

IMAGING AN OBSCURED STAR CLUSTER IN THE INFRARED and HUNTING BROWN DWARFS

Here are your key milestones and some questions for this lab:

1. Collect data needed to calibrate the near-IR camera: dark frames and flat fields. For this lab we will need to observe at three wavelengths: J , H , & K_s . Some of the calibration data depends on the filter used. Do you need a different dark for each filter? What about flat fields? Does the zero point (ADU/s/jansky) vary with filter?
2. Pick a young, star-forming Galactic cluster, e.g., NGC 1333 or NGC 2024 and collect the information you need to observe it: celestial coordinates, finding chart, standard stars for calibrating relative photometry. Also select a “control field”. For a list of potential clusters see Table 1. How will you use the right ascension and declination of the clusters to decide if they are suitable for observing? You will also need to figure out how much exposure time you need to get sufficient signal to noise ratio to see stars of $J = 14$ mag. and $K_s = 13$ mag. or better.
3. Observe your selected target and control field. Don’t forget to observe photometric standard star(s). Note—this lab depends on relative photometry. You need cloud free skies so that your comparison between the standard star and the cluster is valid. The Fall rains are here! Take your data as soon as possible! Do photometry on your standard star(s) immediately—do you get reproducible results?
4. Correct each frame of systematic errors by sky subtracting and flat fielding.
5. A single exposure is insufficient to see faint stars. You will need to accumulate several exposures at each location on the sky and add them together. Because the size of the cluster may be comparable to the field of view you will probably decide to at more than one position

within the cluster. Think about how much overlap there should be between subsequent images. Combine all the observations at each separate wavelength into a **mosaic**. This is the hard part of this lab because each individual exposure will likely not correspond to the same spot on the sky. Each frame will have to be registered to a common reference frame before you proceed.

6. Perform photometry on your mosaic and plot the **luminosity function** (a histogram of K_s -band magnitudes), the **color-magnitude diagram** (a plot of $J - K_s$ vs. K_s). If time permits also investigate the **color-color diagram** ($J - H$ vs. $H - K_s$). Construct a “true-color image” of your field.
7. Discuss: the statistical significance of the detection of the cluster. What is the dimmest star detected in the luminosity function? Examine your color-magnitude and color-color diagrams—is there evidence for interstellar extinction? Estimate the average extinction suffered by a star. Review the astronomical literature for information on the age and distance of your selected cluster. Estimate the mass of the dimmest stars detected in the cluster.

Try and follow this time-line

- Week 1:** Collect observations and calibration data (flat fields photometric standard stars etc.). Sky subtract and flat field all your data. Determine the photometric calibration constant. Convince yourself that you have reliable photometry by examining the repeatability of signal measured for the standard stars.
- Week 2:** Assemble the data at one wavelength into a mosaic. Learn how to shift your images to a common reference frame so that the stars are line in subsequent images. To do this you will have to learn how to measure the position of a reference star that is present in all your images. Understand what an exposure map is and how to use a weighted mean to combine the set of images.
- Week 3:** Perform photometry on your mosaic. Construct a luminosity function. Repeat this activity for the other two wavelengths. Plot color-magnitude and color-color diagrams.

Week 4: Analyze your results and write up your report. **Due 6 PM, Nov. 14. 2006**

1 Introduction

The question of the origin of stars is one of the most fundamental of astronomy. Yet, despite hundreds of years of stellar observations, and early speculations by Newton and Laplace, it has only been in the latter part of the twentieth century that the investigation of star formation has become an active area of astrophysical research. The origin of stars has remained mysterious for so long largely due to the fact that the process of star formation has never been directly observed with the naked eye or even with the most powerful telescopes.

Have the stars been around since the Big Bang, or were they being made all the time? As far as anybody could tell at the start of the 20-th century, the entire universe consisted of a single stellar system, stars gradually cooled as they radiated their internal store of heat, and the question of the origin of stars was a question of cosmology. As such, the problem of star formation was not susceptible to detailed scientific investigation. That is, even the most basic hypotheses concerning stellar origins could not be directly tested by observations. Starting in the 1950's astronomical research has led to the fundamental realization that star formation has been a continuous, ongoing process throughout the history of the Milky Way.

Perhaps the most important step contributing to this realization was the discovery of the nature of stars as natural thermonuclear reactors which fuse H into He. This process is explained by the theory of stellar structure and evolution, perhaps the greatest theoretical achievement of 20-th century astronomy. This theory shows that the hottest stars, the OB stars, burn their H at such a prodigious rate that they can live for only a tiny fraction of the age of the Galaxy. The existence of such stars in stellar nurseries like the Orion molecular cloud indicates that star formation has occurred in the present epoch of Galactic history.

The discovery of the interstellar medium of gas and dust during the early part of the twentieth century provided a crucial piece of evidence in support of the concept of present star formation in the Galaxy. Subsequent observations established that clouds of interstellar gas and dust have roughly the same composition as stars, but are considerably more massive than a single star or

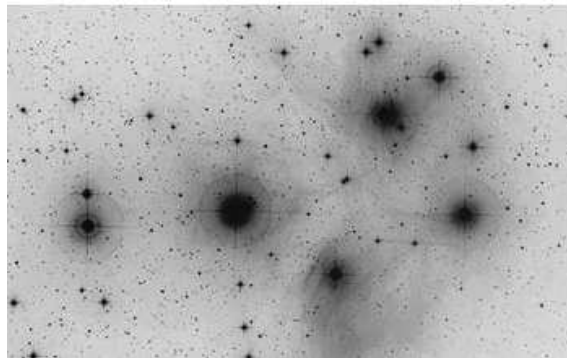


Figure 1: The Pleiades star cluster (M 45). The remnants of the natal gas from which these stars formed is still visible as a reflection nebula. The reflection nebula shows up as faint wisps in this optical image.

group of stars. However, this same dust mixed with interstellar gas obscures our view of star formation. Dust grains absorb more strongly blue light than red. Hence infrared (IR) observations have played a crucial role in permitting the study of star formation. In this lab we will obtain IR images of star forming regions and compare with images obtained at optical wavelengths.

2 Looking for Stellar Clusters

We believe that stars do not form at random locations in the Milky Way. They form in giant molecular clouds which have masses ranging from $10^3 - 10^6 M_{\odot}$. Moreover, stars appear to only form in the densest parts of the cloud where the mutual gravitational pull of the gas causes it to collapse into even denser regions. The best evidence for this picture is that young stars are found in clusters. A good naked-eye example is the Pleiades association, a group of roughly 100 million year-old stars. These stars are observable at visible wavelengths because the gas and dust surrounding the Pleiades has mostly dispersed now; only a ghostly trace of that gas is visible as faint smudges of reflection nebulae which surround the stars. The most massive stars in the Pleiades cluster are A-stars with masses of about $3 M_{\odot}$, which have main sequence lifetimes of 10^8 yr. The more massive OB stars have exhausted their fuel and exploded as supernovae.

The Pleiades stars are widely separated on the sky and occupy a region

Table 1: Some Galactic Star Forming Regions

Name	Distance (pc)	RA	DEC	Equinox
M 17	2100	18 20 26.00	-16 10 36.0	2000.0
W 51	7000	19 23 42.00	+14 30 33.0	2000.0
S 106	2300	20 27 27.7	+37 23 49	2000.0
W 3	2900	02 27 03.90	+61 52 25.0	2000.0
NGC 1333	320	03 29 02.00	+31 20 54.0	2000.0
IC 348	320	03 44 30	+32 17 0	2000.0
NGC 2024	450	05 41 43.50	-01 54 17.0	2000.0
M42/NGC 1976	450	05 35 17.40	-05 23 28.0	2000.0

which is almost a degree in diameter. Our IR camera only has a field of view of about 5 arc minutes by 5 arc minutes — much too small to image the entire Pleiades cluster. However, it is more interesting to go searching for younger clusters that have not yet had time to disperse. More massive stars, such as O and B stars with masses of $10 M_{\odot}$, live only 10^6 yr and are still closely associated with the gas and dust from which they were born. Young OB clusters have not had time to disperse and their stars are still found in close proximity to one another. They are also harder to see at visible wavelength because of the dust extinction, hence the need for IR observations.

3 Infrared Observations and Interstellar Extinction

Table 2 reminds you of the wavelengths of standard optical and infrared bands.

Consider a parallel beam of light passing through a dusty, absorbing medium. The attenuation of light follows the exponential decay law. Imagine a slab of unit area, $A = 1$ and length parallel to the beam $d\ell$. The infinitesimal decrease in the intensity of that beam, dI , traversing the slab of unit area, A ,

$$dI/I = -dA \tag{1}$$

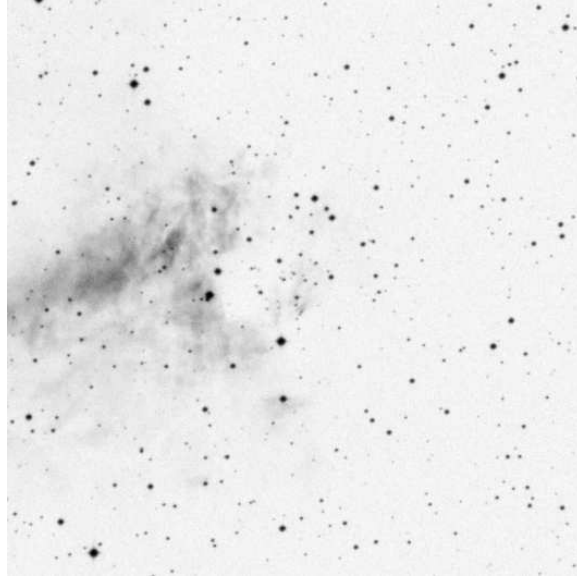


Figure 2: Digitized sky survey image of M 17. The field of view is $15' \times 15'$. North is up and east is to the left.

Table 2: Spectrum of Vega at Selected Wavelengths

Band Name	Central Wavelength (μm)	Band Width (μm)	Flux of Vega = $F_{\nu 0}$ ($10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$)
U	0.37	0.066	1780
B	0.45	0.094	4000
V	0.55	0.088	3600
R	0.66	0.14	3060
I	0.81	0.15	2420
J	1.25	0.21	1570
H	1.65	0.31	1020
K	2.20	0.39	636

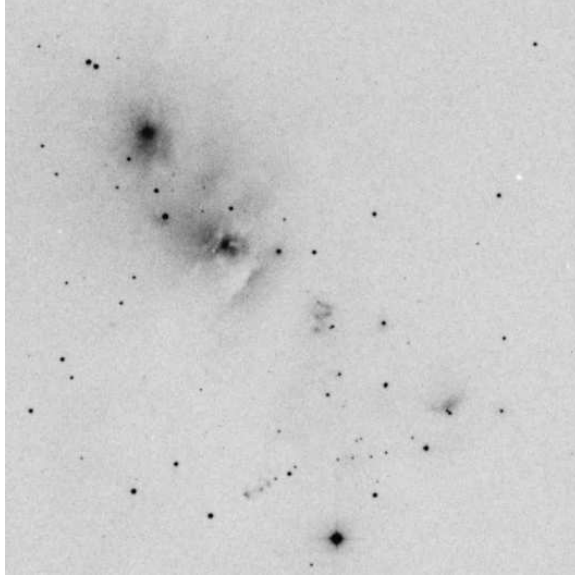


Figure 3: Digitized sky survey image of NGC 1333. The field of view is $15' \times 15'$. North is up and east is to the left.

because dA is the fraction of the total area covered by absorbers. If n is the number density of grains in the volume $A \times d\ell$, each with projected area σ , then the total projected area covered by dust grains is $dA = nd\ell\sigma$. If we integrate Eq. (1) then we find

$$I = I_0 e^{-n\sigma\ell} = I_0 e^{-\tau} \quad (2)$$

under the assumption that the density is uniform so that we can write $\tau = \int n\sigma d\ell = n\sigma\ell$.

Table 3 lists the interstellar extinction curve for typical gas and dust in the Milky Way. The table shows that if there is 1 magnitude of extinction in the visible there is 0.175 mags at H -band ($1.65 \mu\text{m}$). Recall that the relation between optical depth, τ , and extinction, A , defined as $A = -2.5 \log_{10}(I/I_0)$ is $A = 1.086\tau$. If we denote the extinction in the visible band as A_V , then the extinction correction magnitude $V_0 = V - A_V$, similarly $B_0 = B - A_B$, etc., where from Table 3 $A_B = 1.324A_V$.

Using the above definitions, the typical distance a photon travels before being absorbed by an interstellar dust grain is the mean free path $\lambda = 1/(n\sigma)$.

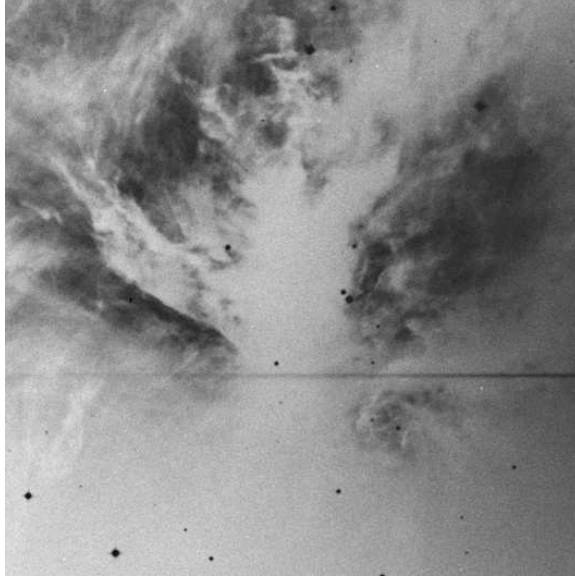


Figure 4: Digitized sky survey image of NGC 2024. The field of view is $15' \times 15'$. North is up and east is to the left.

Table 3: Standard Interstellar Extinction

Band	Wavelength (nm)	A/A_V
U	365	1.531
B	445	1.324
V	551	1.000
R	658	0.748
I	806	0.482
J	1220	0.282
H	1650	0.175
K	2200	0.112

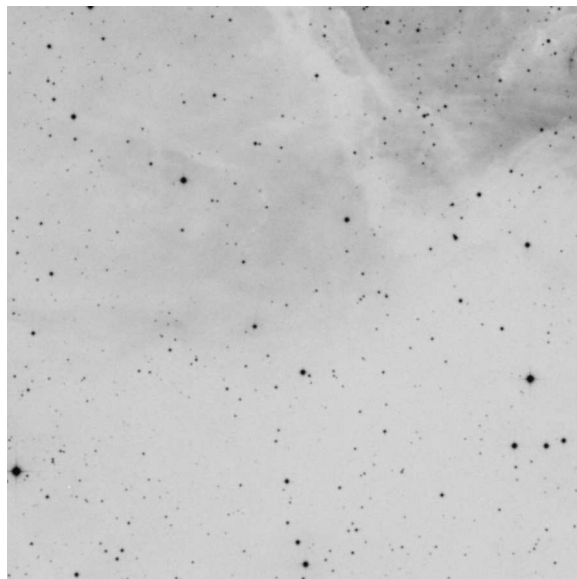


Figure 5: Digitized sky survey image of W3. The field of view is $15' \times 15'$. North is up and east is to the left.

Thus $\lambda = \ell/\tau$; the greater the optical depth the shorter the distance a photon can travel on average. Consulting Table 3 shows that an infrared photon, e.g., at $1.65 \mu\text{m}$, can travel almost six times further than a visible light photon. In this lab we will be observing in the JHK_s bands and using this aspect of IR light to see newly formed stars embedded in the gas and dust where they were born.

4 Observations

The purpose of this lab is to:

- Select a young star-forming cluster and make a deep super-image that is sensitive to stars as faint as $H \simeq 14$ mag.
- Construct a histogram of the magnitudes, e.g., for H -band, known as the luminosity function. Establish the limiting magnitude of your image. Compare the luminosity function with that of a nearby “control” field which contains only background stars in the Milky Way. Show,

Table 4: Colors of Main Sequence Stars

MK Class	M_V	$(U - B)_0$	$(B - V)_0$	$(V - J)_0$	$(J - H)_0$	$(H - K)_0$
O3	-6.0	-1.15	-0.33	-0.73	-0.19	-0.05
O5	-5.7	-1.15	-0.33	-0.73	-0.19	-0.05
O8	-4.9	-1.14	-0.32	-0.72	-0.17	-0.05
B0	-4.0	-1.08	-0.30	-0.68	-0.12	-0.05
B3	-1.6	-0.71	-0.20	-0.46	-0.08	-0.03
B5	-1.2	-0.60	-0.17	-0.38	-0.06	-0.02
B8	-0.2	-0.38	-0.11	-0.24	-0.03	-0.02
A0	0.6	-0.06	-0.02	-0.05	0.00	0.00
A5	1.9	0.11	0.15	0.28	0.08	0.01
F0	2.7	0.06	0.30	0.59	0.16	0.02
F5	3.5	0.01	0.44	0.79	0.20	0.03
G0	4.4	0.10	0.58	0.92	0.24	0.04
G5	5.1	0.23	0.68	1.19	0.31	0.05
K0	5.9	0.45	0.81	1.37	0.38	0.06
K5	7.4	1.03	1.15	2.08	0.57	0.10
M0	8.8	1.25	1.40	2.79	0.65	0.15
M5	12.3	1.22	1.64	4.48	0.52	0.28

using a statistical test, that there is a significant excess of stars in the cluster.

- Use your multiple wavelength data to demonstrate the effect of extinction by constructing the color-magnitude and color-color diagrams for the cluster. Make an estimate of the average extinction towards stars in the cluster.

The best clusters are probably NGC 1333/IC 348 in Perseus and those in the Orion region, NGC 1976 and especially NGC 2024 (see my Web page and the color picture in Graham & Treffers, 2001, PASP 113, 607). The stars in these clusters can be observed with high signal-to-noise because they are relatively close (a few 100 pc).

M 17 is very photogenic, but it is about five times as distant as Orion, so the stars appear fainter. M 17 is also at RA = 18 hours, so observing it in the early evening is tricky. If you choose to observe M 17 you will need to get your data as soon as possible. The Orion cluster M42/NGC 1976 has some very bright stars in its core—the Trapezium. These stars will saturate the IR array unless you take short exposures, so don't point directly at the Trapezium. The scattered light from the Trapezium stars within the Orion HII region will make it difficult to detect fainter companions.

The Perseus clusters, IC 348 and NGC 1333, are excellent targets. They are observable earlier in the night than Orion, so you will not have to stay up so late. They are nearby, so here you have the best chance of seeing brown dwarfs! The clusters in IC 348 and NGC 1333 are large, so you either need to pick your field carefully or observe multiple pointings.

5 The Subtle Art of Sky Subtraction

The following steps are necessary to extract numbers from the IR images suitable for performing photometry. The following steps should be somewhat familiar from IRCAM observations and Lab 3.

- Sky subtract
- Flat field
- Extract star signal (photometry)

Sky subtraction for IR data is tricky, but it is crucial for deep sky observations in the IR. In the previous lab we were looking at bright calibration stars, so we just dark subtracted and flat fielded. We now need to detect stars nearly 100 times fainter. **Every IR frame must be sky-subtracted.** Construct a “sky image” from observations of blank sky (use your control field) and subtract this, pixel-by-pixel from the IR picture of your target. Note that both your object image and your sky image include the dark and bias—so if you subtract the “sky” from the “object” you automatically correct for the dark and bias. Why do you need to sky-subtract *and* flat field?

It is impossible to find truly blank sky. To form a sky image take a sequence of pictures but jog the telescope between each exposure. Then construct an image which is a pixel-by-pixel median of these frames. The process of computing the median will reject any stars that are in your field of view.

5.1 Taking IR Pictures

The big difference in this experiment is that you have to obtain photometry of stars that are much fainter than the previous lab. You will probably need a **total** exposure time of about several minutes, perhaps as much as 10 minutes. That is, if each exposure is 20 seconds, then you will need a total of thirty pictures. Using IDL you can sum up these pictures to synthesize a total effective exposure time of $30 \times 20 = 600$ seconds. To take care of bad pixels and to make a good measurement of the sky background, every picture needs to be observed at a different telescope pointing. To do this write a IDL/c-shell/perl script that automatically offsets the telescope over a grid of, say 5×6 , positions. The offsets should be a few times the FWHM of the stellar images, i.e., about 30 seconds of arc or 0.008 degrees.

Generating the sky frame may be tricky if the star images in the cluster field are so close together that they overlap. If this is the case, then there is no sky between the stars and you will need to take dedicated sky images. As discussed below, you must plan on observing a control field anyway, so select your control field before you observe the cluster and use the observations of this field to provide both the photometry of the control field and the sky measurement for the cluster observations.

Because the sky brightness varies with time, the best sky measurement strategy would involve switching back and forth between the cluster and control field, alternating images of each. However, generating the same offset

pattern in the two fields is a bit tricky when you switch back and forth. If you're too lazy to do this you could do the less desirable alternative of using the `tx offset` command and first making all images of, say, the cluster and then of the control field.

To find a cluster we have to show that there is a statistically significant excess of stars in a particular direction with respect to a neighboring direction. Thus you will also need to observe a control field to measure the average surface density of stars in the Milky Way in the absence of a cluster. For the control field, offset the telescope away from the cluster — for the largest clusters 15-30 arc minutes in any direction should be fine. Repeat your observations at the new location.

The observations of the control field must be identical to the cluster field; otherwise the statistical inference drawn from your data will be suspect. Use the same exposure times, dither pattern, and acquire the same total integration time for the control field.

5.2 Making a Mosaic

Now for the hard part! The major obstacle that you now have to address is that every image of the cluster is located at a slightly different location on the IR detector array because the telescope pointing was jogged after each exposure. The total exposure time cannot be realized simply by adding the stack of processed frames.

Prior to summing the sky-subtracted and flat-fielded images, each one needs to be shifted in x and y so that the stars are aligned. To construct a mosaic of the data set we first need to measure the relative offsets between subsequent frames. This can be accomplished by measuring the centroid of a star that is common to a set of frames. The centroid of a star corresponds to the center of light:

$$\langle x \rangle = \frac{\sum_i x_i I_i}{\sum_i I_i}, \quad \langle y \rangle = \frac{\sum_i y_i I_i}{\sum_i I_i} \quad (3)$$

where i ranges over the pixels within the stellar image. Use your circular masking technique from the photometry lab to isolate the star. Don't perform the sum over the entire image—other stars in the field of view and bad pixels will bias the answer.

Once you know the offsets between each image you could use the IDL routine `SHIFT` to register the images. But wait... First investigate how to

embed a 256×256 image in a larger array. Since the area of the sky covered by the dither pattern exceeds the instantaneous field of view, the final mosaic must be bigger than 256×256 pixels. We don't want to lose the valuable information at the outskirts of the tiled area, so we need to embed each of the individual 256×256 images into a larger array. Figure out, in pixels, the x and y dimensions of the array needed to contain the individual frames. If the largest and smallest telescope offsets, converted from arc seconds to pixels, are x_{max} and x_{min} , then the x -dimension of the mosaic will be $256 + x_{max} - x_{min}$. For example if $x_{max} = y_{max} = 64$ and $x_{min} = y_{min} = 64$ then you'll need a 384×384 array. Copy each original 256×256 frame into its own such super-array. Also, construct one extra image with size equal to that of the super-array, which we will call the exposure map.

5.2.1 Exposure Maps and Weighted Sums

Your goal is to make a single super-image that is the average of all of the original arrays, which are now spatially registered super-arrays. However, even though the super-arrays are registered you can't take a straight average because some pixels are bad and some, the ones near the edge, have contributions from only some of the super-arrays. So take a weighted average of each pixel of all super-arrays¹.

For each super-array, define a new super-array of weights. Set the weight to zero if the pixel is bad, saturated, or if the original 256×256 image didn't cover that super-array pixel; define the weight to be one if the pixel is good. Multiply the super-array image by the weight array. This will set bad pixels to zero. Now multiply the weight array by the exposure time appropriate for the super-image and add to the exposure map array. Repeat this for every super-array image. The exposure map is so named since each pixel contains a value which is the total exposure time of good pixels at that location on the sky.

Finally, sum up all the pixels from the individual weighted super-arrays and divide by the exposure map. Your weighted average has units of ADU per second; remember this when you use the observations of the standard star to convert to an absolute brightness scale. Some pixels in the exposure map will have zero exposure time; these pixels have no valid data. Don't divide

¹If you don't understand weighted averages, see Taylor chapter 7, equation 7.10.

by zero; rather flag these pixels as bad, e.g., set them to a large negative number.

Test your mosaic program on simple data. If the field contains a single star it will be much easier to spot errors, say a sign error in application of the measured offsets, than in a complex region containing a cluster of stars. If the sky subtraction is imperfect then the original edges of the array will be visible in the mosaic as discontinuities. If there are noticeable jumps in the sky level across such boundaries review the accuracy of the sky subtraction.

5.3 Photometry and the Kolmogorov-Smirnov Test

Use the `CONVOL` procedure to perform aperture photometry on the images and make a table of stellar magnitudes. Use observations of an infrared standard star to establish the photometric zero point and put your observations on an absolute scale (check the IR camera web page for lists of IR standards). Make two histograms of the data — one for the stars in the cluster field and one for stars in the control field.

The Kolmogorov-Smirnov test is a statistical test that is used to decide if two histograms are drawn from the same parent population. The algorithm is from the procedure of the same name in “Numerical Recipes” by Press et al 2nd edition, Ch 14 (1992)². If the cluster field and the control field have the same frequency distribution of stars with brightness — the H -band luminosity function — then there is no evidence for a cluster. The KS test provides an objective way to quantify whether or not there are more stars in the cluster than in the control field.

If you can convince yourself that there is a statistically significant excess of stars in given magnitude bins you can make a statistical correction for field contamination. To find the histogram of stellar magnitude corrected for contamination by unrelated stars simply perform a bin-by-bin subtraction of the two histograms. The resultant histogram is the so-called cluster luminosity function. To interpret the luminosity function read Lada & Lada (1995) and Lada et al. (1996).

²You’ll have to write your own K-S routine: IDL doesn’t provide one. But it’s easy and requires only a few lines of IDL code.

5.4 The Color-Magnitude and Color-Color Diagram

Construct the $J - K_s$ vs. K_s color-magnitude diagram for the cluster field and the control field. What are the differences? What is the reason for the difference? Can you estimate the extinction towards the cluster members by knowing the intrinsic colors of the stars in the cluster? How can you use the information in Table 3 & 4? For more information read Lada & Lada (1995) and Lada et al. (1996).

If your photometry is good quality try making a color-color diagram too $J - H$ vs. $H - K_s$

5.5 The Cluster Luminosity Function

In principle, observations of large enough groups of young or newly formed stars should provide fundamental information on the process of star formation, such as the distribution of stellar masses. We can't observe this directly, so we infer it from the distribution of stellar luminosities. Clusters are important laboratories for studying the distribution of luminosities and hence masses because they consist of statistically significant groups of stars that share the common heritage of forming from the same parent cloud at the same epoch.

Young clusters are especially important because they are not old enough to have lost members due to stellar evolution. Moreover, the lowest mass stars, which might include the brown dwarfs, are brightest when still collapsing and are most readily detected at infrared wavelengths.

The key piece of observational information that can be derived from our infrared images is the luminosity function. As discussed above this is simply the histogram of the number of stars as a function of the H -band magnitude corrected for Galactic contamination. The IR luminosity function is related to what we want to know, which is the mass function; it is the product of the underlying stellar mass, M , distribution function and the mass to H -luminosity relation for young stars

$$\frac{dN}{dH} = \frac{dN}{d\log(M)} \frac{d\log(M)}{dH} \quad (4)$$

In this lab we will content ourselves with dealing only with the luminosity function. Predictions for the numbers of stars per magnitude bin for model

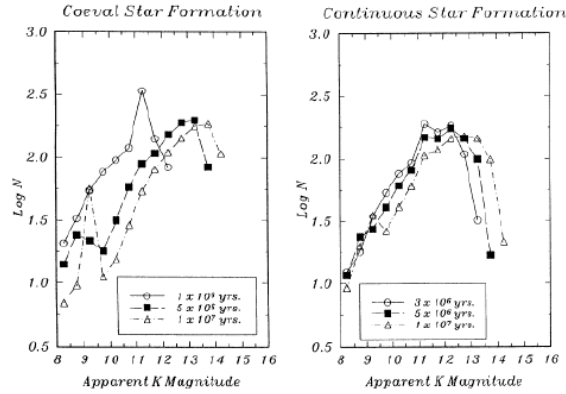


Figure 6: Model luminosity functions for instantaneous star formation and for continuous star formation. The models are normalized to 1000 stars and a distance modulus of $m - M = 7.5$. From Lada & Lada 1995, AJ, 109, 1682.

clusters of different ages are shown in Fig. 5.5. Compare *qualitatively* your luminosity function with these predictions.

To find brown dwarfs in these clusters it will be necessary to reach magnitudes fainter than $H \simeq 14 - 15$ mag. If you find a statistically significant excess of stars at these magnitudes in Orion or Perseus you have found this elusive population!

More likely you will have detected the stars that have masses of $\simeq 0.3 M_{\odot}$ with $H \simeq 13$ mag. In this case your observations provide a measure of the age of the cluster. Make an estimate of the age of the cluster you have observed.

6 Observing Tips

Before opening the dome you need to plan your observing carefully and keep a detailed record!

6.1 Positions

Make sure that your coordinates are correct. Don't take the positions in Table 1 on faith. Check in the literature (try SIMBAD) to make sure that

these are correct. Don't forget to make sure that the equinox is entered correctly. Much of the literature will quote equinox 1950.0.

Some of the clusters in Table 1 are large, e.g., NGC 1333 and IC 348. This is because they are nearby. Their proximity means that the stars appear brighter, but you will have to observe multiple fields to see the entire cluster. For example the core of the IC 348 has a diameter of 8 arc minutes. A 2×2 mosaic would be necessary to cover most of the stars in this region. The cluster NGC 1333 is actually double, with two cores separated by about 6 arc minutes. Before you start observing consult the literature — use the ADS abstract server to look for relevant papers. You will not have to plow through decades of astronomical research to find the relevant information because IR cameras are new, so most of the relevant IR data are from the 90's.

6.2 Photometry

You need to place the photometry of the cluster and control field on an absolute scale. This is done by observing a standard star of known brightness. Make sure that it is not cloudy! Observe the standard star close in time to when you acquire your cluster data—do not wait until the next night. Choose a standard star that is located at a similar elevation to your target field. Given the sidereal time and RA/DEC compute the elevation angle EL . The airmass AM , i.e., the $1/\sin(EL)$ for the two fields, should not differ by more than about 0.5. Thus if the cluster is at the zenith, $EL = 90^\circ$ ($AM = 1.0$), do not observe a calibration star with $AM > 1.5$, ($EL < 42^\circ$).

When you compare the counts from your standard star and the counts from the stars in the cluster make sure to include the fact that the exposure times may be different.

6.3 Pointing Errors

Always check the pointing of the telescope by using the **bright** command to find a nearby star. When you start observing is it a good idea for find a star near the zenith. If you believe that there is a small pointing error recenter the star using **offset**. Update the pointing corrections using **tx zero** and re-issue the **tx point** command. The star should now appear at the center of the array. The pointing corrections are not used until you repoint the telescope, so always check before you move on to the next star. Fine tune

using `tx offset` and `tx zero` until the star is close to the center of the array.

6.4 Focus the Telescope

Since we will be observing in crowded fields it is crucial to have the sharpest possible images. Adjust the telescope focus so that the images are sharp and round. A column and row plot should show that the full width at half maximum of the images is about two pixels. The telescope focus will drift as the telescope cools and the steel truss holding the secondary mirror shrinks. If you focussed right after sunset, then focus again after an hour has elapsed.

Because of friction in the focus mechanism it is a good idea to move the focus mechanism in the same direction while you are focussing. Small back and forth motions of a few mils will not necessarily return the secondary to the same physical position. If you miss best focus back up 100 mils and start again.

6.5 Dithering the Telescope

Write a IDL or C-shell script to jog the telescope over the grid of sky positions you need to accumulate your data (in IDL you can use the `spawn` command). When you offset in hour angle do not forget to include the cosine factor on the command line, i.e., `tx offset ha=0.01 cos`. Your script should also generate unique file names for the `qimage` command.

6.6 Sky Subtraction & the Control Field

Some of the cluster fields are likely to be crowded, i.e., the star images are almost overlapping. Therefore, it may be impossible to use the sequence of dithered images to make your sky frame for subtraction. It may be necessary to make special sky observations at an offset field. The control field used to measure the density of background stars in the Milky Way can also double as your sky field. Check out your control field before you take lots of data. By chance there might be a very bright star right in the middle of the position that you have selected. If there is, then choose a different location, but don't try and find a region that is especially devoid of stars.

6.7 Dynamic Range

The range of stellar magnitudes in clusters can span 5 magnitudes or more. Five magnitudes corresponds to a factor of 100, which is greater than the dynamic range of the IR chip. If you expect to make high SNR detections of the faintest stars ($H \simeq 14$) then the brightest stars ($H \simeq 8$) will be saturated. Make sure that you take some short exposures so that the brightest stars do not saturate. When you check for saturation of stellar images remember that you must include the sky counts too. It's easy to forget about the sky's contribution if you are inspecting a difference image.

7 Some References

The web page for the digitized sky survey is: http://stdatu.stsci.edu/cgi-bin/dss_form

The ADS abstract service web page is: http://adsabs.harvard.edu/default_service.html

The best source for references on Galactic objects is the SIMBAD data base:

<http://simbad.u-strasbg.fr/>. Here are some hints:

Orion/M 42/NGC 1976:

Hillenbrand 1997, AJ, 113, 1733

Ali and Depoy 1995, AJ, 109, 709

NGC 2024:

Comeron et al. 1996, ApJ, 473, 294

IC 348:

Herbig, 1998, ApJ, 497, 736

Lada & Lada et al. 1995, AJ, 109, 1682

NGC 1333:

Aspin et al. 1994 A&ASuppS, 106, 165

Aspin and Sandell, 1997, MNRAS, 289, 1

Lada et al. 1996, AJ, 111, 1964

W 51:

Carpenter and Sanders, 1998, AJ, 116, 1856