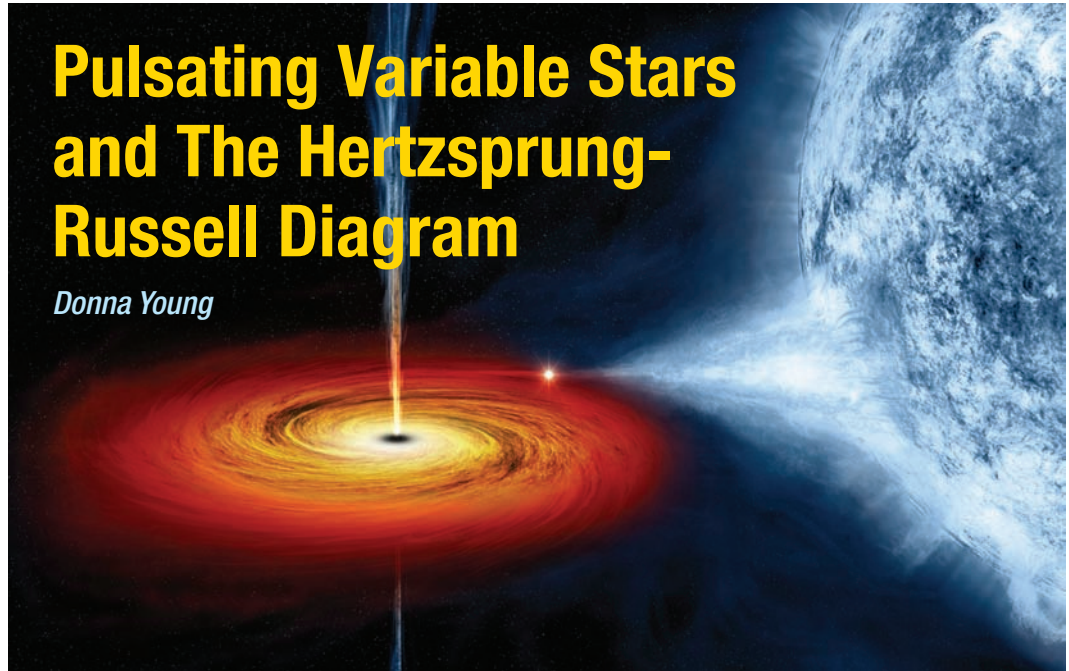# Pulsating Variable Stars and The Hertzsprung-Russell Diagram

Donna Young

Cygnus X-1 is a 15 solar mass black hole in orbit with a massive main sequence blue companion star approximately 6070 light years from Earth. Cygnus X-1 is a stellar-mass black hole - the result of the core collapse of a massive star.

Credit: Artist Illustration: NASA/CXC/M. Weiss

Abstract

Ejnar Hertzsprung, working with Henry Norris Russell between 1911 and 1913, developed the Hertzsprung - Russell diagram (H-R diagram) – an important astronomical tool that represents a major step towards understanding how stars evolve over time. Stellar evolution can not be studied by observing individual stars as most changes occur over millions and billions of years. Astrophysicists observe numerous stars at various stages in their evolutionary history to determine their changing properties and probable evolutionary tracks across the H-R diagram. The H-R diagram is a scatter graph of stars – a plot of stellar absolute magnitude or luminosity versus temperature or stellar classification. Stages of stellar evolution occupy specific regions on the H-R diagram and exhibit similar properties. One class of stars – the pulsating variables which include Cepheids, RR Lyraes, Semiregulars and Miras – occupy regions of instability on the H-R diagram and represent transitional periods between stages of evolution.

Figure 1. Supernova in star forming region in the Small Magellanic Cloud Galaxy

Image courtesy of Chandra

The American Association of Variable Star Observers (AAVSO) and the Chandra X-Ray mission have collaborated with variable star observations and educational materials in their mutual quest to understand stellar processes and evolution. The H-R Diagram student activity is an example of how evidence is used to construct a model to explain complex concepts – in this case the evolution of stars which is fundamental to understanding the origin and evolution of the universe.

The Hertzsprung-Russell (H-R) Diagram

The Hertzsprung-Russell (H-R) diagram is an analog to the periodic table of the elements. It was discovered that when the absolute magnitude (M_V) – intrinsic brightness – of stars is plotted against their temperature (stellar classification) the stars are not randomly distributed on the graph but are mostly restricted to a few well-defined regions. The stars within the same regions share a common set of characteristics, just like the groups, periods, and blocks of elements in the periodic table. Unlike the periodic table, as the physical characteristics of a star change over its evolutionary history, its position on the H-R diagram changes also – so the H-R diagram can also be thought of as a graphical plot of stellar evolution. From the location of a star on the diagram, its luminosity, spectral type, color, temperature, mass, chemical composition, age, and evolutionary history are known.

Figure 2. Basic Hertzsprung-Russell diagram

Diagram courtesy of NASA

Most stars are classified by temperature (spectral type) from hottest to coolest as follows: O B A F G K M. These categories are further subdivided into subclasses from hottest (0) to coolest (9). The hottest B stars are B0 and the coolest are B9, followed by spectral type A0. Each major spectral classification is characterized by its own unique spectra. Though O B A F G K and M are the stellar classifications commonly shown on H-R diagrams, a number of new and extended spectral classes have been designated. These include Wolf-Rayet stars (W), cool dwarfs (L), brown dwarfs (T), carbon stars (C), and stars with zirconium oxide lines that are between M and C stars (S). The carbon stars (C) include stars that were originally classified as R and N stars. Class D (degenerate) is the modern classification for white dwarfs. The major classifications have subclasses – Class D is divided into 7 different subtypes of white dwarfs based upon variations in the composition of their atmospheres, e.g. DQ white dwarfs have a carbon-rich atmosphere.

Spectral lines can show different characteristics within the same spectral type or temperature (T), and so a second type of classification system for stars was devised using luminosity. The differences in spectral lines among stars having the same spectral type are a function of the radius of the star, which results in different
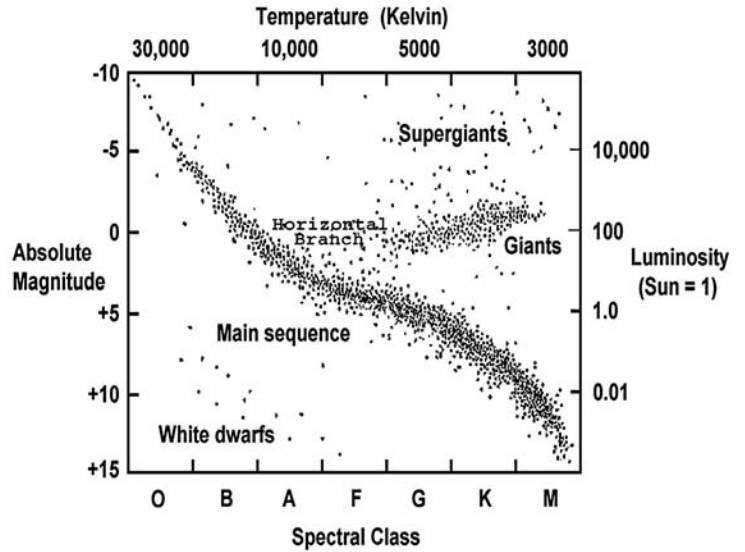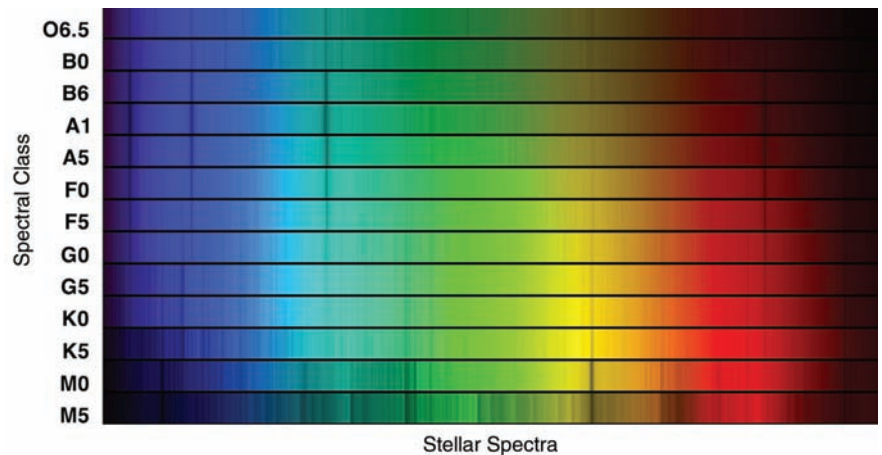

Figure 3 (above). Some examples of Harvard classification stellar spectra
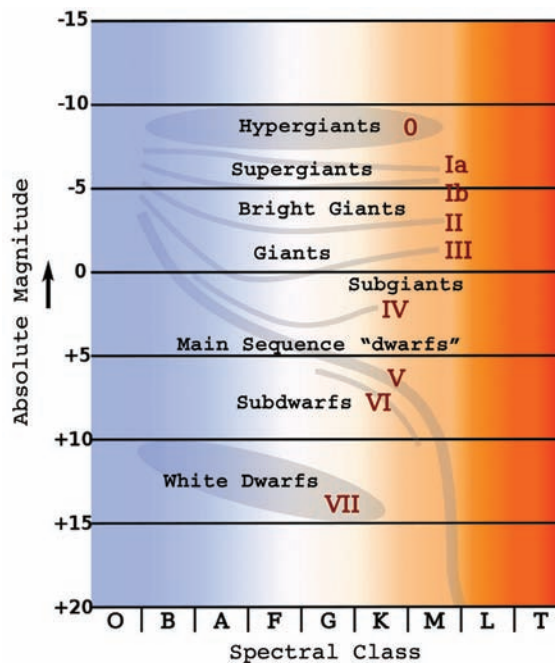
Image courtesy of NASA

Figure 4 (left). The luminosity classifications on the H-R diagram

Diagram courtesy of Wikimedia Commons

luminosities. Luminosity (L) is related to the absolute magnitude (M_V) of a star, and is the total amount of energy radiated per second (luminosity is proportional to T^4). Two stars with similar effective temperatures but greatly different luminosities must differ in size. They belong to different luminosity classes within that spectral type,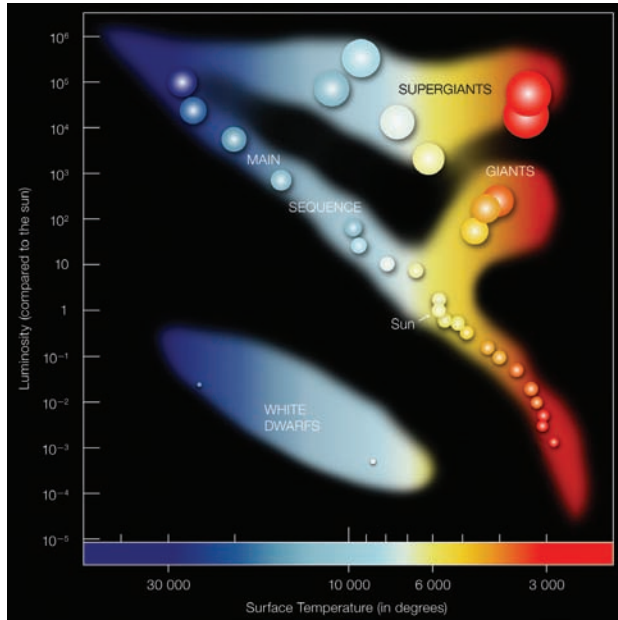 as determined from their spectra. Stellar luminosities range from one million times more luminous than the Sun, to one ten-thousandth of the luminosity of the Sun. The basic luminosity categories from most to least luminous are I and II, supergiants and bright giants respectively, III giants, IV subgiants, V main sequence stars, VI subdwarfs and VII white dwarfs.
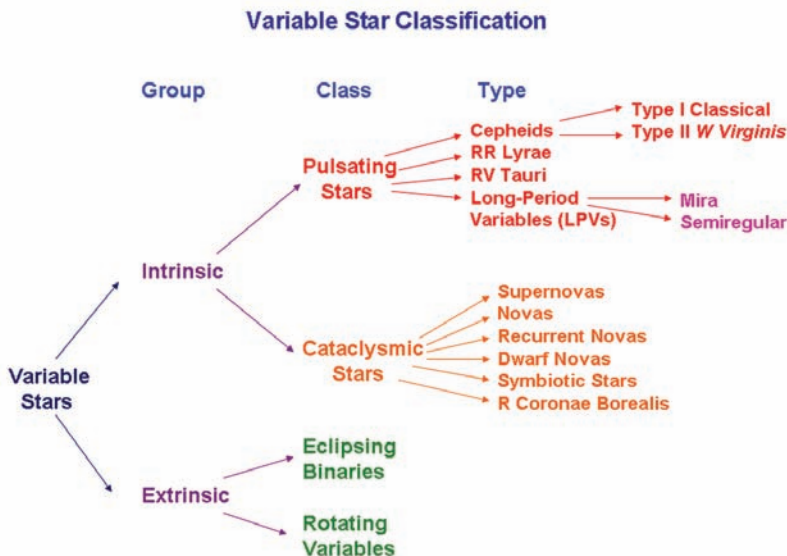
Starting at the upper left-hand corner and curving down to the lower right-hand corner is a band called the main sequence. ~90% of all stars lie within the main sequence. These stars run from the hot and bright O and B stars at the top left-hand corner to the cool, dim K and M stars at the lower right-hand corner. Main sequence stars have a fairly steady rate of hydrogen fusion ongoing in their cores. In main sequence stars, the radiation pressure pushing outward from the fusion process balanced by the inward pull of gravitational forces maintains a state of dynamic equilibrium. When hydrogen in the core is depleted and radiation pressure decreases, the two forces become unbalanced and the star "moves off the main sequence" and begins a series of evolutionary stages – the final end product(s) depending upon the initial mass of the star. The giant and supergiant branches of the H-R diagram are occupied by stars that have transitioned from the main sequence and are fusing heavier atomic nuclei. As most stars transition from the main sequence to the giant and supergiant branches, they exhibit types of variability that are also confined to specific locations on the diagram.

Figure 5. H-R diagram of luminosity vs temperature

Image Courtesy of the European Southern Observatory

Pulsating Variable Stars and Light Curves

As many stars transition from one stage to another on the H-R diagram they vary in brightness. The brightness that a star appears to have (apparent magnitude) from our perspective here on Earth depends upon its distance from Earth and its actual intrinsic brightness, or absolute magnitude (M_V). The behavior of stars that vary in magnitude (brightness) can be studied by measuring their changes in brightness over time and plotting the changes on a graph called a light curve. Light curves are usually plots of apparent magnitude over time. Historically the time scale has been the Julian Day (JD), a counting system starting with January 1, 4713 BC – Julian Day number 1. Measuring and recording the changes in magnitude and plotting the resulting light curves allow astronomers to determine the period of variation. The period is the amount of time it takes for the star to go through one complete cycle from maximum magnitude through minimum magnitude and back to maximum magnitude. The 2011 General Catalog of Variable Stars (GCVS) classifies 43,675 Milky Way Galaxy stars into several different categories and subcategories of variability.

The intrinsic, pulsating variable stars located in the instability regions of the H-R diagram vary in

Figure 6. A variable star classification system

Diagram (revised) courtesy of the Australian Telescope E/PO

brightness due to physical changes within the interior of the star. The pulsations are due to the periodic expansion and contraction of the surface layers of the stars. The change in size is observed as a change in apparent magnitude. Stars pulsate because they are not in hydrostatic equilibrium: the force of gravity acting on the outer mass of the star is not balanced by the interior radiation pressure directed outwards from the interior. If a star expands as a result of increased radiation pressure, the material density and pressure decrease until hydrostatic equilibrium is reached and then overshot, owing to the momentum of the expansion. At this point the star is transparent and photons can escape. Then gravity dominates, and the star begins to contract. The momentum of the infalling material carries the contraction beyond the equilibrium point. The star becomes opaque and photons are trapped and the star becomes dimmer. The pressure again becomes too high, and the cycle starts over again.

The system acts as an oscillator. With loose atmospheric layers of gases, the oscillations get out of phase with one another and set the stage for chaotic motions. Energy is dissipated during such pulsations (analogous to losses caused by frictional forces), and eventually this loss of energy should result in a damping or lessening of the pulsations. The prevalence and regularity of pulsating stars imply that the dissipated energy is replenished in some way. The dynamics of pulsating variable stars is complicated and not well understood.

The different types of pulsating variables are distinguished by their periods of pulsation and the shapes of their light curves. These in turn are a function of their mass and evolutionary stage.

Cepheids, RR Lyraes, and Long Period Variables (LPVs) – Miras and Semiregulars – are pulsating variable stars and occupy regions on the H-R diagram called instability strips.

Cepheid variable stars expand and contract in a repeating cycle of size changes. The change in size can be observed as a change in apparent brightness (apparent magnitude.) Cepheids have a repeating cycle of change that is periodic - as regular as the beating of a heart, with a period of 1 to 70 days with an amplitude variation of 0.1 to 2.0 magnitudes. These massive stars (~8 solar masses) have a high luminosity and are spectral class F at maximum, and G to K at minimum. Cepheids occupy an elongated horizontal instability strip on the H-R diagram as massive stars transition from the main sequence to the giant and supergiant branches.

RR Lyrae variables are older pulsating white giants with low metallicity. They are common in globular clusters – dense groups of old stars in the halos of galaxies.
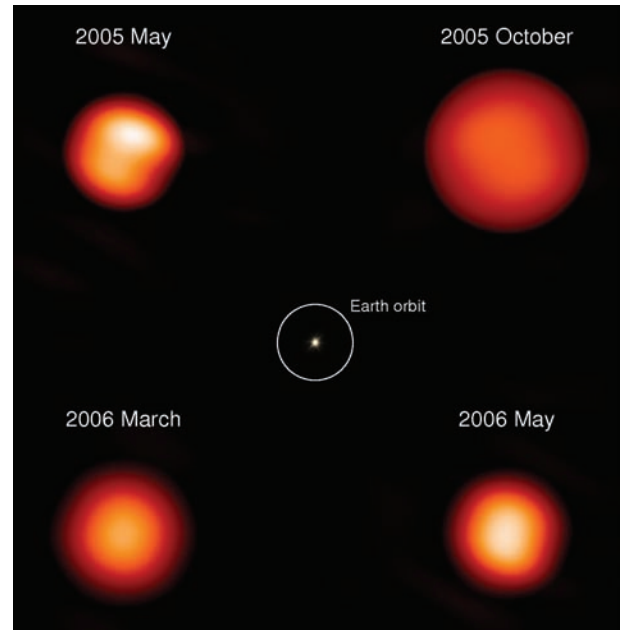

Figure 7. Pulsating mira variable star *(Chi Cyg)*
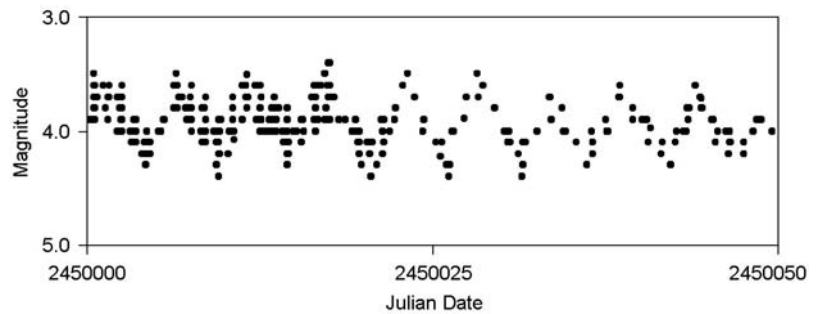Image courtesy of SAO/NASA

Figure 8. Cepheid variable star light curve *(Delta Cep)*
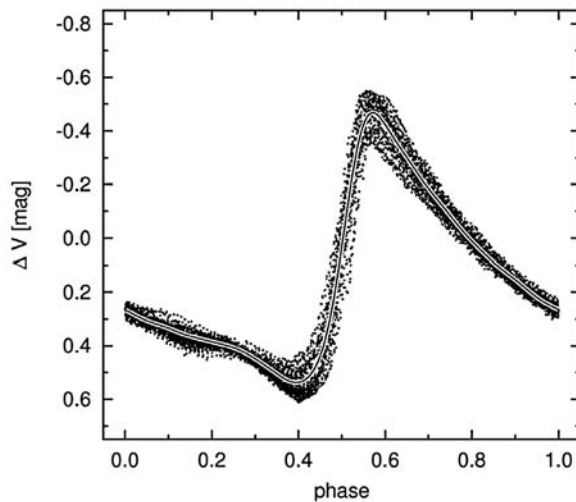Image courtesy of AAVSO, Cambridge, MA

Figure 9. RR Lyrae variable star light curve
Image courtesy of AAVSO, Cambridge, MA

Like Cepheids, their pulsations are periodic. RR Lyraes have ˜0.5 solar mass and have a short pulsation period of 0.05 to 1.2 days and amplitude variations of 0.3 to 2 magnitudes. RR Lyrae stars are usually spectral class A. RR Lyrae stars occupy a small instability strip near the intersection of the main sequence and the horizontal giant branch (HB). The HB stars have left the red giant branch and are characterized by helium fusion in their cores surrounded by a shell of hydrogen fusion.

Cepheids and RR Lyrae variables are periodic and there is a relationship between their period and luminosity – the period-luminosity relationship. The period is calculated from the light curve and the associated luminosity is determined. The luminosity is then either used directly or converted to absolute magnitude and used with the apparent magnitude in the distance modulus equation to calculate cosmological distances within the Milky Way Galaxy and to other galaxies.

Figure 10 (left). Mira variable star light curve *(Omicron Ceti)*
Image courtesy of AAVSO, Cambridge, MA

Figure 11 (right). Semiregular variable star light curve *(Z Uusae Majoris)*
Image courtesy of AAVSO, Cambridge, MA
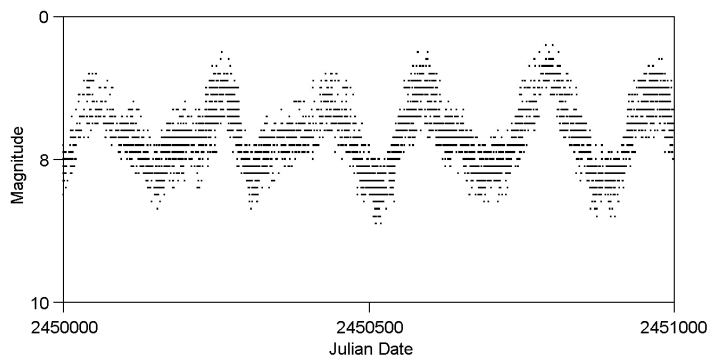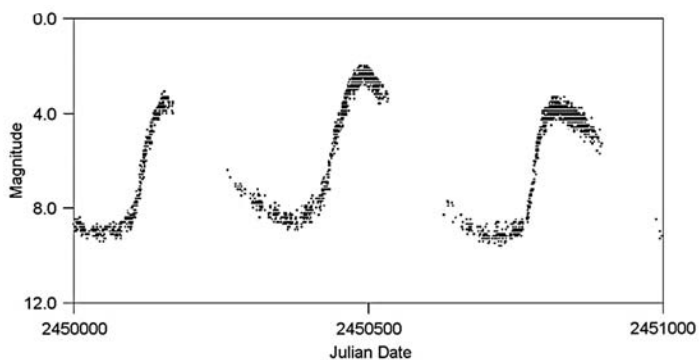
Long Period Variables (LPVs) are pulsating red giants or supergiants with periods ranging from 30-1000 days. They are usually of spectral type M, R, C or N. There are two subclasses; Mira and Semiregular.

Mira variables are periodic pulsating red giants with a periods of 80 to 1000 days. It is a stage that most mid-sized main sequence stars transition through as they evolve to the red giant branch. Miras have amplitude variations of more than 2.5 magnitudes. Mira *(Omicron Ceti)* is the prototype of Mira variable stars. The Sun will eventually become a pulsating Mira star. The Mira instability strip on the H-R diagram is the region between mid-sized stars on the main sequence and the giant branch.

Figure 12. H-R diagram with instability strips labeled
Diagram courtesy of Wikimedia Commons
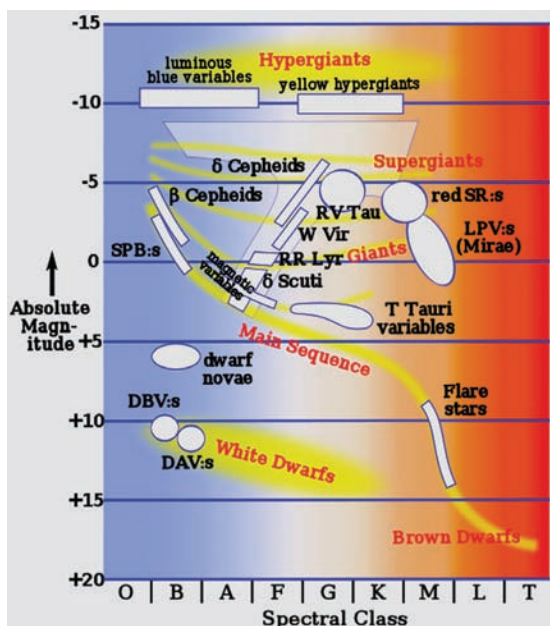
Semiregular variables are giants and supergiants showing periodicity accompanied by intervals of semiregular or irregular light variation. Their periods range from 30 to 1000 days, generally with amplitude variations of less than 2.5 magnitudes. Antares *(α Scorpius)* and Betelgeuse *(α Orionis)* are two prominent examples of LPV semiregular variable stars. These stars occupy a region of instability on the H-R diagram similar to the Mira variables.

Plotting Cepheids, RR Lyrae, Mira and Semiregular pulsating variable stars on the H-R diagram is not a single plot like non-pulsating stars. During their evolution through the instability strips they are pulsationally unstable – expanding and brightening, then contracting and become dimmer. The instability strips for Miras and Cepheids are especially elongated because of these expansions and contractions. Some pulsating variable stars change in temperature by two spectral classes during one cycle from maximum to minimum. To show the entire cycle of change for individual variable stars, it is necessary to plot them twice on the H-R diagram – both at maximum absolute

magnitude ($M_{V_{max}}$) and minimum absolute magnitude (Mv_{min}) – along with the corresponding spectral classes.

Variable Stars & the H-R Diagram Classroom Activities, Materials and Resources

In 1996 a set of curricular materials was written for the American Association of Variable Star Observers (AAVSO) in Cambridge, Massachusetts titled *Hands-On Astrophysics – Variable Stars in Math, Science and Computer Class*. The materials have been converted, with the support of both AAVSO and the Chandra E/PO office, to an electronic PDF version and renamed *Variable Star Astronomy* (VSA). The materials are located at http://www.aavso.org/education/vsa/. The AAVSO *Variable Star Astronomy* (VSA) educational project was funded by the National Science Foundation. The content, activities, investigations and software, based on the AAVSO's unique electronic database of more than 21,000,000 variable star observations, provides

Figure 13. The *Stellar Evolution: A Journey with Chandra* Poster

Illustration courtesy of Chandra

students with the necessary information and skills to study and research variable star behavior. The *VSA* materials are posted on the AAVSO website, and three of the activities and investigations, enhanced with extensions and flash versions, have also been posted on the Chandra website at http://chandra.harvard.edu/edu/formal/index.html. Chandra is designed to observe X-rays from high-energy regions of the universe – including cataclysmic variables (supernovas, novas), and X-ray binary systems such as the pulsating red giant Mira A and its white dwarf companion Mira B.

Plotting Variable Stars on the H-R Diagram

Students plot pulsating variable stars on an H-R diagram. The diagram has several bright and nearby stars plotted to show the locations of the main sequence, giant, supergiant and dwarf branches. Students plot both maxima and minima with corresponding stellar classifications for several variables, then identify the type of variability – Cepheid, RR Lyrae, Mira or Semiregular. The investigation includes extensive background information, student worksheets and answer keys in HTML and PDF.

Figure 14. The pulsating variable star Mira the Beautiful *(Omicron Ceti)*

Image courtesy of Chandra

Student Activity

http://chandra.harvard.edu/edu/formal/variable_stars/plot.html

Stellar Heartbeats is an introductory activity designed to familiarize students with the magnitude scale and the Julian Day by estimating the changing magnitude of a variable star using comparison stars, plotting
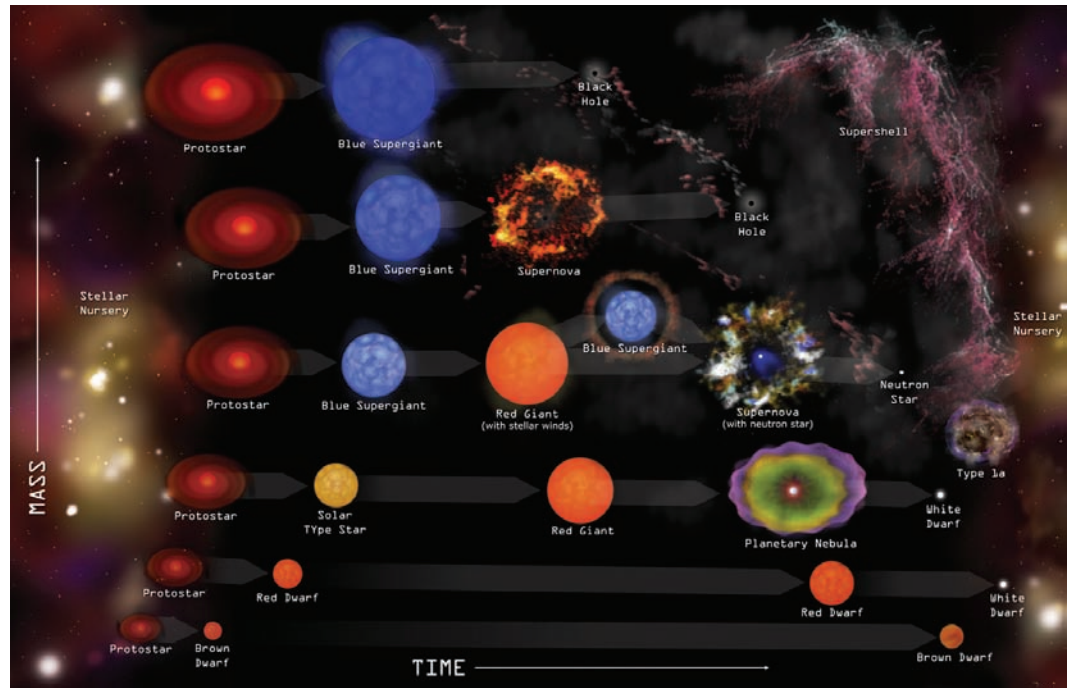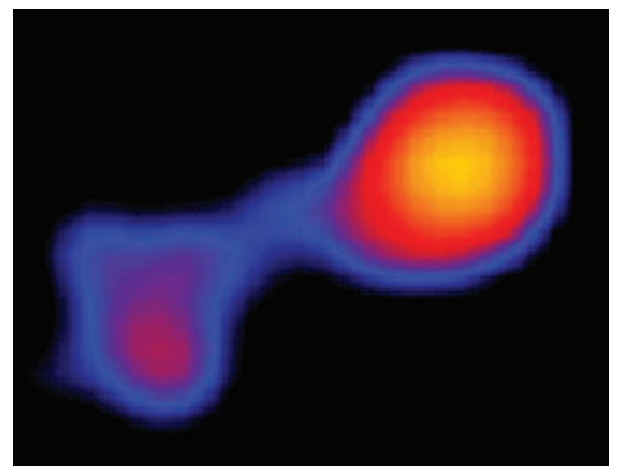
About the Author

Donna Young develops educational materials for the Chandra X-ray mission, and is a staff member at the American Association of Variable Star Observers in Cambridge, MA. She is the National Science Olympiad astronomy event supervisor. She presents Chandra and AAVSO educational materials to formal and informal educators and Science Olympiad coaches and teams at national workshops and conferences. She can be reached at donna@aavso.org.

a light curve and determining the period. There are HTML, Flash, PDF, and PowerPoint versions. http://chandra.harvard.edu/edu/formal/variable_stars/activity1a.html

A Variable Star in Cygnus uses a set of photos of the variable star W Cyg. By using actual images of W Cyg students learn how to estimate the changing magnitudes of a variable star with actual comparison stars against a background of the real sky. Students then plot a light curve and determine the period. There are HTML, Flash, PDF, and PowerPoint versions.http://chandra.harvard.edu/edu/formal/variable_stars/activity2a.html

Stellar Cycles: A pre or post assessment activity complete with a scoring rubric to determine student understanding of stellar evolution. The image set for the activity includes images of the different stages of stellar evolution, light curves and H-R diagrams. (HTML, PDF and PowerPoint (PPT) versions) http://chandra.harvard.edu/edu/formal/stellar_cycle/

NOTE: One, color set of Stellar Life Cycles cards is included with the print version of this journal. Educators can request additional classroom sets with the Card Sets Request Form at http://chandra.harvard.edu/edu/request_special.html

The Chandra Chronicles have two articles describing how the AAVSO amateur observers assisted the Chandra X-Ray Observatory during two observing campaigns of the variable star SS Cygni:

Backyard Astronomers Trigger Multi-satellite Observing Campaign on SS Cygni http://chandra.harvard.edu/chronicle/0101/aavso.html

Astronomers Team Up for Chandra Observations of SS Cygni http://chandra.harvard.edu/chronicle/0300/aavso.html