Digging into dark matter with weak gravitational lensing

Richard Massey

Institute for Astronomy, Royal Observatory, Edinburgh EH9 3HJ, UK

Abstract. Ordinary baryonic particles (such as protons and neutrons) account for only one-sixth of the total matter in the Universe. The remainder is a mysterious “dark matter” component, which does not interact via the electromagnetic force and thus neither emits nor reflects light. However, evidence is mounting for its gravitational influence. The past few years have seen particular progress in observations of weak gravitational lensing, the slight deflection of light from distant galaxies due to the curvature of space around foreground mass. Recent surveys from the Hubble Space Telescope have provided direct proof for dark matter, and the first measurements of its properties. We review recent results, then prospects and challenges for future gravitational lensing surveys.

1. Introduction

The concordance cosmological model poses a practical problem for observational astronomy. Mounting evidence from many quarters now suggests that five sixths of the material in the universe consists of exotic dark matter: outside the standard model of particle physics. In particular, dark matter appears not to interact via the electromagnetic force, and therefore neither emits, reflects nor absorbs light of any wavelength. Traditional modes of astronomical observations are thus rendered blind.

On the other hand, dark matter is expected to interact via gravity. It helps slow the universe’s expansion out of the big bang, and accumulates matter into the growth of large-scale structure. Its gravitational influence is also its giveaway: even invisible dark matter can be found and studied via its effect on visible particles. The most direct technique, known as ‘gravitational lensing’, studies the deflection of photons from a distant light source, as they pass through gravitational fields (from galaxies, clusters of galaxies or dark matter) along our line of sight. Gravitational light deflection is similar in practice to the effect on light rays by an ordinary glass lens with a refractive index different to that of air, magnifying and distorting an image. In astrophysics, since a source cannot be viewed in the absence of lensing, any net deflection of light is of little observational use. However, if light from two sides of a resolved source are deflected by different amounts, its image appears measurably distorted.

When such distortion is strong, a source no longer resemble astrophysical objects, and observations of individual shapes can be used to infer the intervening gravitational field. An example of ‘strong gravitational lensing’ around a massive galaxy cluster is shown in figure 1. However, most lines of sight through the universe do not pass near such a massive galaxy cluster. Farther from the dense cores of clusters, in the first order limit of ‘weak gravitational lensing’, the
images of background galaxies appear sheared: with their axis ratios typically changed by a few percent. Unfortunately, individual galaxies have intrinsic shapes (elliptical bulges, spiral arms, etc.), which cannot be disentangled from the small distortion. However, even galaxies on adjacent lines of sight are usually far apart in 3D. Their true shapes must therefore be uncorrelated, and the average shape must be a circle. Since the lensing signal is correlated over lines of sight separated by a few arcminutes, if sufficient galaxies can be imaged in that small patch of sky, their intrinsically circular mean shape becomes observably elongated into an ellipse. Noise on this measurement is dominated by the galaxies’ intrinsic shapes, and about 100 typical galaxies are required to bring the signal to noise to unity. This has only been achieved via the high spatial resolution of the Hubble Space Telescope (HST).

To measure the distribution of foreground mass, patterns are sought in the apparent mean ellipticities of many thousands of distant galaxies. As illustrated in figure 2, mass overdensities in front of the galaxies produce a tangential E-mode pattern reminiscent of the tangentially-aligned strong lensing arcs. Foreground mass underdensities or voids produce radial E-mode patterns instead. Usefully, there is an additional degree of freedom in the pattern of ellipticities. Curl-like B-modes are not produced by physical gravitational lensing. However, noise and most instrumental systematics occupy both modes equally. The measured B-mode signal can therefore act as an independent realisation of noise and a warning of residual, uncorrected systematic effects in the desired E-mode.
The statistical signals sought by measurements of weak gravitational lensing are slight but coherent distortions in the shapes of distant galaxies. A tangential, circular pattern is produced around a foreground mass overdensity, reminiscent of the tangential arcs of strong lensing. On much larger scales, an opposite, radial pattern is produced by foreground voids. Physical gravitational lensing produces only these “E-mode” patterns. However, there is another degree of freedom in a shear (vector-like) field, and spurious artefacts can typically mimic both. Measurements of “B-mode” patterns therefore provide a free test for residual systematic defects.

2. Instrumental nuisances

Although the weak lensing shear signal is coherent across several arcminutes, it is still weak. Measuring the tiny distortions in the shapes of distant (therefore small and faint) galaxies requires unusually precise control over imaging quality. For example, the galaxies are inevitably viewed after convolution with the telescope’s Point Spread Function (PSF). For ground-based telescopes, this is dominated by turbulence in the Earth’s atmosphere, and is particularly troublesome. Even from space, diffraction through the finite aperture of the primary mirror blurs the shapes of small galaxies in a manner that can mimic or dilute a weak gravitational lensing signal. Furthermore, HST’s low-Earth orbit also brings it in and out of the shadow of the Earth. Thermal expansions and contractions of only a few microns in its 13m length put it sufficiently out of focus to alter the ellipticity of its PSF, and consequently that of galaxies, by an amount comparable to the weak lensing signal. It is therefore necessary to model the shape of the PSF from stars within each image. Unusually for extragalactic observations, the ideal sky location for a weak lensing survey is therefore not necessarily at the galactic poles.

The cameras currently aboard HST also suffer from a second instrumental problem. Harsh radiation in the orbital environment has damaged the CCD detectors, creating charge traps within the silicon lattice. At the end of each exposure, when photoelectrons are transferred to readout electronics at the edge of the CCD, they can be temporarily captured in these traps and released after a short delay. The main packet of photoelectrons will typically have been moved several more pixels by the time the captured electrons are released. The released electrons therefore produce a trail behind each astronomical object. This mimics the weak lensing signal in sinister fashion. It adds a coherent, spurious ellipticity to each object, and is a non-linear process that affects faint and small galaxies more than bright, large ones. Worse still, because of the particular orientation
of the two CCDs in HST’s Advanced Camera for Surveys, the spurious ellipticity is confined to the $E$-mode signal. Current solutions include the empirical calibration of extra ellipticity in the readout direction. Much effort is also being invested in improved designs for future hardware and data reduction software.

3. Observations

3.1. Large-scale structure

The Hubble Space Telescope COSMOS survey (Scoville et al. 2007) is almost as deep as the Hubble Deep Field, and the largest optical survey ever obtained from space. At 2 square degrees, and containing two million galaxies, it was designed to encompass a contiguous volume of the universe at redshift $z = 1$ containing even the largest expected structures, and at least one example of every type of environment. The single-colour HST imaging is backed up by ground-based spectroscopy of ten thousand (and growing) galaxies, plus multicolour imaging at about forty other wavelengths, from radio, through IR with Spitzer, optical, UV with Galex and X-ray with both Chandra and XMM. As well as accurate measurements of the shapes of galaxies, their (photometric) redshifts are also well understood. The X-ray imaging is also sensitive to hot gas, typically found within dense clusters of galaxies.

Figure 3 shows the observed ellipticities of half a million distant galaxies in the COSMOS field, deconvolved from the PSF and corrected for CTE trailing. Several regions exhibit the circular patterns discussed above. Radial patterns are also present on larger scales, but are much less pronounced because the density contrast in a void is limited by the inability of density to be less than zero. A filter to detect the patterns shown in figure 2 has been run over this data, and the measured $E$-mode signal is presented in figure 4. Contours show the reconstructed distribution of foreground mass: its filamentary structure is apparent. Interesting features include not only the concentrated mass peaks at the vertices of filaments, but also the completely empty voids. The coloured background depicts various tracers of baryons. The general correlation between baryonic mass and total mass is striking. This is natural if the dark matter particles interact via gravity. All particles end in the same place via their mutual gravitational attraction; indeed, since the dark matter begins to forms structures first, it acts as a scaffolding within which baryonic material is assembled.

3.2. Galaxy clusters

A similar picture is obtained from reconstructions of the mass in individual galaxy clusters, which are all enveloped by a halo of dark matter. However, subtle differences between the detailed distribution of baryonic and dark matter reflect their different interaction properties. For example, the inner core profile of the total indicates whether its construction was dominated by a single major merger, or gradual accretion of smaller subhalos. The particularly flat central concentration of mass observed in clusters could be explained by either a low level of (self-)interaction of dark matter particles via the weak force, or by partial free-streaming of ‘warm’ dark matter away from the gravitational potential well. However, this picture is complicated by astrophysical processes and events within
Figure 3. (Left): The observed pattern of coherent ellipticity in background galaxies within the 2 square degree HST COSMOS survey. Each tick mark represents the mean ellipticity of several hundred galaxies; the final analysis uses smaller bins containing about 80 galaxies and improves spatial resolution but adds noise. A dot in this plot represents a circular mean galaxy; lines represent elliptical mean galaxies, with the length of the line proportional to the ellipticity, and in the direction of the major axis. The longest lines represent an ellipticity of about 0.06. Several circular patterns are evident in this figure, e.g. (149.9, 2.5), and the $B$-mode signal is consistent with zero. (Right): The reconstructed large-scale distribution of mass in front of the galaxies. Contours show the total distribution of mass, projected onto the plane of the sky. Like an ordinary optical lens, gravitational lensing is most sensitive to structures half-way between the source and the observer. The reconstruction is thus most sensitive to mass at redshift $z = 0.7$ and, to a lesser extent, all mass between redshifts 0.3 to 1.0. The various background colours depict different tracers of baryonic light. Green shows the density of optically-selected galaxies and blue shows those galaxies, weighted by their stellar mass from fits to their spectral energy distributions. These have both been weighted by the same sensitivity function in redshift as that inherent in the lensing analysis. Red shows X-ray emission from hot gas in extended sources, with most point sources removed. This is stronger from nearby sources, but weaker from the more distant ones. (Figure credit: Nature/R. Massey).

the cluster, such as feedback, where the highly energetic explosions of massive stars purge material from the cluster core. Even dark matter can be affected by this, via the dynamical gravitational influence of ejected baryonic material.

The most interesting of all observed galaxy clusters is without doubt the bullet cluster 1E 0657-56, shown in figure 4. The unusual separation of its constituents provides the most direct evidence that dark matter and baryonic matter have very different properties. The bullet cluster is strictly two clusters that collided recently (about 150 million years ago). Rather like the scattered ejections from a particle collider, the trajectories of the detritus allow us to determine the properties of its initial ingredients. Individual galaxies within the clusters were well-spaced and had a very low collisional cross-section: most continued moving during the collision, and today lie far from the point of impact. On the other hand, hot intra-cluster gas was uniformly spread throughout the incident clusters. This had a large interaction cross-section and – like a cosmic car crash – was slowed dramatically by the collision. The two concentrations of gas, seen in X-ray emission, have now passed through each other, but have not travelled far from the point of impact. Interestingly, the collision speed and
Figure 4. The “bullet cluster” 1E0657-56 and “baby bullet” MACSJ0025.4-1222. The background images show the location of galaxies, with most of the larger yellow galaxies associated with one of the clusters. The overlaid pink features show X-ray emission from hot, intra-cluster gas. Galaxies and gas are baryonic material. The overlaid blue shows a reconstruction of the total mass from measurements of gravitational lensing. This appears coincident with the locations of the galaxies, implying it has a similarly small interaction cross-section. However, there is far more mass that that present in the stars within those galaxies, providing strong evidence for the existence of an additional reserve of exotic dark matter. (Figure credit: X-ray: NASA/CXC/CfA/ M.Markevitch et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al. Optical image: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Right: NASA/ESA/M. Bradac et al.).

gas density were sufficient for a shock front to be observed in the gas from the smaller of the two clusters, allowing the determination of the collision speed$^1$.

Crucially, gravitational lensing observations require an additional ingredient in the bullet cluster. A great deal of extra mass ($\sim 30 - 40 \times$ that seen in the galaxies’ stars) is located near the galaxies, and $8\sigma$ away from the gas peaks. This mass clearly had a very low or zero collisional cross-section, but exhibits a usual gravitational influence. Indeed, it behaves exactly like predictions of dark matter. Measurements of its interaction cross-section, incorporating the observed collisional speed, rule out even minimally self-interacting dark matter models that could have explained the flat mass profiles in cluster cores.

The visible separation between the three ingredients of each cluster is temporary. Within another billion years, the mutual gravitational attraction of the galaxies, gas and dark matter will have pulled them back together. They will spiral ever closer together until they resume the usual configuration of baryonic material within a larger dark matter cocoon.

$^1$One interesting controversy surrounding the bullet cluster has recently been resolved. The X-ray shock front at first suggested a collisional speed at the point of impact that would be a $5\sigma$ outlier in the range of speeds expected for such events: an unusually high figure to explain via individual peculiar motions. However, more recent calculations took into account the acceleration of the smaller cluster towards the larger and the relative motion of the gas clouds in the rest frame of the smaller cluster. With these calculations, the apparent velocity implied by the shock front is not unusual but merely high. Furthermore, the shock front that led to the discovery of this object would not have been seen for a low-speed collision.
3.3. Galaxy groups and individual galaxies

The gravitational lensing signal is weaker around the less massive dark matter haloes around individual or small groups or galaxies. However, stacking the signal from many haloes in the large SDSS and COSMOS surveys has consistently revealed a consistent central density peak of baryonic mass, inside a halo of dark matter that exhibits several distinct components. Haloes are most pronounced around red galaxies with older stellar populations but, for a given morphological type, appear to have changed very little since redshift \( z \sim 0.8 \).

4. Future opportunities

4.1. Interesting theoretical challenges

To draw useful conclusions, or constraints on cosmological parameters, weak lensing measurements must be compared to either the distribution of baryonic material or to theoretical predictions. Weak lensing measurements are made on small scales, where the signal is strongest because mass clumps and density grows non-linearly. However, these scales are also the most difficult to model in \( n \)-body simulations because of ‘gastrophysical’ processes; and simulations featuring modified theories of gravity are barely possible. Observations are approaching the current precision of theoretical models and, if future uncertainty is not to be dominated by the inability of theories to predict the signal, advances in computational cosmological modelling must proceed apace.

A significant image analysis challenge is posed by the precision required in the measurement of faint galaxy shapes – even from high resolution, space-based images with a small PSF. A world-wide collaboration of the weak lensing community has recently tested the performance of existing methods in the Shear TEsting Programme (STEP). Simulated astronomical images containing an artificial weak gravitational lensing signal were analysed blindly, such that entrants did not know the input signal when they ran their methods, but could compare to it later. Sufficient precision was demonstrated for current surveys. However, significant advances will be required as larger surveys are obtained, with potentially smaller statistical errors. Improvements are ongoing. To recruit expertise from statistical inference and computational learning fields, STEP has now evolved into the GRavitational lEnsing Accuracy Testing 2008 (GREAT08) and 2010 (GREAT10) challenges.

Insufficient work has focused on correcting measurements of weak gravitational lensing for the Charge Transfer Inefficiency of CCD detectors damaged by harsh radiation in orbit. Empirical calibrations have attempted to quantify the spurious changes in photometry, astrometry and shape measurement that are induced by the trailing of charge. Some pipelines have also been developed to take an imperfect, observed image then move charge back to where it belongs, pixel by pixel. This is the ideal approach, and should be the first step in an ideal data reduction pipeline since the trailing is created during CCD readout, the last process to happen on chip. However, current algorithms have concentrated on long trails from species of charge trap that affect photometry more than morphology. It remains unclear how well such techniques can be applied to correct short trails that alter an object’s shape.
4.2. Construction of dedicated missions

To limit the impact of the PSF on distant galaxy shapes, weak lensing needs to be observed from above the Earth’s atmosphere. Initial surveys have developed into a mature field with the Hubble Space Telescope. However, the current state of weak lensing measurements is rather like that of the CMB before WMAP: a series of measurements all roughly consistent, but showing only a hint of the high precision cosmology that could be possible. HST (and even JWST) is limited by its small field of view. The HST COSMOS mosaic of six hundred adjacent images maps one representative region of the sky, but is merely a proof of concept. Several efforts are proceeding in earnest to construct a wide-field imager on a high altitude balloon (HALO) or in space (Euclid/JDEM/IDECS). Designed for thermal stability and resistant to radiation damage, these will map the entire sky at high precision, revealing our location in the much larger cosmic web, and directly track the growth of structure in our expanding universe.

5. Conclusions

Weak gravitational lensing has long been postulated as a unique way to probe the large-scale gravitational fields of the universe, and serious attempts to detect it have been made since the 1980s. However, it was only with the advent of large-format CCD cameras around 2000 that the tiny signal was first detected. Indeed, the detection was so dependent upon technological innovation that four groups independently reported detections in that one year. Further recent progress in wide-field camera technology has rapidly advanced the field: in only nine years, weak gravitational lensing has become an accepted staple of cosmological tests, with detailed plans for dedicated balloon and space missions. It represents a unique way to probe the distribution of mass in the universe, free of the usual reliance upon (often biased) tracers of electromagnetic radiation. Interesting challenges remain to be solved in theoretical computation, practical image analysis, and engineering design. Yet weak lensing appears to have a bright future as a mature astrophysical and cosmological tool.

References

Bradac M., et al., ApJ 652, 937 (2006)
Bridle S. et al., AOAS submitted, arxiv:0802.12.14 (2008)
Clowe, D. et al., ApJL, 648, 109 (2006)
Heymans C. et al., MNRAS 368, 1323 (2006)
Johnston D. et al., ApJ submitted, arXiv:0709.1159 (2007)
Massey R. et al., MNRAS 376, 13 (2007)
Massey R. et al., ApJS, 172, 239 (2007)
Massey R. et al., Nature, 445, 286 (2007)
Refregier A., ARA&A, 41, 645 (2004)
Rhodes J., et al., ApJS, 172, 203 (2007)
Sand D., Treu T., Ellis R., Smith G. & Kneib, J.-P. ApJ, 674, 711 (2008)
Scoville N., et al., ApJS, 172, 38 (2007)
Schneider, P. 2005, Gravitational Lensing, Springer-Verlag, Berlin, 273