The TRGB Distance Scale
Resolving Tension in the Hubble Constant
A Crisis in Cosmology?
What should we believe?
Hubble Constant
10:02:37 am
October 5, 2019
Walter Baade  Oct 23, 1943

NGC 185

14,400 sec  “Red Light”  Exposure
Walter Baade  Oct 23, 1943
NGC 185
TRGB in IC 1613
Freedman, W.L. AJ, 96, 1248, 1988
TRGB in IC 1613
Freedman, W.L. AJ, 96, 1248, 1988

Truly a Standard Candle
TRGB in IC 1613
Freedman, W.L. AJ, 96, 1248, 1988

Truly a Standard Candle
“BAADE’S SHEET”

CFHT
TRGB in IC 1613

Marginalized Luminosity Function

HST/ACS

(V - I)_{ACS}

Number per bin

Edge Response
TRGB Sequence is a Standard Candle
# Standard vs Standardizable Candles

<table>
<thead>
<tr>
<th>Cepheids</th>
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4.515 MeV @ [M(core) = 0.451 M(solar)]
## Standard vs Standardizable Candles

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Standard vs Standardizable Candles

**Cepheids**
- Mechanical Heat Engine
- Period
- Temperature
- Reddening [Disk]
- Metallicity
- Evolution
- Amplitude Bias
- ... 

**TRGB**
- Standard Candle [Constant]
- [Halo]
- Color [I-Band] 4.515 MeV @ [M(core) = 0.451 M(solar)] [Non-Variable]
- First Principles

**Type Ia SNe**
- Standard Bomb
- Decline Rate
- Intrinsic Color
- Non-Standard ... 

A Pulsating Heat Engine

versus

A Physical Constant of Nature
Red Giant Branch Evolutionary Tracks

Padova Isochrones: TRGB Mass Range
Electron-Degenerate Helium Core Mass-Luminosity Relation

N.B.
No dependence on the total mass of the star. The hydrogen envelope is just “fuel for the fire”.
TRGB In-Sensitivity to Progenitor Mass

Padova Isochrones: TRGB Mass Range

“Mass-Luminosity Relation”

V

M(BOL)

M_{core}

0.47
A Crisis in Cosmology?

What should we believe?
First Principles Underwriting of the Tip of the Red Giant Branch

(1) Triple-Alpha process begins the burning of helium at a threshold temperature of $2 \times 10^8$ K \textit{(Laboratory Astrophysics, Fowler 1954)}

(2) That temperature is reached for a core mass of $M_{\text{core}} = 0.48 M_{\text{solar}}$ \textit{(Core Mass-Luminosity Relation)}

(3) All RGB stars having that core masses simultaneously have the same luminosities \textit{(Ibid.)}

(4) A thermal runaway vaporizes the core, lifting the degeneracy, inflating the core, collapsing the envelope, and driving the star to the Horizontal Branch, which 40 times fainter than the TRGB.

An astrophysical guillotine universally terminates the upward luminosity evolution of all red giant branch stars.
Multi-Wavelength TRGB Sequence Padova Isochrones
Multi-Wavelength TRGB Sequence Padova Isochrones
A Crisis in Cosmology?
What should we believe?
LMC Reddening and Calibration

**M I (TRGB)**
-4.05 +/- 0.023 mag

**LMC (Detached Eclipsing Binary)**
**Geometric Distance Modulus**

(m-M)o = 18.477 mag

**LMC to SMC Extinction Curve**

**LMC to IC 1613 Extinction Curve**
MASER GALAXY

NGC 4258

Dust & Gas

Halo

Disk

Young Stars

Halo

Disk

DISK

HALO
Pure Halo Fields

SNIIa Host Galaxies
TRGB Detections

LMC Calibration
TRGB vs Cepheid Precision

TRGB vs Cepheid Distances: SNe Host Galaxies

- N3021
- N1309
- N3370
- N5584
- N1365
- N1448
- N4038
- N424
- N4536
- M101

\[ \Delta M_{(T-C)} \]

\[ \text{Cepheid modulus} \]

\[ \text{TRGB modulus} \]

\[ N = 10 \]
\[ \sigma = 0.17 \]

Histogram of CSP $M_B'$ values

- Total CSP-I TRGB sample
  - $\sigma = 0.12$, $N=18$
  - $<M_B'> = -19.23 \pm 0.03$

- Total Cepheid sample
  - $\sigma = 0.152$, $N=19$
  - $<M_B> = -19.222 \pm 0.036$
Deconvolution of Pair-wise Scatter Determination of Relative Precision

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<tr>
<th>Indicator</th>
<th>Variance</th>
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<tr>
<td>TRGB</td>
<td>0.0081 mag^2</td>
</tr>
<tr>
<td>Cepheids</td>
<td>0.0169 mag^2</td>
</tr>
<tr>
<td>SNe Ia</td>
<td>0.0064 mag^2</td>
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TRGB Method is a factor of 2x more precise (as measured by its variance) than the Cepheids
The Cepheid Calibrators
Cepheid Calibrators in NGC 4258
A Crisis in Cosmology?

What should we believe?
The Only Standard Candle

TRGB
TRGB in IC 1613
The Only Feature Visible in the Halo

Hatt et al. 2017
TRGB Halo Fields
No Dust, Controlled Crowding

A Crisis in Cosmology?

What should we believe?
The PL Relation
(20 standardization parameters)

- Basic Thermal Physics & Geometry (Static)
- Stellar Pulsation \( (P \sqrt{\rho}) \)
- Stellar Excitation (He\(^+\) Instability: Blue Edge)
- Stellar De-Excitation (Convection: Red Edge)
- Stellar Evolution (Bolometric)
- Stellar Atmospheres (Shocks, Convection, Line Blanketting)
- Stellar Composition (Interior & Atmospheric)
- Star Formation History (Contingent)
- Mass Loss (When, Why & How Much?)
- Reddening (Foreground & Individual)
- Binaries (Calibrators & Targets)
- Crowding (Wavelength & Distance Dependent, the “AGB Floor”)
Cepheid Instability Strip in 3 Dimensions
A Crisis in Cosmology?

What should we believe?
CSP Hubble Diagram
Freedman et al. 2019

TRGB and CSP-I Hubble diagram

Carnegie Supernova Project sample: N = 99
TRGB calibrators: N = 18

\[
\mu \text{ (mag)}
\]

\[
\Delta \mu
\]

\[
\log cz \left(1 + \frac{1}{2}(1 - q_0)z - \frac{1}{6}(1 - q_0 - 3q_0^2 + j_0)z^2\right)
\]
Hubble Constant
10:17:57 am
October 5, 2019

\[ H_0 = 69.5 \pm 1.7 \text{ km/s/Mpc} \]
A Crisis in Cosmology?

What should we believe?
A Pulsating Heat Engine versus A Physical Constant of Nature

Cepheids

TRGB
Closing Case for the TRGB

- Simplicity
- Understood with First Principle Physics
- Standard Candle
- Highest Precision
- Zero Point Multiply Calibrated Geometrically
- Low Reddening
- Low Crowding
- Applies to all Hubble Types