Extragalactic stellar distance indicators need to be bright advanced stages of stellar evolution

- Red Giant Star (SFB)
- Tip of Red Giant Branch (TRGB)
- Horizontal Branch - RR Lyrae
- post-AGB stars, Planetary Nebulae
- Cepheid Stars
- Blue Supergiant Stars
Evolution of low mass stars

$0.5M_{\odot} \leq M \leq 2.5M_{\odot}$

main sequence (MS): H core burning
→ Red Giant Branch (RGB): H shell burning
→ He-flash: ignition of He core burning
→ Tip of RGB (TRGB)
→ Horizontal Branch (HB): He core burning
  H burning shell
  RR Lyrae pulsators
→ Asymptotic Giant Branch (AGB): He burning shell
  H burning shell
→ post-AGB (pAGB): hot Central Stars of PN (CSPN)
→ White Dwarfs (WD): no energy sources, cooling
  supernovae in binaries
all low mass stars ignite He-flash at almost the same luminosity $\rightarrow$ tip of red giant branch
but there is a metallicity dependence
all low mass stars ignite He-flash at almost the same luminosity → tip of red giant branch but there is a metallicity dependence
the nuclear H-burning shell moves outwards until He-burning ignites in the degenerate He-core
Concepcion 2007

NGC 300 Cycle 11 HST/ACS imaging

Distance from TRGB

agrees with Cepheids
Comparison with MASER distance to NGC4258

M. Salaris, MIAPP 2014
TRGB detection (maximum likelihood methods)

The fitted parameters are

\[ m_{\text{TRGB}} = 21.79 \ [21.76, 21.83], \]
\[ \text{RGB slope } a = 0.36 \ [0.30, 0.43], \]
\[ \text{RGB jump } b = 0.44 \ [0.38, 0.50], \]
\[ \text{AGB slope } c = 0.13 \ [0.03, 0.24]. \]

\( \psi = \begin{cases} 
10^{c(m - m_{\text{TRGB}})+b}, & m - m_{\text{TRGB}} \geq 0, \\
10^{c(m - m_{\text{TRGB}})}, & m - m_{\text{TRGB}} < 0. \end{cases} \) (3)

‘noisy’ edge detection response

M. Salaris, MIAPP 2014
after the hydrodynamic He-flash stars with central He-burning and a H-burning shell assemble on the Horizontal Branch (HB)

HB stars have roughly the same He-core mass but different envelope masses $\rightarrow T_{\text{eff}}$ sequence
HORIZONTAL BRANCH MORPHOLOGY

M. Salaris, MIAPP 2014
globular cluster CMD

Hansen & Kawaler, 1994
globular cluster CMD

RR Lyrae pulsators in HB

Hansen & Kawaler, 1994
RR Lyrae stars as distance indicators and stellar tracers

RR Lyrae variables

- Initial mass (MS): $\sim 0.8-0.9 \, M_{\text{sun}}$
- Mass (HB): $\sim 0.6-0.8 \, M_{\text{sun}}$
- Core He + Shell H burning
- $[\text{Fe/H}] \sim -2.5 - 0.0$ (Smith, 2005)
- Old: $>10$ Gyr (GCs, halo, bulge)

Stetson, VFB et al. (2014)
Distance determination to M4 with optical, NIR and MIR photometry of RR Lyrae

M4 CMDs

Vittorio Francesco Braga

Garching, MIAPP, 11/6/2014
HB evolution

Maeder, 2009
HORIZONTAL BRANCH

Core He-burning phase in old stellar populations

Ingredients:

- He-core mass at He-ignition
- Convective-core mixing
- Bolometric corrections
- Star Formation histories/RGB mass loss

M. Salaris, MIAPP 2014
internal structure of AGB star

L = 2 \times 10^3 - 5 \times 10^4 \, L_\odot

\log g = -1 \text{ to } 1.5

\log T_{\text{eff}} = 2600 - 3500 \, K

huge envelope
120 - 800 \, R_\odot

10^4 - 10^{-2} \, R_\odot

H-shell
0.002 \, M_\odot

He-shell
0.02 \, M_\odot

CO core
0.5 - 1.1 \, M_\odot

intershell shell 0.02 \, M_\odot

Maeder, 2009
AGB and post-AGB evolution

CSPN

WD
Evolution of intermediate mass stars

\[ 2.5M_\odot \leq M \leq 8.0M_\odot \]

main sequence (MS): H core burning
→ Red Giant Branch (RGB): H shell burning
→ no He-flash: normal ignition of He core burning on RGB
→ blue loops during He core burning
  Cepheid pulsators
→ Asymptotic Giant Branch (AGB): He burning shell
  H burning shell
→ post-AGB (pAGB): hot Central Stars of PN (CSPN)
→ WD cooling sequence
  supernova in binaries
evolution of a 7 $M_{\text{sun}}$ star
pAGB evolution
note: heavy influence of mass-loss, for instance, 7 $M_{\odot}$ star has only 1 $M_{\odot}$ left
evolution time much faster for luminous objects

Maeder, 2009

pAGB core mass - luminosity relationship

simple fit formula by Paczynski, 1970

$$\frac{L}{L_{\odot}} = 5.29 \times 10^4 \left( \frac{M}{M_{\odot}} - 0.52 \right)$$
evolution of a 7 $M_{\text{sun}}$ star
evolution of a $7 \, M_{\odot}$ star

Cepheid instability strip

Maeder, 2009
instability strip

Hayashi limit of low mass fully convective stars

main sequence
Evolution of massive stars

\[ M \geq 8.0M_\odot \]

main sequence (MS): H core burning

→ blue supergiants (BSG): H shell burning

→ red supergiants (RSG): normal ignition of He core burning

→ \( M < 15 M_{\text{sun}} \) blue loops during He core burning

Cepheid pulsators

→ post RSG evolution leads to

→ iron core collapse supernovae
Blue supergiants - objects in transition

Brightest normal stars at visual light: $10^5 \ldots 10^6 \, L_{\text{sun}}$

$-7 \geq M_V \geq -10 \, \text{mag}$

$t_{\text{ev}} \sim 10^3 \, \text{yrs}$

$L, M \sim \text{const.}$

ideal to determine

- chemical compos.
- abundance grad.
- SF history
- extinction
- extinction laws
- distances of galaxies
IR beacons in universe: red supergiants

Brightest stars at infrared light: $-8 \geq M_J \geq -11$ mag

Advantage: AO supported MOS possible

medium resolution J-band spectroscopy:
atomic lines dominate → medium res. spectra ok

→ enormous potential with Keck/VLT, TMT/E-ELT beyond Local Group out to Coma cluster
structure of a massive star shortly before iron core SN collapse
The bright and beautiful death of many stars: Supernovae
light curves of supernova types and peak magnitudes

Maeder, 2009
The bright and beautiful death of many stars: Supernovae

Maeder, 2009
structure of a massive star shortly before iron core SN collapse
Type IIP supernovae - progenitors

- Several direct detections of progenitors (e.g. Smartt et al. 2009): mostly red supergiants
- Mass range $\sim 9$ to $\sim 18 \text{ M}_\odot$
- Core-collapse explosions of massive, H-rich stars

Image: Mattila et al. 2010
SNe IIP at the GTC

Observational data II: SNe IIP at intermediate redshift
Phenomenology

- Strong Hydrogen lines --> Type II classification
- A long Plateau in their lightcurve
- A sharp fall
- A radioactive tail
Phenomenology

- Strong Hydrogen lines --> Type II classification
- A long Plateau in their lightcurve
- A sharp fall
- A radioactive tail

Olivares et al. 2010
SNe IIP in a nutshell

- The duration of the plateau is usually of the order of ~100 days, ranging between 80 and 120 days.
- The initial velocity of the ejecta is of the order of 1-2 \( \times 10^4 \) km/s.
- The initial temperature is of the order of 1-2 \( \times 10^4 \) K.
- Peak luminosities commonly range between Mv = -15.5 and Mv = -18.5 mag --> how can we use them as distance indicators?

- The SN event is generated by the core-collapse of a massive star.
- Progenitors are usually Red Supergiants (RSG, in some cases we have a BSG, such as SN 1987A).
- Their masses are expected to be up to 25-30 M\( \odot \), but on the basis of the progenitors analysis, the accepted limit is of the order of 15-18 M\( \odot \).

...Until now...
The bright and beautiful death of many stars: Supernovae

- Type I: WD explosion
- Type II: Iron core collapse
  - Type IIp: plateau, massive envelope
  - Type IIl: light curve falls linearly
- Type Ib: from WR without H
- Type Ic: from WR without H and little or no He
- Type Ia: from WD in binary
- Type Ib/c pec: hypernovae, very high masses
- Type IIIn: interaction with circumstellar material

Maeder, 2009
SNe Ia: Far-Reaching Candles

- CO White Dwarf in binary pushed to Chandrasekhar limit (fundamental physics)
- Mass transfer, companion, time scales not well understood.

Most uniform standard candle at this luminosity scale
- Empirical and theoretical calibrations give $M_v = -19$ mag, explain yield of IME
- Identified by strong Si II, absence of H in spectra, come in late/early type host

A. Riess, 2012, Naples WS
Surveying the Universe with Type Ia Supernovae

NOAO 4m image of SN 2011fe in M101 (T.A. Rector, H. Schweiker & S. Pakzad NOAO/AURA/NSF)

SN 2014J in M82 (Marco Burali, Osservatorio MTM Pistoia)

Saurabh W. Jha
MIAPP The Extragalactic Distance Scale  May 28, 2014
SNIa background physics

all stars with $M \leq 8M_\odot$ evolve into the cooling sequence of White Dwarfs
cooling sequence of WDs
White Dwarfs: extremely narrow mass distribution

\( \langle M_{WD} \rangle \approx 0.6 M_{\odot} \)

without mass-loss

stars with such masses cannot have evolved from the main sequence within Hubble time

from the HRDs of open clusters we know that all stars with

\( 0.8 M_{\odot} \leq M \leq 8 M_{\odot} \)

have formed WDs

The mass spectrum observed can be roughly explained by

IMF and stellar evolution with mass-loss applying Reimers’ formula

Note: no WD with masses \( M_{\odot} \geq 1.4 M_{\odot} \) !!!
The Physics of White Dwarfs

The equation of state (EOS) of WDs is different from normal stars because of their much higher densities:

- 0.6 solar masses confined within earth-like radius
- Mean particle distance $\ll$ de Broglie wavelength

Quantum nature (fermions!) of matter important:
1. Pauli principle: only one particle per quantum state
2. Fermi distribution of energies instead Maxwell/Boltzmann
3. Different EOS
\[ \lambda_B = \frac{\hbar}{\sqrt{2\pi mkT}} \]
\[ n = \frac{N}{V} = \frac{1}{r_0^3} \quad r_0 = n^{-\frac{1}{3}} \]
\[ f(\epsilon) = \frac{1}{e^{(-\eta + \frac{\epsilon}{kT})} + 1} \]
\[ \eta = \frac{1.21}{\alpha} \left( \frac{\lambda_B}{r_0} \right)^2 \propto n^{\frac{2}{3}} \quad \text{for} \quad \lambda_B \gg r_0 \]
\[ \alpha = 2 \quad \text{spin degeneracy of electrons} \]
strong degeneracy of free electrons in WD
electrons provide pressure acting against gravity
different EOS
\[ f(\epsilon) = \frac{1}{e^{(-\eta + \frac{\epsilon}{kT})} + 1} \]

WD EOS: degenerate matter pressure de-coupled from temperature

\[ P \sim n_e^{\frac{5}{3}} \]

\[ \epsilon f \sim n_e^{\frac{2}{3}} \]

\[ \epsilon / kT \]

Fermi energy
Mass - radius relationship of WDs

\[ \frac{dP}{dr} = -G \frac{M_r}{r^2} \rho \]

\[ \frac{dP}{dr} \sim \frac{P_0 - P_c}{R - 0} = -\frac{P_c}{R} \sim -\frac{M}{R^2} \bar{\rho} \]

\[ P_c \sim \frac{M^2}{R^4} \quad (1) \]

\[ \bar{\rho} \sim \frac{M}{R^3} \]

on the other hand: EOS

\[ P_c \sim \bar{\rho}^{\frac{5}{3}} \sim \frac{M^{\frac{5}{3}}}{R^5} \quad (2) \]

combine (1) and (2)

\[ R \sim M^{-\frac{1}{3}} \]

WD radii shrink with increasing mass!!!!
The Chandrasekhar limit of WDs

\[ R \sim M^{-\frac{1}{3}} \quad \bar{\rho} \sim M^2 \quad \epsilon_f \sim \rho^{\frac{2}{3}} \]

with higher mass Fermi energy increases and particles become relativistic

\[ \epsilon_f \geq m_e c^2 \]

\[ \epsilon = m_0 c^2 \left( 1 + \frac{p^2}{m_0 c^2} \right)^{\frac{1}{2}} \quad p = m_0 v \left( 1 - \frac{v^2}{c^2} \right)^{-\frac{1}{2}} \]

relationship between energy and momentum \( p \) changes

\[ P = A_2 \rho^{\frac{4}{3}} \left( 1 - B_2 \rho^{-\frac{2}{3}} \right) \]

relativistic EOS

at higher mass
The Chandrasekhar limit of WDs

Combining eq (1) \( P = A_0 \frac{M^2}{R^4} \) and with relativistic EOS yields

\[
R = \frac{B_0^{\frac{1}{3}}}{B_2^{\frac{1}{2}}} M^{\frac{1}{3}} \sqrt{1 - \frac{M}{M_{Ch}}} 
\]

At the Chandrasekhar mass \( M_{Ch} \) the radius is zero

\[
M_{Ch} = \left( \frac{A_2}{A_0} \right)^{\frac{3}{2}} B_0^2 \approx 1.4 M_\odot 
\]

No higher masses than \( M_{Ch} \) possible !!!
Close to the Chandrasekhar limit: 
We will show in the next chapter 
that such configurations are unstable 

collaps and explosive carbon burning

Supernova explosion

\[ P \sim \rho^{\frac{4}{3}} \]
Scenario for SNIa supernova explosions

WD in binary system
  is accreting mass
  approaching Chandrasekhar limit
  and explodes as SNIa

Since explosion happens always at same mass,
released energy (luminosity) should be the same

Bright standard candle !! ??
SNe Ia: Far-Reaching Candles

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Saurabh W. Jha
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What is a Type Ia Supernova?

strong evidence that SN Ia are explosions of carbon-oxygen white dwarfs

but big questions about companion star, white dwarf mass and explosion process

intermediate mass elements are fused from C and O during the explosion ejecta travels at ~10,000 km/s
The Groundbreaking Work: Calán/Tololo

Hamuy et al. (1996a,b)

S.W. Jha, 2014, MIAPP WS
SN Ia are *standardizable* candles, with empirically derived corrections:

- light curve-shape correction (aka the Phillips 1993 relation)
- color-correction (including dust reddening/extinction, e.g. Riess et al. 1996, 1999)
- light curve fitters (in use today):
  - MLCS2k2 (Jha, Riess, & Kirshner 2007)
  - SALT2 (Guy et al. 2007)
  - SiFTO (Conley et al. 2008)
  - BayeSN (Mandel et al. 2009, 2011)
  - SNooPy (Burns et al. 2011)
  - Gaussian Process (Kim et al. 2013, 2014)

...
MLCS2k2 light curve fits

SN 2005ff  z=0.09

SN 2005fb  z=0.18

SN 2005fr  z=0.29

SN 2005gq  z=0.39

Fig. 1.—Light curves for four SDSS-I SNe Ia at different redshifts: SN 2005ff at z = 0.09, SN 2005fb at z = 0.18, SN 2005fr at z = 0.29, and SN 2005gq at z = 0.39. The passbands are SDSS g (top), r (middle), and i (bottom). Points are the SMP flux measurements (flux = 10(11−0.4)m) where m is the SN magnitude) with ±1σ photometric errors indicated. Solid curves show the best-fit mlcs2k2 model fits (see §5.1), and dashed curves give the ±1σ error bands on the model fits. The Modified Julian Date (MJD) under each set of light curves is the fitted time of peak brightness for rest-frame B-band.

μ = 33.46 ± 0.07 mag
SN 1999cp and SN 2002cr, both in NGC 5468

μ = 33.49 ± 0.10 mag

KAIT BVRI photometry

Ganeshalingam et al. (2010)
Standardizing the Candles

\[ \sigma = 22\% \]

\[ \sigma = 9\% \]

\(~6\) to 10\% distance precision per object -- average this down with \(\sqrt{N}\)

S.W. Jha, 2014, MIAPP WS
q₀, 1998: High-z SNe Ia; Acceleration (q₀<0), Dark Energy!

Not just supernovae require “dark energy”...

A. Riess, 2012, Naples WS