

## Hubble Law Part 2: Roughly Calculating Extragalactic Distances

In this part of the lab we'll investigate how extragalactic distances can be estimated for spiral type galaxies. As mentioned in the introduction of part 1, distances are one of the hardest measurements in astronomy & astrophysics. We rely on objects with a consistent and known intrinsic brightness, what we refer to as Standard Candles, to properly survey the distances of these objects surroundings. This is a systematic study where our understanding of the distances of closer objects greatly impacts our measurements of further objects. Sometimes termed the distance ladder, astronomers use a systematic approach of using distances of closer objects to calibrate the methods of finding distances of further objects. Variable stars, like Cepheids, provide one of the first few rungs of the distance ladder, giving us a survey of distances within our galaxy and galactic local group. Whereas extragalactic distances are best estimated using the light output of type 1a supernovae.

For majority of our distance measurements we will be using the average distances measured from (insert method and database). But some galaxies are missing distances. To fill in the gaps of data to extract a hubble constant, a rough estimate of the distance will be made using a calibrated image of the galaxy and knowing it's classification. To accomplish this task you'll gain the skills to process image data and it's metadata that is commonly used throughout astronomy. Specifically,

- Read and display images within a .Fits file.
- Read and extract metadata from the .Fits header.
- Transform pixel coordinates into celestial world coordinates.
- Calculate angular distances from user pixel input.

### Reading .Fits Image File:

All working and amateur astronomers will have worked with some kind of image file. The image file being an  $N \times N$  array of pixels with each pixel carrying either a single value (grayscale) or multiple (RGB). Having only the pixel values isn't enough for astronomers to make sense of the data. These pixels represent stars, galaxies, atmospheres, etc, with their own coordinate systems, backgrounds, contaminations, and the location where the observation took place. Which is why most working astronomers use the FITS file format. A FITS file contains not only pixel information but includes metadata, which may describe the observers coordinates (latitude, longitude), time of observation, exposure, celestial coordinates, and more. The metadata can be anything the observer deems relevant for future analysis of the image.

Open up the image file using MATLAB's internal fits format reader *fitsread(file)*. Then use *fitsdisp(file)* to display the header information which includes all of the metadata we'll use.

```
clear
data = fitsread('NGCData/Fits/6217.fits');
fitsdisp('NGCData/Fits/6217.fits')
```

HDU: 1 (Primary HDU)

SIMPLE	=	T / Written by IDL: Fri Jul 11 12:34:26 2008
BITPIX	=	-32 / Number of bits per data pixel
NAXIS	=	2 / Number of data axes
NAXIS1	=	285 /Number of positions along axis 1
NAXIS2	=	285 /Number of positions along axis 2
DATE	=	'2008-07-11' / Creation UTC (CCCC-MM-DD) date of FITS header
COMMENT	FITS (Flexible Image Transport System) format is defined in 'Astronomy	

```

COMMENT and Astrophysics', volume 376, page 359; bibcode 2001A&A...376..359H
BUNIT = 'KM/S' /
BSCALE = 1.00000 /
BZERO = 0.00000 /
CTYPE1 = 'RA---ARC' /X-axis type
CTYPE2 = 'DEC--ARC' /Y-axis type
CRVAL1 = 248.154921400 /Reference pixel value
CRVAL2 = 78.2012686302 /Reference pixel value
CRPIX1 = 138.00000 /Reference pixel
CRPIX2 = 167.00000 /Reference pixel
CROTA2 = 358.220 /Rotation in degrees
CDELT1 = -0.000189962953777 /Degrees/pixel
CDELT2 = 0.000189962953777 /Degrees/pixel
EQUINOX = 2000.00 /Equinox of coordinates

```

For the this lab, we'll only be concerned with measuring the angular size of the object. Keeping our interest in only the information that'll help up accomplish this task. Each pixel is oriented in the vertical and horizontal direction, but this does not correspond to the celestial coordinates of the sky, right ascension (RA) and declination (DEC). If we inspect the contents the header above, it's easy to see variables that pertain to  $(\alpha, \delta)$ .

Programs such as AstroIMJ, IRAF and MAXIMDL use the positional informational above to transfrom each pixel to the proper celestial coordinates  $(\alpha, \delta)$ . We simply rotate the pixel coordinate system into the celestial coordinate system through an angle CROTA2 about reference pixel point (CRPIX1,CRPIX2) with a known RA and DEC,  $(\alpha_0, \delta_0) = (\text{CRVAL1}, \text{CRVAL2})$ ,

$$\alpha = s_1 \sum_{j=(\alpha,\delta)}^N m_{1,j}(p_j - r_j) + \alpha_0, \quad \delta = s_2 \sum_{j=(\alpha,\delta)}^N m_{2,j}(p_j - r_j) + \delta_0$$

Where  $m_{i,j}$  is the rotation matrix from the pixels  $(i, j)$  to  $(\alpha, \delta)$ .  $s_i = \text{CDELT}i$  is the scale factor in [degree/pixel],  $p_i$  are the  $i^{th}$  pixel number,  $r_i = \text{CRPIX}i$  the reference pixel positions, and  $N = \text{NAXIS}$  the number of axes.

Create variables and initalize them with the header data you extracted above.

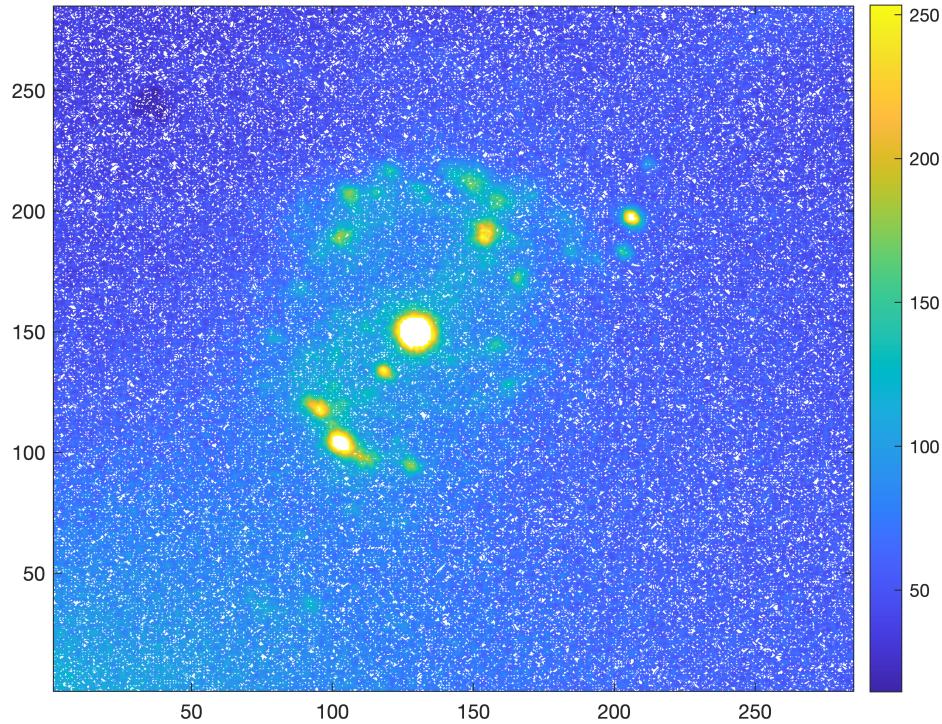
NAXIS = 2;	% Number of axes
NAXIS1 = 285;	% Number of points/pixels in first axis
NAXIS2 = 285;	% Number of points/pixels in second axis
CRVAL1 = 248.1549;	% Reference pixel RA
CRVAL2 = 78.2013;	% Reference pixel Dec
CRPIX1 = 138;	% Refernece pixel first axis position
CRPIX2 = 167;	% Refernece pixel first axis position
CROTA2 = deg2rad(358.2200);	% Convert rotation angle from rads to degree
CDELT1 = -1.8996e-04;	% First axis pixel to degree conversion
CDELT2 = 1.8996e-04;	% Second axis pixel to degree conversion

## Viewing the Raw Image

Next would be to view the image of the galaxy. There are two methods of ploting an image away. 1) using `imshow()` or `imagesc()` to plot the grid values of the array into a 2D plot. Deep field images taken by your

telescopes CCD can be noisy and the contrast used to display the image may leave out some information to the viewer. Modern astronomical Fits readers like AstroIMJ cut out some of the darks and highlights to optimally view the objects in the image. To bypass image histogram manipulation we'll plot the image as Contour plot with high number of contours. This way we'll capture the essence of the low luminosity of the galactic spiral arms.

```
X = uint8(data);
contour(X,150)
%colormap(gray)
colorbar
% Image value as an integer within (0,255)
% contour plot of image with N=200 contours
% Use a grayscale
```



## Conversion to Celestial World Coordinates:

Converting the pixel coordinate system into the celestial world coordinate system involves using the above equations on each pixel. A better way of thinking of this transformation is that for each pixel we will assign an RA and DEC on top of its intensity value,  $(I_i, \alpha_i, \delta_i)$ . The first ingredient is to construct the rotation matrix using the angle of rotation CROTA2.

$$R(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}.$$

```
rotate = [cos(CROTA2), -sin(CROTA2); sin(CROTA2), cos(CROTA2)];
```

Below is the loop that'll will iterate through each pixel  $(i, j)$  and calculate its  $(\alpha, \delta)$  using the header data and the rotation matrix. The array before the loop will be filled with the calculated values. It'll be sliced into three two dimensional arrays one for each; intensity, Ra, and DEC. Your look should include:

- shifted pixels with respect to the reference pixel CRPIX1(2)
- scaled pixels using calibration values CDELT1(2)
- construct a vector of pixel coordinates
- rotate this pixel vector
- finally shift the rotated values by the reference RA, DEC using CRVAL1(2)

```
full = zeros(NAXIS1,NAXIS2,3);

for i = 1:NAXIS1    % loop over rows of pixels
    for j = 1:NAXIS2    % loop over columns of pixels

        iprime = i - CRPIX1;      % shift pixels to relative coords
        jprime = j - CRPIX2;

        iscaled = iprime * CDELT1;    % scale by conversion factor
        jscaled = jprime * CDELT2;

        pixel = [iscaled; jscaled];    % create vector of pixels

        transform = rotate * pixel;    % rotate the vector into new frame

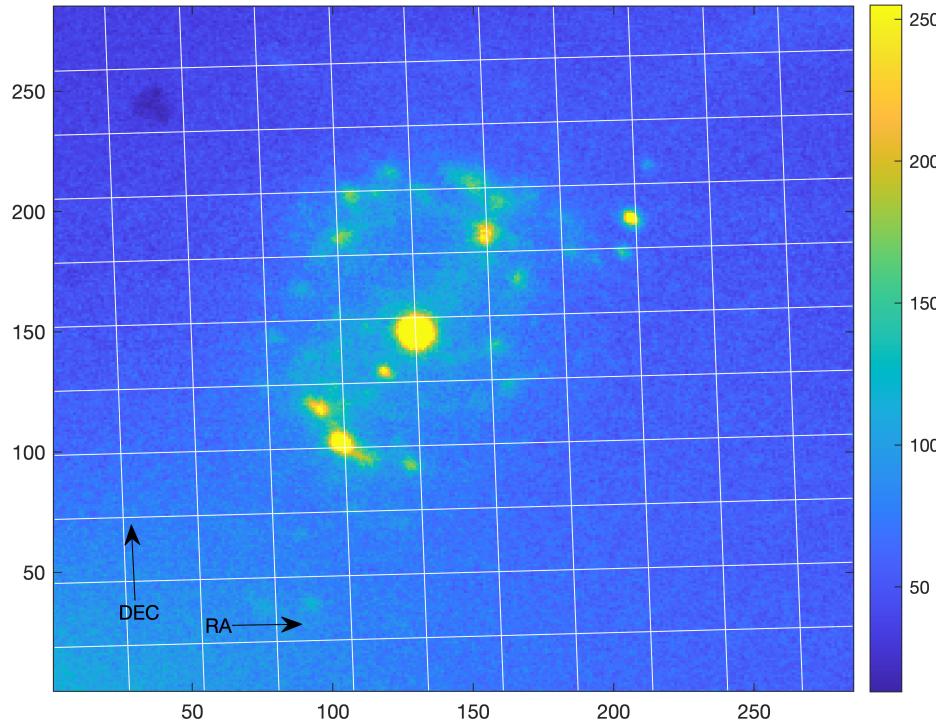
        full(i,j,1) = (transform(1) + CRVAL1);    % calibrate to know RA
        full(i,j,2) = (transform(2) + CRVAL2);    % calibrate to know DEC
        full(i,j,3) = X(i,j);

    end
end

ra = full(:,:,:1);
dec = full(:,:,:2);
intensity = full(:,:,:3);
```

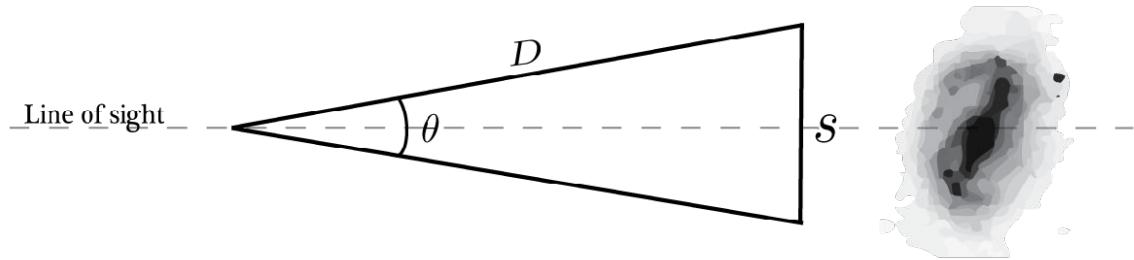
Visualize the new coordinate system by overlaying it ontop of the original image. The easiest way would be to plot the contour plots of both variables. Reason being, each slice of the counter would correspond to a single RA (DEC) value, giving us a new coordinate grid.

```
hold on
%contour(intensity,150)
imagesc(intensity)
colorbar
contour(ra,10,'-w')
contour(dec,10,'-w')
annotation('textarrow',[0.1927 0.1894],[0.2182 0.308],'String','DEC')
annotation('textarrow',[0.2793 0.3414],[0.1887 0.19],'String','RA')
hold off
```



## Finding Angular Size and Extragalactic Distance:

The key assumption for this lab is that we are measuring galaxies of similar Hubble type (spiral sb galaxies). We then assume that they are all the same physical size, no matter where they are. This is known as "the standard ruler" assumption in cosmology [cite]. Under this assumption, we can use basic geometry to approximate the distance by relating it's angular size to it's diameter. This relation is  $D \approx S/\theta$  and shown in the following diagram,



Where  $D$  is the distance between the observer and the galaxy in Mpc,  $\theta$  the angular size in radians, and  $S$  is the galactic diameter. The variable which we have to estimate is  $S$  using the standard ruler of spiral galaxies. The standard ruler we'll use for S(b) galaxies is  $S = .020\text{Mpc}$ . Use the the image you plotted to find the pixel values

of the edge of the semi-major axis of the galaxy. You can do this by just hovering your mouse over the point or by visual inspection.

**Quote the difference in DEC of each end point (in rads):**

```
distance_DEC = (dec(50,50)-dec(220,220))*(pi/180)
```

```
distance_DEC = -5.8086e-04
```

**Quote the difference in RA of each end point (in rads):**

```
distance_RA = (ra(50,50)-ra(220,220))*(pi/180)
```

**Calculate and quote the total angular distance (square root of the sum of squares):**

```
angular_arc = sqrt(distance_DEC^2 + distance_RA^2)
```

```
angular_arc = 7.9708e-04
```

**Lastly, use simple geometry to calculate the distance (in Mpc):**

```
distance = .020/angular_arc
```

```
distance = 25.0915
```

Append the final distance value to the *distance.txt* for this galaxy. Make sure to leave it in the proper ordering, increasing in NGC ID number.

## Questions:

(1) What other affects might arise in the image taking process that the fits header should include? (we've already mentioned rotation)

(2) Give some sources of systematic errors for the distance method used in this lab? (There are many)