Nova Search

Cosmic Easter Eggs

Travis A. Rector, Jeffrey F. Lockwood and George H. Jacoby

The National Optical Astronomy Observatory
950 N. Cherry Ave., Tucson, AZ 85719 USA
email: rector@noao.edu

Teaching Notes

A Note from the Authors

The goal of this research project is to find and to study novae in M31, the Andromeda Galaxy. Novae are thermonuclear eruptions that occur on the surface of a white dwarf star as the result of mass transfer from a binary companion star. These eruptions briefly make the binary star system visible from large distances. We use images of M31 to find novae. We wish to know how often novae erupt in M31, as well as their locations and energetics.

The WIYN 0.9-meter Telescope

Please note that it is assumed that the instructor and students are familiar with the prerequisites listed below. This document is an incomplete source of information on these topics, so further study is encouraged. This is a real research program; and as such the “answers” are not known.

Prerequisites

To participate in this project, you will need a basic understanding of the following concepts:

- Celestial coordinates
- Stellar evolution
- Galaxies
- Novae
- Photometry

M31 Fields

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

Each 2048 x 2048-pixel CCD image is divided into sixteen 512 x 512-pixel fields.

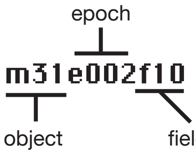
Description of the Data

The data of M31 used in this project were obtained with the WIYN 0.9-meter, MDM 1.3-meter and KPNO 2.1-meter telescopes at Kitt Peak National Observatory, which is located about 40 miles west of Tucson, Arizona. The original images are large—2048 x 2048 pixels. To make them easier to use, each image has been divided into 16 *subraster* images or “fields” as shown on the right.

Each subraster, or field, of the image is 512 pixels on a side. If all 16 subrasters were combined into a single grid, you would reconstruct the original 2048 pixel square image of Andromeda.

Decoding file names

The nova image file names contain the name, epoch and field number of the image. For example, the **m31e002f10** image is field 10 of the epoch 2 observation of M31.



The data files are named for the subraster and field, as well as the epoch of the observation. For example, an image named *m31e002f10.fits* indicates it is M31, epoch 2 and field 10. To examine all fields of Andromeda taken at one time, look at the 16 images with the same epoch number (e.g., e002). To examine one field of Andromeda and see how it changes with time, choose images with the same field number (e.g., f10) and look at all available epochs. Observations are completed ideally once a month, the Kitt Peak schedule allowing. There is also a gap from late January to late June, during which M31 is not visible from Earth.

Note!

Use only the new datafiles that have a three-digit epoch number (e.g., e002). The old dataflles use only a two-digit number (e.g., e02). *Do not use the old datafiles.*

About the Software

This project is designed for *ImageJ*, a JAVA implementation of the popular program *NIH Image*. *ImageJ* runs on many platforms, including Macintosh OS 9 and OS X as well as on Microsoft Windows and LINUX on the PC. *ImageJ* is free and can be found online at *http://rsb.info.nih.gov/ij/*

In this documentation an "🖳" icon appears when analysis of the data with the *ImageJ* is necessary.


ImageJ

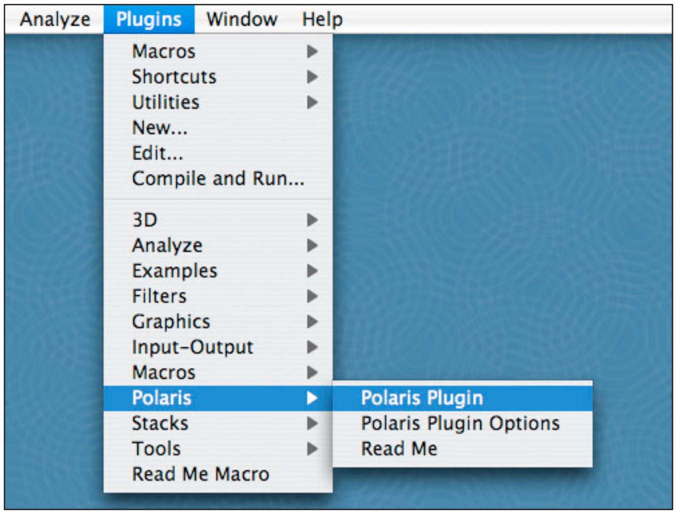
Installation of the Polaris Plug-In

A "plug-in" called **Polaris** has been written for *ImageJ*. It is designed for analysis of astronomical imaging data in FITS format. The plug-in is distributed as a zip file with a name such as "Polaris_20080515.zip" When unzipped, a folder will appear titled "Polaris." Place this folder inside the "plugins" folder within the ImageJ application directory. Note: Do *not* place it inside the "macros" folder. Also note: The current version of the plug-in requires ImageJ version 1.34 or higher.

After starting *ImageJ*, check to make sure that the plug-in is properly installed by looking under the Plugins menu. A submenu titled "Polaris" should be present, as shown below:

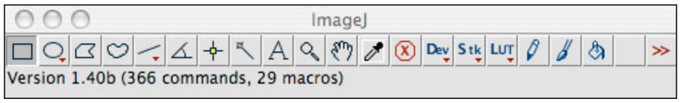
Nomenclature:

FITS stands for **F**lexible **I**mage **T**ransport **S**ystem. It is the standard format for storing astronomical data.



The ImageJ Toolbar

When *ImageJ* is started a toolbar will appear that looks like the one shown below. The rectangle tool is shown as selected. At the bottom of the toolbar the current location of the cursor, and pixel value underneath the cursor, are shown.



Version 1.40b (366 commands, 29 macros)

The name of a tool is shown when the cursor is floated over the tool's button. There are several tools in the toolbar that are useful for this project:

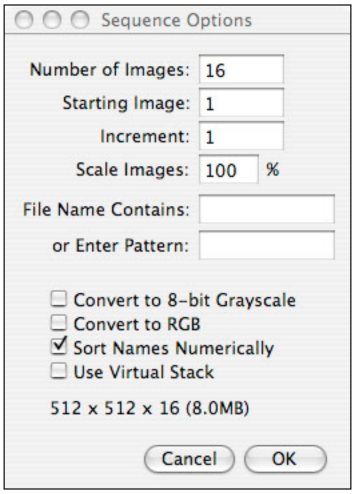
Selection tools The first seven tools can be used select portions of the image.

Each tool functions differently. These tools can also be used to draw on the image. This is useful for marking regions that have been inspected, or need to be inspected. The perimeter of the selected region can be drawn onto the image by typing ctrl+d (hold down the ctrl key and hit the “d” key).

Text tool The text tool can be used to write comments on the image. This is useful for labeling novae, imposters, etc. Once the text is entered it is drawn onto the image by typing ctrl+d.

Magnifying glass tool This tool can be used to zoom in to portions of the image. On the PC, to zoom in on a region of the image, left-click on the center of that region. To unzoom right-click on the image. On the Macintosh, to zoom in click on the region. To unzoom, hold down the control key while clicking on the image. To completely zoom out, double-click on the 🔍 icon in the toolbar window.

Scrolling tool This tool is useful for panning around an image after zooming in with the magnifying glass. Click and drag within the image to move around.



Number of Images: 16
Starting Image: 1
Increment: 1
Scale Images: 100 %
File Name Contains:
or Enter Pattern:

☐ Convert to 8-bit Grayscale
☐ Convert to RGB
☑ Sort Names Numerically
☐ Use Virtual Stack

512 x 512 x 16 (8.0MB)

The sequence options window

Summary of Menu Commands

Below is a summary of some of the useful menu commands in *ImageJ*:

File/Open...

This command will open a single FITS image file. Use this command to open a file for astrometric and photometric measurements.

File/Import/Image Sequence...

This command will open a sequence of images as a stack for blinking. Use this command to search for novae. Set the starting image to the first epoch you wish to search. And set the number of images you wish to search. The increment should be set to one; otherwise images will be skipped.

File/Save As/Image Sequence...

This command can be used to save a stack as a sequence of images to be reloaded at a later time. *Do NOT overwrite the existing FITS files*. This command is useful for saving a stack that has been drawn upon with the text and selection tools. Note: Do not use these images for the astrometry or photometry measurements.

Edit/Options/Memory...

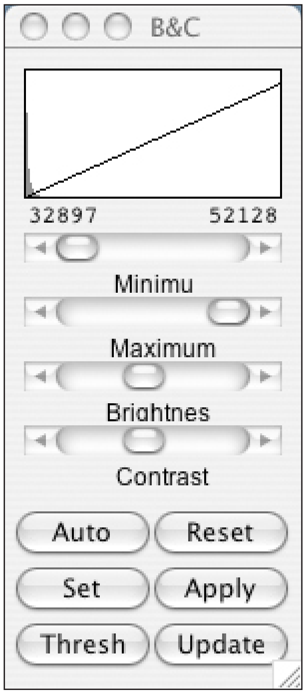
This command can be used to adjust the maximum amount of memory that *ImageJ* will use. It can be increased if a very large stack is to be loaded.

Image/Show Info

Displays the FITS header. Contains useful information such as the date of observation, exposure time, etc. When used on a stack of images this command shows the FITS header for the first image in the stack.

Image/Adjust/Brightness & Contrast

Opens the control panel that is used to adjust the display of the data. The “auto” button is especially useful. Click on it a few times to get a good display range.



The brightness and contrast (B&C) window

Image/Lookup Tables

Different color “look-up tables” (LUTs) can be used to display the data. Choose whatever color scheme you like best.

Image/Lookup Tables/Invert LUT

Inverts the image color table. If used on the normal grayscale LUT, the stars will appear black and the background white. Many find it easier to see novae with the LUT inverted. The Polaris plug-in options can be set for this to be done automatically.

Image/Stacks/Start Animation

Use this command to animate a stack of images.

Image/Stacks/Animation Options...

Adjust the speed of the animation (frame rate) as well as the loopback.

Process/Image Calculator...

Use this command to subtract one image from another. This is another way to search for novae. It is especially useful for searching in the center of the galaxy.

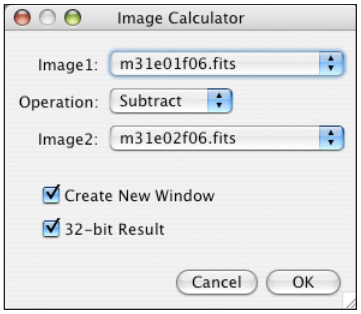


Image1: m31e01f06.fits
Operation: Subtract
Image2: m31e02f06.fits

☑ Create New Window
☑ 32-bit Result

The image calculator window

Plugins/Polaris/Polaris Plugin

Use this command to start the Polaris plug-in. This will attach a data window to the image. The Polaris plug-in will work on either an image or a stack.

Plugins/Polaris/Polaris Plugin Options

Use this command to change the Polaris plug-in options:

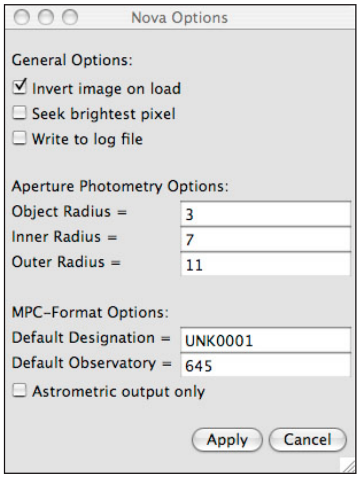
The “Invert image on load” option will automatically invert the LUT of the image or stack when the Polaris plug-in is started.

The “Seek brightest pixel” option will attempt to center the photometry aperture on the nearest star. Note that the centering can fail on faint stars.

The “Write to log file” option allows the output of the plug-in to be written to a file. By default the file is written in the ImageJ application directory. If the user does not have write permission to this directory, ImageJ will ask for another location to save the logfile.

The aperture radii for photometry measurements can also be adjusted here. If the “Astrometric output only” option is selected, pressing the space bar will not generate photometric measurements of the selected object. This is useful if no, or insufficient, photometric standards are available.

The MPC-Format Options are not used for the nova project.



General Options:
☑ Invert image on load
☐ Seek brightest pixel
☐ Write to log file

Aperture Photometry Options:
Object Radius = 3
Inner Radius = 7
Outer Radius = 11

MPC-Format Options:
Default Designation = UNK0001
Default Observatory = 645
☐ Astrometric output only

The Polaris plug-in options window

Summary of Polaris Plugin Keystrokes

Once the Polaris plug-in is started, the following keystrokes are used for the aperture photometry:

b	Calibrates the photometer by measuring the brightness of stars of known magnitude (known as “standard stars”). Place the cursor over a standard star and hit the “b” key. An *enter magnitude* box will appear, into which you enter the known magnitude of the standard star (from the finder charts). You must measure at least two standard stars before measuring magnitudes of unknown stars and novae. For best results, measure three or more standard stars.
space bar	Measures the brightness of a star or nova. Results are valid only for images calibrated with two or more standard stars.

Note!

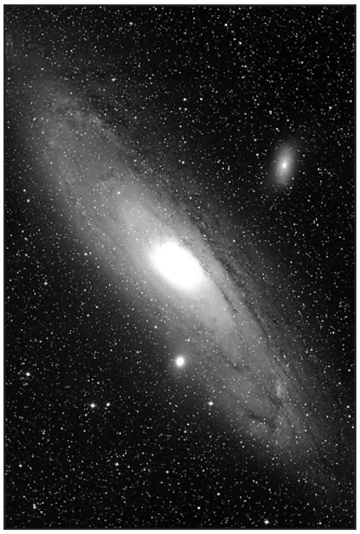
If the user does not have write permission to the ImageJ application folder, the nova options cannot be saved. Any changes to the options will remain in effect until the application is closed.

Nova Search

Content Background for Nova Research

Introduction

Throughout much of history, humans have regarded the heavens as fixed and unchanging. One of the first indications that this was not truly the case was the occasional appearance of *novae*, stars that suddenly flare into view. Every five to ten years, a nova that is bright enough to be seen with the naked eye will occur within the Milky Way. The word nova literally means "new star." The name comes from ancient civilizations which interpreted these events as the creation of a new star. In reality however, novae are caused by stars near the end of their lives. To understand how novae work it is important to understand how stars form, live and die.



M31 - The Andromeda Galaxy

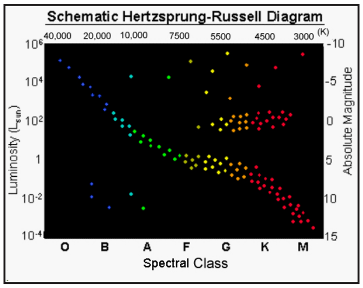
The Life of a Star

The Universe contains an immeasurable number of stars: some of these stars are old while others are quite young. There are at least 200 billion stars in our galaxy alone. Depending on their mass, stars can live from one million to 100 *billion* (10^6 to 10^{11}) years, or even longer. Astronomers estimate that, in our Galaxy, approximately 3 – 10 solar masses of gas are formed into new stars each year. Although it is impossible to follow the lifecycle of an individual star, we can learn about how stars live and die by studying the general population of stars.

Nomenclature:

The word *nova* refers to a single nova. The plural form is *novae*.

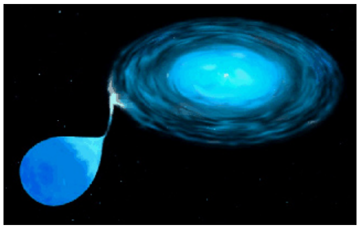
The formation of a star takes place in the interiors of enormous clouds of dust and gas that contain the raw materials needed to make a star. Once formed, a star spends approximately 90% of its life fusing hydrogen (H) into helium (He) in its core. During this time, it is known as a *main-sequence* star. Massive stars have more hydrogen gas than smaller stars like the Sun, but they use it up a lot faster and therefore are main-sequence stars for less time. Eventually the hydrogen in the core of the star is nearly exhausted, and the core begins to contract. For stars up to eight times the mass of the Sun, as the core collapses the temperature increases inside the star, causing the outer layers of the star to expand and cool. Due to its larger size and cooler temperature it is known as a *red giant*. The red giant phase ends when temperatures in the core rises sufficiently for helium core fusion to begin. The helium is fused into heavier elements such as carbon, nitrogen and oxygen. Eventually, the helium also becomes depleted and the temperatures again start to rise. The star now has an inert carbon core, with shells of helium and hydrogen burning around it. In low-mass stars (less than 2.5 times the mass of the Sun), the core does not reach temperatures hot enough to undergo carbon ignition and fusion within the cores stops. The core can no longer support itself with radiation pressure and it starts to collapse under the influence of gravity. As the core gets hotter the star blows off its outer layers, which become a *planetary nebula*. The core itself is very small but still very hot, and is known as a *white dwarf*. A white dwarf has exhausted all its available nuclear energy sources. If left alone, it will spend the rest of its years slowly cooling, a glowing ember in space.



The Hertzsprung-Russel diagram plots stars as a function of their color (X-axis) and luminosity (Y-axis). Stars on the diagonal line are main sequence stars, those in the upper right are red giants and the few in the lower left are white dwarfs.

Binary Stars and Novae

Most stars are not alone: they are in *binary systems* in which two stars closely orbit each other. Due to their proximity, one star can influence the other. Imagine the case of a binary system with two old, low-mass stars. If one of the stars is more massive it will age faster and become a white dwarf while the other star is still a main-sequence star. If the two stars are close enough, it is possible for gas from the main-sequence star to be pulled over onto the white dwarf. Eventually enough material piles up on the white dwarf for nuclear fusion of hydrogen into helum to resume. The effect is akin to dumping lighter fluid onto hot coals. The result is an explosion that blows off some or all of the accumulated gas, which includes not only hydrogen but also important elements such as carbon, nitrogen and oxygen. Once the explosion occurs, a shell of gas is blown into space. The explosion itself is what is referred to as the nova. Initially the nova is very bright- about a million times brighter than the binary stars before the explosion. Eventually, the nova will fade back to its original brightness in a few months to a few years.



Artist's visualization of an interacting binary star such as a nova (courtesy NASA/HST).

Note that the nova does not destroy the white dwarf nor the companion star. The process will eventually repeat itself roughly every 10,000 years. The time between outbursts may be related to the intensity of the nova. Roughly speaking, the more intense the outburst, the longer until the next one occurs.

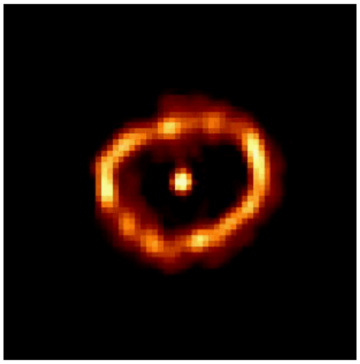
Studying novae helps astronomers understand the late stages in a star's life. It also provides information about the evolution of binary star systems. Perhaps most importantly, it helps to determine the enrichment of the interstellar medium with carbon, nitrogen and oxygen. Novae are an important contributor of these elements, which are the building blocks of life. Much of the carbon, nitrogen and oxygen that was used to form our Sun and its Solar System (including the Earth and the life on it) originated in novae explosions that occurred billions of years ago in our galaxy.

Why are novae important?

Novae play a role in creating much of the nitrogen, carbon and oxygen in the Universe. These are important elements for the formation of life-habitable planets like the Earth.

The Project

In this project, you will search for novae in the Andromeda galaxy by comparing images taken weeks or months apart. This will be done by using a technique called *blinking* in which one searches for "new stars" that appear in one image and not the other. The Andromeda galaxy, or M31, is a spiral galaxy that is about 2.2 million light years away from Earth. A handful of M31's 400 billion stars go nova each year. It is an excellent galaxy to study because it is large and relatively nearby. It is the only galaxy you can see without a telescope from the Northern Hemisphere. From a dark site, it looks like a faint, fuzzy patch in the sky. M31 is of particular interest because it is similar in size and structure to our galaxy, the Milky Way. For this reason M31 is often called our "sister galaxy." By studying M31 we can therefore learn much about our own galaxy.



A Hubble Space Telescope image of Nova Cygni 1992 A shell of gas is blown off the white dwarf in the nova's explosion. Note that the bright spot at the center is light from both stars in the binary.

Although a nova's rise to maximum brightness occurs in a short period of time (perhaps 1 to 5 days), the decrease in brightness back to the star's stable state varies considerably. The rate of decreasing brightness can be quantified by taking the slope of the decreasing portion of the light curve. The units of the slope can be expressed in magnitudes per day. The decline in brightness may ultimately be related to the mass of the white dwarf progenitor.

$$f \propto \frac{L}{r^2}$$

The inverse square law states that the brightness (f) of a star is directly propotional to the luminosity (L) of the star and inversely proportional to the distance (r) to the star *squared*.

The apparent brightness of novae is measured using a technique called photometry. By the inverse-square law, a nova's brightness is proportional to the luminosity of the nova, which is the total amount of energy that it emits per unit of time, and inversely proportional to the distance to the object *squared*. Because the distance to the novae does not change, the change in brightness is directly proportional to the total amount of energy emitted. You will measure the apparent brightness of the novae on what astronomers call the *magnitude scale*.

The Magnitude Scale

Always trying to be difficult, astronomers use an unusual scale to measure the apparent brightness of an object. The *magnitude scale* is a logarithmic scale in which each integral step corresponds to a change of approximately 2.5 times in brightness. In addition, the scale is inverted, so that brighter objects have smaller magnitudes than dimmer ones. For example, an object with magnitude $m=1$ is about 2.5 times *fainter* than an object with magnitude $m=0$.

The origin of the magnitude scale dates back to Hipparchus, who cataloged about 1000 stars that were visible to the naked eye. He classified the twenty brightest stars as 1st class (magnitude $m=1$), the next brightest as 2nd class, and so on down to 6th class ($m=6$), the faintest stars he could see. The human eye isn't very good at determining brightness, so the magnitude scale was at first very approximate. Once astronomers were able to make accurate photometric measurements, the magnitude scale was quantified. The British astronomer N. Pogson determined that 6th magnitude stars (as Hipparchus had classified them) were roughly 100 times fainter than 1st magnitude stars. Thus, 5 steps in magnitude was specified to equal a factor of 100 in brightness. Each step in magnitude is therefore the 5th root of 100, or 2.512 times fainter than the last step.

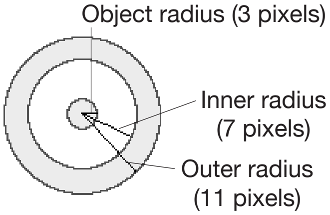
The bright star Vega, in the constellation of Lyra, "the harp," is defined to be an $m=0$ star. And the brightness of all other objects are measured relative to it. Sirius, the brightest star in the sky (except for the Sun of course) has a magnitude of $m=-1.4$. The Sun's magnitude is $m=-26.8$, or about 10 billion times brighter than Sirius. This is of course because the Sun is so much closer than Sirius. The novae you will study have magnitudes ranging from roughly $m=15$ to $m=20$, or approximately 10,000 to one million times fainter than what you can see with your naked eye. Their faintness is due to their distance since they are located in M31, which is about 2 million light years away from us. What this means is that the novae you discover actually erupted more that 2 million years ago. It is just now that their light is reaching us.

Aperture Photometry

You will measure the magnitude of each nova candidate using a technique known as aperture photometry. The term aperture refers to an opening of a specific size; and photometry refers to the measurement of light.

Most of the stars or novae have a radius of 3 pixels or less. Thus, light within a three-pixel radius from the center of the object represents most of the light from the object, plus some additional background light from the rest of M31 as well as from our own atmosphere. The amount of background light near the object must be measured and subtracted to determine the object's actual brightness. The background level is calculated by measuring the brightness of pixels in a ring surrounding the object. The default ring, or annulus, has an inner radius of 7 pixels and an outer radius of 11 pixels. All three radii can be changed by the user.

Aperture radii



While it may sound complex, aperture photometry isn't difficult because most of the steps are done by the computer. First, the photometry software in the nova plug-in in *ImageJ* must be calibrated. This is done by identifying *standard stars* in the field. Standard stars are stars that have been studied before and for which their brightness is known to be unchanging and their magnitudes are well measured. Several standard stars are identified for each subraster. Their positions and magnitudes are given on the finder charts. Once two or more standard stars are identified and their positions and magnitudes are entered into the software, the magnitudes of novae in the field can also be measured.

Celestial Coordinates

Astronomers measure the positions of objects in the sky by imagining that astronomical objects lie upon a *celestial sphere*, an imaginary hollow sphere inside which the Earth resides at the center. The positions of objects on the celestial sphere are described by two *celestial coordinates, right ascension* and *declination*.

Right ascension (α) is analogous to longitude on Earth; it describes an object's position in the East-West direction. Because the celestial sphere appears to complete one rotation every 24 hours (due to the Earth's rotation), right ascension is measured in units of time. Right ascension is reported in units of hours, minutes and seconds. Like real units of time, there are 60 minutes in an hour and 60 seconds in a minute of right ascension. Declination (δ) is equivalent to latitude; it describes an object's position in the North-South direction. Declination is measured in degrees (°), arcminutes (‘), and arcseconds (“), wherein there are 60 arcminutes in a degree and 60 arcseconds in an arcminute. A declination of 0 degrees marks the *celestial equator*, which divides the sky into the northern and southern hemispheres. The celestial equator is the projection of the Earth's equator onto the celestial sphere. A declination of +90 degrees marks the north celestial pole (just as +90 latitude is the North Pole on Earth) and -90 degrees marks the south celestial pole. A celestial coordinate marks a unique location, and is used by astronomers to mark the locations of objects in the night sky. For example, the celestial coordinates for the center of M31 is: α = 00h42m45.9s, δ = +41°16’18". For simplicity they are written with colons, e.g., α = 00:42:45.9, δ = +41:16:18.

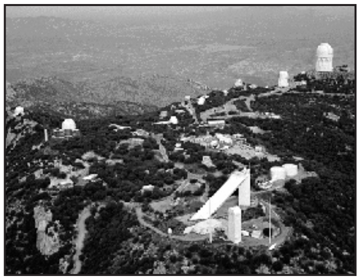
The nova search plug-in will also be used to measure the celestial coordinates for stars and novae in the field. The information necessary for the plug-in to measure the coordinates is given in the FITS file header and is used automatically. However, it is worthwhile to confirm that the coordinate system is accurate by using the standard stars. Coordinates for the standard stars are located on finder charts and should be used to confirm the accuracy of the values given by the nova plug-in.

Nova Search

A Night on the Mountain

A personal perspective by Jeffrey F. Lockwood

When Robin Ciardullo was a graduate student, an astronomer down the hall discovered something unusual about a star called SS433. This star had jets of gas shooting out from it at speeds approaching 50,000 miles per second — almost one-third the speed of light. Robin decided to search for other stars like SS433 in Andromeda, also called M31, the nearest spiral galaxy to the Milky Way. Robin never found any SS433 clones, but he stumbled across many starry diamonds nestled among the billions of ordinary stars in M31.

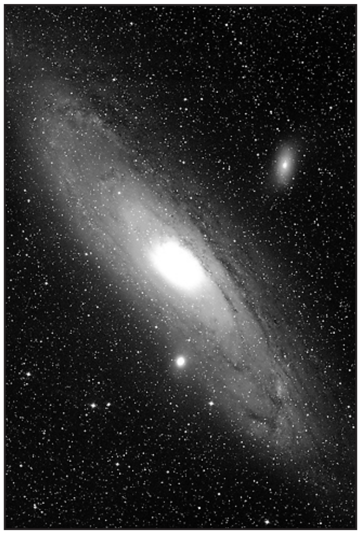


Kitt Peak National Observatory

As a high school astronomy teacher, I jumped at the chance to visit Robin during an observing run at the Mayall 4-meter telescope on Kitt Peak, west of Tucson, Arizona. Sitting at the computer console in the telescope control room, Robin explained "In astronomy, you search the sky for gold nuggets but sometimes you find something completely different. You often find nothing at all, but occasionally an entirely new object comes into view. It's like finding a diamond among a million leaves in your backyard."

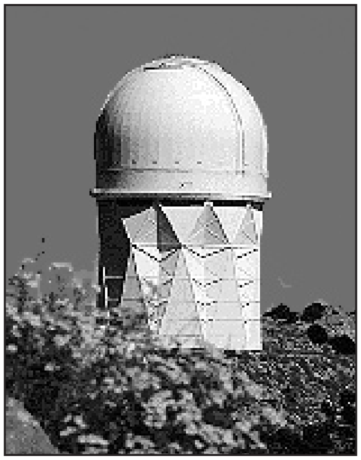
New Stars

Starry diamonds? I thought astronomy involved looking through telescopes, impossible mathematical equations, and computerized confusion, not diamonds. Using a filter for a particular color of red light called Hydrogen alpha, Robin took images of M31 and discovered many unexpectedly bright "new" stars, or novae.



M31 - The Andromeda Galaxy

Novae are stars that suddenly increase their brightness as much as one hundred million times. They are born in "close binary" systems consisting of a cool low-mass main-sequence star and a hot white dwarf star orbiting very close to each other. Normal binaries are millions of miles apart but, in these unusual systems, the stars are separated by about a million miles. Due to their closeness, hydrogen gas from the atmosphere of the cool red star is pulled by gravity onto the surface of the hot white dwarf. When the layer of hydrogen gas on the white dwarf reaches critical temperature, it begins to fuse explosively. The result is a brilliantly-glowing "bubble" of gas, expanding into space at 1000 km/sec. From our viewpoint, the bubble shines like a brilliant cut diamond.



4-meter Mayall Telescope

After discovering a dozen novae in M31, Robin applied for telescope time at three different observatories. His goal was to determine the rate and distribution of novae in other galaxies. Comparing images of these galaxies to ones taken previously, the novae stand out like tiny beacons where no star was seen before. Repeated observations are used to plot a curve showing the change in the nova's brightness over time. Novae decrease in brightness over a period of a few months as the bubble expands away from the white dwarf.

A Typical Night on the Mountain

Robin's day begins with an hour and a half drive from the NOAO headquarters in downtown Tucson to Kitt Peak National Observatory. After a quick lunch, Robin and his colleague, Allen Shafter from the San Diego State University, meet with Chuck Claver, an Instrument Technician and staff scientist. Their first order of business is to discuss which filters they want installed for their observing run. The filters are mounted in a revolving wheel placed in the path of the incoming light. Each filter restricts the incoming light spectrum to a specific band of wavelengths. Chuck tells them that the CCD camera is already mounted in the prime focus cage, a black tube some 25 feet above the primary mirror, and that he'll be ready to install the filters at 1:30 PM.

In the telescope control room, where the astronomers will spend the night working, a technical assistant arrives to calibrate the CCD camera. The astronomers are not allowed to move the telescope themselves, so an operator must be present all night to guide the telescope and determine when the weather is too poor to open the dome. The operator's area looks like a jet plane console with dials and gauges—some familiar, like wind speed and humidity, and some unfamiliar like *LUP*. Three monitors sit above the operator's console: one to show the position of the telescope, one so the operator can see what the telescope sees, and one to view what the camera is recording. On the other side of the control room, the scientists and guests camp out with their own set of monitors, including one that allows them to analyze their data as it comes from the telescope.

The Camera

The heart of the CCD imaging system is a 5-cm by 5-cm silicon chip. It contains a grid of over 4 million tiny light detectors arranged in a 2,048 by 2,048 square. The telescope optics gather and focus photons of light onto the CCD. When enough photons have been collected, the shutter is closed and each detector sends its photon count to the computer to be stored and reconstructed into an image.

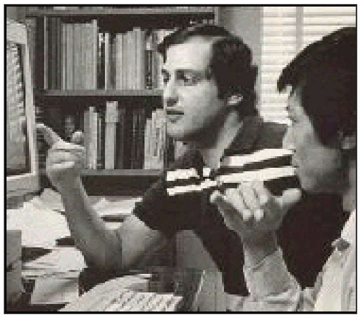
Calibrating the chip involves two steps, each designed to correct a different kind of error. In the first step, the operator takes 15 *bias* frames—images made with the shutter closed—and averages them. This creates a picture of what the chip records when no light is falling on it. Next, the chip is *flat-fielded* to measure each individual detector's response to light. The operator points the telescope at a large white panel attached to the inside of the dome. The panel is illuminated by four floodlights mounted on the end of the telescope. Five images are taken of the panel through each filter, and these are averaged. Later, when the astronomer wants to view a calibrated image of a galaxy, the bias frame is subtracted from the image and the appropriate flat-field is divided into it. The result is a processed or "clean" image.

Waiting for Night to Fall

At 5 PM it's time for dinner, so we drive over to the dining hall. After dinner, I follow Robin to the library where he shows me a few of the papers about nova production rates that he has published in astronomical journals. Other astronomers are surprised at his results, because his nova rate is 6 times higher than predicted by current theory. Robin continues to collect data to confirm his earlier findings. Knowing the nova production rate will help astronomers measure distances to far away galaxies, fix the rate and nature of binary star formation, and estimate the amount of heavy elements formed by these stellar explosions. We can hear the wind whistling through the trees outside the library and the sky looks gray and water-laden as we go out to jump into the car. There are no rain checks in

Nomenclature:

NOAO is the National Optical Astronomy Observatory. It is the national center for ground-based nighttime astronomy in the United States and is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation.



Dr. Robin Ciardullo (on left)

Dr. Allen Shafter

astronomy, so we hope the clouds break up soon.

Everyone arrives back at the control room at 6:45 PM but the operator says it's too windy and cloudy to open the dome. Robin takes another set of flat fields and outlines the data collecting procedure. Tonight's primary target is a spiral galaxy called M101. He plans to take seven 15-minute exposures using the H-alpha filter, then seven 1-minute exposures using the R or red filter. The H-alpha images will be compared with last year's by *blinking* them to see if any novae have appeared since last year. Novae are very bright in H-alpha, but are less noticeable in the red images. Variable stars are readily apparent in *both* the H-alpha and the red images. This helps Robin verify whether nova candidates are truly novae.

Evening's First Light

At 9:45 PM, the sky has miraculously cleared, so the telescope operator opens the dome. The operator announces that the mirror is much warmer than the outside air. A warm mirror heats the air above it and generates image-degrading convection currents in the light path. The primary mirror, a 10-ton hunk of fused quartz glass, may need an hour to "cool off" before steady images can be taken. Robin shrugs his shoulders, sighs "Oh well," and starts fiddling on his computer. Allen picks up some tests from his Astronomy 101 class and starts to grade them.

At 11:00 PM, the mirror has cooled somewhat and a test exposure is taken. Everything appears to be working, so Robin enters the command into his computer to take the first 15 minute exposure. Since it takes the CCD chip 3 minutes to dump an image to the computer, the M101 data set will take two and a half hours to complete. On a perfect observing night, he can study three or four galaxies.

Five minutes into the first exposure, the telescope operator yells, "Abort the exposure. The humidity has risen to 95%—I'm closing her up!" He is afraid that moisture will condense on the telescope mirror and damage the thin aluminum coating. The astronomers express their frustration but the dome closes quickly and whatever data the camera has collected are lost.

Mother Nature 1; Astronomers 0

Midnight arrives, and clouds continue to envelop the telescope in fog. Everyone heads to the cafeteria for the night-lunch meal. By 2:30 am the clouds part, but the air is still moist, and the wind is blowing at 40 mph. Robin and Allen decide to wait until tomorrow night to try to collect useful data. "The diamonds will still be there," Robin says, looking a little tired and irritated, "all we need is Mother Nature to cooperate." He continues, "Think about it—light travels trillions of miles towards our waiting telescopic eyes only to be turned away by a cloud layer one mile above the dome! Hardly seems fair, does it?"

As I travel back to Tucson in the early hours of the morning, I wonder if Mother Nature will cooperate in Robin and Allan's attempt to verify and quantify the nature of novae. Astronomy is different from other branches of science—we can't take field trips to the stars and we can't collect samples from them to analyze in our laboratories. Instead, we harvest photons with our telescope mirrors and count them with CCDs to decipher the information they hold about the mysteries of the universe and our creation.

Sublime Luminosity

I search the starr'd sky
Seeking for what I found
        A time ago

Your luminosity arous'd
        my eyes
Through a return of gaze
No longer inconsequential

Filling the blackness
        with new star light
Erasing the darkness
with Hydrogen

Then fading back
        in the void
The elements transformed

Where did you go as my eyes
        flashed upon you
        sublime nova?

-Michelle Denham
January 2000

This page intentionally blank.

Nova Search

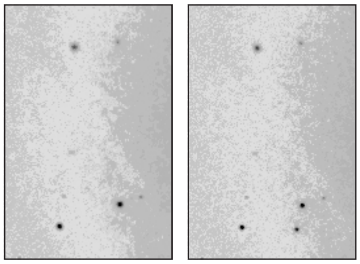
Data Analysis Instructions

Searching for Novae

The easiest way to find novae is to compare images of the same field taken at different times. Each folder in the M31 data contains images of the same field taken at different times or epochs. Pick one of the sixteen M31 fields to explore. If you have not done so already, follow the "cosmic popcorn" tutorial to better learn how to use these tools.

- Launch *ImageJ*.
- Create a stack of images for blinking:
  - Choose **File/Import/Image Sequence...** and select the first dataset from the field you wish to blink.
  - Enter the range of epochs you wish to blink. The software will build a stack of images labeled with epoch numbers.
  - Choose **Image/Lookup Tables/Invert LUT** to invert the LUT.
  - Open the brightness & contrast control panel with **Image/Adjust/Brightness & Contrast** and click on the auto button a few times to display the stars as clearly as possible. For better control, you can adjust the different sliders as well.
- Blink between the images:
  - Choose **Image/Stacks/Start Animation** to start blinking the stack. Hit the equal (=) key to start and stop the blinking. The speed of the blinking can be changed with the **Image/Stacks/Animation Options...**.
  - The slider on the bottom of the stack can be used to move through the stack. Alternatively, press the **<** and **>** keys to move forward or back one image at a time. The name of the image currently visible is shown in the upper-left corner of the window.
- To better see the novae, use the magnifying glass tool 🔍 to zoom in on portions of the image. On the PC, to unzoom right-click on the image. On the Macintosh, hold down the control key while clicking on the image. Alternatively, double-click the 🔍 in the tools window to unzoom.

Blink through the stack and visually inspect each image for fuzzy black dots that appear in one epoch but not the other. Once a nova candidate is discovered, measure the X,Y coordinates (sometimes referred to as the "device coordinates") of the nova candidate. Place the cursor over the nova candidate and the X and Y values should be given at the bottom of the *ImageJ* toolbar. If no coordinates appear, click on the nova candidate and jiggle the cursor a little until the coordinates appear. Record the X,Y coordinates and the first *and last* epochs in which the nova candidate appears.



These two images show the same portion of M31, one month apart. Can you find a nova?

Nomenclature:

Blinking is rapidly alternating between two or more aligned images.

Nomenclature:

An *epoch* (pronounced "eh-pock") is a single date of observation, e.g., July 24th, 1990. The time between epochs varies tremendously. In some cases the time between epochs is only a day. In other cases it is more than a year.

Warning!

Note that the data on the edges of the outer fields (i.e., all but fields 6, 7, 10 and 11) can be bad or missing. Make sure any apparent novae on the field edges are real and not due to missing data.

Beware of impostors!

When you find a nova candidate, zoom in and examine it closely. Not everything that appears in the images are novae. Some of the images contain artificial features or “bad pixels” from the CCD camera. To tell the difference, look at the shape of the object. Real novae look like the other stars in the image. The imposters look like as sharp black rectangles, squares or other odd shapes . Novae are fuzzy, not sharp.

Also beware of suspected novae near the edges of the fields along the outer edges of the dataset, i.e., in all of the fields but the central subrasters of 6, 7, 10 and 11. The pointing of the telescope is not exactly the same for all epochs. A star may appear or disappear simply because it was cut off in one image and not another. If you find a nova candidate near the edges of the image, to determine whether or not it is real adjust the brightness and contrast so that you can see the edges of the data. If the nova candidate disappears because the data are cut off in later epochs then it is not a nova.

Measuring Celestial Coordinates

Once you have found a nova candidate measure its celestial coordinates:

- Use **File/Open...** to open the epoch of your field in which the nova candidate first appears. Invert the LUT and adjust the B&C as you did before so that you can see the nova candidate clearly.
- Use **Plugin/Polaris/Polaris Plugin** to start the Polaris plug-in. A new window should attach itself to the image. To measure the location of nova candidate, position the cursor on the star. To get a more accurate measurement it is helpful to magnify the image.

Note that both the X,Y coordinates and the celestial coordinates are displayed in the top of the Polaris plug-in window. Be sure to record both the X,Y and celestial coordinates. The device coordinates will be useful for finding the nova later when measuring its magnitude.

Calibrating the Photometer

To measure the magnitude of nova candidates, the photometer must be calibrated to read magnitude from pixel brightness values. This calibration is accomplished by recording known magnitudes of two or more standard stars in the image field. You will need a printed copy of the “M31 Finder Charts.pdf.” It lists standard stars for each field.

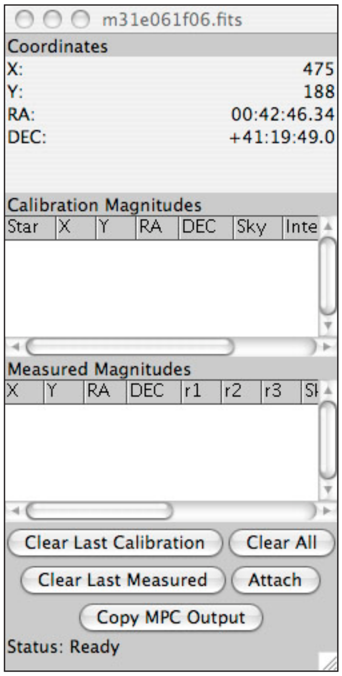
To calibrate the photometer:

- Adjust the brightness and contrast sliders in the B&C window to display the stars clearly. Make sure you can identify the numbered standard stars from the handout on your screen. The number is to the upper right of the standard star. Choose at least two (three or more is preferred) standard stars in the image.

- Place the cursor over the first standard star and hit the **b** key on the keyboard. An “Enter Magnitude” box should be displayed. If it does not appear, click on the star and hit the **b** key again. Once the Enter Magnitude box appears, enter the known magnitude of the standard star, given on the finder chart for that field, and click on the Ok button. Note:

Note:

If you see a nova candidate which appears to be a defect in the data, check and see if it appears in only one epoch. If the object appears in more than one epoch it is almost certaily real. Note however that many novae appear in only one epoch, so seeing an object in only epoch does not necessarily mean its not a nova.



m31e061f06.fits

Coordinates

X: 475
Y: 188
RA: 00:42:46.34
DEC: +41:19:49.0

Calibration Magnitudes

Star	X	Y	RA	DEC	Sky	Inte

Measured Magnitudes

X	Y	RA	DEC	r1	r2	r3	Sk

Status: Ready

The Polaris plug-in window

The X,Y and celestial coordinates of the current cursor location are shown in the top part of the window. The recorded magnitudes of standard stars are listed in the middle. And the measured magnitudes of nova candidates are listed at the bottom.

Nomenclature:

A *standard star* is a star which has been studied prior and is known to stay a constant magnitude. Since you know its magnitude, you may use it to calibrate your photometer.

Do not enter the uncertainty. Data should appear in the center box of the Polaris plug-in window entitled "Recorded Magnitudes."

- Repeat the above step for the other standard stars you've selected. Be sure to enter the correct magnitude for each star from the finder chart.

The standard star's number and its measured flux are labeled directly on the image. The Polaris plug-in window displays the location and magnitude information for each standard star in the recorded magnitude window.

Measuring the Magnitudes of Novae

After you have calibrated the photometer with two or more standard stars you can measure the magnitudes of novae within the field:

- Use the X,Y coordinates you recorded earlier to locate your nova candidate again. Move your cursor over a nova candidate and hit the space bar once. The magnitude of the nova will be displayed in the "Measured Magnitudes" area of the Polaris plug-in window.
- Repeat the above step for the other nova candidates in the field.

The measured magnitudes window will also show the X,Y and celestial coordinates for the nova. These values, as well as the epoch number and measured magnitude should be recorded for each nova candidate.

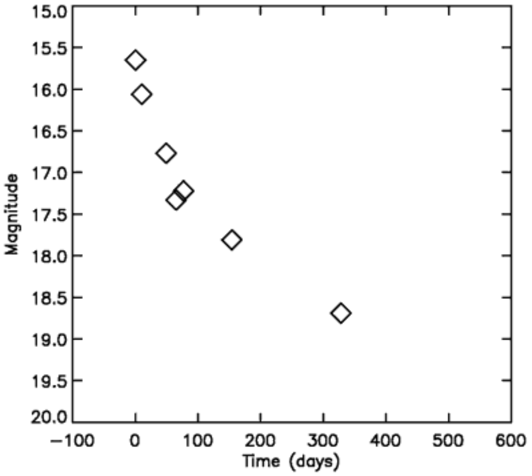
A Useful Tip:

You should document your work by writing it down in a log book as well as saving it electronically. The logbook can be used as a backup in case your electronic file is lost or damaged.

Measuring Magnitudes in Other Epochs

Due to weather and changing electronics, the telescope performs slightly differently during each observing epoch, so each image must be calibrated separately to read magnitudes correctly *even if you are using the same standard stars*.

- Follow the steps outlined above to measure the magnitude of the nova candidate in each epoch that the nova is visible.



Nomenclature:

A *light curve* is a plot of an object's brightness over time. Usually the Y-axis of a light curve has brighter magnitudes (i.e., lower numbers) on top. And the X-axis is usually measured in days, where the first epoch in which the nova is seen is day zero.

Constructing a Light Curve

Some novae will be visible in only one epoch; however many will be visible in multiple epochs. For each nova candidate you can identify in successive epochs, you can construct a *light curve* to plot how the nova's brightness changes over time. An example is given above for a nova seen in seven epochs.

Possible Research Questions

- Compare light curves produced by novae in the inner and outer portions of the Andromeda galaxy. Is there a correlation between the location of a nova and the shape of its light curve?
- What is the distribution of "speeds" of novae? What fraction are slow novae? Medium? Fast?
- Is there a correlation between the peak brightness of a nova and the length of time it is visible?
- How many nova erupt in M31 each year? Does the number vary significantly from year to year?
- Novae are known to erupt more than once. Compare the locations of novae you find to those found by other astronomers in the past and see if any are in the same location.
- Compare nova rates, locations, and light curves of novae in M31 to novae in other galaxies.
- While most of the epochs are spaced out by about a month or more, there are a couple of periods where observations of novae were obtained roughly once a night. How do the short-term light curves of novae compare to their long-term light curves?

Nova Search

An Example

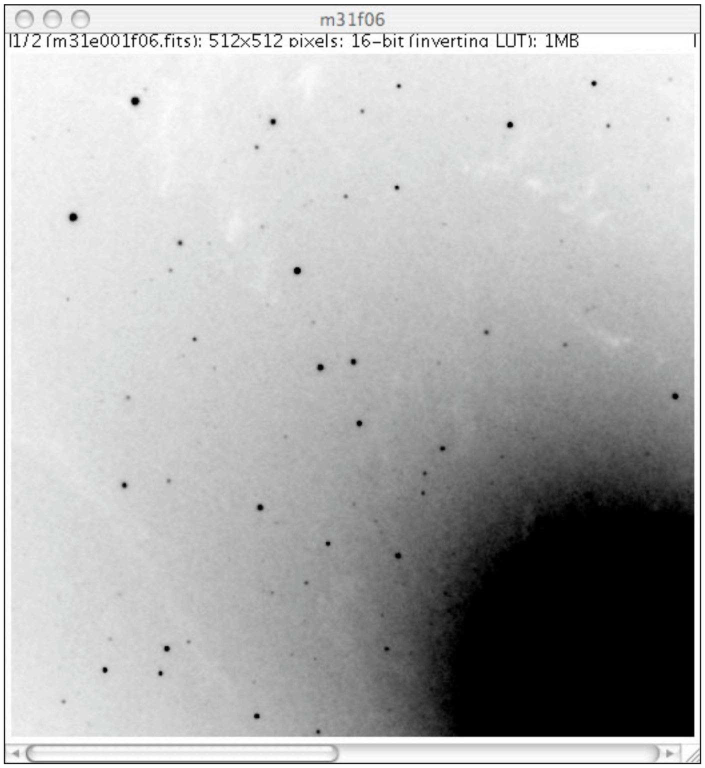
An Example: Cosmic Popcorn

We will blink two images in search of novae. Any object which appears in one image but not the other will be considered a nova candidate. In this example we will blink the first and second epoch of field 6, a field near the center of M31. The images we will study are *m31e001f06.fits* and *m31e002f06.fits*.

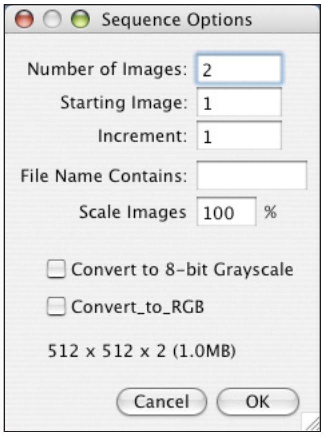
Create a stack of images for blinking:

- Choose **File/Import/Image Sequence...** and go to the folder that contains the data for field #6. Select the file *m31e001f06.fits*. In the sequence options window, set the number of images to 2, the starting image to 1 and the increment to 1. Click Ok.
- Use **Plugins/Polaris/Polaris Plugin** to start the Polaris plug-in. The plug-in window will attach to the right edge of the stack.
- If the Polaris options are not set to do this automatically, choose **Image/Lookup Tables/Invert LUT** to invert the LUT. This will cause the stars to appear dark against a gray background.
- Choose **Image/Adjust/Brightness & Contrast** to adjust the brightness and contrast to better see the stars. At first the image will be mostly white. Move the sliders until the fainter stars in the image are visible. To start try clicking on the “auto” button a few times.

You should have a stack of two images that looks roughly like this:


m31f06

1/2 (m31e001f06.fits); 512x512 pixels; 16-bit (inverting LUT); 1MB


Sequence Options

Number of Images: 2

Starting Image: 1

Increment: 1

File Name Contains:

Scale Images 100 %

☐ Convert to 8-bit Grayscale

☐ Convert_to_RGB

512 x 512 x 2 (1.0MB)

The settings for the sequence options window should be set as shown above.

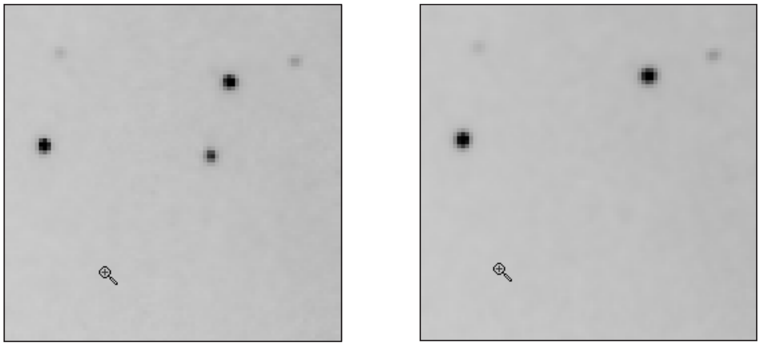
A Useful Tip:

You may wish to detach the plug-in window and resize it. To do so, click on the “detach” button, and then resize the window so that you can read the values in the recorded and measured magnitude tables more easily.

- Now blink between the images:
  - Choose `Image/Stacks/Start Animation` to blink the stack. If it blinks too fast adjust the animation options to slow it down. Hit the equal key again to stop the blinking.
  - Alternatively, move the slider at the bottom of the image or press the **<** and **>** keys to move forward or back.

An object in the lower-left corner near X=112, Y=464 is readily visible in epoch 1 but not in epoch 2. There is another bright object that appears in the upper-left corner near X=43, Y=9 in epoch 2 but not in epoch 1.

- Use the magnifying glass tool 🔍 to zoom in twice on the nova located in the lower-left corner of epoch 1. It should look like below:

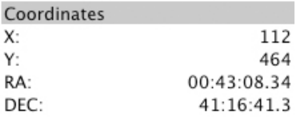


Epoch 1 Epoch 2

The object looks fuzzy like the other stars in the image, suggesting that it is real. We will now measure the location of the nova in epoch 1:

- Use the magnifying glass 🔍 to zoom in on the nova.
- Move the cursor onto the position of the nova and record its celestial coordinates (the RA and DEC).
- Double-click on the magnifying glass 🔍 in the toolbar to unzoom.

Now we will measure the magnitude of the nova in epoch 1. First we must calibrate the photometer by recording the magnitude of two or more standard stars in field #6. Use a printed copy of "M31 Finder Charts.pdf" as your guide to find standard stars. In this example we will use standard stars #18, #19 and #20:



Coordinates	
X:	112
Y:	464
RA:	00:43:08.34
DEC:	41:16:41.3

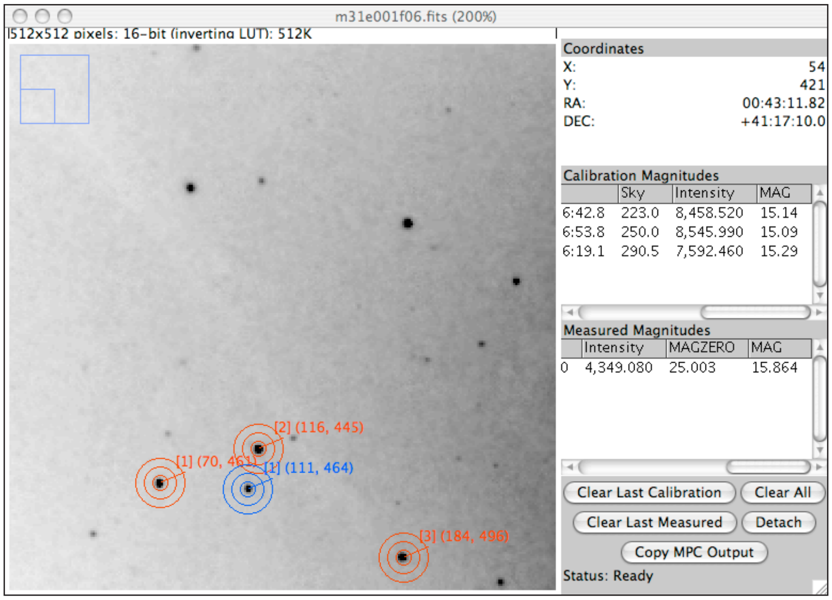
The top of the nova plug-in window should look like this when the cursor is placed over the nova.

- Move the cursor over standard star #18 at coordinates X=71, Y=462, in the bottom left corner of the image and hit the **b** key.
- When the "enter magnitude" box appears, enter the known magnitude of 15.14. If the box does not appear, click on the star and hit the **b** key again. Note: Do not enter the uncertainty in the magnitude (i.e., the ±0.05 part). The photometry apertures and labels will be drawn in red.
- To complete the calibration, repeat the previous three steps for standard stars #19 and#20. Note that I chose to skip standard star #21 because it is more than a magnitude fainter than the other standard stars and therefore is less accurate.

After you have calibrated the photometer with the standard stars you can measure the magnitudes of nova candidates:

Recall that the nova is located at X=112, Y=464. Place the cursor over the nova and hit the space bar once. If the "Seek brightest pixel" option is selected, the nova plug-inwill attempt to center the photometry aperture on the star nearest the cursor. Note that this option can fail on faint stars, in which case you should turn off this option and try to position the cursor as close to the center of the star as possible before pressing the space bar. The photometry apertures and labels will be drawn in blue.

The measured magnitude is given in the measured magnitudes part of the plug-in window (scroll to the right side). After the photometer has been calibrated and the nova has been measured, the window should look similar to that shown below (after zooming in on the nova and standard stars).


m31e001f06.fits (200%)

512x512 pixels; 16-bit (inverting LUT); 512K

Coordinates

X: 54
Y: 421
RA: 00:43:11.82
DEC: +41:17:10.0

Calibration Magnitudes

	Sky	Intensity	MAG
6:42.8	223.0	8,458.520	15.14
6:53.8	250.0	8,545.990	15.09
6:19.1	290.5	7,592.460	15.29

Measured Magnitudes

	Intensity	MAGZERO	MAG
0	4,349.080	25.003	15.864

Status: Ready

Note:

Each measured star will be labeled with three concentric circles: the aperture radius, and the inner and outer radii of the sky annulus. Each star will also be labeled with a set of numbers. The first number, shown in brackets, is the star number in the calibration magnitudes table. The second set of numbers, shown in parenthesis, is the X,Y location of the center of the star.

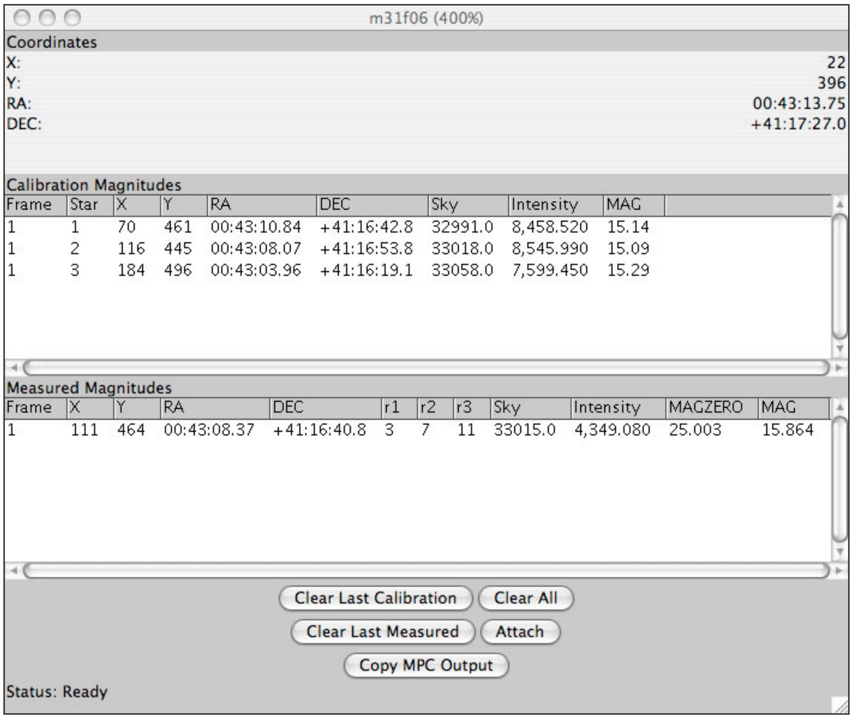
Calibration (i.e., "standard") stars are shown in red. And measured unknown stars are shown in blue.

In this example, the magnitude of the nova is determined to be 15.864. Note that you may get a slightly different value. Like all measurements, there is an inherent error in this value. There are two sources of error: the error in the determined values for the standard stars and the intrinsic error in the measurement of the nova itself. The determined error values for the standard stars are given on the finder charts. The error values range from ±0.02 to ±0.10. As one might expect, the measurements are usually more accurate for the brighter standard stars. When possible it is better to use the standard stars with smaller error values.

The overall error in the measured value for the nova can be estimated by measuring the magnitude of the nova several times, each time calibrating the photometer with different combinations of standard stars.

Useful tip:

To test the accuracy of your photometer you should first calibrate with three or more standard stars and then measure the brightnesses of other standard stars in the field. The measured values should be close to those given on the finder chart. If the measured values greatly exceed the errors, something may be wrong with the calibration.



Coordinates

X: 22
Y: 396
RA: 00:43:13.75
DEC: +41:17:27.0

Calibration Magnitudes

Frame	Star	X	Y	RA	DEC	Sky	Intensity	MAG
1	1	70	461	00:43:10.84	+41:16:42.8	32991.0	8,458.520	15.14
1	2	116	445	00:43:08.07	+41:16:53.8	33018.0	8,545.990	15.09
1	3	184	496	00:43:03.96	+41:16:19.1	33058.0	7,599.450	15.29

Measured Magnitudes

Frame	X	Y	RA	DEC	r1	r2	r3	Sky	Intensity	MAGZERO	MAG
1	111	464	00:43:08.37	+41:16:40.8	3	7	11	33015.0	4,349.080	25.003	15.864

Status: Ready

Note:

If you make an error, you can use the buttons at the bottom of the plug-in window. The "clear last calibration" button will delete the last standard star measurement (red circles). The "clear last measured" will delete the last measured star (blue circles). And the "clear all" button will delete all of the measurements from both lists. Note that the "copy MPC output" button is not used for the nova search project.

The detached and enlarged plug-in window should look as shown above. The plug-in window provides useful tables of values, including the frame and star number, X,Y coordinates, celestial coordinates (RA and DEC) and magnitudes. It also lists the photometry parameters: the object radius (r1), the inner and outer radii of the sky annulus (r2 and r3), and the magnitude offset value (MAGZERO). In this example the aperture radii are set to the default values of 3, 7 and 11. The magnitude offset value was determined from the standard star measurements and should be around a value of 25.0. Should an error have occurred during the photometer calibration (e.g., if you selected the wrong star, or entered the wrong magnitude), this value may be very different. If the MAGZERO value is not shown then you are using an older version of the plug-in. To ensure the best accuracy, you should upgrade latest version of the plug-in.

In this example the nova was seen in only one epoch, so we are unable to generate a light curve. If a nova is seen in multiple epochs, you may create a light curve by following the steps shown above for each image. Note that the photometer must be recalibrated for each image.

An Alternative Way to Search

Another way of searching is especially useful for finding novae near the center of the galaxy. In principle, the only difference between the images of M31 are the presence of novae. Thus, if you were to subtract one image from another, the two images should cancel each other out, *except* for the nova present in the two epochs.

One image can be subtracted from another by using the image calculator. First, both the first and second epochs of field #6 need to be opened:

Use **File/Open...** to open *m31e001f06.fits* and *m31e002f06.fits*. It is not necessary to invert the LUTs or adjust the brightness & contrast.

Now use the image calculator to subtract the first epoch from the second:

- Use **Process/Image Calculator...** to open the image calculator. Set image1 to *m31e001f06.fits*, the operation to "subtract" and image2 to *m31e002f06.fits*. This will subtract epoch two from epoch one. Make sure that "Create New Window" and "32-bit Result" are turned on.
- Click on the auto button once in the B&C window to rescale the image.

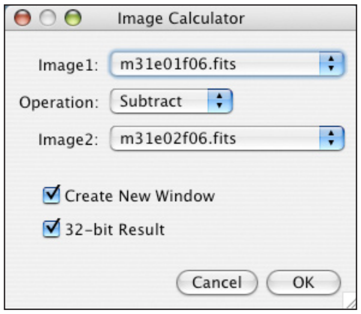
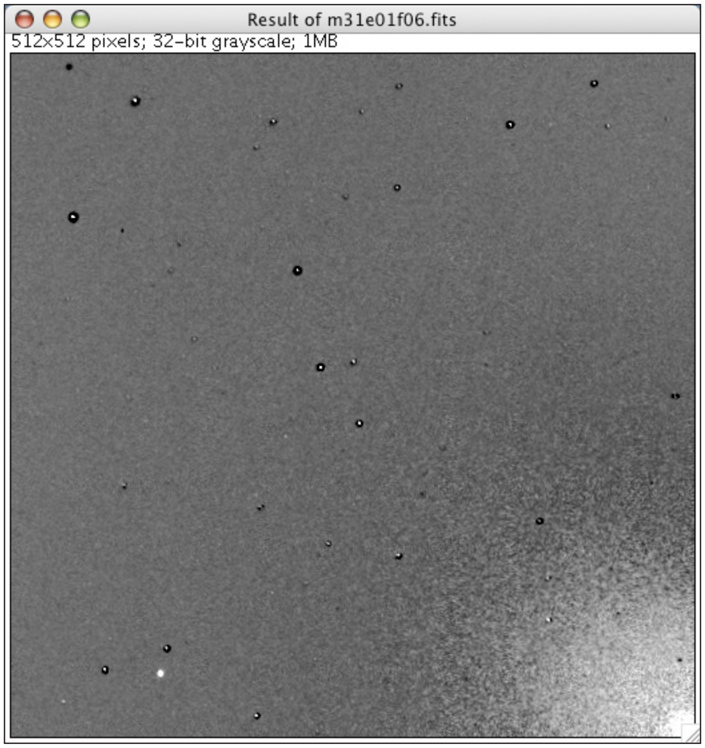


Image1: m31e01f06.fits
Operation: Subtract
Image2: m31e02f06.fits

☑ Create New Window
☑ 32-bit Result

The settings for the image calculator should be set as shown above.



A new window will be created that looks like the one below:

As you move the cursor through the window, notice that most of the pixel values are close to zero. You'll also notice that most of the stars now look like funny black donuts with white centers. This is the result of subtracting two images that are of different image quality. The image quality for epoch 1 is better; and the stars look like sharper points. In epoch 2 the image quality is poorer and the stars look fatter. The result when the second epoch is subtracted from the first is that the stars don't completely disappear, but instead take on this unusual donut appearance.

What's important is to notice that the nova in the lower-left corner of epoch 1 does not have this donut shape. That is because it was not in epoch 2 and therefore nothing was subtracted from it. The nova in the upper-left corner of epoch 2 is also visible, but now as a pure black dot. It is black because epoch 2 as subtracted from epoch 1. The black dot is a negative "ghost" of the nova in epoch 2. If the order had been reversed (that is, if epoch 1 had been subtracted from epoch 2), then this nova would appear white.

While this method is not necessarily better than blinking for finding the two above novae, it is useful for finding fainter novae, particularly near the center of the galaxy where light from the bulge can obscure the novae. Subtracting one image from another removes most of the light from the bulge, making it easier to find novae there. Notice that a nova that is also present in the lower-right corner at X=501, Y=454.