Engineering Measurement of the *Hubble Constant*

aka Distances to ALL the Galaxies

Rachael L. Beaton

**NOW:** Carnegie Observatories (Pasadena)

**Soon:** Hubble Fellow, Carnegie-Princeton Fellow
Princeton University
The Hubble Constant

Graph showing the Hubble constant ($H_0$) over time with various data points and error bars. The graph illustrates the evolution of the Hubble constant from 2000 to 2015, with different data sets represented by symbols and error bars.

Legend:
- Blue squares: Distance Ladder
- Red triangles: $\Lambda$CDM

Data sources:
- Freedman 2017
- Beaton et al. 2016
Distance Modulus [mag] vs. log10(zCMB) for SNe Ia in Hubble Flow and Local SNe. SNe in Hubble Flow have a standard deviation of 0.5%. Local SNe have a standard deviation of 2%. The Carnegie Supernova Project and CfA4 datasets are also shown.

Local SNe Ia (8)
Carnegie Supernova Project (130)
CfA4 (94)

Beaton et al. 2016
Why so few SNe Ia Calibrators?
Why so few SNe Ia Calibrators?

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

Stats as of March 2016
Why so few SNe Ia Calibrators?

or that they have only been discovered recently.

SN Ia within ~40 Mpc [NED Distance]

$N_{SN_{Ia}} = 95$
SNe Ia Are Now Found Earlier

1. March 10, 2017: Transient Detected in NGC5643
2. March 11, 2017: Typed as very young SN Ia
3. March 11, 2017: Start building light curves

Earlier means more insight into SNe Ia physics.
# SNe Ia Suitability

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<thead>
<tr>
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- ... and related issues.
SNe Ia Suitability

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

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

and herein lies the limitation.
The real voyage of discovery consists not in seeking new landscapes, but in having new eyes.

Marcel Proust
The Foundation: Gaia

GAIA’S REACH

The Gaia spacecraft will use parallax and ultra-precise position measurements to obtain the distances and ‘proper’ (sideways) motions of stars throughout much of the Milky Way, seen here edge-on. Data from Gaia will shed light on the Galaxy’s history, structure and dynamics.

10 µas = 10% distances at 10 kpc

*1 parsec = 3.26 light years
Gaia gives us access to the whole HR-Diagram
**Miras**
100 dy < P < 600 dy
1 Gyr < Age < few Gyr

**Cepheids**
3 dy < P < 150 dy
Age < 500 Myr

**Tip of the Red Giant Branch**
All metallicities
~1 Gyr < Age < ??

**RR Lyrae**
0.25 dy < P < 1 dy
~1 Gyr < Age < ??

Metal rich HB stars
~1 Gyr < Age < ??

Too faint for SNe Ia hosts en masse
Tip of the Red Giant Branch

**Theory:** Lifting of core degeneracy => ignition of He shell => He-Flash

**Empirical:** sharp terminus or edge to the RGB sequence

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**Review:** Salaris et al. 2002

**Updates in:** Serenelli et al. (1706.09910)

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**Review:** Lee, Madore, and Freedman 1993

**Review:** Beaton et al. 2016
In Practice:

Erica Carlson
OCIS Intern
Now grad student
UW-Madison

Hubble Space Telescope

WFIRST

James Webb Space Telescope

NGC6822
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NGC6822

2.5 3.5 4.5 2.5 3.5 4.5 2.5 3.5 4.5 2.5 3.5 4.5

Apparent Magnitude

Absolute Magnitude

V-K [mag]
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TRGB

Absolute Magnitude

Apparent Magnitude

V - K [mag]

NGC6822

B 0.44 µm
V 0.55 µm
R 0.65 µm
I 0.8 µm

0.44 µm
0.55 µm
0.65 µm
0.8 µm

P=60 dy
P= 6 dy

0.8 µm
1.2 µm
1.6 µm
2.2 µm
3.5 µm
4.5 µm

2.5 3.5 4.5

Cepheids
TRGB

WFIRST
James Webb Space Telescope
Hubble Space Telescope
The Tip of the Red Giant Branch technique can be applied to EVERY Galaxy (with differing error bars).
~Equal Precision Near & Far

**NEAR-FIELD**

- IC1613
- NGC1365

**FAR-FIELD**

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

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ArXiv:1703.06468

NORDITA July 27, 2017

Rachael L. Beaton
~Equal Precision Near & Far

Dylan Hatt
Grad @ U Chicago

In Sung Jang
PhD/Now Postdoc@AIP

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

Jang, Hatt, Beaton et al. (submitted)
ArXiv:1703.10616
\[ D = 18.1 \pm 0.3 \text{ (stat)} \pm 0.4 \text{ (sys) Mpc} \]
\[ \mu_0 = 31.29 \pm 0.04 \text{ (stat)} \pm 0.05 \text{ (sys) mag} \]

\[ D = 784 \pm 17 \text{ (stat)} \pm 40 \text{ (sys) kpc} \]
\[ \mu_0 = 24.30 \pm 0.03 \text{ (stat)} \pm 0.05 \text{ (sys) mag} \]

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

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ArXiv:1703.10616
Derivation of Uncertainties

NEAR-FIELD
IC1613

FAR-FIELD
NGC1365
~Equal Precision Near & Far

Hatt, Beaton et al. (in prep)
NORDITA July 27, 2017

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Not limited to One Sample

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Rachael L. Beaton – Carnegie Observatories
Not limited to One Sample

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Direct Calibration in *Gaia* DR2?

Optical photometry from TMMT @ LCO

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

We need more than *Gaia*, we need good magnitudes, colors, etc.
Direct Calibration in *Gaia* DR2**?

Optical photometry from TMMT @ LCO

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

Merge with large scale stellar surveys to study behavior with [M/H], log(g), $T_{\text{eff}}$.

APOGEE (SDSS), RAVE, GALAH, LAMOST, TESS

** 2017 Gaia Sprint Project (last week @MPIA)
Direct Calibration in Gaia DR2**?

\[ V, I, J, H \text{ on HST now} \]
\[ V, I, J, H \text{ on non-cryo JWST*} \]
\[ V, J, H \text{ on WFIRST} \]

*JWST optical resolution very minor improvement over HST

NORDITA July 27, 2017

Rachael L. Beaton

** 2017 Gaia Sprint Project (last week @MPIA)
We see consistency

**IC1613**

24.2

+5 more galaxies in the Local Group

**NGC1365**

24.4

+6 more SNe Ia hosts

---

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

Jang, Hatt, Beaton et al. (submitted)
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**Note:** Zero points are not yet fully independent between TRGB and Cepheids
CCHP $H_0$ Error Budget

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

- **Galactic RR Lyrae**
  - pre-Gaia: 1.7%
  - Gaia: 0.5%

- **Local Group RR Lyrae/TRGB NGC 4258 Maser**
  - pre-Gaia: 0.9%

- **12 SNe Ia & TRGB**
  - pre-Gaia: 2.1%

- **221 SNe Ia into Hubble Flow**
  - pre-Gaia: 0.5%
  - Gaia: 2.3%

- **H$_0$**
  - pre-Gaia: 6.3%
  - Gaia: 2.3%

[Diagram with pathways and error percentages]
Haloes are See-Through
A Prospectus for WFIRST:
(modulo calibration of TRGB in WFIRST filters ...)

Guest Investigator (Archive):
Within HLS:
(m-M) \sim 31.7 [mag]
22 Mpc

Everything in the footprint is “free” @-1%

Guest Observer:
Using $H$ for the TRGB luminosity function and $Y$ for the CMD color:

@HLS Depth => 30 mins
< 22 Mpc

@ 1 mag fainter => 1.25 hours
< 35 Mpc

@ 2 mag fainter => 3.15 hours
< 55 Mpc

@ 3 mag fainter => 7.8 hours
< 87 Mpc
Summary

• Measurement of $H_0$ should be engineered like other cosmological parameters.
• The Tip of the Red Giant Branch method is a very promising standard candle for this measurement. Highlights include:
  – ~Equal precision near and far.
  – Universally present stellar population.
  – Luminous in near-infrared.
  – Can test with multiple pointings in an object.
  – Direct calibration is not far away …
• In our first measurements, we see consistency with Cepheid distances.
• TRGB comes/will come for free for nearby galaxies in most large scale galaxy surveys – keep this in mind and let me make distances from your star-trash 😊.
Backup Slides
The Original Hubble Diagram

\[ v = H_0 \cdot d \]

Recession Velocity (v)

Distance (d)

FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.
AGB Stars in NGC 147

Confirmed C-Stars from Hamren, Beaton et al. 2016
IR Stellar Populations

Adapted from Dalcanton et al. 2011
The LMC is the test

Distance Modulus (mag)

18.33  18.39  18.44  18.50

2MASS

NORDITA July 27, 2017
Hoyt, Seibert, (incl. Beaton) in prep.
The LMC is the test

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Besla et al. 2016

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Distance Modulus (mag)

2MASS

BINS

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