 29.39 \pm 0.05$, which we adopt.

Shappee & Stanek (2011) have suggested $I^*$ to lie at $24.98 \pm 0.06$ for a reference color of $(V-I)^* = 1.6$, yet the magnitude is clearly too bright. The value is measured in two inner fields of M101. The authors have taken the precaution to exclude the stars within 4.75 from the center, but in spite of this the field contains a mixture of old and young stars. Some of the latter are very bright and red and hide the true TRGB. The authors’ edge detection function shows a weaker maximum at $I^* \sim 25.3$ which could be the signature of the true TRGB in agreement with Sakai et al. (2004) and Rizzi et al. (2005).

Several similar cases are known. Already Sakai et al. (2004) have shown in case of NGC 3621 that the TRGB is unambiguously detected in halo fields, whereas an inner field contains so many equally red, but brighter stars that the TRGB becomes undetectable. A good illustration is also provided by NGC 4038, where Saviane et al. (2008), considering a field containing clear tracers of a young population, suggested a TRGB magnitude that is $\sim 0.9$ mag brighter than the convincing TRGB found by Schweizer et al. (2008) in another field of this galaxy that does not show evidence for a young popu-
lateral.

We suspect that also the claimed TRGBs of NGC 3368 at \( I^* = 25.66 \) (Mould & Sakai 2009a) and NGC 3627 at \( I^* = 25.77 \) (Mould & Sakai 2009b) are determined by very red and luminous stars of a younger population. The two galaxies are considered to be bona fide members of the Leo I group where four other members have a mean TRGB magnitude about 0.7 mag brighter (\( \langle I^* \rangle = 26.42 \)). Also their implied TRGB distances of \( (m-M) = 29.71 \) and 29.82 are smaller by ~0.65 mag than their respective Cepheid distances of 30.34 and 30.50 (Saha et al. 2006). Finally the SNe Ia 1998bu in NGC 3368 and 1989B in NGC 3627 would become fainter by ~0.7 mag with the proposed TRGB distances than SN 2011fe in M101. Considering the luminosity dispersion of SNe Ia of only 0.14 mag, this corresponds to a 4.7\( \sigma \) discrepancy.

For the reasons given we discard the inner-field TRGB detection of M101 by Shappee & Stanek (2011).

Unfortunately Cepheids cannot be used to buttress the TRGB distance of M101, although, in general, Cepheid and TRGB moduli agree to within 0.05 mag on average with a dispersion of ~0.08 mag (Sakai et al. 2004; Rizzi et al. 2007; Tammann et al. 2008b). The problem of M101 is that the Cepheids in an outer, metal-poor field (Kelson et al. 1996) and in two inner, metal-rich fields (Shappee & Stanek 2011) yield discordant distances. A recent discussion of these Cepheids gives \( (m-M) = 29.28 \pm 0.05 \) for the outer field (in acceptable agreement with the TRGB distance) and 29.14 ± 0.01 (statistical error) for the inner fields (Tammann & Reindl 2011). The discrepancy of 0.1~0.2 mag is not due to the specific choice of the period–luminosity (P–L) relation, but is confirmed by several authors using different P–L relations (see Sakai et al. 2004, their Table 3).

4. THE CALIBRATION OF \( H_0 \)

Sixty-two SNe Ia with \( 3000 < V < 20,000 \) km s\(^{-1} \) define a Hubble relation of the form

\[
\log H_0 = 0.2M^\text{corr}_V(\text{max}) + C_V + 5, \tag{1}
\]

where \( C_V = 0.693 \pm 0.004 \), \( C_W = 0.688 \pm 0.004 \), and \( C_I = 0.637 \pm 0.004 \). These values are the intercepts of the respective Hubble lines for an adopted \( \Lambda \)CDM model with \( \Omega_M = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \) (RTS 05, eq. 26).

The detected apparent maximum magnitudes of SN 2011fe in Table 1 give together with the TRGB modulus of M101 from Section 3 the absolute magnitudes \( M^\text{corr}_V = -19.45 \pm 0.07 \), \( M^\text{corr}_B = -19.46 \pm 0.05 \), and \( M^\text{corr}_I = -19.26 \pm 0.06 \). These values inserted into Equation (1) give large-scale values of \( H_0(B) = 63.5 \pm 2.2 \), \( H_0(V) = 62.5 \pm 1.6 \), and \( H_0(I) = 61.0 \pm 1.8 \). The weighted mean value is \( H_0 = 62.2 \pm 0.9 \). In view of the internal luminosity dispersion of SNe Ia of 0.14 mag we adopt a large statistical error of \( H_0 = 62.2 \pm 4.4 \) from M101 and its SN Ia alone. The systematic error is negligible in comparison.

There are four additional SNe Ia with direct or circumstantial TRGB distances. They are compiled in Table 2 together with SN 2011fe. The galaxy, its type, and its SN are listed in Columns 1–3. The apparent maximum \( V \) magnitudes are from Wells et al. (1994, SN 1989B) and from Section 2 (SN 2011fe). The remaining magnitudes are from Altavilla et al. (2004, since only the \( B \) magnitudes are published, the \( V \) magnitudes were kindly provided by the authors). The magnitudes \( M^\text{corr}_V \) in Column 4, corrected for Galactic and internal absorption and normalized to \( \Delta m_{15} = 1.1 \), are listed in Table 2 of RTS 05; their errors are estimated to include also the errors of the internal absorption corrections and of the \( \Delta m_{15} \) normalization. The mean TRGB distances, assuming \( M^H_V = -4.05 \) throughout (see Section 1), and their sources are in Columns 5 and 6. The resulting corrected absolute magnitudes \( M^\text{corr}_V \) are in Column 7.

The apparent magnitude of SN 1937C depends heavily on the work of Schaefer (1996) who has transformed the old photometry into a modern system. The SN is in addition a slow decliner and requires a relatively large \( \Delta m_{15} \) correction. SNe Ia 1989B and 1989Bu have large corrections for internal absorption (\( E(B-V) \sim 0.3 \)). Moreover, the TRGB distances of their host galaxies, NGC 3627 and 3628, have been rejected in Section 3. Instead it is assumed that they are genuine members of the Leo I group whose mean distance of \( (m-M) = 30.47 \pm 0.06 \) is secure from four other group members with good TRGB magnitudes. These galaxies are NGC 3351, 3377, 3379, and 3384 with TRGB determinations by Sakai et al. (1997, 2004), Rizzi et al. (2007), and Mould & Sakai (2009a). The group membership is particularly compelling for NGC 3368 (M96) which lies between the two TRGB galaxies NGC 3351 (M95) and NGC 3379 (M105).

The mean value of \( M^\text{corr}_V \) in Table 2 is remarkably stable. The dispersion of 0.13 mag agrees with what one expects from distant SNe Ia. The weighted mean is \( \langle M^\text{corr}_V \rangle = -19.40 \pm 0.06 \), the unweighted mean is only 0.02 mag fainter, as is the mean if SN 2011fe is omitted. If one suspects SN 1937C because of its old, yet modernized photometry and if one excludes SNe 1938Bu and 1989B because their TRGB distances depend on group membership, the remaining two SN 2011fe and SN 1972E give \( \langle M^\text{corr}_V \rangle = -19.41 \pm 0.07 \). The gain of the overall mean over the determination from only SN 2011fe is that the statistical error is now much reduced. We adopt the above weighted mean luminosity of the five SNe Ia that, inserted in equation (1), gives

\[
H_0 = 64.3 \pm 1.9 \pm 3.2. \tag{3}
\]

The systematic error depends now mainly on the assumption that NGC 3627 and 3628 do not lie at their suggested TRGB distances, but that they are actual members of the Leo I group. For the additional reasons given in Section 3 we are convinced that the attribution is correct within the (small) depth effect of the group. We therefore estimate the systematic error to be not more than 5%.

For comparison it is noted that the TRGB distances of 78 field galaxies with \( v_{\text{hel}} > 280 \) km s\(^{-1} \) (\( v_{\text{hel}} \) is the velocity corrected for a local Virgocentric infall vector of 220 km s\(^{-1} \)) give a local value of \( H_0 = 62.9 \pm 1.6 \) (TSR08b). A slightly augmented sample of Saha et al. (2006), comprising now 29 Cepheid distances with \( 280 < v_{\text{hel}} < 1600 \) km s\(^{-1} \), yields \( 63.4 \pm 1.8 \) (TSR08b). Twenty Cepheid-calibrated SNe Ia with \( v_{\text{hel}} < 2000 \) km s\(^{-1} \) lead to a still quite local value of \( H_0 = 60.2 \pm 2.7 \) (TSR08b). A large-scale value comes from the summary paper of the \textit{HST} Supernova Project, based on ten SNe Ia with Cepheid distances and a total of 62 SNe Ia with \( 2000 < v < 20,000 \) km s\(^{-1} \), that resulted in \( H_0 = 62.3 \pm 1.3 \pm 5 \) (Sandage et al. 2006).

Population I and Population II distance indicators point here consistently to a value of 60 < \( H_0 < 65 \). However other authors have found \( H_0 > 70 \) from a different — as we believe inadequate — treatment of the period-color and period-luminosity relations of Cepheids (e.g., Freedman et al. 2001;
Additional support for a rather low value of $H_0$ comes from Reid et al. (2010) who have derived, by combining the catalog of luminous red galaxies (LRG) from the Sloan Digital Sky Survey DR7 with the 5-year WMAP data and the Hubble diagram of the SN Ia Union Sample, a value of $H_0 = 65.6 \pm 2.5$ on the assumption of a $\Lambda$CDM model.

5. DISCUSSION

The importance of the RR Lyr star-calibrated TRGB is that it uses exclusively Population II objects and provides an independent check on the Population I Cepheid distance scale. The determination of Cepheid distances is time-consuming and complex. The metallicty dependence of their colors makes the determination of internal absorption uncertain and implies also that their period-luminosity relation changes with metallicity (Sandage & Tammann 2008). Notwithstanding the general agreement, already cited, of Cepheid and TRGB distances, the discrepancies of the Cepheid distances of the two galaxies, where these variables were observed in two separate fields, viz. M101 (see Section 3) and even more pronounced in case of NGC 4258 (Tammann & Reindl 2011), are unexplained. Alarming are also the Cepheids in NGC 1309 by Riess et al. (2009b) whose observed $(V-I)$ color — uncorrected for internal reddening — is bluer by 0.15 mag on average than that of any other long-period Cepheids (Tammann & Reindl 2011). Also the Cepheids of NGC 3021 (Riess et al. 2009b) are very blue. Other blue Cepheids may be concealed by internal reddening. The properties of blue Cepheids must be influenced by one or more hidden parameters, as for instance the Helium content. Since the luminosity of these Cepheids is unknown, they cannot be used for a distance determination.

The difficulties with some Cepheids illustrate the need for an independent confirmation of the large-scale distance scale. The test can be provided by TRGB distances which carry the distance scale — if used for the luminosity calibration of SNe Ia — to the limit where SNe Ia can be observed.

The present result will be much improved by future TRGB distances of galaxies that have produced a SNe Ia. It is desirable that the search for the TRGB in NGC 3368 and 3627 in the Leo I group will be repeated in some uncontaminated halo fields. The next easiest targets at present are the Virgo cluster galaxies NGC 4526 with SN 1994D and NGC 4639 with SN 1990N. Slightly more difficult are the Fornax cluster galaxies NGC 1316 with three(!) SNe Ia (1980N, 1981D, and 2006dd) and NGC 1380 with SN 1992A. These SNe, except SN 1981D, are blue and hence little affected by internal absorption. The Virgo and Fornax galaxies will be rather nearer than NGC 4038 where Schweizer et al. (2008) have demonstrated that the TRGB can be reached.

It is foreseeable that the route to a precision value of $H_0$ through the TRGB and SNe Ia will become highly competitive with any Cepheid-based distance scale.

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TABLE 2

| Galaxy      | Type | SN   | $m^\text{ext}$ | $(m-M)_{\text{TRGB}}$ | Ref. | $M^\text{corr}$ |
|-------------|------|------|----------------|-----------------------|------|----------------|
| NGC 5457    | Sc   | 2011e| 9.93 ± 0.08    | 29.39 ± 0.05          | 1.2  | −19.46 ± 0.09 |
| NGC 5253    | Am   | 1972E| 8.49 ± 0.08    | 27.79 ± 0.10          | 1.2  | −19.30 ± 0.13 |
| IC 4182     | Im   | 1937C| 8.99 ± 0.15    | 28.21 ± 0.05          | 1.2  | −19.22 ± 0.16 |
| NGC 3368    | Sab  | 1998Ba| 11.04 ± 0.10  | 30.47 ± 0.10          | 3    | −19.43 ± 0.14 |
| NGC 3627    | Sb   | 1989B| 10.95 ± 0.12   | 30.47 ± 0.10          | 3    | −19.52 ± 0.16 |

unweighted mean | −19.38 ± 0.05
weighted mean   | −19.40 ± 0.06

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