The Dark Side of the Universe

Jenny Dickhaus and Sabine Loos

GLASP, grade 12

Mr. Rodriguez

The Dark Side of the Universe

I. **Abstract**
Summary of the entire experiment (purpose, experiment, and results).

II. **Information**
Contains background information on gravitational lensing and dark matter, as well as the purpose and hypothesis of our experiment.

III. **Materials List**
List of items used in the experiment and how they were obtained.

IV. **Procedure**
A systematic list of what was done during the experiment.

V. **Results**
Written and graphic representation of our data and results.

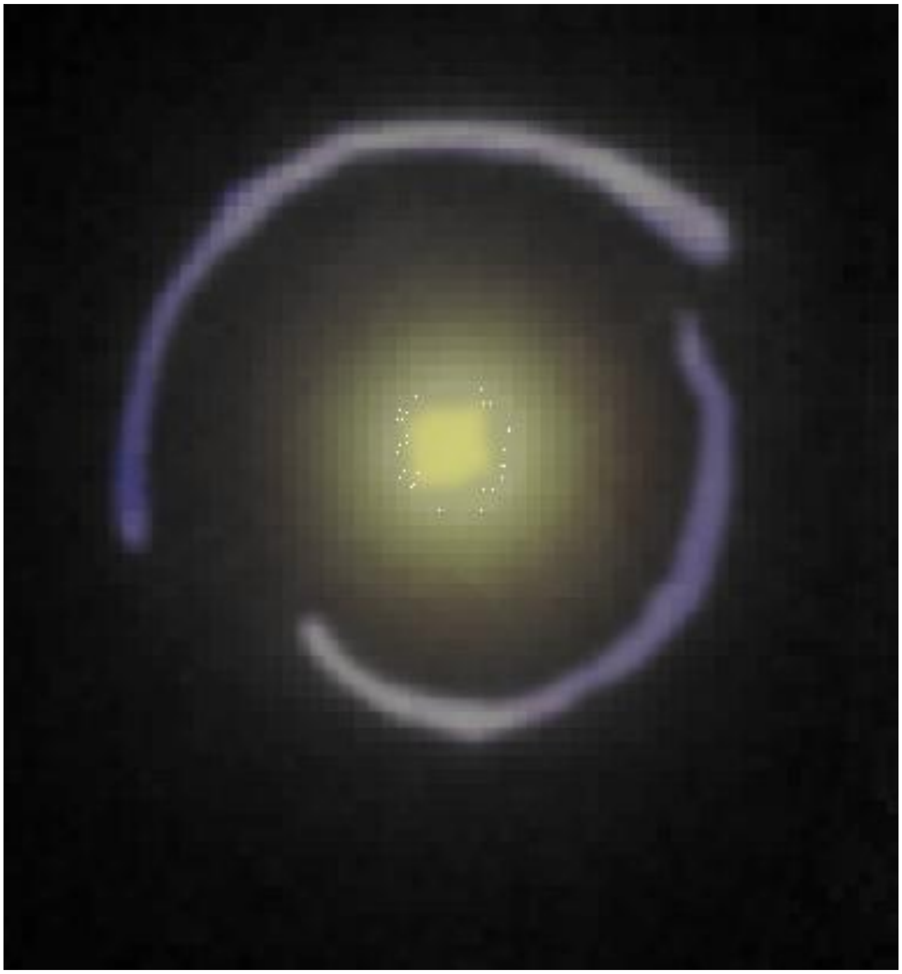
VI. **Conclusion**
Concludes our results by comparing them to our hypothesis.

VII. **Discussion**
Explains our results, sources of error, and mentions experiment that could further research on our experiment.

VIII. **Bibliography and Acknowledgements**
Lists the sources that were used and acknowledges people and organizations that aided us in creating this project.

Abstract

The purpose of the experiment was to determine if there is a relationship between the amount of mass of a galaxy and its amount of dark matter. We think that there will be a relationship between the two variables because dark matter should be dependent on the amount of real matter present in a galaxy. In order to determine if this was true, we examined various gravitational lenses taken from the Hubble telescope archives, and by using IRAF, cygwin, and SAODS9, we calculated the mass, radius, and luminosity of each galaxy. From there we were able to determine the amount of dark matter that exists by comparing the mass and luminosity of the galaxies. We also hoped to prove Einstein's theory of gravitational lensing. Our results showed that the best-fit line between the mass of the galaxy and the radius of its Einstein ring was $y = 3E+20x^2 + 1E+17x - 5E+11$, with a coefficient of determination of 0.7333 ($r^2=0.7333$); there was a squared relationship between the two. We also determined that the best-fit line between the mass of a galaxy and its amount of dark matter was $y = 8E-12x + 0.798$ with an r^2 value of 0.7963. Our data has led us to believe that there is a definite positive relationship between mass of a galaxy and its amount of dark matter.

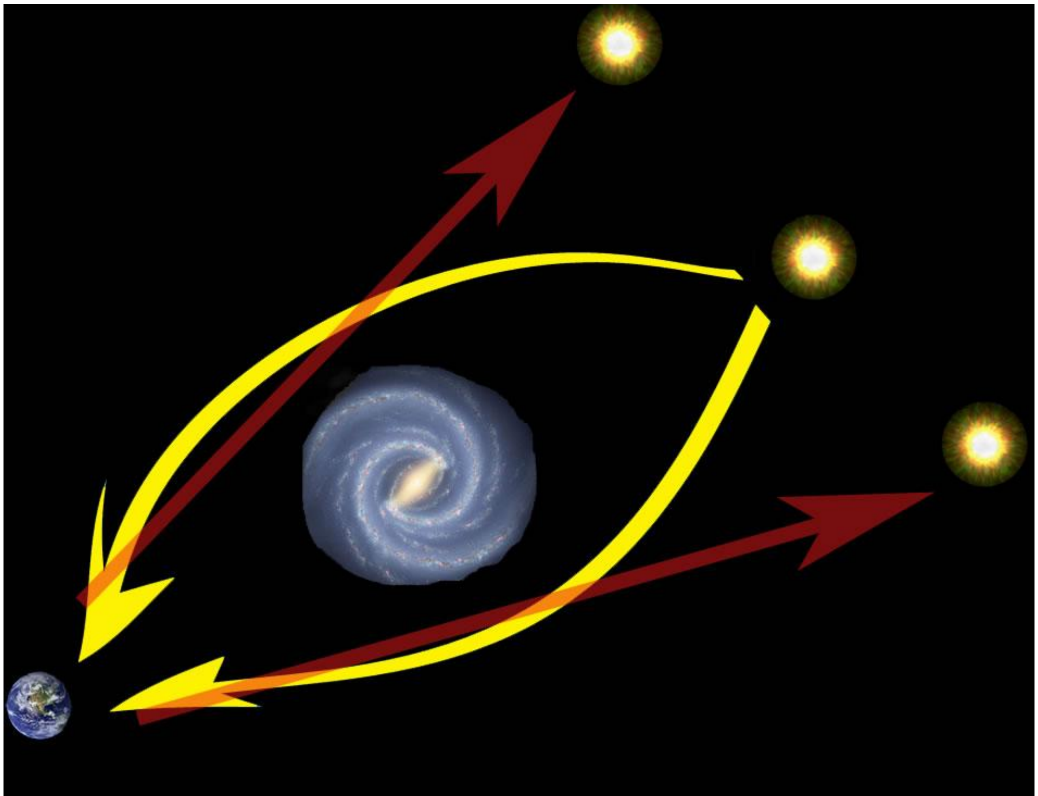


Introduction

Background Information

What is gravitational lensing?

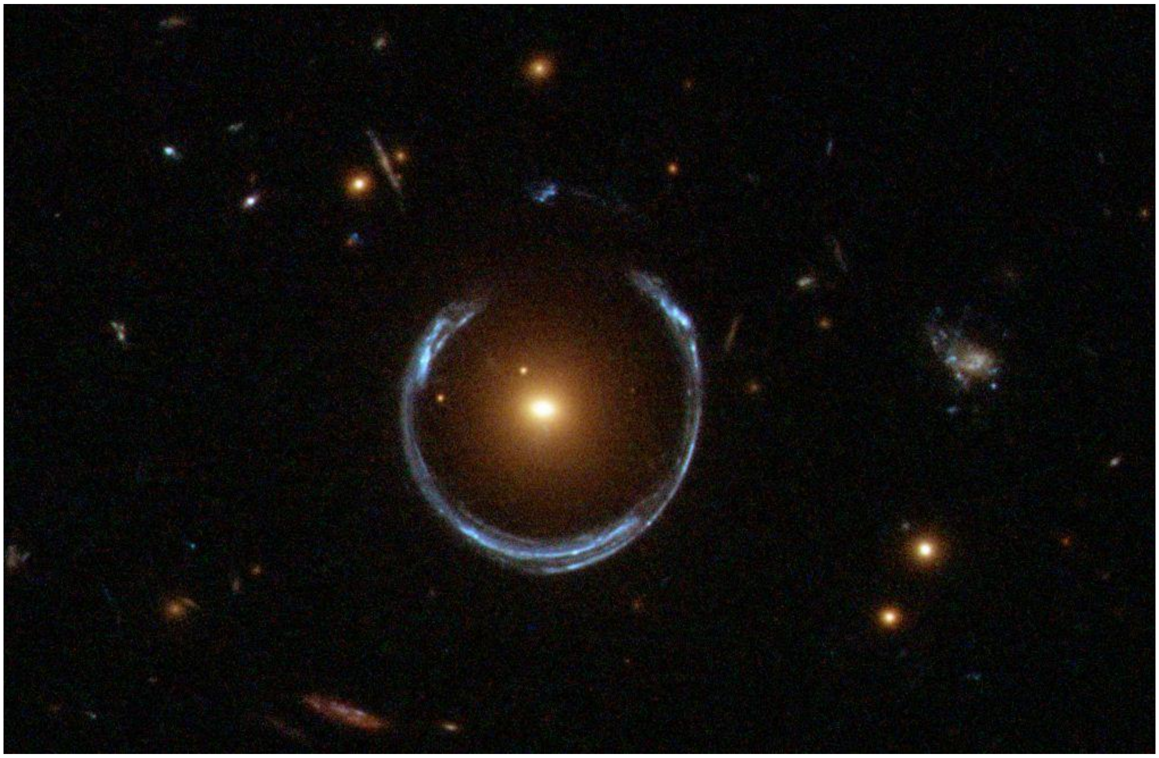
Gravitational lensing is a way for scientists to view distant galaxies. According to Einstein's theory of relativity, gravity should bend light. Because of this, the light coming from distant galaxies should be bent around any source of gravity that is closer to the earth. For example, if we were looking at a somewhat near galaxy, galaxy A, with a more distant galaxy behind it, galaxy B, and galaxy B's light would bend around galaxy A and produce an image of itself around galaxy A. There are two types of gravitational lensing, strong and weak, but weak is more readily common today. Weak and strong lensing occurs when light rays from a distant source are bent around a massive object in space. Strong lensing is less common because all three objects (lens, observer, and source) must be aligned in order for lensing to occur; in weak lensing, there are so many objects in the gravitational area that the background galaxy gets bent into many different images.



The image above displays the effects of strong gravitational lensing. The light emitted from the object (yellow arrows) is bent by the mass of the galaxy. Since we cannot see the bending of light, the observer sees two images (red arrows).

What is an Einstein ring?

An Einstein ring is an image that is created through gravitational lensing. When light from a background galaxy or star is bent , sometimes the resulting image is a ring that is formed around the mass that bends the light. In order for this to occur, all three objects must be aligned (the observer, the mass bending the light, and the galaxy behind the mass); Einstein rings only occur in strong gravitational lensing.



What is dark matter?

Nobody really knows what dark matter is, but we do know that it makes up most of the universe. Dark matter does not give off light and thus cannot be detected by telescopes. In order to detect dark matter, scientists use gravitational lensing and calculate the amount of matter that we can see and compare it to the amount of light that is given off from that particular area or galaxy in the universe. More specifically, by calculating the mass-to-light ratio, we can see how much dark matter there is because this quantity gives a picture of how much mass there is that does not radiate light photons. When the mass to luminosity ratio is larger than one, it can be said that there is dark matter. This can be explained when estimated masses are compared to the observed amount of light from galaxies. If the ratio is smaller than one, it means that the luminosity is greater than the mass; thus, this matter can be seen. If the ratio happens to be larger than one, the mass is larger than the luminosity; meaning that most, if not, all of the matter cannot be seen. Therefore, if the ratio of mass to luminosity is larger than one, there is dark matter.

Purpose

Gravitational lensing offers unique capabilities in the analysis of dark matter in the universe. Our mission was to take advantage of these unique capabilities in order to determine how the mass of a galaxy affected the amount of dark matter.

Hypothesis

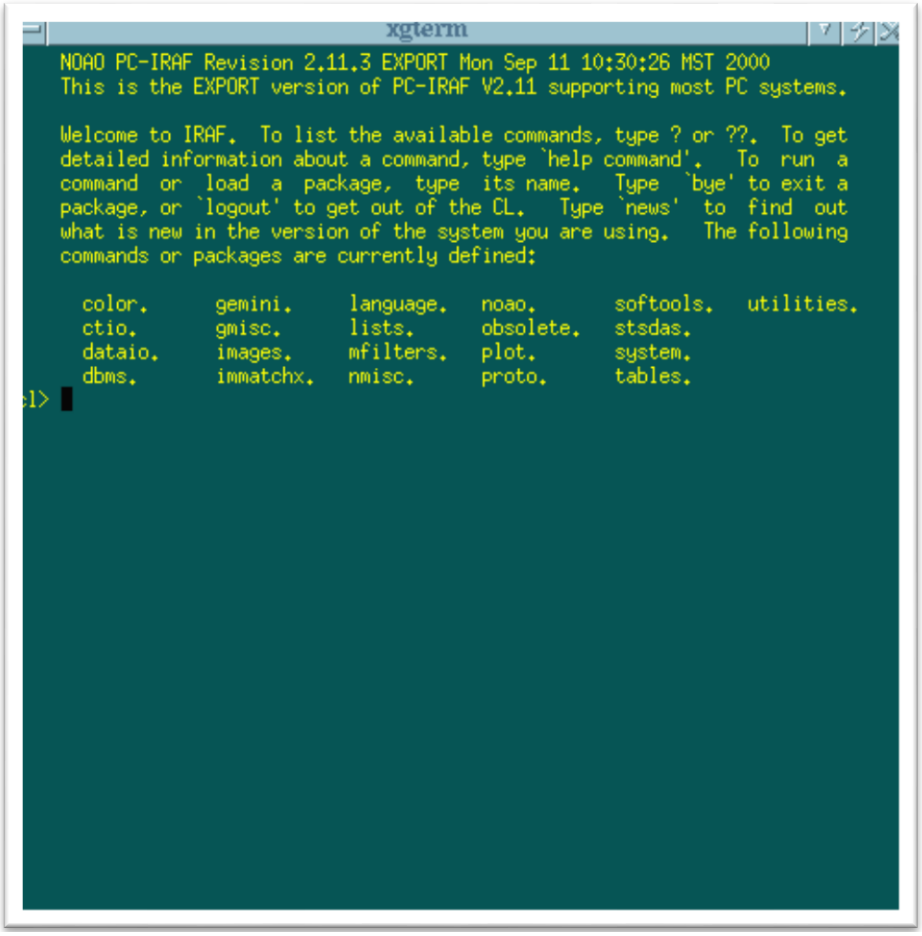
If the mass of a galaxy is large, then the radius of the Einstein ring will be large and there will be more dark matter. After looking at information regarding dark matter, we figured that there would be a squared relationship between mass of a galaxy and its corresponding Einstein ring.

Materials List

- Computers – provided by Anderson High School
- External Hard drives – purchased through grant money
- Photoshop – provided by Anderson High School
- IRAF – downloaded with the aid of Professor Natalia Connolly
- Cygwin – downloaded with the aid of Professor Natalia Connolly
- SAOimageDS9 – downloaded with the aid of Professor Natalia Connolly
- Calculator
- Microsoft Excel

Procedure

1. Obtain the dataset of gravitational lenses to be analyzed by searching the right ascensions and declinations of each object in the Hubble Space Telescope archive. There are a total of 63 objects that need to be sorted and categorized.
2. Download programs to further analyze each gravitational lens.
    - The first program to download is Cygwin, which is a command-line interface for Microsoft that allows us to work with our second program.
    - The second program that must be downloaded is Image Reduction and Analysis Facility (IRAF). This program allows our PC operating system to function as a Linux operating system. With IRAF, we are able to reduce astronomical images in pixel array form. Basically, it aids us in analyzing the extraordinarily large images on our basic operating systems. With IRAF we can examine the radius, mass, luminosity, and other characteristics of each gravitational lens. IRAF is solely command based.
    - The third program to be downloaded is SAOImage DS9. DS9 works in conjunction with IRAF. It displays the images that IRAF analyzes.



```
NOAO PC-IRAF Revision 2.11.3 EXPORT Mon Sep 11 10:30:26 MST 2000
This is the EXPORT version of PC-IRAF V2.11 supporting most PC systems.

Welcome to IRAF.  To list the available commands, type ? or ??.  To get
detailed information about a command, type `help command'.   To  run  a
command  or  load  a  package,  type  its name.   Type  `bye' to exit a
package, or `logout' to get out of the CL.   Type `news'  to  find  out
what is new in the version of the system you are using.   The following
commands or packages are currently defined:

  color.      gemini.     language.   noao.       softools.   utilities.
  ctio.       gmisc.      lists.      obsolete.   stsdas.
  dataio.     images.     mfilters.   plot.       system.
  dbms.       immatchx.   nmisc.      proto.      tables.
cl> 
```

3. After downloading each program, we must analyze the FITS images in IRAF, Cygwin, and DS9.
    - Open Cygwin and type command to open IRAF
    - In IRAF window, type command to open DS9
    - Display image of gravitational lens that is to be analyzed on DS9 by typing display command on IRAF
    - Analyze image in IRAF and DS9 through different commands including imcopy, imheader, and imcombine.
    - Getting rid of cosmic rays might be necessary in order to properly analyze the images. This can be done by combine multiple images of the same lensing galaxies.
    - The program provides specific data on each galaxy, including the luminosity and radius, which are vital to the final analysis of our data.
4. Calculations:
    - Calculate mass of each lensing galaxy through the following equation obtained from Einstein’s 1936 paper on gravitational lensing:

$$M = \frac{\theta_E^2 c^2 (d_S d_L)}{4G(d_S - d_L)}$$

Where G is Newton's gravitational constant ($G = .0043[\frac{pc(\frac{km}{s})^2}{M_\odot}]$), c is the speed of light, d_s is the distance between the observer and inner ring (background galaxy), and d_L is the distance between the observer and the lensing galaxy (foreground galaxy).

- To calculate the distances, use the redshifts provided by the Hubble Space Telescope. Taking the redshift into account acknowledges the fact that the universe is expanding and the galaxies are moving.

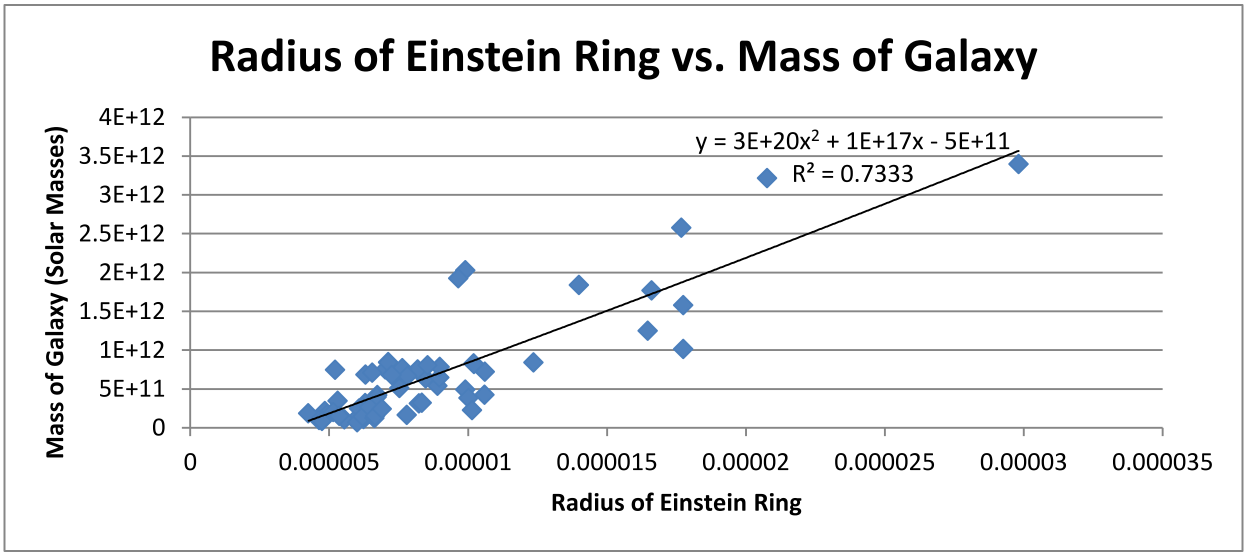
  $$d \approx \left(\frac{c}{H_0}\right)\left(\frac{(z+1)^2-1}{(z+1)^2+1}\right)$$

  Where H_0 is the Hubble constant ($71\frac{(\frac{km}{s})}{Mpc}$)
- Calculate mass to light ratio which provides the amount of dark matter present in the galaxy, because it explains the amount of mass that does not radiate photons. If the ratio is greater one, there is more mass than the amount of light given off, and therefore there is evidence of dark matter.

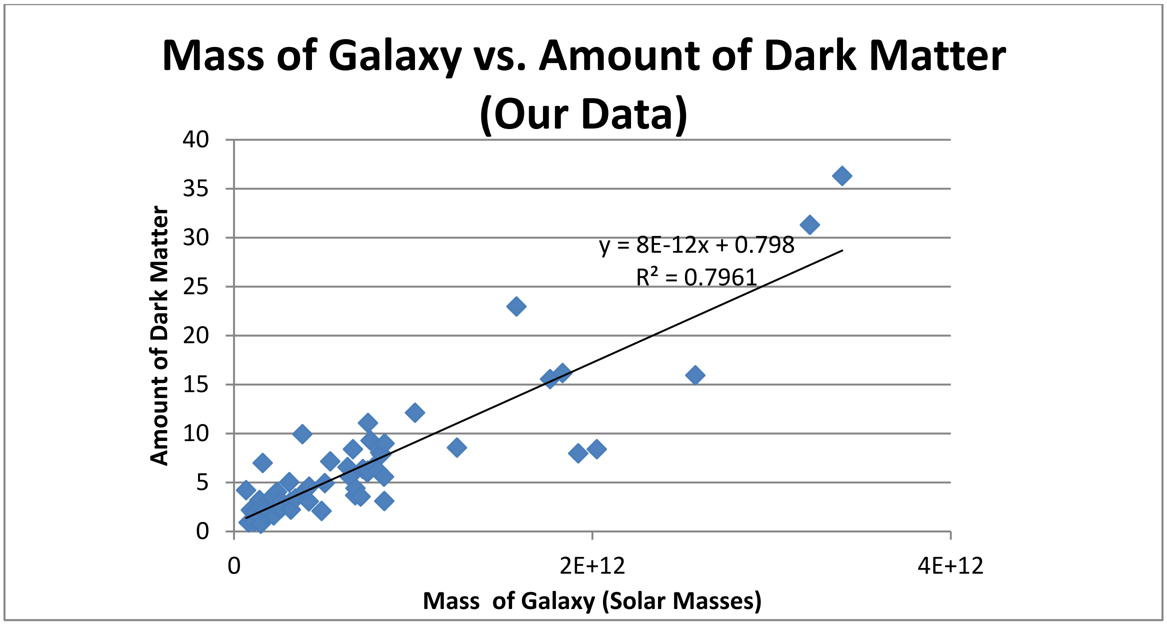
5. Record Data

Results

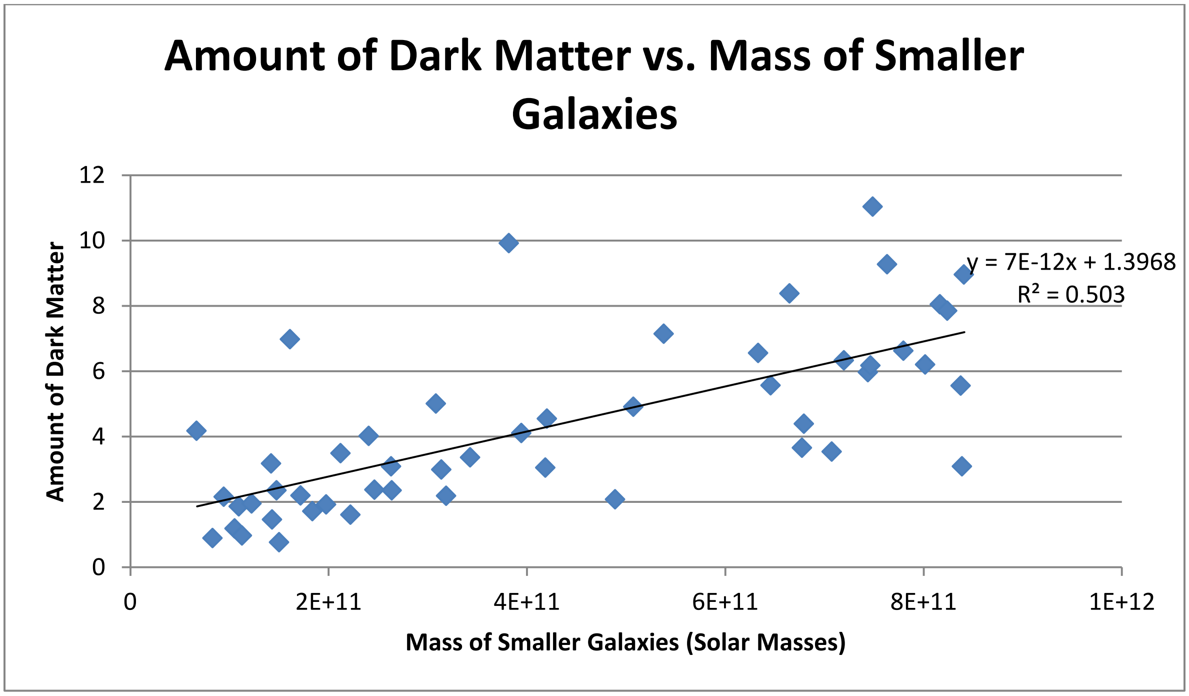
From our scientific experiment, we calculated and recorded the masses of each lensing galaxy and compared them to their respective radii and luminosities. According to the equation for the mass of a lensing galaxy (see procedure), there should be a squared relationship between the mass of a galaxy and the radius of its Einstein ring. When plotting our data, we discovered that the best fit regression line was indeed a polynomial equation with a degree of two (thus, it was a squared relationship). To determine whether the line fit the data well, we examined the r^2 value of the regression line. The r^2 value is also called the coefficient of determination, as it determines the goodness of fit of the model with the observed data. An r^2 value of one would imply that the regression line was a perfect fit for the data, therefore the closer the r^2 value is to one, the better the fit. The lower r^2 value of 0.7333 for the graph below says that the relationship between a galaxy's mass and the radius of its Einstein ring explain 73.33% of the variance in the data.



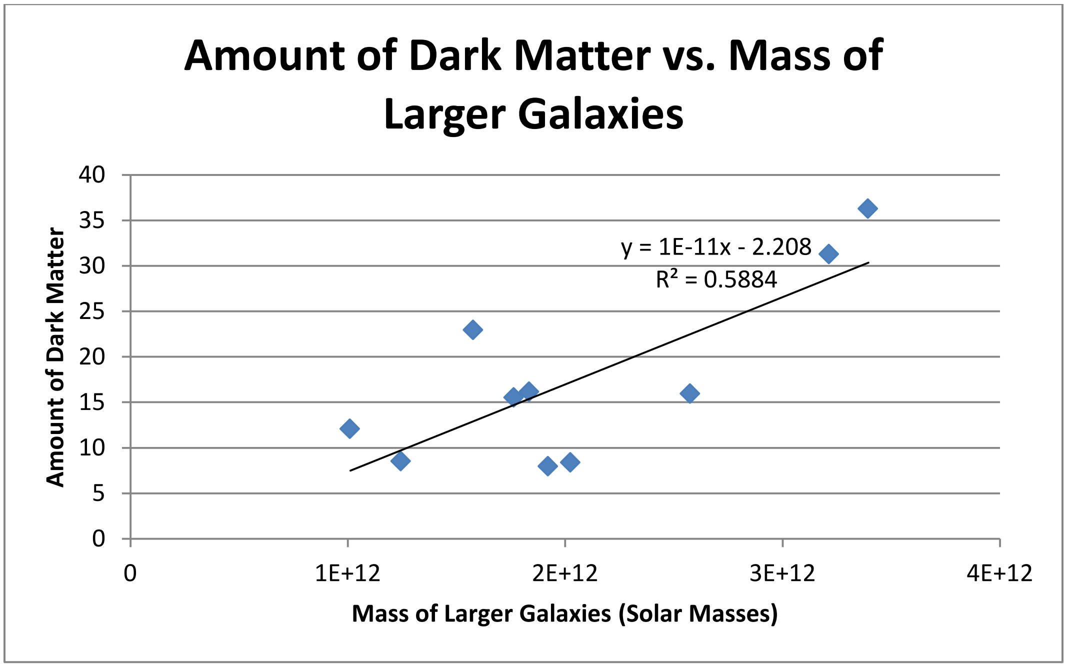
Furthermore, our data shows that the relationship between the mass of a galaxy and its dark matter is to the sixth power. The regression line is y = 8E-12x + 0.798, a linear fit, and the coefficient of determination, r^2, is 0.7961.



After noticing that the majority of the calculated masses were under 1.0E12 solar masses, we decided to compare the linear regression lines of the masses under and above that value. The graph below represents the relationship between the galaxies with smaller mass and the amount of dark matter. The linear regression line is y = 7E-12x + 1.3968 with r^2 value of 0.503.



The graph below represents the linear relationship between the galaxies with masses larger than 1.0E12 and the amount of dark matter. The linear regression line is y = 1E-11x - 2.208 and has a coefficient of determination, r^2, of 0.5884.



Our Data

Galaxy I.D.	Mass	Luminosity	Radius	M/L Ratio
J1205+4910	6.33363E+11	96626575291	8.47994E-06	6.5547
J0946 + 1006	3.1382E+11	1.05094E+11	6.29938E-06	2.9861
J1630+4520	2.57603E+12	1.61655E+11	1.76867E-05	15.9353
J2341+0000	8.37582E+11	1.50677E+11	1.23565E-05	5.5588
J1531-0105	1.24436E+12	1.45738E+11	1.64753E-05	8.5383
J0252+0039	2.1225E+11	60816563875	4.84568E-06	3.49
J0946 + 1006	8.24155E+11	1.0501E+11	1.02098E-05	7.8483
J0956+5100	7.46554E+11	1.20941E+11	8.19404E-06	6.1729
J0029-0055	2.63852E+11	1.12155E+11	6.20247E-06	2.3526
J0008-0004	8.41029E+11	93867688318	7.13284E-06	8.9597
J0037-0942	1.76534E+12	1.13698E+11	1.66158E-05	15.5266
J0044+0113	5.38108E+11	75366659226	8.90151E-06	7.1399
J0109+1500	7.49056E+11	67872458446	7.02623E-06	11.0362
J0157-0056	7.44136E+11	1.2463E+11	5.22364E-06	5.9708
J1020+1122	7.63525E+11	82378186862	7.63679E-06	9.2685
J0841+3824	1.12968E+11	1.16617E+11	5.98441E-06	0.9687
J0216-0813	2.02533E+12	2.41729E+11	9.90941E-06	8.3785
J0822+2652	4.18773E+11	1.37596E+11	6.74034E-06	3.0435
J2303+1422	4.89173E+11	2.35839E+11	9.90941E-06	2.0742

J1023+4230	1.43107E+11	98357882801	4.89898E-06	1.455
J1213+6708	1.05361E+11	89232744357	5.55799E-06	1.1807
J0330-0020	3.43038E+11	1.02269E+11	5.31086E-06	3.3543
J1029+0420	1.09688E+11	59044779816	6.24123E-06	1.8577
J0405-0455	67185541362	16086857657	6.01833E-06	4.1764
J1218+0830	4.20332E+11	92425467371	1.06023E-05	4.5478
J2300+0022	1.83909E+11	1.07362E+11	4.25451E-06	1.713
J0728+3835	2.46403E+11	1.0414E+11	6.08617E-06	2.3661
J1250+0523	3.2149E+12	1.0275E+11	2.07686E-05	31.2886
J0903+4116	6.79633E+11	1.54936E+11	6.31877E-06	4.3865
J0737+3216	8.38984E+11	2.71581E+11	7.12799E-06	3.0893
J1103+5322	3.08494E+11	61625550739	8.23765E-06	5.0059
J0037-0942	7.20081E+11	1.13698E+11	1.0612E-05	6.3333
J1402+6321	6.45912E+11	1.16062E+11	8.97904E-06	5.5653
J0955+0101	3.82154E+11	38540688579	1.00209E-05	9.9156
J1636+4707	8.167E+11	1.01542E+11	1.02147E-05	8.043
J0956+5100	7.80022E+11	1.17797E+11	8.98389E-06	6.6217
J1403+0006	1.71888E+11	78440248986	4.9329E-06	2.1913
J0959+0410	1.42406E+11	44911215838	6.21216E-06	3.1708
J2238-0754	3.39485E+12	93549971740	2.98203E-05	36.2892
J1250+0523	1.97756E+11	1.03129E+11	5.15096E-06	1.9176
J1100+5329	1.61452E+11	23147260150	7.7967E-06	6.975
J0216-0813	1.92171E+12	2.41729E+11	9.65259E-06	7.9498
J1205+4910	3.94713E+11	96154582186	6.71127E-06	4.105
J0936+0913	2.63125E+11	85399747910	6.45444E-06	3.0811
J2321+0939	2.22164E+11	1.38577E+11	1.01469E-05	1.6032
J1416+5136	6.65163E+11	79423279474	7.82577E-06	8.3749
J1106+5228	1.22535E+11	62952799646	6.63858E-06	1.9465
J1112+0826	8.01775E+11	1.29203E+11	8.54778E-06	6.2056
J1430+5115	6.77726E+11	1.8565E+11	7.26367E-06	3.6506
J1432+6317	1.50329E+11	1.97508E+11	6.66281E-06	0.7611
J1134+6027	2.40599E+11	59932220123	6.90025E-06	4.0145
J1621+3931	1.83498E+12	1.1363E+11	1.39992E-05	16.1487
J1142+1001	5.07532E+11	1.03392E+11	7.53503E-06	4.9088
J1538+5817	94371536188	43916727420	4.64216E-06	2.1489
J1143-0144	1.01137E+12	83653312700	1.77497E-05	12.0901
J1532-0105	3.18823E+11	1.45738E+11	8.33941E-06	2.1876
J1153+4612	1.47834E+11	63009332696	5.36901E-06	2.3462
J1525+3327	7.07733E+11	2.0029E+11	6.55136E-06	3.5335
J1204+0358	1.57761E+12	68788773552	1.77497E-05	22.9342
J1451-0239	83222007529	93342869731	4.74392E-06	0.8916

Sample Calculations:

Conclusion

According to our experiment, there is a squared relationship between the mass of a galaxy and the radius of its Einstein ring. This means that for every x amount increase in the radius of the Einstein ring, the mass of the lensing galaxy increases by $x^{2.}$ Since the radius of the Einstein ring increases with every increase in the mass of the galaxy, we can say that there is definitely a positive relationship between mass and radius of the Einstein ring. Furthermore, there is a linear relationship between the mass of the galaxy and its amount of dark matter in both large and small galaxies. Therefore, when the mass of the galaxy increases, the amount of dark matter will increase as well. Thus a positive relationship exists between the mass and the dark matter of a galaxy. In conclusion, we can accept our hypothesis to an extent, because there is a large variance in the equations due to a lower r^2 value. This value will be explained more in our discussion.

Discussion

Our results from our experiment make various implications on the relationship of the mass of a galaxy and the amount of dark matter in the universe. The r^2 value of 0.7333 for the relationship between the mass of the lensing galaxy and the radius of its Einstein ring shows that the majority of the radius of the Einstein ring is based on the mass of the galaxy, but because it is not closer to one we know there are other factors affecting it. This is reflected in the Einstein's theory of gravitational lensing, since the mass of a galaxy is calculated using the Einstein ring's radius, the speed of light, and the galaxies' distances from earth. Therefore, our data proves Einstein's theory of gravitational lensing.

Furthermore, there is a linear relationship between the mass of the galaxies and the amount of dark matter surrounding that galaxy. We used an r^2 value to determine how well the model fits the data of gravitational lenses, because the r^2 value is usually used to examine linear relationships. This linear relationship can only realistically be applied to our gravitational lenses that have a mass below 1.0×10^{12} solar masses, because we do not have enough data for gravitational objects with a higher mass to make a plausible relationship between mass and dark matter. The r^2 value of .5309 means that only 53.09% of the data can be accounted for in the linear relationship. Therefore, there is evidence for a strong variance around the linear model, but the linear model still applies.

There were many flaws in our experiment that could have caused unreliable data in our results. For one, our programs were not designed for PC operating systems, so it took an extraordinarily long amount of time to obtain the various data on our gravitational lenses. Also, there was human error, since one cannot be completely sure that the programs used to calculate the luminosities and the radii are totally exact. We calculated the radii as more of a qualitative measure, since we did not have a command to calculate the radius itself. Lastly, we did not have nearly enough data points to make a strong conclusion. If we had more than 60 gravitational lenses to analyze, we would be able to have better evidence for the relationship between mass and dark matter.

If we were to extend this experiment, we would first and foremost obtain at least five times more gravitational lenses to analyze. This would create a more reliable dataset to be used to examine the relationship between the mass of the lensing galaxy and the dark matter in the galaxy. In addition, we would analyze the relationship between dark matter and other variables related to the Einstein ring, including luminosity and radius. We would have to continue our research further into Einstein rings and dark matter.

Bibliography

Brainerd, Jerome J. "The Astrophysics Spectator: Simulator of a Point-Source Gravitational Lens." The Astrophysics Spectator: Home Page. 2 Nov. 2009. Web. 19 Aug. 2011.

Cain, Fraser, and Jeff Barbour. "Near Perfect “Einstein Ring” Discovered." Universe Today — Space and Astronomy News. Universe Today, 29 Apr. 2005. Web. 19 Aug. 2011.

Einstein, A. "Lens-Like Action Of A Star By The Deviation Of Light In The Gravitational Field." Science 84.2188 (1936): 506-07. Print.

Ellis, R. S. "Gravitational Lensing: A Unique Probe of Dark Matter and Dark Energy." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 368.1914 (2010): 967-87. Print.

Sauer, Tilman. "A Brief History of Gravitational Lensing " in: Einstein Online Vol. 4 (2010), 1005. Web.

Treu, Tommaso. "Strong Lensing by Galaxies." Annual Review of Astronomy and Astrophysics 48.1 (2010): 87-125. Print.

We would like to acknowledge many organizations and people who aided us in completing our research and experiment. First, we would like to thank Jeffrey Rodriguez of Anderson High School and Natalia Connelly of Hamilton College for organizing our research group. Next, the data we obtained was from the Multimission Archive at STScl (MAST) of the Hubble Space Telescope. Without the courtesy of their public archive of gravitational lenses, we would not have been able to complete this project. Lastly, we would like to thank the creators of IRAF, Cygwin, and SAOImage DS9 for making their respective programs accessible to the public.