GRAVITATIONAL LENSING AS A COSMOLOGICAL PROBE

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Gravitational Lensing is an efficient tool to probe: the mass distribution of collapsed systems: galaxies and clusters; high redshift objects thanks to the gravitational amplification; and the geometry of the Universe. I will review here some important aspects of lensing and related issues in observational cosmology.

1 Introduction

Geometry of Space-Time depends on its mass content, therefore the wave-front of cosmologically distant sources, traveling through the Universe, will be curved by any mass fluctuation en-route. The more concentrated the mass fluctuation along the light-of-sight the larger the distortion of the wave front. For collapsed systems like galaxies or galaxy clusters the ‘angular’ mass column-density in the central region is high enough (larger than $\Sigma_{\text{crit}}$) to ‘break’ the wave-front into multiple wave-fronts leading to a multiple number of images. The multiple wavefronts, reach us at different times, the time delay ($t_d$) between images is proportional to angular distance and hence to the Hubble constant $H_0$. In the outer parts of collapsed systems, the ‘angular’ mass column-density is much smaller (smaller than $\Sigma_{\text{crit}}$) and the wave-front is only slightly distorted, thus the signature of the mass is detected by a gravitational-shear of the background images. Only distant mass concentrations will act as lenses as the wave-front distortion gets larger when propagating to larger distances through the Universe. Lensing is sensitive to the mass, expansion factor and distances, it is thus a perfect cosmological tool.

This review is observationally motivated and will focus on two main areas: Field Lensing where the targeted gravitational structures are galaxies and Large-Scale-Structure (LSS), and for which field/all-sky surveys are the primary source of data; Cluster Lensing where the cluster mass distribution can be measured accurately and can then be used to probe the high-redshift Universe thanks to gravitational amplification.

2 FIELD LENSING – From Strong to Weak

2.1 Golden Lenses – the Perfect Lenses

Golden lenses are those lenses for which time-delays are or can be measured accurately, and given a physically motivated mass model the value of $H_0$ can be
estimated. Three systems currently deserve this honour:

- **Q0957** ($H_0 = 61, \varepsilon_{td} \sim 1\%, \varepsilon_{model} \sim 10\%$)
- **PG1115** ($H_0 = 53, \varepsilon_{td} \sim 10\%, \varepsilon_{model} \sim 15\%$)
- **B0218** ($H_0 = 70, \varepsilon_{td} \sim 25\%, \varepsilon_{model} \sim 30\%$)

More systems are potentially gilded, but although deriving a simple mass model can always be done, the critical part is the measurement of the time-delay. Kundic et al. have demonstrated that such a precise measurement is feasible, and we can hope for a handful of measurements in the years to come, which will then provide a cosmological estimate of the Hubble constant.

### 2.2 Dark Lenses – Mysteries?

**Dark lenses** are lenses with unusually high Mass-to-light ratio (M/L) derived either from wide separation images and/or the lack of optical/IR detection of the stellar component of the primary lens. Recently 3 dark lenses have been examined in detail:

- **MG2016** (the dark cluster): Hattori et al. have detected using ASCA/ROSAT a $z_Fe \sim 1$ X-ray cluster. However, galaxies seem to be missing from the cluster compared to its X-ray luminosity;
- **Cloverleaf**: Kneib et al. have detected an overdensity of red galaxies within 15$''$ of the quad - suggesting the existence of a $z \sim 1.7$ cluster, this could help to explain why the primary lens has not been detected yet; **Q2345+007** (a complex puzzle): Bonnet et al. reported a weak shear field near the double QSO more or less centered on Pelló et al. cluster candidate at $z_{photom} \sim 0.7$, however no rich cluster-like X-ray emission has been detected with ROSAT and ASCA (Hattori, priv. com.) in this field. Fisher et al. find clues of $z \sim 1.5$ galaxies near the double-quasar. However, adding all these pieces of evidence, does not produce a simple explanation - is it really a lens system or a physical pair?

### 2.3 Search for New Multiple-Images Systems – More Lenses!

Searching for a larger and possibly un-biased sample of multiple image systems is an important task to increase the sample size which will allow us to: • better understand the mass distribution of lenses; • increase the number of possible golden lenses; • enable statistical analyses of lenses.

The JVAS/CLASS surveys analysed more than 10000 flat spectrum radio-sources, and find 12 probable lenses, which are currently being studied at higher resolution in the radio and in the optical wave-bands to identify the deflector and determine the redshift of the lens and source. Extension of this survey to wide-separation multiple-images is currently in progress (see Marlow this conference). Radio selection is probably the most efficient and un-biased provided we have a good understanding of the redshift distribution of these sources.
An unexpected result is that new lenses discovered have been classified as Spirals or S0s (e.g. B1600, B0218). This new discovery has motivated the development of a number of new lensing models for spiral galaxies (see also Koopmans this conference).

2.4 Deep Imaging and Spectroscopy – Unveiling the Complexity

As underlined above, studying the environment of lenses can be of great importance in mass modelling. Both deep multi-wavelength (X-ray, optical, IR) high-resolution imaging (e.g. NIC2/WFPC2 Falco dataset) and spectroscopy are therefore of prime importance. Spectroscopy of the surrounding galaxies has been undertaken, and surprisingly, in 3 cases a group of galaxies has been detected: PG1115 N_gal = 5, \( \tau \sim 0.33 \), \( \sigma_{los} \sim 300 \text{ km/s} \); B1422 N_gal = 6, \( \tau \sim 0.34 \), \( \sigma_{los} \sim 600 \text{ km/s} \); HST14176 N_gal = 10, \( \tau \sim 0.81 \), \( \sigma_{los} \sim 450 \text{ km/s} \). Similar spectroscopic investigations are currently underway in other systems, namely MG2016, Q2345 and Q0957.

2.5 Mass Distribution – Toward the Solution

Keeton, Kochanek & Seljak show that quads are best modeled by the sum of an elliptical Singular Isothermal Sphere (SIS) mass model and an additional component of pure external shear. However, in some cases there is a discrepancy between the orientation of the light and the mass. Besides, the magnitude of the modeled external shear is too large to arise from LSS fluctuations, but it is likely the results of:

- the primary lens (if \( \rho \) is steeper [resp. flatter] than a SIS then the shear is smaller [resp. larger] than a SIS model), however the change of slope can not easily account for the orientation discrepancy;
- nearby galaxies in a group or a cluster, can easily account for the external shear and the orientation discrepancy.

The number of constraints for a simple multiple-image system goes like \( C(N - 1) + L \), where \( C \) is the number of parameter per image (C=3 for a quasar), \( N \) the number of multiple images (N=4 for a quad, N=2 for a double), \( L \) the number of external constraints on the lens - the stellar component - (center position, ellipticity, orientation, profile). Obviously, quads are much preferred specially when the stellar component is observed (L large). It is important to increase the number of free parameters - in particular the mass profile of lenses - to match the high quality of data now available in optical (HST) and in radio (MERLIN), however the model solution has to remain physically motivated and should include the stellar component. Saha & Williams recently proposed an alternative non-parametric modeling based on linear programming, where the mass distribution is ‘pixelised’. Although, it does indeed increase
the number of parameters, the current technique suffers from the fact it allows too many degrees of freedom, compared to the available number of constraints.

2.6 The Case of HST14176

The HST14176 multiple system has been found among HST/WFPC2 survey of field galaxies - where we expect roughly 1 such system within $\sim 100$ arcmin$^2$. The lens is a $z = 0.81$ elliptical galaxy ($M_B = -22.9$), the source is at $z = 3.4$.

Hjorth & Kneib modelling consistently the stellar and dark component, as well as surrounding galaxies, are able for the first time to put an upper limit (maximum light hypothesis) on the stellar $M^*/L_B < 2.5 h_{50}$ and on the expected stellar line-of-sight velocity dispersion $\sigma_{\text{los}} < 270 \text{km/s}$. Folding this result into the Fundamental Plane, allows the computation of an independent measure of the evolution of elliptical galaxies, which is compatible with synthetic evolution model of elliptical galaxies. That particular example demonstrates that detailed modeling of a particular system can be of great interest.

2.7 Galaxy-Galaxy Lensing – Mass Profile at Large Radius

Distant galaxies not aligned with the lensing galaxy, will not be multiply imaged but will suffer a small distortion by the lens. The high density of faint galaxies allows us then to probe in a statistical way the mass, and mass profile of an ‘average’ galaxy to larger distance ($\sim 100 h_{50}^{-1} \text{kpc}$) compared to multiple images which mainly concentrate on the $\sim 1$ to $\sim 20 h_{50}^{-1} \text{kpc}$ range. It is only recently that observations have been successful to detect this effect. The main limitation in this technique is the errors in the determination of shape parameters of faint (distant) galaxies, the unknown redshift distribution of galaxies, the adopted scaling laws and finally the limited size of the sample. Schneider & Rix proposed a maximum likelihood method to consistently take into account the effect of multi-plane and multi-deflector lensing. An improvement of this method (that takes into account detection noise) is in progress by Ebbels, Kneib & Ellis and is applied to a large HST/WFPC2 archival dataset, which includes $\sim 250$ measured redshifts for the brightest galaxies. The mass derived is consistent with dynamical estimates in the central part, and requires extended dark halo, although its extent is currently not well constrained.
2.8 Large Scale Structure – Yet to Be Detected

Although, we do expect weak gravitational shear from LSS, the expected signal on degree scale is of the order of 2 to 5% depending on the cosmology. Its small amplitude have precluded up to now any secure and positive detection. The no-detection is in turn triggering a great deal of efforts: • to find the best estimator that can constrain both the power spectrum and the cosmological parameters; • to determine the best method to detect/correct the weak shear signal; • and to develop efficient wide-field mosaic-CCD cameras.

Two strategies can be followed to measure LSS weak shear signal: • observe a wide contiguous field (of the order of a few square degrees), and extract the power-spectrum of mass fluctuations, from small to large scales; • observe random fields deep and wide enough to beat the noise of the width of the ellipticity distribution and allow a significant measure of a mean gravitational shear on each individual field. The mean shear statistics in the various fields can then be folded to constrain the mass power-spectrum at the observed scale.

3 CLUSTER LENSING – The New Area

3.1 Multiple-Images Modelling – Understanding Cluster Cores

The discovery in the late 80’s of giant arcs (results of the merging of faint galaxy multiple images on a critical line) in cluster cores opened a new window for lensing investigation. It was quickly understood that multiple-images are key constraints on the central mass distribution of cluster-lenses. Furthermore if the redshift of one giant-arc/multiple image is known then the mass can be calibrated in an absolute way. Therefore, the redshift of any other multiple-images can then be estimated as their angular separation is a function of their redshift. The mere existence of these gravitational arcs lead to the demonstration that cluster total mass profile require a small ‘core radius’.

The first cluster-lens images acquired with the HST/WFPC2 camera unveiled the complex nature of the mass distribution in the cluster core: indeed any bright (typically L* or brighter) galaxies contribute importantly to lensing effects by increasing the multiplicity of some images and slightly changing the location of others. The large number of multiple-images revealed by HST (thanks to its high-resolution) allow us to reconstruct a detailed mass distribution that include not only the cluster mass but also cluster-galaxy halos. The detailed theoretical interpretation was first presented by Natarajan & Kneib who furthermore show that the galaxy-galaxy lensing approach can
be extended to cluster-field. The converging picture of cluster-core is a global M/L_V (< 300 h^{-1} Mpc) = 140 ± 20 h_{50} for the cluster and M/L_V = 12 ± 5 h_{50} for galaxy halos (see also Natarajan - this conference for a more extended discussion). These results compare nicely with the recent high-resolution numerical simulations of galaxy clusters (e.g. Moore et al this conference).

3.2 Cluster Weak Lensing – mass profile at large radii

It is now well known that weak gravitational shear of clusters can be inverted to obtain mass estimates of clusters and a wealth of observations have detected the signal in many different clusters e.g. Cl0024, MS1224, A2218, A2390, A2163, A1689, Cl0939 (see also Van Kampen et al this conference).

The requirements for successfully using weak lensing to constrain the mass distribution are the following: • high resolution images (HST or sub-arcsec seeing ground based images); • wide field camera; • deep images in order to increase the number density of faint galaxies; • and a good understanding of the ellipticity correction that would otherwise easily induce an under- or over-estimate of the total mass.

The main results are: • mass profile is compatible with ρ ∼ 1/r^2; • M/L(< 1 h_{50}^{-1} Mpc) ∼ 200 h_{50}, but in some cases one gets M/L ∼ 300-400.

The new developments are: • to probe mass of galaxy groups • to probe the central mass profile in low-z clusters; • to probe structures between medium-z clusters; • to weight high-z clusters to constrain cluster evolution and the mean redshift-distribution of faint galaxies.

3.3 Comparison with Other Mass Estimates: X-ray and Dynamics

Miralda & Babul noticed that lensing and X-ray estimate within the arc-radius differs significantly by a factor of ∼ 2. This discrepancy can however easily be resolved when proper careful lensing and X-ray analysis are performed. Allen, Fabian & Kneib have shown that in the cooling-flow cluster PKS0745, multi-phase X-ray model does agree with the lensing mass estimate but a simple X-ray mass model would be discrepant by a factor of 2–3). Allen has further extended this comparison to a larger set of clusters. X-ray cooling flow clusters with a multi-phase model do agree with lensing mass estimates. For non-cooling flow clusters however, one has to require the total mass to have a smaller core radius than one expected from the X-ray data to match the lensing mass estimates. Clearly, a systematic and detailed study will enable a better understanding of the ICM and its dynamical state.
HST observations are and will be (specially with the forthcoming Advanced Camera for Survey) ideally suited to study the physics of galaxy clusters when combined with the upcoming generation of X-ray telescopes (AXAF/XMM). Natarajan & Kneib have shown that lensing can help to understand the dynamics of galaxies in the global potential well. The velocity anisotropy can be recovered showing evidence for the nature of orbits in the virialized core, as well as orbits in the outskirts.

3.4 Cluster as Low Resolution Spectrograph – Distance of Faint Galaxies

The probability redshift distribution of an arclet for a given mass of the cluster and the shape of the arclet depends only on the ellipticity distribution of faint galaxies: the larger the redshift, the larger (in general) the deformation induced by the cluster. From a secure mass distribution defined by a few sets of multiple-images, we can then estimate the likely $z$ of arclets behind well constrained clusters. This is most interesting as this method is purely geometrical and therefore does not suffer from the spectroscopic bias that provides redshifts only for those faint galaxies with (strong) optical emission lines. To evaluate the accuracy of this technique on a cluster-lens A2218 Ebbels et al. have successfully measured on WHT the redshift of 19 arclets providing a first confirmation of the lensing method. Similar work is now in progress in other cluster lenses such as A2390 and AC114.

3.5 Statistical Analysis

The number of arcs/arclets behind cluster cores is a complex function of the detailed mass distribution, and the evolution of faint galaxies. On an individual cluster-basis, if the mass distribution is well understood, (granularity in the mass distribution can dramatically change counts of arclets, in a redshift dependent way) the statistics of arclets can be a possible way to constrain galaxy evolution and in particular puts limits on the UV emission of distant galaxies - providing we understand correctly the surface-brightness and detection biases.

Using a cluster sample, the number of arcs/arclets will be sensitive to cluster masses (therefore on cluster evolution which critically depends on the density parameter $\Omega$) and the volume element (i.e. the cosmological constant $\lambda$) (see Bartelmann & Bahcall this conference for a more complete discussion). Therefore, counting arcs in clusters may constrain models of cluster evolution and therefore the values of cosmological parameters.
3.6 Probing the Distant Universe – New Windows

Cluster-lenses offer a large amplification (typically 1 to 2 mag) over a few arcmin$^2$. Hence these clusters can be used as telescopes to probe the distant Universe, and detect sources that would otherwise be extremely difficult to detect. A particular application is the detection of ‘normal’ distant $z > 2$ galaxies behind clusters: $z = 2.24$ (Cl2244), 2.55 (A2218), 2.72 (MS1512), 3.33 (Cl0939), 3.98 (Cl0939), 4.05 (A2390), 4.92 (Cl1358). Another promising avenue is the first identification in yet unexplored windows like IR/sub-mm/mm bands of distant $z > 3$ objects – because we do expect to detect redshifted dust-emission from these distant galaxies. A first tentative application in sub-mm has been recently presented by Smail, Ivison & Blain.

4 Future and Prospects

Thanks to improvement in lensing techniques and deeper, wider, higher-resolution images, lensing is rapidly becoming a useful tool to weigh the Universe (from small to large scales), probe the distant Universe and constrain the evolution and its fundamental parameters.

In the years to come we might have: a lensing estimate of $H_0$ with 2 significant digits; a lensing estimate of $\Omega$ with 1 significant digit and an upper limit on $\Lambda$; a good knowledge of the mass distribution of collapsed systems (galaxies and clusters), and therefore the physics of the ICM as well as the mass exchange between cluster and galaxies; some constraints on the mass power spectrum; a better understanding of the redshift distribution of faint galaxies and their evolution; a better view of the distant Universe and its dusty galaxies.

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