Lab 5: Imaging Complex Astronomical Objects

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Your report is due on December 4, 2012, at 5:59 PM PST.

1 Imaging of Globular Clusters

Globular clusters (GCs) are dense aggregations of stars located in the Milky Way. GCs have played a critical role in understanding the structure of the Galaxy, the evolutionary paths of stars, and the detailed dynamics of stellar interactions. For this lab, you will obtain multi-color images of a GC and construct some basic diagnostics of the cluster. Your goals are to create:

- A multi-color image of the cluster, with at least three filters;
- A Hertzsprung-Russell diagram of the stars in the cluster;
- A profile of the surface brightness of the cluster as a function of radius; and,
- A function giving the number of stars as a function of luminosity, also known as the luminosity function.

All of these goals have been central areas of research for decades and there are considerable theoretical underpinnings to these measurements. This gives you lots of context with which to interpret your results: e.g., What stellar populations are present in your observations? What does the structure tell you about the history and physics of the cluster? Can you estimate the cluster mass from your observations?

Many GCs are bright and extended over arcminutes on the sky. This should make imaging of one to be fairly straightforward. A significant challenge in this project is the confusion that comes from the high density of stars, especially in the central regions of the GC. You need to apply good imaging and analysis techniques to be able to separate out individual stars. Obtaining a good focus and observing with good seeing, for instance, can be very helpful for increasing the number of stars that you can identify. Getting observations that are far from the dense cluster center can help but these regions have an increasing amount of contamination from field stars. How can you address this problem? You will probably need to experiment with the depth of your imaging to find the optimal integration.

Time permitting, observe a second cluster or, better yet, an open cluster. These are much younger (a few 100 Myr at most) than globular clusters and their structure and stellar content should be very different.

There are many websites providing atlases of GCs [1] You want to select your cluster based on its brightness, size, and observability. Many GCs are near the Sun this time of year. An important reference on the science of GCs is Chapter 6 of Binney and Merrifield, "Galactic Astronomy."

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[1] For instance, `http://www.atlasoftheuniverse.com/globular.html`.

2 The Orion Nebula Cluster

The Orion Nebula Cluster (ONC) is the nearest site of massive star formation in the Milky Way as well as being part of one of the most identifiable constellations on the sky. The ONC, when imaged in multiple colors and filters, presents some of the most striking imagery of this stellar nursery with a combination of starlight, nebular emission, and dust extinction [2] Due to its proximity, the ONC is the standard cluster with which we interpret star-formation throughout the Milky Way and the Universe.

Your goals here are similar to those of globular cluster project but with modifications specific to the ONC:

- A multi-color image of the cluster, with at least three broadband filters and the Hα filter;
- A Hertzsprung-Russell diagram of the stars in the cluster; and,
- Maps of reddening and extinction throughout the cluster.

Ultimately, we would like to understand the history of the cluster through the stellar properties. Star formation ended recently (or is ongoing — there is debate on this topic!), which means that the stellar population includes main sequence stars as well as young stellar objects that have yet to join the main sequence. Given the size and distribution of the stars, what can you say about the dynamics of the stellar population?

If it is available, the Hα filter will provide unique information about the nebular gas and the ionization processes caused by massive stars in the cluster.

The ONC is a very large region on the sky spanning degrees. So, you will need to make a large-scale mosaic of the region in multiple colors. The paper[3] by Hillenbrand (1997, AJ, 113, 1733) can give you guidance about what kind of observing parameters will be suitable for characterizing the cluster.

3 Structure of a molecular cloud

Molecular clouds are the birthplace of stars and contain copious amounts of cold gas and dust. Because dust efficiently absorbs visible light, these clouds are most easily observed as dark patches ("dark clouds") surrounded by regions filled with many stars. Most of these stars lie much further away from us than the molecular cloud and so their starlight is blocked by the cloud. Because of the wavelength dependence of dust extinction, these dark clouds are gradually less opaque as wavelength increases. Indeed, measuring how "reddened" a star lying behind the cloud appears provides an estimate of the column density of dust in the cloud. Stars located behind the denser parts of the clouds will appears reddest[4].

Your goals in this lab are the following:

- A deep multi-color image of the dark cloud, with at least 3 filters;

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[2] See `http://hubblesite.org/newscenter/archive/releases/2006/01/image/a/` for an example of what high resolution, high sensitivity, multi-color images can reveal.

[3] `http://adsabs.harvard.edu/abs/1997AJ....113.1733H`

[4] See `http://www.eso.org/public/news/eso0102/` for an illustrationof the method.

- Measurements of the colors of many stars in your image, both those lying within the apparent contour of the cloud and outside of it (to serve as reference);
- Maps of reddening and extinction throughout the dark cloud.

The final goal should reveal the overall structure of the cloud: Does the cloud break up in smaller, separate cloudlets? Where is the center of the cloud(lets)? How large is the cloud? What is its surface density profile? These cloud represent the inital conditions for star formation and estimating their physical structure is key to understanding the whole star formation process.

For this lab, it is safe to assume that most stars are physically located behind the cloud and unrelated to it. Also, while there is a broad intrinsic range of colors for main sequence stars, stars are dominated by low-mass objects (0.2–$0.4 M_\odot$), so that we can assume that all stars have the same colors in first approximation.

As for the other labs above, a dark cloud can extend across the entire field-of-view of the Leuschner CCD. You will need to create a mosaic.

Possible targets for this lab include the L1258 and L1249 clouds in Cepheus and L1554 in Taurus-Auriga, but you can also search for other possible targets. You should aim to observe two clouds, depending on weather and available time, although you may have time for analysis of only one cloud. Lynds' Catalog of Dark Nebulae [5] is a great resource for this purpose.

4 Structure of a spiral galaxy

Spiral galaxies, such as our own Milky Way, can be decomposed in a central (spheroidal) bulge surrounded by clumpy spiral arms. Sometimes, a linear feature (a "bar") extends out of the bulge toward the spiral arms. The bulge is primarily made of old stars while the spiral arms are the location of ongoing star formation. The arms are dotted with clusters of high-mass stars, which make them particularly bright. Because young massive stars have bluer colors than old, low-mass stars these components can be disentangled by generating a color image of a spiral galaxy[6].

The goals of this lab are:

- Make deep images of a spiral galaxy in at least three broadband filters and the Hα filter;
- Generate a map of the visible colors of the galaxy;
- Generate an image of the Hα emission from the galaxy;
- Identify and characterize the features of the galaxy (bulge, bar, spiral arms);
- Search for the presence of stars in between the spiral arms and characterize them (young or old?);
- Identify some clumps in the spiral arms, which are presumed to be massive clusters, and determine their absolute brigthness, hence their total mass.

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[5] The catalog is available online at `http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=VII/7A` and Lynds' 1962 paper at `http://adsabs.harvard.edu/abs/1962ApJS....7....1L`

[6] Compare the optical and ultraviolet images of the Andromeda Galaxy at `http://en.wikipedia.org/wiki/Andromeda_Galaxy`

Imaging and studying in detail other spiral galaxies, which we can see in their globality, is a prime method to learn more about our own Galaxy, most of which is hidden from our view by dusty clouds in the galactic plane.

One particular aspect of this lab is that it is not possible to disentangle individual stars in our images. Instead, you will have to estimate the surface brightness of (regions of) the galaxy, i.e. the flux per square arsecond.

Possible spiral galaxies to study in this lab include M81, M74, NGC 7479 and NGC 7331, but you can look online for catalogs of galaxies to pick another one if you prefer[7]. Try observing at least two galaxies, if time and weather permit. You can then select the most promissing one, based on the quality of the raw data.

5 Imaging Solar System comets

Comets are small (typically km-sized) bodies orbiting in our Solar System. Their main constituents are ice, and dust. When they get close enough from the Sun, the ice can evaporate, releasing a tail of dust trailing the comet's orbit. At the same time, outgasing produces a large "coma" around the nucleus, as well as an extensive tail that extends opposite the direction of the Sun.

The goals of this lab are:

- Make deep images of a comet in at least three broadband filters and the Hα filter;
- Generate a color image of the comet;
- Compute the apparent (angular) motion of the comet in the sky and convert it to a linear velocity (in km/s);
- Identify and characterize the features of the comet (coma, gas tail, dust tail) - in particular, estimate dimensions in linear units (km, AU, ...);
- Search for the presence of Hα emission in the coma or the tail.

The colors and presence/absence of Hα emission provides key information on the physical characteristics of the constituents of a comet. For instance, dust-dominated features are likely to be relatively blue.

One particular aspect of this lab is that comets move fast. As a result, the stars in your images could appear as short trails if you use long integration times. You should find an optimal balance between short exposure (no "blurring") and long exposure (high sensitivity). In addition, you will need to realign your images before combining them (try "blinking" between two frames!). Also, the coma and tail could be quite faint as they can extend well over $1'$. Make sure to take several relatively long exposures, especially with the narrowband filter.

Possible comets to study in this lab can be identified based on the "Comet chasing" website[8] and Seiichi Yoshida's website[9]. To obtain precise positions and apparent motion of your target(s), use the Horizons ephemerises tool[10] maintained by NASA's Jet Propulsion Laboratory.

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[7] See for instance `http://www.oarval.org/Galax.htm` or `http://messier.seds.org/`

[8] `http://http://cometchasing.skyhound.com/`

[9] `http://http://www.aerith.net/index.html`

[10] `http://http://ssd.jpl.nasa.gov/?horizons`

Finally, make sure to get good finding charts before your observations, showing the location of the comet on that particular night to make sure you spot it. You can use the Aladin tool[11] from the Centre de Données Astronomiques de Strasbourg. Try observing at least two comets and to take observations in two separate nights, if time and weather permit. You can then select the most promissing one, based on the quality of the raw data.

6 Technical aspects

6.1 Image depth

In most cases, your images will contain both faint and bright stars. Unlike the previous lab, where only a handful of stars were used in the analysis, this time we want to create images in which as many stars a spossible are detected, yet unsaturated. You will need to adjust the integration time and take many exposure that you will then average together to reach a satisfying compromise. It might be useful to take both relatively short (a few seconds) and long (1-2 minutes) exposures, so long as tracking issues can be avoided. Longer exposures will be required for imaging with the Hα filter (which is narrow band) and the B filter (because of poor sensitivity of the camera). Also, the observing strategy will vary with filters and observing conditions. If you observe your target for several hours, the seeing might change, and you will certainly observe it through varying amounts of atmosphere. Keep an eye on conditions as you observe and adjust integration as needed!

6.2 Mosaicing

In several cases, the target of your lab is big enough that it will extend beyond the field-of-view of the camera. To generate a global image of your object, you will need to move around the telescope and take exposures in different pointings to create what astronomers call a “mosaic”. To get this right, you need to make sure that there are enough stars in common between two images so that you can determine the exact offset between them. In other word, do not offset by an entire field-of-view, but a fraction of it (depending on the density of stars in the image, you may need offsets as small as half the field-of-view but maybe you can use somewhat larger values).

6.3 Astrometric calibration

While we have a rough estimate of the pixel scale ($\approx$ 0.3”/pix, unbinned) and we know that the camera is oriented with North up, neither has been particularly well determined for this camera. As part of your analysis of the images, you will produce an astrometric solution for the camera, namely a precise estimate of the pixel scale and its exact orientation relative to North. To do this, select 3 or 4 bright (but unsaturated) stars as far from one another as possible in a single image (not in a mosaic) and determine their position as precisely as you can (you should reach an uncertainty of $\approx$0.01 pixel or less). Then find their absolute coordinates from the USNO astrometric catalog using the Aladin tool (check this before selecting the stars!). You can then solve for the two unknown quantities (pixel scale and rotation angle) that relate the pixel position and the astronomical coordinates. This is the astrometric solution.

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[11] `http://http://aladin.u-strasbg.fr/aladin.gml`

6.4 Photometric calibration

Since we will be measuring the fluxes of stars, we need to apply a photometric calibration, i.e., find a conversion between counts/s and units of flux density (e.g., Jansky). To do this, you should observe 2 or 3 stars whose flux has been established before and that have been deemed to be good calibrators (in particular, these stars show no significant amount of variability). You should observe these stars with all filters used for your project, ideally at airmass (elevation) similar to your object to minimize effects of atmospheric absorption. Links to catalogs of photometric standards are available on the class webpage. Generally, these standards are relatively bright, so you can observe them relatively rapidly and focus your observing time on your science target. You can also check the accuracy of your calibration by comparing the magnitudes of a few stars in your image that are in the USNO catalog. Large discrepancies may represent cases where your observations were obtained under "non-photometric" conditions, typically through thin cirrus clouds. If you notice such a problem, you may revert to using the USNO stars in your image to perform photometric calibration, but there is no guarantee that these are not variable stars.

6.5 Hα imaging

The purpose of using the Hα filter is to map ionized gaseous in your astronomical object. Ideally, this is best done with a spectrometer, butthis is difficult to apply to large-scale imaging. Instead, astronomers use a narrowband filters like the one installed in the Leuschner camera and combine it with images taken in the R band filter. Consider a star with no line emission. Its appearance (the seeing) is exactly the same in both filters. If the two images are perfectly aligned and scaled up/down appropriately, subtracting the R band image from the Hα image will result in pure noise. If, on the other hand, the star is surrounded by low level emission, this will show up in the difference image. The trick is to align and scale the broadband image precisely.

6.6 Extension to the near-infrared

The CCD camera we use for this lab contains broadband filters that span the visible light and into the "very near" infrared withe I filter (whose bandpass roughly covers the 700-900nm range), which allows to estimate the colors of objects and make nice three-colors images. However, to increase the contrast in colors between different stars, it is generally better to use an even broader range of wavelengths. To achieve this, you should gather 1–2.5μm images from the 2MASS near-infrared all sky survey and compare that to your visible light images. Once you have obtained this image, describe the similarities and differences between your visible light and the near-infrared image of your object. If time permits, use a quantitative method, such as computing visible-to-near-infrared colors for stars, or comparing the surface density of stars in a certain region as a function of wavelength.