Weak Gravitational Lensing

Sofia Sivertsson

October 2006

1 General properties of weak lensing.

Gravitational lensing is due to the fact that light bends in a gravitational field, in the same fashion as for massive objects. The prediction that light bends when passing near massive bodies is valid also in Newtonian physics but is more significant in the theory of General Relativity. [1]

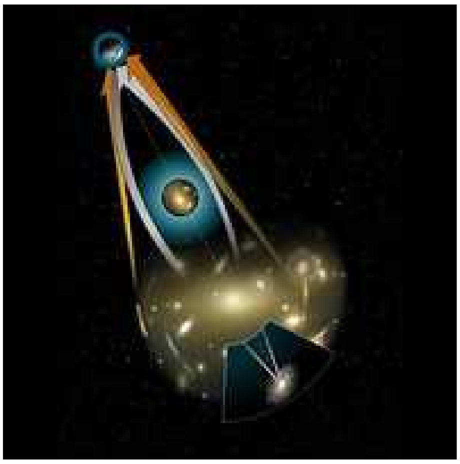

Figure 1: Illustration of the concept of gravitational lensing. Credit [9]

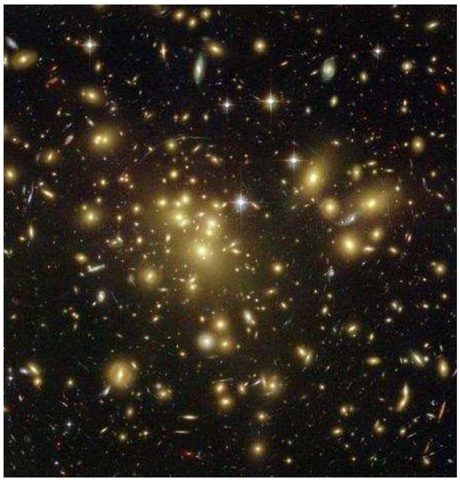

Figure 2: Picture taken with the Advanced Camera for Surveys aboard NASA's Hubble Space Telescope. In this observation the Hubble telescope peered straight through the galaxy cluster Abell 1689 which is one of the most massive galaxy cluster known. The observation is made in visible light and near-infrared in June 2002. Credit [8]

Due to this lensing effect a bright object behind a massive cluster will appear as distorted/sheared when viewed from earth. Lensing effects can also make an object seem brighter or produce several images of the same object. The most apparent lensing effects, such as multiple images or arcs and rings, is referred to as strong lensing. The deep observation of the massive cluster Abell 1689 with its apparent arcs is an example of strong lensing, some of the fainter galaxies being very far away and enhcanced by the lensing effects. In weak lensing the image is only slightly distorted and hence the distortion/shear can not be identified from just one individual source. Weak lensing observations can only be made in a statistical sense through observing a large number of sources, since the distortion of a single galaxy is small and the true shape of the galaxy is not known. The observed ellipticity of a galaxy is, hence, a combination of the shear and the intrinsic ellipticity of the galaxy. To find the average shear of many observed galaxies one assumes the intrinsic ellipticity of the galaxies to be randomly oriented. [2]

Weak lensing surveys needs the observations of a large number of sources; the larger number of sources that is averaged over the smaller the noise in the measurements. In weak lensing surveys aiming at measuring the mass of a single cluster the region in which the shear can be assumed to be constant is limited. Hence these measurements requires a high density of sources with measurable shape, which in turn requires deep observations. To reach a large number density in the observations also the fainter, and more numerous, galaxies needs to be probed. Faint galaxies are, however, small and hence it can be difficult to measure their shape. The observed shape of small galaxies is strongly affected by the atmospheric disturbances, for ground based observations, and also by distortion effects of the telescope. These effects needs to be understood and corrected for, which is the largest observational challenge in using weak lensing. On the other hand, weak lensing surveys observing large regions of the sky quickly leads to large data sets which can be difficult to handle. [2]

2 Usage of weak lensing.

Weak lensing can be used to "weigh" galaxy clusters and to obtain a two-dimensional projection of the mass distribution of the cluster. Weak lensing can also be used for cosmological observations such as to probe the inhomogeneous large sale distribution of matter in the universe. Also the temperature fluctuations of the Cosmic Microwave Background is subject to weak lensing, and hence it contains information about the evolution of the universe. Weak lensing offers a unique tool to study the cosmological dark matter distribution, which is so far only observable through its gravitational interaction. [2]

The small distortion of the image of distant galaxies through weak lensing depends on the density fluctuations all the way along the line of sight. Hence, the effects on the observed shape of the distant galaxy depends on the large scale structure and its evolution over a long period of time. Because of this weak lensing is potentially a very useful tool to learn about structure formation and general cosmological properties. [4]

2.1 Finding the mass of individual clusters using weak lensing

Weak lensing offers a unique tool for measuring cluster masses, weak lensing does not need any extra assumptions regarding the state and structure of the cluster. Weak lensing is also very useful since it naturally includes the dark matter halo of the galaxy cluster. However measuring the mass of a cluster using weak lensing is not trivial nor problem free.

First of all weak lensing gives a two-dimensional projection of the mass distribution of the cluster. This in itself gives an error which, if not taken into account, tends to give an overestimation of the mass. [5]

The theoretical aspects on how to treat the weak lensing statistics and projection errors have been analysed by several authors. One way to analyse this is to set up a theoretical mass configuration and luminous sources and then simulate the lensing effects in the theoretical system. Since the mass configuration is known one can then analyse the accuracy of the methods of estimating the mass distribution from the lensing information. [4] [5] Using statistical methods the positive bias of the projection effect is largely cancelled. [5]

The shear of a distant galaxy depends both on the lensing effect due to the foreground object that we wish to study and the effects of other mass fluctuations along the line of sight, such as other mass halos. To find the mass of a specific dark matter halo other massive halos affecting the lensing should be taken in account and be corrected for. Since galaxies tend to follow dark matter halos one should be able to find at least the heavier dark matter halos through looking for groups of galaxies. However, less massive unknown dark matter halos and unclustered matter can still influence the lensing field significantly. [4] In real weak lensing measurements one can, however, compare the lensing effects somewhat between sources at different redshift in order to find signs of other massive sources disturbing the lens field along the line of sight, as done by [3].

Also, of course, the inaccuracy in the measurements of the ellipticity of the galaxies adds a noise to the weak lensing measurements. [5]

There have been comparisons made between the mass estimations of clusters using weak lensing, X-ray observations and galaxy kinematics. [6] have studied the mass distribution of the massive cluster MS 1008.1-1224 using X-ray observations and weak lensing. They found the two observations to be consistent with each other with high accuracy. [7] have studied 13 X-ray luminous clusters using shear measurements (weak lensing) and modelling the mass profile using spectroscopic velocity dispersions. It was found that the two methods were in fair agreement for all of these clusters, except two. Either these two clusters are not in dynamical equilibrium, as assumed, or there are problems with the weak lensing measurements due to projection effects or other disturbing mass concentrations.

It is, however, unlikely that the lensing field can be used to determine individual halo masses with a higher accuracy than the 10% level. [4]

2.1.1 An important discovery using weak lensing - the observed separation of dark and baryonic matter in the "bullet cluster"

Since gravitational lensing can be used to measure the mass distribution of a galaxy cluster it is very useful in the search of dark matter. One great weak lensing observation, connected to the search for dark matter, is the recent observation of the cluster merger 1E0657-558, also known as the Bullet Cluster. [3] In the collision between those two clusters the dissipationless stellar component and the X-ray emitting plasma are separated. The observation is shown in figure 3. Without any dark matter in the merging cluster the plasma would be the dominant mass component. In this observation, however, one sees that the gravitational potential traces the stellar component rather than the plasma. This is exactly what is expected of a cluster whose mass is dominated by a collisionless dark matter component, behaving in the same way as the stellar component in the collision. The great advantage of this dark matter measurement is that it does not require any assumptions of the dark matter properties. This observation also indicates that the dark matter problem is really due to dark matter and not modifications of gravity; it would be very difficult to modify the laws of gravity in such a way that the gravitational centre do not coincide with the centre of mass of the system.

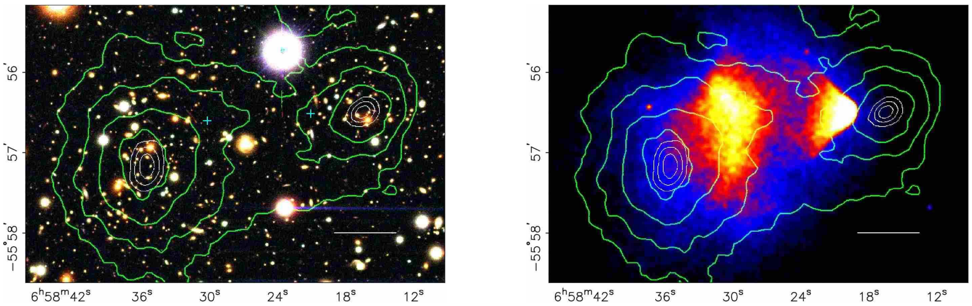

Figure 3: Observations of the cluster merger 1E0657-558, also know as the "bullet cluster". These images show the separation of the dissipationless dark matter from the dissapative plasma. In the left picture shows an image from the Magellian images of the cluster. The left figure is a Chandra X-ray image of the cluster, showing the colliding gas. The green contours shows the weak lensing reconstruction of the mass distribution. The weak lensing map is created using both wide-field ground based images and the Advanced Camera for Surveys (ACS) in the Hubble Space Telescope. The central white circles shows the errors in the measured peak of the mass distribution.

3 Summary

Weak lensing is a rapidly growing field giving rise to new great opportunities in exploring the universe. Weak lensing is also, however, a method in which it is yet not possible to make measurements with high accuracy, which is partly due to our poor knowledge of the universe. Weak lensing could be used as a tool for finding dark massive structures on one hand while on the other hand these unexplored dark structures could add great uncertainties to other weak lensing measurements. Lensing effects of distant galaxies takes into account lensing effects very far away, i.e. long ago, which is useful in cosmological studies but makes things more difficult in studies of individual halo masses. Weak lensing is, however, a complicated but promising field that has not yet reached its full potential. The cosmological implications of weak lensing observations is also a rapidly growing field which, unfortunately, is not discussed in this report.

References

[1] Bergstrom L. & Goobar A. 1999 *Cosmology and particle physics* (textbook)

[2] Schneider P. astro-ph/0509252 v1 9 Sep 2005 *Weak Gravitational Lensing*

[3] Clowe D., Bradac M., Gonzalez A., Markevitch M., Randall S., Jones C. & Zaritsky D. 19 Aug 2006 *A direct empirical proof of the existence of dark matter.*

[4] de Putter R. & White M. 2004 *Using weak lensing to find halo masses.*

[5] Wu J., Umetsu K., Chien C. & Chiueh T. astro-ph/0607542 v1 24 Jul 2006 *How well can weak lensing measure the mass of galaxy clusters?*

[6] Ettori S. & Lombardi M. 2003

[7] Irgens R.J. & Lilie P.B. 2002,597,227

[8] Picture taken by the Hubble telescope, found at: http://hubblesite.org/newscenter/newsdesk/archive/releases/2003/01/image/a

[9] Illustration found at: http://hubblesite.org/newscenter/newsdesk/archive/releases/2000/07/i