Variable Star Classification and Light Curves

An AAVSO course for the

Carolyn Hurless Online Institute for Continuing Education in Astronomy (CHOICE)

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Course Description and Requirements for Completion

This course is an overview of the types of variable stars most commonly observed by AAVSO observers. We discuss the physical processes behind what makes each type variable and how this is demonstrated in their light curves. Variable star names and nomenclature are placed in a historical context to aid in understanding today's classification scheme.

This class will last four weeks. There are four chapters, so we will progress rapidly through one chapter per week, more or less. There will be topics for discussion regarding each chapter and a quiz or exercise each week on Friday.

The discussion topics will be fun as well as enlightening. Often there will not be a right or wrong answer. The questions will be designed to make you think and look at variable star classification in a critical or unconventional manner.

You will also be asked to do a paper review of a journal article on some variable star classification or light curve related subject. You will share this with the class as a brief description of the paper and its main points in the discussion forum. Papers can be selected from arXiv or any astronomical journal you can access freely. You may also want to select a paper from the AAVSO in Print section of the AAVSO website, and tell us how AAVSO data was used to further the research presented.

At the end of the course you will either pass or fail. There are no grades. Those that pass will be awarded a certificate of completion and your AAVSO website profile and your membership records in our DB will reflect that you are a graduate of the course.

In order to pass this course you must successfully complete all the quizzes, exercises and participate in the online forum discussions. You cannot pass if you do not participate in the discussions.

One or more of you may also be asked to be the instructor for the next cohort of students taking this course. Those that act as teachers will be given free admission to another CHOICE course of their choosing in the future.

Chapter One - Introduction

What are variable stars?

When we look at the night sky we see stars twinkling overhead, joined in familiar patterns that have remained the same for thousands of years. The Sun, Moon and planets perform their celestial dance across the sky against a fixed background of stars. To the casual observer, these stars seem perfect, steady, peaceful, serene, and unchanging.

Nothing could be further from the truth. The universe we know today is a violent and dangerous place, with dark clouds of dust and gas so cold atoms almost cease to move and explosions so extreme that entire star systems are wiped out in the blink of an eye. Stars fuel most of the restless insanity of our universe.

So, what is a star? Stripped to its simplest components, a star is a giant ball of gas that is performing a delicate balancing act between the force of gravity trying to crush all the mass into a smaller ball in the center of the star and the force of nuclear burning at the core of the star trying to blow it apart. As the star evolves throughout its lifetime, there are sometimes battles fought between these two forces that ebb and flow, swelling and shrinking the star. If one or the other of these forces finally wins the battle, the star loses its life, either being crushed out of existence into a black hole, or exploding into space as a supernova.

These are only a few of the reasons a star may vary or appear to vary from our station on Earth. There are many more, as you are about to learn. Every star has been and will be variable in its light output at one time or another. It is inevitable. If you could just live long enough you'd see every star is a variable star.

Indeed, we can tell a lot about stars by their variability, like how far away, how old, how massive, or how large or small. This is precisely why variable stars are so important to the study of our universe. To understand variable stars is to understand the secret lives of stars.

Stars are the building blocks of the larger structures in our universe. They form pairs and clusters, and aggregate by the billions to form galaxies, which then form even larger groups and structures. They also play an important role on smaller scales, playing host to planets, asteroids and comets. On a molecular scale, stars are the material factories of the universe. They make the stuff our Earth and you and I are composed of. Where ever there is life in the universe you can be sure there will be a star not too far away, supplying the raw materials and energy needed for life to exist.

To know our place in the cosmos you have to understand stars. To know the stars you must understand their variability.

The first known variable stars

Ancient peoples were much more in tune with the night sky than we are today. Probably because, unimpeded by our current day light pollution, they could actually see the stars from their homes at night, and let's face it, they didn't have television or the Internet to distract them!

They used the Sun, Moon and stars to tell time, plant and harvest crops, prepare for winter, celebrate spring, and to predict floods and annual migrations of animals they hunted for survival.

They were well aware of the motion of the planets among the background stars, solar and lunar eclipses, the flashes of meteors and the occasional visit of a bright comet, but to most societies, for thousands of years, the stars were considered to be fixed and unchanging. In fact, it was actually ingrained in some cultures philosophies that the stars were "perfect" and therefore could not change.

Oriental cultures were not so restricted, and records exist today of their observations of supernovae, novae, great comets and eclipses. Among these are some 80 'new stars' before 1600 A.D. Although other cultures my have noted some of them, these are the best surviving records we have of these events. We know these today as supernovae and novae, variable stars in the extreme.

The sixteenth century not only brought enlightenment and a renaissance to the West, but coincidentally, two supernovae in our galaxy within about thirty years. The first erupted in November 1572 and was nearly as bright as the planet Venus! Tycho Brahe not only established its position to a high degree of precision, but he placed it at a distance among the stars. This was indeed a 'new star', not an atmospheric phenomena or a planetary interloper. He also recorded its decreasing brightness in relation to planets and other bright stars to a high degree of precision.

In 1596, David Fabricius discovered omicron Ceti, now known as Mira, and in 1638 Johannes Holwarda determined it was a periodic variable, brightening and dimming in approximately 11 months. Mira was probably the first known case.

Tycho's supernova was followed in 1604 by another 'new star' whose fixed position among the stars was established by Johannes Kepler. Kepler's star was as bright as Jupiter, and also the last supernova to be seen in our galaxy since then. We are long overdue for another spectacular display of a galactic supernova event.

Once Galileo turned his telescope to the heavens the floodgates to astronomical knowledge were swung open, but it still took a hundred years for variable stars to begin to take their place in the studies of astronomers.

William Herschel discovered the variability of alpha Herculis and 44i Bootis in the 1700's. Later that century, two English gentlemen, John Goodricke and Edward Pigott, made a special point of studying variable stars. Pigott discovered eta Aquilae, R Corona Borealis and R Scuti, while Goodricke discovered the variability of delta Cephei and beta Persei (Algol). Together they proposed the theory that Algol's variability might be caused by eclipses of the star by a planetary companion, an astounding insight that was very close to the truth!

By the middle of the nineteenth century there were some 18 known variable stars and another several dozen suspected variables. The organized study and recording of observations led to the establishment of the Variable Star Section of the British Astronomical Association (BAAVSS) in 1890, followed soon after by the establishment of variable star studies at Harvard College Observatory which eventually led to the founding of the American Association of Variable Star Observers (AAVSO) in 1911.

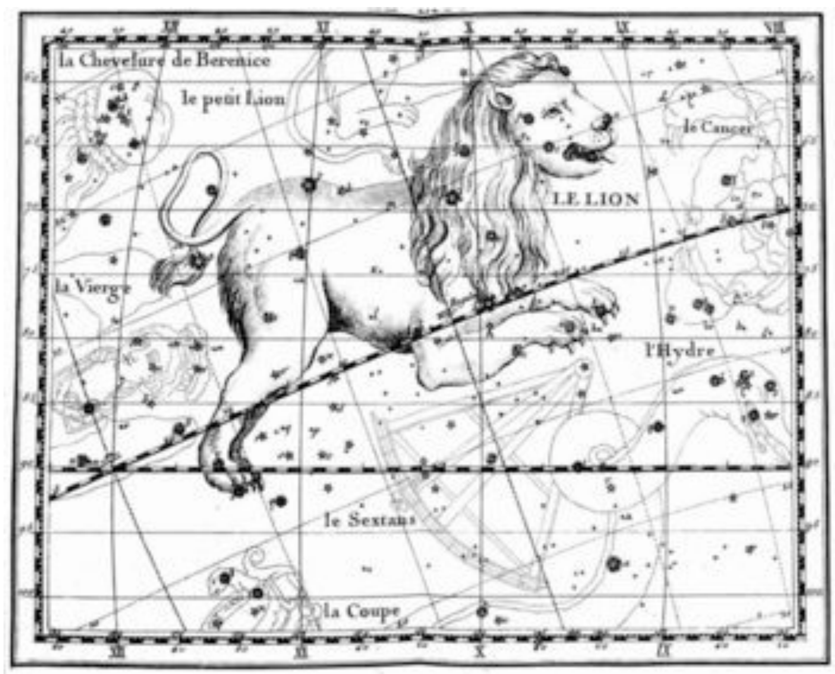
There are now hundreds of thousands of known variable stars, and more are being discovered all the time. Sorting out the names and taxonomy of the variable star zoo is the object of this course.

Constellation Names

Traditional variable star names are a combination of a letter and/or number combination prefix and a constellation name in genitive (possessive) form, such as R Leonis, or V849 Herculis. So it is useful to understand constellation names and their origins and usage.

Today there are 88 constellations officially recognized by the International Astronomical Union (IAU), the body responsible for naming the stars, planets, moons, comets and variable stars. But that is a recent development. People have been assigning names to stars, groups of stars, and constellations for over 6,000 years, and frankly, it's been somewhat of a free-for-all! Until the twentieth century, celestial mapmakers were free to make up constellations and boundaries based on whatever people, animals, or mythical beasts they could dream up.

Ancient astronomers and cultures had names for the groupings of stars along the ecliptic, because this was the path through which the Sun, Moon and known planets of the time traveled, and they assigned magical and future predicting qualities to these cyclical motions. Hardly any of the very ancient constellation names survive to today. It wasn't until 150 B.C. that Claudius Ptolemy published the *Almagest,* his famous treatise on mathematics and astronomy that constellation names we recognize today were formalized in writing. Of the 48 original star patterns he described, only two, the Pleiades and Argo Navis, are no longer recognized as constellations.



A star map of Leo the Lion, one of the few constellations
that actually looks like its namesake to modern observers.

In the 1500's navigators exploring the southern hemisphere began naming southern constellations. Italian navigator, Amerigo Vespucci, was the first to describe the Southern Cross, Crux, and Triangulum Australe. Dutch navigators Frederick de Houtman and Pieter Dirksz Keyser created Apus, Chamaeleon, Dorado, Grus, Hydrus, Indus, Musca, Phoenix, Tucana and Volans.

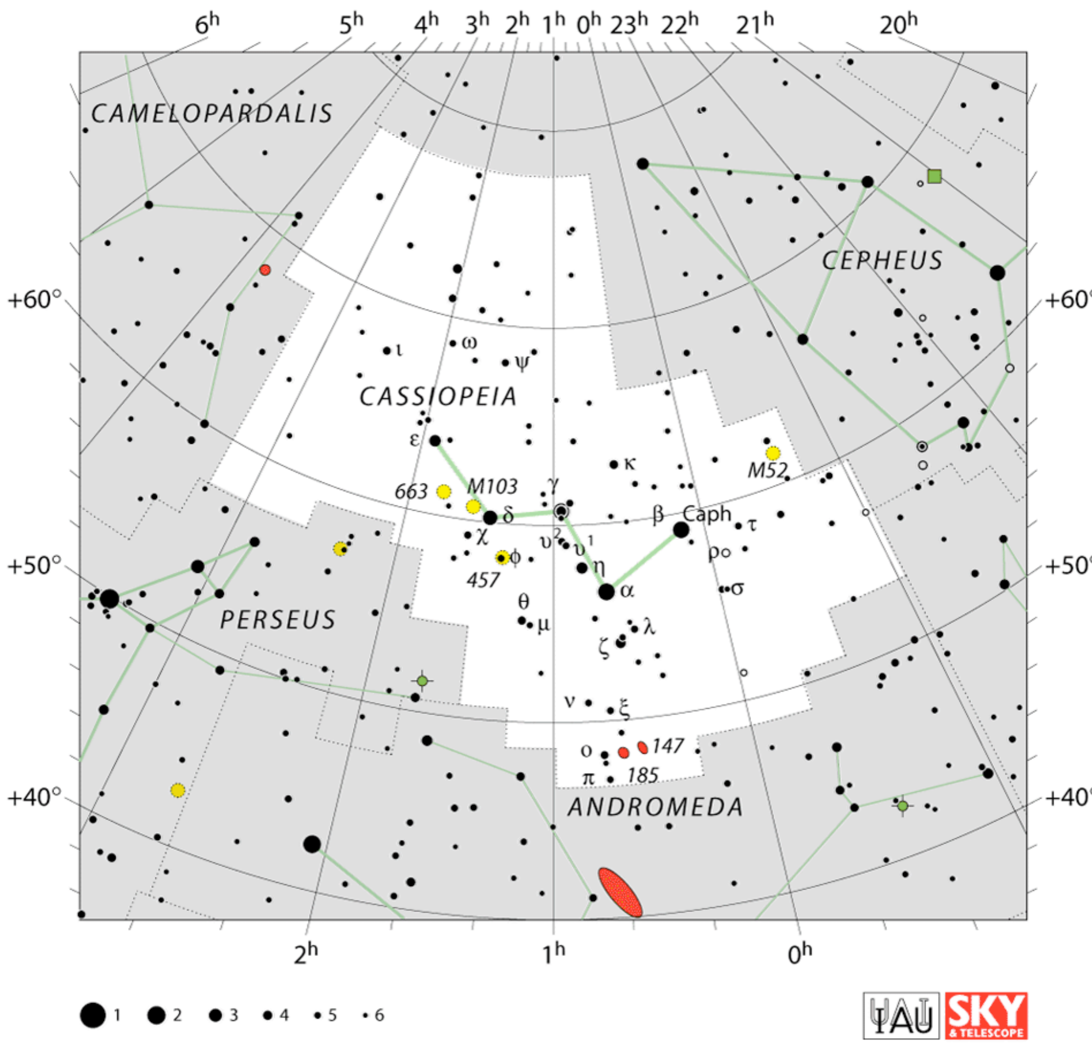
Sixteenth century mapmakers, Gerard Mercator and Petrus Flemish created the new constellations of Coma Berenices and Columba, respectively. In 1690, German astronomer, Johannes Hevelius documented Canes Venatici, Lacerta, Leo Minor, Lynx, Scutum, Sextans and Vulpecula in his atlas of the heavens.

Not to be outdone, in 1756 the French astronomer Nicolas Louis De Lacaille invented 14 new constellations representing scientific equipment of the day: Antlia, Caelum, Circinus, Fornax, Horologium, Mensa, Microscopium, Norma, Octans, Pictor, Pyxis, Reticulum, Sculptor and Telescopium. And in 1764, French mapmaker, Gilles Robert de Vaugondy divided up Ptolemy's Argo Navis into Carina, Puppis and Vela.

In an effort to bring order to the madness, American astronomer Henry Norris Russell proposed a system of three letter abbreviations for the constellations at the First General Assembly of the IAU in 1922, and by 1928 the IAU had set official boundaries for the 88 constellations we recognize today.

This process did leave a few orphan stars in its wake. The variable star T Leo no longer resides in the constellation of Leo and was renamed QZ Virginis, and the 4th magnitude star 10 Ursae Majoris now is part of the constellation Lynx.

The IAU maintains an excellent page that lists the 88 constellations, their abbreviations and pronunciations, and includes star maps with the borders of each well defined. You can visit it here: http://www.iau.org/public/constellations/



The IAU/Sky and Telescope constellation map of Cassiopeia

Greek Letter Names (Bayer Designations)

A Bayer designation is a stellar designation in which a specific star is identified by a Greek letter, followed by the genitive form of its parent constellation's Latin name. The original list of Bayer designations contained 1,564 stars.

Most of the brighter stars were assigned their first systematic names by the German astronomer Johann Bayer in 1603, in his star atlas Uranometria. Bayer assigned a lower-case Greek letter, such as alpha (α), beta (β), gamma (γ), etc., to each star he catalogued, combined with the Latin name of the star's parent constellation in genitive (possessive) form. For example, Aldebaran is designated α Tauri (alpha Tauri), which means "alpha of the Bull".

A single constellation may contain fifty or more stars, but the Greek alphabet has only twenty-four letters. When these ran out, Bayer began using lower-case Latin letters: hence s Carinae and d Centauri. Within constellations having an extremely large number of stars, Bayer eventually advanced to upper case Latin letters, as in G Scorpii and N Velorum. The last upper-case letter used by Bayer was Q.

As luck would have it, many of these bright stars turned out to be variable stars, so they are often known by their Bayer designations. Examples are alpha Orionis, beta Lyrae, delta Cephei and eta Aquilae.

Variable Star Names

Argelander's System for Naming Variable Stars

Generally regarded as the father of variable star science, Frederich W. A. Argelander invented the traditional system used to name variable stars today. Under this system, variable stars are named using a variation on the Bayer designation format, combining an identifying label with the Latin genitive (possessive) of the name of the constellation in which the star resides. He started with the letter R to avoid confusion with the Bayer designated stars. As each new variable in a constellation was discovered it received the next letter combination in line.

The rules for naming stars in order of their discovery is this:

- Stars with existing Greek letter Bayer designations are not given new designations.
- Otherwise, start with the letter R and go through Z.
- Continue with RR through RZ, and then use SS through SZ, TT through TZ and so on until ZZ.
- Then it reverts to the beginning of the alphabet, AA through AZ, BB through BZ, CC through CZ and so on until reaching QZ, omitting J in both the first and second positions.

- Note that the first letter is never further up the alphabet than the second, that is to say no star can be BA, CA, CB, DA or so on.
- The Latin script is abandoned after 334 combinations of letters and numbers are used, starting with V335, V336, and so on.

It seems like a cumbersome way to name things, but you must realize that in Argelander's time stellar variability was considered to be a rare phenomenon. I doubt they thought they would ever run out of letter combinations. Astronomers of the day would be shocked to learn that we now have names like V2346 Cyg and V5558 Sgr.

Other Naming Conventions

As if that weren't confusing enough, there are now a host of other prefixes and numbers assigned to variable stars and objects. The following is a guide to help you understand what these names mean and where they came from.

NSV xxxxx - These are stars in the Catalog of New and Suspected Variable Stars, produced as a companion to the Moscow General Catalog of Variable Stars (GCVS) by B.V. Kukarkin et al. All stars in the NSV have reported but unconfirmed variability, in particular, lacking complete light curves. Some NSV stars will eventually prove truly variable; others will be spurious. Information about this and the General Catalog of Variable Stars can be found at: http://www.sai.msu.su/groups/cluster/gcvs/gcvs/intro.htm

VSX Jhhmmss.s+ddmmss- This is the system used by the International Variable Star Index (VSX), maintained by the AAVSO. These J2000 coordinate designations are applied to newly cataloged objects in VSX. http://www.aavso.org/vsx/

Many stars and variable objects are assigned prefixes based on astronomer, survey or project names. Many are temporary designations until they are assigned a conventional name in the GCVS.

3C xxx - These are objects from the Third Cambridge (3C) catalog (Edge et al. 1959), based on radio-wavelength observations at 158 MHz. There are 471 3C sources, numbered sequentially by right ascension. All 3C sources are north of -22 declination. The 3C objects of interest to variable star observers are all active galaxies (quasars, BL Lacs, etc.).

Antipin xx- Variable stars discovered by Sergej V. Antipin, a junior researcher working for the General Catalogue of Variable Stars Group.

HadVxxx - This represents variables discovered by Katsumi Haseda. Haseda's most recent discovery was Nova 2002 in Ophiuchus, V2540 Oph.

LD xxx - Variables discovered by Lennart Dahlmark, a Swedish retiree living in southern France are given this prefix. Dahlmark has been conducting a photographic search for new variable stars; discovering several hundred to date.

He-3 xxxx - Variables from Henize, K. G. 1976, "Observations of Southern Emission-Line Stars", Ap.J. Suppl. 30, 491.

HVxxxxx - Preliminary designations of variables discovered at Harvard Observatory.

Lanning xx - Discoveries of UV-bright stellar objects by H. H. Lanning from Schmidt plates centered primarily on the galactic plane. In all, seven papers entitled "A finding list of faint UV-bright stars in the galactic plane" were published.

Markarian xxxx - The widely used abbreviation for Markarian objects is Mrk. These are active galaxies from lists published by the Soviet Armenian astrophysicist B.E. Markarian. Markarian looked for galaxies that emit unusually strong UV radiation, which comes from either pervasive star-formation HII regions or from active nuclei. In 1966, Markarian published 'Galaxies With UV Continua'. Around that time, he started the First Byurakan Spectral Sky Survey (FBS), which is now completed. In 1975, Markarian initiated a Second Byurkan Survey (SBS). His collaborators continued the SBS after his death. For more information see 'Active Galactic Nuclei', by Don Osterbrock.

MisVxxxx - The stars are named MisV after MISAO Project Variable stars. The MISAO Project makes use of images taken from all over the world, searching for and tracking astronomically remarkable objects. The number of variables discovered so far reached 1171 on May 15, 2002. Few of these stars have light curves, and the type and range of many are still undetermined. The project website URL is: http://www.aerith.net/misao/

S xxxxx - These are preliminary designations of variables discovered at Sonneberg Observatory.

SVS xxx - Soviet Variable Stars, indicates preliminary designations of Soviet-discovered variables.

TKx - TK stands for T.V. Kryachko. The TK numbers of new variables continue a numbering system first introduced in Kryachko and Solovyov (1996). The authors invented this acronym.

Another group of objects is labeled with the prefix O, then a letter, then a number (OJ 287 for example). These objects were detected by the Ohio State University radio telescope "Big Ear" in a series of surveys known as the Ohio Surveys.

Many variables are named with prefixes associated with surveys or satellites, combined with the coordinates of the object.

2QZ Jhhmmss.s-ddmmss - Objects discovered by the 2dF QSO Redshift Survey. The aim is to obtain spectra of QSOs out to redshifts so high the visible light emitted by these objects has shifted into the far infrared. The observations are actually of the ultra-violet part of the spectrum that has been redshifted into the visible. As with most QSO surveys,

a serendipitous byproduct is the discovery of CVs and other blue stars. A description and awesome pictures of the equipment can be found here:
http://www.2dfquasar.org/Spec_Cat/basic.html
Home site: http://www.2dfquasar.org/index.html

ASAS hhmmss+ddmm.m - This is the acronym for All Sky Automated Survey, which is an ongoing survey monitoring millions of stars down to magnitude 14. The survey cameras are located at the Las Campanas Observatory in Chile, so it covers the southern sky from the pole to about +28 degrees declination.

FBS hhmm+dd.d - Stands for First Byurakan Survey and the coordinates of the object. The First Byurakan Survey (FBS), also known as the Markarian survey, covers about 17,000 square degrees.

EUVE Jhhmm+ddmm - These are objects detected by NASA's Extreme Ultraviolet Explorer, a satellite dedicated to studying objects in far ultraviolet wavelengths. The first part of the mission was dedicated to an all-sky survey using the imaging instruments that cataloged 801 objects. Phase two involved pointed observations, mainly with the spectroscopic instruments. One of the highlights of the mission was the detection of Quasi Periodic Oscillations (QPOs) in SS Cyg.

FSVS Jhhmm+ddmm - Discoveries from the Faint Sky Variability Survey, the first deep wide field, multi-color, time-sampled CCD photometry survey. It was specifically aimed at detecting point sources as faint as 25th magnitude in V and I and 24.2 in B. Targets were faint CVs, other interacting binaries, brown dwarfs and low mass stars and Kuiper Belt Objects.

HS hhmm+ddmm- The Hamburg Quasar Survey is a wide-angle objective prism survey searching for quasars in the northern sky, avoiding the Milky Way. The limiting magnitude is approximately 17.5B. The taking of the plates was completed in 1997.

PG hhmm+DDd- Palomar Green Survey conducted to search for blue objects covering 10714 square degrees from 266 fields taken on the Palomar 18-inch Schmidt telescope. Limiting magnitudes vary from field to field, ranging from 15.49 to 16.67. The blue objects detected tend to be quasars and cataclysmic variables. The CVs were documented in Green, R. F., et al. 1986, "Cataclysmic Variable Candidates from the Palomar Green Survey", Ap. J. Suppl. 61, 305.

PKS hhmm+ddd - This was an extensive radio survey (Ekers 1969) of the southern sky undertaken at Parkes (PKS), Australia, originally at 408 MHz and later at 1410 MHz and 2650 MHz. These sources are designated by their truncated 1950 position. For example 3C 273 = PKS 1226+023. This is still the most common, and useful, system of naming quasars.

ROTSE1 thru 3 Jhhmmss.ss+ddmmss.s - The Robotic Optical Transient Search Experiment (ROTSE) is dedicated to the observation and detection of optical transients on time scales of seconds to days. The emphasis is on gamma-ray bursts (GRBs). Objects detected by this survey are designated with positions to 0".1 precision.

ROSAT is an acronym for the ROentgen SATellite. ROSAT was an X-ray observatory developed through a cooperative program between Germany, the United States, and the United Kingdom. The satellite was designed and operated by Germany, and was launched by the United States on June 1, 1990. It was turned off on February 12, 1999.

Prefixes for x-ray sources detected by ROSAT include, 1RXS, RXS and RX. The J2000 coordinates for the source are then stated according to the accuracy of the X-ray position and the density of stars in the field.

arcsecond accuracy ---> RX J012345.6-765432
tenth-arcmin accuracy ---> RX J012345-7654.6
arcmin accuracy ---> RX J0123.7-7654

Distressingly, these can all refer to a single object!

Rosino xxx or N xx - Variables discovered by Italian astronomer L. Rosino, primarily in clusters and galaxies through photographic surveys.

SBS hhmm+dd.d - Indicates objects discovered by the Second Byurakan Sky Survey, plus the coordinates of the object.

SDSSp Jhhmmss.ss+ddmmss.s - These are discoveries from the Sloan Digital Sky Survey. The positions of the objects are given in the names. SDSS- (Sloan Digital Sky Survey), p- (preliminary astrometry), Jhhmmss.ss+ddmmss.s (the equinox J2000 coordinates). In subsequent papers on CVs detected by SDSS (Szkody et al) the p was dropped and the names became simply SDSS Jhhmmss.ss+ddmmss.s.

TAV hhmm+dd - The Astronomer Magazine, in England, has a program that monitors variable stars and suspected variable stars. TAV stands for The Astronomer Variable, plus the 1950 coordinates.

TASV hhmm+dd - TASV stands for The Astronomer Suspected Variable, plus the 1950 coordinates. The Astronomer Variable star page can be found at this url: http://www.theastronomer.org/variables.html

XTE Jhhmm+dd - These are objects detected by the Rossi X-Ray Timing Explorer Mission. The primary objective of the mission is the study of stellar and galactic systems containing compact objects. These systems include white dwarfs, neutron stars, and possibly black holes.

CSS yymmdd: hhmmss+ddmmss- This system was invented by the geniuses at the Catalina Sky Survey to completely blow your mind and to guarantee typos and errors.

The prefix stands for Catalina Sky Survey followed by the date in yymmdd form, then the coordinates in a very non-scientific and unsatisfactory format.

With more and more surveys being conducted, and more new variables being discovered, this list of non-conventional names will undoubtedly grow.

Supernovae have their own naming scheme. You can read more on that topic here: http://simostronomy.blogspot.com/2011/01/supernovae-alphabet-soup.html

Naming Variable Star Types

In a perfect world, the classification scheme for variable stars would use only those quantities that are directly observable, distinguished between physically different systems and put similar objects into well-defined groups. Unfortunately, we do not live in a perfect world, nor do we perform observations in a perfectly ordered universe, so this is rarely, if ever possible. In fact, more often than not, we actually classify stars and give them names before we understand the processes that make them variable. This of course leads to more problems down the road as better information becomes available, as you will learn.

Other classifications, such as those of Cepheids, lump together stars based on *stellar populations,* based on age, mass, metallicity, higher velocities in the galaxy and lower concentrations along the plane of the Milky Way. And yet another issue arises when we discuss binary systems, whose binarity can have a profound effect on stellar variability. So in many cases, we must now classify the *star system* also.

Furthermore, some stars exhibit more than one type of variability at the same time, so eclipses, rotational and flaring activity may be occurring at the same time!

One of the most common ways of naming variable star types is by naming the group after the first discovered or best-known case. These names are then often shortened which makes them slightly more confusing.

For example eclipsing binaries are classified as either Algol type variables, (abbreviated EA), or Beta Lyrae type variables, (abbreviated EB), or W Ursae Majoris type variables, (abbreviated EW) after their namesakes. The subtypes of dwarf novae are named after the prototypical stars of their class. UG for U Geminorum, UGSS for SS Cygni, UGSU for SU Ursae Majoris, UGZ for Z Camelopardalis and UGWZ for WZ Sagittae.

Certain classifications are broken down further into sub-groups, such as the RR Lyrae stars (RR, RRAB, RRC and RRD) and the RV Tauri stars (RV, RVA and RVB).

Other classes are named after their behavior or some characteristic. Semi-regular variables are named SR with sub-types of SRA, SRB, SRC and SRD.

Other acronyms simply stand for what they are, such as HADS, which stands for High Amplitude Delta Scuti stars.

Not only is the system for naming these types inconsistent, it also isn't well agreed upon. For many decades the General Catalog of Variable Stars has defined the "official" classification system, based on light curve, temperature, luminosity and population type. But this system is in need of revision and updating as astronomers have continued to subdivide the sub-groups into more and more specialized groups and introduced new names and acronyms into the literature.

For this course we will rely on the variable type designations and definitions used in VSX. This document, in pdf format, is provided along with the course manual as a supplemental source of information. If there is a question or debate about types, we will use this document to determine the answer. This is your Rosetta stone.

The Main Types of Variability

There are two main types of variability, extrinsic and intrinsic.

Extrinsic variables are stars where the variability is caused by external properties like rotation or eclipses. The total energy output of the star is not varying, (or is not the *primary* reason for its variability) but the amount of light we see from our vantage point on Earth varies. The main types of extrinsic variability are:

<u>Eclipsing variables</u> vary because the orbital plane of the star and its companion coincides with our line of sight to the system. As one component passes in front of the other, from our viewpoint, we see a dip in the light output.

<u>Rotating variables</u> may have any number of reasons for varying. There may be star spots that rotate in and out of view, making the star appear to fade and brighten more or less cyclically. A pair of stars may be so close that they are tidally locked, and one star is super-heating the portion of the other star facing it, which is then reflected back into space as additional energy we perceive as a brightening each time it rotates into view. Other rotating variables may be orbiting each other so close the components are stretched by gravity into non-spherical shapes. As the stars rotate the area of their surface presented towards the observer changes and this in turn affects their brightness as seen from Earth.

<u>Microlensing variables</u> brighten, and then fade, when an object acting as a gravitational lens passes in front of the star from our point of view, magnifying the light from the more distant object.

Intrinsic variables are stars where the variability is caused by changes in the physical properties of the stars themselves. The primary types of intrinsic variability are:

Pulsating variables vary as their stellar radii swell and shrink, causing changes in their magnitude and spectrum. They may be periodic, semi-periodic or irregular in their variability.

Eruptive variables undergo irregular episodes of variability due to mass ejection or chromospheric activity.

Cataclysmic variables are generally interacting binary systems containing white dwarfs or systems that undergo large amplitude outbursts.

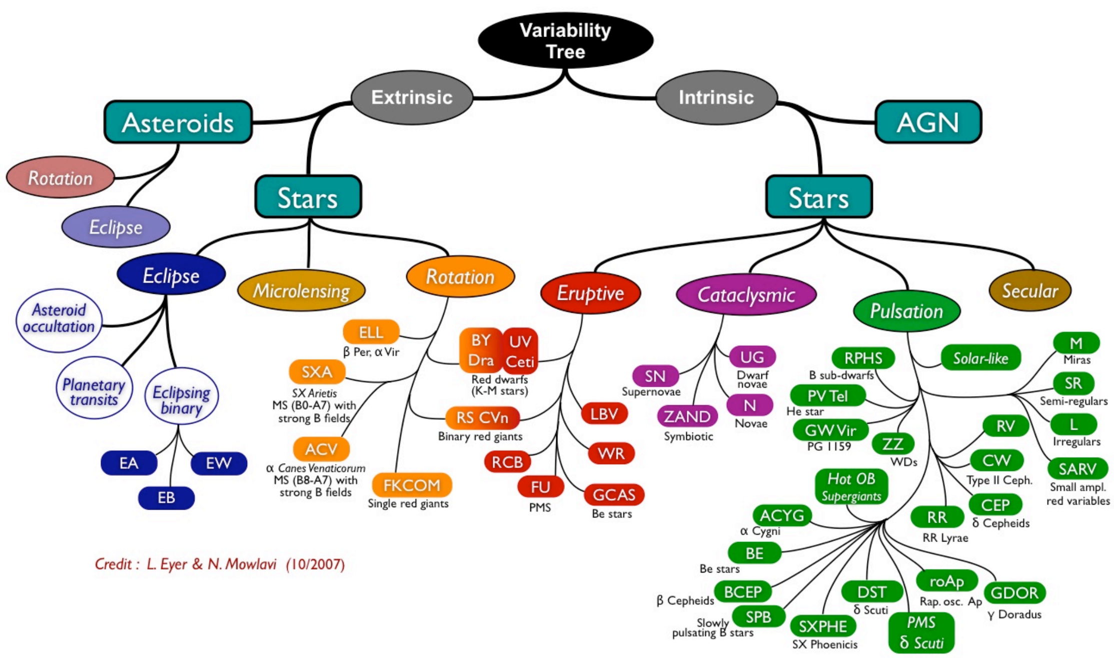
X-Ray variables are binary systems containing neutron stars or black holes.

The Variability Tree

The diagram below is a useful illustrative guide to all the types of variability that, more or less, follows the scheme of variability laid out in this course.

You will not be required to learn every single type listed here. This course will concentrate on those variable stars most typically observed by AAVSO observers.

From *"Variable stars across the observational HR diagram"*
Laurent Eyer and Nami Mowlavi
2008JPhCS.118a2010E

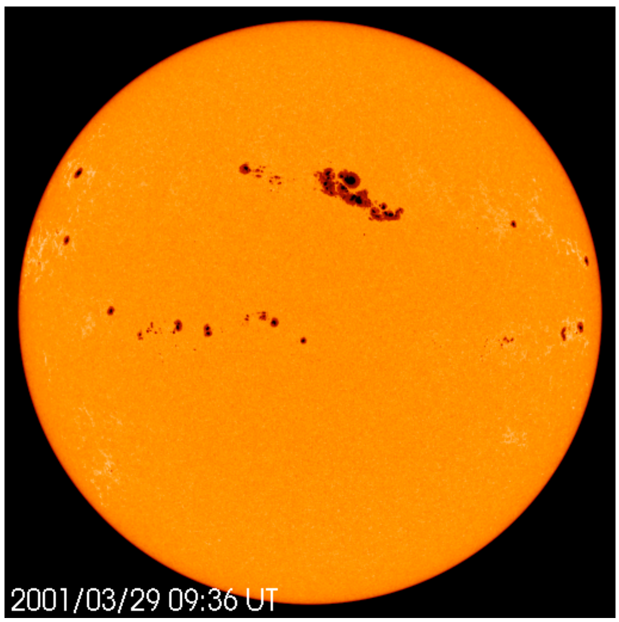


Chapter Two-

Rotating Variables

All stars rotate, so what does the term “rotating variables” mean? These stars are variable due to irregularities in the surface brightness of the star- or -because they have been distorted into ellipsoidal shapes by the gravitational tug of a nearby companion star. As these irregularities or shapes rotate in and out of view we perceive changes in the stars brightness.

Let’s start with an average main sequence star like our Sun. Its face is at times blotched, with sunspots that rotate in and out of view as the Sun rotates. This creates a very small, almost imperceptible, variation in the Sun’s brightness as viewed from Earth. We also see these spots come and go, not only each month, as the Sun rotates, but in longer periods of increased and then decreased spot activity-- the well-known 11-year sunspot cycle.



A large sunspot group crosses the face of the Sun

If we were measuring the Sun’s brightness from several thousand light years away with very sensitive instruments we could theoretically determine the approximate period of rotation of the Sun in days or hours. We could also determine the 11 year cycle in the amplitude of this periodic variation based on the rotation of spots across the face of the Sun as seen from our point of view.

We could also deduce that we were not looking at the star pole on, or we wouldn’t see any variation, because we would always see the same hemisphere from our point of view and it wouldn’t matter what the longitude of the spots were. We’d see all the spots and bright sections all the time as the Sun rotated about its poles.

Indeed, by observing sun-like stars we've learned a lot about the Sun and its evolutionary track. What we find is the amount of stellar activity is related to the speed of rotation, which produces the magnetic fields that, which in turn produce star spots. As newly formed stars migrate towards the main sequence their rotation speeds up as they collapse. As they grow older and swell, they begin to slow down. The Sun is a middle-aged star, rotating slower than it did in its youth and is likely much less active than when it was younger. Stars with rapid rotation periods tend to be more chaotic. Stars with periods similar to the Sun tend to show more regular cycles of activity, like the 11-year solar cycle.

The Sun has relatively modest spots, as stars go. Even added altogether, at the height of solar maximum, the spots only cover a very few percent of the surface area of the Sun. What if the Sun had gigantic spots, covering 25% or 50% of the surface area we could see at any given time? It's not hard to imagine being able to see the Sun vary, even from great distances in space, with that much of its surface darkened periodically as it rotated about its axis.

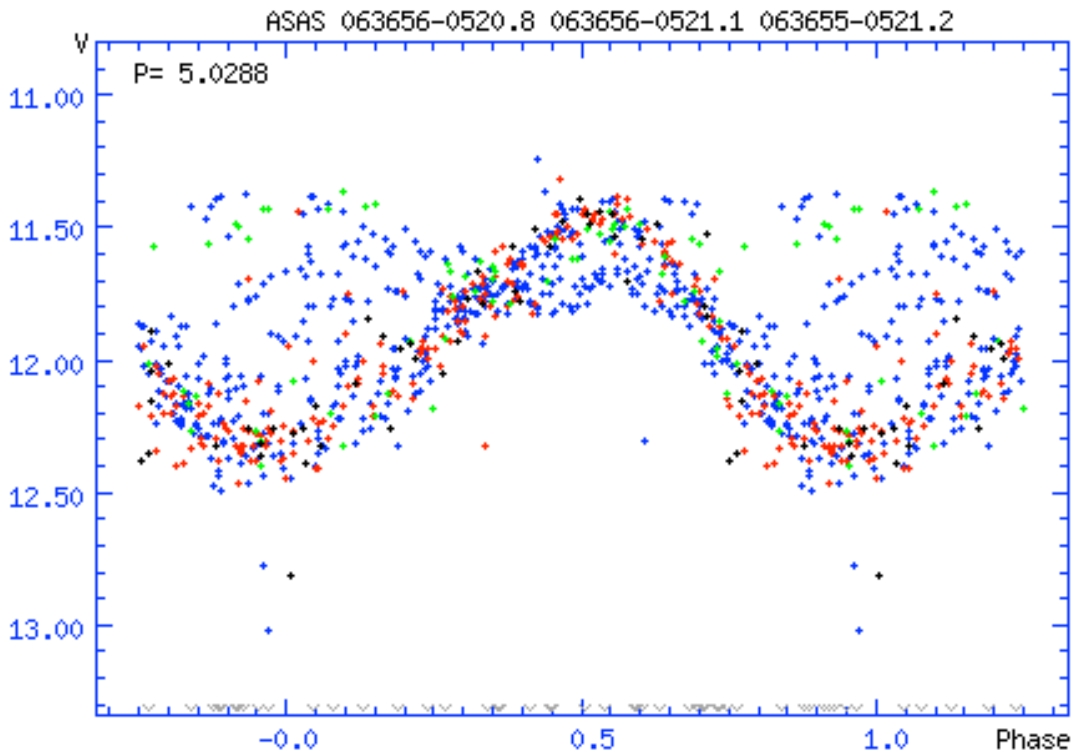
The fact is some stars have enormous spots in proportion to their overall size. And we are able to see the variation in brightness that occurs as these gigantic star spots rotate in and then out of view.

The view from an imaginary planet near a star with large spots.
Copyright Mark A. Garlick space-art.co.uk

BY Dra stars are red dwarf variables that show quasi-periodic variability in their light curves, with periods ranging from hours to 120 days due non-uniform areas of brightness (dark spots and bright spots) coming in and out of view as the star rotates about its axis. The amplitude of variations ranges from 0.001 to 0.5 magnitudes in V. Interestingly, BY Dra variables can be binary or single stars.

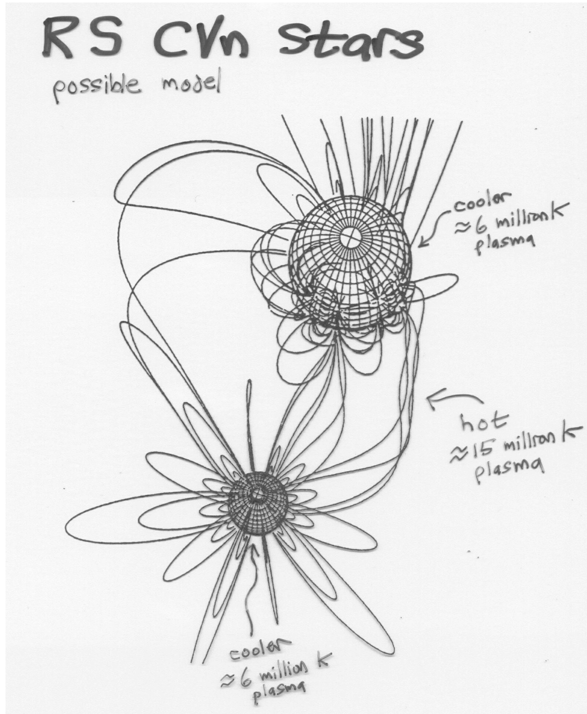
The prototype, BY Dra, was discovered in 1966 and star spots were proposed to explain its variability. Several stars found to be BY Dra type variables in later years were previously misclassified as eclipsing binaries.

Just as sunspots are often associated with solar flares, the large spots created by the magnetic fields of BY Dra stars are believed responsible for the UV Ceti type flares seen at times, making some of them both rotational and eruptive variables at the same time!



Light curve of a BY Dra variable utilizing ASAS data

RS CVn stars are binary red giants. These stars exhibit variable emission lines in their spectra as well as radio and x-ray emissions, indicators of solar type chromospheric activity, but on a much grander scale. This high level of activity is caused by the strong magnetic fields of the rapidly rotating components of the binary. RS CVn stars rotation rates have been “spun up” by the tidal interactions with their companions, resulting in rotation rates several times higher than “normal” stars of comparable size and mass.

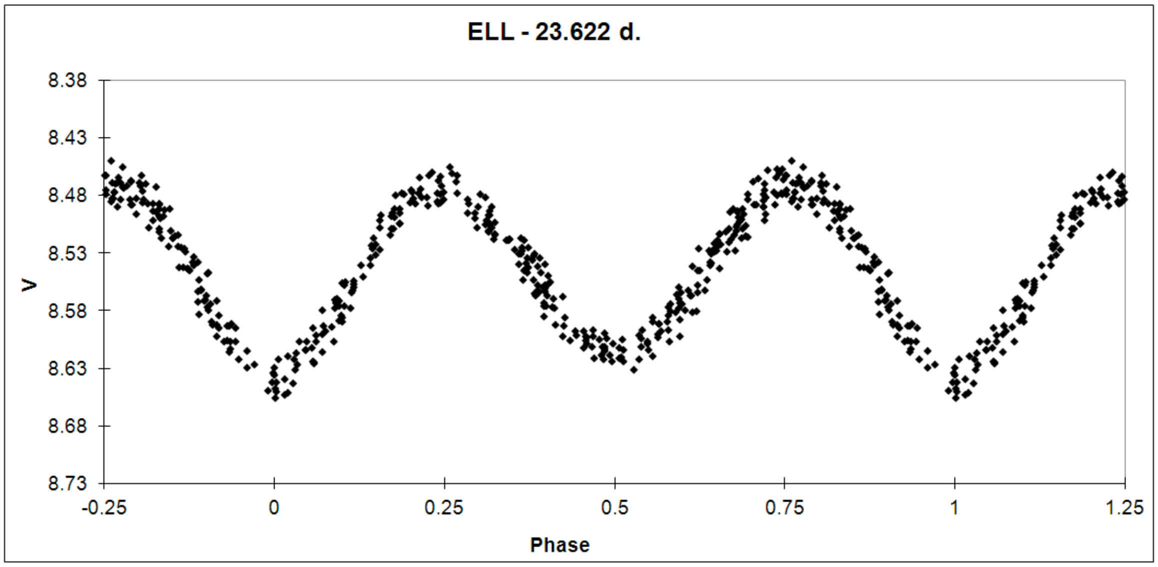


RS CVn stars are “chromospherically active” because they are
rapidly rotating stars with strong magnetic fields.

RS CVn stars exhibit both primary and secondary eclipses, as seen from Earth, as well as a “distortion wave” that runs throughout the light curve. This wave is caused by the presence of star spots that migrate in longitude, creating a gentle hump that moves across the light curve profile in relation to the eclipses.

Most RS CVn variables are relatively bright and their amplitudes can be 0.2 magnitudes or greater, which makes them well suited for systematic amateur photometric observations.

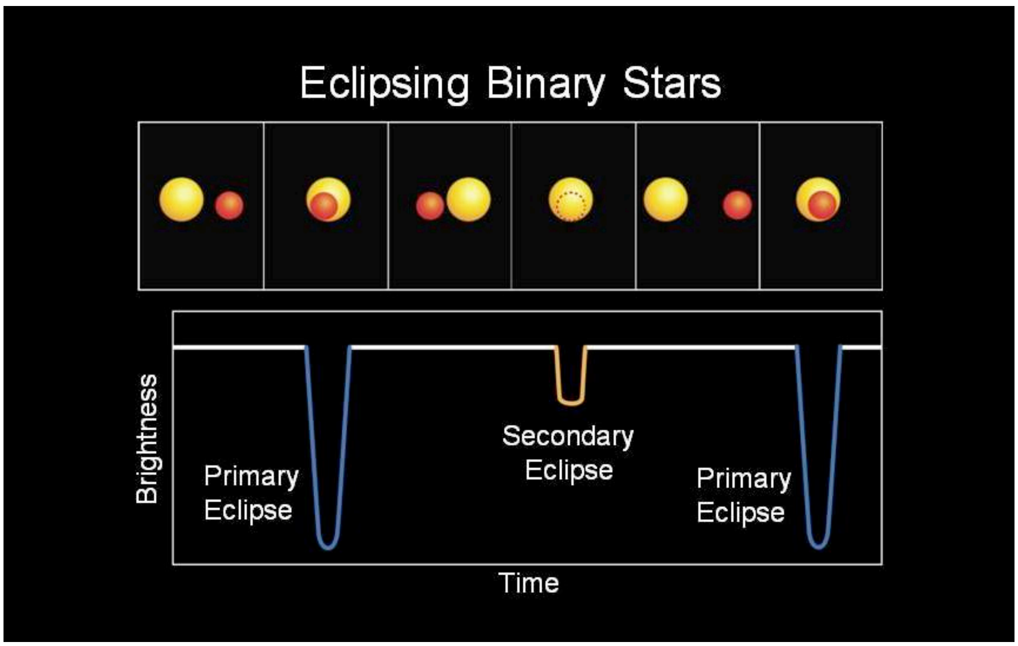
<u>Rotating ellipsoidal variables (ELL)</u> are close binary systems that vary with periods equal to their orbital motion. The components of ellipsoidal variables are stretched out of shape in response to the tremendous gravitational stress put on them by their ultra-close companion star. The mathematical probability of the orbital plane of these systems being coincident with our line of sight, causing one star to eclipse the other is greater than zero. But by definition, an ellipsoidal variable *cannot* show eclipsing behavior.



There is debate in many circles as to whether or not one can classify stars based strictly upon an arbitrary observational phenomenon that has nothing to do with the physical processes going on. After all, viewed from another planet elsewhere in the galaxy these systems may be eclipsing binaries! This loosely defined, "catch-all" group of stars doubtless contains misclassified astrophysically interesting stars upon which amateurs can conduct serious research.

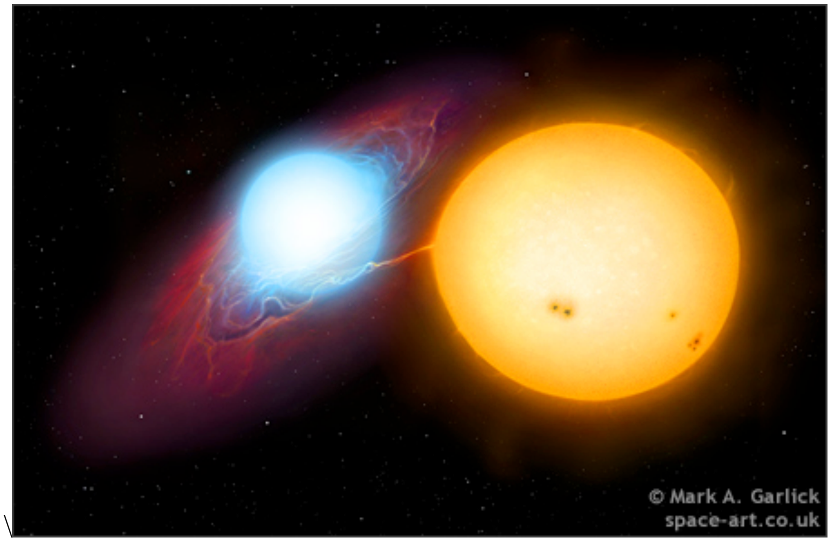
Eclipsing Variables

Eclipsing variables (E) are close binaries whose orbital plane coincidentally lines up with our line of sight. As one star passes in front of the other it eclipses the light from the other and a dip in the combined brightness of the pair occurs. The most light is lost when the fainter of the two companions passes in front of the brighter. These are known as *primary eclipses*. In many cases the brighter star can also pass in front of the fainter, resulting in a *secondary eclipse*. The time lapse between primary eclipses is equal to the orbital period of the system.



Binary systems are interesting for many reasons. More than half of all stars are in binary or multiple systems. The origins of binary systems are still not well known, and there are likely several different scenarios by which they can be created. The fact that eclipsing binaries are in close proximity to each other can dramatically affect how the individual stars evolve. The light curves of eclipsing binaries give important clues in determining the physical properties, such as the size, mass, luminosity and temperature of the stellar components.

Eclipsing Variable Classifications

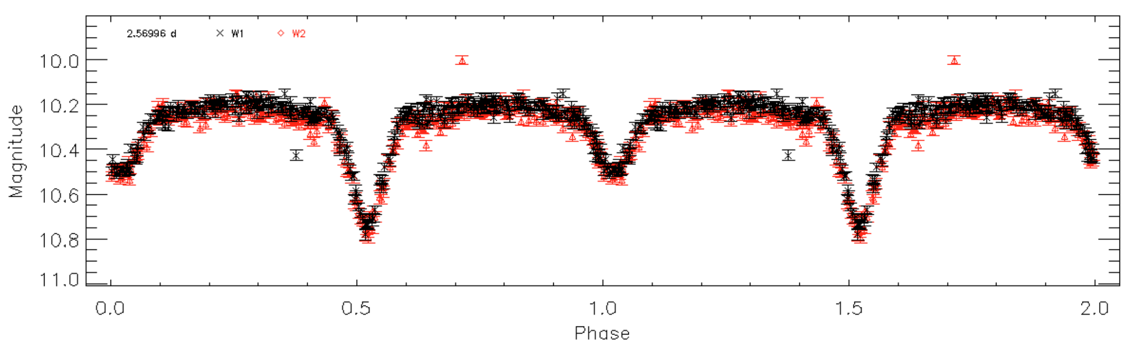


Artists rendering of Algol
Copyright Mark A. Garlick space-art.co.uk

Algol variables (EA) are eclipsing systems containing spherical or slightly ellipsoidal components. The precise moments of the beginning and ending of eclipses are well defined in their light curves. Secondary eclipses may be absent. The light curve is essentially flat between eclipses, or may vary slightly due to ellipsoidality or physical variability of the components, or due to *reflection effects*. Orbital periods range from 0.2 to more than 10,000 days, and the amplitudes of variation can reach several magnitudes.

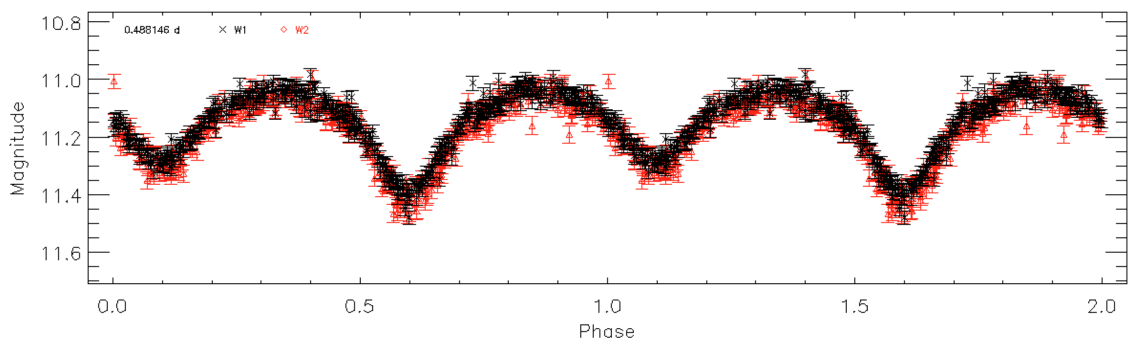
Reflection Effect

If two stars orbit each other very closely, some of the energy from each star will strike its companion, be absorbed and then re-emitted. The side of the star facing its companion is hotter and thus slightly brighter than the side facing away. Calling this phenomenon "reflection" is somewhat misleading. The effect is most obvious just prior to the eclipse of the cooler, fainter star. It produces "shoulders" in the light curve of the secondary eclipse.



A typical Algol type (EA) light curve

Beta Lyrae type variables (EB) are eclipsing variables containing ellipsoidal components. The exact times of onset and end of eclipse are impossible to determine because the brightness of the system is continuously varying. There are always secondary minima. The depth of these secondary eclipses is usually considerably shallower than the primary eclipse. Their periods are primarily longer than 1 day and the amplitude of the light changes can be as large as 2 magnitudes in V. The stars in the system are usually early spectral types B and A.



Light curve of a typical Beta Lyrae (EB) type variable

It is worth mentioning here that Beta Lyrae is such a bizarre case that is should not be the prototype for any class of variable star.

Beta Lyrae

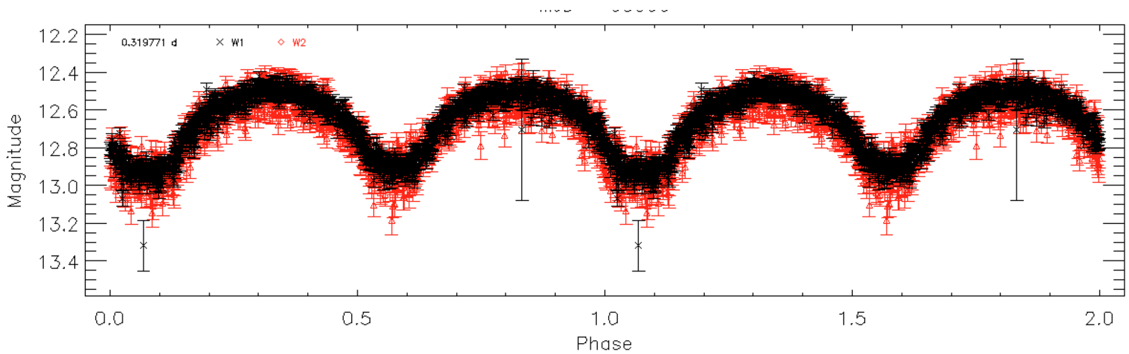
(Adapted from Harmanec, P. (2002) 'The ever-challenging emission line binary Beta Lyrae', AN, 323, 87-98.)

The current picture of beta Lyrae is that it is an eclipsing binary in a stage of mass transfer between the components. The mass-losing star is a B6-8II object, with a mass of about 3 M(sun), which is filling its Roche lobe and sending material towards its more massive companion at a rate of about 2 × 10-5 M(sun) yr-1. This leads to the observed rapid increase of the orbital period at a rate of 19 seconds per year. The mass-gaining star is as early B star with a mass of about 13 M(sun). It is completely hidden inside an opaque accretion disk, jet-like structures, perpendicular to the orbital plane and a light-scattering halo above the poles of the star.

The observed radiation of the disk corresponds to an effective temperature which is much lower than what would correspond to an early B star. The disk shields the radiation of the central star in the directions along the orbital plane and redistributes it in the directions perpendicular to it. That is why the mass-losing star appears the brighter of the two in the optical region of the spectrum.

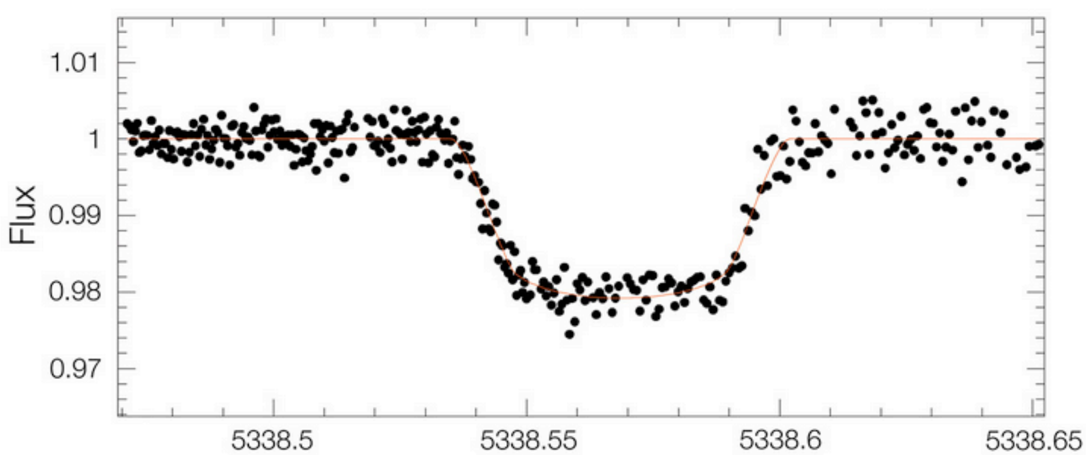
At present, rather reliable estimates of all basic properties of the binary and its components are available. However, in spite of great progress in understanding the system in recent years, some disagreement between the existing models still remains.

[W Ursae Majoris type variables (EW)] are eclipsing variables containing ellipsoidal components nearly in contact as they orbit a common center of mass. Like EBs, the exact times of onset and end of eclipse are impossible to determine because the brightness of the system is continuously varying. The depths of the primary and secondary eclipses are almost equal. Orbital periods are usually less than 1 day and the amplitudes of variability are typically less than 0.8 magnitudes in V. The components are usually spectral types F-G and later.



Light curve of a typical W Ursae Majoris (EW) type variable

Exoplanet transiting variables (EP) are stars whose infinitesimal light variation is caused by the eclipse of one or more of its planets transiting the face of the star as seen from our point of view.



The light curve of an exoplanet transiting its parent star, WASP-19b
Image Credit: TRAPPIST/M. Gillon/ESO

Suggested reading:
VSOTS Beta Persei
http://www.aavso.org/vsots_betaper

VSOTS Beta Lyrae
http://www.aavso.org/vsots_betalyr
VSOTS W Ursae Majoris
http://www.aavso.org/vsots_wuma

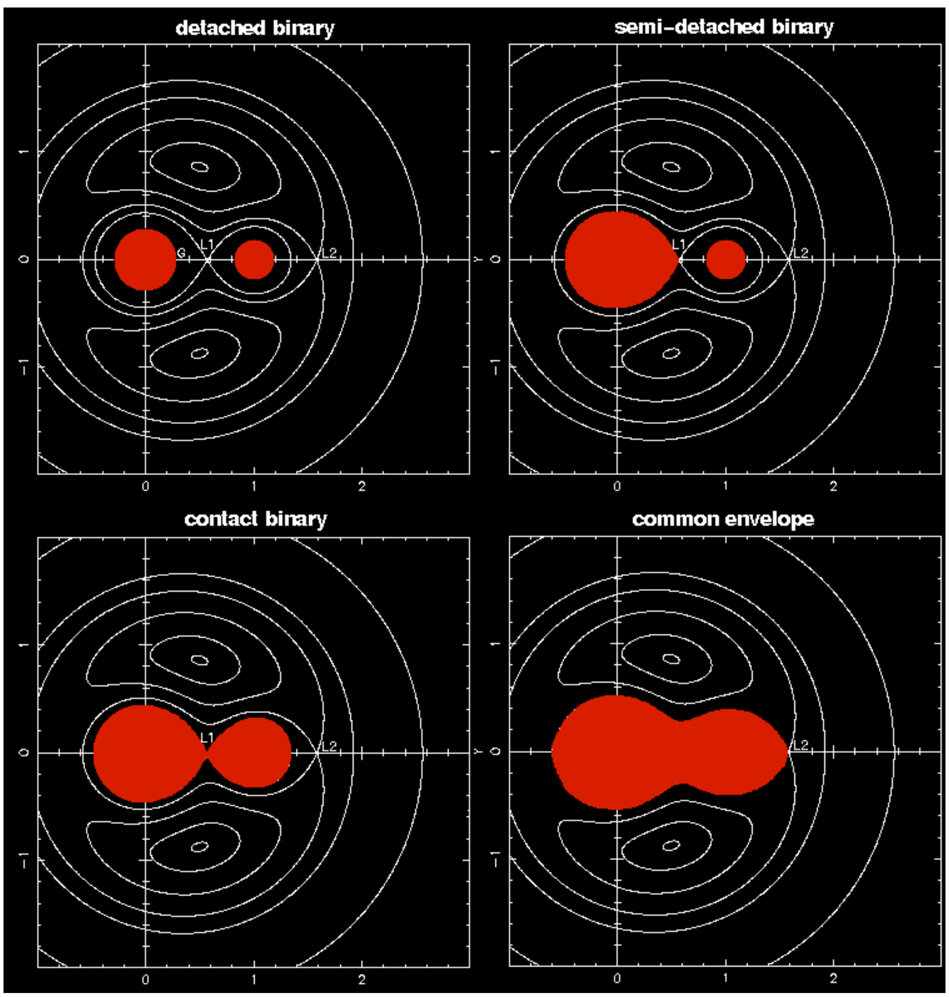
Roche Lobes

Modern classification schemes of binaries, including eclipsing binaries, are based on the concepts of Roche lobes and Lagrangian points.

Detached binaries are systems where both components are well within their Roche lobes. The stars remain nearly spherical and tidal distortion is minimal.

Semi-detached binaries are systems where one star fills its Roche lobe and is distorted. It is probably losing mass through accretion at the Inner Lagrangian point onto its companion star.

Contact binaries occur when both stars fill their Roche lobes and are essentially in contact with each other. In some cases a common envelope of material that blurs the distinction between individual stars may also surround the pair. These are often referred to as *common envelope* or *over-contact binaries*.



Diagrams of the Roche geometry of different binary systems

Chapter Three

Pulsating Variables
When we think of stellar pulsation, what most people think of is *radial pulsation.* This is the spherical and symmetrical expansion and contraction of the outer layers of a star. Just as if you were blowing up a balloon, then letting the air out slowly. The volume of the balloon (or star) actually increases and decreases cyclically.

The large amplitude pulsating variables-Cepheids, Miras and RR Lyrae stars- pulsate primarily in the radial modes.

There are stars whose pulsation is non-radial. *Non-radial pulsation* is when the star changes shape, but not volume. Picture our balloon now filled with water. If you pick it up by one end and squeeze it. The balloon shrinks under the pressure of your fingers and expands outwards at the other end. It still holds the same amount of water, though. The volume hasn't changed, only the shape.

Non-radial pulsation tends to produce smaller amplitudes of variation, and these stars, such as pulsating B stars and white dwarfs, are less well observed by AAVSO observers. Some stars-- Beta Cephei and Delta Scuti stars-- pulsate in both radial and non-radial modes!

One explanation for the pulsation of Cepheids, and other variables, is called the *Eddington valve*. Helium is the gas that makes this work. That is why it is usually older, evolved stars that pulsate. They have used up their hydrogen and are now burning and heating the helium in their outer shells.

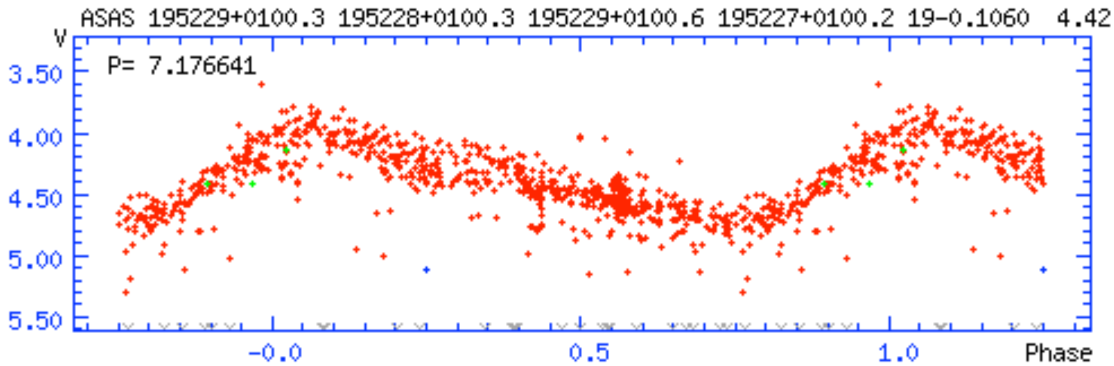
Doubly ionized helium (helium atoms missing two electrons) is more opaque than singly ionized helium. Since radiation from the stellar core cannot escape efficiently it is absorbed and causes yet more ionization. The more helium is heated, the more ionized it becomes.

At the dimmest part of a Cepheid's cycle, the ionized gas in the outer layers is heated by the star's radiation, and due to the increased temperature, begins to expand. As it expands, it cools, and becomes less ionized and therefore more transparent, allowing the radiation to escape. Then the expansion stops, and contraction begins, due to the star's gravitational attraction. The process then repeats.

Some pulsating variables are very strictly periodic. Their pulsations are regular as clockwork and predictable. Other pulsating stars are less periodic, while others are only semi-regular. In fact, that's what we call them, semi-regular variables!

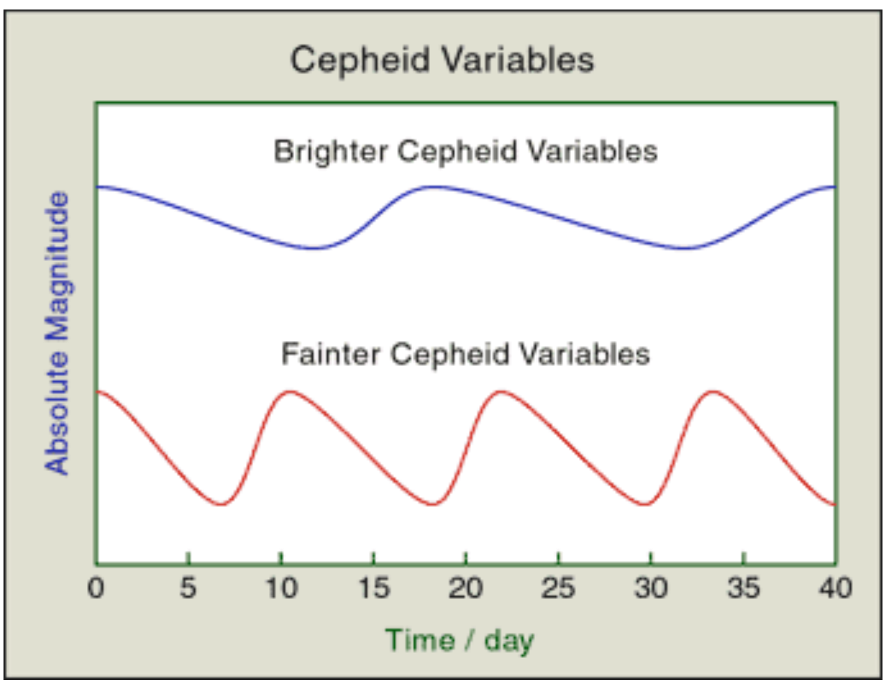
<u>Classical Cepheids (DCEP)</u> are bright yellow, highly luminous, supergiant pulsating variables. Their amplitudes are from a few hundredths to 2 magnitudes in V and their periods range from 1- 135 days. Their variability is strictly regular over very long time

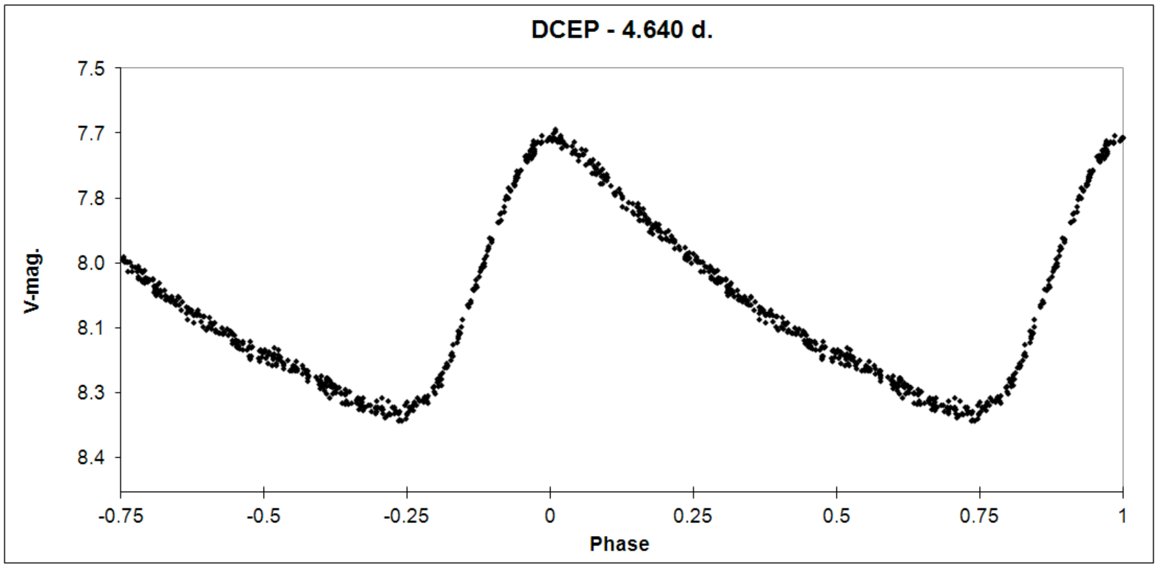
periods. Their spectral type at maximum light is F and at minimum ranges from G to K- the longer the period, the later the spectral type.



The phased ASAS light curve of eta Aquilae

Classical Cepheids are probably the most famous and most important pulsating variables. They are bright, numerous and generally have large amplitudes, so they are visible to astronomers throughout our galaxy and can even be observed in other galaxies in our Local Group, such as the Magellanic Clouds, M31 and M33. Because of the well-known period-luminosity relation, they have been used as the standard candles upon which our knowledge of distances in the universe is built.





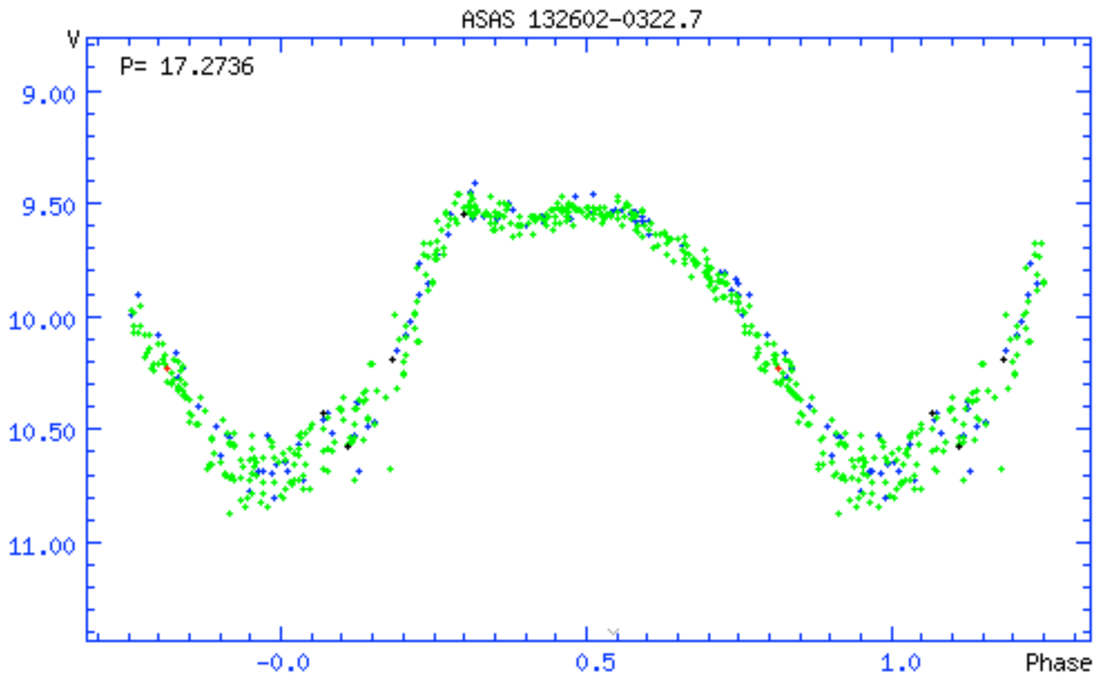
Phased light curve of a 4.64 day period Cepheid

See also VSOTS Delta Cephei
http://www.aavso.org/vsots_delcep

Type II Cepheids pulsate for the same reasons as classical Cepheids, and it is difficult to distinguish between them by their light curves alone. But their physical nature and evolutionary history is quite different. Population II Cepheids are older, low mass stars- typically 0.5 to 0.6 solar masses. Type II Cepheids tend to reside away from the disk of the galaxy and have lower metal abundances than classical Cepheids, making them important 'fossils' of the first generation of stars in our galaxy.

Type II Cepheids obey a different period-luminosity relationship, so it is important to distinguish between the two types. Once this error was discovered and the P-L relationship for Cepheids was re-calibrated in the 1950's, the distance scale of the universe doubled!

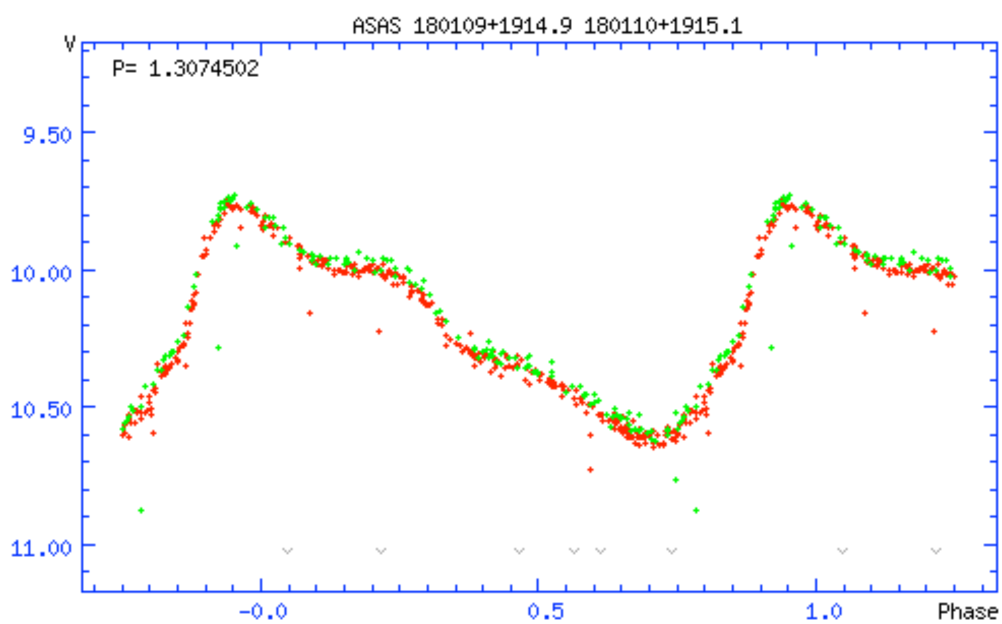
W Virginis (CW) vary with amplitudes from 0.3 to 1.2 magnitudes in V, and have periods that range from 0.8 to 35 days. The light curves of CW stars sometimes exhibit humps on the descending branch of the light curve, or sometimes a broad flat maximum.



The phased ASAS light curve of W Virginis

As with classical Cepheids, their spectral type at maximum light is F and at minimum ranges from G to K- the longer the period, the later the spectral type.

W Virginis type variables are further sub-divided into CWA and CWB. CWA are those with periods longer than 8 days, and CWB, also known as BL Herculis type stars, have periods shorter than 8 days.



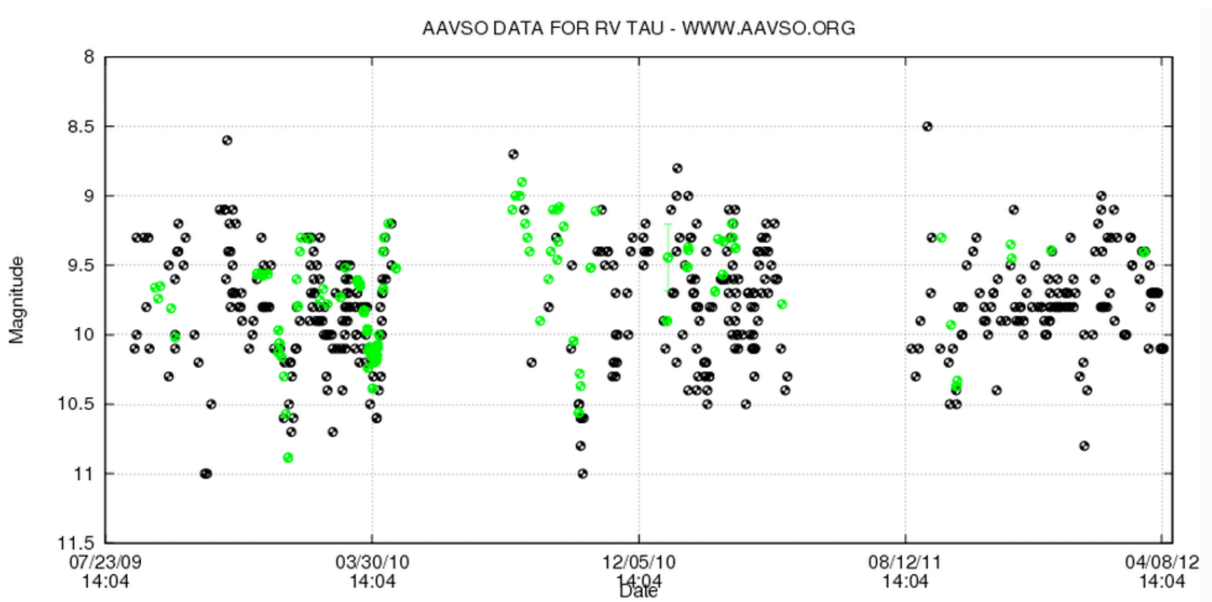
The phased ASAS light curve of BL Herculis

Highly recommended further reading:
VSOTS W Virginis
http://www.aavso.org/vsots_wvir

RV Tau stars are yellow supergiant stars whose light curves exhibit alternating deep and shallow minima. The period from one deep minimum to the next ranges from 30 to 150 days. The amplitude of the variability can be as much as 3-4 magnitudes in V. They have spectral types F to G at maximum light and K to M at minimum.

These are sub-divided into RVA and RVB types. RVA are those that do not vary in mean magnitude *(example: AC Her)*. RVB are those RV Tau stars that vary in mean magnitude by up to 2 magnitudes in V, with periods of 600- 1500 days. *(examples: RV Tau, DF Cyg)*

Extremely highly recommended reading:
VSOTS RV Tauri
http://www.aavso.org/vsots_rvtau

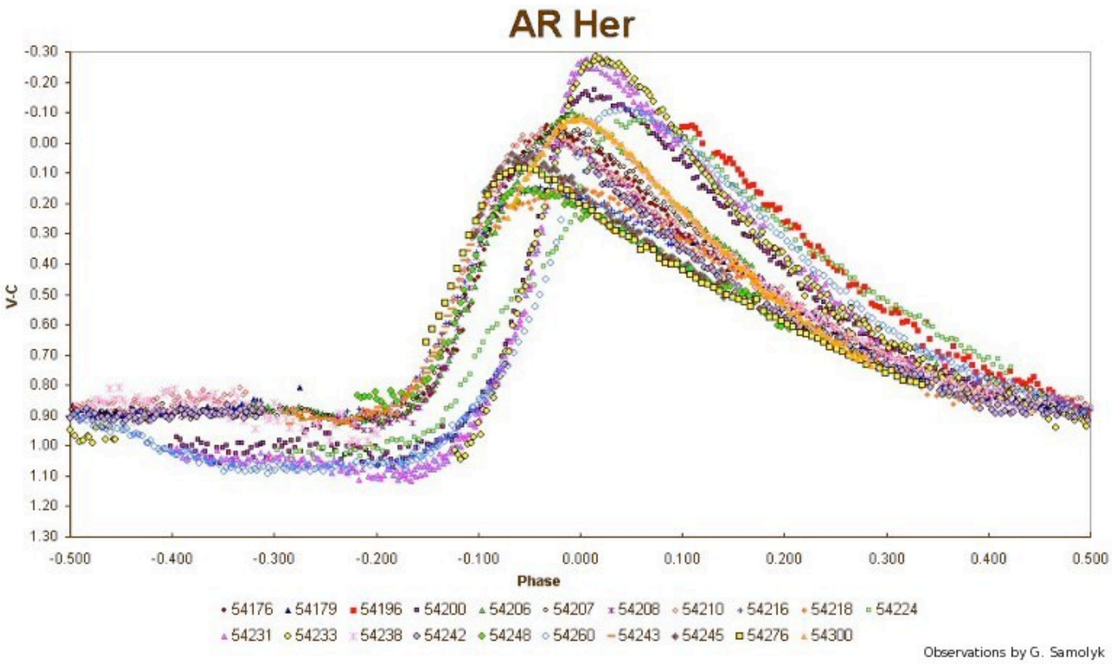


1000 day light curve of RV Tauri

RR Lyr stars are rapidly pulsating variables with periods ranging from 0.1 to 1 day, and amplitudes up to 1.5 magnitudes in V. They are spectral type A5 to F5 and have masses equal to about ½ solar. They are old stars that have exhausted almost all the hydrogen in their cores and are now burning helium. RR Lyraes are numerous in some globular clusters, and at one time were known as 'cluster variables'. They are important in astronomy in the same way as the Cepheids, in that they help us to calibrate the distance to objects in the universe.

In 1916, Harlow Shapley discovered that the light curve of RR Lyrae was modulated in both amplitude and shape, with a period of about 41 days. This modulation became known as the *Blazhko effect,* whose explanation remains one of the enduring mysteries in astrophysics to this day.

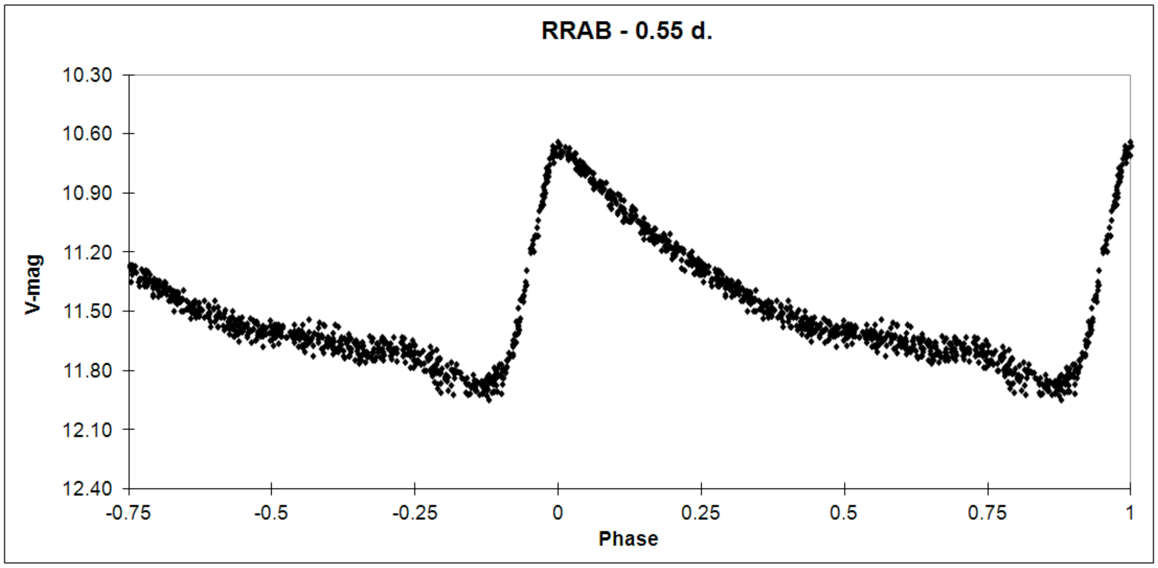
Highly recommended further reading:
VSOTS RR Lyrae
http://www.aavso.org/vsots_rrlyr



Light curve of AR Her demonstrating the modulation in the light curve of this known RR Lyrae star

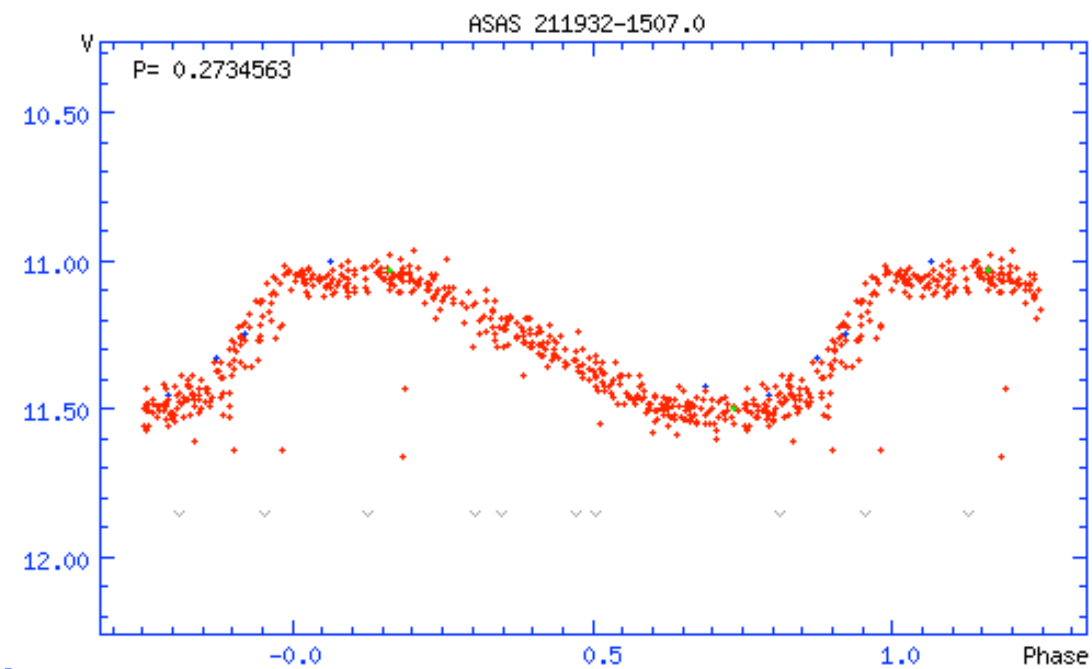
RR Lyr are further divided into RRAB, RRC and RRD classes.

RRAB are variables with asymmetrical light curves, displaying steep ascending branches. They have periods from 0.3 to 1.2 days and amplitudes ranging from 0.5 to 2 magnitudes in V.



An excellent representative light curve of an RRAB star

RRC are variables with nearly symmetrical light curves. Periods range from 0.2 to 0.5 days and amplitudes of variation not greater than 0.8 magnitudes in V.



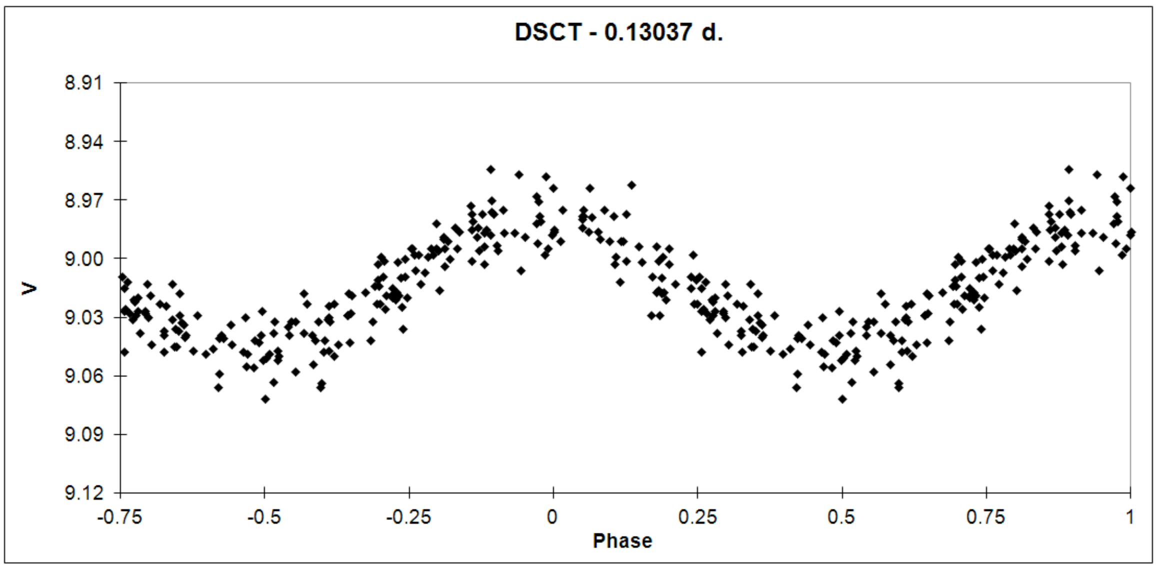
Light curve of YZ Cap, and RRC star

RRD are 'double mode' RR Lyrae stars that pulsate in both the fundamental and first overtone, with a period ratio of 0.74 days and a fundamental period of approximately 0.5 days. These are referred to as RRB in the GCVS.

Delta Scuti (DSCT) stars are the most numerous pulsating variables among all the bright stars. The pulsation mechanism for DSCTs is well understood. It is basically the same as for Cepheids. They are spectral types A to F, have short periods ranging from 0.01 to 0.2 days, and have amplitudes that range from 0.003 to 0.9 in V. Many of these stars are multi-periodic. FG Virginis, for example, pulsates in 79 different modes! This, along with their small amplitudes makes determining their periods very challenging.

Period changes can be measured, and this makes them an interesting class of objects for AAVSO observers to follow.

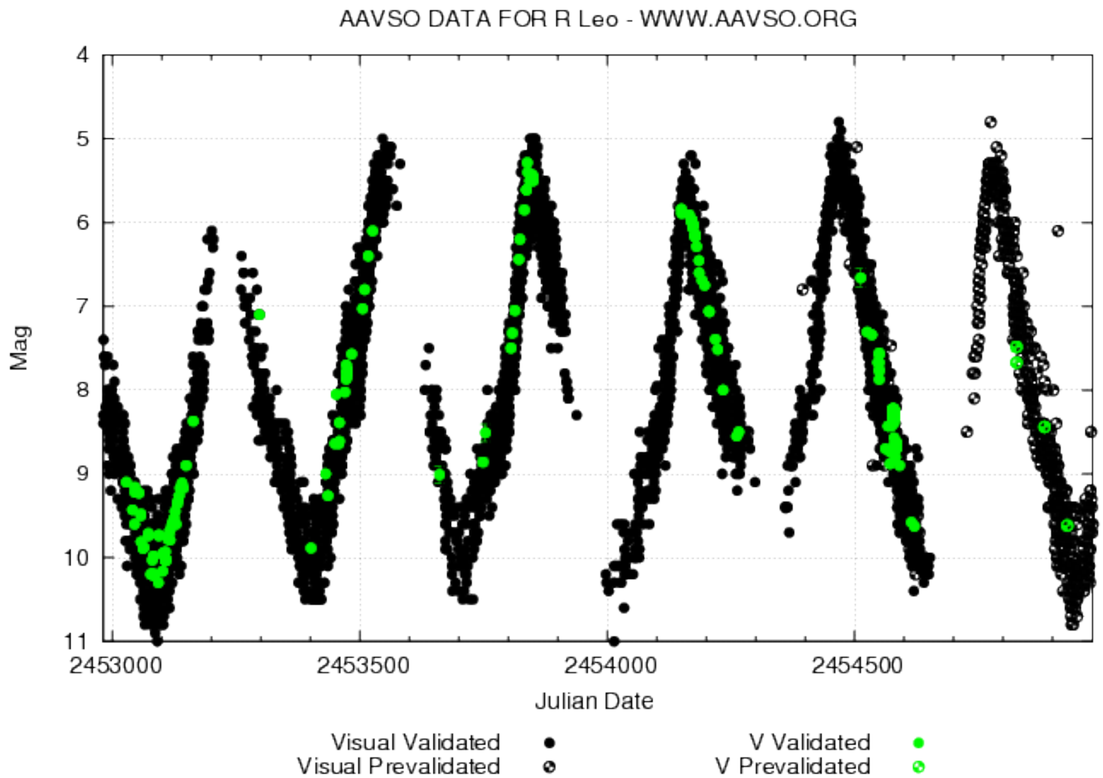
DSCT stars with amplitudes greater than 0.2 magnitudes are called High Amplitude Delta Scutis, or HADS.



A delta Scuti light curve. Note the very short period.

Recommended reading:
VSOTS Delta Scuti
http://www.aavso.org/vsots_delsct

Mira type variables (M), named after omicron Ceti (aka Mira), have relatively stable periods of 100-1000 days, with most falling between 150 and 450 days. Amplitudes in V can range from 2.5 to 10 magnitudes. With such large amplitudes they have historically been the most numerous and well-observed stars in the AAVSO program.



1000 day light curve of the Mira, R Leo

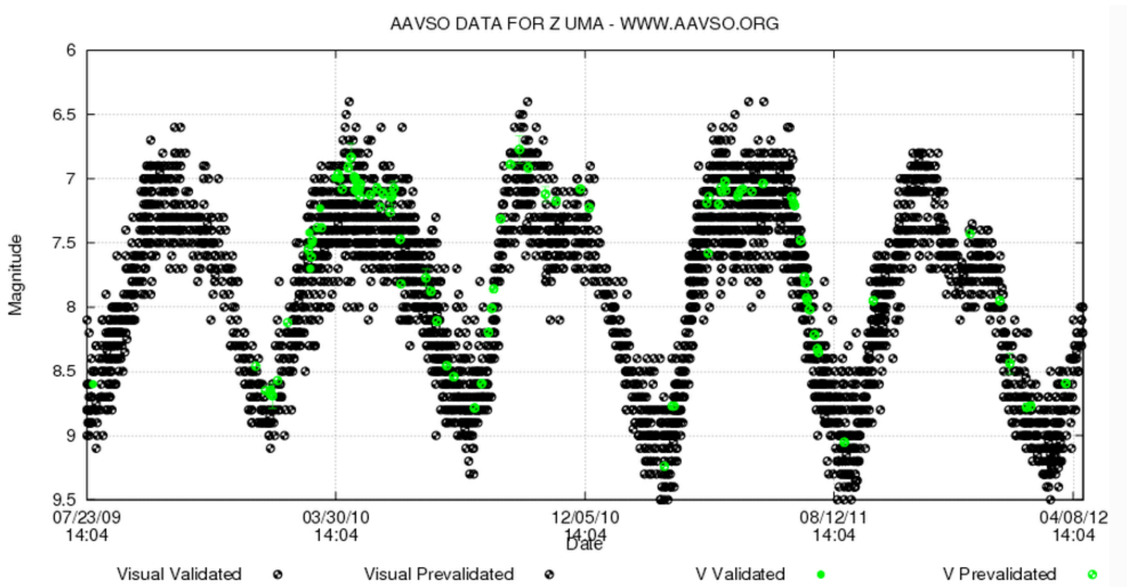
There are two reasons for the extreme visual amplitudes of Miras. First, as the star gets fainter, it also becomes cooler, so less of the total energy of the star is released in the visual part of the spectrum. Second, and more important, as the star becomes cooler it forms TiO molecules which are extremely efficient at absorbing light in the V band.

Miras are highly evolved stars with masses ranging from 0.6 to several times the Sun. Their radii can be several hundred times the Sun, where if they were placed in our solar system the outer atmosphere would extend beyond the Earth's orbit. They are the coolest, largest and most luminous red giants

Recommended reading, VSOTS:
VSOTS Mira 2
http://www.aavso.org/vsots_mira2
VSOTS RU Virginis
http://www.aavso.org/vsots_ruvir
And Miras with period changes
http://www.aavso.org/mira-variables-period-changes

*The following definitions are taken directly from the GCVS and VSX documentation.

<u>Semi-regular stars (SR)</u> are giants or supergiants of intermediate and late spectral types showing noticeable periodicity in their light changes, accompanied or sometimes interrupted by various irregularities. Periods lie in the range from 20 to >2000 days, while the shapes of the light curves are rather different and variable, and the amplitudes may be from several hundredths to several magnitudes (usually 1-2 mag in V).



1000 day light curve of Z UMa

(SRA) Semiregular late-type (M, C, S or Me, Ce, Se) giants displaying persistent periodicity and usually small (<2.5 mag in V) light amplitudes (Z Aqr). Amplitudes and light-curve shapes generally vary and periods are in the range of 35-1200 days. Many of these stars differ from Miras only by showing smaller light amplitudes.

(SRB) Semiregular late-type (M, C, S or Me, Ce, Se) giants with poorly defined periodicity (mean cycles in the range of 20 to 2300 days) or with alternating intervals of periodic and slow irregular changes, and even with light constancy intervals (RR CrB, AF Cyg). Every star of this type may usually be assigned a certain mean period (cycle), which is the value given in the Catalogue. In a number of cases, the simultaneous presence of two or more periods of light variation is observed.

(SRC) Semiregular late-type (M, C, S or Me, Ce, Se) supergiants (Mu Cep) with amplitudes of about 1 mag and periods of light variation from 30 days to several thousand days.

(SRD) Semiregular variable giants and supergiants of F, G, or K spectral types, sometimes with emission lines in their spectra. Amplitudes of light variation are in the range from 0.1 to 4 mags, and the range of periods is from 30 to 1100 days (SX Her, SV UMa).

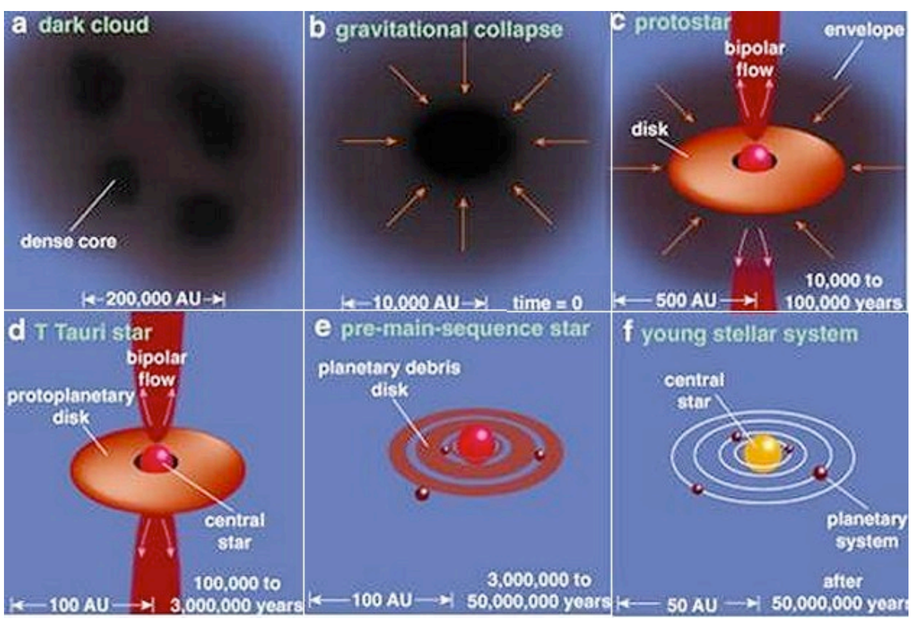
Suggested reading:
VSOTS W Hya
http://www.aavso.org/vsots_whya
VSOTS V725 Sagittarii
http://www.aavso.org/vsots_v725sgr

Eruptive Variables

Eruptive variables are a rather inhomogeneous group of objects. There is no single mechanism for their variability. The reasons for their behavior can be unique, unrelated to the other eruptive variables, or in some cases ill defined or poorly understood. In fact, many of the stars labeled as *irregular* in the GCVS may actually be assigned to other classes of stars once they are better understood.

Young Stellar Objects (YSOs)

Stars are born out of the gas of a giant molecular cloud in the interstellar medium contracting into a protostar. During this pre-main sequence phase of their evolution, variability may occur due to instabilities in their accretion disks. YSO can be used as a general term to describe all these pre-main sequence stars, or it may refer to a pre-main sequence star of unknown type.



Model of stellar and planetary birth

T Tauri stars (TTS) very young, lightweight stars, less than 10 million years old and under 3 solar masses. A T Tau star is still undergoing gravitational during a phase in its evolution between being a protostar and a low-mass main sequence star like the Sun.

T Tauri stars are found only in nebulae or very young clusters, have low-temperature (G to M type) spectra with strong emission lines and broad absorption lines.

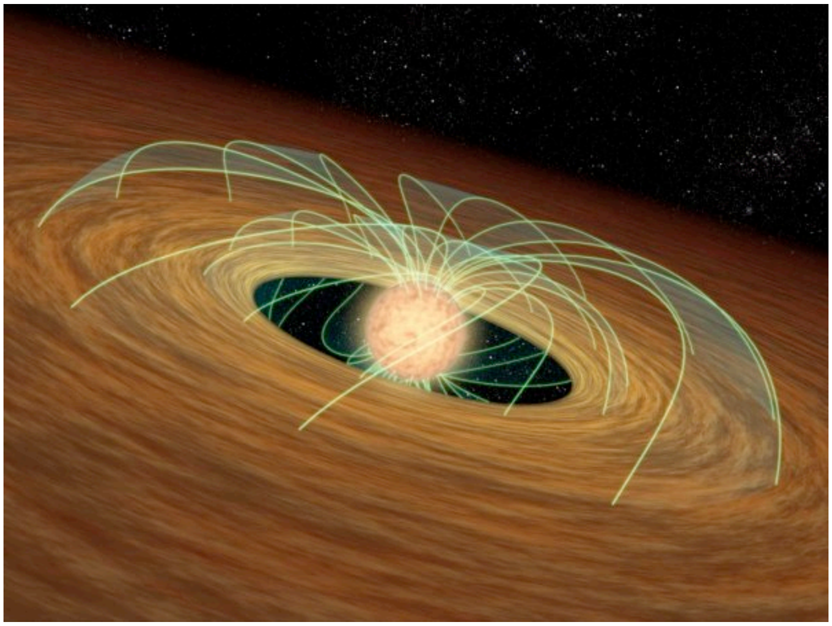
They often have large accretion disks left over from stellar formation. Their erratic brightness changes may be due to instabilities in the disk, violent activity in the stellar atmosphere, or eclipses from nearby clouds of gas and dust that sometimes block the starlight.

Two broad T Tauri types are recognized. Classic T Tauri stars (CTTS) and Weak-lined T Tauri stars (WTTS). Classical T Tauri stars have extensive disks that result in strong emission lines. Weak-lined T Tauri stars are surrounded by either a very weak disk or none at all.

The weak T Tauri stars are of particular interest since they provide astronomers with a look at early stages of stellar evolution unencumbered by nebulous material. Some of the missing disk matter may have gone into making planetesimals, from which planets might eventually form.

According to one estimate, about 60% of T Tauri stars younger than 3 million years may possess dust disks, compared with only 10% of stars that are 10 million years old.

Recommended reading:
VSOTS- The Trapezium, BM Orionis, and Young Stellar Objects
http://www.aavso.org/vsots_bmori
VSOTS T Tauri
http://www.aavso.org/vsots_ttau
The What and Why of YSOs!
http://www.starman.co.uk/ysosection/whatandwhy.php
http://www.starman.co.uk/ysosection/whatandwhy2.php



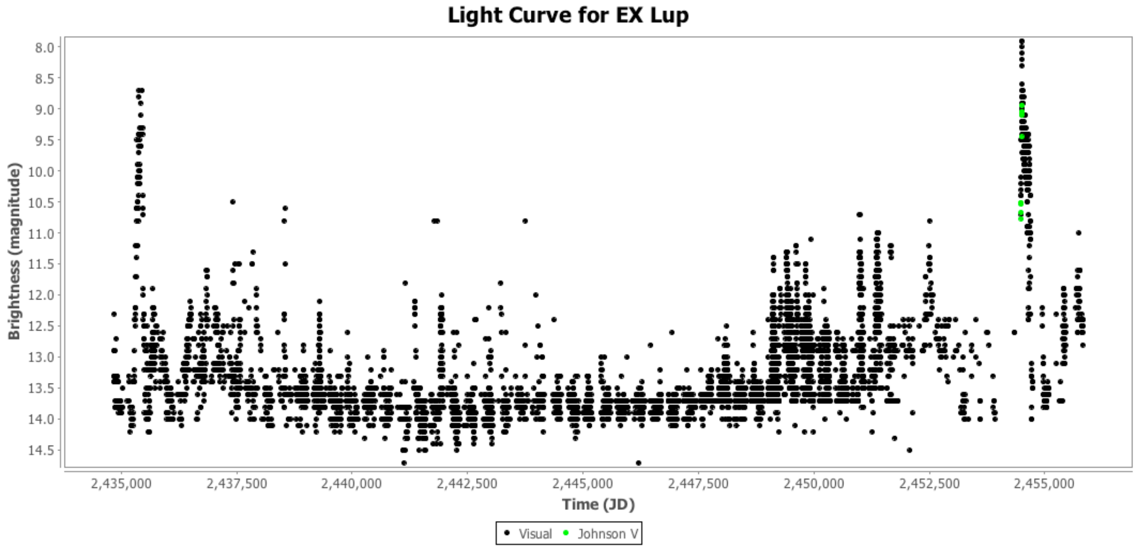
This artist's concept shows a young stellar object
and the whirling accretion disk surrounding it.
NASA/JPL-Caltech

FU Orionis variables (FUORs) are YSOs like T Tauri stars. They are the stars with the largest amplitude of variation in this group of stellar toddlers. They are characterized by a gradual increase in brightness of 4-6 magnitudes. They may then stay at maximum brightness for years or slowly fade.

The prototype, FU Ori, rose to fame in 1937 when an obscure at 16th magnitude object brightened by a factor of over 100 in 100-200 days. Accompanying the phantom star was a bright nebulosity, which glowed by the reflection of light from the luminous star. After increasing by 6 magnitudes in a period of a year, FU Ori continued to linger around maximum magnitude, where it has resided in a high state, along with its ghostly nebula, ever since. A similar reflection nebula accompanies all known FUORs.

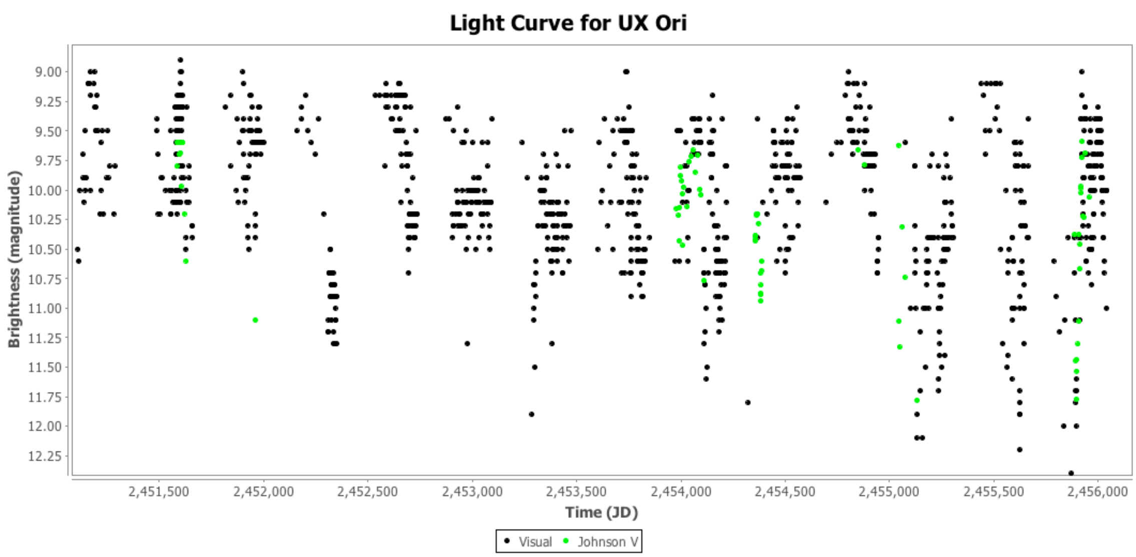
Recommended reading:
VSOTS- FU Orionis
http://www.aavso.org/vsots_fuori
The Furor Over FUors
http://simostronomy.blogspot.com/2010/11/furor-over-fuors.html

EXors (EXOR), named after EX Lupi, are eruptive T Tauri stars that show brightening episodes of a few magnitudes on timescales of several months or more. These outbursts are less luminous than FUOR outbursts and may repeat, as opposed to being just one brightening episode. The EXor phase seems to follow the FUor phase rather than being simply another manifestation of T Tau evolution.



Historical AAVSI light curve of EX Lupi

UXors (UXOR) are a highly variable subset of Herbig-Ae stars, pre-main sequence stars of intermediate mass, named after the prototype object UX Orionis. The nature of UXORs is a matter of on-going debate, but one possibility is that they are young systems viewed through some portion of their circumstellar environment that occasionally obscures the central star. Their light curves are characterized by irregular variations on time scales of days, and sometimes mean changes on longer time scales, and irregular episodes of deep minima.



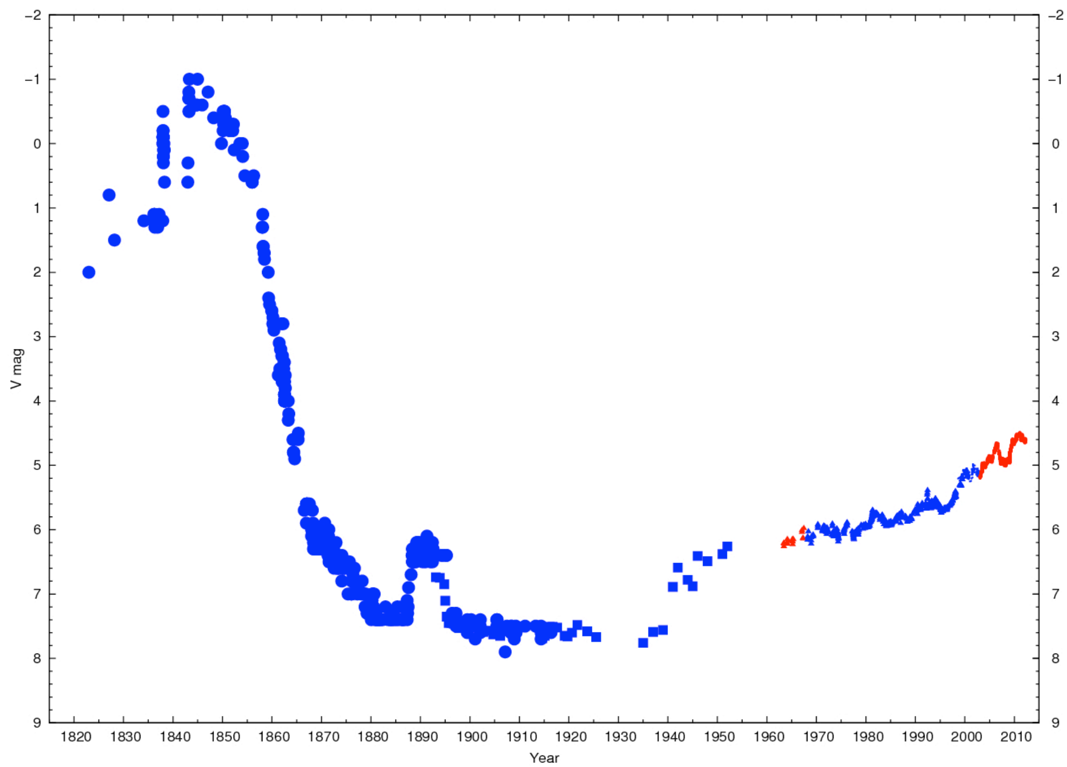
AAVSO light curve of UX Orionis

UV Cet stars (UV) are flare stars, showing bright flares, up to several magnitudes, that occur within seconds and subside within seconds or minutes. These stars are red dwarfs of K Ve to M Ve spectral type.

Gamma Cas stars (GCAS) are rapidly rotating irregular variables of spectral type O, B or A, with mass outflow from their equatorial zones. A temporary brightening or fading, by as much as 1.5 magnitudes, accompanies the formation of equatorial rings or disks.

See VSOTS: Gamma Cassiopeia and the Be Stars
http://www.aavso.org/vsots_gammacas

S Doradus stars (SDOR) are also known as luminous blue variables (LBVs). These are extremely luminous stars whose variations take place on time scales of days to decades. S Doradus is the most luminous star in the Magellanic Clouds. Brighter members in our own galaxy include P Cygni and eta Carinae. Although rare, because they are so luminous they can be seen at great distances, making them both interesting and useful to astronomers.



This light curve depicts the visual apparent brightness of Eta Car since 1822 up to date. It is based on the references given by Fernández-Lajús et al. (2009, A&A, 493, 1093), and the present observations. It contains visual estimates (big circles), photographic (squares), photoelectric (triangles) and CCD (small circles) observations through different visual filters and photometric systems. All of them have been fitted for consistency of the whole data. Red points are observations from La Plata (Feinstein 1967; Fernández-Lajús et al. 2009a, 2009b, 2010). New CCD data obtained from RXTE Star Tracker has been plotted to complete the gap in the light curve before 2003 (Craig Markwardt & Mike Corcoran, private communication, 2009).

Recommended reading:
VSTOTS- Eta Carinae
http://www.aavso.org/vsots_etacar
Eta Carinae, A Naked Eye Enigma
http://simostronomy.blogspot.com/2009/12/eta-carinae-naked-eye-enigma.html

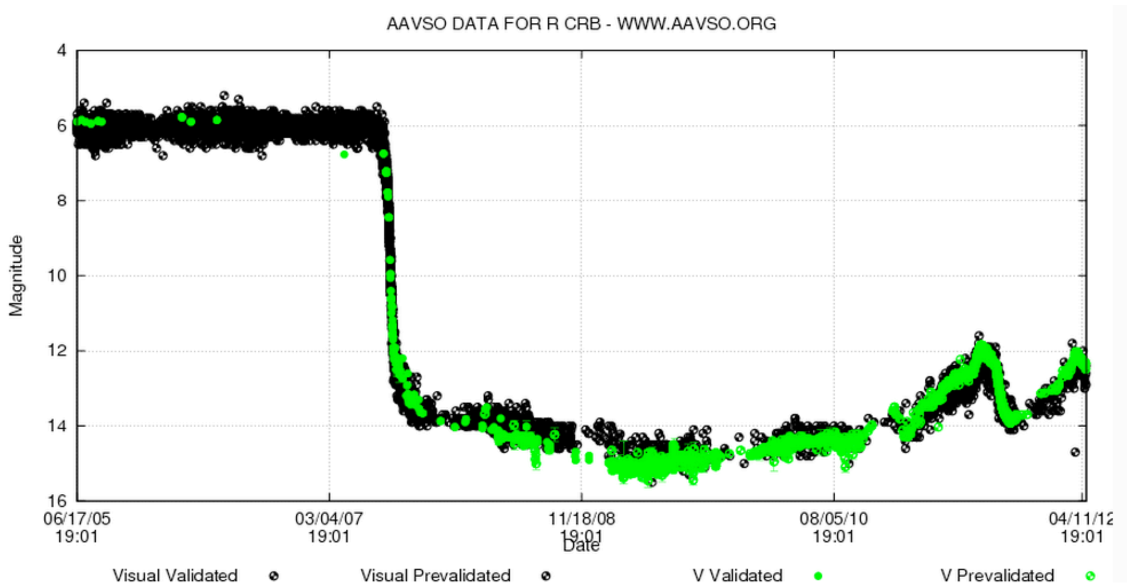
R Corona Borealis stars (RCB) are unlike any other class of variables, and although typically included in the eruptive class of variables, they probably deserve their own distinction.

RCB are a small group of hydrogen poor, carbon rich supergiants that decline in brightness unpredictably and rapidly by up to 9 magnitudes, and remain at or near minimum light for several weeks or months, even years in some cases. It is generally accepted that the declines are the result of the formation of a cloud of carbon soot that obscures the stellar photosphere, and that this condensation takes place in matter that has been ejected from the stellar surface toward the observer.

Some RCBs exhibit more or less regular variations that may be interpreted as pulsations. The amplitudes of these changes are small, on the order of a few tenths of a magnitude, and have periods of approximately 30 days to 150 days. This pulsation appears to have no relationship to the obscuring events, and has been seen to continue through fading episodes in several cases.

RCBs are intriguing because they challenge our models for stellar structure and evolution. At first, they were believed to be highly evolved post-AGB stars, but most scenarios fail to explain the hydrogen abundance or trace their evolution back to the AGB.

Two more recent ideas suggest that 1) these may be ‘born again’ planetary nebula, created when the last thermal pulse is delayed to the point that it occurs as the star reaches the white dwarf phase. If the pulse is intense enough it may re-ignite a helium burning shell and expand the star to giant dimensions, moving it to the AGB for a second time, or that 2) RCBs may be the result of the merger of helium and CO white dwarfs. The merger theory goes a long way to explaining the exotic chemical composition of these stars.



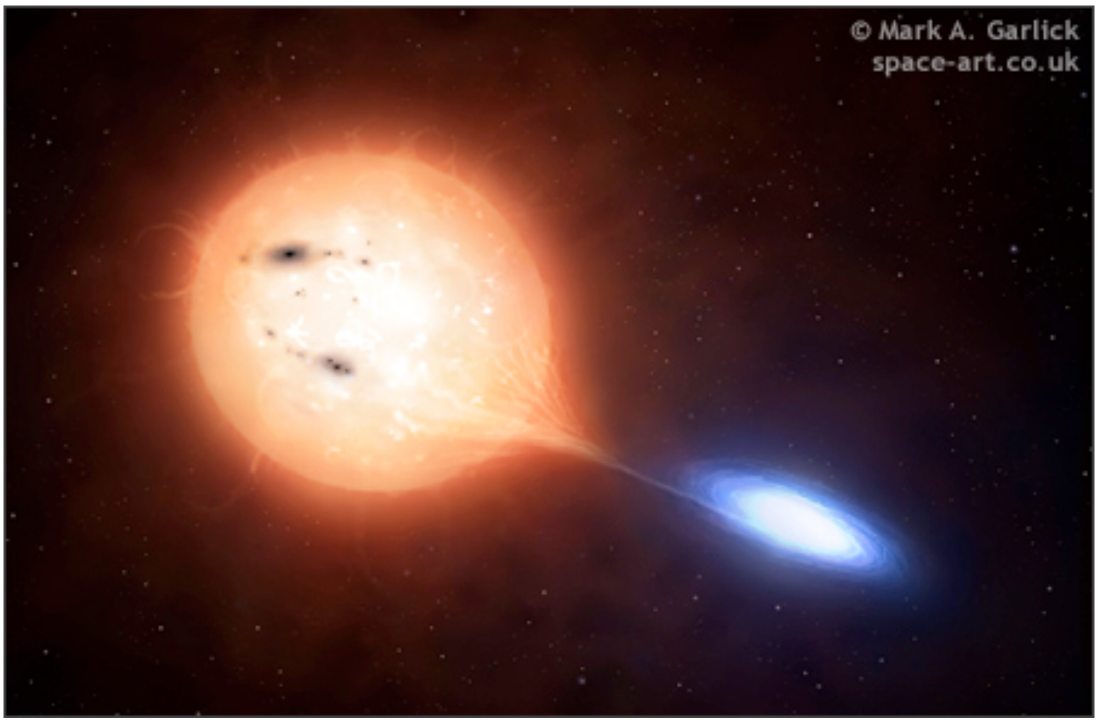
The AAVSO 2500-day light curve of R CrB

Further reading:
VSOTS R Corona Borealis
http://www.aavso.org/vsots_rcrb
Northern R Cor Bors: The Good, the Boring and the Unknown
http://simostronomy.blogspot.com/2011/10/northern-r-cor-bors-good-boring-and.html

Chapter Four

Cataclysmic Variables (CVs)

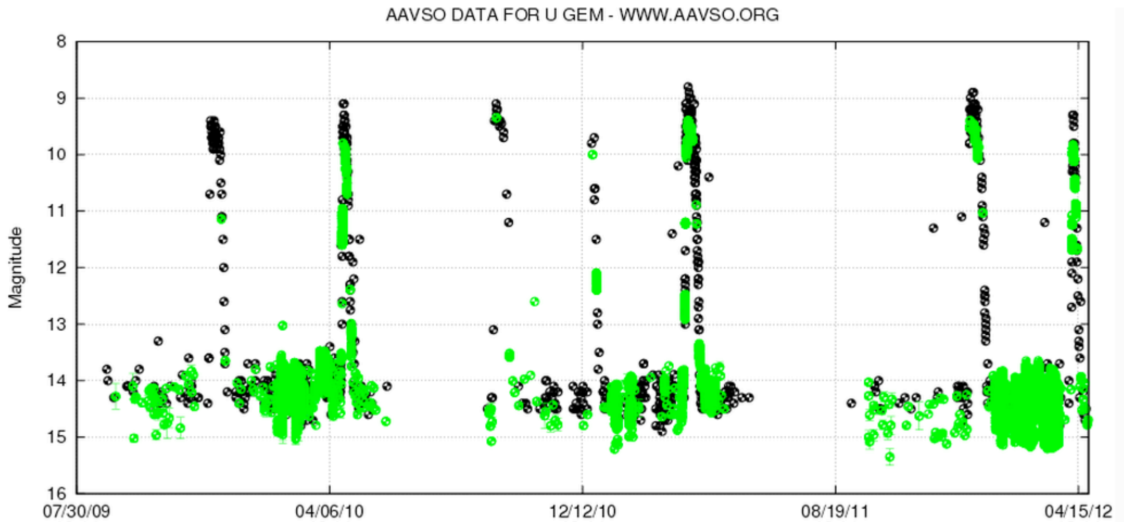
CVs are semi-detached close binary systems in which a white drwarf (WD) accretes material from a Roche-lobe-filling secondary. In most known CVs, the secondary is (almost always) a main sequence star, and the transfer of mass from the secondary to the WD happens via an accretion disk. The orbital periods of CVs are typically between 75 min and 6hrs, although there are exceptional systems– usually with evolved or compact donor stars–with periods outside this range.



A typical cataclysmic variable, consisting of a red dwarf secondary that has filled its Roche lobe and is losing matter, via an accretion disk, onto a white dwarf primary.

Dwarf Novae

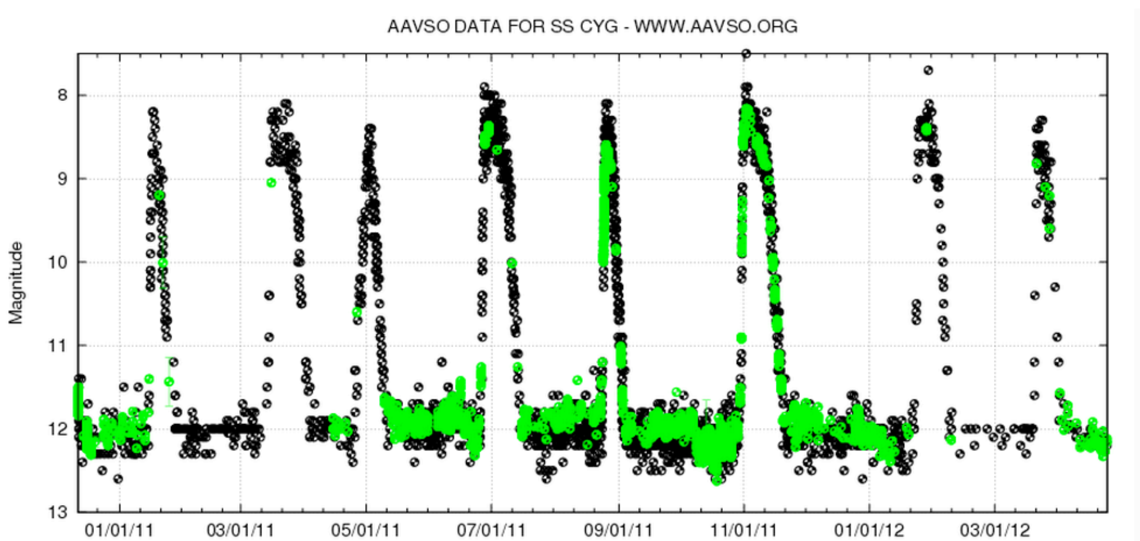
Dwarf Novae (DNe) or U Geminorum-type variable stars (UG), are cataclysmic variables consisting of a close binary star system in which one of the components is a white dwarf, which accretes matter from its companion. They are similar to classical novae in that the white dwarf is involved in periodic outbursts, but the mechanisms are different. Current theory suggests that dwarf novae result from instability in the accretion disk, when gas in the disk reaches a critical temperature that causes a change in viscosity, resulting in a collapse onto the white dwarf that releases large amounts of gravitational potential energy.



1000 day light curve of U Gem

There are three subtypes of U Geminorum star (UG), based mostly on their light curves: UGSS, UGSU and UGZ.

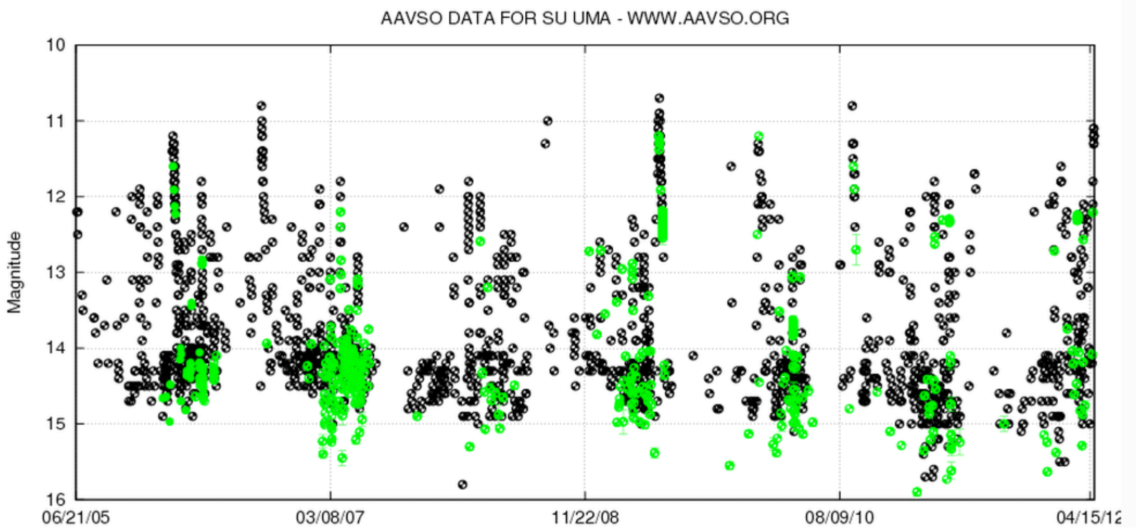
SS Cygni stars (UGSS), which increase in brightness by 2-6 mag in V in 1-2 days, and return to their original brightness in several subsequent days. Cycle times between outbursts ranges from a few days to years. Orbital periods are usually longer than 3 hours.



500 day light curve of SS Cygni. Note the two distinct types of outbursts.

SU Ursae Majoris stars (UGSU), which, along with normal outbursts, have brighter and longer "super-outbursts." The cycle times of superoutbursts (super-cycle) are usually several times the length of time between normal outbursts. Orbital periods are usually shorter than 2 hours.

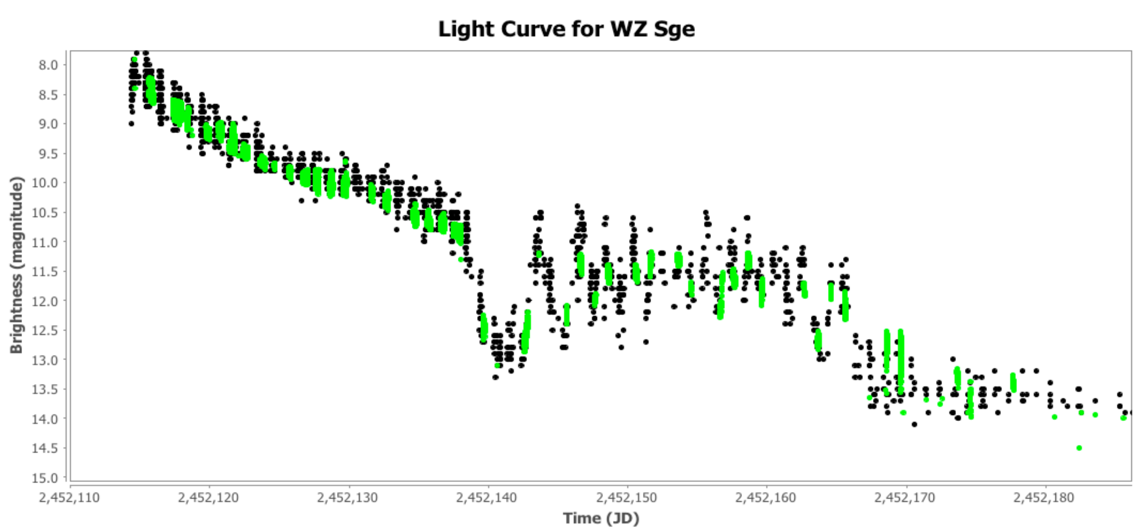
During a superoutburst, UGSU show an additional modulation of the light curve, a "superhump", which is caused by precession of the accretion disc. Superhumps show up in the light curve as a modulation with a period slightly longer (a few percent) than the orbital period.



AAVSO 2500 day light curve of SU UMa showing normal and superoutbursts

UGSU have two recognized sub-classes.

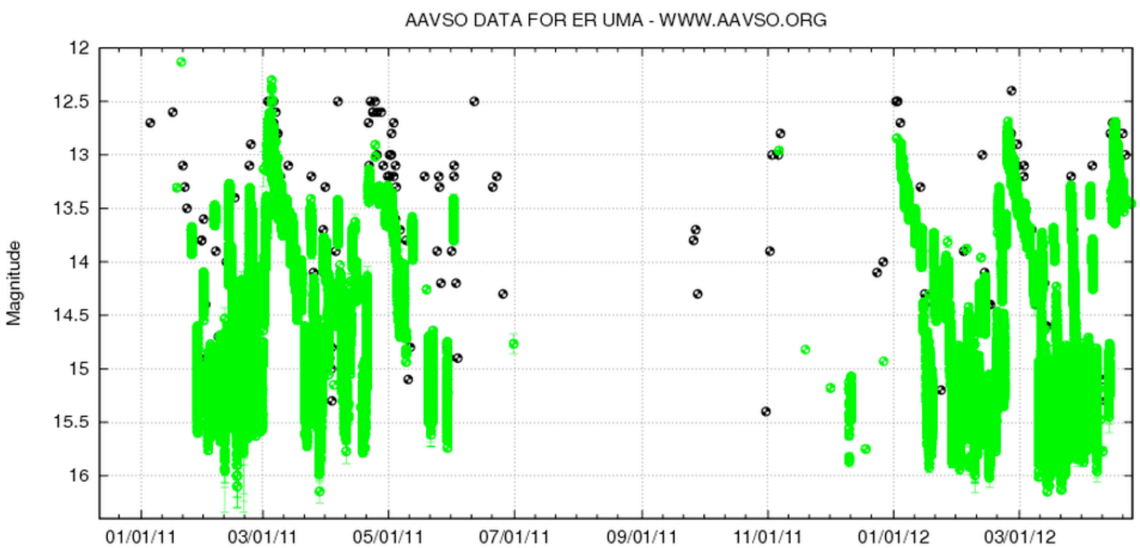
WZ Sagittae stars (UGWZ) are ultra-short period UGSU (typically 90 minutes or less) that only exhibit superoutbursts, and the cycle time between outbursts ranges from a few years to decades. The amplitudes of the outbursts can rival those of novae (6-9 magnitudes). Many of the UGWZ also show re-brightenings or "echo outbursts" as they fade from maximum.



2001 outburst of WZ Sge and subsequent echo outbursts

Suggested reading:
VSOTS SU Ursae Majoris
http://www.aavso.org/vsots_suuma
VSOTS WZ Sagittae
http://www.aavso.org/vsots_wzsge

ER Ursae Majoris stars (UGER) are dwarf novae in which the interval between super-outbursts is usually short (only 20 to 50 days). ER UMa stars typically spend a third to a half their time in super-outburst. When not in super-outburst these stars show frequent normal outbursts- one every few days. (*Sometimes referred to as RZ LMi stars*)



500 day light curve of ER UMa showing frequent normal outbursts and several superoutbursts.

UGER often show negative superhumps in their light curves. Negative superhumps result when the accretion disc is tilted with respect to the orbital plane. The nodes of the tilted disc precess slowly in the retrograde direction (nodes are the points where the edges of the tilted disk pass through the orbital plane), resulting in a photometric signal with a period slightly less than the orbital period.

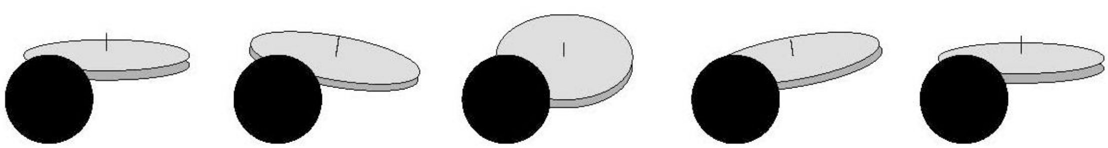
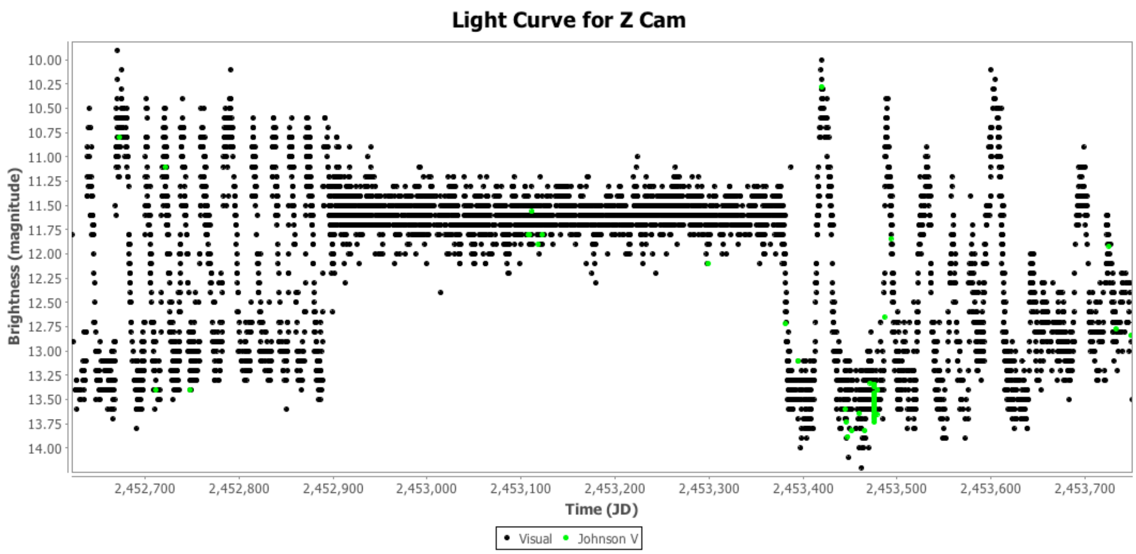


Illustration of a tilted disk at the same orbital phase while the tilt precesses through the cycle.

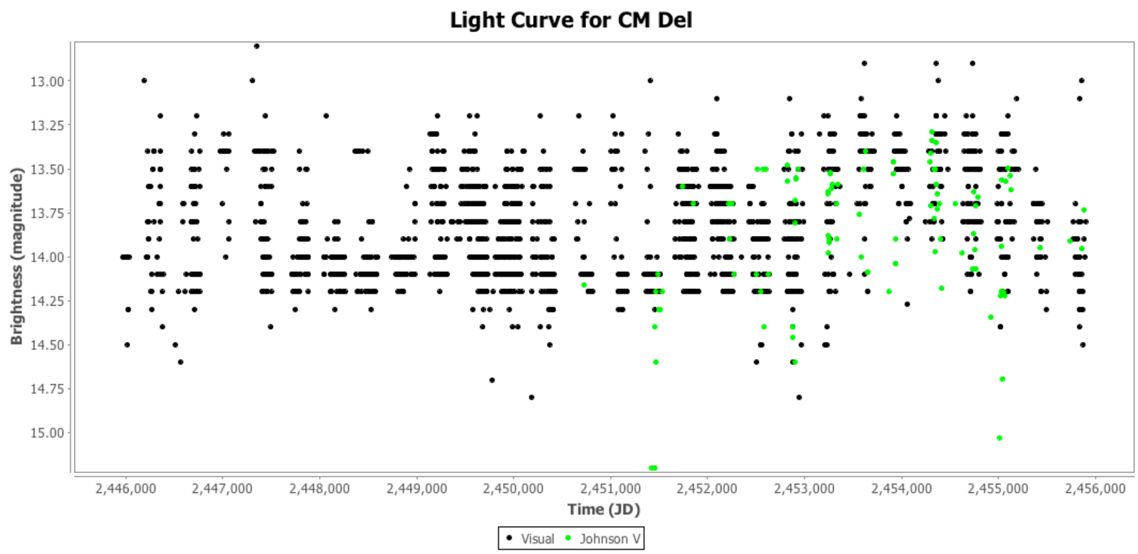
Z Camelopardalis stars (UGZ) are DNe that in exhibit normal U Gem-type outbursts (a rise from quiescence of 2–6 magnitudes and 1–3 day durations), as well as random standstills. A standstill usually starts at the end of an outburst and consists of a period of constant brightness, 1 to 1.5 magnitudes below maximum light that may last from a few days to 1,000 days. Standstills are thought to occur when the mass transfer rate from the secondary star into the accretion disk around the primary star is too large to produce normal outbursts.



A standstill in the light curve of the prototype of the class- Z Cam

Why Observe Z Cam Stars?
https://sites.google.com/site/thezcamlist/why-observe-z-cam-stars
VSOTS RX Andromedae
http://www.aavso.org/vsots_rxand

Nova-like (NL) variables are those CVs that have such a high mass transfer rate that they are essentially stuck in outburst all the time. Their light curves are basically flat, showing fluctuations on the order of one magnitude at most.



AAVSO light curve of CM Del, a nova-like variable showing activity limited to about 1 magnitude in V

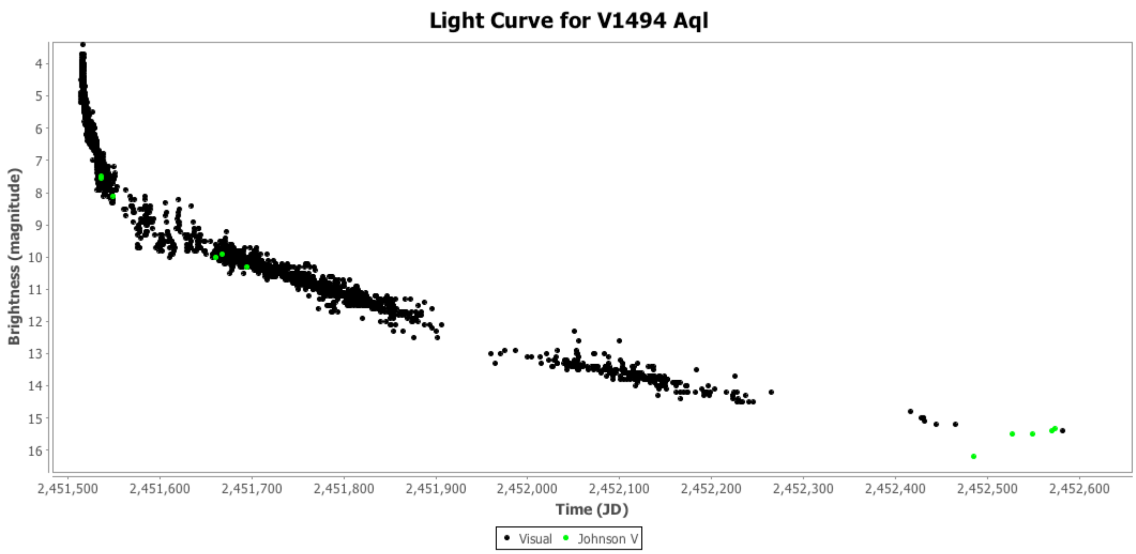
The name is confusing, and deserves a bit of explanation. Early observers knew of novae and dwarf novae, but also discovered some stars that were similar to the remnants of past novae. They called them "nova-likes" because they assumed (correctly) that novalikes and old novae were the same type of star, the only distinction being whether they had been observed to undergo a nova eruption or not.

Suggested reading:
VSOTS UX Ursae Majoris
http://www.aavso.org/vsots_uxuma
VSOTS Dwarf Novae
http://www.aavso.org/vsots_archive#ugem

Novae

Novae (N) are close binary systems with orbital periods from 0.05 to 230 days. The cause of a nova eruption is a thermonuclear reaction on the surface of the white dwarf. After years of mass exchange between the binary pair, temperature and pressure at the surface of the white dwarf build sufficiently to cause the layer of accreted material to explode like a hydrogen bomb. This bomb, however, can have the mass of 30 Earths! Once the temperature becomes high enough, this layer begins to expand. Minutes into the process the shell can be radiating at 100,000 solar luminosities and expanding outwards at 3000 km/s. Eventually the shell envelopes the entire binary and the orbital motion of the pair acts like a propeller to whip things up. After 1000 days or so the envelope expands to the point it can be seen as nebulosity surrounding the pair. Over hundreds of years the shell dissipates into the interstellar medium.

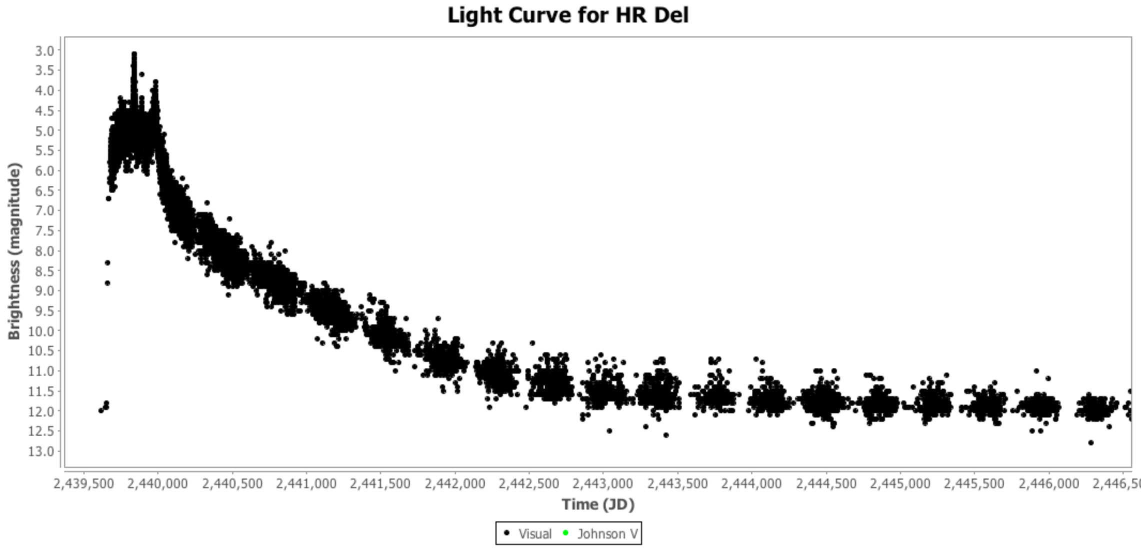
Most novae probably erupt more than once in their lifetime, with the mass of the white dwarf determining the amount of accreted material that needs to accumulate before triggering on outburst. Systems with a white dwarf of 0.6 solar masses might take as long as 5 million years between eruptions. A system with a 1.3 solar mass white dwarf might only take 30,000 years between eruptions.



Light curve of V1494 Aql (NA) showing its rapid decline from maximum

The novae with the largest outburst amplitudes fade the fastest. Novae are further sub-divided by the time it takes to fade by 3 magnitudes from maximum light.

- (NA) Fast novae, with a rapid brightness increase, followed by a brightness decline of 3 magnitudes within 100 days.
- (NB) Slow novae, with a 3 magnitudes decline in 150 days or more.
- (NC) Very slow novae, staying at maximum light for a decade or more, fading very slowly. It is possible that NC type novae are objects differing physically very much from normal novae. The cool components of these systems are probably giants or supergiants, sometimes semi-regular variables, and even Mira variables. They may be planetary nebulae in the process of formation.



AAVSO light curve of HR Del a typical slow nova (NB)

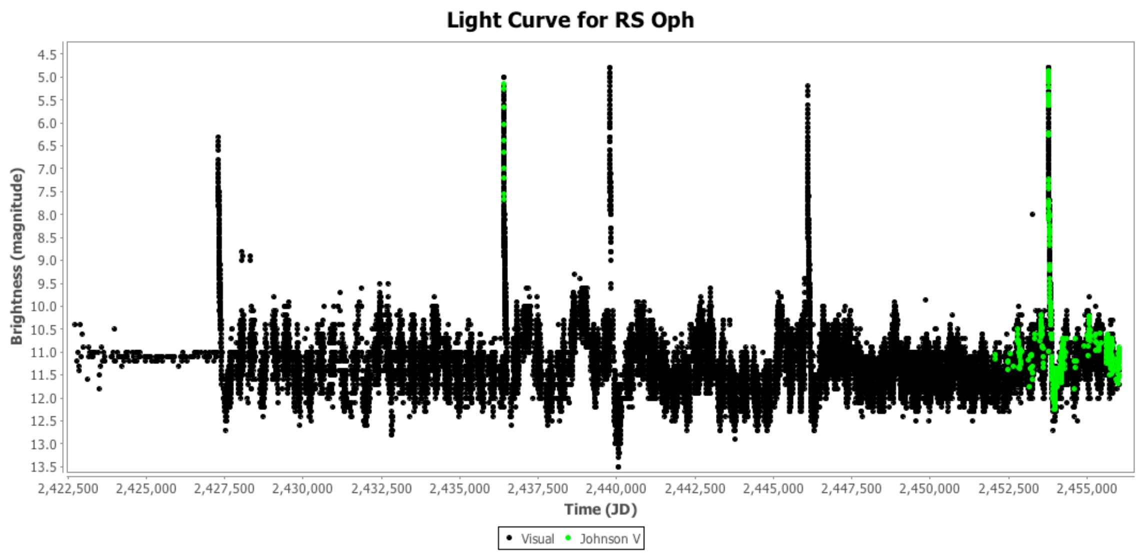
Suggested reading:
VSOTS Novae (2012 Edition)
http://www.aavso.org/vsots_novae

Recurrent Novae (NR)

In the General Catalog of Variable Stars (GCVS) recurrent novae are included in the same category as novae, with the main distinction being the features of their light curves. "According to the features of their light variations, novae are subdivided into fast (NA), slow (NB), very slow (NC), and recurrent (NR) categories.
Recurrent novae differ from typical novae by the fact that two or more outbursts (instead of a single one) separated by 10-80 years have been observed (T CrB)."

This implies that the outburst mechanism, orbital periods, spectra and the nature of the components of these close binaries are the same or very similar.

So are recurrent novae simply the same type systems with even more massive white dwarfs? The accretion rate of a system with a 1.4 solar mass white dwarf could have a recurrence time of less than 100 years. T Pyx may be one such system, but it is unclear at present if the outburst mechanism for all recurrent novae is the same as novae, or if some are the result of accretion by Roche-lobe overflow or stellar winds, or a result of disc instabilities.



The entire historical AAVSO light curve of RS Ophiuchi showing the known outbursts

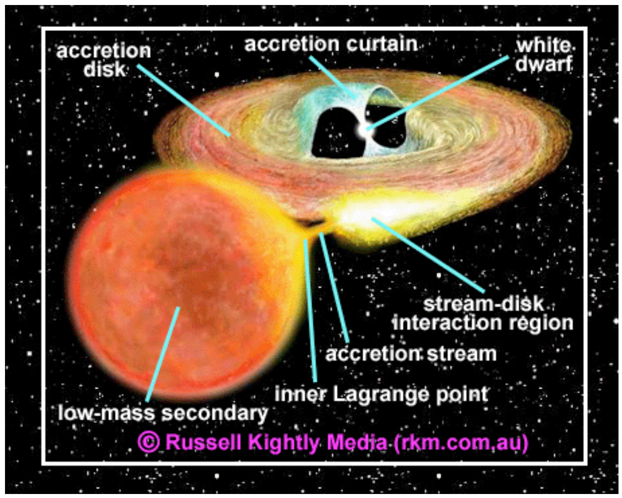
Even more interesting is the possibility that recurrent novae may actually be progenitors of Type Ia supernovae. Observations of novae eruptions and the resulting nebulae indicate the mixing of the accreted layer with the outer layers of the white dwarf may cause the white dwarfs to lose mass over time and repeated eruptions.

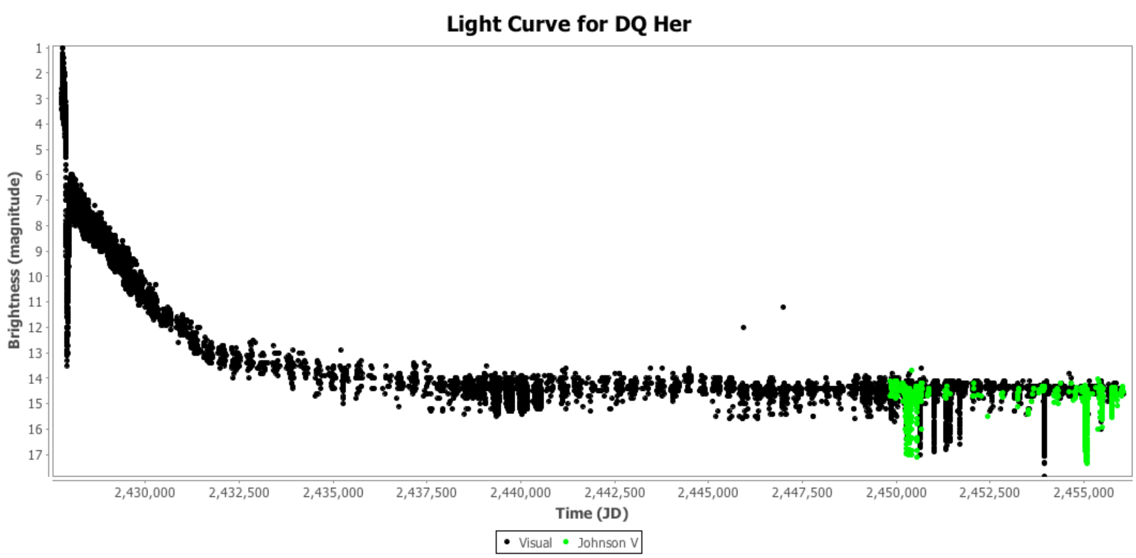
The heaviest white dwarfs, with their higher accretion rates, may actually gain mass over time! Although a large part of the envelope mass is blown away in the wind, these primaries may retain a substantial part of the envelope mass after hydrogen burning ends. The white dwarfs in some recurrent novae have now grown up to near the Chandrasekhar mass limit and might soon explode as a Type Ia supernova.

Suggested reading:
VSOTS U Scorpii
http://www.aavso.org/vsots_usco
VSOTS T Pyxidis
http://www.aavso.org/vsots_tpyx
VSOTS RS Ophiuchi
http://www.aavso.org/vsots_rsoph
Hubble's 1923 Nova in Andromeda Erupts Again!
http://simostronomy.blogspot.com/2012/02/hubbles-1923-nova-in-andromeda-erupts.html
Amateur Astronomers Alert the World to a Rare Stellar Eruption
http://simostronomy.blogspot.com/2010/01/amateur-astronomers-alert-world-to-rare.html

Magnetic CVs

<u>DQ Herculis stars (DQ)</u> *Intermediate Polars*
The intermediate polars or DQ Her stars (named after the prototype DQ Her) show magnetic field strengths around the white dwarf star on the order of 1-10 Mega Gauss. An accretion disk forms, but is disrupted close to the white dwarf (primary) star due to the magnetic field. The magnetosphere is not strong enough to synchronize the orbits of the rotating white dwarf with the orbital period of the system (as seen in AM Her stars)

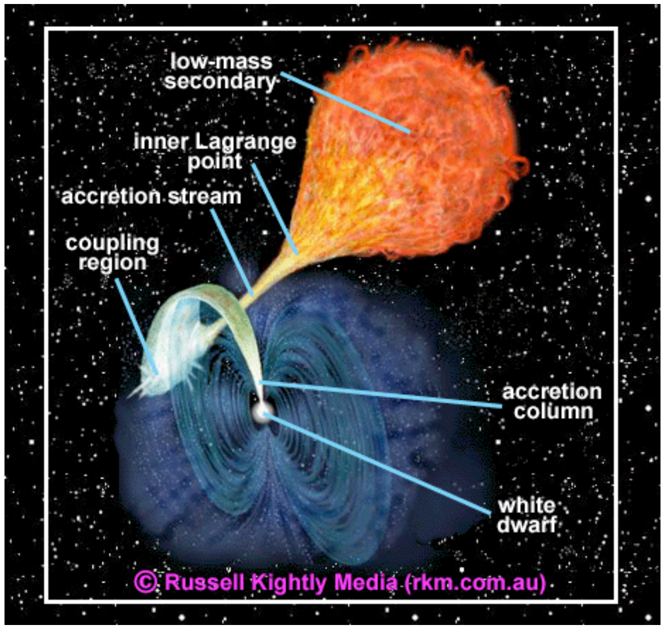


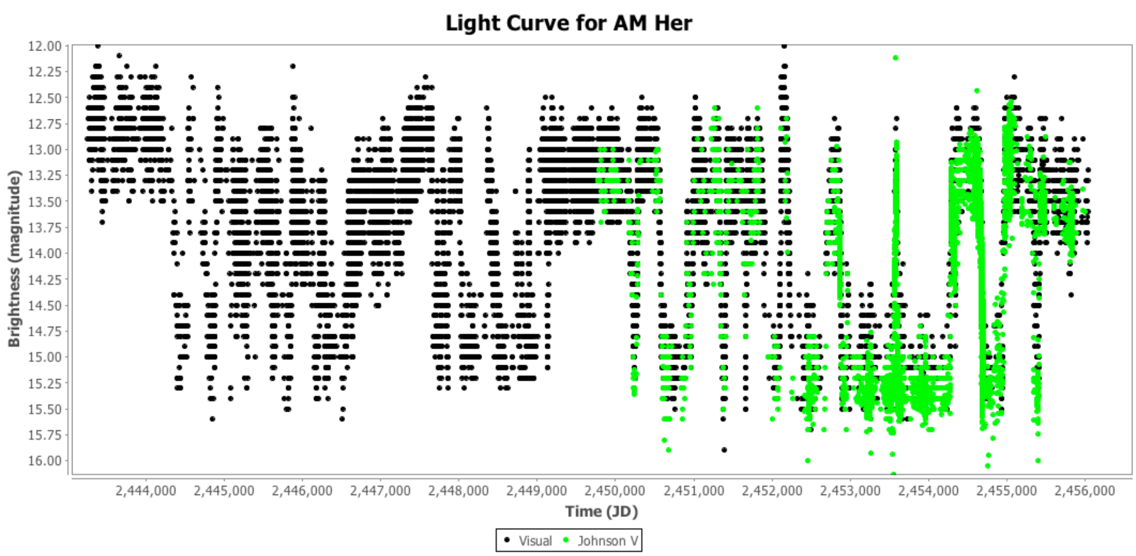


The historical light curve of DQ Herculis, showing the initial nova eruption and subsequent activity

<u>AM Her stars (AM)</u> *Polars*
The polars or AM Her stars (named after the prototype AM Her) display magnetic field strengths on the order of 10-100 Mega Gauss. This magnetic field is so powerful that it prevents the formation of an accretion disk around the white dwarf and locks the two stars together so they always present the same face to each other. Thus the white dwarf

star spins at the same rate as the two orbit each other - a synchronous rotation that is the defining characteristic of an AM Her star. (About 10% of AM Her stars are asynchronous, where the rotations of the white dwarf and the orbit are off by ~ 1%)

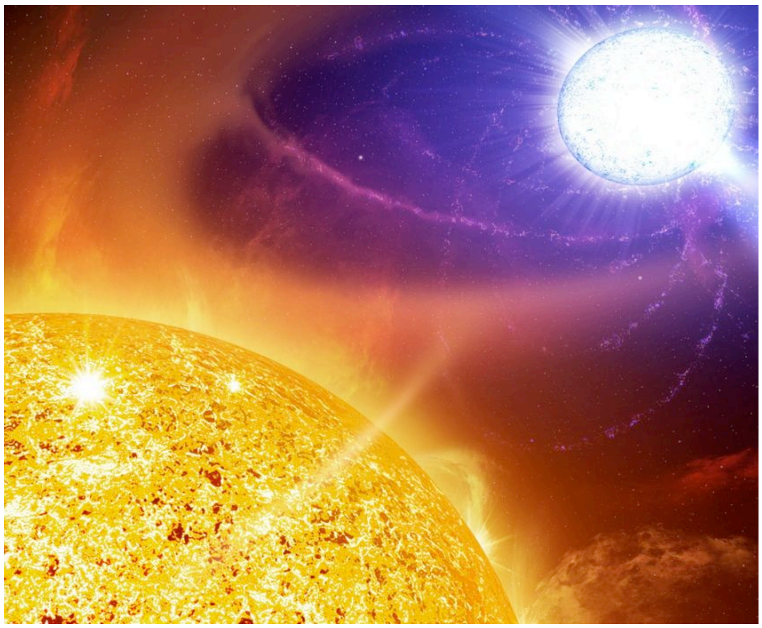




This light curve shows the alternating high and low states of AM Herculis.

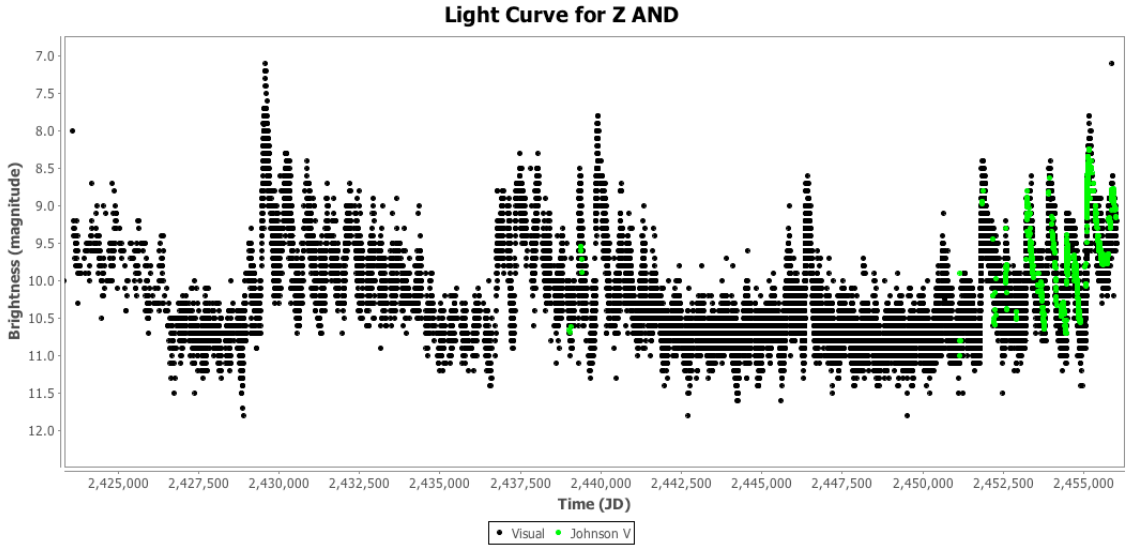
Suggested reading:
VSOTS AM Herculis
http://www.aavso.org/vsots_amher

Symbiotic Variables, or Z Andromedae stars (ZAND) are interacting binary stars composed of an evolved red giant and a hot companion star. Most symbiotics have orbital periods of a few years; some systems orbit over several decades. In all systems, the hot component - a main sequence star, a white dwarf, or a neutron star - accretes material lost by the red giant. This accreted material powers most of the symbiotic variability, including occasional eruptions and jets. Some systems are also eclipsing systems, so there can be a lot to untangle when considering symbiotic variability!



An illustration of a swollen red giant and a hot blue companion star inside a common envelope.
The recipe for symbiotic variables.

Spectra of symbiotic stars suggest that there are three regions that emit radiation: the individual stars themselves and the nebulosity that surrounds them both. The nebulosity is thought to originate from the red giant, which is in the process of losing mass quite rapidly either through a stellar wind or through pulsation. The symbiotic phase represents a late stage in stellar evolution and a brief span in the life of the binary. Because of the short timescale involved, symbiotic stars are relatively rare objects. Only a few hundred are known.



The historical AAVSO light curve for Z And, showing outbursts an periods of relative quiescence.

Besides their erratic, multi-causational variability, astronomers are also interested in ZAND stars because they are likely progenitors of bipolar planetary nebulae and could make up some of the systems that later explode as Type Ia supernovae.

Suggested reading:
VSOTS Z Andromedae
http://www.aavso.org/vsots_zand
Symbiotic Variable On the Verge of Eruption?
http://simostronomy.blogspot.com/2010/11/symbiotic-variable-star-on-verge-of.html
VSOTS CI Cygni
http://www.aavso.org/vsots_cicyg
VSOTS CH Cygni
http://www.aavso.org/vsots_chcyg
VSOTS R Aquarii
http://www.aavso.org/vsots_raqr

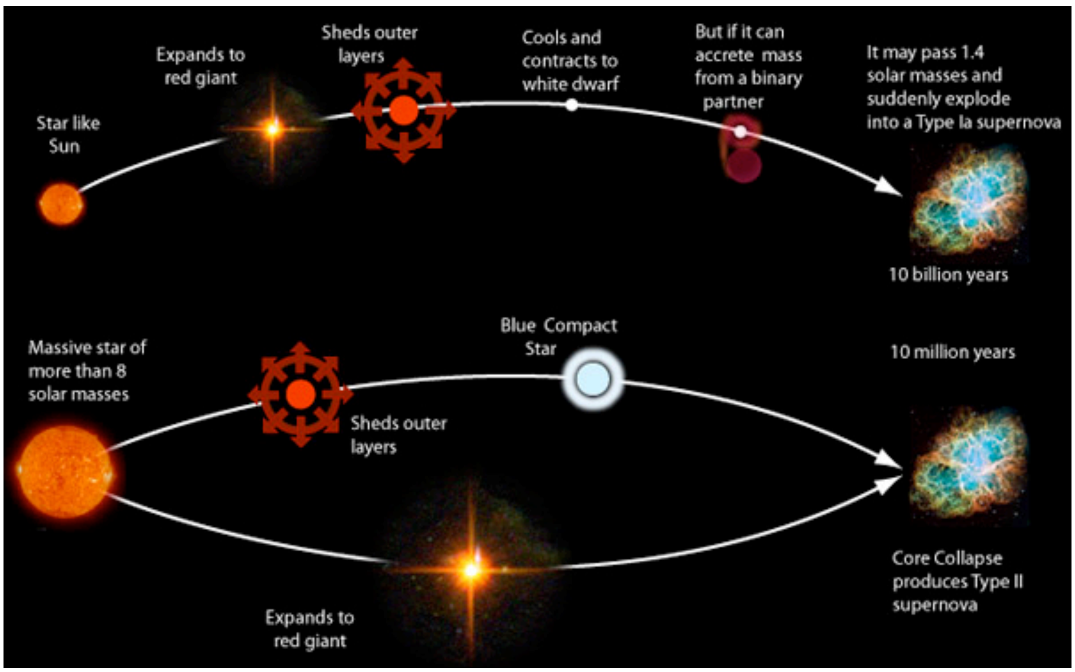
Supernovae

Supernovae are the ultimate cataclysmic variable. When they erupt, they brighten by 10 to 20 magnitudes, reaching an absolute magnitude of -15 to -20, then, they slowly fade over periods of months to years. In the process the star is transformed into a rapidly expanding shell of material and a collapsed core, consisting of a neutron star or black hole.

Despite the similarity to novae explosions, the eruption mechanism and the consequences are totally different. A supernova is the end of the line in a star's evolution. It is either destroyed completely or transformed into an exotic object.

Astronomers classify them according to the absorption lines of different chemical elements that appear in their spectra. The primary element used to classify SNe is hydrogen. Type II supernovae show the presence of the element hydrogen in their spectra. Type I supernovae do not show any hydrogen in their spectra. Among those main types, there are subdivisions according to the presence of lines from other elements and the shape of the light curve.

Although there is still plenty of discussion about SNe progenitors, it is largely accepted that Type I SNe are old population binaries where one component is a white dwarf that reaches a critical mass, *the Chandrasekhar limit*, and then blows itself to pieces. Type II supernovae are the spectacular result of the short evolutionary track of massive single stars.



Because Type I SNe have similar light curves and a small range of absolute magnitudes, they are used as standard candles to measure great distances in the universe. A more detailed discussion of supernovae theory and observation is beyond the scope of this course, but would make an excellent subject for a future CHOICE course.

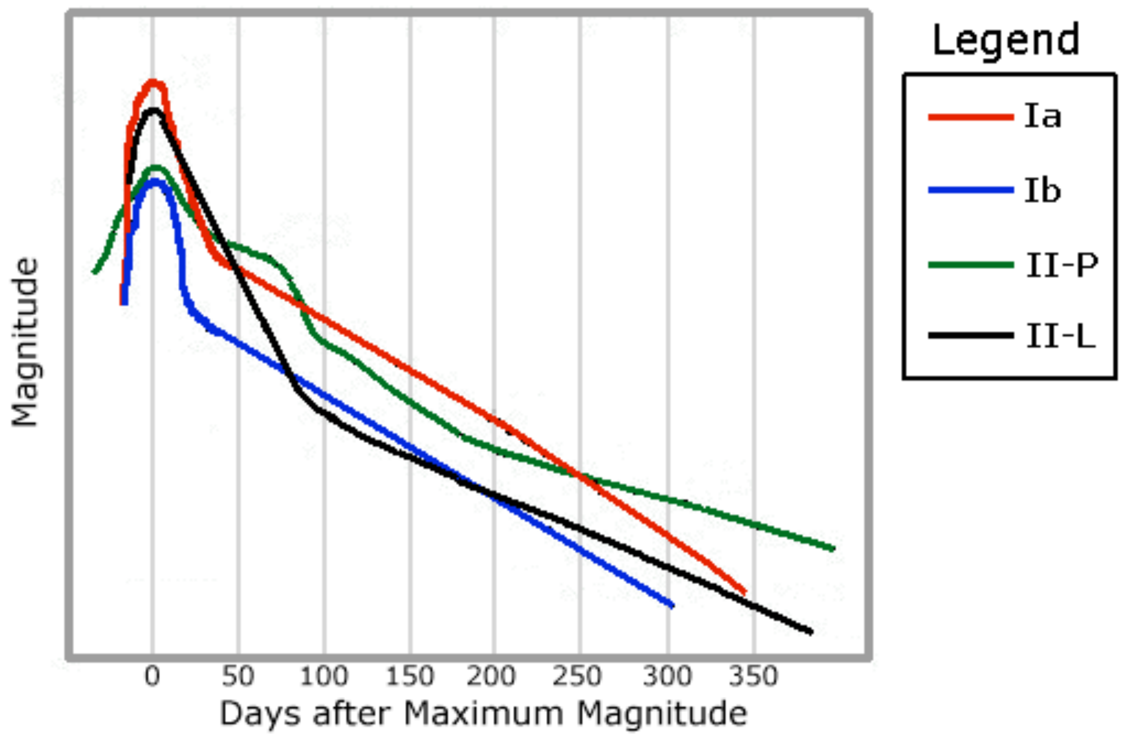


Illustration showing the different shapes of supernovae light curves

Further reading:
Type Ia Supernovae (Wikipedia)
http://en.wikipedia.org/wiki/Type_Ia_supernova
Type II Supernovae (Wikipedia)
http://en.wikipedia.org/wiki/Type_II_supernova
Supernovae, Supernova Remnants and Young Earth Creationism FAQ
http://www.talkorigins.org/faqs/supernova/
Supernova Cosmology Project
http://panisse.lbl.gov/
Supernovae, Dark Energy, and the Accelerating Universe
http://www.lbl.gov/Science-Articles/Archive/sabl/2005/October/Supernovae-Dark%20Energy-Accelerating.pdf
Supernovae Alphabet Soup
http://simostronomy.blogspot.com/2011/01/supernovae-alphabet-soup.html

Other Variables

Gamma-Ray Bursters (GRB)

Adapted from Wikipedia
Gamma-ray bursts (GRBs) are flashes of gamma rays associated with extremely energetic explosions that have been observed in distant galaxies. They are the most luminous electromagnetic events known to occur in the universe. Bursts can last from ten milliseconds to several minutes; a typical burst lasts 20–40 seconds. A longer-lived "afterglow" emitted at longer wavelengths (X-ray, ultraviolet, optical, infra-red, microwave and radio) usually follows the initial burst. This after glow is what amateur astronomers are chasing after in the moments after a GRB is detected.

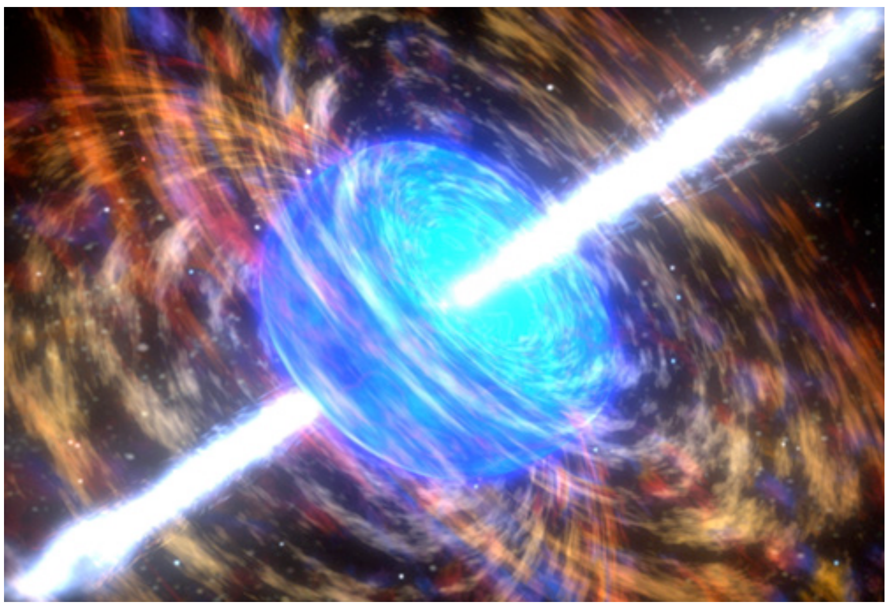


Illustration of a gamma ray burst. Credit: NASA/SkyWorks Digital

Most observed GRBs are believed to consist of a narrow beam of intense radiation released during a supernova event, as a rapidly rotating, high-mass star collapses to form a neutron star, quark star, or black hole.

A subclass of GRBs (the "short" bursts), appear to originate from a different process. This may be the merger of binary neutron stars and perhaps specifically the development of resonance between the crust and core of such stars as a result of the massive tidal forces experienced in the seconds leading up to their collision, causing the entire crust of the star to shatter.

The sources of most GRBs are billions of light years away from Earth, implying that the explosions are both extremely energetic (a typical burst releases as much energy in a few seconds as the Sun will in its entire 10-billion-year lifetime) and extremely rare (a few per galaxy per million years).

Highly recommended reading:
(Yes, Wikipedia is actually a *VERY* good source on this topic!)
http://en.wikipedia.org/wiki/Gamma-ray_burst

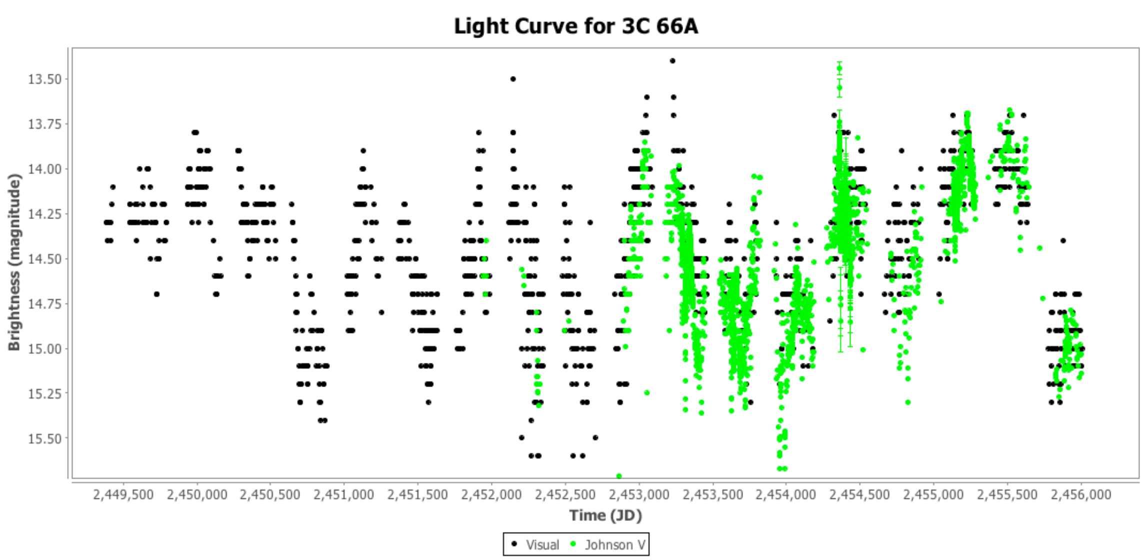
Active Galactic Nuclei (AGN)

AGN are point-like sources, but they are not stars. They are galaxies that have a small core of emission embedded in an otherwise typical galaxy. This core may be variable and very bright compared to the rest of the galaxy.

Most models of active galaxies depict a supermassive black hole lying at the center of the galaxy. The dense central galaxy provides material which accretes onto the black hole releasing a large amount of gravitational energy. Part of the energy in this hot plasma is emitted as x-rays and gamma rays.

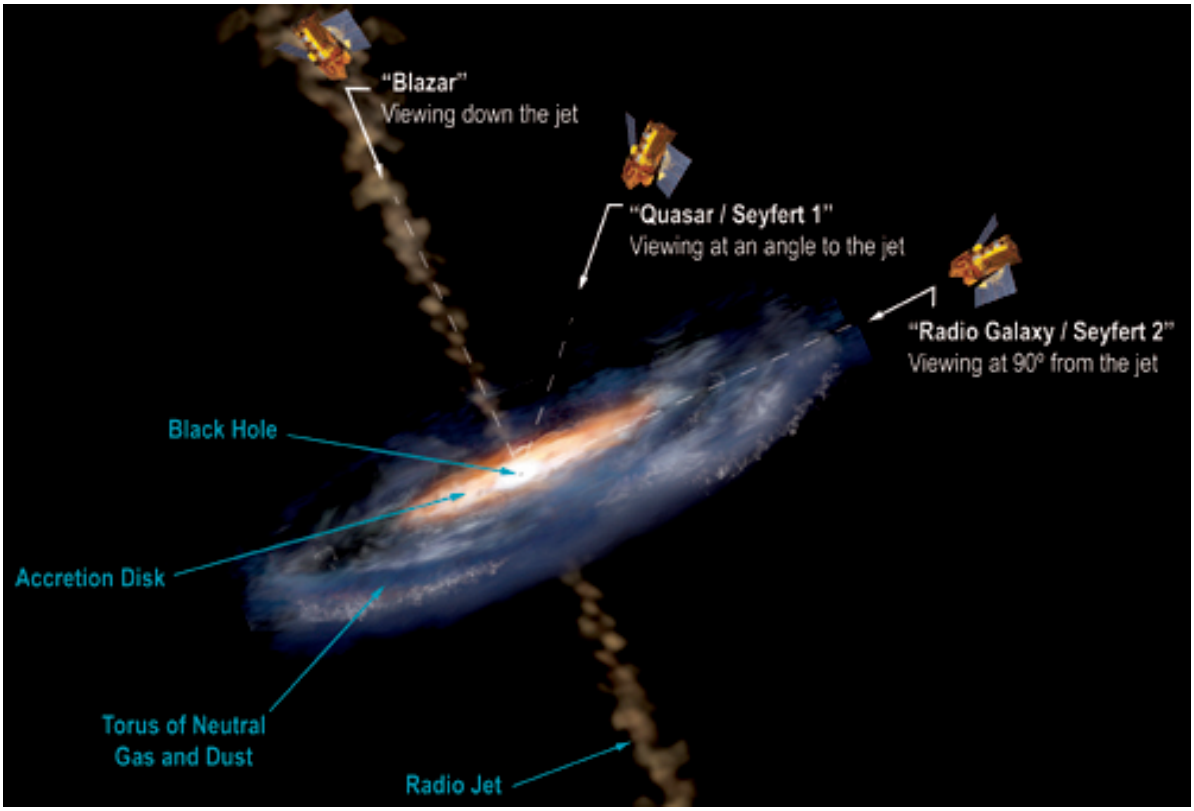
There are three main types of active galaxies: quasars, blazars and Seyferts. Most scientists believe that, even though these types look very different to us, they are really all the same thing viewed from different orientations!

Quasars are active galaxies that are very, very far away from us. Some of the quasars we have seen so far are 12 billion light-years away. 3C 66A is a quasar you can see in an amateur telescope, and it is some 3 billion light years away! Given the large distances to these objects and the strong emission of high-energy gamma rays, these are the most powerful particle accelerators in the Universe.



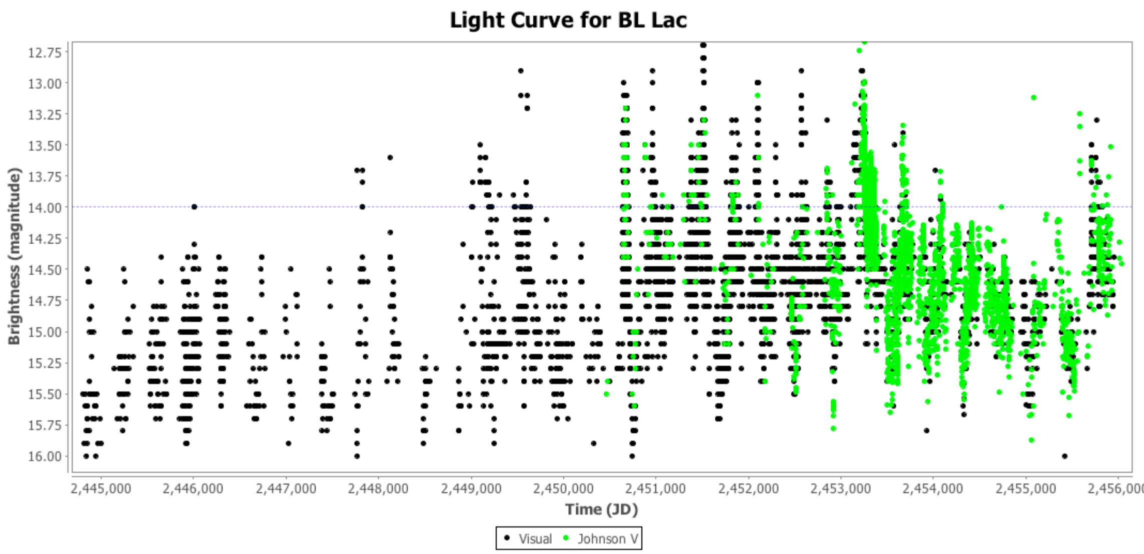
AAVSO light curve of 3C 66A in Andromeda

Some quasars display changes in luminosity, which are rapid in the optical range and even more rapid in the X-rays. Because these changes occur very rapidly they define an upper limit on the volume of a quasar; quasars are not much larger than the Solar System! The mechanism of brightness changes probably involves relativistic beaming of jets pointed nearly directly toward us.



The components of an AGN and what we call them, depending on our point of view.
Image credit: Aurore Simonnet, Sonoma State University.

A blazar is believed to be an AGN which has one of its relativistic jets pointed toward the Earth so that what we observe is primarily emission from the jet region. They are thus similar to quasars, but are not observed to be as luminous. The visible and gamma-ray emission from blazars is variable on timescales from minutes to days. Although theories exist as to the causes of this variability, the sparse data do not yet allow any of the ideas to be tested.



Historical light curve (1981 to present) of BL Lac, the prototype of a class of blazars

Blazars are very bright in the radio band, which results from looking directly down a jet which is emitting in synchrotron radiation. On the other hand, if the jet is not pointing toward us, and the dusty disk of material residing in the plane of the galaxy is in the way, you would see just what we see from the Seyferts.

Seyfert galaxies are characterized by extremely bright nuclei, and spectra containing very bright emission lines of hydrogen, helium, nitrogen, and oxygen. Unfortunately, their optical light curves tend to be rather dull and unexciting as a whole.

Suggested reading:
VSOTS BL Lacertae
http://www.aavso.org/vsots_bllac
VSOTS Markarian 421
http://www.aavso.org/vsots_mark421
VSOTS The quasar 3C273
http://www.aavso.org/vsots_3c273

Acknowledgements

Carolyn J. Hurless

1934-1987

Carolyn J. Hurless was the most active and prolific woman observer in the history of the AAVSO, with 78,876 observations in the International Database. But that only scratches the surface of this remarkable woman's life and career as an AAVSO observer, councilor, officer, mentor and ambassador.

Born in Lima, Ohio, November 24, 1934, Carolyn became interested in astronomy at the age of 13 through her love of science fiction. As a young woman, she was invited to join the Lima Astronomy Club, when President Herbert Speer found her name on the borrowers cards of people who had checked out astronomy books from the public library.

Shortly after that, she decided to make her own 8-inch reflector with the guidance of fellow astronomy club members. When the initial grinding was done, Carolyn found that in her excitement she had hogged out a short focus mirror of f/4, instead of the typical f/8 or f/9 scope most were making at the time. In the end it turned out to be a fine instrument. In fact the short tube length gave her, as she described it, a "feminine" telescope, easily transported and set up for observing. Most of her observations were made with this telescope and she never felt the need to upgrade to something else.

Carolyn learned variable star observing from legendary AAVSO observer and fellow Ohioan, Leslie Peltier. Carolyn would make the trip to Delphos, Ohio to observe faint "inner sanctum" stars with Peltier's 12-inch refractor nearly every week during their lifelong friendship. She was more than happy to pay it forward by mentoring other newcomers and sharing her enthusiasm with other variable star observers around the world.

One way she managed to do that was by publishing the informal monthly newsletter *Variable Views* in which she shared ideas about astronomy, stories of variable stars and amateur astronomers and humorous notes about her own experiences. She started the newsletter at her own expense and published it for 22 consecutive years. Carolyn invited her *Variable Views* readers to summer gatherings each year at Leslie Peltier's home where she was able to inspire young people with her love of the stars and observing.

She managed to reach out and touch people across international boundaries also, in a time when this was not easy to do. She sponsored a Czechoslovakian observer, Jaroslav Kruta, to AAVSO membership. Through persistent correspondence, mainly tape recordings, she taught Jaroslav English, and was able to introduce several other AAVSO members to him by arranging for them to meet when they visited Czechoslovakia.

Besides sharing her enthusiasm for astronomy with the public, she managed to hold down a full-time position as a music teacher, inspiring countless young musicians along the way.

The Carolyn Hurless Online Institute for Continuing Education is proud to carry on in the tradition of this remarkable woman.

Writing this course would not have been possible without the invaluable contributions of AAVSO staff, members and volunteers, including Arne Henden, Aaron Price, Matthew Templeton, Chris Watson, Sebastian Otero, Patrick Wils, Doug Welch, Ken Mogul, David Benn, Will McMain and Richard 'Doc' Kinne. My sincere thanks to them all.

Mike Simonsen
April 2012