**PROJECT 11: ESTIMATING THE STELLAR MASS IN GALAXIES**

**Introduction:** Among the most important physical properties we often need to measure in extragalactic astrophysics is the stellar mass of distant galaxies. In principle this is not a trivial question as due to the distance of these objects we can not resolve, let alone count, the billions and billions of individual stars they contain. As a result we have to rely on the integrated light emitted by the galaxies and find a way to estimate from this the mass and type of stars they contain.

In this exercise we will present how one can use observations in infrared wavelengths in order to estimate the stellar mass in a galaxy.

We will analyse ground based observations with the 1kx1k near-infrared camera of the 1.3m Skinakas Observatory to measure the stellar mass of a galaxy in Hickson Compact Group (HCG) 54. This is a group of four galaxies located at a distance of 19.6 Mpc.
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1. THE INFRARED WAVELENGTH RANGE

As infrared we call electromagnetic radiation with wavelengths from 1 to few hundred microns. The infrared radiation was discovered by William Herschel nearly 200 years ago. In Figure 1, we see an old drawing depicting the historic experiment of Herschel. Light from the sun is passing from a prism and is resolved to the well known colors of the rainbow. A thermometer is placed along the beam of light right after the end of the red color. Herschel noted that the temperature of this thermometer was raised compared to the temperature measured by the other two thermometers which were placed nearby, but not along the direction the prism was dispersing light.

This was a clear indication that some form of radiation, unseen to the human eyes, with wavelength longer than the red color was falling on the thermometer. This radiation was called “infra-red” as it was further than the red part of the spectrum.

We typically divide the infrared in three ranges. The near-infrared which covers the 1-5μm, the mid-infrared covering the 5-30 μm and the far infrared which extends all the way to 500μm.
1.2. ADVANTAGES OF THE INFRARED

There are several advantages in studying the universe in the infrared. The most important one is the fact that we are less affected by extinction. As light passes through space, dust absorbs a fraction of this. The exact amount depends primarily on the total quantity of dust between the observed and the emitting source. Since dust is formed during the late stages of stellar evolution regions such as nuclei of galaxies, where many generations of stars are actively forming or have formed, evolved and “died” are often enshrouded by dust which absorbs light. This extinction of light though, depends on the wavelength of the radiation. Even though the details are fairly complex, the extinction is substantially less as the wavelength increases, in many cases scaling as one over the fourth power of the wavelength.

As an example, if we were to observe the nucleus of our galaxy, the Milky Way, only 1 in $10^{12}$ (that is on in a trillion optical photons) emitted from the nucleus come to our eyes and telescope. This is due to the large amounts of dust found near the center of the galaxy. However, if we were to image the galaxy in the near-infrared 1 out 10 2.2um wavelength photons (Ks-band photons) reach us. It is thus obvious that radiation with wavelengths longer than the optical can be used to probe dust enshrouded regions in galaxies.
As an example we display above two images, one in the optical and one in the near-infrared, of NGC253 a nearby galaxy actively forming stars. We note the dark lanes due to dust being clearly visible in the optical image. In the near-infrared though we pierce through the dust and we can thus see much more clearly the underlying constituents of the galaxy.

Similarly we can see the image of the plane of our galaxy just bellow.

In the optical the dust lanes are blocking our view, to the plane and the center of the Galaxy, while in the infrared we see the dust emission from the disk.

More specifically for the problem we are trying to address here, even though near all stars emit in the optical, most of the stellar mass in a galaxy is found in cool stars not much more massive than the Sun. These stars emit nearly as black bodies with most of their light coming in the near-infrared.
1.2. CHALLENGES OF INFRARED OBSERVATIONS

On of the main challenges in observing at infrared wavelengths is that the atmosphere of the Earth heavily absorbs all incoming radiation from space at this range.

As we can see from the image above, which displays a depiction of the atmospheric transmission as a function of wavelength, even though all light can reach the earth’s surface in the optical, in the infrared only distinct windows exist. These are mostly in the near-infrared and a couple in the mid-infrared (around 10 and 20 micron).

Furthermore, the atmosphere as well as the telescope itself, since they do have a finite temperature they also emit infrared radiation. As a consequence the infrared sky from the ground is much “brighter” as we say than in the optical. The signal reaching us from space is a small addition to this emission from the atmosphere. This has severe consequences to the way we collect and analyze information in the infrared.
Examining the near-infrared range in more detail we can see in the picture above the atmospheric transmission in this range marked with the light blue curve. Here 100% signifies that all incoming light reaches the ground. In areas with “dips”, the atmosphere, mostly due to water vapor, absorbs the incoming photons.

We also marked in the picture the typical near-infrared broad band filters used indicated with J, H and Ks, centered at 1.2, 1.6, 2.2microns, areas where the transmission is good.

3. MEASURING THE STELLAR MASS OF A GALAXY

As an example on how we can measure the mass of a galaxy we use the near-infrared photometry in the Ks band obtained with the camera of Skinakas observatory.
A picture of the camera inside its dewar while being filled with liquid nitrogen is shown here.

The camera has a 1k x 1k Hawaii chip and has a field of view of nearly 7 arcminutes on each side. The large field of view presents a clear advantage in the analysis we will do.

As we mentioned earlier the atmosphere as well as the telescope mirror itself emits in the near-infrared due to their temperature. This light follows the optical path and falls on the camera. As a consequence the light from the astronomical source, in our case the galaxy, is only a very small fraction of the light received.
Thus in order to be able to perform our analysis, in addition to the usual steps performed in the optical, bias/dark subtraction and division by the flatfield, OFF observations are also needed.

If we have a camera with a large field of view these are obtained by simply dithering the source on our field of view. Then we subtract one position from the other, and we are left with a positive and negative image of our source.

Let's see those steps though with some Skinakas Ks band data on galaxy A of HCG54.

**Step 1:** As a preparatory work we obtained several dark frames (with the camera shutter closed) at the exposure time that were to be used during our observations. These darks will have to be subtracted by all subsequent frames we obtained. In the steps which follow all images have been normalized by dividing them which their corresponding exposure time. Thus each contains the counts per second. All images created by the camera are in FITS format.

For our analysis we will use the IDL Interactive Data Language software package. This provides extensive flexibility as numerous astronomy and image manipulation routines are readily available. IDL is fairly simple to use and we refer novice users to extensive tutorials available on the web.

Using IDL we can reading an image with the command:

```
IDL> image = readfits('file.fits')
```

We can display the image using a program call ATV

```
IDL> ativ, image
```

ATV, is an extremely powerful program for displaying an analyzing images. Details on this program can be obtained at:

```
http://www.physics.uci.edu/~barth/ativ/
```

We read the five darks:

```
IDL> dark1 = readfits('dark1.fits')
IDL> dark2 = readfits('dark2.fits')
IDL> dark3 = readfits('dark3.fits')
```
IDL> dark4 = readfits('dark4.fits')
IDL> dark5 = readfits('dark5.fits')

We median combine the five 1024x1024 arrays using the medarr routine

IDL> darkcube=[dark1, dark2, dark3, dark4, dark5]
IDL> medarr, darkcube, dark_fin

The array “darkcube” is a 3D cube 1024x1024x5 and the array “dark_fin” is the final median combined 1024x1024 dark

**Step 2:** We then opened the dome and kept the telescope fixed. We let the stars drift and waited until enough signal was obtained by the camera, while remaining in the linear range of the detector. The image we obtained is displayed here:

![Image](image.png)

We note the star trails on the detector, since the telescope was kept fixed. The exposures we used in this case were 1min long. We have obtained several flats similar to the above, with the star trails at different locations on the array. Following the same procedure as with the darks we create one final median combined flat 1024x1024 image called “flat”. We then subtract the final dark (“dark_fin”) from that image and we normalize it to unity my dividing it by the median value:

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Step 3: We have two on source exposures of our galaxy, taken by dithering the position of the galaxy on the near-IR detector.

IDL> s1 = readfits('source1.fits')
IDL> s2 = readfits('source2.fits')

We subtract the final dark and flat field the images:

IDL> s1_fin = (s1 - dark_fin) / flat_fin
IDL> s2_fin = (s2 - dark_fin) / flat_fin

Despite the above since the infrared sky is bright and we are background dominated we difference the two images before we perform our analysis. If we display the difference:

IDL> atv, s1_fin - s2_fin

we obtain the following image:

We observe our science target as well as the stars, appear in positive (white) and negative (black). As a result of this operation the sky emission is now nearly zero.
Step 4: We can perform photometry on the target and measure the total counts per second, by identifying the area of interest. This can be done directly using IRAF as it has been shown in other exercises or within ATV.

We start ATV, change the mouse mode to “ImExam” and the left click on the position of the target. An additional photometry window appears and it is visible in the following picture. In that one can set the radius where the photometry will be performed as well as the radii of the inner and outer annuli where any residual sky will be computed. A radial profile of the target can also be displayed with the above-mentioned radii marked. We select the option of “subtract median sky” as the way to calculate and subtract any sky emission when performing the photometry of source.

We find the total number of counts per second of our source is 47038 (indicated in the photometry window named “Object counts”).
Step 5: We can perform an identical analysis to steps 3 and 4 for a field which contains near-infrared standard stars visible during the night at elevations similar to our science target. A catalogue of near-infrared standards for the northern hemisphere is available at:

http://www2.keck.hawaii.edu/inst/nirc/UKIRTstds.html
and
http://www2.keck.hawaii.edu/inst/nirc/Elias_standards.html

Since the Ks magnitude of the standard star is known we can create a conversion factor from counts/second to mJy. We multiply that conversion factor with the 47038 counts/sec of our galaxy and we find that the Ks flux of the galaxy is \( F_K = 5.63 \text{ mJy} \).

At the distance of the galaxy \( d=19.6\text{ Mpc} \) this corresponds to a Ks band luminosity of \( L(\text{Ks}) = 4 \pi d^2 F_K = 9.14 \times 10^6 \) solar luminosities.

Step 6: We can convert the Ks luminosity to stellar mass using the formulae of Bell et al. 2003 who indicate that the stellar mass \( (M_*) \) and Ks luminosity are related with:

\[
M_* = 0.95 \times L(\text{Ks}) = 8.6 \times 10^6 \text{ solar masses}
\]

We have thus found the stellar mass of this dwarf galaxy.