Dwarf Galaxies

Variable Stars in Dwarf Galaxies

Dr. Nina Hernitschek
December 9, 2022

Motivation

From supernovae to stars with exoplanets, variable stars are of high interest in astronomical research.

Motivation

From supernovae to stars with exoplanets, variable stars are of high interest in astronomical research.

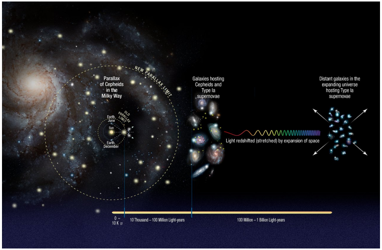
Research on variable stars **provides information about stellar properties**, such as mass, radius, luminosity, temperature, internal and external structure, composition, and evolution.

Motivation

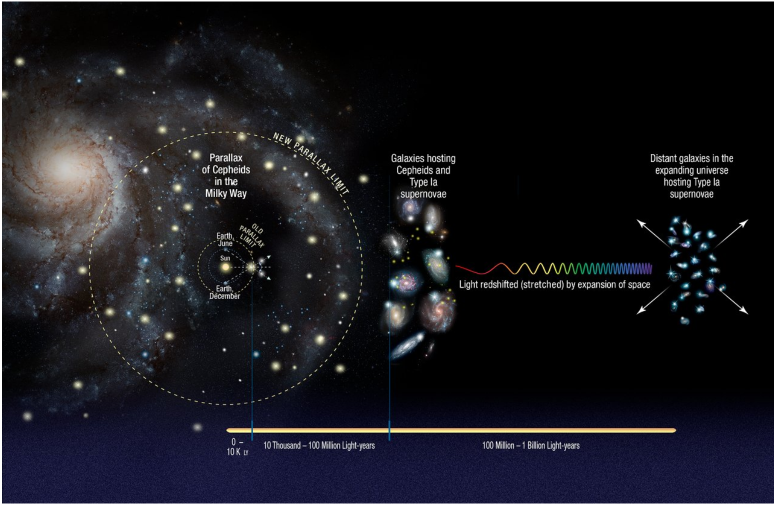
From supernovae to stars with exoplanets, variable stars are of high interest in astronomical research.

Research on variable stars **provides information about stellar properties**, such as mass, radius, luminosity, temperature, internal and external structure, composition, and evolution.

In addition, variable stars provide **distance information** (keyword: *distance ladder*) in our galactic neighborhood.



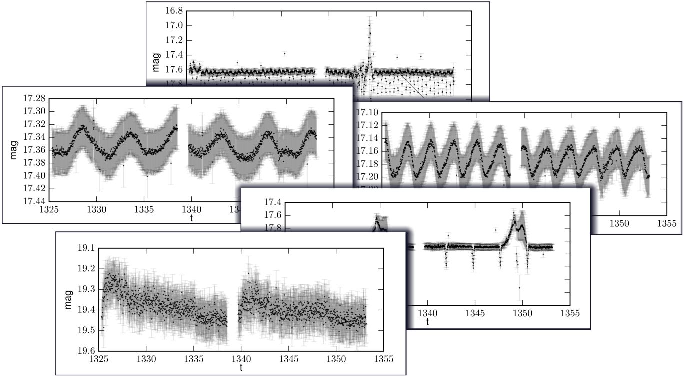
Motivation



Credit: NASA, ESA, A. Feild (STScI), and A. Riess (STScI/JHU)

Variable Stars

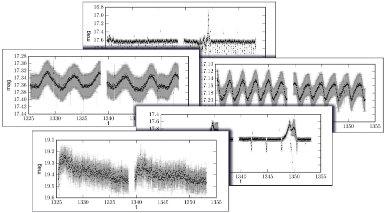
Variable stars are stars showing a change in brightness.



A selection of variable star light curves from the TESS survey.

Variable Stars

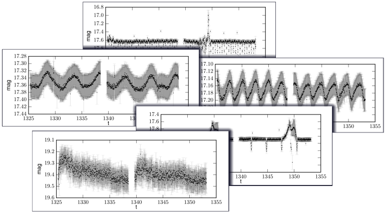
Variable stars are stars showing a change in brightness.



few parts per million — **change in luminosity** — factor 1000

Variable Stars

Variable stars are stars showing a change in brightness.



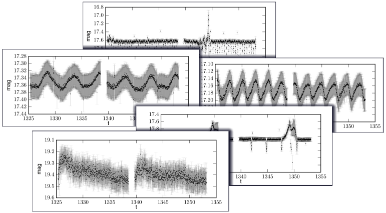
few parts per million — **change in luminosity** — factor 1000

seconds — **temporal baseline** — centuries

Variable Stars

Motivation
Variable Stars
Pulsating Variable Stars
Distances
Further Pulsation Analysis

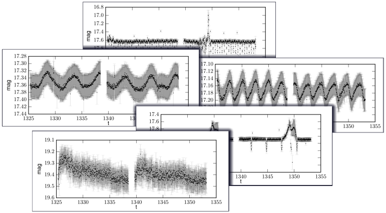
Variable stars are stars showing a change in brightness.



few parts per million	**change in luminosity**	factor 1000
seconds	**temporal baseline**	centuries
periodic	**signal shape**	aperiodic/ random

Variable Stars

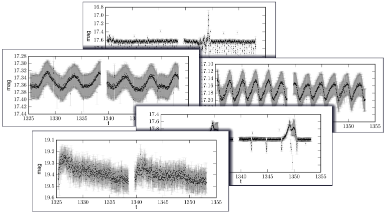
Variable stars are stars showing a change in brightness.



variations provide important and often unique information about the nature and evolution of stars

Variable Stars

Variable stars are stars showing a change in brightness.

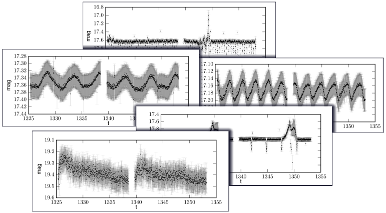


variations provide important and often unique information about the nature and evolution of stars

and the galaxies that host them

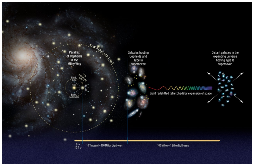
Variable Stars

Variable stars are stars showing a change in brightness.



variations provide important and often unique information about the nature and evolution of stars

and the galaxies that host them



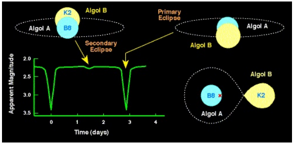
and our universe in general

Variable Stars

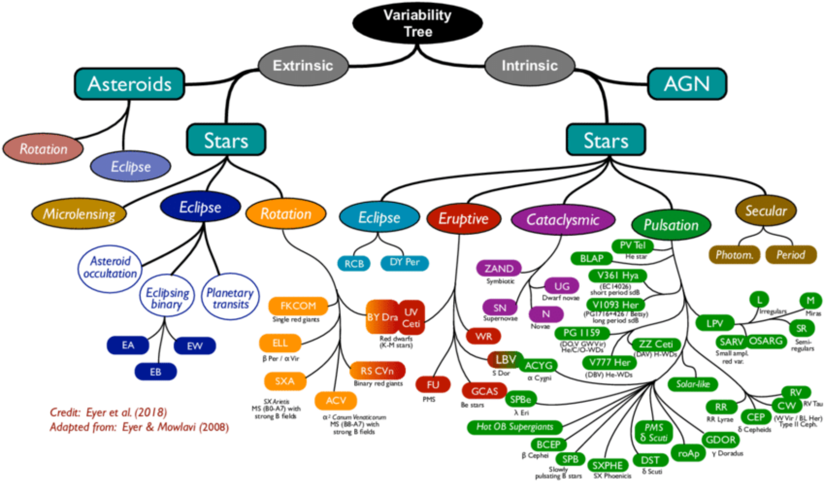
Variable stars are stars showing a change in brightness.

Intrinsic Variables
Stars whose energy output actually varies (pulsating stars, erupting or explosive stars)

Extrinsic Variables
Stars that only appear to vary due to geometric/ external effects (eclipses in binary systems, etc.)

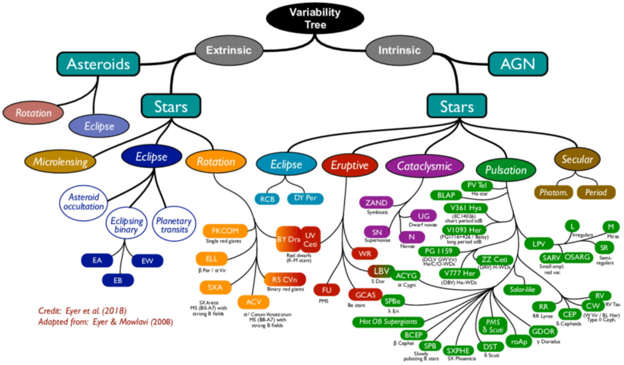


Variability Tree



Credit: Eyer et al. (2018)
Adapted from: Eyer & Mowlavi (2008)

Variability Tree



many astronomical sources vary - describe, classify and select astronomical sources by their variability

Discovery of Variable Stars

historically: discovered sporadically

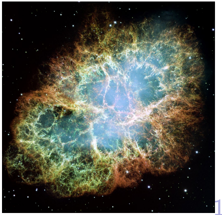
periodic variable stars:
1596: David Fabricius noted that the star *o* Ceti (now known as Mira) was sometimes visible, sometimes not
1638: Johannes Holwarda found a visibility cycle of 11 months for Mira
1700s: William Herschel discovered the variability of α Herculis and 44i Bootis

Discovery of Variable Stars

historically: discovered sporadically

periodic variable stars:
1596: David Fabricius noted that the star o Ceti (now known as Mira) was sometimes visible, sometimes not
1638: Johannes Holwarda found a visibility cycle of 11 months for Mira
1700s: William Herschel discovered the variability of α Herculis and 44i Bootis

supernovae:
oldest mention of a "new star": 185 AD a "guest star" was observed by Chinese astronomers
1054: supernova mentiones by Chinese astronomers
1572: Tycho's supernova
1604: Johannes Kepler's supernova



The Crab Nebula is a pulsar wind nebula associated with the 1054 supernova.

Discovery of Variable Stars

historically: discovered sporadically

1850s: $\sim$18 variable stars known
1890: establishment of the Variable Star Section of the British Astronomical Association (BAAVSS)
1911: founding of the American Association of Variable Star Observers (AAVSO)

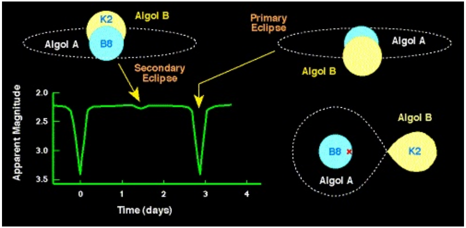
Discovery of Variable Stars

causes of variability?

John Goodricke and Edward Pigott: proposed the theory that Algol's variability might be caused by eclipses of the star by a planetary companion

we know today:

Algol is a three-star system, consisting of β Persei (Per) A, β Per B and β Per C. They regularly pass in front of each other, causing eclipses. This is an **eclipsing binary star**.



(Early) Classification of Variable Stars

systematic observation of variable stars reveiled **differences in their light curves**

Pigott (1780s): variable stars: nova, long-period variables, short-period variables

(Early) Classification of Variable Stars

systematic observation of variable stars reveiled **differences in their light curves**

Pigott (1780s): variable stars: nova, long-period variables, short-period variables

Pickering (1880s): a more detailed scheme:

- (Ia) normal novae: now known to be nearby ones in our own galaxy;
- (Ib) novae in nebulae: now known to be supernovae in other galaxies;
- (IIa) long-period variables: cool, large-amplitude pulsating variables;
- (IIb) U Geminorum stars: dwarf novae;
- (IIc) R Coronae Borealis stars: stars which suddenly and unpredictably decline in brightness;
- (III) irregular variables: a motley collection;
- (IVa) short-period variables such as Cepheids and RR Lyrae stars;
- (IVb) Beta Lyrae type eclipsing variables; and
- (V) Algol type eclipsing variables.

Pulsating Variable Stars

Motivation

Variable Stars

Pulsating Variable Stars

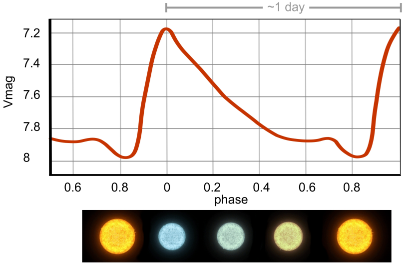
Distances

Further Pulsation Analysis

unterlying physics of variability:

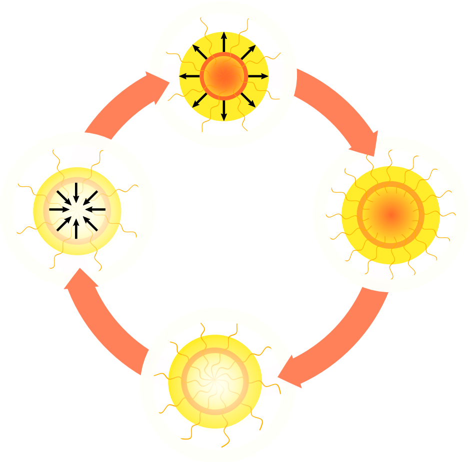
idea: (at least some) periodic variability might be caused by pulsations (A. Ritter 1873)

Observational studies by Harlow Shapley and others around 1915, and the concurrent theoretical studies by Eddington, established the pulsational nature of the Cepheids, cluster type variables (RR Lyrae stars), and long-period variables.



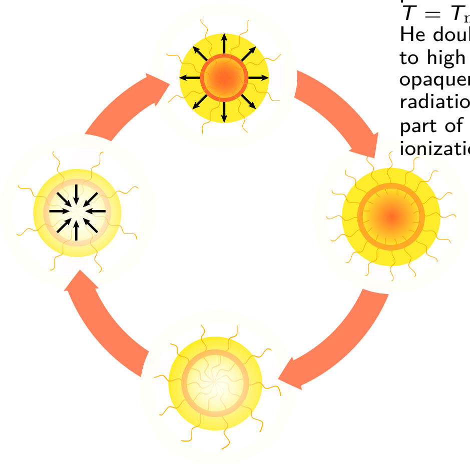
Cause of Pulsation

cause of pulsation: Lack of hydrostatic equilibrium beneath the surface drives the pulsation cycle with expansion and contraction of the outer layers of a star and subsequent change in brightness:



Cause of Pulsation

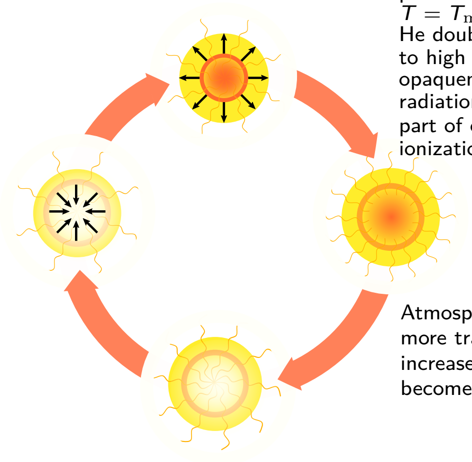
cause of pulsation: Lack of hydrostatic equilibrium beneath the surface drives the pulsation cycle with expansion and contraction of the outer layers of a star and subsequent change in brightness:



point of greatest compression:
$T = T_{\max}$
He doubly ionized (HeIII) due to high T
opaqueness of HeIII causes radiation absorption (dimmest part of cycle) $\Rightarrow$ increase of ionization, T and pressure.

Cause of Pulsation

cause of pulsation: Lack of hydrostatic equilibrium beneath the surface drives the pulsation cycle with expansion and contraction of the outer layers of a star and subsequent change in brightness:

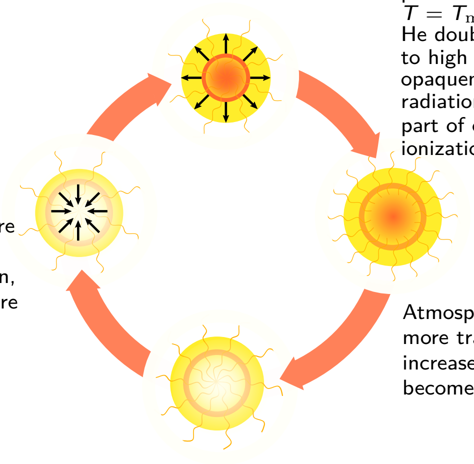


point of greatest compression: $T = T_{\mathrm{max}}$
He doubly ionized (HeIII) due to high T
opaqueness of HeIII causes radiation absorption (dimmest part of cycle) $\Rightarrow$ increase of ionization, T and pressure.

Atmosphere expands, becomes more transparent (brightness increases) and cools. HeIII becomes HeII.

Cause of Pulsation

cause of pulsation: Lack of hydrostatic equilibrium beneath the surface drives the pulsation cycle with expansion and contraction of the outer layers of a star and subsequent change in brightness:



point of greatest compression: $T = T_{\max}$
He doubly ionized (HeIII) due to high T
opaqueness of HeIII causes radiation absorption (dimmest part of cycle) $\Rightarrow$ increase of ionization, T and pressure.

Atmosphere expands, becomes more transparent (brightness increases) and cools. HeIII becomes HeII.

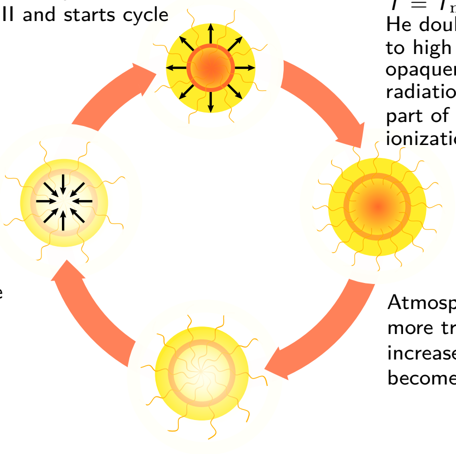
Atmosphere falls back, contraction, temperature rises.

Cause of Pulsation

cause of pulsation: Lack of hydrostatic equilibrium beneath the surface drives the pulsation cycle with expansion and contraction of the outer layers of a star and subsequent change in brightness:

Before it reaches equilibrium, HeII becomes HeIII and starts cycle over again.

point of greatest compression: $T = T_{\max}$
He doubly ionized (HeIII) due to high T
opaqueness of HeIII causes radiation absorption (dimmest part of cycle) $\Rightarrow$ increase of ionization, T and pressure.



Atmosphere falls back, contraction, temperature rises.

Atmosphere expands, becomes more transparent (brightness increases) and cools. HeIII becomes HeII.

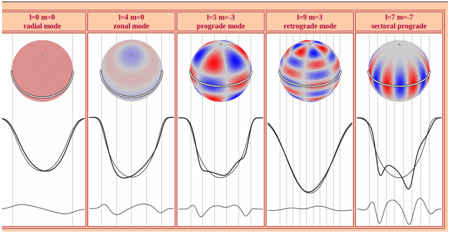
Cause of Pulsation

This is called **radial mode** pulsation. It is found in large-amplitude pulsating variables in the HR-diagram *instability strip*: Cepheids, Miras and RR Lyrae stars.

Cause of Pulsation

This is called **radial mode** pulsation. It is found in large-amplitude pulsating variables in the HR-diagram *instability strip*: Cepheids, Miras and RR Lyrae stars.

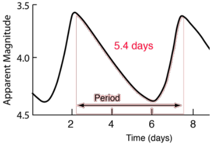
There are stars whose pulsation is **non-radial**: a star changes shape, but not volume. Non-radial pulsation leads to smaller amplitudes of variation. Some stars – β Cephei, δ Scuti stars and to a small amount also RR Lyrae stars – pulsate in both radial and non-radial modes.



models of stars with non-radial pulsations (copyright Coen Schrijvers) http://staff.not.iac.es/ jht/science/

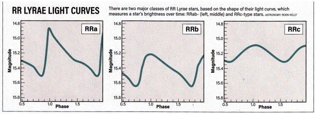
Types of Pulsating Variable Stars

we are looking for **bright, strictly periodic*** stars
*caveat: this condition cannot always be met



Cepheids

- brightness enables us to observe them in other galaxies in our Local Group (such as the Magellanic Clouds, M31 and M33)
- period-luminosity relation makes them important standard candles ⇒ distance ladder



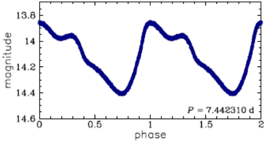
RR Lyrae stars

- numerous in the Milky Way halo (globular clusters), thus once called *cluster variables*
- less bright than Cepheids
- period-luminosity relation and their age makes them important tracers of the old Milky Way halo substructure

Cepheids

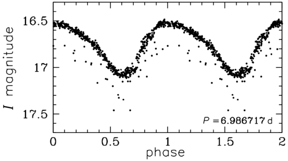
Classical (Type I) Cepheids
bright yellow, highly luminous, supergiant pulsating variables

- amplitudes: ~0.01 - 2 mag_V
- periods: 1 - 135 days
- variability is strictly regular
- spectral type: F at maximum light, G to K at minimum light; the longer the period, the later the spectral type



Population II (Type II) Cepheids
similar light curve than Type I, but different evolutional history

- older, low mass stars
- important fossils of the first generation of stars in our galaxy



Soszyński et al. (2018), OGLE data

RR Lyrae stars

prototype: RR Lyrae (variability discovered by Williamina Fleming, $\sim$ 1900); RR Lyrae stars are old helium-burning variable stars of spectral type A5 to F5 with 0.5 $M_\odot$

RRab
asymmetrical light curves with steep ascend

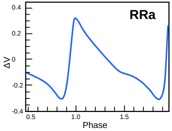
- periods: 0.3 - 1.2 days
- amplitudes: 0.5 - 2 mag_V

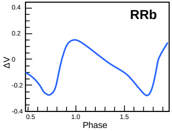
RRc
nearly symmetrical light curves

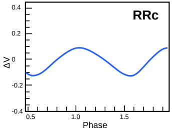
- periods: 0.2 - 0.5 days
- amplitudes: $< 0.8\ \mathrm{mag}_V$

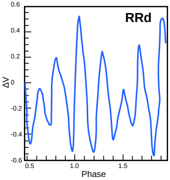
RRd
double-mode RR Lyrae stars, fundamental and first overtone

- fundamental period: 0.5 days
- period ratio: 0.74 days









RR Lyrae stars

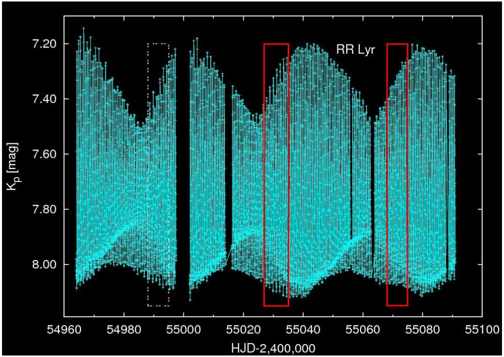
discovery by Harlow Shapley and Richard Prager (1916) independently:

RR Lyrae (the prototype's) light curve is modulated in amplitude and shape

RR Lyrae stars

discovery by Harlow Shapley and Richard Prager (1916) independently:

RR Lyrae (the prototype's) light curve is modulated in amplitude and shape



modern observation of a RR Lyrae star with Blazhko effect from the Kepler survey

RR Lyrae stars

⇒ period-amplitude-shape modulation is today known as the **Blazhko effect**
its explanation remains one of the enduring mysteries in astrophysics to this day

RR Lyrae stars

⇨ period-amplitude-shape modulation is today known as the **Blazhko effect**
its explanation remains one of the enduring mysteries in astrophysics to this day

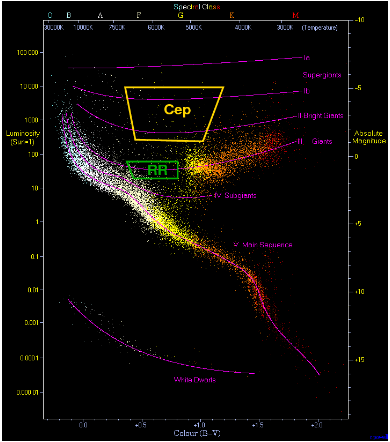
two promising **theories** for explaining the Blazhko effect:

(i) resonance between the radial fundamental period of pulsation, and a non-radial period; or

(ii) a deformation or splitting of the radial period by a magnetic field in the star

Evolutionary Stages - the Hertzsprung-Russel (H-R) Diagram

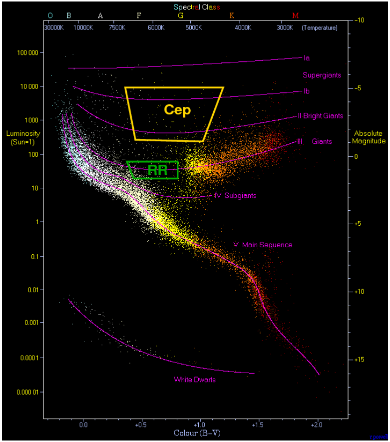
early 20th century: E. Hertzsprung and H. N. Russell noted that a scatter plot of a measure of stellar **luminosity** (absolute magnitude) vs. a measure of the stellar **temperature** (spectral type, color) shows structure:



An observational Hertzsprung-Russell diagram with 22,000 stars from the Hipparcos Catalogue and 1,000 from the Gliese Catalogue of nearby stars.

Evolutionary Stages - the Hertzsprung-Russel (H-R) Diagram

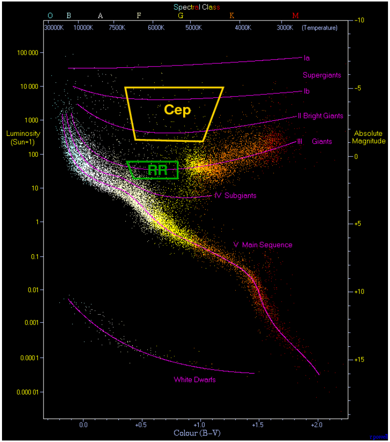
early 20th century: E. Hertzsprung and H. N. Russell noted that a scatter plot of a measure of stellar **luminosity** (absolute magnitude) vs. a measure of the stellar **temperature** (spectral type, color) shows structure:



main sequence: a band extending from hot, high-luminosity stars to cool, low-luminosity stars, containing the vast majority of stars; burning H $\rightarrow$ He in their cores

Evolutionary Stages - the Hertzsprung-Russel (H-R) Diagram

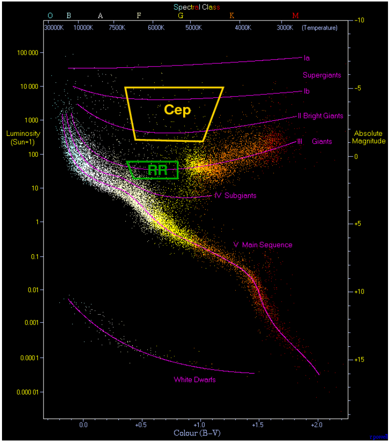
early 20th century: E. Hertzsprung and H. N. Russell noted that a scatter plot of a measure of stellar **luminosity** (absolute magnitude) vs. a measure of the stellar **temperature** (spectral type, color) shows structure:



giants: After $\sim 10\%$ of the mass of a $M < M_\odot$ star has been converted from H to He, the star expands: it becomes a red giant with a helium core and a hydrogen buring shell. The star heats up and moves along the horizontal branch in the H-R diagram, then cools off as the core burning stops. The once again red star then goes to higher luminosity on the asymptotic giant brach (AGB). Finally it ejects its envelope and becomes a planetary nebulae containing a white dwarf ($M \leq 1.4 M_\odot$, $R {\sim} R_{\mathrm{earth}}$).

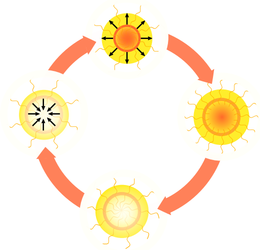
Evolutionary Stages - the Hertzsprung-Russel (H-R) Diagram

early 20th century: E. Hertzsprung and H. N. Russell noted that a scatter plot of a measure of stellar **luminosity** (absolute magnitude) vs. a measure of the stellar **temperature** (spectral type, color) shows structure:



instability strip:

Stars, such as RR Lyrae stars and Cepheids, that have evolved off the main sequence and pulsate due to He III (doubly ionized helium).



Pulsating Stars as Distance Estimators

The **distance modulus** equation alone is not enough:

$$d = 10^{(m - M + 5)}/5 \text{ parsec}$$

Pulsating Stars as Distance Estimators

The **distance modulus** equation alone is not enough:

$$d = 10^{(m - M + 5)/5} \text{ parsec}$$

?

Pulsating stars are a powerful tool for determining distances in astronomy, because the period of pulsation is correlated with the luminosity of the star, and this relation can be calibrated

⇒ the **period-luminosity(-metallicity) relation**

Pulsating Stars as Distance Estimators

The best-known relation between period and absolute magnitude is the direct proportionality law for **Classical Cepheid variables** (Henrietta Swan Leavitt (1908)).

⇨ foundation for scaling **galactic and extragalactic distances**

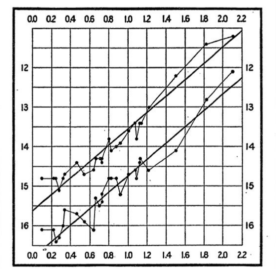


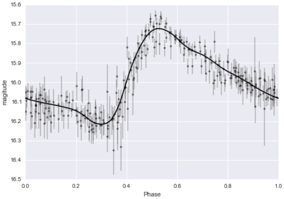
FIG. 2.

Plot from Leavitt's 1912 paper. The horizontal axis is the logarithm of the Cepheid's period, and the vertical axis is its apparent magnitude.

Pulsating Stars as Distance Estimators

Cepheid and RR Lyrae stars are variable stars with the period being directly related to their true (absolute) brightness.

basic concept:

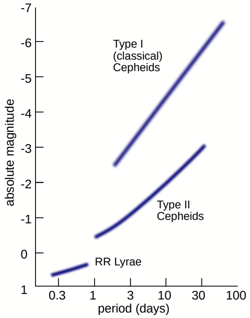


- measure apparent mean brightness m
- measure period P

Pulsating Stars as Distance Estimators

Cepheid and RR Lyrae stars are variable stars with the period being directly related to their true (absolute) brightness.

basic concept:

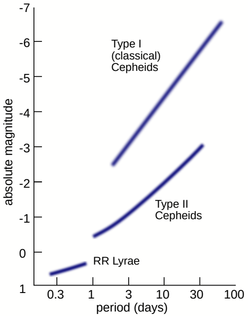


- measure apparent mean brightness m
- measure period P
- using **period-luminosity relation**, get absolute brightness M
- solve for distance using **distance modulus** equation
  $d = 10^{(m-M+5)}/5$ parsec
  where 1 parsec $= 3.086^{16}$ m $= 3.26156$ lyr

Pulsating Stars as Distance Estimators

Cepheid and RR Lyrae stars are variable stars with the period being directly related to their true (absolute) brightness.

basic concept:



- measure apparent mean brightness m
- measure period P
- using **period-luminosity relation**, get absolute brightness M
- solve for distance using **distance modulus** equation
  $d = 10^{(m-M+5)}/5$ parsec
  where 1 parsec $= 3.086^{16}$ m $= 3.26156$ lyr

$\Rightarrow$ allow us to create *3D maps* of structures within and beyond our Milky Way

The Period-Luminosity(-Metallicity) Relation

Globular clusters have only little depth - we can treat all the stars in a cluster as being at ∼ the same distance from Earth

color-magnitude diagram of stars in a globular cluster (M3):

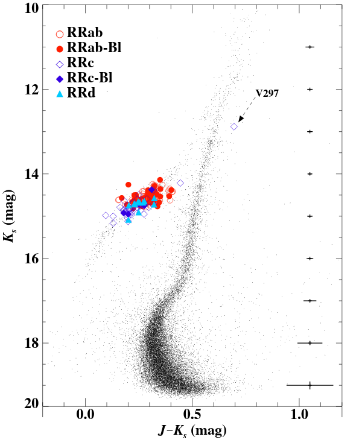
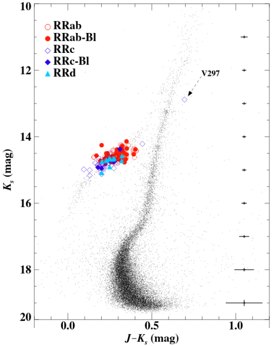


Figure 3 taken from Bhardwaj et al., AJ 160, 220 (2020)

The Period-Luminosity(-Metallicity) Relation

Globular clusters have only little depth - we can treat all the stars in a cluster as being at ∼ the same distance from Earth

color-magnitude diagram of stars in a globular cluster (M3):



all RR Lyrae stars have ∼ the same apparent magnitude

⇒ as the distance must be ∼ the same, they also have the same absolute magnitude

once we know the value of that absolute magnitude, we can compute the distance to each star from the distance modulus

The Period-Luminosity(-Metallicity) Relation

A closer look:

for each RR Lyrae star in the cluster, plot the apparent magnitude as function of its period

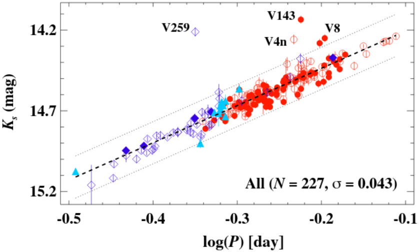


Figure 10 (slightly modified) taken from Bhardwaj et al., AJ 160, 220 (2020)

⇒ slight **trend**: stars with longer periods are a bit brighter

The Period-Luminosity(-Metallicity) Relation

To put everything together:

1. we know the **distance modulus** equation:
$d = 10^{(m-M+5)}/5$ parsec

The Period-Luminosity(-Metallicity) Relation

To put everything together:

1. we know the **distance modulus** equation:
$d = 10^{(m-M+5)}/5$ parsec

2. stars at approximately the same distance show a slight **trend**: stars with longer periods are a bit brighter

The Period-Luminosity(-Metallicity) Relation

To put everything together:

1. we know the **distance modulus** equation:
$d = 10^{(m-M+5)}/5$ parsec

2. stars at approximately the same distance show a slight **trend**: stars with longer periods are a bit brighter

(3. There is also a small trend on metallicity Z.)

The Period-Luminosity(-Metallicity) Relation

To put everything together:

1. we know the **distance modulus** equation:
$d = 10^{(m-M+5)}/5$ parsec

2. stars at approximately the same distance show a slight **trend**: stars with longer periods are a bit brighter

(3. There is also a small trend on metallicity Z.)

metallicity is the abundance of elements present in star that are heavier than hydrogen and helium

?

For $d(m, P, Z)$, we need to **calibrate** the Period-Luminosity(-Metallicity) Relation.

The Period-Luminosity(-Metallicity) Relation

calibrate the Period-Luminosity(-Metallicity) Relation:

The following methods can be used to determine absolute magnitudes, e.g.:

- Statistical study of the motions of field RR Lyrae stars: statistical parallax. This gives values of M_V ranging from $+0.9$ for short-period, high-metallicity stars, to $+0.5$ for longer-period, lower-metallicity stars. As a statistical method, it must be applied to a large sample of stars, which might not be homogeneous.

The Period-Luminosity(-Metallicity) Relation

calibrate the Period-Luminosity(-Metallicity) Relation:

The following methods can be used to determine absolute magnitudes, e.g.:

- Statistical study of the motions of field RR Lyrae stars: statistical parallax. This gives values of M_V ranging from $+0.9$ for short-period, high-metallicity stars, to $+0.5$ for longer-period, lower-metallicity stars. As a statistical method, it must be applied to a large sample of stars, which might not be homogeneous.
- Fitting of the main sequence of globular clusters containing RR Lyrae stars to a standard main sequence determined for nearby Population II stars with known distances; there are, however, very few of these. This method gives a mean of about $+0.4$ for the RR Lyrae stars in several clusters.

The Period-Luminosity(-Metallicity) Relation

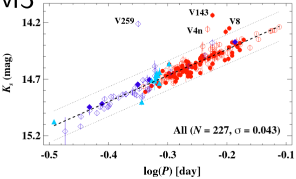
calibrate the Period-Luminosity(-Metallicity) Relation:

The following methods can be used to determine absolute magnitudes, e.g.:

- Statistical study of the motions of field RR Lyrae stars: statistical parallax. This gives values of M_V ranging from $+0.9$ for short-period, high-metallicity stars, to $+0.5$ for longer-period, lower-metallicity stars. As a statistical method, it must be applied to a large sample of stars, which might not be homogeneous.
- Fitting of the main sequence of globular clusters containing RR Lyrae stars to a standard main sequence determined for nearby Population II stars with known distances; there are, however, very few of these. This method gives a mean of about $+0.4$ for the RR Lyrae stars in several clusters.
- The Baade-Wesselink method (infer distance from measurement of change in radius (from velocity) and angular diameter) has been applied to some of the brightest RR Lyrae stars; it gives an absolute magnitude of about $+0.5$.

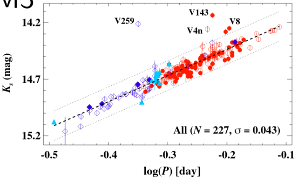
The Period-Luminosity(-Metallicity) Relation

example 1: Distance to the cluster M3



Q: What is the average apparent K magnitude for RR Lyrae stars in M3?

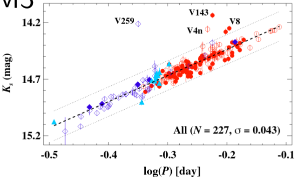
example 1: Distance to the cluster M3



Q: What is the average apparent K magnitude for RR Lyrae stars in M3?

A: The average K-band apparent magnitudes is about $m(K) = 14.70$.

example 1: Distance to the cluster M3



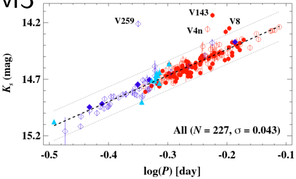
Q: What is the average apparent K magnitude for RR Lyrae stars in M3?

A: The average K-band apparent magnitudes is about $m(K) = 14.70$.

Q: The absolute magnitude of RR Lyrae stars in the K filter is approximately $M(K) = -0.35$. What is the distance to the cluster M3?

The Period-Luminosity(-Metallicity) Relation

example 1: Distance to the cluster M3



Q: What is the average apparent K magnitude for RR Lyrae stars in M3?

A: The average K-band apparent magnitudes is about $m(K) = 14.70$.

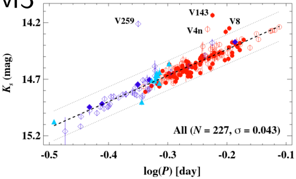
Q: The absolute magnitude of RR Lyrae stars in the K filter is approximately $M(K) = -0.35$. What is the distance to the cluster M3?

A: First, we compute the distance modulus, the difference between apparent and absolute magnitude:

$$m(K) - M(K) = 14.70 - (-0.35) = 15.05 \text{ mag}$$

The Period-Luminosity(-Metallicity) Relation

example 1: Distance to the cluster M3



Q: What is the average apparent K magnitude for RR Lyrae stars in M3?

A: The average K-band apparent magnitudes is about $m(K) = 14.70$.

Q: The absolute magnitude of RR Lyrae stars in the K filter is approximately $M(K) = -0.35$. What is the distance to the cluster M3?

A: First, we compute the distance modulus, the difference between apparent and absolute magnitude:

$$m(K) - M(K) = 14.70 - (-0.35) = 15.05 \text{ mag}$$

We then use the distance modulus to calculate the cluster's distance:

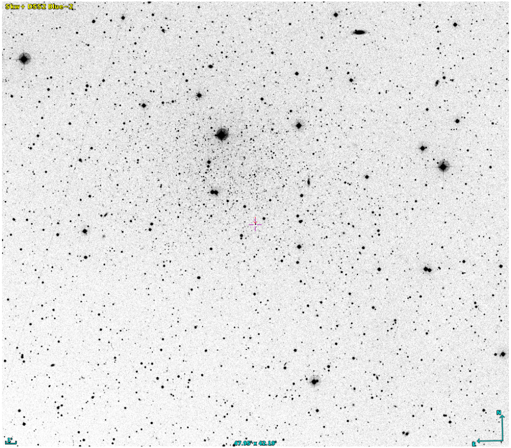
$$m - M = 15.05 = 5 \times log(d) - 5$$

$$log(d) = 4.01$$

$$d = 10^{4.01} = 10200 \text{ pc}$$

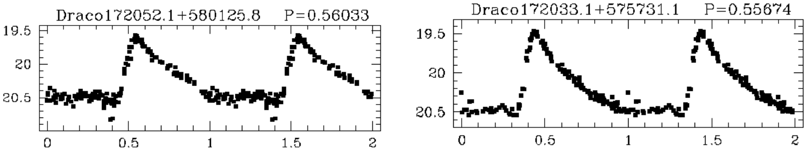
The Period-Luminosity(-Metallicity) Relation

example 2: Distance to Draco dwarf spheroidal (dSph) galaxy



example 2: Distance to Draco dwarf spheroidal (dSph) galaxy

light curves of two RR Lyrae stars within Draco dSph, measured in the V passband

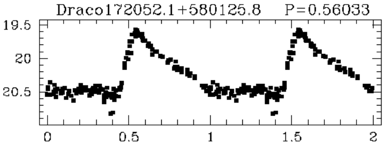


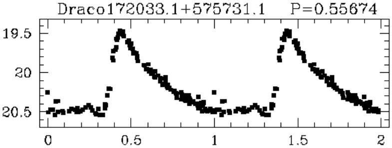
taken from Fig. 1 of Bonanos et al., AJ 127, 861 (2004)

The Period-Luminosity(-Metallicity) Relation

example 2: Distance to Draco dwarf spheroidal (dSph) galaxy

light curves of two RR Lyrae stars within Draco dSph, measured in the V passband



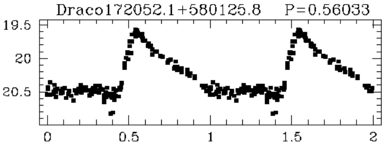


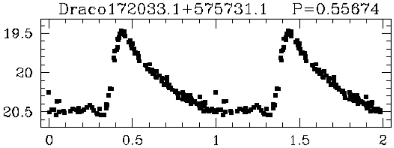
Q: The absolute magnitude of RR Lyrae stars in the V filter is approximately $M(V) = +0.77$. What is the distance to Draco dSph?

The Period-Luminosity(-Metallicity) Relation

example 2: Distance to Draco dwarf spheroidal (dSph) galaxy

light curves of two RR Lyrae stars within Draco dSph, measured in the V passband





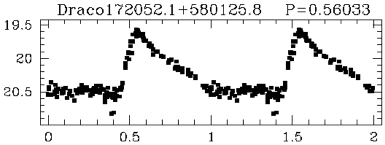
Q: The absolute magnitude of RR Lyrae stars in the V filter is approximately $M(V) = +0.77$. What is the distance to Draco dSph?

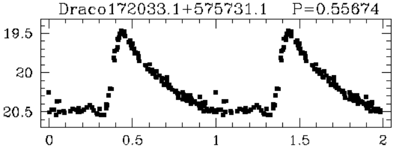
A:
First, we compute the difference between apparent and absolute magnitudes, which is called the "distance modulus":
With the average of the V-band apparent magnitudes being about $m(V) = 20.20$, we get

$$m(V) - M(V) = 20.20 - (+0.77) = 19.43 \text{ mag}$$

example 2: Distance to Draco dwarf spheroidal (dSph) galaxy

light curves of two RR Lyrae stars within Draco dSph, measured in the V passband





Q: The absolute magnitude of RR Lyrae stars in the V filter is approximately $M(V) = +0.77$. What is the distance to Draco dSph?

A:
Next, we use the distance modulus equation to calculate the distance to the cluster:

$$m - M = 19.43 = 5 \times log(d) - 5$$

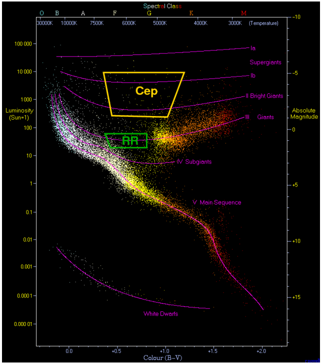
$$5 * log(d) = 24.43$$

$$d = 10^{4.89} = 77000 \text{ pc} = 77 \text{ kpc}$$

The Period-Luminosity(-Metallicity) Relation

RR Lyrae stars allow for calculating the distance to globular clusters and dwarf galaxies from measuring their average apparent magnitude, and using the known absolute magnitude.

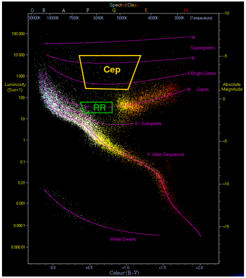
problem: RR Lyrae stars aren't really luminous. Take a look again at this HR diagram:



The Period-Luminosity(-Metallicity) Relation

RR Lyrae stars allow for calculating the distance to globular clusters and dwarf galaxies by measuring their apparent magnitude, and using the known absolute magnitude.

problem: RR Lyrae stars aren't really luminous. Take a look again at this H-R diagram:

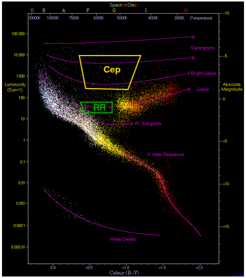


A typical RR Lyrae has a luminosity $\sim 50 M_{\odot} \Rightarrow$ not powerful enough for us to see these stars in distant galaxies.

The Period-Luminosity(-Metallicity) Relation

RR Lyrae stars allow for calculating the distance to globular clusters and dwarf galaxies by measuring their apparent magnitude, and using the known absolute magnitude.

problem: RR Lyrae stars aren't really luminous. Take a look again at this H-R diagram:



We can use RR Lyrae to measure distances only to the very closest galaxies - members of our own Local Group.
A better choice for **larger distances: Cepheids** wich are 100 times more luminous than RR Lyrae stars.

The Period-Luminosity(-Metallicity) Relation

we've seen for RR Lyrae stars: assumption of identical absolute magnitude holds well

not so for Cepheids:

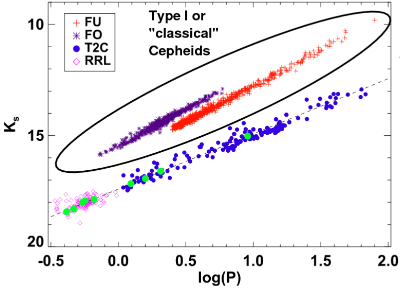


Figure 9. Comparison of K_s-band P–L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

RR Lyrae stars at $\sim$ the same distance have little variation in period and magnitude, whereas Cepheids show large variation in both

The Period-Luminosity(-Metallicity) Relation

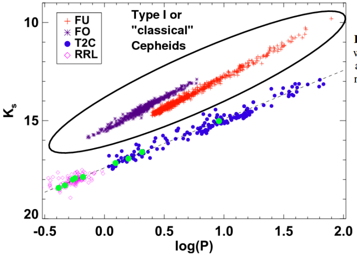


Figure 9. Comparison of K_s-band P–L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

Q: What is the range of periods for these Cepheids?

The Period-Luminosity(-Metallicity) Relation

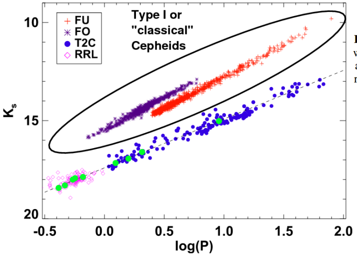


Figure 9. Comparison of K_s-band P–L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

Q: What is the range of periods for these Cepheids?

A: The range is from $\log(P) = -0.1 \Rightarrow P = 0.8$ days to $\log(P) = +1.9 \Rightarrow P = 79$ days
$\Rightarrow$ that is about a factor of 100

The Period-Luminosity(-Metallicity) Relation

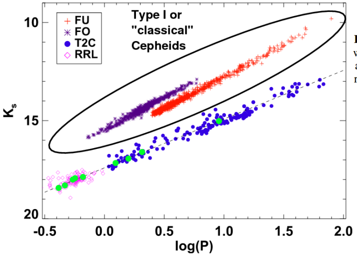


Figure 9. Comparison of K_s-band P–L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

Q: What is the range of periods for these Cepheids?

A: The range is from $\log(P) = -0.1 \Rightarrow P = 0.8$ days to $\log(P) = +1.9 \Rightarrow P = 79$ days
$\Rightarrow$ that is about a factor of 100

Q: What is the range of magnitudes of these Cepheids?

The Period-Luminosity(-Metallicity) Relation

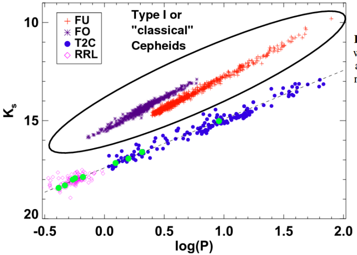


Figure 9. Comparison of K_s-band P–L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

Q: What is the range of periods for these Cepheids?

A: The range is from $\log(P) = -0.1 \Rightarrow P = 0.8$ days to $\log(P) = +1.9 \Rightarrow P = 79$ days
$\Rightarrow$ that is about a factor of 100

Q: What is the range of magnitudes of these Cepheids?

A: The apparent magnitudes in the K-band range from ~ 16 to 10, which is a range of 6 magnitudes $\Rightarrow$ a factor of about 250 in brightness!

The Period-Luminosity(-Metallicity) Relation

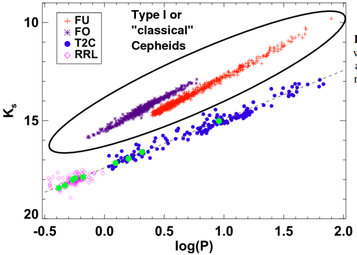


Figure 9. Comparison of K_s-band P–L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

Q: What is the range of periods for these Cepheids?

A: The range is from $log(P) = -0.1 \Rightarrow P = 0.8\ days$ to $log(P) = +1.9 \Rightarrow P = 79\ days$
$\Rightarrow$ that is about a factor of 100

Q: What is the range of magnitudes of these Cepheids?

A: The apparent magnitudes in the K-band range from $\sim$ 16 to 10, which is a range of 6 magnitudes $\Rightarrow$ a factor of about 250 in brightness!

here we absolutely need a **period-luminosity relation**

The Period-Luminosity(-Metallicity) Relation

⇨ here we absolutely need a **period-luminosity relation**

to measure the distance to a Cepheid, we need to carry out four steps:

1. measure the average apparent magnitude m of the star
2. measure the period P of variation of brightness
3. use the period to compute the absolute magnitude M
4. use the distance-modulus formula to compute the distance to the star

example 3: A Period-Luminosity Relation for Cepheids

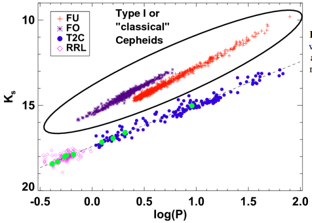


Figure 9. Comparison of K_s-band P–L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

Q: Write an equation of the form

$$M(V) = A \times \log(P) + B$$

which is consistent with the data in the graph.

The Period-Luminosity(-Metallicity) Relation

example 3: A Period-Luminosity Relation for Cepheids

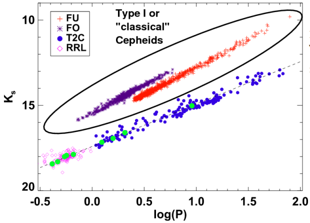


Figure 9. Comparison of K_s-band P–L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

Q: Write an equation of the form

$$M(V) = A \times \log(P) + B$$

which is consistent with the data in the graph.

A: From the line drawn on the diagram, we can find the endpoints $(0.6, -3.0)$ and $(2.0, -6.5)$. The slope of the line is then approximately

$$A = \frac{-6.5 - (-3.0)}{2.0 - 0.6} = -0.25$$

The Period-Luminosity(-Metallicity) Relation

example 3: A Period-Luminosity Relation for Cepheids

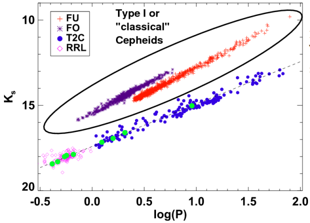


Figure 9. Comparison of K_s-band P–L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

Q: Write an equation of the form

$$M(V) = A \times \log(P) + B$$

which is consistent with the data in the graph.

A (continued): If we plug into the equation

$$-3.0 = (-2.5 \times 0.6) + B$$

and solve for B, we can find the y-intercept:

example 3: A Period-Luminosity Relation for Cepheids

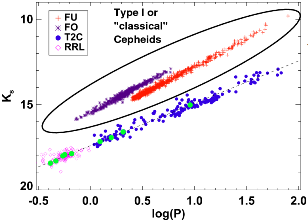


Figure 9. Comparison of K_s-band P–L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

Q: Write an equation of the form

$$M(V) = A \times \log(P) + B$$

which is consistent with the data in the graph.

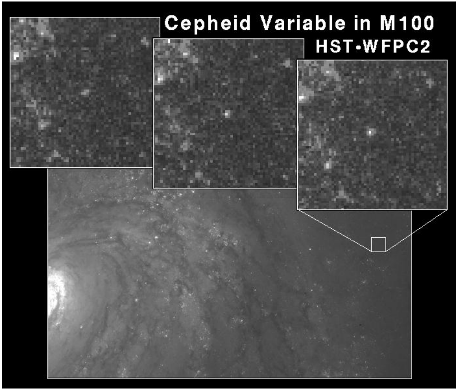
A (continued): So the relationship between period and absolute magnitude is approximately

$$M(V) = -2.5 \times \log(P) - 1.5$$

The Period-Luminosity(-Metallicity) Relation

example 4: The Distance to M100

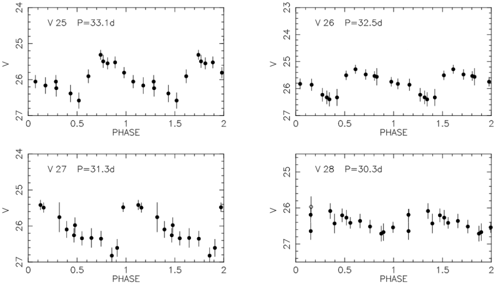
we apply this relationship to measurements of Cepheid variable stars in a relatively nearby galaxy: M100.



The Period-Luminosity(-Metallicity) Relation

example 4: The Distance to M100

We determine the period and apparent magnitude of a few Cepheid light curves in this galaxy.



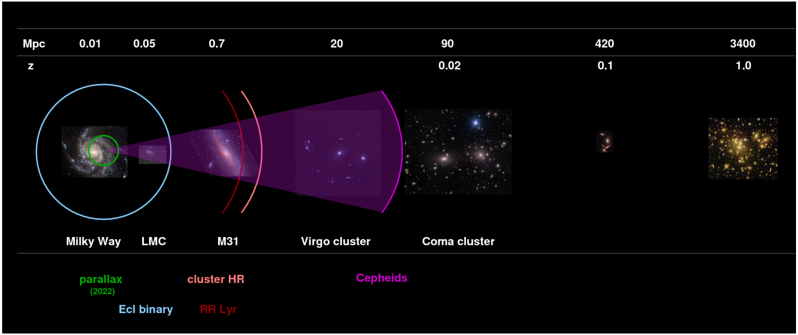
1. Pick one variable star. Measure its average apparent magnitude, m_v.
2. Use its period to determine its absolute magnitude M_V.
3. Compute the distance modulus $(m_V - M_V)$.
4. Compute the distance to this galaxy, in Mpc.

Answer: You should get a distance of $\sim$ 17 Mpc.

The Period-Luminosity(-Metallicity) Relation

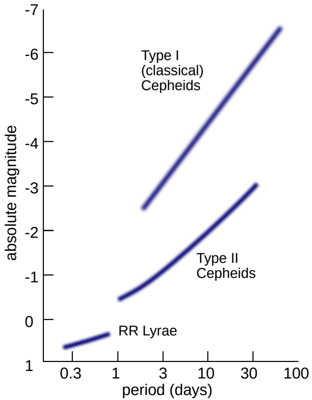
As Cepheids are more luminous than RR Lyrae, with them we can measure distances farther into the depths of space.

In particular, Cepheids allow to measure the distance to the nearest galaxy cluster, the Virgo Cluster.



Period-Luminosity(-Metallicity) Relations for Cepheids and RR Lyrae

Period-luminosity relations are known for several types of pulsating variable stars: type I Cepheids, type II Cepheids, RR Lyrae variables, Mira variables, and other long-period variable stars.



Period-Luminosity(-Metallicity) Relations for Cepheids and RR Lyrae

Population I Cepheids:
Population I Cepheids are stars with relatively high metallicity (like our Sun) and thus are *second generation* stars, found in the disk of our galaxy. Classical Cepheids (also known as Population I Cepheids, type I Cepheids, or Delta Cepheid variables) undergo pulsations with very regular periods on the order of days to months.

The following relationship between a Population I Cepheid's period P and its mean absolute magnitude $_{\mathrm{v}}$ was established from Hubble Space Telescope trigonometric parallaxes for 10 nearby Cepheids (Thomas et al. (2007), Benedict et al. (2002)):

$$M_{\mathrm{v}} = (-2.43 \pm 0.12)\,(\log_{10} P - 1) - (4.05 \pm 0.02)$$

Period-Luminosity(-Metallicity) Relations for Cepheids and RR Lyrae

Population II Cepheids:

Population II Cepheids are stars found in globular clusters that are low-metallicity "first generation" stars. Type II Cepheids are fainter than their classical Cepheid counterparts for a given period by about 1.6 magnitudes (about 4 times less luminous).

Period-Luminosity Relations of Population II Cepheids (McNamara 1995):

$P < 10$ days: $M_v = -1.61 \log P - 0.05$,

$P > 10$ days: $M_v = -4.17 \log P + 3.06$

The steep slope for stars with $P > 10$ days may be due to an increase of mass with the period of pulsation.

Period-Luminosity(-Metallicity) Relations for Cepheids and RR Lyrae

RR Lyrae Stars:
The PLZ relation is given as (e.g. Catelan2004, Sollima2006):

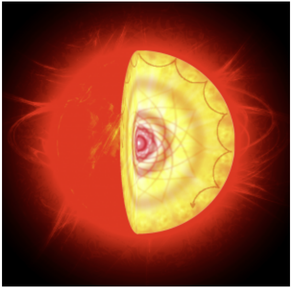
$$M_\lambda = \alpha_\lambda \log_{10}(P/P_{\mathrm{ref}}) + \beta_\lambda([\mathrm{Fe/H}] - [\mathrm{Fe/H}]_{\mathrm{ref}}) + M_{\mathrm{ref},\lambda} + \epsilon$$

where λ denotes the bandpass, P is the period of pulsation, M_{ref} is the absolute magnitude at a reference period and metallicity, and α, β describe the dependence of the absolute magnitude on period and metallicity. The ϵ is a standard normal random variable centered on 0 and with a standard deviation of the uncertainty in M_λ in order to model the intrinsic scatter in the absolute magnitude convolved with unaccounted measurement uncertainties.

Further Pulsation Analysis

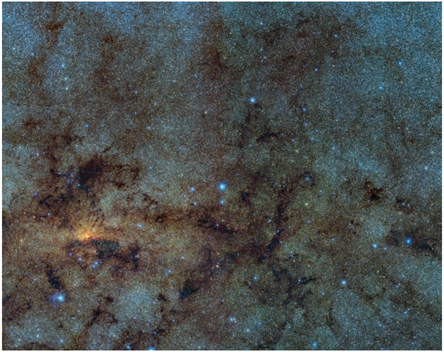
Pulsation is useful for **probing the interiors of stars**, and testing models of stellar structure and evolution: **Asteroseismology**.

Stars have many resonant modes and frequencies, and the path of sound waves passing through a star depends on the speed of sound, which in turn depends on local temperature and chemical composition.



Further Pulsation Analysis

As pulsating stars allow for calculating distances, we can use them to **estimate interstellar reddening** (from dust).



This IR view of the Milky Way's crowded center (taken as part of the ESO's VISTA Variables in the Via Lactea Survey) reveils numerous RR Lyrae stars in our galaxy's bulge, hinting that it is old and may have been built up as primordial star clusters merged over time.