Pulsating variable stars and the Hertzsprung-Russell diagram

Studying intrinsically pulsating variable stars plays a very important role in stellar evolution understanding. The Hertzsprung-Russell diagram is a powerful tool to track which stage of stellar life is represented by a particular type of variable stars. Let's see what major pulsating variable star types are and learn about their place on the H-R diagram. This approach is very useful, as it also allows to make a decision about a variability type of a star for which the properties are known partially.

The Hertzsprung-Russell diagram shows a group of stars in different stages of their evolution. It is a plot showing a relationship between luminosity (or absolute magnitude) and stars' surface temperature (or spectral type). The bottom scale is ranging from high-temperature blue-white stars (left side of the diagram) to low-temperature red stars (right side). The position of a star on the diagram provides information about its present stage and its mass. Stars that burn hydrogen into helium lie on the diagonal branch, the so-called main sequence.

In this article intrinsically pulsating variables are covered, showing their place on the H-R diagram.

Pulsating variable stars form a broad and diverse class of objects showing the changes in brightness over a wide range of periods and magnitudes. Pulsations are generally split into two types: radial and non-radial. Radial pulsations mean the entire star expands and shrinks as a whole, while non-radial ones correspond to expanding of one part of a star and shrinking the other. Since the H-R diagram represents the color-luminosity relation, it is fairly easy to identify not only the effective temperature and absolute magnitude of stars, but the evolutionary component of their development stage as well.

According to the concept, stars plotted in the upper left corner of the chart will be the brightest ones with the highest surface temperature, therefore, according to the evolutionary status, they must be very young. Top right part contains cool and bright supergiants. Bottom part of the H-R diagram represents dwarf stars, which are in a very late evolutionary state: left size for hot dwarfs and the opposite – for cool brown dwarfs.

H-R diagram

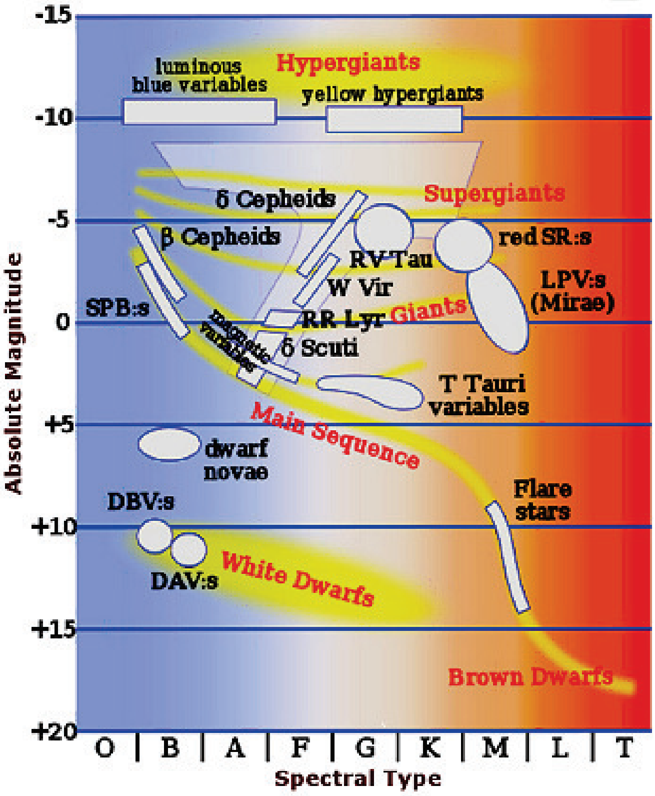
Stars are classified into seven main luminosity classes.

Supergiants (I)

Very massive and luminous stars near the end of their lives. They are subclassified as Ia or Ib, with Ia representing the brightest of these stars. The nearest supergiant star is Canopus (F0Ib), about 310 light years away. Some other examples are Betelgeuse (M2Ib), Antares (M1Ib) and Rigel (B8Ia).

Bright giants (II)

Stars which have a luminosity between the giant and



Intrinsic variable types on the Hertzsprung–Russell diagram. Image credit: Wikipedia

supergiant stars. Some examples are Sargas (F1II) and Alphard (K3II).

Giants (III)

These are mainly low-mass stars at the end of their lives that have swelled to become giant stars. This category also includes some high-mass stars evolving on their way to supergiant status. Some examples are Arcturus (K2III), Hadar (B1III) and Aldebaran (K5III).

Subgiants (IV)

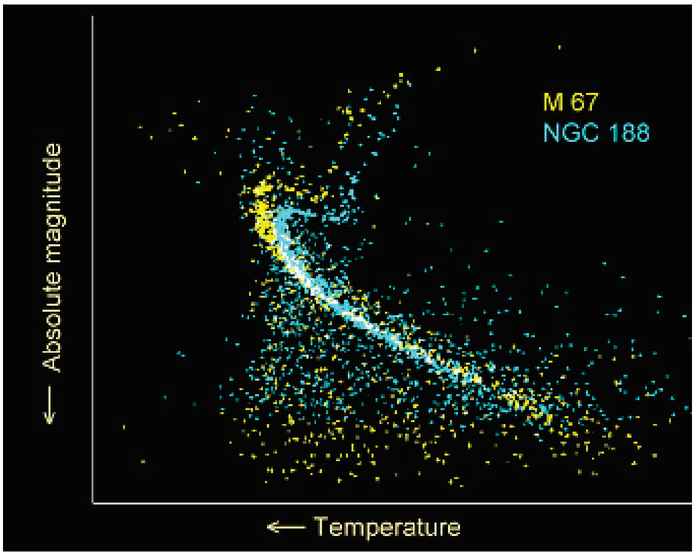
Stars which have begun evolving to giant or supergiant status. A subgiant star is a star that is slightly brighter than a normal main-sequence (dwarf) star of the same spectral class. Some examples are Alnair (B7IV) and Muphrid (G0IV). Note also the Procyon, which is entering this category and therefore is F5IV-V.

Main sequence (V)

All normal hydrogen-burning stars. Stars spend most of their lives in this category before evolving up the scale. Class O and B stars in this category are actually very bright and luminous and generally brighter than most giant stars. Some examples are the Sun (G2V), Sirius (A1V), and Vega (A0V).

Subdwarfs (VI) and White Dwarfs (VII)

The *Yerkes spectral classification* distinguishes two additional classes - for subdwarfs and white dwarfs. On an Hertzsprung–Russell diagram subdwarfs appear to lie below the main sequence. White dwarfs are thought to represent the end point of stellar evolution for main-sequence stars with masses from about 0.07 to 10 solar masses.



H-R diagram for two open clusters (M67 and NGC 188), showing the main sequence turn-off at different ages. Image credit: Wikipedia

The ***Instability Strip*** is a region on the H-R Diagram in which many variable stars can be found. This strip extends through the A, F, and occasionally G classes above and below the main sequence. In this strip, stars have a tendency to be unstable and pulsate, thus causing them to have some variability.

Below is a brief overview of the most commonly encountered pulsating variables types, with their typical properties and representatives.

α **Cygni (ACYG)**

Alpha Cygni variables are a type of rare blue supergiant pulsating variable stars that undergo non-radial pulsations, typically with a period of 5 to 10 days. The spectral types are Bep to Aep Ia, and the optical amplitude is of the order of 0.1 mag. They are often referred to as luminous blue variables (LBV) and occupy the top left part of the H-R diagram. Variable stars of this type are sometimes called S Doradus variables, and there are reasons to assume these variables represent the next stage of evolution of S Dor stars.

The light variations often appear irregular, being caused by the superposition of multiple pulsation frequencies with close periods. Cycles from several days to several weeks are observed. The prototype of these stars, Deneb (α Cygni), exhibits fluctuations in brightness between magnitudes +1.21 and +1.29.

Typical examples: α Cyg, ρ Leo, β Ori, η Ori, PX Gem, κ Cas, η CMa.

β **Cephei** or β **Canis Majoris (BCEP)**

Beta Cephei are short-period variable stars of O8-B6 I-V spectral types, which exhibit variations in their brightness due to radial pulsations of the stars' surfaces. These variables lie slightly above the upper main sequence and have typical periods between 0.1 and 0.6 days, and their brightness varies from 0.01 to 0.3 mag. They are particularly interesting because the nature and cause of their pulsations are totally unknown. Maximum brightness corresponds to the minimum radius of the star. For several stars there are indications of non-radial pulsations though, like for β Cen, 53 Per/V469 Per.

Typical examples: β Cep, β Cen, β CMa, δ Cet, α Lup, KP Per, η Hya, ε Per.

δ **Scuti (DSCT)**

Delta Scuti variables are a well-known type of pulsating variable belonging to the main sequence. This type of stars is notable for a very short period, lasts for hours. Typically, periods are in the range of 0.02-0.4 days. Brightness varies between 0.02m and 0.8m.

These variables are important standard candles and have been used to establish the distance to numerous globular and open clusters, as they follow a period-luminosity relation in certain passbands. Spectral class can be A2 to F5 III-V. The recently discovered rapidly oscillating main-sequence Ap stars are also a subclass of Delta Scuti variables. Both radial and non-radial pulsations are observed for Delta Scuti stars.

Typical examples: δ Sct, DQ Cep, GG Vir, δ Del, OX Aur, DY Her, YZ Boo, V703 Sco

δ **Cephei (DCEP)**

Classical Cepheids (or Delta Cephei variables) are population I yellow supergiants which undergo pulsations with very regular periods on the order of days to months.

Radially pulsating, Cepheid variables change their brightness with periods from 1 to 135 days, with amplitudes of 0.1 to 2.0 magnitudes in V. These massive stars have high luminosity and are of F spectral class at maximum, and G to K at minimum. The later the spectral class of a Cepheid, the longer it takes to complete a cycle. This mainly depends on the metallicity of the star, which divides them into Population I and Population II. Population I stars are generally found closer to the galactic plane, often in open clusters. They have relatively high concentrations of metals, compared to Population II stars (W Virginis), which are found around the galactic halo and in globular clusters.

Classical Cepheids are relatively young stars, and lie at the intersection of the instability strip with the supergiant branch in metal-rich stars. They are also famous due to a period-luminosity relationship (δ Cep, η Aql, l Car).

There is also a DCEPS subtype, characterized by amplitudes less than 0.5m in V and almost symmetrical light curves (rise duration is 40-50%). Periods usually do not exceed 7 days, except for a couple of objects with periods of 8 to 13 days. Presumably, this type of stars pulsate in the first overtone and crossing the instability strip on the H-R diagram for the first time (e.g. *SU Cas*) .

Typical examples: δ Cep, RT Aur, X Cyg, η Aql, U Aql, W Gem, T Mon, Z Lac, S Sge, T Vul.

W Virginis (CW)

Oppositely to the Classical cepheids, W Virginis stars lie at the intersection of the strip with the supergiant branch in metal-poor stars. These are pulsating variables of the galactic spherical component population with periods of approximately 0.8 to 35 days and amplitudes from 0.3 to 1.2 mag in V. Type II Cepheids are population II stars and thus are old - typically metal-poor, low-mass objects. They were historically called W Virginis variables.

W Vir variables are present in globular clusters and at high galactic latitudes. They may be separated into the following subtypes:

- **CWA** - periods longer than 8 days (W Vir, RU Cam);
- **CWB** - periods shorter than 8 days (BL Her, AU Peg, VY Pyx).

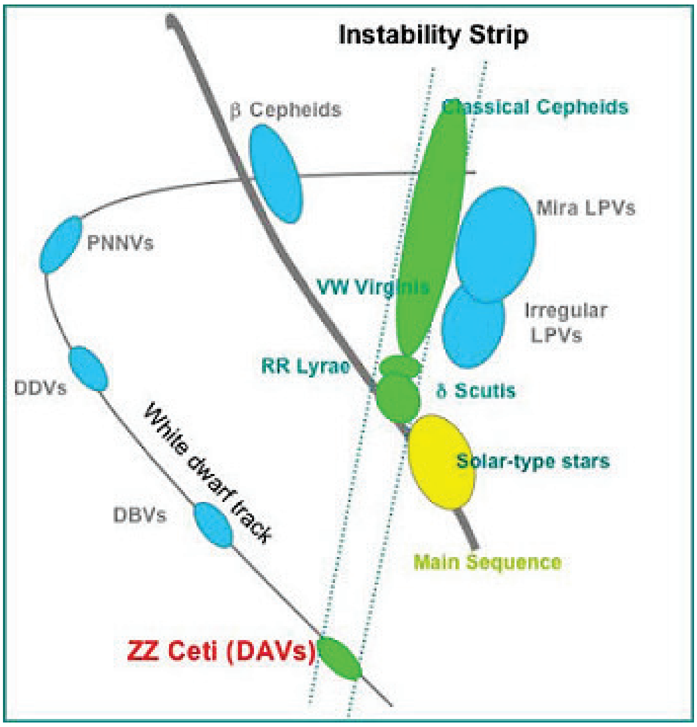
Some DCEP and CW stars are quite often called Cepheids because it is often impossible to discriminate between them on the basis of the light curves for periods in the range 3 - 10 days. Having the same period, CWs are 0.7-2.0m dimmer, comparing to DCEP. A common case is humps on the descending branch, sometimes growing into a flat maximum.

Typical examples: W Vir, RU Cam, κ Pav, BL Her, VY Pyx, TX Del, V0553 Cen, UY CMa.

RR Lyrae (RR)

RR Lyrae variables are old, low-mass, radially pulsating stars with periods in the range between 0.2 and 1 day, which are located where the instability strip intersects the horizontal branch in globular clusters. These are giants of A to F spectral types, and are sometimes referred to as *dwarf Cepheids*. Despite their high abundance in globular clusters, there are many RR Lyrae stars discovered in the galactic plane as well. Initially, they were classified (Bailey, 1902) into three classes - RRa, RRb and RRc – based upon the amplitude and skewness of the light curves. Later, RRa and RRb were merged into a single type – RRab.

RRab stars change their brightness between 0.1m and 0.3m in V-band with periods 0.35 to 1.0 days (e.g. RR Lyr). Variables of the RRc class have amplitudes of about 0.5m, but shorter periods (5-10 hours) and higher light curve symmetry (typically, the rise duration is 40-50%, e.g SX UMa).

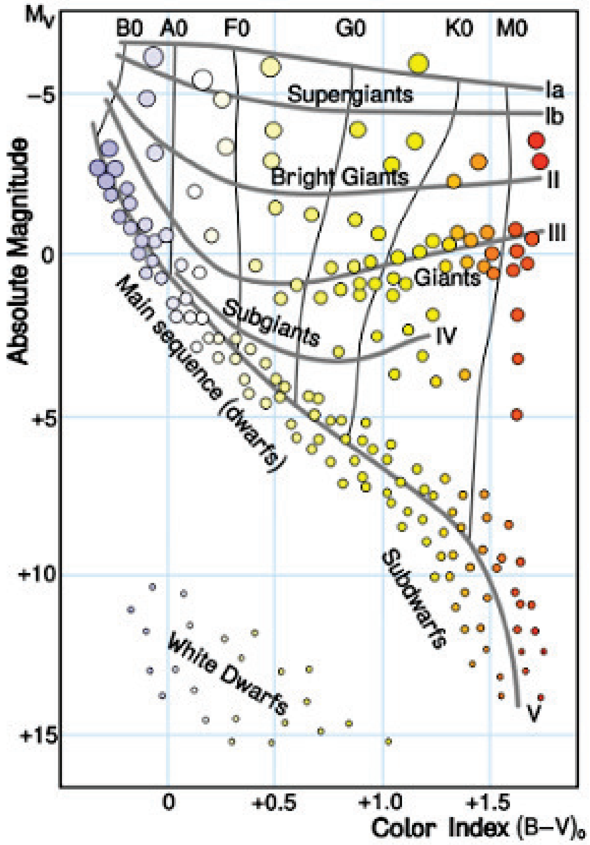


The Instability strip in relation to various types of stars. Cepheids, RR Lyrae, W Virginis, and ZZ Ceti stars can all be found in this region, as well as other, less common variable stars. Image is used for education purpose only. Credit: http://astronomy.swin.edu.au (Swinburne University of Technology)

From the point of stellar evolution, RR Lyrae variables are instability strip pulsators. Their place on the H-R diagram can be easily found as an intersection between the horizontal branch and the instability strip. It appears that RRab stars pulsate in the fundamental frequency of radial pulsations, while RRc variables pulsate in the first overtone. In addition, these types of stars are different from others due to the presence of Blazhko effect.

There is also the RRd subclass for RR variables, characterized by the presence of two simultaneously operating pulsation modes - the primary P0 and the first overtone period P1. Typically, the ratio R1/R0 ≈ 0.745 (e.g. AQ Leo, Z Gru).

Typical examples: RR Lyr, V0764 Mon, SW And, RS Boo, RZ Cep, X Ari, U Lep.



The Hertzsprung–Russell diagram relates stellar classification with absolute magnitude, luminosity, and surface temperature. Image credit: Wikipedia

PV Telescopii (PVTEL)

This class of variables is defined in GCVS as "helium supergiant Bp stars with weak hydrogen lines and enhanced lines of He and C". That is, the hydrogen spectral lines of these stars are weaker than normal for a star of stellar class B, while the lines of helium and carbon are stronger. The PV Tel stars are extremely hydrogen-deficient compared to other B-class stars and vary in luminosity on time scales ranging from a few hours to several years.

Typical examples: PV Tel, FQ Aqr, V1920 Cyg, DN Leo, V2076 Oph.

RV Tauri (RV)

Variables of the RV Tauri type are radially pulsating supergiants having spectral types F-G at maximum light and K-M at minimum. The light curves are characterized by the presence of double waves with alternating deep and shallow minima that can vary in depth. The primary minimum may become secondary and vice versa. The complete light amplitude may reach 3-4 mag in V. Periods between two adjacent primary minima (usually called formal periods) lie in the range 30-150 days.

On the H-R diagram, RV Tau variables ranks between Cepheids, Miras and red semi-regular variables. Since the transition from the AGB to the white dwarf stage of stellar evolution is not fully understood, RV Tau stars are considered as a potential bridge across this evolutionary gap. This post-AGB phase of stellar evolution lasts only a few thousand years. Two subtypes, RVA and RVB, are recognized:

- **RVA -** RV Tauri variables that do not vary in mean magnitude (AC Her);
- **RVB -** RV Tauri variables that periodically (with periods from 600 to 1500 days and amplitudes up to 2 mag in V) vary in mean magnitude (DF Cyg, RV Tau).

Typical examples: R Sct, U Mon, AC Her, V Vul, R Sge, TX Oph, RV Tau, UZ Oph, TW Cam.

Long-Periodic Variables (LPV)

Variability, caused by pulsations, appears to be a fundamental characteristic of cool giant luminous stars. LPVs form a very diverse group of stars. Typical periods are months-long, or even a couple of years. Long-period variables may have spectral class F and cooler, but most are red giants and AGB-giants, meaning spectral class M, S or C. They are usually deep orange or red.

The GCVS distinguishes four classes of red semi-regular variables: SRa, SRb, SRc and SRd. The major difference between the SRa class and the Miras is that an SRa may have a visual light amplitude less than 2.5 magnitudes.

Miras are long-period variable stars belonging to the class of asymptotic giant branch (AGB) stars the (e.g. o Cet, χ Cyg). Their periods are in the range of 80 to 1000 days, and the amplitude of light variations is from 2.5m (by definition) to 11m. Mira variables belong to the late spectral types with emission spectrum - Me, Ce, Se. Their study is very important, as it allows to shed some light on the future fate of Sun-like stars, with masses up to a few solar.

SR is a vast group of pulsating AGB-stars of late spectral types (W Hya, RV Boo). In most cases, periods are from 20 to 2300 days. An *SRs* class has been introduced recently to mark those red giants with periods less than 30 days, like EL Psc. Presumably, these stars pulsate in higher overtones. One of the best known red supergiant is μ Cep.

SRd stars are giants and supergiants of F, G, or K spectral types. Amplitudes of light variation are up to 4 mag, and the range of periods is from 30 to 1100 days (e.g. SX Her).

The rest are irregular red variable stars. Their light variations are unpredictable, so non-stop photometric measurements are highly sought after. LB irregular variables are represented by giants (e.g. CO Cyg), and LC variables are supergiants (e.g. TZ Cas).

Typical examples: α Ori, Z Aqr, R Boo, T Cep, TZ Cas, RR CrB, R Leo, R Sgr, SX Her, SV Uma, AF Cyg, R Lep, R And.

ZZ Ceti (ZZ)

ZZ Ceti are a class of non-radial pulsating white dwarf stars. Falling in the instability strip of the Hertzsprung-Russell diagram, these stars pulsate with periods of minutes (mostly, up to 25 minutes). These stars are difficult to study because of their faintness and small/rapid variability. They are characterized by modest luminosity variations (from 0.001 to 0.2 V magnitudes). Sometimes, up to 1m outbursts are detected, which can be explained by the close presence of an UV Cet component.

ZZ Ceti stars are divided into three subclasses:

- **ZZA** – hydrogen variables of spectral type DA, having only hydrogen absorption lines in the spectrum (ZZ Cet).
- **ZZB** – Helium variables of spectral type DB, having helium absorption lines in the spectrum (e.g. V1063 Tau).
- **ZZO** – variables of DO spectral type showing HeII and CIV absorption lines in their spectra.

On the H-R diagram, ZZ stars occupy the lower left part, and lie in a band roughly parallel to the main sequence, but several magnitudes below it.

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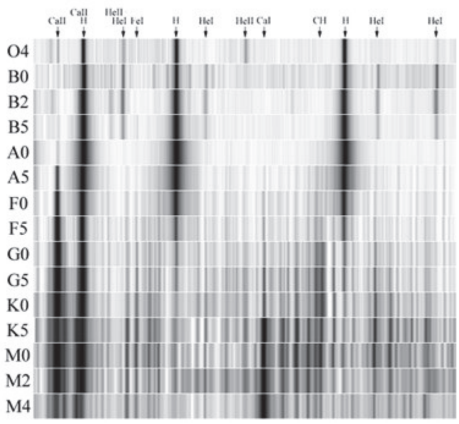
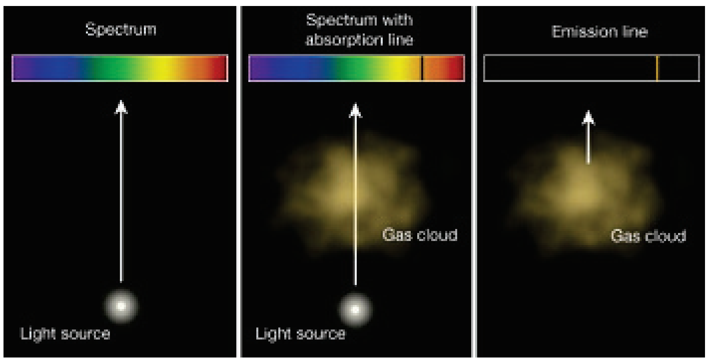
Stellar spectral classification: a brief story of early steps

While *Isaac Newton* (1643 – 1727) observed the continuous spectrum of the Sun, he missed the discovery of absorption lines. In 1802, *William Hyde Wollaston* (1766-1828) reported dark gaps between colors in the continuous spectrum. Later, *Joseph von Fraunhofer* (1787-1826) observed the Solar spectra more detailed and found that the dark gaps are different in strength. German physicist *Gustav Kirchhoff* (1824-1887) published his fundamental work in 1859, which explained the nature of the Fraunhofer lines in the solar spectrum and the composition of its atmosphere. In the 1860's, *William Huggins* (1824-1910) and his wife Margaret used spectroscopy to determine that the stars are composed of the same elements as found on Earth. Another classification scheme was proposed by Father *Angelo Secchi* (1818-1878) from Italy in 1863, who visually observed prismatic spectra of about 4000 stars and divided them into groups. By 1868, his classification defined four classes of stars. Group I was reserved for “blue-white stars showing hydrogen lines”, Group II represented stars with numerous metallic lines and yellow or orange stars like Capella or the Sun; Group III was added for orange to red stars. Group IV comprised of carbon stars. In 1877, Secchi added a fifth class for emission-line stars.



Stellar spectra sequence, O to M.

In the early XX century, astronomers began photographing the spectra of stars, but the diversity of spectral features was too confusing and complex to explain. *Edward Pickering* (1846-1919) re-arranged the spectral sequence, taking into consideration the changes in other lines. Building upon this idea, a team of astronomers at the Harvard Observatory, led by *Annie Cannon* (1863-1941), grouped similar appearing spectra together, designated by letters: A, B, C, etc. They also started a project on spectra classification. Soon, a smooth sequence of spectral types was found, and the assigned letters combined into O-B-A-F-G-K-M. For better distinction, the classes were further divided into subclasses, marked from 0 to 9 within the class. The results of that work, the Henry Draper Catalog, was published between 1918 and 1924.



An example of Kirchhoff’s three laws of spectroscopy. Image credit: The Pennsylvania State University

The early Harvard spectral classification system was based on the appearance of the spectra, but the physical reason for these differences in spectra were not understood until the 1930’s and 1940’s. Then it was realized that the main thing that determined the spectral type of a star was its surface temperature. *Cecilia Payne* (1900-1979) took the data from the HD catalog and discovered its physical significance: the great variation in stellar absorption lines was due to different amounts of ionization (differing temperatures), not different abundances of elements.

The spectral classification system used today is a refinement called the MK system, introduced in the 1940’s and 1950’s by Morgan and Keenan at Yerkes Observatory. A new feature was added to the classification – stellar luminosity classes (I to V), showing that stars with the same temperature can have different sizes.