The Extragalactic Distance Scale in the Gaia Era

Rachael L. Beaton
Carnegie Observatories
(Fall 2017 - @Princeton)
It is common to think of the distance scale in terms of “reaching out” from the Galaxy. Let’s think of it in terms of backward design.
The Hubble Diagram

$H_0$ is the proportionality constant between distance (x-axis) and redshift (y-axis).
$H_0$ is measured in the smooth Hubble Flow where over 200 SNe Ia are well-characterized.

Almost a century later …

$\sigma_{\text{SNe Ia}} = 0.15$ mag with 221 SNe Ia

0.7 % uncertainty
The best we can do with current local sample is 2.1% uncertainty regardless of how we calibrate the SNe Ia.
In the (recent) past this was okay:

The large uncertainties from the other terms that set the Cepheid scale were much larger than the 2% from the SNe Ia.
But, today it is not:

Even an 0.05 mag uncertainty (2.5%) is a detail to worry about.
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Beaton et al. 2016

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Beaton et al. 2016

Most recent determinations differ by 3.4σ (i.e., 96% percentile).

Not good.

Freedman et al. 2016
HST Key Project

10%

Riess et al. 2016

2.4%

Planck Collaboration 2016

1.6%

Even an 0.05 mag uncertainty (2.5%) is a detail to worry about.
Why so few SNe Ia Calibrators?

It is just not for a ‘lack’ of SNe Ia in the ‘Local Volume’

**As of March 2016.**
Why so few SNe Ia Calibrators?

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Shappee (incl. Beaton) et al. (in prep.)
## SNe Ia Suitability

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SNe Ia Suitability

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(2) Can I measure its distance?

**Thanks to a phenomenal effort from the SNe/transient communities 40 SNe Ia within 40 Mpc have this data (~50%).**

**Chris Burns (CSP) & Ben Shappee (ASAS-SN)**
## SNe Ia Suitability

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**With Cepheids? MAYBE?**

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and herein lies the limitation.
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### Cepheids are amazing tools, but their applicability to the SNe Ia host population is limited.

The data needed to find, characterize, and use the Leavitt law is expensive, relies on numerous ground and space facilities, and multiple techniques.

Thanks to a phenomenal effort from the SNe/transient communities, 40 SNe Ia within 40 Mpc have this data (~50%).

*“Chris Burns (CSP) & Ben Shappee (ASAS-SN)*

and herein lies the limitation.
With Gaia, more tools.
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Too faint for distances to SNe Ia hosts.
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Cepheids:
- < 400 Myr
- Range [Fe/H]
- Galaxy Disks
- variable

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- Disk, bulge, halo
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**TRGB:**
- > few Gyr
- Mostly metal-poor
- Disk, bulge, halo
- Not variable

Too faint for distances to SNe Ia hosts.
Tip of the Red Giant Branch

IC 1613 – Local Group Dwarf Irregular

Optical: Hatt, Beaton et al. (submitted)
NIR: Madore (incl. Beaton) et al. (in prep.)
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- Apply to low-density regions of galaxies.
- Few differences between local stars and distant stars.
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1. Build a Sample of SNe Ia

The CCHP Pathways to a 3% Determination of the Hubble Constant

Beaton et al. 2016
2. Standardized Techniques

NEAR-FIELD

FAR-FIELD

Hatt, Beaton et al. (submitted) ArXiv:1703.06468

Jang, Hatt, Beaton et al. (submitted) ArXiv:1703.10616
2. Standardized Techniques

NEAR-FIELD

IC1613

D = 784 ±17 (stat) ±40 (sys) kpc

Hatt, Beaton et al. (submitted) ArXiv:1703.06468

FAR-FIELD

NGC1365

D = 18.1 ±0.3 (stat) ±0.4 (sys) Mpc

Jang, Hatt, Beaton et al. (submitted) ArXiv:1703.10616
2. Standardized Techniques

Dylan Hatt
PhD Student
Univ. of Chicago

NEAR-FIELD

M31

FAR-FIELD

NGC1316

Hatt, Beaton et al. (in prep.)

Jang, Hatt, Beaton et al. (in prep.)
2. Standardized Techniques

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Beaton, Hatt et al. (in prep.)
3. Direct Calibration

Optical photometry from TMMT @ LCO

Instrument + RR Lyrae Campaign in:
Monson, Beaton et al. 2017

Hipparcos
Perryman et al. 1997

Gaia DR1
TGAS Catalog
$\sigma_\pi / \pi < 25\%$

Beaton, Monson et al. (in prep.)
3. Direct Calibration

Monson, Beaton et al. 2017

55 RRL with 10-band Data

10 band PL Relations with TGAS
Pop I & II: Consistency

IC1613

Cepheids

TRGB

RRL

24.2

24.4

NGC1365

Cepheids

Freedman+01

Riess+16

TRGB

31.1 31.2 31.3 31.4 31.5 31.6

Distance Modulus, $\mu_0$

Hatt, Beaton et al. (submitted) ArXiv:1703.06468

Jang, Hatt, Beaton et al. (submitted) ArXiv:1703.10616
NIR: JWST & WFIRST

Adapted from Dalcanton et al. 2011
Conclusions

• Path to 1% $H_0$ requires standard candles that provide access to high no. of SNe Ia.
  – TRGB has numerous advantages toward this goal.
• Scale and volume probed by Gaia makes secondary distance indicators primary distance indicators.
• So far, Cepheid, RR Lyrae, and TRGB distances are remarkably consistent.
  – More tests on-going in 6 Local Group galaxies and 9 SNe Ia hosts.
• TRGB in NIR could permit every SNe Ia within 40 Mpc to have a < 5% distance.
To Close:

It’s got to be fun, I don’t think anybody should tell you that he’s slogged his way through 25 years on a problem and there’s only one reward at the end, and that’s the value of the Hubble constant.

That’s a bunch of hooey.

The reward is learning all the wonderful properties of the things that don’t work.

From Obituary in NYTimes by D. Overbye

Sandage, Beaton & Majewski 2016