Draft version February 15, 2010
Preprint typeset using LaTeX style emulateapj v. 11/12/01

LRP 2010 GRAVITATIONAL LENSING WHITE PAPER

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1. ROLE OF GRAVITATIONAL LENSING IN MODERN ASTROPHYSICS/COSMOLOGY

Over the past decade, knowledge in cosmology progressed immensely thanks to dedicated surveys which probed the Universe to unprecedented depth and area over a wide wavelength range. Gravitational lensing is unique in that it allows astronomers to observe directly the dark matter and dark energy which do not emit any radiation. For that reason, the cosmological value of gravitational lensing has been emphasized by a large community in various white papers and proposals (Albrecht et al. 2006; Peacock et al. 2006; LSST 2009; Euclid 2010). It is acknowledged that we can not completely and correctly understand the Universe without a direct probe of its dark component which constitutes 95% of the energy budget of the Universe today. Gravitational lensing is meant to do exactly just that.

2. THE PAST DECADE OF GRAVITATIONAL LENSING IN CANADA

The science enabled by gravitational lensing is multidisciplinary in nature because lensing is just a *tool* which addresses a wide range of astrophysical questions; it is not a scientific objective in itself. Canada played a critical role in the early development of strong and weak gravitational lensing, nearly two decades ago, and still remains a leader in this field today. The following sections review the status, highlights, successes and failures of the gravitational lensing research performed in Canada over the past ten years. Nearly all the quoted scientific results involved Canadian astronomers either as project leader(s) or collaborator(s).

2.1. *Clusters of Galaxies*

Clusters of Galaxies trace the densest mass concentrations of the underlying mass distribution. The physics in clusters of galaxies, how they form, how galaxies form within dark matter halo, can also reveal what dark matter is made of and whether the theory of gravity itself should be modified.

Some progress has been accomplished in our understanding of cluster physics and how baryons trace the dark matter distribution. It is now well established that the X-ray temperature in relaxed cluster cores provides an unbiased estimate of the cluster mass (Hoekstra 2007). This result was obtained on a sample of 50 clusters, and masses were compared in the central region of the mass overdensity. On the other hand, the same cannot be said about the X-ray luminosity, one of many indicators that the hot cluster gas has been impacted by poorly understood non-gravitational heating most likely associated with SNe and AGN feedback (Babul et al. 2002; McCarthy et al. 2004; McCarthy et al. 2008). There is now evidence that the physics in the outer regions of clusters is more complicated (Clowe et al. 2006; Mahdavi et al. 2007; Powell et al. 2009), probably due to a combined effect of substructures and non-equilibrium physics. The lensing analysis of Abel 101-102 cluster from the STAGES project (Gray et al. 2009) is also a marked progress in that direction with the most precise dark matter map ever obtained at the super-cluster scale (Heymans et al. 2008). Another recent study on the most Xray luminous cluster, RX J1347-1145, also resolved a long standing mass estimate discrepancy, thanks to newer and better calibrated data (Lu et al. 2010). However, a lot remains to be understood concerning the physics of baryons and dark matter in individual clusters.

The distribution of galaxy clusters as function of redshift and mass is a strong probe of cosmology. It is a powerful probe of dark energy because the time left to clusters to form is a strong function of the dark energy equation of state.

The key step in cluster cosmology is the identification of clusters and the estimation of their mass. There are two main issues with the practical implementation.

One issue is the projection effects. This can be characterized using ray-tracing simulations (White et al. 2002) and semi-analytical estimates (Hoekstra 2001). The quest for an improved cluster selection algorithm is a difficult and ongoing effort. The red sequence technique has been a milestone in this field (Gladders & Yee 2000). The Red Sequence Cluster (RCS) survey was very successful in identifying galaxy clusters in the redshift range [0.5,1]. Cluster populations can also be used to understand statistically cluster physics such as the origin on cool core/non-cool core dichotomy in the properties of the ICM (Yee et al. 2010), the thermal and dynamical state of the ICM (Mahdavi et al. 2007a; Mahdavi et al. 2008), and the formation epoch of early-type cluster galaxies (Hoekstra et al. 2005).

The other issue is to find a suitable proxy for the cluster mass. A number of such proxies have been proposed over the years: the X-ray temperature of the ICM, the X-ray luminosity of the ICM, the SZE decrement, and most recently, the product of gas mass and gas temperature (the so-called Y_x) parameter. Ideally, one would like to calibrate cluster mass proxies against a true measurement of the cluster mass using weak and strong gravitational lensing. A number of groups with strong Canadian representation - the Canadian Cluster Comparison Project [1] and Local Cluster Substructure Survey (Zhang et al. 2010) - are attempting to do just this. These surveys represent an important step forward; however, they involve a relatively small number of clusters and therefore there is a worry

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[1] http://www.astro.uvic.ca/ hoekstra/CCCP.html

that the proxy-mass relationship could be dominated by a specific population (due to mergers, AGNs, etc...). There is a clear need for a systematic lensing survey of a large number of galaxy clusters, in combination with Xray and SZ observations.

Higher redshifts are particularly interesting as a key probe of cluster formation $1 < z < 2$, the one which is also the most sensitive to the world model and dark energy. The most successful approach so far is to apply the red sequence technique to mid infrared data such as in SpARCS/SWIRE (Muzzin et al. 2009). A few clusters in that redshift range have been found so far, but the need for systematic cluster search is clear.

2.2. *Groups of Galaxies - Galaxies dark matter haloes*

At the low mass end of the cluster mass function, groups of galaxies characterize this important mass scale which contains precious information on how galaxies form in dark matter haloes, whether they form preferably in group assembly or not; it probes the hierarchical model. At even lower mass is galaxy-galaxy lensing, which probes the galaxy individual dark matter halo.

Galaxy-galaxy lensing was used for the time to probe the dark matter halo flatness, which is a powerful probe of the nature of dark matter (Dubinski & Carlberg 1991). The results indicate a detection of halo flatness at $\sim 3\sigma$ (Hoekstra et al. 2004; Parker et al. 2007). Another world premiere was the detection of gal-gal-gal lensing (Simon et al. 2008), which although difficult to interpret theoretically, opens the path to a detailed study of the substructure of galactic haloes with gravitational lensing.

The COSMOS treasury survey show that deep space data can still achieve a mass measurement on individual groups (Leauthaud et al. 2010). Combining lensing and X-ray data, they showed that the Xray luminosity-mass relation can be well constrained, and concluded that the self-similar model can already be rejected at the 3.7 σ limit.

The future of group and galaxy-galaxy lensing relies on wide field imaging and the use of appropriate proxy to stack the weak lensing signal. Such proxy does not necessarily have to be the mass, it could be set by number density, luminosity, flux in other wavelengths, etc... A very exciting possible development for the future is the challenge of theories of gravity (Tian et al. 2009)

2.3. *Strong Lensing*

Strong lensing is a powerful probe of the densest regions in galaxies and groups/clusters of galaxies. It can be used in different ways: 1) as a gravitational telescope to probe the structure of very distant highly magnified galaxies 2) to probe the dark matter distribution at tiny angular scales, one arcseconds for galaxies and $\sim 10 - 30$ *arcseconds for clusters of galaxies.*

Wide field optical surveys used for cluster and cosmological lensing are also very good at finding strong lensing features in galaxies and groups. The CFHTLS produced the first catalogue of strong lensing systems in groups of galaxies, opening up new window for future surveys to probe the dark matter power spectrum down to angular scales of one arseconds (Limousin et al. 2009). The large area RCS2 survey is creating a strong lensing catalog based on their cluster sample, expecting to discover the order of 200 systems. In the NIR range, the future large telescopes (TMT and ELT) will completely revolutionize strong lensing and our knowledge of galactic halo substructures, thanks to the high resolution achieved by Adaptive Optic (Carlberg 2004). There is a great synergy between wide field surveys (PanSTARRS, KIDS, VISTA), which can find strong lensing systems, and the future ELTs which will look at them to unprecedented resolution.

At submillimeter wavelengths, it has been shown that strong lensing magnification of distant dusty galaxies can be used as a powerful tracer of the foreground mass distribution (Paciga et al. 2009). Canada is already involved in large scale submm surveys to explore this promising new direction.

2.4. *Cosmic shear and magnification*

Cosmic shear is the name given to the effect of weak lensing by large scale structures on distant galaxies. The effect is so weak that it can only be detected statistically by looking at how distant galaxy shapes correlate across the sky as function of their angular separation. This technique gives can constrain the cosmological parameters and it gives a direct measurement of the dark matter power spectrum which can serve as a test alternative theories of gravity. Lensing also changes the apparent brightness of distant galaxies, this effect is called magnification and can also be detected.

Canada led the pack by detecting cosmic shear for the first time in 2000 (Van Waerbeke et al. 2000). Progress was quick and many of the early issues, such as PSF modelisation/correction, were resolved in the following years (Van Waerbeke et al. 2001; Van Waerbeke et al. 2002; Hoekstra 2004; Van Waerbeke et al. 2005). The more recent studies used a much better calibration of photometric redshifts in order to obtain the right source distribution function (Benjamin et al. 2007). The CFHTLS-WIDE was used to show for the first time one can measure the dark matter clustering at angular scales of one degree, which opens the possibility to probe dark matter clustering in the linear regime (Fu et al. 2008) and will enable a direct connection with the primordial power spectrum observed from CMB. Measurement of weak lensing from space with the COSMOS survey has demonstrated for the first time evidence for acceleration of the expansion of the Universe with weak lensing data alone independently from the Supernovae and CMB results (Schrabback et al. 2010). One has to deplore however that CFHTLS-WIDE has not been exploited at its full potential yet due to the lack of significant support that could have been used to hire a critical mass of qualified postdocs to work on this huge data set.

The main technical limitation of weak lensing studies remains residual systematics that severely hampers the scientific exploitation of space and ground based data. For that reason a huge effort was initiated to rethink the shape measurement from scratch, and new shape measurement techniques are being developed (Miller et al. 2007). Simulated images and data are being used in conjunction in order to understand residual systematics, this is the work behind the STEP and GREAT projects (Heymans et al. 2006;

Massey et al. 2007; Bridle et al. 2009).

Significant progress on the theoretical side has been made too. The use of high order shear statistics was shown to be valuable probe of the non-linear clustering (Van Waerbeke et al. 2002), and the combination of lensing with optical data allows to study galaxy biasing. Only one measurement of galaxy basing has been made to date (Hoekstra et al. 2002), based on a theoretical idea developed in (Van Waerbeke 1998). Some of these idea are just being barely tested on real data, e.g. the measurement of 3 points function (Pen et al. 2003).

(Hildebrandt et al. 2009) presented the first measurement of magnification of distant galaxies by foreground matter. This promises to be a very rich field of study in the future because it does not depend on a large number of issues that plagued the shear such as imperfect PSF correction and intrinsic alignment.

Weak lensing from 21 cm data also offers an exciting new window for the future, e.g. CHIME where Canada has strong involvement (Pen et al. 2010). It will map dark matter in redshift regions unaccessible to optical/NIR imaging and provide unambiguous source redshift estimates, which is necessary for the theoretical interpretation (Kiyoshi et al. 2009; Lu et al. 2009; Dore et al. 2009)

2.5. *Numerical simulations*

The first order weak lensing theory is straightforward and all calculations can be done semi-analytically. The correct cosmological interpretation of high precision lensing measurements require to take into account a large number of small effects. Those effects include intrinsic alignment, deviation from the Born approximation, non-linear lensing effects. None of them can be estimated analytically without relying on strong assumptions and unacceptable simplifications, this is where ray tracing simulations play a central role in lensing studies.

Earlier work on ray tracing simulations involved relatively small and low resolution simulations to look at intrinsic alignment (Heymans et al. 2006; Semboloni et al. 2008), non-gaussian contribution to errors like sampling variance (Semboloni et al. 2007) and source clustering (Forero-Romero et al. 2007). The largest Canadian effort to produce nearly stream-lined simulations is based at CITA (Trac & Pen 2006). There has been continuous effort to make larger and better simulations with a new P3M code (Merz et al. 2005; Harnois-Deraps et al. 2010). They have been used to investigate high order effects in shear measurement (Zhang et al. 2003; Vafaei et al. 2010).

There appear that the future of numerical simulations will focus on two well distinct aspects: 1) the construction of low or moderate resolution of very large volumes with dark matter particles only which will be needed for full sky surveys to address any statistical analysis and 2) the production of high resolution, small volume, which include details of *gas*trophysics, hydro, feedback, AGNs, magnetic fields, etc,...

3. FUTURE OF THE FIELD INTERNATIONALLY

It is clear that weak and strong lensing can answer many central questions in cosmology: how is dark matter distributed, what is the precise shape and profile of dark matter halos, how and when galaxy and cluster formation did take place within these halos, what is the equation of state of dark energy? Lensing can also provide critical insights to investigations aimed at understanding the physics, and particularly the thermal and dynamical state, of the ICM. Unlike e.g. CMB, lensing measurements do not require a dedicated instrument specially built for this purpose. Lensing science can be achieved with wide field imaging at any wavelengths, the same as for a large range of other science goals, from planetary to stellar and extragalactic science.

The current international situation is that a few optical/NIR surveys are about to start to carry out a few thousand square degrees multicolor optical surveys (KIDS, VISTA, DES, PanSTARRS-1). They are transitional surveys, between CFHTLS, which just finished, and the future *full sky* and *deep* surveys, planned for 2017-2019. The later are mainly characterized by ground based surveys (LSST, PannSTARRS-4) and space based surveys (Euclid, JDEM, WISH). Euclid was accepted for phase A early january 2010, while JDEM is pending until US decadal plan is released mid 2010, LSST and PanSTARRS-4 are not fully funded yet. ALL of the these projects have lensing either top or very high on their science goals list. Some probing of dark matter and dark energy with lensing can be done with PLANCK, SKA and 21cm. However, the international community recognizes that a full exploitation of these data is possible only with an optical/NIR followup, e.g. to obtain redshifts, stellar populations, stellar masses, star formation rates, and extragalactic activity (AGNs).

4. FUTURE OF THE FIELD IN CANADA

Exciting lensing science in the future will only be possible with wide field surveys, and for the reasons outlined above, optical/NIR surveys are crucial. Canada is still a world leader in lensing, thanks to wide field surveys such as CFHTLS and RCS1-2. Paradoxically, the future of optical wide field imaging in Canada is now threatened. Canada is currently not part of any of the transitional or future full sky optical/NIR surveys. The proposed AO wide field imager at CFHT, IMAKA, could prolong the life of CFHT for a few more years, but nothing is currently in place, or even envisioned, for after 2015 in terms of optical wide field imaging, and it is not clear CFHT will remain competitive after that, particularly if IMAKA is not built. Some possible options are:

a) Get involved in ESO wide field survey facilities, e.g. with a new hardware contribution.

b) Buy in LSST (in kind contributions possible), as data will not be public outside US and Chile.

c) Partner a future wide field optical imaging in space lead by another country (e.g. Euclid, JDEM, WISH).

d) Develop a complement to future wide field surveys, e.g. spectroscopic like MegaMOS, or refurbish existing equipment to perform target -followup- observations in the future, e.g. an extremely deep cluster coverage in order to bring in a unique data set and gain access to e.g. LSST, PanSTARRS. For instance, it is clear that ESA's Euclid and the US's LSST complement each other for image quality/wavelength coverage.

By no means this is an exhaustive list. The canadian wide field imaging solution will have to be competitive, affordable and of interest to a broad community, which also complements/resonate with/strengthen the science enabled by TMT, SKA, ALMA, PLANCK and JWST.

The last issue the community is facing is a significant lack of funding to attract high caliber postdocs; this problem has become more dramatic after the cancelation of the NSERC SRO program, which has not been replaced by anything else. The issue cuts across the observational/computational/theoretical boundary and it affects every field, not just gravitational lensing. Our community has access to top-class telescopes from the ground and space, it built strong computing facilities across the country, and it is involved and/or leading international new projects dealing with increasingly complex observational datasets. Yet, there is clear and present danger that Canada will fall behind because we lack programs and mechanisms that would facilitate the recruiting of high caliber postdoctoral fellows and build strong, world-class research groups at multiple sites across the country. This is key if we are continue moving forward and build a strong, vibrant, national community that can successfully exploit its world-class resources and scientific prowess.

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5. LENSING RELATED PRESS RELEASES

- Cosmic shear (2000):
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- COSMOS 3D weak lensing (2007):
  http://www.spacetelescope.org/news/html/heic0701.html
- Cosmic "Train Wreck" (2007):
  http://chandra.harvard.edu/press/07_releases/press_081607.html
- Cosmic shear CFHTLS (2008):
  http://www.publicaffairs.ubc.ca/media/releases/2008/mr-08-019.html
- Abell 901/902 highest resolution dark matter map (2008):
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