Chapter 7: Observing Variable Stars in the Real Sky

Introduction

Every night hundreds of amateur astronomers around the world look at the night sky from their backyards, just as you are now preparing to do. Stargazers contemplate the splendor and poetry of the dancing jewels above them, and feel serene within the solitude of night and the constancy of the universe. Amateur astronomers, too, appreciate the wonders of the stars; however, they also know that the stars are not constant, but vary in their brightness. So they observe them systematically, filling their logbooks with data which they plot and analyze. They not only want to enjoy the stars, but want to investigate and analyze their behavior and share their findings with other astronomers around the world. Amateur astronomers do not feel alone in the darkness. They know they have nighttime companions with a similar mission: to become intimately acquainted with stellar behavior, to decode the messages from variable stars. So when you go out to your backyard and begin your quest, remember that there are many eyes observing the heavens along with you.

There are over 30,000 stars known to be changing in brightness and another 14,000 stars suspected to be changing in brightness. These known and suspected variable stars require continual, systematic observation over decades to determine their short-term and long-term behavior, and to catch and record any unusual activity. During the last two decades, variable stars have been closely monitored using specialized instruments on large ground-based telescopes, and x-ray, ultraviolet, and infrared detectors aboard satellites. It is essential to have ongoing visual data from amateur astronomers to correlate with the multi-wavelength observations these specialized instruments obtain.

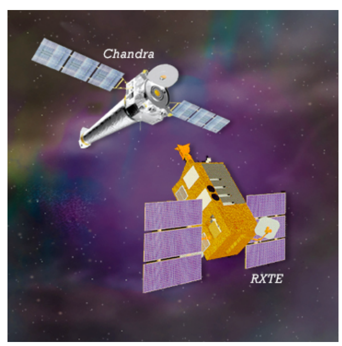
For three-and-a-half years the *HIPPARCOS* satellite measured the distances to stars within 500 light-years of the Sun with incredible precision. The satellite also measured the magnitudes of several thousand variable stars, some with very large fluctuations between their brightest and dimmest phases. Because the dimmer the star the longer the satellite had to point at it, the HIPPARCOS team had to know exactly where the star was in its magnitude cycle in order to allow enough time to gather the necessary data. For many variable stars, this behavior is unpredictable. Here is an example of where the amateur astronomer's work is so vital. Groups of amateurs have long been members of various variable star organizations around the world, such as the *American Association of Variable Star Observers (AAVSO)* in Cambridge, Massachusetts. As the HIPPARCOS satellite orbited Earth, these amateur observers sent more than 6,000 observations a month of specific variable stars to AAVSO headquarters. The AAVSO director used these observations to help the HIPPARCOS astronomers predict the brightness of these stars at any time during the mission. This collaboration between amateurs and professionals enabled the HIPPARCOS scientists to collect crucial data on some of the most intriguing variable stars in the sky. High-tech instruments have an extreme degree of precision, but amateurs compensate for their lower degree of precision by the sheer volume of data they produce. Amateurs also are able to watch variables over long periods of time—crucial to determining the light curves for long-period stars. This contrasts with the short observing times allotted to the many professional astronomers who want to access satellites such as HIPPARCOS, or ground-based telescopes at large observatories around the world. Both amateurs and professionals play a vital role in variable star astronomy.

The full scientific impact of the HIPPARCOS mission is only beginning to be gauged. One of the most inspirational aspects of this effort is the staggering degree of human cooperation required, from space agencies such as the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA), to HIPPARCOS' science teams, to many variable star organizations, to the not-so-lonely amateur astronomer surveying the heavens from his or her backyard.

The significance of amateurs' contributions to astronomy was first realized 150 years ago by Friedrich Argelander, a German astronomer who is considered to be the father of variable star astronomy. In 1844, when only 30 variable stars were known, he wrote the following:

> *I lay these hitherto sorely neglected variables most pressingly on the heart of all lovers of the starry heavens. May you increase your enjoyment by combining the useful and the pleasant while you perform an important part towards the increase of human knowledge.*

You now have the basic tools, knowledge, and skills necessary to begin observing variable stars. Perhaps one day your observations will be in the AAVSO International Database, assisting professional astronomers in their unceasing scrutiny of the universe.



HIPPARCOS is not the only scientific mission that has teamed up with the AAVSO observers. The Chandra X-Ray Observatory is the most sophisticated X-ray observatory launched by NASA. Chandra is designed to observe X-rays from high-energy regions of the universe, such as X-ray binary stars. Chandra, the Extreme UltraViolet Explorer (EUVE), and the Rossi X-ray Timing Explorer (RXTE) provided an opportunity for observational collaborations with members of AAVSO. For years, amateur astronomers have informed professional scientists of novae, supernovae and other cataclysmic events. The cooperation between an organized group of dedicated amateur astronomers, and the professional astrophysicists who need these observations, is now quite finely tuned. When scientists are in need of ground-based observations to follow simultaneous satellite observations, they know that the AAVSO worldwide network of amateurs can be depended upon for fast, efficient, and reliable results. The Chandra Chronicles describe the fascinating process involved with the two observation projects. The Chronicles can be accessed at http://chandra.harvard.edu/chronicle/0300/aavso.html and http://chandra.harvard.edu/chronicle/0101/aavso.html .

Initial Preparations

These preparations should be followed for every observing session.

A. Choose the variable star(s) you will be observing. Determine with your planisphere if the constellation in which the star is located will be well-placed for observation on the day and time you plan to observe.

B. Using the AAVSO *finder* charts, determine the exact location of the variable, and the location and magnitudes of the comparison stars.

C. Do not observe alone—bring someone with you. Find a safe location that is as dark as possible and unobstructed by trees or buildings. Wear sunglasses indoors for 10 minutes or give yourself 15 to 20 minutes outside before you observe to allow your eyes to adjust to the darkness. Avoid street lights, yard lights, or automobile headlights, since a moment of exposure to any bright light destroys your darkness adaptation and you will have to wait 10–15 minutes for your eyes to become reaccustomed to the dark.

D. Check the latest weather conditions or forecast for the night you plan to observe. Do not do your observing when cirrus clouds are present because it is difficult to tell when they cover part of your view. Use your *Sky Gazer's Almanac* to determine the phase and rise/set time for the Moon to make sure it will not interfere with your viewing. Also check the almanac for other celestial events that will be taking place in the sky that you might not want to miss.

E. If you are not observing with the unaided eye, then familiarize yourself with the adjustments of the binoculars you are using. Have a logbook and pencil ready to record observations. A sample entry page is included which illustrates the necessary information to record (see next page). Carrying a dim red light, or a flashlight covered by a red filter is essential. The red light will allow you to read the charts and record your data without destroying your darkness adaptation.

F. Dress appropriately, especially if it is cool. It can be quite uncomfortable working with binoculars if you are cold. An air mattress, a lounge chair, or other comfortable chair is very practical. Observing while reclining, rather than standing or sitting, will help prevent you from having sore neck muscles. Make yourself as comfortable as possible for maximum viewing time.

The AAVSO Report Form (a sample of the front is shown here). Use this form to report observations of variable stars to the AAVSO.

THE AMERICAN ASSOCIATION OF VARIABLE STAR OBSERVERS
25 Birch Street, Cambridge, MA 02138, USA

VARIABLE STAR OBSERVATIONS

Sheet ________ of _________ Report No. _________

For Month of ___________________ Year _____________

Observer _______________________________________

Street ____

City _____________________ State ________________

Country ___________________ Zip Code _____________

Time Used, GMAT or ______________________________

Instrument(s) ___________________________________

AAVSO Observer Initials

____

For AAVSO HQ Use Only

Received _________________

Entered _________________

Verified _________________

Designation	Variable	JD & Decimal	Mag.	Key* &	Remarks	Comp. Stars	Chart and Date

Total Number Observations Reported

* KEY field contains AAVSO-selected one-letter abbreviations for REMARKS. Obtain list from AAVSO Headquarters or web site.

(turn sheet over)

The AAVSO Report Form (a sample of the back is shown here). Use this form to report observations of variable stars to the AAVSO.

AMERICAN ASSOCIATION OF VARIABLE STAR OBSERVERS
25 Birch Street,
Cambridge, MA 02138 USA

Observer ______________________________

For Month of ________________ Year __________

AAVSO Observer Initials

____

For AAVSO HQ Use Only

Received ______________

Entered ______________

Verified ______________

***Explanation of Key field characters**

IMPORTANT—If an observation is uncertain, please put this character : [a colon] immediately after the magnitude. Each time you use the : character, please be sure to include the reason(s) for the uncertainty in the Remarks field and the appropriate one-letter character(s) in the Key field. This will maximize the amount of information contained in your observations, as well as assist the AAVSO in its record-keeping.

The Key field is for AAVSO-selected one-letter abbreviations of comments about an observation, or for multi-letter abbreviations describing instrumentation such as PEP or CCD. The complete list of all these abbreviations may be obtained from AAVSO Headquarters or fromthe AAVSO web site (http://www.aavso.org). Use as many letters as needed for an observation. Even if there is no uncertainty, please use these letter characters whenever you choose to make a remark about any observation. (However, please do NOT use : if there is no uncertainty.) If you do not wish to make any remarks, please leave the Key & Remarks field blank.

Designation	Variable	JD & Decimal	Mag.	Key* &	Remarks	Comp. Stars	Chart and Date
					Total Number Observations Reported		

* KEY field contains AAVSO-selected one-letter abbreviations for REMARKS. Obtain list from AAVSO Headquarters or web site.

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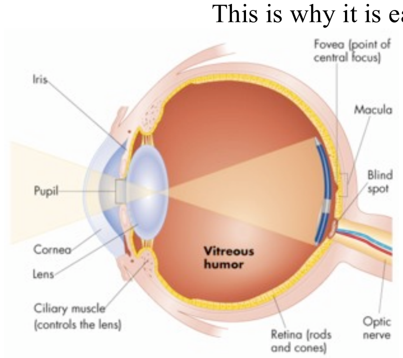
Starlight in Your Eyes

The human eye resembles a camera. The eye is equipped with a built-in cleaning and lubricating system, an exposure meter, an automatic field finder, and a continuous supply of film. Light from an object enters the cornea, a transparent covering over the surface of the eye, and passes through a transparent lens held in place by ciliary muscles. An iris in front of the lens opens or closes like the shutter on a camera to regulate the amount of light entering the eye by involuntarily shrinking or dilating the pupil. The iris gradually constricts with age. Children and young adults have pupils that can open to 7 or 8 mm in diameter or larger, but by the age of 50 it is not unusual for the maximum pupil size to shrink to 5 mm, greatly reducing the amount of light-gathering capability of the eye. The cornea and lens together act as a lens of variable focal length that focuses light from an object to form a real image on the back surface of the eye, called the retina. Because the pupil size shrinks with age, the retina of a 60-year-old person receives about one-third as much light as does that of someone who is 30.



The retina acts like the film of a camera. It contains about 130 million light-sensitive cells called cones and rods. Light absorbed by these cells initiates photochemical reactions that create electrical impulses in nerves attached to the cones and rods. The signals from individual cones and rods are combined in a complicated network of nerve cells and transferred from the eye to the brain via the optic nerve. What we see depends on which cones and rods are excited by absorbing light, and the way in which the electrical signals from different cones and rods are combined and interpreted by the brain. Our eyes do a lot of "thinking" about what information gets sent and what gets discarded.

The cones are concentrated in one part of the retina called the fovea. The fovea is about 0.3 mm in diameter and contains 10,000 cones and no rods. Each cone in this region has a separate nerve fiber that leads to the brain along the optic nerve. Because of the large number of nerves coming from this small area, the fovea is the best part of the retina for resolving the fine details of a bright object. Besides providing a region of high visual acuity, the cones in the fovea and in other parts of the retina are specialized for detecting different colors of light. The ability to "see" the colors of stars is greatly reduced because the intensity of the colors is not great enough to stimulate the cones. Another reason is that the transparency of the lens decreases with age. Babies have very transparent lenses that pass wavelengths of light down to 3500Å in the deep violet.

The concentration of cones decreases outside the fovea. In these peripheral regions, the rods predominate. Their density in the retina ($\sim$150,000/m^2) is about the same as that of the cones in the fovea region. However, the light signals from perhaps 100 adjacent rods are brought together into a single nerve cell that leads to the brain. This combining of the rod signals reduces our ability to see the fine details of an object but helps us see dimly lit objects, since many small signals are combined to produce a larger signal. This is why it is easier to estimate the magnitude of a dim variable star by using a technique called "averted vision," i.e., not looking directly at the star, but to one side of the star.

A normal eye can focus on objects located anywhere from about 25 cm to hundreds of miles away. This ability to focus on objects at different distances is called accommodation. Unlike the camera, which uses a fixed focal length lens and a variable image distance to accommodate different object distances, the eye has a fixed image distance of about 2.1 cm (the distance from the cornea and lens to the retina) and a variable focal length lens system.

When the eye looks at distant objects, the ciliary muscle attached to the lens of the eye relaxes, and the lens becomes less curved. When less curved, the focal length increases and an image is formed at the retina. If the lens remains flattened and the object moves closer to the lens, the image will then move back behind the retina, causing a blurred pattern of light on the retina. To avoid this, the ciliary muscles contract and cause an increase in the curvature of the lens, reducing its focal length. With reduced focal length, the image moves forward and again forms a sharp, focused image on the retina. If your eyes become tired after reading for many hours, it is because the ciliary muscles have been tensed to keep the lenses of your eyes curved.

The far point of the eye is the greatest distance to an object on which the relaxed eye can focus. The near point of the eye is the closest distance of an object on which the tensed eye can focus. For the normal eye, the far point is effectively infinity (we can focus on the Moon and distant stars) and the near point is about 25 to 50 cm. This variable "zoom lens" changes with age and the minimum focus distance changes until it is difficult to focus on objects even 20 cm away, making charts and instruments difficult to read. The aging eye gradually alters the way we perceive the universe.

The aperture is the clear diameter of the objective lens in a refracting telescope or of the primary mirror in a reflecting telescope. As the aperture is increased, the telescope gathers more light, and so will discern fainter objects: the light-gathering power depends on area (i.e., the square of the aperture). The aperture ratio is the ratio d/f of the effective diameter (aperture), d, of a lens or mirror to its focal length, f. In near-total darkness, the pupil of the human eye expands to its greatest diameter in an attempt to collect as much light as possible. The fully expanded pupil of the human eye is ~7 mm. Telescopes have a ratio of magnification to aperture that yield a 7 mm exit pupil to match and fill with starlight the fully expanded pupil of the human eye. However, there is a range of expanded pupil sizes. Studies have shown that even at the age of 15, when pupil size tends to peak, individual values range from 5 mm to 9 mm. And after age 30, it's mostly downhill. To maximize light-gathering capability, older people need to have larger telescope apertures, and everyone should have their dark-adapted pupil size measured and choose the magnification that will optimize the exit pupil of the eyepiece.

How might differences in eyes have affected early astronomers, such as the Mayans, American Indians, Chinese, Babylonian, and Egyptians? What age were the observers? What kind of eyesight did they have? When were vision problems discovered? When were corrective procedures developed, such as lenses and glasses? Galileo lost his sight for a week after observing sunspots with a telescope. In early days of telescope use, smoked glass was used as a protective filter. Such a filter is ineffective against damaging UV radiation. Why? Did Galileo's observations eventually lead to the glaucoma that greatly reduced the vision in his right eye and blinded the left? Johannes Kepler, the first person to understand the function of the eye's light-sensitive retina, was myopic and suffered from severe astigmatism. How would this interfere with what he saw in the night sky? Can excessive exposure to ultraviolet light cause long-term damage to the eye? Did other famous astronomers have vision problems?

Dresden Codex,
detailing Mayan astronomical observations

Occupational Hazards of the Variable Star Observer

The following stories were shared in the AAVSO on-line discussion group, and were subsequently printed in AAVSO Newsletter No. 19 as part of the Observers' Forum feature.

Dave Sworin (California):

I visited my dermatologist today... I took the opportunity to ask him about my hands, which have gotten pretty raw after a full night of observing. He suggested that my hands are losing moisture in the cool dry air at night in the open, and that I should try various kinds of creams or lotions.... I explained that I'm handling optics (that means Nagler eyepieces in case you were wondering), and that I did not want to get any junk on my eyepieces. At any rate I have something to try.

It occurred to me that perhaps Variable Star Observing has its own set of "occupational" hazards. ...Here is a list of physical problems I have run into while observing:

1. Raw finger and thumb from turning focuser all night.
2. Mosquito bites on hands, arms, face, and neck.
3. Tired back from observing in awkward positions.
4. Eye inflammation possibly picked up from eyepiece sharing with another amateur.

Have you run into others or had similar experiences?

Georg Comello (The Netherlands):

Yes, I had some physical problems too while variable star observing. They are a little bit different from those of Dave Sworin.

1. In 1963 my eyebrow froze to the eyepiece of the finder at -19.5°C.
2. Once I fell off the observing ladder while looking for T Dra with the 6-inch refractor. There is still blood on the chart of this Mira star.
3. A few years ago I slipped on a snail in the garden while observing with the transportable C8, and hurt my leg.
4. The neighbor's cat once was pursuing a competitor, while I was estimating R Crv with the portable telescope in the garden. She hit my leg and the tripod. No damage occurred. So observing variable stars can be quite dangerous....

Gary Poyner (England):

In 1982 I had an eyepiece stick to my eye in -18 degrees temperature. Very painful! Also in September 1996 my aluminum stepladder broke in the observatory whilst I was on the top step! This resulted in quite serious damage to my left leg and back. Ruined my night that did (and it was very clear too!).

One other story. Not so much physical problems but interesting to relate. I was returning from a Variable Star Section meeting in November 1981 with four others, when we were stopped by no less than SEVEN police cars, and arrested for armed robbery of a bank. It appears that our car was stolen during the day, and returned to the same place after taking part in the robbery. At the end of the meeting we innocently returned to the car which was under surveillance by the police. We were all locked up until we could prove where we had been that day (which was no problem because we had about 60 witnesses).

Rik Hill (Arizona):

1. I had a counterweight slide off my mount and land on my big toe, busting it. There's still blood in the cement!
2. Back in '76 I was carrying out an RV-6 telescope, looked up to see if it was still clear, and completely missed the porch steps. That resulted in torn ligaments, but the telescope is fine.

Jerry McKenna (New Jersey):

I must tell about two of my local hazards:

1. Skunks. Some years ago there was an outburst of UV Per that was best visible from the front of the house. At 2:30 a.m. I was carrying my 8" Celestron from its normal station in the rear to the front. While I was setting up the telescope a skunk crossed my path. ... I made a quick observation and pulled my telescope away. My own neighborhood has been favored by skunks all of my life.

2. Tires. I live at the base of a hill. Until recently we were allowed to throw used tires out with the trash. Several times in the last 20 years tires have come crashing down. One has crashed into my front door; several have crashed into the rear of my property. It is only luck that my telescope has not been hit.

Dan Kaiser (Indiana):

...Below is an excerpt from a letter I wrote the following day after my own personal `CLOSE ENCOUNTER.' What follows is a TRUE story! It really happened!

17 July, 1990. Last night, around midnight, I was at my primary observing site, my backyard. I was busy taking photographs with my camera piggybacked on a C-8 telescope.

I had also set up a second telescope so that I could do some visual work simultaneously. While making variable star estimates with the second telescope my kitchen timer rang, indicating it was time to end an exposure. As I approached the C-8, I was startled to see what at first appeared to be a very large object hovering almost directly overhead.

It was oval in shape and very dark, making what looked like a hole in the starry sky overhead. After a few moments I realized it was not big and far away, but small and near, perhaps 20 feet directly above my telescope. It seemed to be just floating there.

I circled around the C-8 to approach from another direction. This is when I noticed that it was descending, very slowly. I stopped and watched as it gently came lower and lower. After maybe 45 seconds, it finally stopped about 3 feet above the ground and maybe 6 feet from the C-8. It just hovered there. I had no idea what it was, and quite frankly was apprehensive about approaching it.

Another minute went by. The unidentified flying object still hovered three feet off the ground. When it failed to move any more I stepped closer. I turned on my flashlight, but it being a red light I could not really see well. I had to get close before I could see clearly. There, on the side of my mystery object, I could make out lettering! It read "Wikes Lumber Co." It was then that I realized it was a balloon! It wasn't until I came even closer that I saw the string hanging down to the ground. The weight of the string must have pulled it down through the calm air until it touched ground, at which time it no longer weighed enough to pull the balloon all the way to the ground.

Sometimes I wonder, "What are the odds of a balloon coming down, in the middle of the night, right next to a sky gazer and his telescope?"

One more occupational hazard. When I was not quite 12, I was looking forward to the solar eclipse of July 20, 1963. I had recently gotten an Edmund 3" reflecting telescope. In preparation for the big day I tried out various ways of possible solar viewing. ... Edmund recommended solar projection, using an oatmeal carton. Of course, I was too impatient to do it the right way. I tried to view the Sun with a thick layer of photographic negatives. It only took a few seconds for me to hear a crackling sound. Luckily for me I never actually looked at the Sun. I implored my mother to save the next oatmeal box for me.

David B. Williams (Indiana)

While observing a visual minimum of eclipsing binary Y Leonis from a national park in Arizona, I had a skunk wander over and stick its nose up my pant leg. I heard something snuffling along the ground and looked down. Fortunately, there was a quarter moon, which offered enough light at the otherwise black site so that I could see the double white stripe moving toward me. It wasn't cold, but this was a situation in which I froze to the eyepiece too!

Core Activity 7.1: Observing Your First Variable Star—Delta Cephei

From most latitudes in the northern hemisphere in the autumn, delta Cep is bright and high in the sky—away from the horizon and local light pollution. It is outside the Milky Way and in a fairly dark and uncluttered region of the sky.

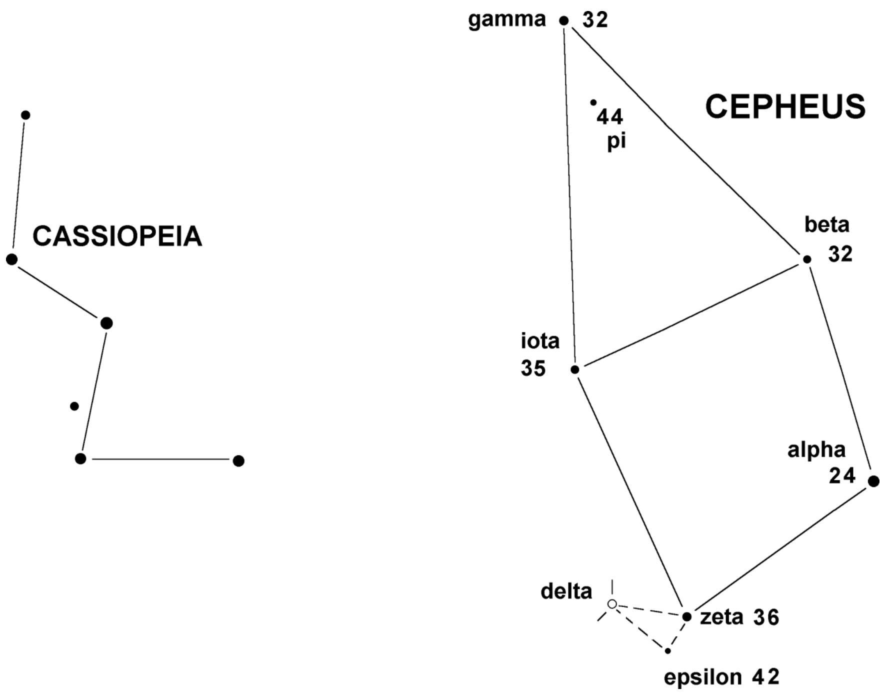


Figure 7.1

1. Enter in your logbook the name of the star (delta Cephei), the date of the observing session and the hour (later you will enter the minutes to the nearest quarter hour).

2. Using your planisphere or star charts, find the Big Dipper and Polaris using the pointer stars.

3. "Star hop" to Cassiopeia and then to Cepheus (Figure 7.1 above).

4. Find the group of three stars near one corner of the rectangular portion of Cepheus. Here is delta Cephei and its comparison stars zeta Cephei (magnitude 3.6) and epsilon Cephei (magnitude 4.2). This is the most difficult part and may take you several attempts, as you alternately look at the chart (Figure 7.1) and the sky.

5. Using averted vision, observe the variable star and its comparison stars at the center of your field of view. Averted vision is a technique in which you orient the star at the center of your field of view, and then gaze at the edge of the field.

Peripheral vision is more sensitive to black and white, so the difference in magnitude will be easier to discern.

6. Estimate your variable star's magnitude to the nearest tenth by using the nearby comparison stars. Look quickly back and forth and ask yourself: Is it dimmer or brighter than this comparison star? Is it dimmer or brighter than the second comparison star? If it is brighter, by how many tenths? Make a note of it. Then estimate the magnitude of your variable star again, and do it a third time. Enter the three numbers and average them in your logbook; then record your result in the data table.

7. Record the names and magnitudes of the comparison stars used.

8. Record the time of your observation to the nearest quarter hour.

9. Place a colon [:] after your observation if you are unsure of your observations due to a bright Moon or possible cirrus clouds. Do not be discouraged if you initially cannot tell the difference between a star of 3.0 and 3.5 in magnitude. Remember, your observations are a valuable "part of the whole" even if you are not yet an expert observer. With experience, you will be able to make your observations much more accurately and quickly.

10. After observing, calculate the Julian Date (JD), and record it in your log book. The Julian day runs from noon to noon, so you will have to convert your observation time to the fraction of the day starting from noon. Use the following steps to convert to the Julian Date:

    a. Convert the quarter of the hour to a decimal as follows. An observation time of 9:45 is 9.75 hr (45 minutes is 75% of an hour); an observation time of 2:15 is 2.25 hr (15 minutes is 25% of an hour); an observation time of 5:30 is 5.50 hr (30 minutes is 50% of an hour).

    b. Convert your time of observation to Greenwich Mean Astronomical Time (GMAT) (the starting time of the day for astronomers) by taking the time from (a) above and:

       During Daylight Savings Time:

       - adding 4 hours in the Eastern Time Zone (EDT)
       - adding 5 hours in the Central Time Zone (CDT)
       - adding 6 hours in the Mountain Time Zone (MDT)
       - adding 7 hours in the Pacific Time Zone (PDT)

During Standard Time:

- adding 5 hours in the Eastern Time Zone (EST)
- adding 6 hours in the Central Time Zone (CST)
- adding 7 hours in the Mountain Time Zone (MST)
- adding 8 hours in the Pacific Time Zone (PST)

For example, using the 9.75 hr from part (a) above, an observation taken during Eastern Daylight Savings Time would add 4 hours, therefore 9.75 + 4 = 13.75.

c. Convert this time [the number from (b) above] to the fraction of the day by dividing the time by 24; 13.75 divided by 24 = 0.57 or 0.6.

d. Look up the Julian day for the date of your observation from the Julian day calendar provided. For example, July 28th, 1995, is 2,440,000 + 9927 = 2449927.

Adding the result from (c) above, the JD = 2449927.6.

To summarize the above example for a magnitude estimation of delta Cep at 9:45 PM on July 28, 1995, in Boston, MA:

1. 9:45 PM = 9.75 hr;
2. You are on EDT, so add 4 hours: 9.75 + 4 = 13.75;
3. Convert to fraction of the day: 13.75 hr divided by 24hr/day = 0.57 = 0.6;
4. July 28 is 2,449,927 on the JD calendar. Add the fraction of the day: 2449927 + 0.6 = 2449927.6.

Julian Day tables are provided. They give the Julian Day (JD) number for the zero day of every month from 1951 through 2050 (see Julian Day chart on the next page). For example, the JD for January 0, 1951, is 2433647. If you want the JD for January 10, simply add 10 to 2433647; the JD for January 10, 1951, is 2433657.

11. Observe delta Cep on every night possible for the next month. If you wish to have a more complete light curve, observe it twice a night with 3 hours between each observation. You may decide to plot your data on a graph and calculate the period of delta Cep. Your instructor will give you the actual period of this variable and you can determine how closely your results agree with the accepted value. In the following chapters you will learn how to further analyze your results mathematically.

Using the Julian Day Tables

The next page contains a table giving the Julian Days from 1951 to the year 2000, and on the reverse side the Julian Days from 2001 to 2050.

You will note that the start of each month is not indicated by 1 (such as January 1), but rather with zero (e.g., January 0). This means that January 0 is actually December 31 of the previous year. This numbering convention is used so that you can easily determine the Julian Date for any particular date in a month simply by adding the number of days to the zero date for that month. For example, the Julian Date for January 8, 1996, is:

Julian Date for January 0, 1996 = 2450083 + 8 (days) = 2450091

Julian Day Numbers 1996-2025

To use this table, add the calendar date (based on the noon to noon astronomical time) of your observation to the zero day of the appropriate month for the desired year. For example, for an observation made on February 6, 2015, the Julian date would be: 2457054 + 6 = 2457060.

Year	Jan 0	Feb 0	Mar 0	Apr 0	May 0	Jun 0	Jul 0	Aug 0	Sep 0	Oct 0	Nov 0	Dec 0
1996	2450083	2450114	2450143	2450174	2450204	2450235	2450265	2450296	2450327	2450357	2450388	2450418
1997	2450449	2450480	2450508	2450539	2450569	2450600	2450630	2450661	2450692	2450722	2450753	2450783
1998	2450814	2450845	2450873	2450904	2450934	2450965	2450995	2451026	2451057	2451087	2451118	2451148
1999	2451179	2451210	2451238	2451269	2451299	2451330	2451360	2451391	2451422	2451452	2451483	2451513
2000	2451544	2451575	2451604	2451635	2451665	2451696	2451726	2451757	2451788	2451818	2451849	2451879
2001	2451910	2451941	2451969	2452000	2452030	2452061	2452091	2452122	2452153	2452183	2452214	2452244
2002	2452275	2452306	2452334	2452365	2452395	2452426	2452456	2452487	2452518	2452548	2452579	2452609
2003	2452640	2452671	2452699	2452730	2452760	2452791	2452821	2452852	2452883	2452913	2452944	2452974
2004	2453005	2453036	2453065	2453096	2453126	2453157	2453187	2453218	2453249	2453279	2453310	2453340
2005	2453371	2453402	2453430	2453461	2453491	2453522	2453552	2453583	2453614	2453644	2453675	2453705
2006	2453736	2453767	2453795	2453826	2453856	2453887	2453917	2453948	2453979	2454009	2454040	2454070
2007	2454101	2454132	2454160	2454191	2454221	2454252	2454282	2454313	2454344	2454374	2454405	2454435
2008	2454466	2454497	2454526	2454557	2454587	2454618	2454648	2454679	2454710	2454740	2454771	2454801
2009	2454832	2454863	2454891	2454922	2454952	2454983	2455013	2455044	2455075	2455105	2455136	2455166
2010	2455197	2455228	2455256	2455287	2455317	2455348	2455378	2455409	2455440	2455470	2455501	2455531
2011	2455562	2455593	2455621	2455652	2455682	2455713	2455743	2455774	2455805	2455835	2455866	2455896
2012	2455927	2455958	2455987	2456018	2456048	2456079	2456109	2456140	2456171	2456201	2456232	2456262
2013	2456293	2456324	2456352	2456383	2456413	2456444	2456474	2456505	2456536	2456566	2456597	2456627
2014	2456658	2456689	2456717	2456748	2456778	2456809	2456839	2456870	2456901	2456931	2456962	2456992
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2016	2457388	2457419	2457448	2457479	2457509	2457540	2457570	2457601	2457632	2457662	2457693	2457723
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2018	2458119	2458150	2458178	2458209	2458239	2458270	2458300	2458331	2458362	2458392	2458423	2458453
2019	2458484	2458515	2458543	2458574	2458604	2458635	2458665	2458696	2458727	2458757	2458788	2458818
2020	2458849	2458880	2458909	2458940	2458970	2459001	2459031	2459062	2459093	2459123	2459154	2459184
2021	2459215	2459246	2459274	2459305	2459335	2459366	2459396	2459427	2459458	2459488	2459519	2459549
2022	2459580	2459611	2459639	2459670	2459700	2459731	2459761	2459792	2459823	2459853	2459884	2459914
2023	2459945	2459976	2460004	2460035	2460065	2460096	2460126	2460157	2460188	2460218	2460249	2460279
2024	2460310	2460341	2460370	2460401	2460431	2460462	2460492	2460523	2460554	2460584	2460615	2460645
2025	2460676	2460707	2460735	2460766	2460796	2460827	2460857	2460888	2460919	2460949	2460980	2461010

She Discovered How to Calculate the Distances to Galaxies

Henrietta Swan Leavitt (1868-1921) was born in Lancaster, Massachusetts and graduated from Radcliffe College in 1892. In 1902 she became a permanent staff member of the Harvard College Observatory. She soon rose "by her scientific ability and intense application" to head the department of photographic stellar photometry.

She spent a great deal of time searching Harvard photographic plates for variable stars in the Magellanic Clouds. Using a laborious process called superposition, in 1904 she discovered 152 variables in the Large Magellanic Cloud (LMC), and 59 in the Small Magellanic Cloud (SMC). The next year she reported 843 new variables in the SMC. These discoveries led Charles Young of Princeton to remark in a letter to HCO director E. C. Pickering, "What a variable-star `fiend' Miss Leavitt is-one can't keep up with the roll of the new discoveries."

Leavitt's greatest discovery came from her study of 1777 variable stars in the Magellanic Clouds. She was able to determine the periods of 25 Cepheid variables in the SMC and in 1912 announced what has since become known as the famous Period-Luminosity relation: "A straight line can be readily drawn among each of the two series of points corresponding to maxima and minima, thus showing that there is a simple relation between the brightness of the variable and their periods." Leavitt also realized that "since the variables are probably nearly the same distance from the earth, their periods are apparently associated with their actual emission of light, as determined by their mass, density, and surface brightness." Today the Period Luminosity relation is one of the backbones of the "distance ladder" used to calculate the distances to galaxies.

In the course of her work, Leavitt discovered four novae and about 2400 variables-about half of all the variable stars then known to exist. She also studied Algol-type eclipsing binaries and asteroids. She was a member of Phi Beta Kappa, the American Association of University Women, the American Astronomical and Astrophysical Society) the American Association for the Advancement of Science, and an honorary member of the American Association of Variable Star Observers. Unfortunately, she died young of cancer before her work on a new photographic magnitude scale could be completed. Her death was viewed as a "near calamity" by her colleagues. Her important contribution to scientific advancement was internationally acknowledged when, in 1925, the Swedish Academy of Sciences nominated her for the Nobel Prize.

Miss Leavitt inherited in a somewhat chastened form the stern virtues of her puritan ancestors. She took life seriously. Her sense of duty, justice and loyalty was strong. For light amusements she appeared to care little. She was a devoted member of her intimate family circle, unselfishly considerate in her friendships, steadfastly loyal to her principles, and deeply conscientious and sincere in her attachment to her religion and church. She bad the happy faculty of appreciating all that was worthy and lovable in others, and was possessed of a nature so full of sunshine that to her all of life became beautiful and full of meaning.

- Solon 1. Bailey, 1922

In the late 1800's, in a move considered bold and controversial at the time, Harvard Observatory began hiring women as "computers" to do tedious and time-consuming mathematical computations and examinations of photographic plates of stars. Conventional wisdom held that women had the patience to endure monotonous tasks that men would find too menial and boring; furthermore, women workers in all segments of society were paid far less than men. The women "computers" at Harvard Observatory were paid only one-fourth the wages that men were paid. Despite these inequities, however, the hiring of women at Harvard Observatory was extremely important, in that it first opened the doors for women to pursue careers as professional astronomers.

Conventional wisdom also held that only men had the intellectual capacity to engage in independent or theoretical research. Not surprisingly, however, a number of women "computers" (including Henrietta Leavitt) made many significant astronomical discoveries for which they generally received little recognition. Even the most talented female astronomers were hampered in their work by social prejudices and conventions, to say nothing of the jealousies and politicking of less-accomplished men. Indeed, Cecilia Payne-Gaposchkin, whose 1925 doctoral dissertation *Stellar Atmospheres* has been called "the most brilliant Ph.D. thesis ever written in astronomy," had this advice for young women thinking about a career in astronomy: *"Do not undertake a scientific career in quest of fame or money.... Undertake it only if nothing else will satisfy you, for nothing else is probably what you will receive. "*

Despite all odds and obstacles, more and more women have flourished in astronomy, in no small measure because of the efforts of earlier women astronomers who paved the way. Some, such as Dorrit Hoffleit, Senior Research Astronomer Emeritus at Yale University, and past Director of the Maria Mitchell Observatory (MMO) on Nantucket Island, made a special effort to mentor young women. While MMO Director, Hoffleit began a summer internship program for young women majoring in astronomy or related fields. More than 100 young women—affectionately referred to as "Dorrit's Girls"—participated in this unique program, and many of them have pursued notable careers in astronomy.

Caroline Furness, an important astronomer with a special interest in variable stars, also mentored many young women during her tenure as Director of Vassar Observatory. This same nurturing of women with an interest in astronomy continued with her successor, Maud Makemson. One of Makemson's students was Vera Rubin, who is currently one of America's most respected astronomers. Rubin discovered that the mass of a galaxy is not distributed in the same way that its light is-that, in fact, the vast majority of a galaxy's mass is concentrated away from its disc. This "missing mass" problem has had the astronomical community engaged ever since.

Rubin was the first woman to be granted official permission to observe at Mt. Palomar Observatory in California. The application sent to her from Mt. Palomar in 1964 included the printed statement, "Due to limited facilities, it is not possible to accept applications from women." At the time, there was only one bathroom at Mt. Palomar, labeled "Men." Fortunately, attitudes have changed (along with plumbing!) there and in many other parts of the scientific world.

In contrast to times past, contemporary women's dreams of becoming astronomers, astrophysicists, and astronauts seem entirely do-able, given enough desire, talent, and hard work. While much remains to be done to "open the heavens" for women and men in developing nations, thanks to the path-breaking achievements and nurturing efforts of Dorrit Hoffleit, Caroline Furness, Maud Makemson, and many others, astronomy is quite possibly the most "female friendly" of all the sciences.

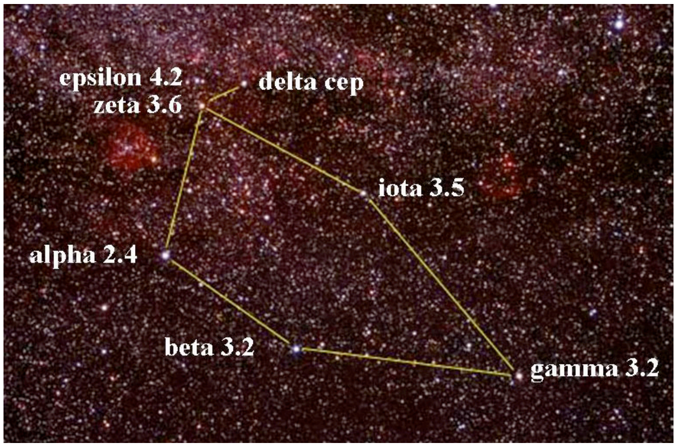
Activity 7.2: Observing the Variable Stars W Cygni and Chi Cygni

Now that you have practiced magnitude estimations with delta Cep—or if you are starting your variable star observations in the summer or early autumn—you may consider observing W Cyg. This is the variable star you used to learn how to estimate magnitudes in the previous chapter. The added familiarity makes this an ideal variable for you to observe.

Another interesting and dramatic variable star is chi Cyg. This is a red star with a large magnitude range. Both W Cyg and chi Cyg are located within the background clutter of the Milky Way and are not as easily visible as delta Cep.

If you have dark skies, you can observe chi Cyg with your unaided eye or binoculars only when it is at or near its maximum, which is magnitude 4.3. At other times, it is too faint to see without using a small to moderate-size telescope. In fact, chi Cyg drops to magnitude 14.1 at minimum!

SPACE TALK



Delta Cephei belongs to a class of variable stars called **pulsating variables**; in fact, delta Cep is the prototype for one type of pulsating variable known as **Cepheid variables.** Due to instability within their atmospheres, they continuously undergo rhythmic expansions and contractions, like a rock song with a definite beat. Some Cepheid variables have a quick rhythm, completing a cycle or period in a day; others take as many as 70 days. They are all giants or supergiants—delta Cep is a supergiant just over 1000 light-years away and 3300 times more luminous than our own Sun. Maximum brightness occurs near the time of greatest expansion, while minimum brightness coincides with the greatest contraction. There is evidence that not all the atmospheric layers are pulsating together; in other words, as the innermost layers have finished contracting and started expanding again, the outer layers are still contracting. When these layers meet they produce interior oscillations. The amazing fact is that in spite of all the bumping and grinding and colliding of different layers of chaotically expanding and contracting atmospheres, Cepheid variables pulsate with a period as regular as clockwork. Their periods are known to a fraction of a second, and the regularity of period hardly ever changes. The periods of only a few stars of this type change as much as 2 or 3 seconds within a 50-year period. When changes do occur, they usually happen smoothly. Sometimes, however, odd things happen. One strange case is that of RU Camelopardalis, which exhibited several sudden changes in periodicity, and then in 1965 stopped pulsating. Ever since, RU Cam has produced light at an apparently constant magnitude of 8.5. Except for these few eccentric relatives, however, most pulsating variables are locked into their own individual internal rhythms.

Another famous Cepheid variable is Polaris, the North Star! It is not surprising that its variation goes unnoticed, as it varies only from magnitude 2.5 to 2.6 with a four-day period.

In 1781, a 17-year-old Englishman by the name of John Goodricke began observing stars with his friends and neighbors, the Pigotts. Two years later, in 1783, the Royal Society of London presented him with the prestigious Godfrey Copley science medal.

Goodricke, deaf since birth, merited the honor through his patient observation and measurement of the star Algol's variability. Goodricke would later be credited with the discovery of an entirely new class of variable stars—the short period Cepheid variables, so named for the first star of its type discovered, delta Cephei.

Had Goodricke been born much earlier than 1764, he might never have had the chance to develop his talent for astronomy. Only a few years prior to his birth, most people equated deafness with idiocy, and did nothing to try to train or educate the deaf.

Fortunately, Goodricke's father had the means and knowledge necessary to find a place for John to be taught to read lips, speak, and to use an early method of sign language, along with the usual branches of learning available to well-to-do boys at the time.

The Cepheids are special in another way which makes them very important to a branch of astronomy known as **cosmology**—the study of the evolution of the universe. Cosmologists want to find the answers to such questions as: How did the universe begin? How will it end? What is the age of the universe? Cepheids can help answer that last question. In the early 1900's, Henrietta S. Leavitt discovered several faint Cepheids in the Small Magellanic Cloud (at the time thought to be a nebula within the Milky Way Galaxy). Henrietta calculated their light curves and determined their periods. She plotted an average brightness against the period and discovered that longer-period Cepheids are brighter than shorter-period ones. This led to the **period-luminosity relationship**, a plot of absolute magnitude versus period. In this form, Cepheids can be used at indicators of distance by applying the following steps:

1. Identify a star as a Cepheid variable by studying its spectrum (if possible) and/or by the shape of its light curve.
2. Calculate its period.
3. Use the period-luminosity relationship to determine the absolute magnitude.
4. Use the inverse-square law to calculate how far a star of that absolute magnitude would have to be moved from the standard distance of 32.6 light- years to appear as a star of the apparent magnitude observed.

Therefore, by finding a Cepheid variable and measuring its period and median apparent magnitude, one can determine its distance. When Edwin Hubble found 12 Cepheids in what was called the Andromeda nebula in 1923, and applied the period-luminosity relationship, he determined that Andromeda was so far away that it was not a nebula within the Milky Way but a galaxy in its own right. Hubble then devised his own relationship, called **Hubble's Law**, which states that the other galaxies in the universe are all moving away from the Milky Way—that in fact the universe is expanding. Hubble's Law states that the farther away a galaxy is, the faster it is moving away from us. Hubble's Law is written as follows:

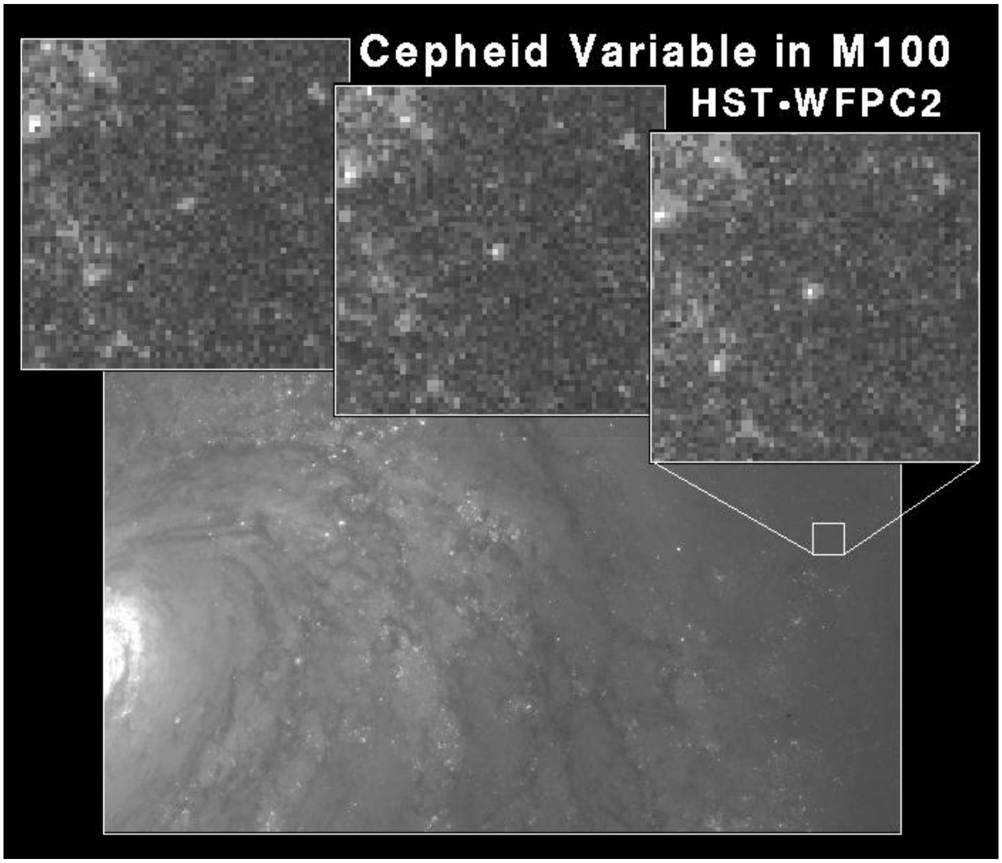
$$V_r = H_o d$$

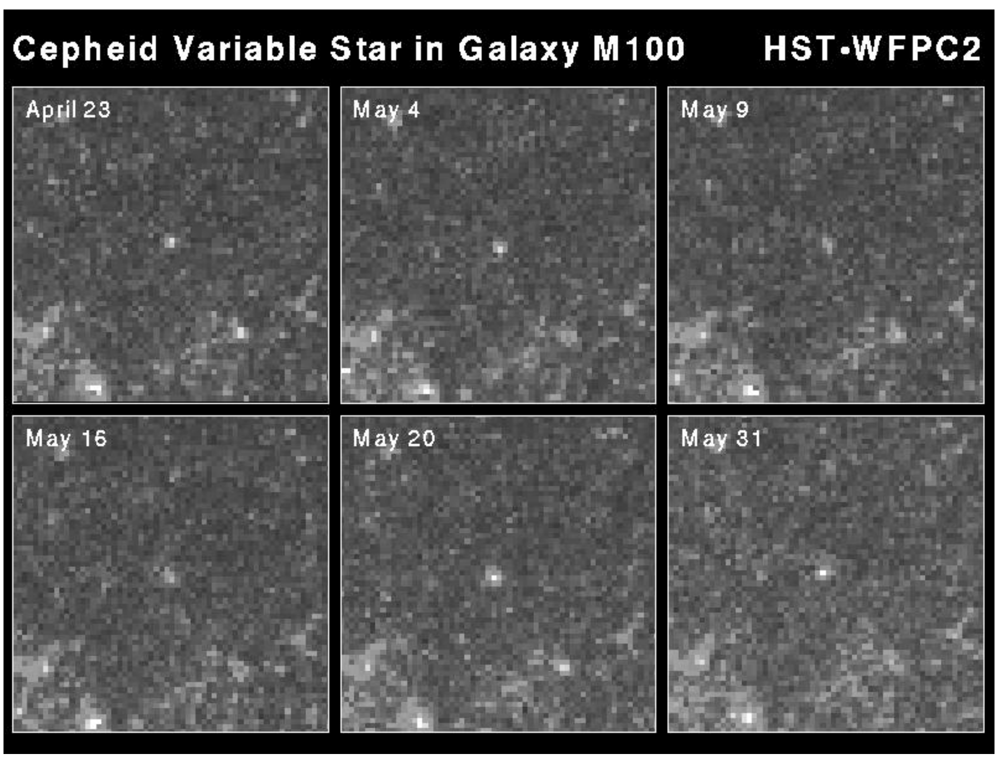
V_r = recessional velocity (how fast the galaxy is moving away from us)

d = distance (how far away the galaxy is from us)

H_o = Hubble's constant (the rate at which the velocity changes with distance)

Hubble's constant, then, is a measure of the rate at which the universe is expanding. The reciprocal of Hubble's constant is related to the age of the universe. The value of Hubble's constant depends upon knowing both the **recessional velocity** and the distance to faraway galaxies. The velocity can be measured by looking at the spectrum of a galaxy. One method of determining the distance to a galaxy is by finding a Cepheid in the galaxy and applying the period-luminosity relationship.


Cepheid Variable in M100
HST•WFPC2


Cepheid Variable Star in Galaxy M100
HST•WFPC2
April 23
May 4
May 9
May 16
May 20
May 31

Determining exactly how fast the universe is expanding is one of the most crucial unsolved problems in observational astronomy, fundamental to understanding the structure of the universe and verifying if the Big Bang theory is correct. It is so important that it is one of the high-priority missions of the Hubble Space Telescope (HST). To ascertain the value of Hubble's constant, the HST will measure the distances to Cepheid variables in 20 galaxies across the sky, as well as measure distances to Cepheids located in two galaxy clusters nearest to us centered in the constellations Virgo and Fornax.

HST has already proven that Cepheid variables can be found and tracked in galaxies more than 50 million light-years away. Using 20 Cepheids discovered by HST in M100—a spiral galaxy in the Virgo Cluster—a distance greater than 56 million light-years was measured. (See the two Hubble Space Telescope images on the preceeding page.) As the recessional velocity of the Virgo Cluster is approximately 1400 km/s, this yields a value of 80 for Hubble's constant. This value creates a serious problem, because the higher the value of Hubble's constant, the younger the age of the universe. The value of 80 implies an age of 8 billion years, in which case the universe would be younger than the objects it contains! However, the globular clusters which inhabit the galactic halo are thought to be 13 billion years old, which sets a lower limit on the age of the galaxy and therefore the universe. Of the several methods astronomers use to measure cosmological distances, ranges of 40–100 are obtained for the value of the Hubble constant.

So what is wrong here? First, the measurements HST determined using M100 may be wrong. After all, they are only one data set. Perhaps because of its huge mass and proximity to the Milky Way, it is gravitationally-bound in a way that gives a false value for its recessional velocity. Maybe M100 does not lie at the center of the Virgo Cluster as thought, but in front of or behind it. In this case, its recessional velocity would not be the same as the Cluster itself, since M100 has its own motions besides the motion of the whole Cluster. Is this a cosmological crisis of universal proportions? Will fundamental assumptions and theories survive? The universe is under no obligation to fulfill the expectations of current cosmological principles. This is an exciting time for astronomy. Our technology is becoming refined enough to test hitherto untestable theories—theories that have been in textbooks for decades. It will be interesting to see what happens!

There are other intrinsic variable stars besides Cepheids and other pulsating variables. There are several types of variables which undergo eruptions instead of pulsations. The most spectacular of these "eruptive variables" are supernovae, which are caused by catastrophic stellar explosions in massive dying stars. As stars die, heavier and heavier elements are produced by the fusion process. Eventually, in the most massive stars, the nuclear fires burn so hot that iron starts to fuse. All elements lighter than iron produce energy during fusion, but iron consumes energy. When iron starts to fuse, the stage is set for destruction—nothing can stop the complete and total collapse of the star. A star that has shone for millions of years ceases to exist in the visible universe in the cosmological blink of an eye, leaving behind beautiful layers of its atmosphere torn from its surface during its unimaginably violent death. Supernovae display light increases of 20 magnitudes or more and can outshine all other stars in a galaxy.

Another example of eruptive variables is novae. Novae result from stars in close binary systems in which each star is at a different evolutionary stage. For example, a star with its atmosphere bloated during the red giant stage may be orbiting a dense, hot white dwarf. The outer layers of atmosphere of the red giant whirl into a disk and spiral onto the surface of the white dwarf, causing nuclear explosions on the white dwarf's surface. The increase in brightness can range from 5 to 20 magnitudes.

While you perform your magnitude estimates in the backyard, take a moment to ponder this vast and ancient universe we inhabit. How ancient? How vast? Cepheid variables, just like the one you are studying, hold the key to unlocking the answers to these questions. Above you stars are exploding, literally tearing themselves apart with incredible violence. Others are locked into gravitational tugs-of-war as stellar atmospheres are stolen from red giants by their orbital companions, causing nuclear explosions to light up the sky. In the quiet solitude of backyard observing, remember that the stars above you are not eternal—stars are being born in the nuclear fires of stellar nurseries and dying when the fires begin to sputter and go out. As you progress with your quest to study the stars, the observations you make can help advance our understanding of the complex changes occurring overhead.

AM Herculis

One interesting example of a cataclysmic binary system variable star is AM Herculis. You can learn more about this unique system at http://www.aavso.org/vstar/vsots/0601.shtml