Scientific Project

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1 Introduction

For a few years, observational cosmology has been collecting an increasing number of constraints on theoretical models for the universe. In particular, the recent outstanding results of WMAP satellite together with observations of SNIa, clustering of galaxies, Lyα forest and cosmic shear seem to converge toward a "concordance" model for the universe (*e.g.* Spergel et al., 2003), a flat Λ dominated cosmology with a large amount of cold collisionless dark matter. This common picture provides a comprehensive scheme for the universe, from its earliest stages to highly evolved structures such as present-day galaxies and their content. The dark side of such a success is that the actual ΛCDM paradigm requires 70% of unknown Dark Energy and 30% of unknown Dark Matter.

Yet, this general scenario still requires important validations on galaxy scales or below. The history of galaxy formation and the global interplay between dark matter and baryons are not definitively solved. For instance, the density profile of dark matter halos is still under debate. This so-called cusp-core problem requires detailed modeling, including rotation curves of galaxies, dynamics, X-rays and SZ properties of clusters (*e.g.* de Blok et al., 2001; Katgert et al., 2003; Kelson et al., 2002; Romanowsky et al., 2003). In this context, observations and analyses of gravitational lensing effect are quite crucial because they can probe the structures without prior assumptions on the dynamical state of the systems. Precisely for this reason, gravitational lensing has become one of the most promising tool for analyses of the various mass contents in the universe.

My PhD work has been devoted to the development of weak and strong lensing tools together with applications to the study of dark matter halos and their relation to the light distribution (clusters and wide field surveys). This project is organized as follows. In section 2, I briefly summarize the basis of gravitational lensing and its current status. Section 3 describes my PhD work. Possible outlooks and future projects are exposed in section 4. Section 5 concludes.

2 Gravitational lensing current status

This section provides a brief summary of the state of the art of gravitational lensing. (For more exhaustive reading, see *e.g.* Schneider, Ehlers, & Falco, 1992; Mellier, 1999; Bartelmann & Schneider, 2001). Gravitational lensing is a rather new topic of modern observational cosmology. Multiple QSOs analysis has emerged during the 80's. After that, strongly lensed galaxies in clusters were developed during the 90's and followed by pioneering weak lensing detections in clusters of galaxies. Since 2000, cosmic shear on wide field surveys is becoming a new probe of the large scales structures of the universe.

The fact that gravitational lensing is directly sensitive to the whole gravitational potential,

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regardless of the matter nature or dynamical state, makes lensing the ideal tool for dark matter investigations and CDM tests. Besides, strong lensing also acts as a natural telescope and one can scan the vicinity of critical lines in order to find magnified high redshift galaxies (Pelló et al., 2001).

These properties give lensing the possibility to address several important issues of modern cosmology like the large scale distribution of dark matter (cosmological parameters, biasing...) and tests on the large scale behavior of gravity (as proposed by brane world cosmologies) or dark energy/quintessence models and as a consequence to put more constraints on the ΛCDM model.

Besides the rather specific microlensing topic that mainly concerns stellar astronomy, gravitational lensing activities are generaly split into two distinct regimes : strong and weak lensing.

2.1 Strong Lensing

Strong lensing regime occurs when the deflector convergence is so high that multiple images of the same source are observed. In most cases, one is interested in constraining lenses parameters that are consistent with observed images and the unicity of the underlying source.

A particular area, in which lens is a foreground galaxy and source is a background QSO, has early been focusing on detailed modeling of lenses allowing to puts constraints on the Hubble constant using time delays, on perturbing substructures (micro/milli-lensing) (*e.g.* Kundic et al., 1997; Wambsganss et al., 2000; Kochanek, 2002; Kochanek & Dalal, 2003). Moreover, statistics of multiple QSOs – in terms of angular separation between components or in terms of occurrence frequency – are strongly dependent of cosmological parameters and provide complementary tests. So far, theses analyses do not match well the ΛCDM paradigm (*e.g.* Chae et al., 2002).
On the other side, people has been interested in strong lensing of background extended galaxies by foreground clusters of galaxies. Multiple arcs of multiple sources at different redshifts strongly constrain the mass distribution in the central parts of clusters (Smail et al., 1996; Smith et al., 2001; Gavazzi et al., 2003). For this purpose, radial arcs play a unique role. A promising research field is the simultaneous use of strong lensing at the center and weak lensing outward in order to constrain density profiles over many radial magnitude ranges (Gavazzi et al., 2003; Kneib et al., 2003). Also, central demagnified images currently predicted by modeling of outer arcs are not definitively observed but could provide important hints on the cusp-core debate. Like statistics of multiple quasars, statistics of arcs may probe cosmological models (Bartelmann et al., 2003).

2.2 Weak Lensing

The nature of weak lensing is statistical because weak tidal shear effects only show up across ensemble averages of background sources. Since the pioneering applications that were made on clusters of galaxies, a flourishing set of deflector mass scales have been investigated, from galaxies (Galaxy-Galaxy lensing) (Brainerd et al., 1996; Hoekstra et al., 2003) and superclusters of galaxies (Kaiser et al., 1998; Gavazzi et al., 2004) to even larger scale structures of the universe (*e.g.* Van Waerbeke & Mellier, 2003, and references therein). Moreover, weak statistical magnification effects can now be performed in the same way (Ménard et al., 2003). Together with cosmic shear measurements, it is now possible to put constraints on cosmological parameters (σ_8, Ω_m), dark matter power spectrum and galaxy biasing (Hoekstra et al., 2002).

A common observational feature of weak lensing is the compelling systematics subtraction process and the need of deep wide field observations. Many efforts have been devoted to PSF smearing correction. The increase of sources samples is followed by an increase of systematics-to-noise ratio. Therefore, a better control of systematics is a crucial task for future surveys. Another requirement is a good knowledge of redshift distribution of sources and lenses down to deep magnitudes. Such a prescription implies multiband photometry and has historically boosted photometric redshifts development (*e.g.* Athreya et al., 2002; Gavazzi et al., 2003).

The intrinsic high noise level of weak lensing analyses that aim at measuring fainter and fainter signal nowadays prohibits further investigations of individual clusters of galaxies but rather implies large statistical approaches within wide surveys such as the CFHTLS[1].

3 My contributions

During my PhD I have mainly been working on gravitational lensing (either strong or weak) of clusters of galaxies. My work has been balanced between data processing/modeling, software development/validation and physical interpretation within a cosmological/extragalactic framework. The two first subsections resume my published or submitted papers. The third subsection presents my developments of codes dedicated to weak lensing analysis and thoses related to strong lensing. The last subsection details the independent analyses I plan to achieve/write up within the following months.

3.1 Strong (+Weak) lensing application : MS2137-23 galaxies cluster

This work (Gavazzi et al., 2003) has been published in A&A and a special application to MOND phenomenology is proposed in (Gavazzi, 2002). Here I report a brief summary of main results.

Using HST/WFPC2 imagery, we performed a strong lensing modeling of MS2137 tangential and radial arcs systems. We challenged core radius elliptical isothermal profiles with elliptical Generalized NFW (Navarro et al., 1997; Wyithe et al., 2001) density profiles in order to derive a range of inner slope for dark matter halo consistent with the data at hand. We also used VLT/FORS2 UBVRI and VLT/ISAAC JK wide field imagery to get larger scale information of density profile through weak lensing analysis. The large number of filters allowed precise photometric redshifts estimates of background weakly lensed sources and especially of arcs. These latter have also been spectroscopically confirmed (Sand et al., 2002). We also reported a marginal detection of the central demagnified image associated to the tangential arc system. Its detection is still controversial and further data in UV would be needed to give definitive conclusions.

Nevertheless, both softened isothermal profiles and GNFW profiles with an inner slope range $0.8 \lesssim \alpha \lesssim 1.2$ are consistent with the data at hand. The fifth demagnified image might give discriminative additional constraints. Kinematic information of stars inside the central cD galaxy provides an additional strong constraint that has been used by Sand et al. (2003) to conclude that the inner slope shall be $\alpha \simeq 0.5$. Such a conclusion has recently been refuted (Bartelmann & Meneghetti, 2003; Dalal & Keeton, 2003) because they neglected the potential ellipticity. In a forthcoming paper (Gavazzi & Miralda-Escudé, 2004, in preparation), we plan to show that velocity dispersion data have to be used with caution. In particular, the distribution function of stars is far from Maxwellian and neglecting this highly biases velocity dispersion estimates like those published in Sand et al. (2003). We demonstrated that the bias is more important than statistical observational uncertainties implying that estimates of these authors dramatically have to be corrected and inferred values of α to be increased toward $\alpha \approx 1$.

3.2 Weak lensing application : MS0302+17 supercluster of galaxies

This work has been submitted to A&A and is available on astro-ph/0401403[2].

We investigated the supercluster MS0302+17 ($z \approx 0.42$) using weak lensing analysis and deep wide field BVR photometry with the CFH12K camera. Using $(B-V)$-$(V-R)$ evolution tracks we identified supercluster early-types members and foreground ellipticals and derived a R band

[1] http://www.cfht.hawaii.edu/Science/CFHLS/left.html
[2] http://www2.iap.fr/users/gavazzi/publications/ms0302.ps.gz

background galaxies catalogue for weak lensing analysis. We computed the correlation functions of light and mass and their cross-correlation in order to test if light from early-type galaxies traces mass on supercluster scales. We showed that the data at hand are consistent with this assertion. The ζ-statistics close the cluster centers and global correlation functions analysis on the whole field converge toward the simple relation $M/L = 300 \pm 30\, h_{70}\,(\mathrm{M/L})_\odot$ in the B band. This independent work confirms and strengthens the results of Kaiser et al. (1998).
We also modeled dark matter halos around each early-type galaxy by a truncated isothermal sphere and found that the linear relation $M \propto L$ still holds. However, averaged dark matter halos truncation radius have $s_* \lesssim 200\, h_{70}^{-1}$ kpc close to clusters cores, whereas s_* reaches a lower limit of $\sim 300\, h_{70}^{-1}$ kpc at the periphery of clusters. This change of s_* as a function of radius and local density may give indications on tidal stripping processes. Nevertheless, these results for s_* depend on prior assumptions on scaling relation between mass, light and velocity dispersion.
Therefore we concluded that mass is traced by the light from early-type galaxies. We were not able to describe in detail the contribution of late type galaxies because of a lack of depth-color-redshift information. Their contribution is however found to be small as compared to that of early-types. Only larger surveys obtained in the future, like the CFHTLS, will offer the possibility to estimate the contribution of late type galaxies.

3.3 Development of lensing tools

During my DEA (French master's degree) research training and the beginning of my PhD, I got a good knowledge of `lenstool` facilities (Kneib, 1993) and mainly `lensmodel` (Keeton, 2001) ray-tracing inversion softwares. I also contributed to the implementation of weak lensing capabilities into the latter. My work on strong lensing using `lensmodel` has been followed by developments of visualization tools. My experience in strong lensing modeling of arcs[3] has convinced myself that an iterative sequence of { identify conjugate patterns within arcs, adjunction of these news constraints, χ^2 minimization } requires good visualization tools. Such facilities are also essential when seeking new multiple images through the field of view using an assumed lens model. At the moment, I am constructing a personal ray-tracing inversion tool. It shall include three-dimensional informations (like triaxial halos) and have a modular design in order to easily integrate additional constraints like dynamics of stars in BCGs, dynamics of galaxies, X-rays and SZ properties of ICM, etc...

In addition, some personal contributions to the development of weak lensing tools are:

- From catalogues generated by either `SExtractor` or `Imcat`, I developed a weak lensing processing pipeline based on `F90` codes and `perl`, `awk` or `shell` scripts. The pipeline includes stars-galaxies discrimination handling, PSF correction based on the Kaiser et al. (1995) (KSB) method and plotting facilities. The PSF correction process fully handles masking schemes on individual chips and provides a direct weighting scheme for further weak lensing analysis.
- General tools like mass (or aperture mass) reconstruction algorithms based on Kaiser & Squires (1993) or maximum likelihood inversions (Bartelmann et al., 1996). One can also mention codes that estimate the radial shear profile, fit parameterized models using maximum likelihood methods (Schneider et al., 2000).
- Facilities for correlation analyses (basically designed for cosmic shear). These codes calculate correlations functions like $\xi_{+/-}$, $\xi_{T/X}$, $\langle M_{\rm ap}^2 \rangle$, $\langle |\gamma|^2 \rangle$, $\langle \kappa^2 \rangle$, or $\langle \gamma_T \rangle$ for galaxy-galaxy lensing purpose. This correlation analysis tool is followed by bootstrap algorithms in order to handle errors.
- Note that most of the codes are written in `F90` and parallelized with `OPENMP` directives. However, I plan to fully implement them in `C` with `MPI` directives better suited for hardware commonly used in data processing.

[3]that shall include a large number of morphological details

I plan to invest the latest months of my PhD on weak lensing data processing using alternative PSF deconvolution schemes. This shall be a prospective work largely independent of those already started/achieved. It would consist of testing PSF corrections algorithms applied on a wide CFH12K field centered on the CL0024+16 cluster of galaxies and compared to seeing free data from HST mosaic.

3.4 Forthcoming works/papers

Besides the forthcoming dynamics/strong lensing paper (Gavazzi & Miralda-Escudé, 2004), I have undertaken a $1.5\,\mathrm{deg}^2$ wide field weak lensing analysis of the deep VIRMOS/DESCART F02 field[4]. It is the sum of 4 pointings of the CFH12K camera like that of MS0302+17 and complements my expertise in wide fields data processing. This field has been followed up by XMM observations[5]. The purpose of this work is to compare X-rays and weak lensing capabilities of clusters detection. It is important to compare robustness and completeness of both methods on a coherent uniform survey. The former method is based on X-ray emissivity detection and is related to cluster's mass only through low redshift scaling relations. For this reason, weak lensing can achieve a truly mass selected cluster sample with a peculiar sensitivity as a function of redshift provided one is able to manage contamination by projection effects. Photometric redshifts can overcome such projection effects. Mass selected cluster counts provide important constraints on the underlying cosmological model. This work aims at testing methods and sensitivities on a reduced cross-correlated homogeneous sample.

4 Future projects

During my PhD various visible/NIR imagery data from instruments like HST, VLT or wide field CFH12K allowed me to address several issues of cosmology focusing on non-linear scales like clusters of galaxies, superclusters and larger scales. Furthermore, I acquired skills on image processing and massive statistical data analyses. Most of the questions dealt with the spatial distribution of dark matter relative to its luminous (visible/X) surrounding. I have been interested in dark matter halos characterization from galactic scales to LSS. I would like to be involved in pursuits on that topic, either from a strong or a weak lensing point of view, for the reasons developed above.

In the particular case of strong lensing, future analyses shall rely on high resolution HST/ACS and would enable many detailed local modeling in clusters cores. Sophisticated inversion softwares are necessary and future tools should be able to propose complex models including three-dimensional information such as triaxial halos, projected filaments, LSS. They should be able to receive additional constraints like X-rays or Sunyaev-Zeldovich. It is now possible to address the question of fine structure of galaxies and clusters. In a more distant future, instruments like ALMA or JWST will certainly sharpen the importance of strong lensing.
From a more statistical point of view, the issue of multiple QSOs separation together with the statistics of strongly lensed galaxies by clusters[6] will give important indications on the cosmological evolution of halos driven by gravity.
Such a statistical approach may require two simultaneous ways of investigation in which I would be willing to contribute. First, large surveys (DLS, GOODS, CFHTLS) are well suited for this purpose and second N-body numerical simulations are an important laboratory for modeling development. One can think about the impact of substructures in strong lensing modeling, of central BCGs or central hot gas content. Moreover, it would be interesting, for instance, to estimate strong galaxy-galaxy lensing occurrence probability and deriving observational strategies (imagery *vs* spectroscopy)...

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[4] http://terapix.iap.fr/cplt/oldSite/Descart

[5] http://vela.astro.ulg.ac.be

[6] One can also think about strong lensing by intermediate scales dark matter halos, that is expected by CDM but is not yet observed.

On the other side, future weak lensing pursuits of my work would of course deal with wide field surveys. My expertise on weak lensing data analysis could easily be oriented toward two important issues. By looking at larger scales, I could address promising questions like large scales tests of gravity, dark energy investigation of cosmic shear. When concentrating on smaller scales, galaxy-galaxy lensing and correlation mass-luminosity analyses could benefit of my knowledge in cross-correlations. Thus, I could interest myself to physical processes that are more related to the formation of galaxies and the interplay between baryons and dark matter. Here also, from my point of view, it is important to take the most of numerical simulations that have reached a high level of achievement. For instance, I would like to probe galaxy-galaxy lensing analyses within N-body numerical simulations by checking probability of multiple lens planes events.

5 Conclusions

I plan to finish my PhD under the supervision of Bernard Fort and Yannick Mellier at IAP in Paris by Fall 2004. During these years I acquired a good expertise in data processing, signal extraction, noise characterization, physical interpretation and model fitting. I applied this knowledge to various kinds of data, including HST, VLT and particularly wide field images of the CFH12K camera.

I fully built an operational weak lensing pipeline for such images. I developed tools in order to address cosmological issues like large scale distribution of dark matter and its interplay with respect to baryonic components. In particular, I studied the various contents of the supercluster of galaxies MS0302+17. Hence, a direct and promising extension of this work would be straightforward on wider fields.

I also got expertise in strong lensing modeling of gravitational arcs produced by lensing clusters of galaxies using widely used existing softwares I am developing my own ray-tracing inversion code and I have already built useful visualization facilities for strong lensing data analyses (getting constraints, looking for new ones). The strong lensing analysis of MS2137-23 allowed me as well to get knowledge on dynamics of gravitating systems.

In the future, I would really like to diffuse and use my expertise in gravitational lensing into other domains of cosmology or extragalactic physics. I would like to learn about numerical simulations by incorporating lensing properties. In addition, I would be pleased to address a few dedicated astrophysical issues that I have mentioned above (detailed 3D modeling of dark matter halos including the dynamics and eventually the physics of ICM gas)

To conclude during the next years I would like to apply and improve the techniques learned during my doctoral stage. Since the present research project builds on my previous research work, I can guarantee having the potential and skills for the successful implementation of the proposed project.

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