

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

Variable Stars

Pulsating  
Variable Stars

Distances

Further  
Pulsation  
Analysis

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

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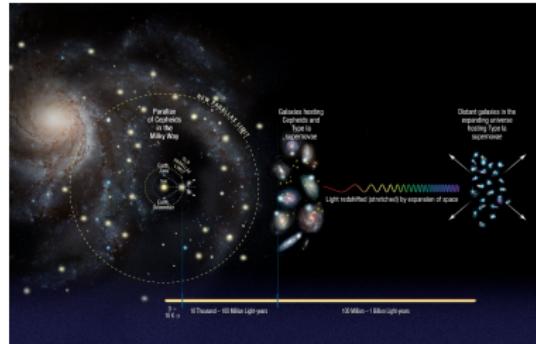
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# Motivation

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.



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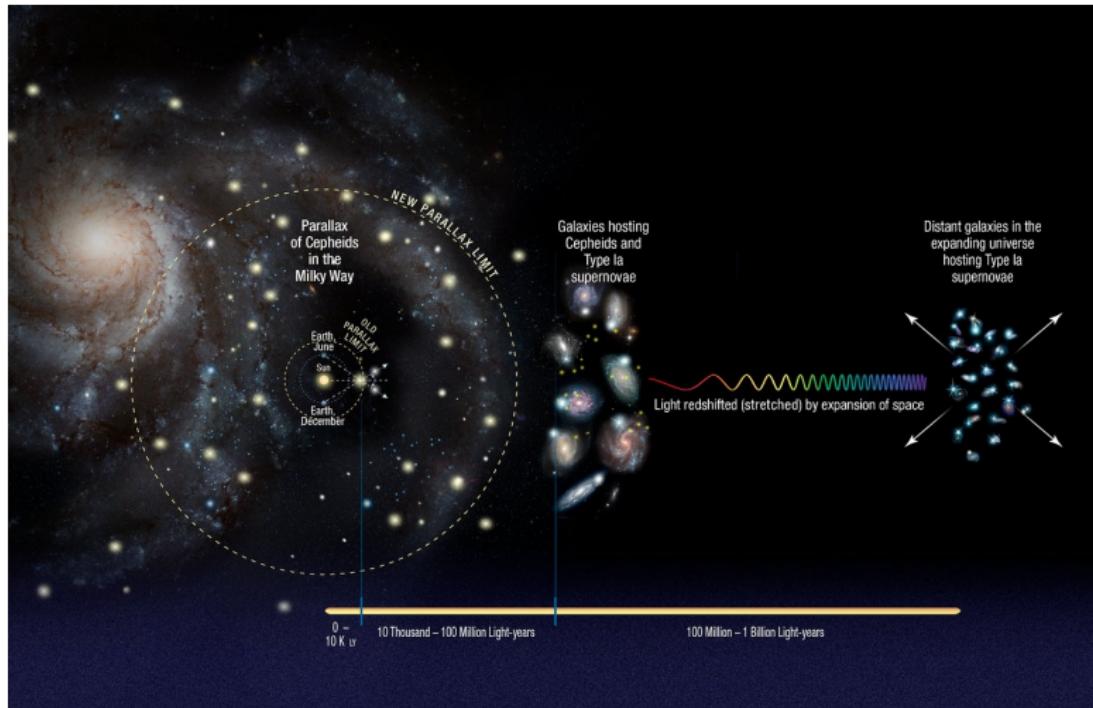
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Credit: NASA, ESA, A. Feild (STScI), and A. Riess (STScI/JHU)

# Variable Stars

Variable stars are stars showing a change in brightness.

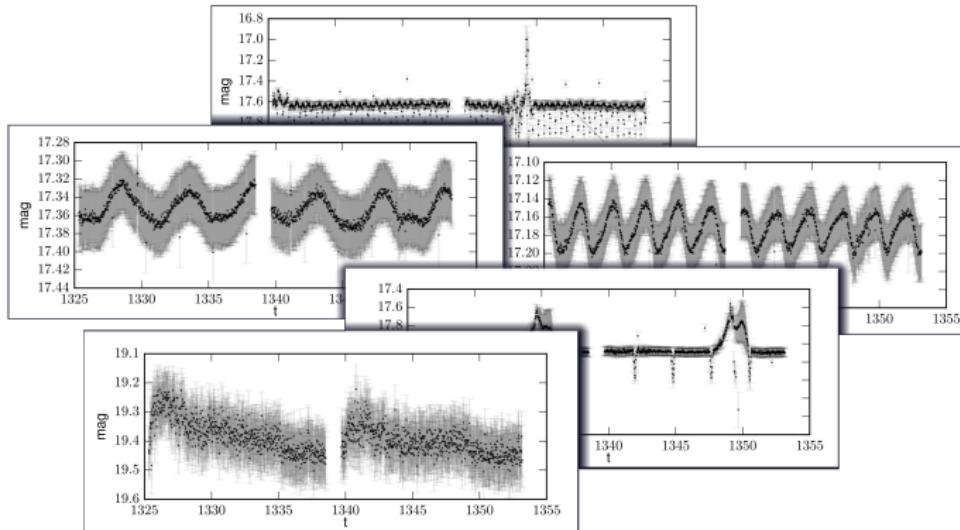
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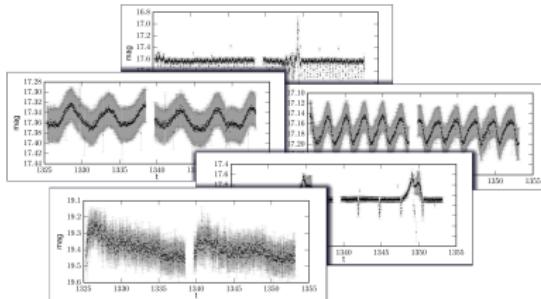
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A selection of variable star light curves from the TESS survey.

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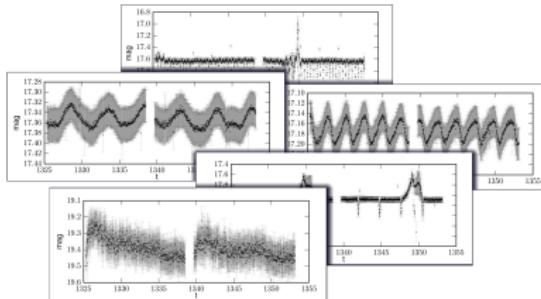
few parts  
per million

change in luminosity

factor 1000

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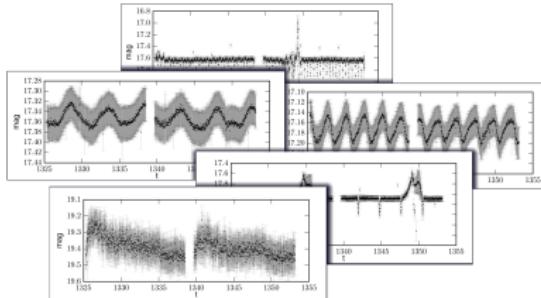
seconds

**temporal baseline**

centuries

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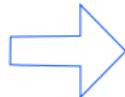
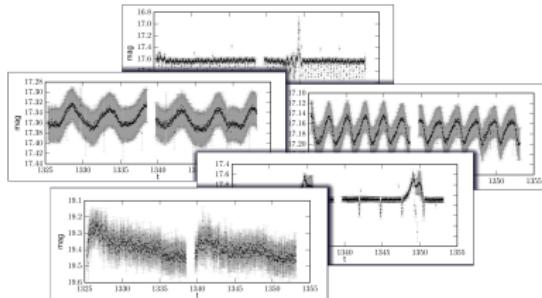
periodic

**signal shape**

aperiodic/  
random

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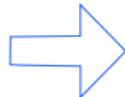
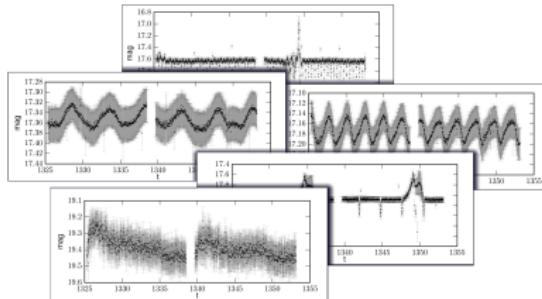


variations provide important and often unique information about the nature and evolution of stars



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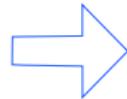
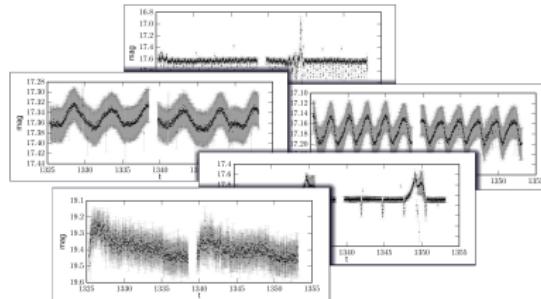
variations provide important and often unique information about the nature and evolution of stars

and the galaxies that host them



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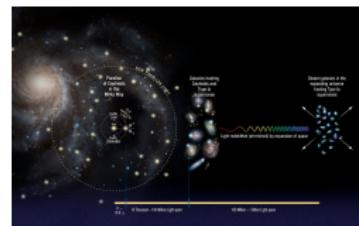
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variations provide important and often unique information about the nature and evolution of stars

and the galaxies that host them

and our universe in general



# Variable Stars

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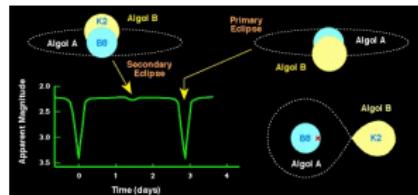
## Intrinsic Variables

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



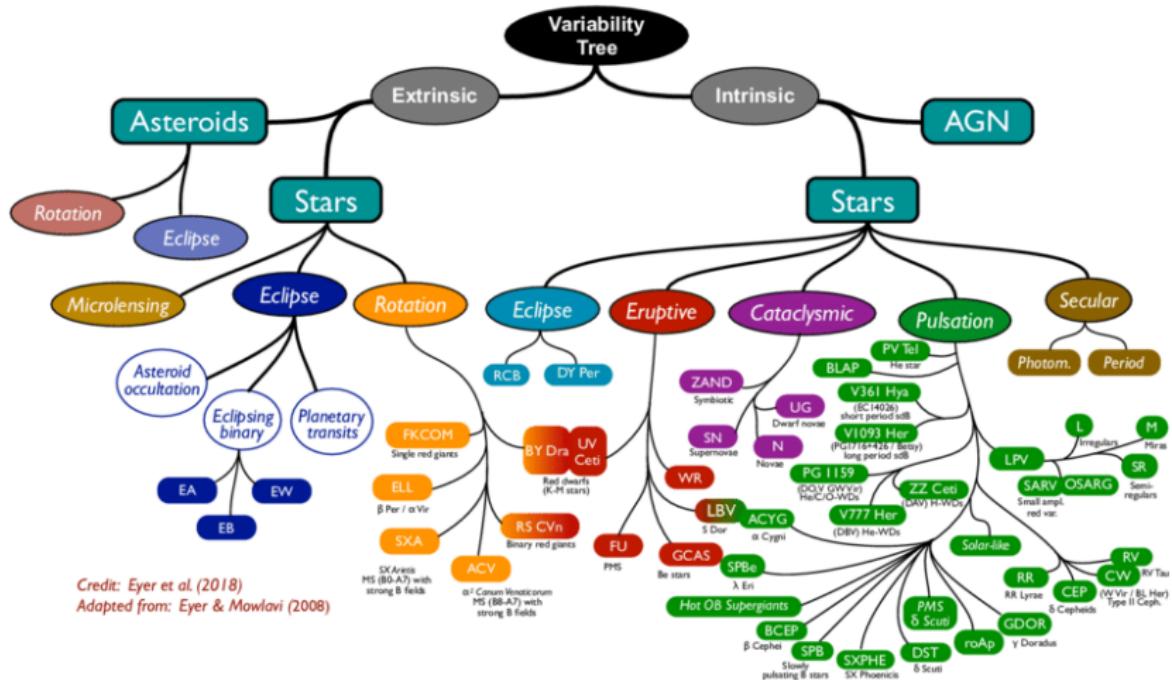
## Extrinsic Variables

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



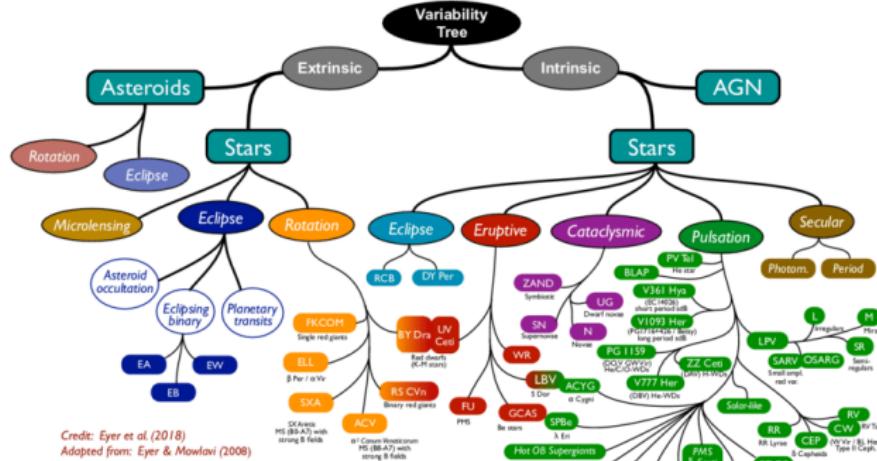
# Variability Tree

Motivation  
Variable Stars  
Pulsating Variable Stars  
Distances  
Further Pulsation Analysis



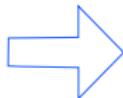
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Credit: Eyer et al. (2018)  
Adopted from: Eyer & Mowlavi (2008)

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  $\alpha$  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  $\alpha$  Herculis and 44 Bootis

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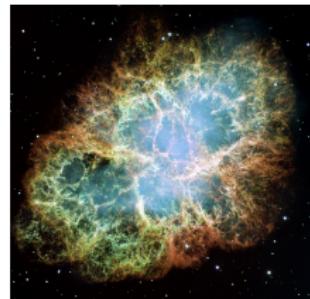
supernovae:

oldest mention of a “new star”: 185 AD a “guest star” was observed by Chinese astronomers

1054: supernova mentioned 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**

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1850s: ~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)

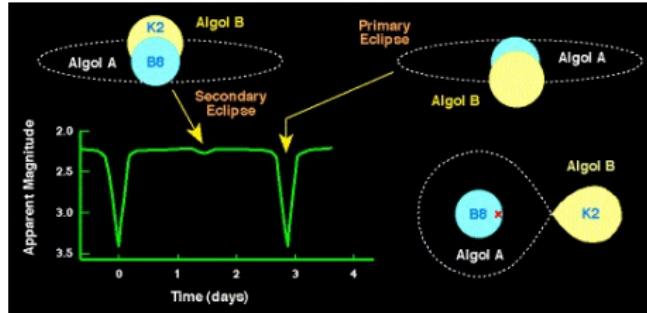
# Discovery of Variable Stars

## 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  $\beta$  Persei (Per) A,  $\beta$  Per B and  $\beta$  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 revealed **differences in their light curves**

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

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

Pickering (1880s): a more detailed scheme:

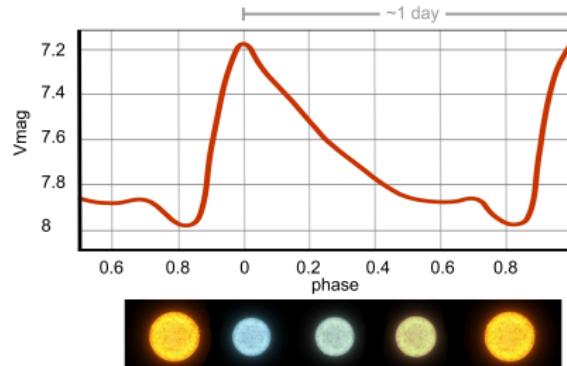
- (Ia) normal novae: now known to be nearby ones in our own galaxy;
- (Ib) novae in nebulae: now known to be supernovae in other galaxies;
- (IIa) long-period variables: cool, large-amplitude pulsating variables;
- (IIb) U Geminorum stars: dwarf novae;
- (IIc) R Coronae Borealis stars: stars which suddenly 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

## underlying physics of variability:

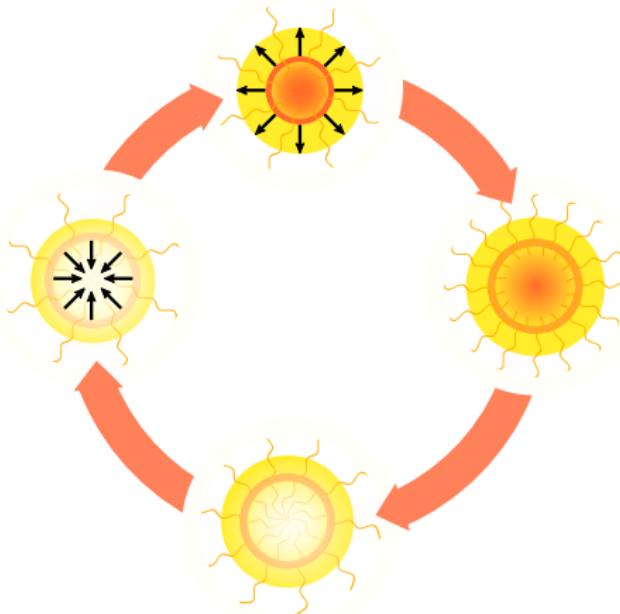
idea: (at least some) periodic variability might be caused by pulsations (A. Ritter 1873)

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:



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# Cause of Pulsation

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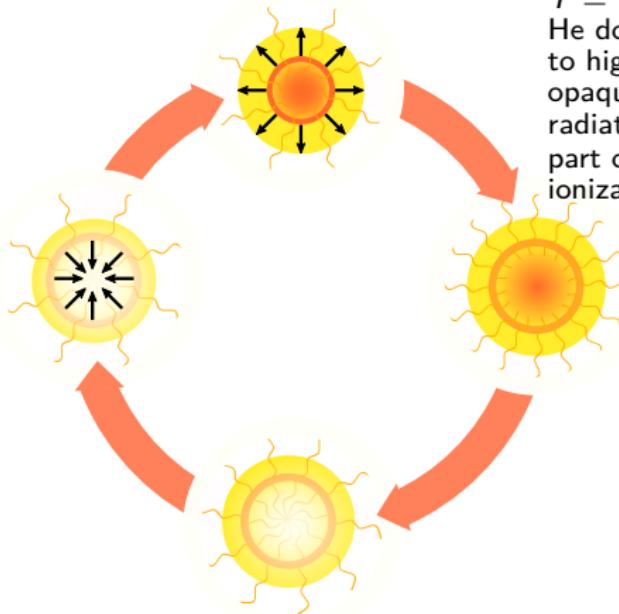
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**cause of pulsation:** Lack of hydrostatic equilibrium beneath the surface drives the pulsation cycle with expansion and contraction of the outer layers of a star and subsequent change in brightness:



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

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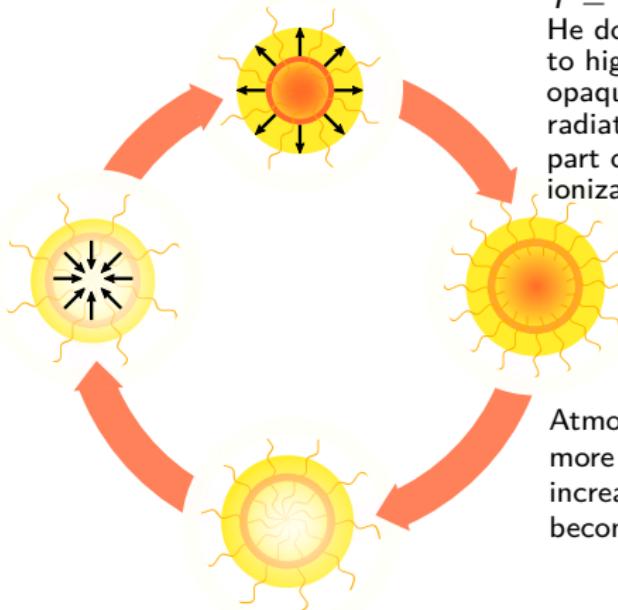
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Atmosphere expands, becomes more transparent (brightness increases) and cools. HeIII becomes HeII.

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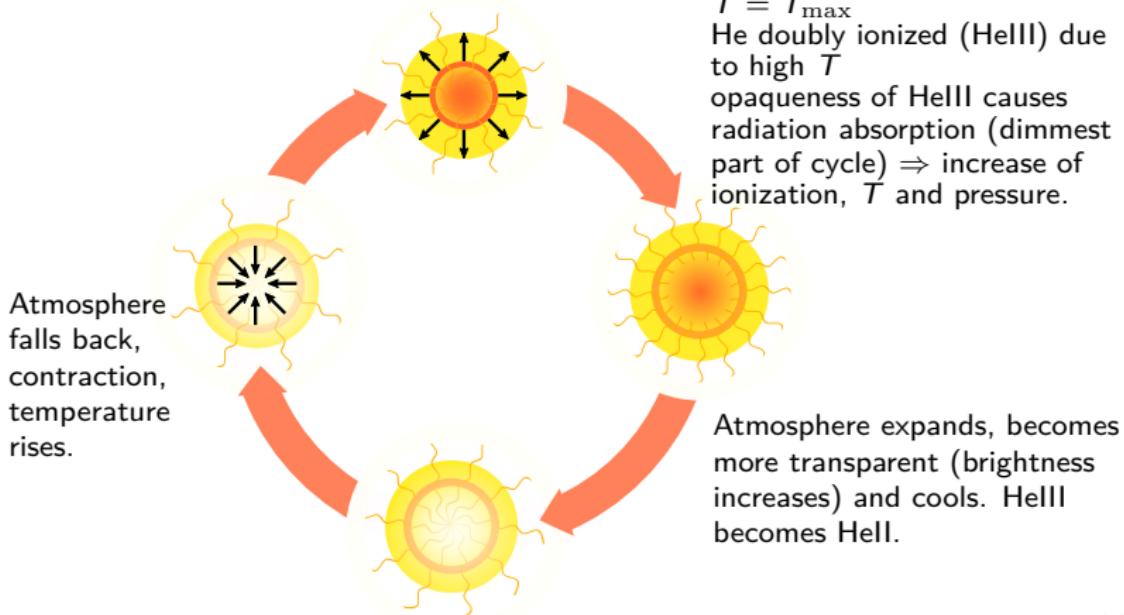
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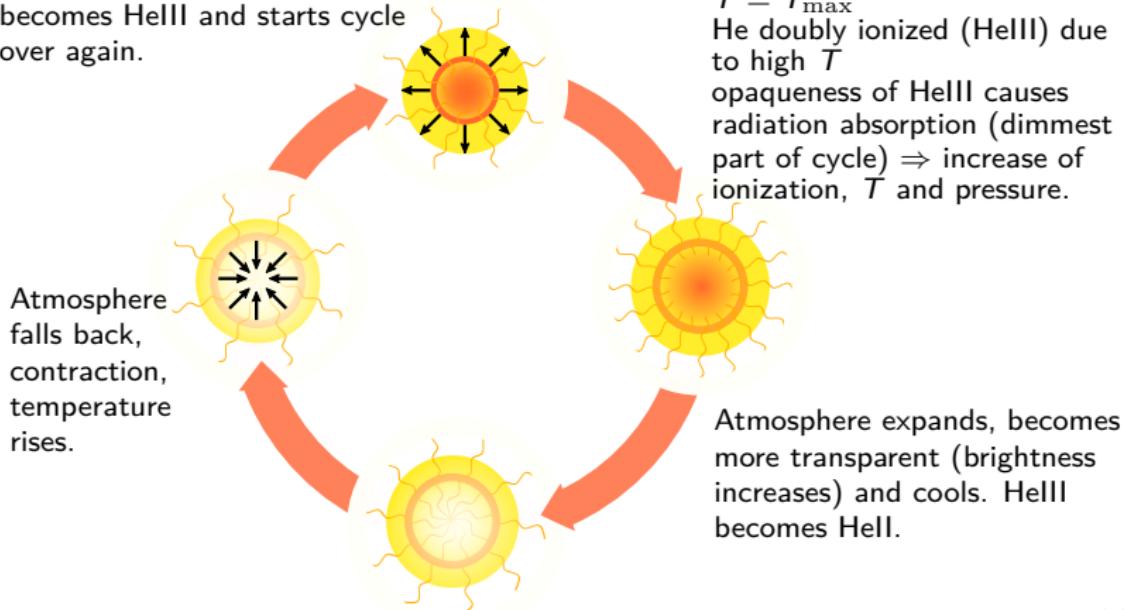
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**cause of pulsation:** Lack of hydrostatic equilibrium beneath the surface drives the pulsation cycle with expansion and contraction of the outer layers of a star and subsequent change in brightness:

Before it reaches equilibrium, Hell becomes HellII and starts cycle over again.



# 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.

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# Cause of Pulsation

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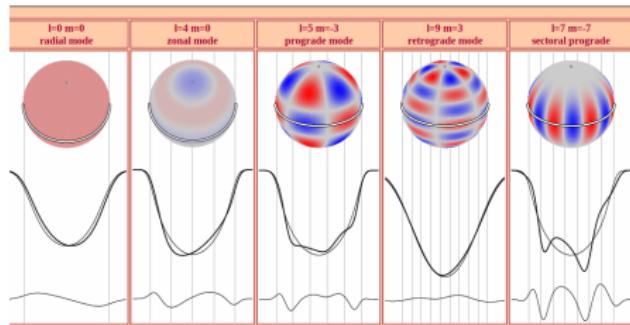
Pulsating Variable Stars

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Further Pulsation Analysis

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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 –  $\beta$  Cephei,  $\delta$  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

Motivation

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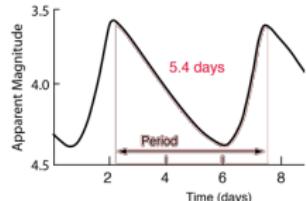
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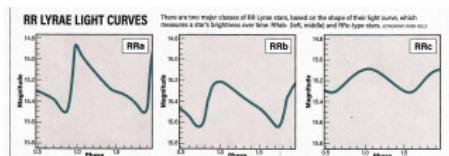
## Cepheids

- 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  $\Rightarrow$  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

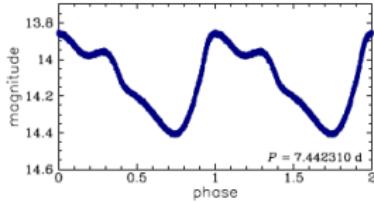
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## Classical (Type I) Cepheids

bright yellow, highly luminous,  
supergiant pulsating variables

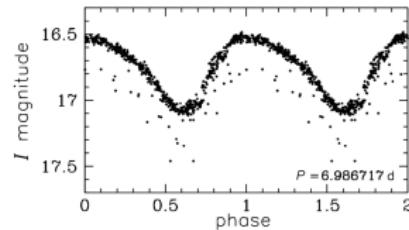
- amplitudes:  $\sim 0.01 - 2 \text{ mag}_V$
- periods: 1 - 135 days
- variability is strictly regular
- spectral type: F at maximum light, G to K at minimum light;  
the longer the period, the later the spectral type



## Population II (Type II) Cepheids

similar light curve than Type I, but different evolutionary history

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

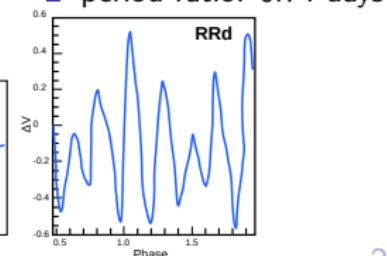
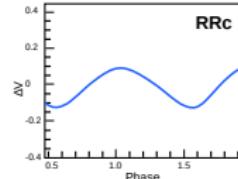
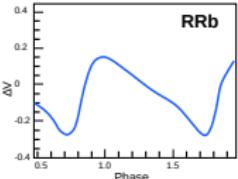
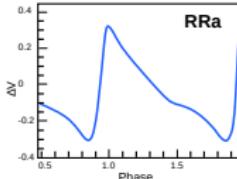


# RR Lyrae stars

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  $0.5 M_{\odot}$

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- RRab**  
asymmetrical light curves with steep ascend
  - periods: 0.3 - 1.2 days
  - amplitudes: 0.5 - 2 mag<sub>V</sub>
- RRc**  
nearly symmetrical light curves
  - periods: 0.2 - 0.5 days
  - amplitudes: < 0.8 mag<sub>V</sub>
- 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

Motivation

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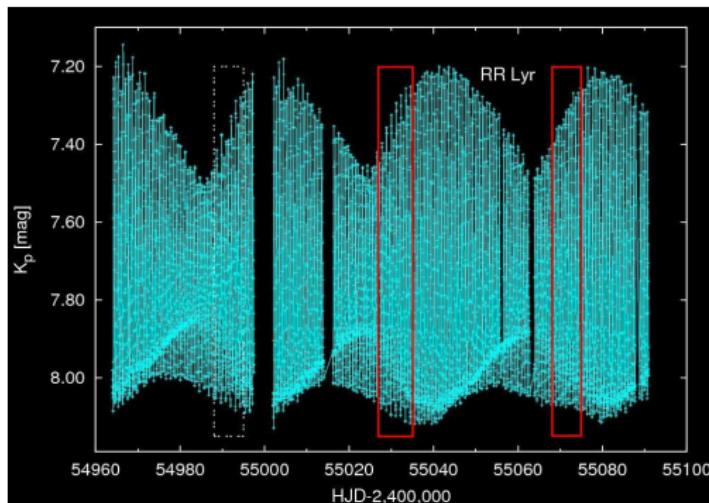
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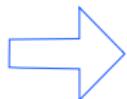
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modern observation of a RR Lyrae star with Blazhko effect from the Kepler survey

# 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

Motivation

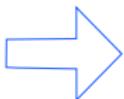
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two promising **theories** for explaining the Blazhko effect:

- (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

Motivation

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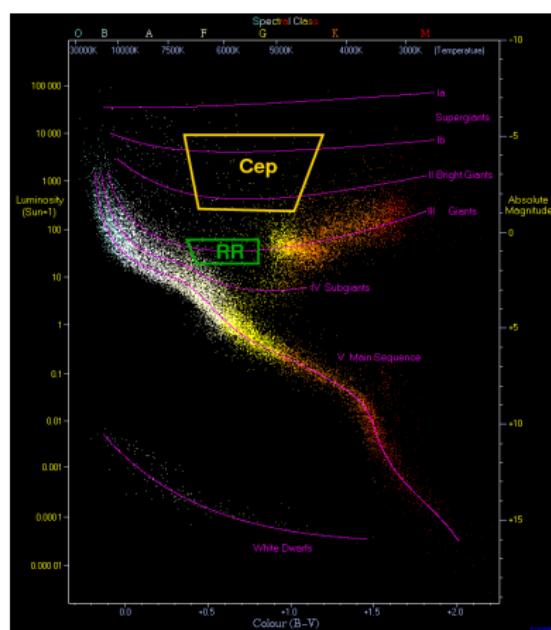
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# Evolutionary Stages - the Hertzsprung-Russel (H-R) Diagram

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.

Motivation

Variable Stars

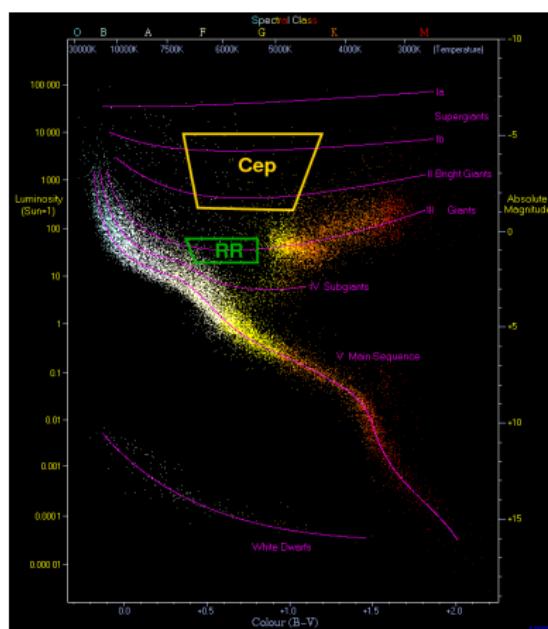
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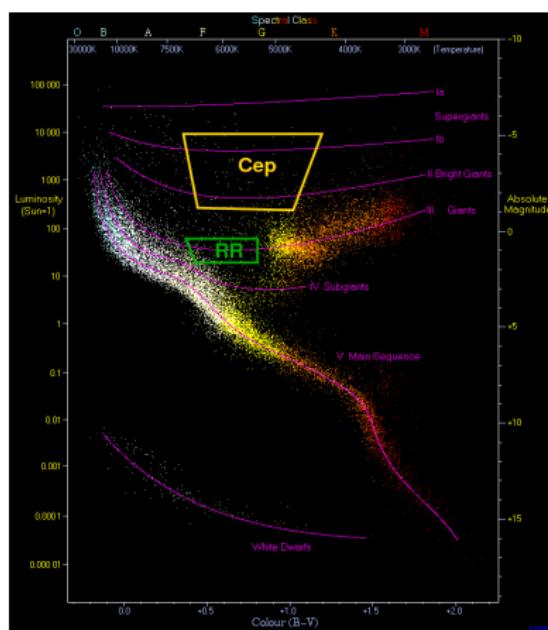
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**main sequence:** a band extending from hot, high-luminosity stars to cool, low-luminosity stars, containing the vast majority of stars; burning H  $\rightarrow$  He in their cores

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**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 burning 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 branch (AGB). Finally it ejects its envelope and becomes a planetary nebulae containing a white dwarf ( $M \leq 1.4M_{\odot}$ ,  $R \sim R_{\text{earth}}$ ).

Motivation

Variable Stars

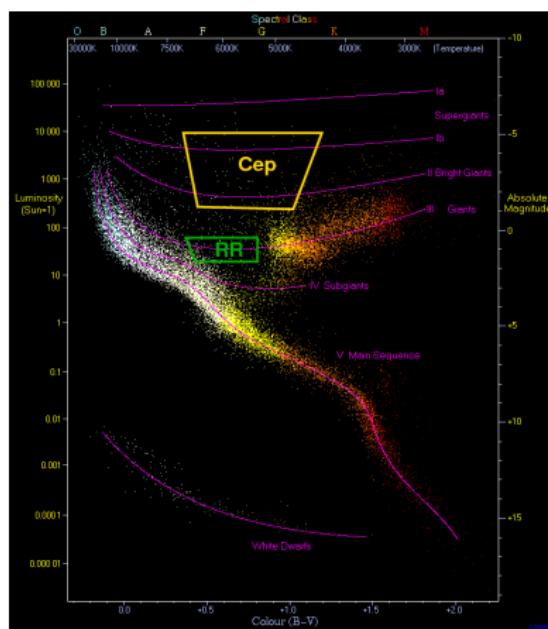
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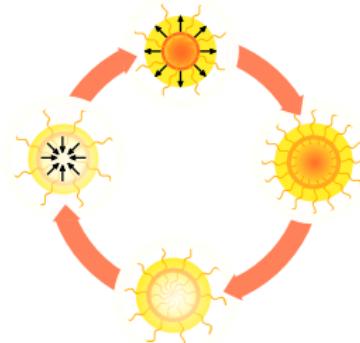
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## instability strip:

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:

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

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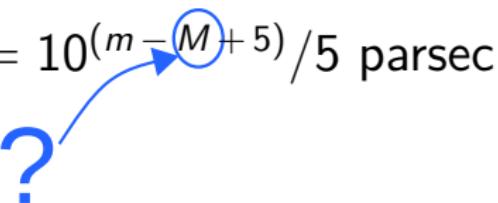
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Variable Stars

**Distances**

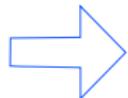
Further  
Pulsation  
Analysis

# Pulsating Stars as Distance Estimators

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

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


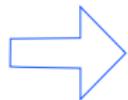
Pulsating stars are a powerful tool for determining distances in astronomy, because the period of pulsation is correlated with the luminosity of the star, and this relation can be calibrated



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**

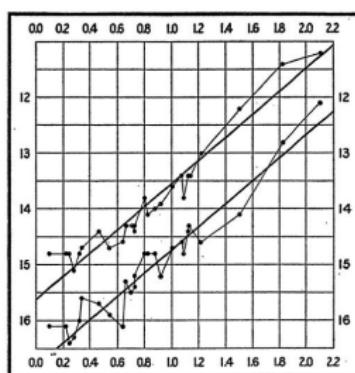


FIG. 2.

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

Motivation

Variable Stars

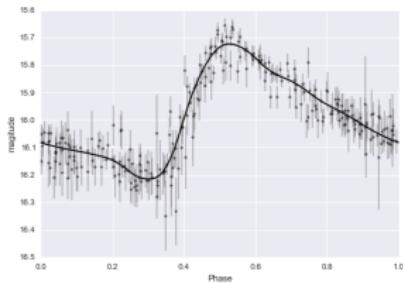
Pulsating  
Variable Stars

Distances

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

basic concept:

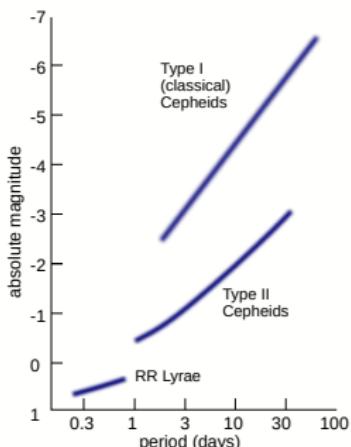


- measure apparent mean brightness  $m$
- measure period  $P$

# Pulsating Stars as Distance Estimators

Motivation  
Variable Stars  
Pulsating Variable Stars  
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basic concept:



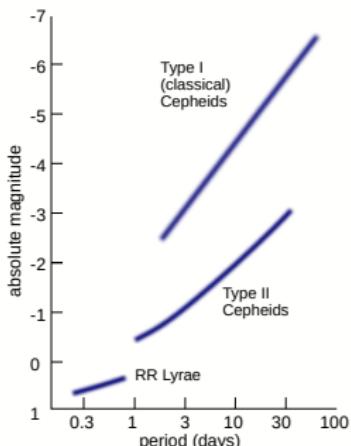
- measure apparent mean brightness  $m$
- measure period  $P$
- using **period-luminosity relation**, get absolute brightness  $M$
- solve for distance using **distance modulus equation**  
$$d = 10^{(m-M+5)/5} \text{ parsec}$$
where 1 parsec =  $3.086^{16}$  m = 3.26156 lyr

# Pulsating Stars as Distance Estimators

Motivation  
Variable Stars  
Pulsating Variable Stars  
Distances  
Further Pulsation Analysis

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

basic concept:



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where 1 parsec =  $3.086^{16}$  m = 3.26156 lyr

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

# The Period-Luminosity(-Metallicity) Relation

Motivation  
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Globular clusters have only little depth - we can treat all the stars in a cluster as being at  $\sim$  the same distance from Earth  
color-magnitude diagram of stars in a globular cluster (M3):

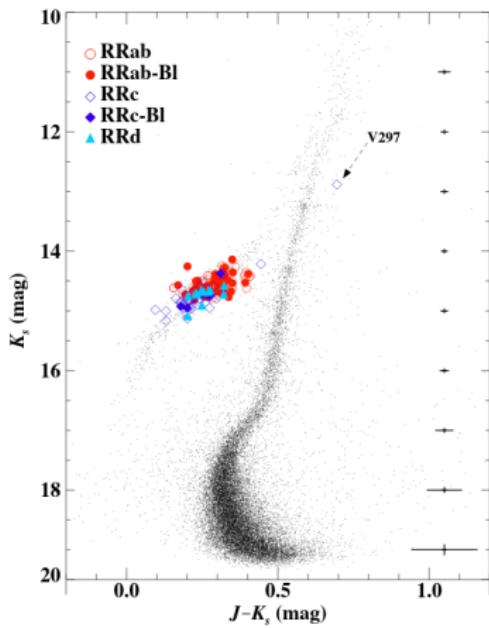
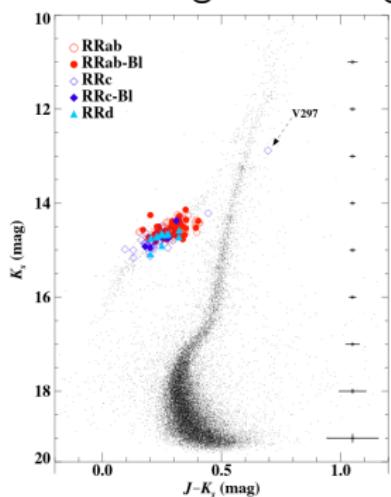


Figure 3 taken from  
Bhardwaj et al., AJ 160,  
220 (2020)

# The Period-Luminosity(-Metallicity) Relation

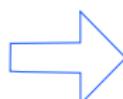
Motivation  
Variable Stars  
Pulsating Variable Stars  
Distances  
Further Pulsation Analysis

Globular clusters have only little depth - we can treat all the stars in a cluster as being at  $\sim$  the same distance from Earth  
color-magnitude diagram of stars in a globular cluster (M3):



all RR Lyrae stars have  $\sim$  the same apparent magnitude

$\Rightarrow$  as the distance must be  $\sim$  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

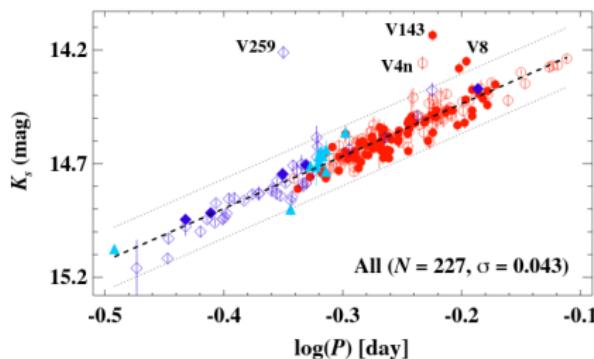
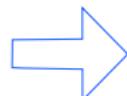


Figure 10 (slightly modified)  
taken from Bhardwaj et al., AJ  
160, 220 (2020)



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:

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

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# The Period-Luminosity(-Metallicity) Relation

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

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

Motivation

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# The Period-Luminosity(-Metallicity) Relation

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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.

Motivation

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- 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.

Motivation

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# The Period-Luminosity(-Metallicity) Relation

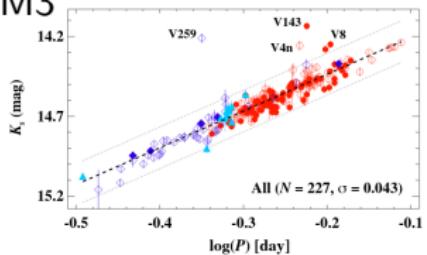
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- The Baade-Wesselink method (infer distance from measurement of change in radius (from velocity) and angular diameter) has been applied to some of the brightest RR Lyrae stars; it gives an absolute magnitude of about +0.5.

# The Period-Luminosity(-Metallicity) Relation

**example 1:** Distance to the cluster M3

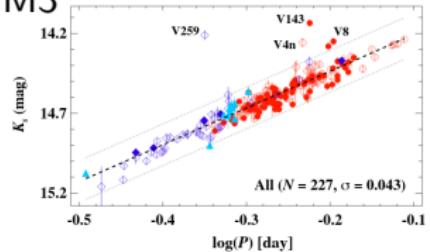


**Q:** What is the average apparent  $K$  magnitude for RR Lyrae stars in M3?

Motivation  
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# The Period-Luminosity(-Metallicity) Relation

## example 1: Distance to the cluster M3

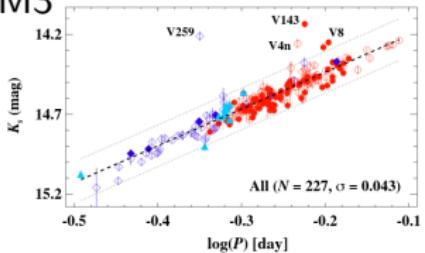


**Q:** What is the average apparent  $K$  magnitude for RR Lyrae stars in M3?

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

# 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?

Motivation

Variable Stars

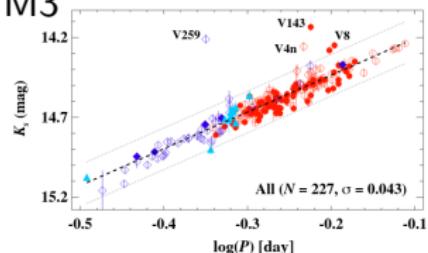
Pulsating  
Variable Stars

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Analysis

# The Period-Luminosity(-Metallicity) Relation

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

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

Motivation

Variable Stars

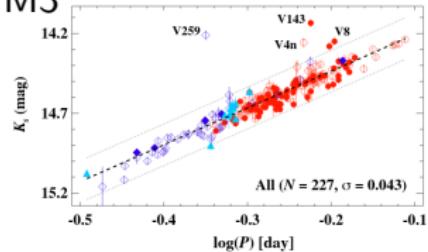
Pulsating  
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# The Period-Luminosity(-Metallicity) Relation

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**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:

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

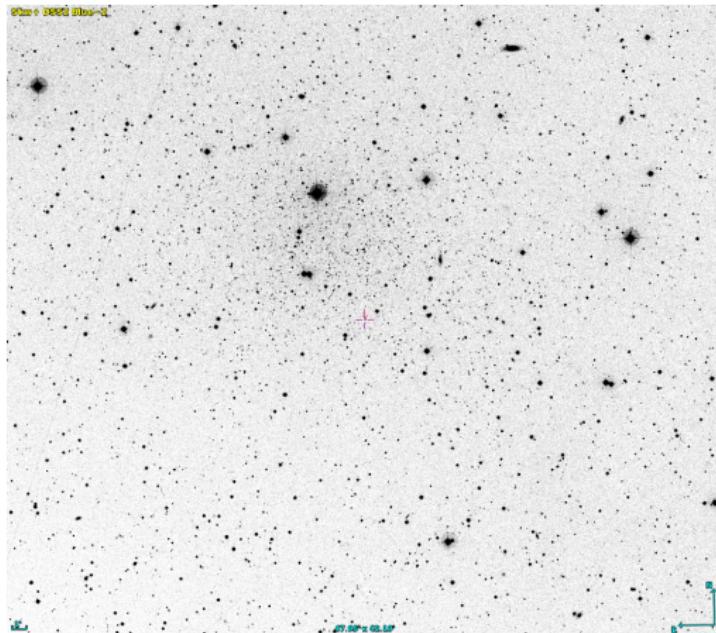
$$\log(d) = 4.01$$

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

# The Period-Luminosity(-Metallicity) Relation

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

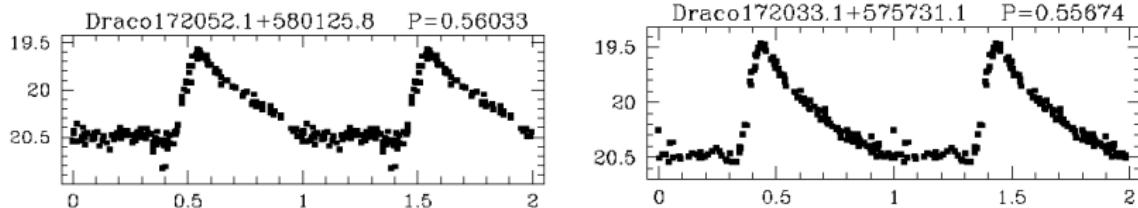
Motivation  
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Pulsating Variable Stars  
**Distances**  
Further Pulsation Analysis



# The Period-Luminosity(-Metallicity) Relation

Motivation  
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Pulsating  
Variable Stars  
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**example 2:** Distance to Draco dwarf spheroidal (dSph) galaxy  
light curves of two RR Lyrae stars within Draco dSph, measured in the  $V$   
passband

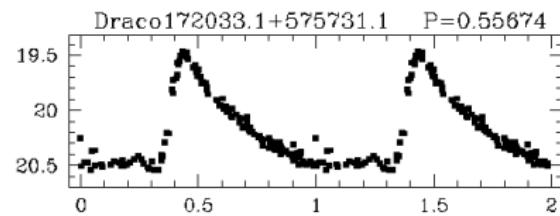
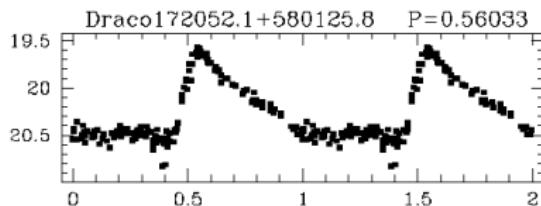


taken from Fig. 1 of Bonanos et al., AJ 127, 861 (2004)

# The Period-Luminosity(-Metallicity) Relation

Motivation  
Variable Stars  
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Distances  
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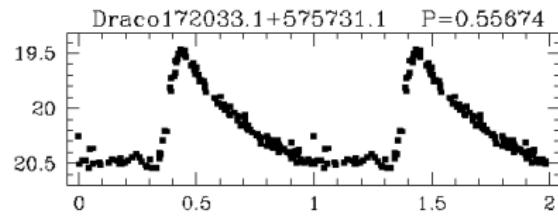
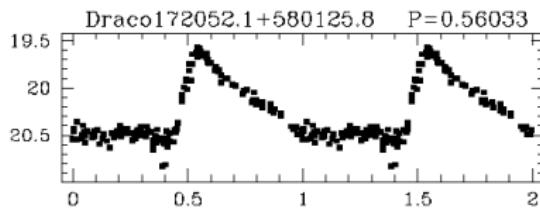


**Q:** The absolute magnitude of RR Lyrae stars in the  $V$  filter is approximately  $M(V) = +0.77$ . What is the distance to Draco dSph?

# The Period-Luminosity(-Metallicity) Relation

Motivation  
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**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":

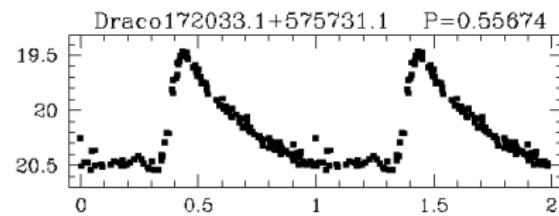
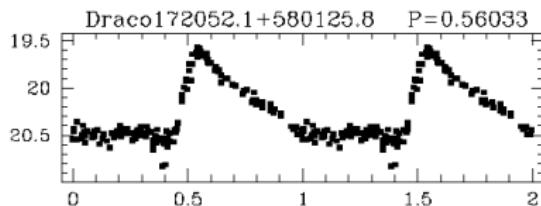
With the average of the  $V$ -band apparent magnitudes being about  $m(V) = 20.20$ , we get

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

# The Period-Luminosity(-Metallicity) Relation

Motivation  
Variable Stars  
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Further Pulsation Analysis

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

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

$$m - M = 19.43 = 5 \times \log_{10}(d) - 5$$

$$5 \times \log_{10}(d) = 24.43$$

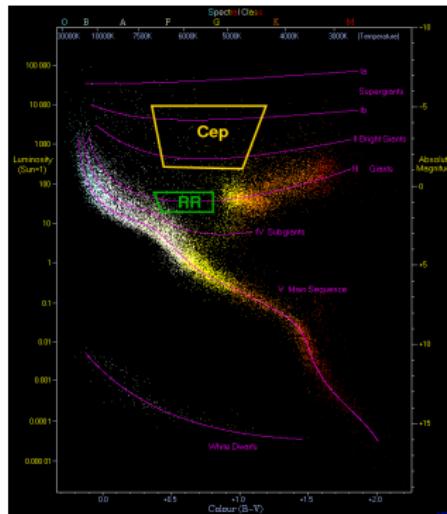
$$d = 10^{4.89} = 77000 \text{ pc} = 77 \text{ kpc}$$

# The Period-Luminosity(-Metallicity) Relation

Motivation  
Variable Stars  
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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.

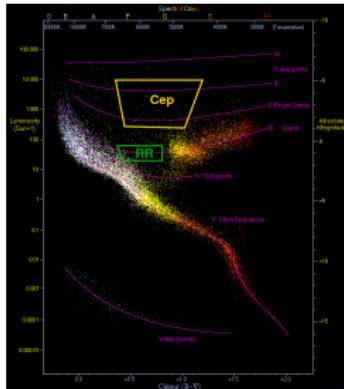
**problem:** RR Lyrae stars aren't really luminous. Take a look again at this HR diagram:



# The Period-Luminosity(-Metallicity) Relation

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

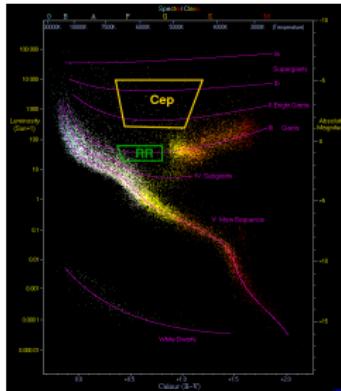


A typical RR Lyrae has a luminosity  $\sim 50 M_{\odot}$   $\Rightarrow$  not powerful enough for us to see these stars in distant galaxies.

# 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.

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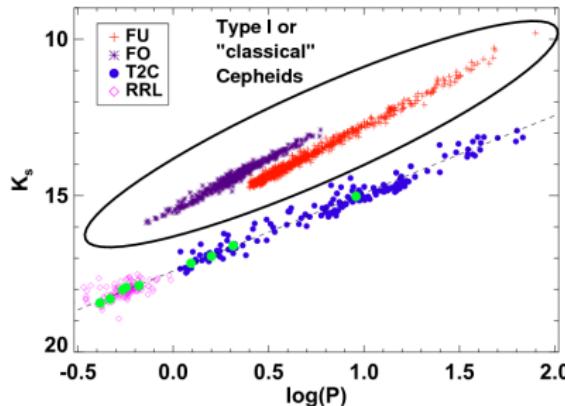
We can use RR Lyrae to measure distances only to the very closest galaxies - members of our own Local Group.  
A better choice for **larger distances**: Cepheids which are 100 times more luminous than RR Lyrae stars.

# The Period-Luminosity(-Metallicity) Relation

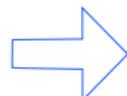
Motivation  
Variable Stars  
Pulsating Variable Stars  
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we've seen for RR Lyrae stars: assumption of identical absolute magnitude holds well

not so for Cepheids:

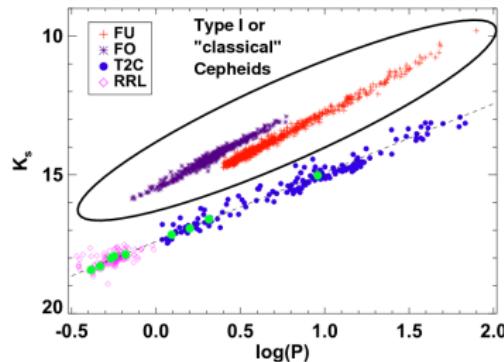


**Figure 9.** Comparison of  $K_s$ -band P-L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.



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

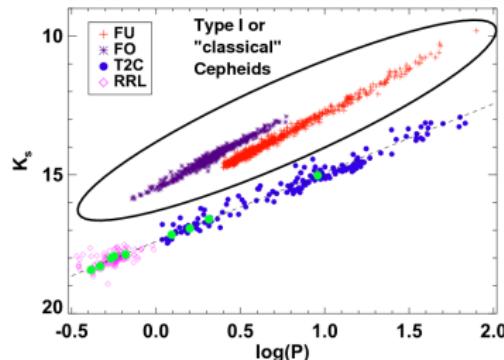
# The Period-Luminosity(-Metallicity) Relation



**Figure 9.** Comparison of  $K_s$ -band P-L relation with Classical Cepheids from LMCNIISS 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



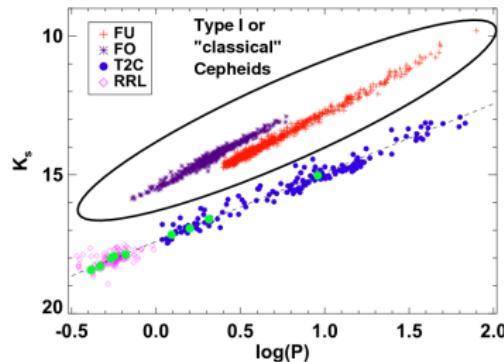
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**Q:** What is the range of periods for these Cepheids?

**A:** The range is from  $\log_{10}(P) = -0.1 \Rightarrow P = 0.8$  days to  $\log_{10}(P) = +1.9 \Rightarrow P = 79$  days  
 $\Rightarrow$  that is about a factor of 100

# The Period-Luminosity(-Metallicity) Relation



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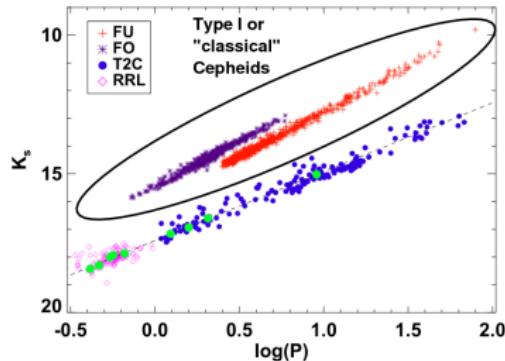
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**Q:** What is the range of magnitudes of these Cepheids?

# The Period-Luminosity(-Metallicity) Relation

Motivation  
Variable Stars  
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**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!

# The Period-Luminosity(-Metallicity) Relation

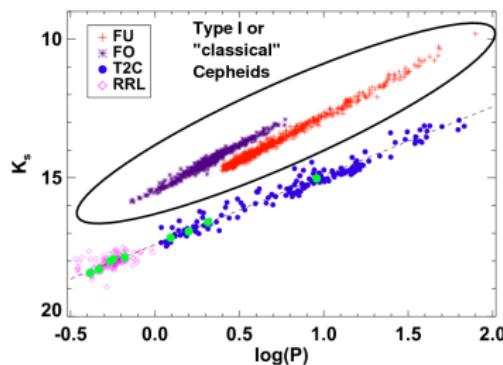


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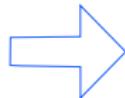
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**Q:** What is the range of periods for these Cepheids?

**A:** The range is from  $\log_{10}(P) = -0.1 \Rightarrow P = 0.8 \text{ days}$  to  $\log_{10}(P) = +1.9 \Rightarrow P = 79 \text{ days}$   
 $\Rightarrow$  that is about a factor of 100

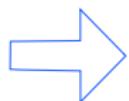
**Q:** What is the range of magnitudes of these Cepheids?

**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

# The Period-Luminosity(-Metallicity) Relation

## example 3: A Period-Luminosity Relation for Cepheids

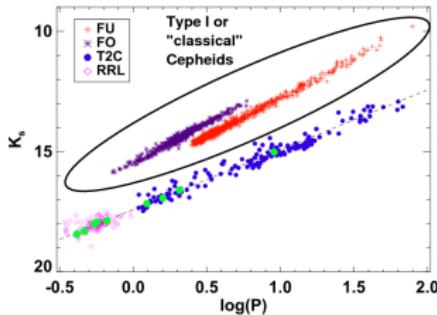


Figure 9. Comparison of  $K_s$ -band P-L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

**Q:** Write an equation of the form

$$M(V) = A \times \log_{10}(P) + B$$

which is consistent with the data in the graph.

# The Period-Luminosity(-Metallicity) Relation

## example 3: A Period-Luminosity Relation for Cepheids

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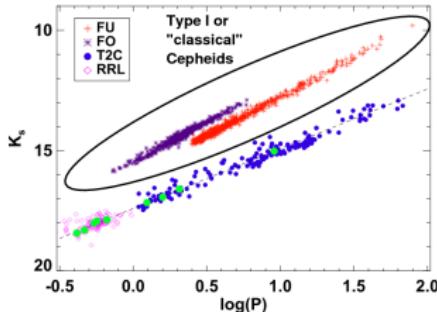


Figure 9. Comparison of  $K_s$ -band P-L relation with Classical Cepheids from LMCNISI data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

**Q:** Write an equation of the form

$$M(V) = A \times \log_{10}(P) + B$$

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

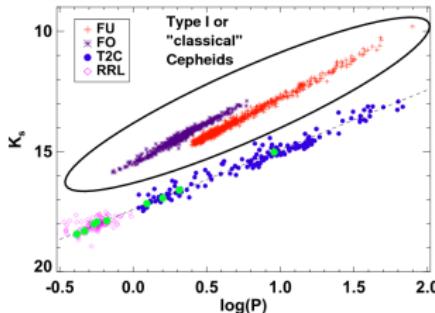


Figure 9. Comparison of  $K_s$ -band P-L relation with Classical Cepheids from LMCNISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

**Q:** Write an equation of the form

$$M(V) = A \times \log_{10}(P) + B$$

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:

# The Period-Luminosity(-Metallicity) Relation

## example 3: A Period-Luminosity Relation for Cepheids

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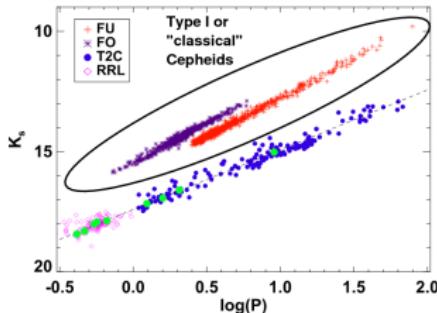


Figure 9. Comparison of  $K_s$ -band P-L relation with Classical Cepheids from LMCNIISS data and RR Lyraes in the LMC. The green circles represent the calibrator T2Cs and RRLs.

**Q:** Write an equation of the form

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which is consistent with the data in the graph.

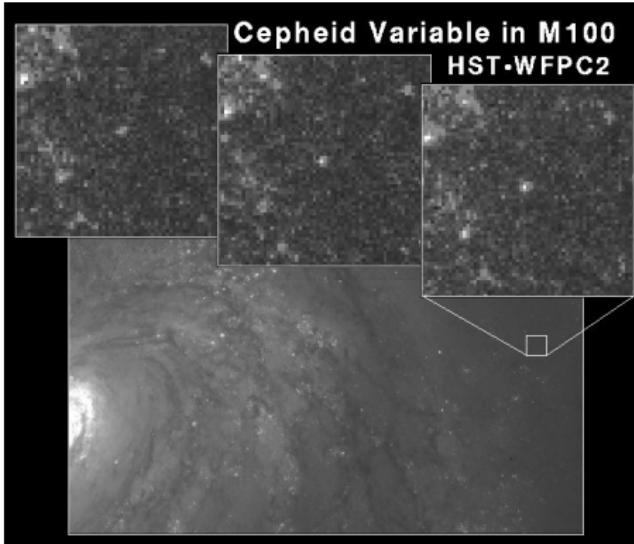
**A (continued):** So the relationship between period and absolute magnitude is approximately

$$M(V) = -2.5 \times \log_{10}(P) - 1.5$$

# 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.

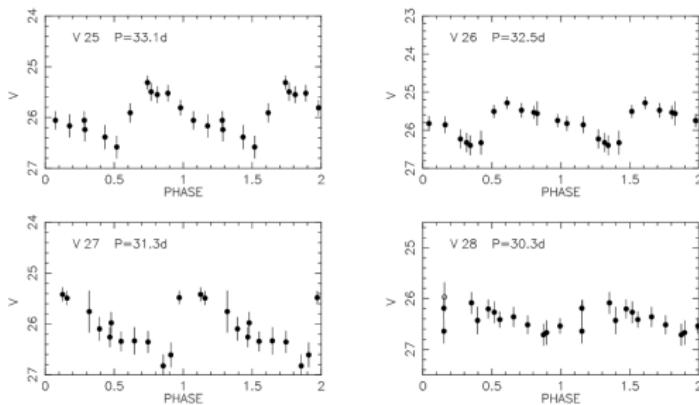


# The Period-Luminosity(-Metallicity) Relation

Motivation  
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## example 4: The Distance to M100

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



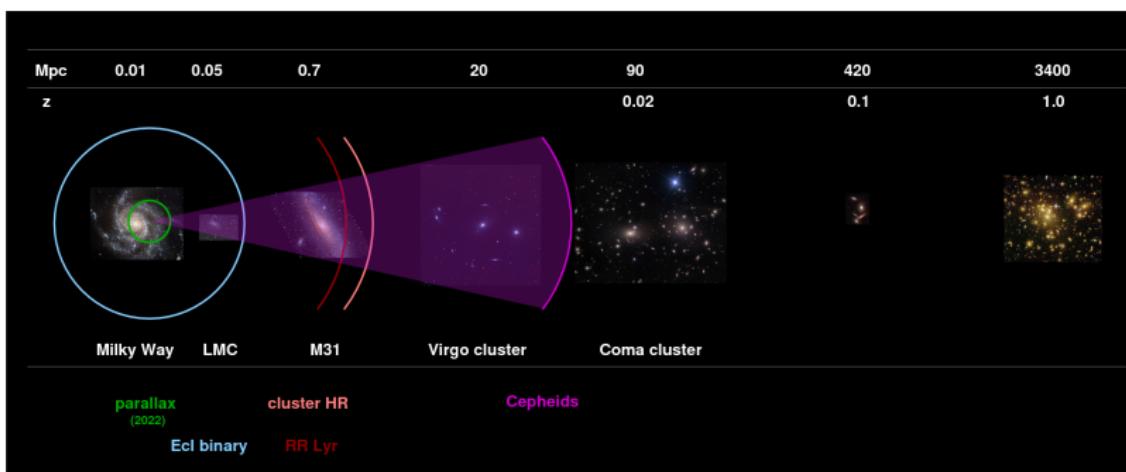
1. Pick one variable star. Measure its average apparent magnitude,  $m_V$ .
2. Use its period to determine its absolute magnitude  $M_V$ .
3. Compute the distance modulus ( $m_V - M_V$ ).
4. Compute the distance to this galaxy, in Mpc.

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

# The Period-Luminosity(-Metallicity) Relation

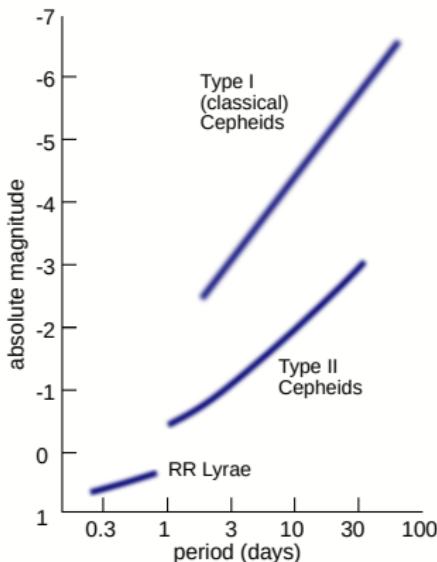
As Cepheids are more luminous than RR Lyrae, with them we can measure distances farther into the depths of space.

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  $M_v$  was established from Hubble Space Telescope trigonometric parallaxes for 10 nearby Cepheids (Thomas et al. (2007), Benedict et al. (2002)):

$$M_v = (-2.43 \pm 0.12)(\log_{10} P - 1) - (4.05 \pm 0.02)$$

# 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):

$$P < 10 \text{ days: } M_v = -1.61 \log_{10} P - 0.05,$$

$$P > 10 \text{ days: } M_v = -4.17 \log_{10} P + 3.06$$

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

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

## RR Lyrae Stars:

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

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

where  $\lambda$  denotes the bandpass,  $P$  is the period of pulsation,  $M_{\text{ref}}$  is the absolute magnitude at a reference period and metallicity, and  $\alpha$ ,  $\beta$  describe the dependence of the absolute magnitude on period and metallicity. The  $\epsilon$  is a standard normal random variable centered on 0 and with a standard deviation of the uncertainty in  $M_\lambda$  in order to model the intrinsic scatter in the absolute magnitude convolved with unaccounted measurement uncertainties.

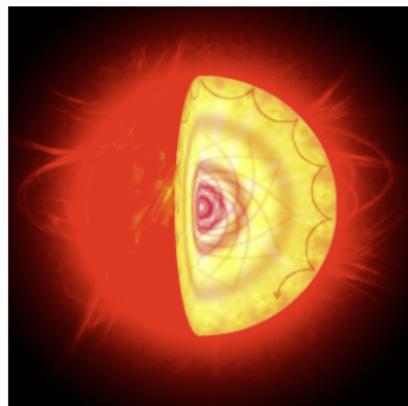
# Further Pulsation Analysis

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

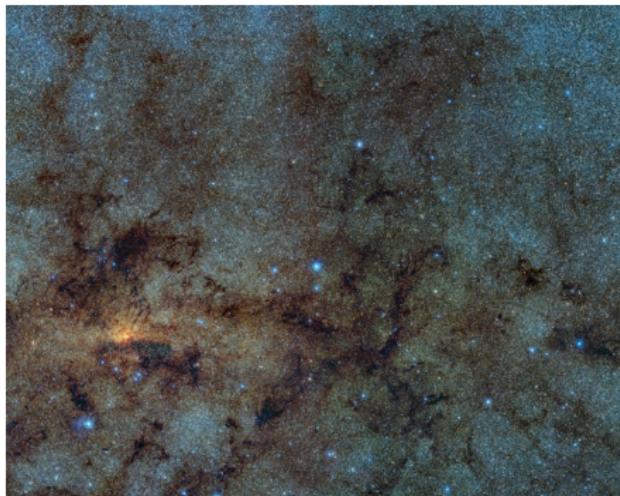
**Asteroseismology.**

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) reveals 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.

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