Analyzing the Mass along the Line of Sight to Gravitational Lenses

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Abstract

Gravitational lensing is important in determining the Hubble Constant, H_0, used to calculate the rate of expansion of the universe. Known gravitational lens fields are compared with non-lens fields to determine if there tends to be more mass than average along a line of sight from Earth to a lens. The mass distribution of the universe is uniform on large scales, but more locally, certain regions that contain more mass can influence the lensing properties of that particular line of sight. Images taken by the Advanced Camera for Surveys on the Hubble Space Telescope are analyzed, and the number of galaxies and total flux along each line of sight are compared. The results may indicate slightly more objects in lensing regions, but are inconclusive and will require further analysis.

Introduction

The phenomenon of gravitational lensing occurs when the light emitted from an object is bent by a large mass, typically a galaxy that is positioned almost directly between Earth and the object. This results in a distorted image of the original object, called the "lensed" object, appearing in a region of space very close to the "lensing" object that bends the light. In some cases, the light may be deflected in such a way as to produce multiple distorted images of the same object. This will usually occur if the lensing object is directly between Earth and the lensed object.

The bending of light by a massive object was first predicted in 1911 by Albert Einstein while he was forming his theory of general relativity. He developed a formula for the deflection angle of a ray of light as a function of the lensing mass and the distance between the mass and the path of the light. Sir Arthur Eddington was able to confirm Einstein's prediction in 1919 by observing the deflection of light that was bent by the mass of the sun. He measured the deflection angle of the light emitted by a star that was near the sun in the sky at the time of a solar eclipse, which agreed with the angle predicted by Einstein's theory, but not the angle predicted by classical theories. The apparent shift in the position of the star from where it should have been was a direct confirmation of the theory of general relativity.

Studies on gravitational lensing were sparse until 1979, when the first double image of a quasar was discovered by Dennis Walsh. The two images had identical spectra, and further observations confirmed that they were images of the same object that was being lensed by a galaxy. Since then, studies on lensing have increased dramatically, and gravitational lenses have become a popular topic of research among the astrophysical community.

Analysis of gravitational lenses can provide insight into the properties of the lensing galaxy or cluster. By measuring the deflection angle and examining the distortion of the bent light, the total mass and the mass distribution of the lensing object can be determined. In this way, astronomers have been able to determine the properties of several galaxies and galaxy clusters and how they evolved over time.

Other studies of gravitational lenses have also been used to determine the value of the Hubble Constant, H_0. H_0 is a number which is used in Hubble's Law, $v = H_0 d$, to estimate the rate at which the universe is expanding through a relationship between a galaxy's distance from Earth and the velocity at which it is receding. Although a precise value of the Hubble Constant has not been determined, lensing studies have narrowed the range of possible values for the constant significantly. A high value for H_0 would suggest that the universe is expanding at rapid rate, while a low value suggests a slower rate of expansion.

Background and Goals of This Project

The large-scale distribution of mass throughout the universe is fairly uniform. However, on smaller scales, fluctuations in this distribution become apparent. Along any given line of sight from Earth, the number of galaxies of a certain magnitude may vary greatly depending on the direction chosen. As dimmer and dimmer magnitudes are observed, this number will tend to even out for all lines of sight.

The goal of this project is to determine if gravitational lenses are more likely to be found along lines of sight that contain greater mass, as opposed to being randomly distributed. Galaxies with more mass will tend to emit more light than less massive clusters, so our main assumption will be that the total amount of light from a given region is proportional to the mass along that line of sight. Although this is not always a directly proportional relationship, data collected over many regions of space will tend to average out to an approximate correlation between the two. The dark matter halo of galaxies, which emits no light but can contain roughly 90% of a galaxy's mass, should not have a significant impact on the results because the data collected over several different regions will tend to average out any inconsistencies in the data. Galaxies of the same type (spiral or elliptical) tend to contain roughly the same proportion of dark matter to luminous matter, so the average proportion in each image should be similar, assuming a relatively similar proportion of spiral to elliptical galaxies. Again, the large sample of images should average out these inconsistencies. To test this, I will analyze regions of space that are known to contain lensing systems and compare them to a sample of regions that do not have lenses. The flux and number of galaxies along the line of sight of the two sets of images should provide data that can be used to estimate the average mass of the regions.

The images used in this project were taken by the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope. The lens images were taken from the Harvard-Smithsonian Center for Astrophysics - University of Arizona Space Telescope Lens Survey (CASTLeS), a survey of all known galaxy-mass gravitational lens systems. These images were taken using the F814W infrared filter, as well as the F555W optical filter. The control sample, images of non-lensing regions, was taken from the Cosmic Evolution Survey (COSMOS), a survey over a two-square degree area of the sky.

Methods

The lens images used in this project were taken from the Multimission Archive at Space Telescope (MAST) database, and the non-lens images were taken from the COSMOS archive. After collecting and organizing the images, a program called Multidrizzle was run on the data, which processed and reduced the files into a clean format by removing most of the noise present in the data. Although it is nearly impossible to remove all of the noise in the images, Multidrizzle eliminates the major sources of interference and cleans up the image to an extent where the remaining noise has a small impact on the data. The new files were then run through a program called SExtractor, which detected sources of light in the image and printed out a catalog of every object, along with information including the magnitude, position, and flux of the object.

Once catalogs had been made for every image, macros were run on them to filter out stars by placing restrictions on the class of the objects, which determines whether an object is a star or galaxy. One problem was that not all of the stars were filtered out using this method, so the catalogs and images had to be examined by hand to remove any remaining stars. Thin lines of light from bright stars also registered as objects in the catalogs, so these had to be filtered out by placing restrictions on the ratio of an object's semimajor axis to semiminor axis.

The COSMOS images had an excessive amount of noise along the right and left edges of the field. To eliminate this, the sides were cut by 100 pixels each. This was a bit tricky since the image was slanted, and the sides with the noise did not have the same slope. The images fell into one of two categories. Most of them had a slope of -4.4 for the left side of the image, and a slope of -5 for the right side of the image. The rest were reversed, with a slope of -5 for the left side and -4.4 for the right side. Two different SM macros had to be written to deal with each case. Fortunately, both types of images had distinct x and y coordinates for the corners of the field. After a list of the reversed images were made, one macro was run on the "normal" images, using the coordinates of the corners to create two cuts of approximately 100 pixels each on the sides of the image. A second macro used the coordinates of the corners of the "reverse" images to create a similar cut on the data.

Once the catalogs had been appropriately modified, several SM macros were used to extract various data sets from them and produce several graphs. The first graph was a plot of the average number of galaxies per magnitude. The magnitude range from 15 to 27 was divided up into half-magnitude bins on the x-axis, while the average number counts for each bin was plotted on the y-axis. This was done for both the lenses and COSMOS fields, and then the two graphs were plotted on the same set of axes for comparison. This graph was made twice, once using corrected isophotal magnitude and once using auto magnitude.

Another graph was made to show the average corrected isophotal flux per field as a function of cutoff magnitude. The magnitude range from 15 to 21 was divided up into single-magnitude bins on the x-axis. On the y-axis, the average total flux of the fields from objects that were dimmer than the cutoff magnitude was plotted. The plot of the COSMOS fields was placed on the same axes as the plot of the F814W lens fields and the plot of the F555W lens fields for comparison. The idea behind this plot is that the light from any region tends to be dominated by nearby objects. By setting a cutoff magnitude and only taking the flux from objects dimmer than that magnitude, it is possible to see and average trend rather than fluctuations caused by brighter objects.

The last graph was one that plotted average flux per magnitude bin as a fraction of total average flux per field. To do this, the average flux per field was calculated for both the lenses and COSMOS images. Then, the mean flux per half-magnitude bin from 15 to 27 was calculated and divided by this average and plotted on the y-axis against magnitude on the x-axis. This plot was also made as a cumulative fraction of the flux per magnitude, as well as all brighter magnitudes. This graph shows the average contribution to total flux per field from each magnitude bin. By comparing the COSMOS graph to the lenses graph, the trends of how objects at certain magnitudes influence the data can be compared.

Results

Figure 1

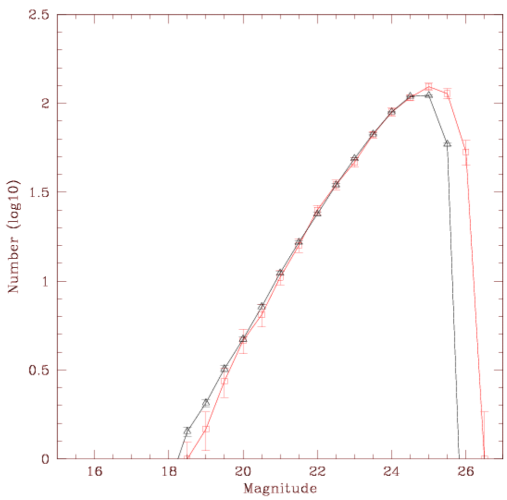

Figure 2

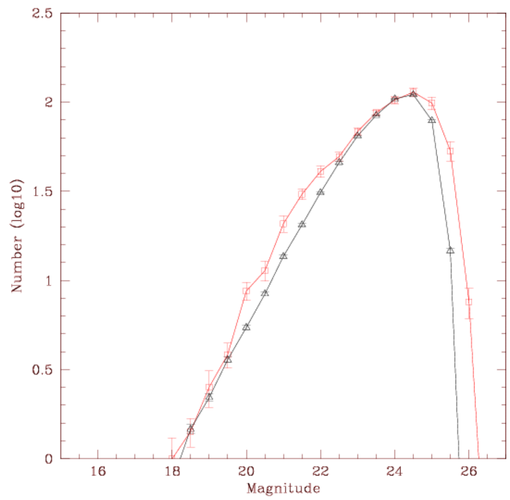

Figure 1 and 2 shows the plots of number counts against magnitude. The red squares represent the lens fields, while the black triangles represent the COSMOS fields. Figure 1 was made using corrected isophotal magnitude. Figure 2 was made using auto magnitude. The y-axis is scaled logarithmically, and the drop-off at roughly 25th magnitude is a result of the limiting magnitude of the telescope.

Figure 3

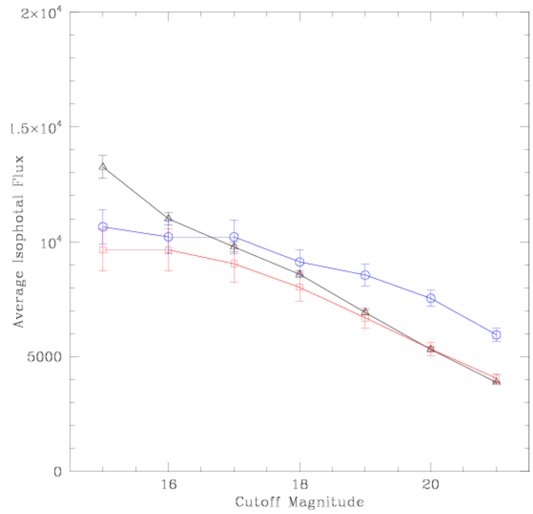

Figure 3 is a graph of average isophotal flux per field against cutoff magnitudes from 15 to 21. The blue circles represent the F555W filter data for the lenses, while the red squares are the F814W filter data.

Figure 4

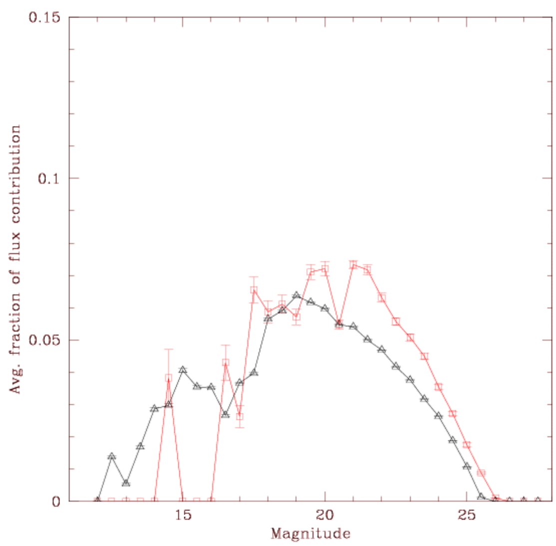

Figure 5

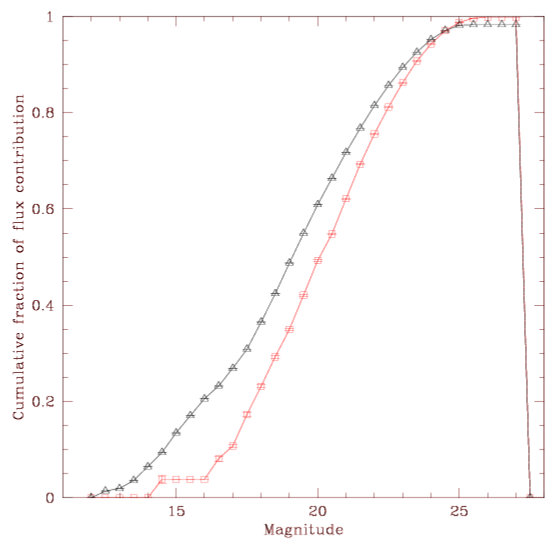

Figure 4 shows the average fraction of total corrected isophotal flux per field contributed by each magnitude bin from 12 to 27. Figure 5 shows the same data plotted as a cumulative fraction of the flux from each magnitude, as well as all brighter magnitudes.

Discussion

Analysis of figures 1 and 2 shows that the number of galaxies along the line of sight to lenses and non-lenses follow a similar pattern. The difference between using corrected isophotal magnitude and auto magnitude appears to shift the data for the lens fields. As of now, the reasons for this are unknown, and will require further examination to determine. It appears that the lens fields may contain slightly more objects, but this is uncertain.

Figure 3 shows that the COSMOS fields tend to have more flux from objects at brighter magnitudes than the lens fields, especially at 17^{th} magnitude or brighter. As the cutoff magnitude is set dimmer and dimmer, the two data sets start to come closer together. This is also shown by figures 4 and 5, which clearly show a large fraction of flux for the COSMOS fields coming from objects below 17^{th} magnitude, and even some from 12^{th} or 13^{th} magnitude.

The results, as of now, are somewhat uncertain. More analysis of the graphs shown may reveal some conclusions. Also, more data may be needed to produce more revealing results. Further research will be conducted to shed light on the meaning of this data.

References

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