Chapter 2: Variable stars – The what, why, and how of measuring them

What are you measuring with photometry?

Variable stars are stars whose light varies measurably due to physical processes inside, on, or around the star. There are many classes of variable star, and each represents a different way that a star can vary. Stars may change in size, shape or temperature over time (pulsators), they may undergo rapid changes in light due to physical processes around the star (accretors and eruptives), or they may be eclipsed by stars or planets in orbit around them (binaries and exoplanets). The key is that something is physically happening to the star itself or in its immediate vicinity. You may see a star twinkle in the sky, but that variation is due to the Earth's atmosphere. Variable stars vary all on their own, independent of anything happening here on Earth.

Different kinds of stars vary on different timescales. Some stars may take weeks, months, or years to undergo changes that we can detect. Others take days, hours, minutes, seconds or much less. Some stars vary regularly, and we can see patterns in the variations that repeat over time. Other stars undergo chaotic changes that we can never predict exactly. Some stars vary the same way for centuries, while others — like supernovae — may flare up briefly and then disappear, never to be seen again.

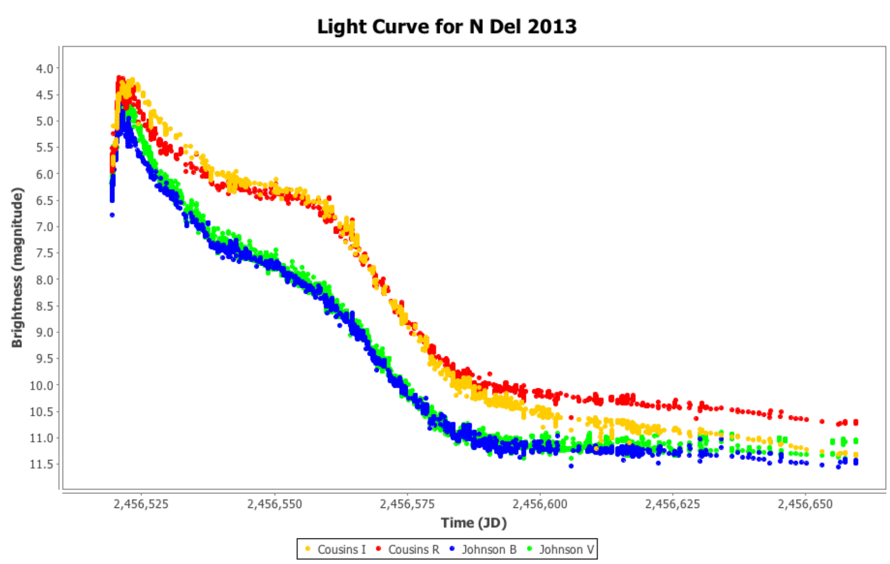
Variable stars also exist with a range of apparent brightnesses (how bright they appear to us) as well as a range of intrinsic luminosities (how much light they actually give off). A star may be intrinsically luminous, but if it is thousands of light years away, it will appear to be faint. Variables also have a range of *amplitudes* — how much their light changes over time. Some variable stars can vary by ten magnitudes or more, which is a factor of ten thousand in flux, a huge change! Some variable stars vary by a millimagnitude, or even less, and their variations may be impossible for you to detect. There are innumerable variables in between, and there's no shortage of targets that you'll be able to do productive work on, regardless of the size of your telescope.

Why are you doing photometry?

Variable stars are interesting for a number of different reasons, but ultimately we study them because they're like physics laboratories. We can't go and touch a star or change it in some way to study it, but if we can understand how the light from a variable star changes, we can learn more about how the universe works. The same fundamental physical processes that operate here on Earth — gravity, fluid mechanics, electromagnetism, light and heat, chemistry, and nuclear physics — operate exactly the same way all over the universe. By watching *how* stars change over time, we can learn *why they change*. What you're doing with your observations is providing the raw material that powers scientific inquiry. Scientists can speculate endlessly about why things appear and behave the way they do, but ultimately those hypotheses have to be tested in order to productively advance our scientific understanding. That's where observing comes in, and it's where you have the greatest chance of making a valuable contribution to variable star science. If you give researchers valid and accurate data, they can make accurate models for how the universe works, and our understanding increases and improves. Conversely, if they have bad data, those scientists may make bad models, which can mislead us and hinder progress in the field.

As for the broader question of why variable stars are interesting, variable stars often tell us more than what a specific star is doing at a given time. They can also tell us something about the circumstances under which stars form, how they spend their lives, and how they eventually evolve and die. Learning more about what stars are and why they behave the way they do gives us a more complete picture of the universe that we live in both in the present and over cosmic timescales, providing insights on everything from planets and stars to galaxies and beyond. That's ultimately what all of variable star astronomy is about.

In this document we'll concern ourselves mainly with variability at optical wavelengths — light with wavelengths observable with the human eye — but keep in mind that there are any number of stars that are variable at wavelengths of light from radio waves up to X–rays and gamma rays. Often stars are variable at optical and other wavelengths of light, and even in the optical spectrum, some changes may appear different at different wavelengths. That's a key thing to remember, especially for doing CCD photometry: often we're not only interested in how much the overall amount of light is changing but in the properties of that light variation as a function of wavelength.



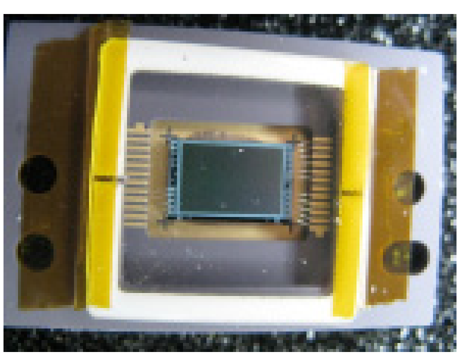
Light curve of Nova Del 2013 (V339 Del) as plotted with VStar. Note how the overall brightness changes, but the relative brightnesses of each band also changes as different physical processes dominate in the nova evolution.

Knowing both the overall change and the wavelength dependence may help us understand the underlying physics of what's happening to the star, which is ultimately what we're after in variable star astronomy. Later in this guide we'll spend some time talking about how we can measure (or at least constrain) the spectral properties of the stars we observe. By doing so, we have a much more comprehensive picture of how and why some stars vary.

How do we perform photometry?

The details of that question are going to form the bulk of this guide that follows, but in brief, you will use a piece of electronic equipment — a charged–coupled device or "CCD" camera — to measure the number of photons that your telescope receives from a variable star along with a set of known "comparison stars" observed at the same time. You'll take those numbers along with some additional calibration data that you'll obtain, to turn your measure of the number of photons into a calibrated, physical measure of the brightness of a star at one moment in time. By repeating that measurement over and over again, you can measure how the light from the star changes over time. That's the essence of photometry, regardless of what equipment you're using to make the measurements, but it's worthwhile taking a moment to explain what's happening inside the camera when it's exposed to light.

A CCD camera has at its heart a semiconductor wafer (made out of silicon) that's been divided into a large number of electrically charged, isolated squares that we call "pixels". This is referred to as a "CCD chip". When the chip is exposed to light, photons strike each pixel and release electrons via the photoelectric effect. Each pixel and its associated electronic gates act like a small capacitor, collecting these electrons from the silicon pixels as the light strikes them. Each pixel is wired to a central processor, and the charge that collects in each pixel accumulates until the chip is "read out" by the camera's electronics. During readout, the central processor measures the collected charge on each pixel. This is an analog voltage that is converted into a digital number using an analog–to–digital converter. What is sent from the CCD chip into your computer is the *position* of the pixel on the chip and a digital representation of the *amount of charge it held* at the time of readout. This is what creates the *image* that comes out of your system.



An example of an (older) CCD chip. The detector area is the gray rectangle in the middle. Note the wiring at the edges; the chip is read out through the wiring, which is connected to an analog–to–digital converter within the camera. (Courtesy Arne Henden)

What makes the image useful for variable star astronomy is that the image is also tagged in some way (typically in the image header) with the *time* it was taken. So at this point you have most of what you'll want — *a measurement of light at a specific moment in time* — to do "photometry". However, this is just the first step. There are several more important things to do in between opening the shutter on your camera and getting a final set of numbers — a time, a magnitude, and an uncertainty for each measurement — primarily involving how the counting of electrons by your CCD chip relates to a physical quantity like the amount of light at a certain wavelength that the star emits. This calibration step is a long but straightforward process that transforms that CCD data into physical information about the star.

The calibration process will involve measuring

- the noise inherent in your camera's electronics
- the peculiarities of your telescope's optics, from aperture to CCD chip
- the wavelength response of your system — how different wavelengths of light are registered, and eventually...
- the wavelength response of the atmosphere through which you observed.

Each of these steps will be covered later in this guide, but for now, realize there is more to doing photometry of variable stars beyond making a single observation. The calibration data you'll take for your variable star observing will eventually become routine, but we'll explain what you have to take and why.

The key point to take away from this chapter is that the goal of photometry isn't the numbers that come out of the CCD camera and your data processing, it's the *science* that you can do with those numbers. In order to do science, your results have to represent something physically meaningful, and have to be presented in a way that is useful for rigorous scientific analysis. That's our goal, and that's where we're aiming with this guide.

In the next chapter, we'll cover the very basics of what equipment and software you'll need before you can start doing CCD photometry. Every telescope, mount, and CCD camera manufacturer will have its own peculiarities, but there's enough overlap in what they do that we'll cover what you should have when you go out to the observatory for a night of variable star photometry. Many of the parameters of your system are relevant to what you'll be able to observe effectively to get good data. You won't be able to obtain good data for every variable star in the sky with any single system, regardless of its size or cost. However, there will be many objects that can be observed easily and effectively no matter what you have — just realize you should figure out what those objects are *before* you get to the telescope.