Measuring Lightcurves

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Things that go bump in the night[*]

One normally thinks of using astronomical images to study the appearance or color of an object: a single grayscale image just shows the angular structure of objects on the sky (position, size, and shape) at a particular wavelength; two or more grayscale images taken at different wavelengths can be put together to show the "color" of the image, i.e. how the angular structure and/or amount of light changes with wavelength.

Stars don't have any particularly interesting shape in images (just the smearing effects of the atmosphere and the telescope) and producing color images of stars has only limited use. One might think individual stars are therefore relatively boring objects to observe, but in fact the opposite can be true: some of the most exciting objects to observe are those that change not in position or wavelength but *time*.

There are many astronomical objects that change their brightness with time:

- stars that change their sizes and temperatures when ringing like bells, e.g. the Cepheid stars used to measure astronomical distances (see the chapter on ▸ Measuring Distances to Galaxies ◂);
- objects that explode catastrophically, e.g. supernovae and gamma-

ray bursts;
- objects that change their brightness due to heating, e.g. so-called cataclysmic variables;
- objects that change their brightness due to rotation, e.g. because of the appearance and disappearance of starspots;
- eclipsing binary stars orbiting around each other can sometimes cover each other up when viewed from the Earth;
- eclipses or magnifications of two unrelated objects that just happend to be on the same line-of-sight when viewed from the Earth, e.g. gravitational microlenses (see the chapter on ▶ Hands-On General Relativity ◀).

The time it takes for these events to happen can be as short as a few seconds (e.g. gamma-ray bursts) to months and years (e.g. supernovae). Many of these events take place on timescales as short as a single night or over a few days, making them ideal objects to study - not many things happen in the universe over times short enough to be interesting to humans!

A record of the changes in the brightness of astronomical objects with time is called a "lightcurve", usually a simple graph with time on the X-axis and some measure of the brightness on the Y-axis. If the data are taken over a long time, there are usually gaps in the data due to cloudy nights or simple lack of access to a telescope, so it may be difficult to know for sure just what is happening. If the phenomena happen on very short timescales of hours or less, it is possible to make a complete record of the variations.

This chapter explains how to measure and display the light variations from a simple stellar object. The general methods apply to any set of images taken over time from the same object, but the main focus is the special case of a uniform set of images taken with the same camera and telescope on the same night, where the major problem is simply dealing with a large number of very similar images:

1. Prepare a stack containing the images to be measured;
2. Find the star to be measured and one or more reference stars;
3. Perform aperture photometry on the stars;
4. Produce a plot of the relative brightness of the object as a function of time.

[*] *"From ghoulies and ghosties and long-legged beasties and things that go bump in the night, good Lord deliver us!" (supposedly Scottish prayer usually attributed to Walter de la Mare).*

Astronomical Time

For most purposes, the time associated with an astronomical observation is about the same as civil time - the pictures were taken, e.g., in Texas on the 21st of June, 2009, at 9:00 PM, Central Standard Time (expressed in a standard international format as 2009-06-21T21:00:00-7), or in Göttingen on the 24th of December, 2009, at 11:59:59 PM, Middle-European-Time (2009-12-24T23:59:59+1).

If you are studying the changes in a supernova over the course of months, this is all you may need to know, but it is also very difficult to compute the exact amount of time that has passed between the two observations. For this reason, astronomers often use not the normal civil date and time but the JULIAN DATE (or **Julian Day**, usually abbreviated as "J.D."), the number of days which has passed since 12 o'clock noon on January the 1st, 4713 B.C.E. in Greenwich. This makes the time independent of the location, making it easier to compare observations taken at different places, and is independent of things like leap-years.

Concepts 💡

JULIAN DATE

There are many tools on the internet which can help you to convert back and forth between civil time and Julian Date. Thus, the previous two dates can be expressed as

Date, Time, & Place	ISO Date-Time	Julian Date (J.D.)
21st of June, 2009 9:00 PM, Central Standard Time Texas	2009-06-21T21:00:00-7	2455004.66667
24th of December, 2009 11:59:59 PM, Middle-European-Time Göttingen	2009-12-24T23:59:59+1	2455190.45832

Note that midnight in Greenwich is always when the fractional Julian Date is 0.5, not 0.0. When using this system, it's easy to compute the amount of time between the two events: 2455190.45832 minus 2455004.66667 is 185.79165 days.

If more exact time is needed, then

one has to correct for the fact that the Earth was at two different places in it's orbit in June and in December: it takens light 149,598,000 km / 299,792 km/s = 499 seconds (8.3 minutes) to traverse the distance between the Sun and the Earth, resulting in a correction to <u>HELIOCENTRIC JULIAN DATE</u> (**HJD**, the Julian Date for an observer at the center of the Sun). Even more exact corrections can be made for having different observers at different locations on the Earth or for putting the standard observe not at the Sun but the center-of-mass of the Solar System ("Barycentric Julian Date"). Modern astronomers no longer think that the astronomical day stars at noon and get tired from writing so many decimal places, so a <u>MODIFIED JULIAN DATE</u> (**MJD**) where 2400000.5 has been subtracted, is commonly used.

Concepts 💡

HELIOCENTRIC JULIAN DATE
MODIFIED JULIAN DATE

For many astronomical purposes, simple J.D. is simply, handy, and good enough.

If you are measuring FITS images, the image headers should contain enough information to compute the Julian Date for each observation:

1. Take a look at the FITS header using `Image > Show Info...` and see if you can see the typical header entries `DATE-OBS` (the date and hopefully date-time of the observation), `TIME-OBS` (the time of the observation if not already contained in `DATE-OBS`), `EXPTIME` (the exposure time for very accurate times), and maybe even `JD`;

2. Using `Plugins > Astronomy > Set Aperture` (or double-click on the Aperture Photometry Tool icon), select `List ... Julian Date of image (if available)`;

3. If the Julian Date is given explicitly in the FITS header, you can select `List ... the decimal values for the FITS keywords called ...` and enter the keyword containing the Julian Date (e.g. "JD" or "JUL-DAY");

Pre-processing the images

If the set of images taken of an object over a period of time is very inhomogenous, then each image must be calibrated and measured individually. If the data are reasonably homogenous - as is the case when the observations were made with the same instrument under the same conditions or even in one observing session - then the images can be calibrated and measured *en masse* using ImageJ's stack capabilities:

1. **Produce and save any calibration images needed** (see the chapter ▶ Calibrating Raw Images ◀ or the ▶ Data-Reduction Recipe Book ◀); Load the calibration images into ImageJ (but you may want to iconify them to get them out of the way);

2. **Load the images into a stack** using the `File > Import > Image sequence...` command (the number of images you can load into a stack depends upon the amount of memory available on your computer and allocated by ImageJ; see `Edit > Options > Memory & Threads...`);

3. **Calibrate all the images in the stack** using `Plugins > CCD > Process Images`;

4. **Align all the images in the stack** if the images wander somewhat (e.g. poor tracking by the telescope over the long times observed) using the `Plugins > Stacks > Align Stack` plugin (see the chapter on ▶ Making Movies ◀));

5. You may want to crop the stack to contain only the parts of the images of interest (mainly the object to be measured and the reference star(s) used to measure the relative brightness variations) using a rectangular section selection and the `Image > Crop` command, particularly if you aligned the images in the stack.

The end-result is a stack of images showing the object to be measured and one or more reference stars.

Defining the objects to measure

If your object is very bright, you'll have no problem measuring the variable in each image, but if there are many objects in the field, you may have to employ a <u>FINDER CHART</u>, an image of the field where the object has been identified, or calibrate the image astrometrically. You will need one or more reference images, preferably several that are brighter than the variable object (but not so bright that the image is saturated).

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FINDER CHART

If your object is very faint or occationally disappears alltogether, you will need to know the position of the star exactly so that you can force ImageJ to measure it at the right position. The simplest way to do this is to

1. Align the images in the stack so that all stars are always at the same position (`Plugins > Stacks > Align Stack` as described before);

2. Construct an average image using `Image > Stacks > Z-Project ...`;

3. Measure the exact position of all your stars in the average image using the `Aperture Photometry` tool; make sure you select the option within `Plugins > Set Aperture` (or double-click on the aperture photometry tool icon) to print out the centroid positions and to re-center the aperture to obtain a very accurate position (unselect the "Use the clicked position, do not reposition" option);
4. The results will be shown in a results table - note the X- and Y-positions of the stars (to several decimal places) - these are the positions you should use!

Multi-Aperture Photometry

The light from the objects is measured using the simple technique of <u>APERTURE PHOTOMETRY</u>: a circle with a particular radius R_* is defined encompassing the light of the object plus any background light (due to the Moon, etc.); an annulus defined by an

inner radius R_{in} and an outer radius R_{out} centered on the same circle defines the background around the object and from which the background contribution at the position of the object can be subtracted. Of course, the radii have to be selected carefully: see the chapter ▶ Measuring Brightness ◀ for more details.

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APERTURE PHOTOMETRY

While you can measure all of the objects and standard stars by hand, the simplest technique is to measure all of the stars in all of the images in the stack at once using the `Plugins > Astronomy > MultiAperture` plugin:

1. Display the first image of the stack;

2. Enter the number of stars to be measured (one main target object and one or more reference stars) as `Number of apertures per image`;

3. Select the option `All measurements from one image on the same line.`;

4. Select the option `Compute ratio of 1st aperture to others (only if on same line).`;

5. Press "OK" and then click on each image to be measured on each image, in the correct order - the main target object first!

If your object is faint and so hard to measure in individual images, it's better to force ImageJ to use a specific position for the apertures:

1. Find the positions of the stars using the average image from the whole stack, as mentioned in the previous section;

2. Using `Plugins > Astronomy > Set Aperture` (or double-click on the Aperture Photometry Tool icon), select `Use the clicked position, do not reposition` (only works if the images stay at the same positions or if the stack has been aligned);

3. Select the stars using `Plugins > Astronomy > MultiAperture` as above, put click only after the cursor is at the right positions (displayed in the ImageJ toolbar window).

If the plugin is unable to get throught the entire stack (e.g. a too large

shift in the position of your stars, try the following:

- increase the size of your apertures to allow for more motion before ImageJ gets lost;
- perform the `MultiAperture` analysis only on blocks of the stack at a time;
- align the stack if you haven't already.

The result should be a `Measurement` table containing at least the entries

- `image` (name of image);
- `x` (pixel X-position of target object);
- `y` (pixel Y-position of target object);
- `source-sky` (total brightness of target object minus the sky background);
- `ratio1` (ratio of target object brightness to sum of reference star brightnesses).

and perhaps `J.D.-2400000` (Julian Date measured relative to 2400000) if you selected the option to calculate the Julian Date.

Advanced users can also have the errors of the measurments calculated using the gain and read-out-noise of the camera.

Plotting the lightcurves

The tables produced by the `MulitAperture` plugin can be stored as simple text files and read into graphing programs such as *Excel* (Windows, OSX), *OpenOffice* (all operating systems), and *gnuplot* (mostly Unix-like operating systems such as Linux and OSX). Import the data into a spreadsheet and plot the "J.D.-2400000" axis versus the "ratio1" axis. If you weren't able to let ImageJ calculate the Julian Date, you may have to enter the date and/or time by hand (e.g. by deriving it from the file name).

Starting with the 2009 version of the Göttingen Astronomy plugins, there is a `Plugins > Input-Output > Read Measurement Table` tool which enables you to read tables stored as text files back into ImageJ.

Starting with the 2009 version of the Göttingen Astronomy plugins, there is a `Plugins > Graphics > Plot Table Columns` tool which enables you to plot one column of table data against another, just as you are

accustomed to doing within a spreadsheet program (though not as well). The columns to be plotted and a few other parameters can be input to the plugin but the appearance of the standard (and pretty stupidly simple) ImageJ plot image can be modified by invoking `Edit > Options > Plot Profile Options ....`
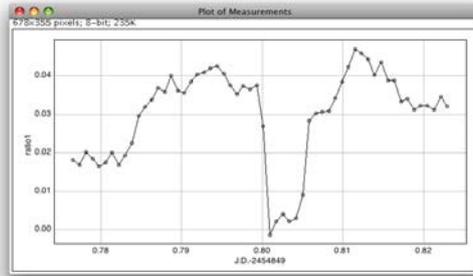
A lightcurve plot made directly from an ImageJ Measurement table.

Example Data

Here are some test data showing a very clean eclipse of a compact white dwarf star by its binary companion. Load all of this data into a stack, convert the stack to 32-bits (floating numbers), align it (best by shifting to whole pixels rather than interpolating), and then measure the brightness of the eclipsing binary using an aperture which doesn't get re-centered.