Summary

In one century of evolution, astronomy has become a multi-disciplinary science involving complex scientific notions from many domains, i.e. mathematics, signal and image processing, optics, electronics, electromagnetism, computer science, aeronautics, engineering, etc., even business. Because of the increasing need for larger and more efficient instruments, it is impossible at present for a research institute to finance, design, develop and operate simultaneously highly complex instruments. Thus, consortia of institutes are created to share cost, knowledge and man-power in order to succeed in building such complex instruments. The creation of consortia is a necessary but not the only condition for success. The astronomical society has to rely on a network of commercial manufacturers for the provision of the necessary basic components for building instruments. The success of many scientific projects today results from such partnerships. The OmegaCAM project, a one square degree optical wide field camera, is an example of such a collaboration. Research institutes are linked to the commercial manufacturers by an astronomical organisation responsible for building the camera, all working to answer the new questions astronomers are facing. In this summary, we briefly describe the evolution of our knowledge about the Universe, next we report the new challenges the astronomical society encounters and we discuss the strategy and tools used.

Evolution of the Models of the Universe

Before 1900, the development of the astronomy as well as the continuous improvement of the observing tools have made the scientists abandon the model of the Universe of Ptolemee and replace it by a more complex and realistic Universe model. In the end of the nineteenth century, it was commonly accepted that the universe contained several hundreds of thousands of stars randomly distributed in a volume not larger than hundred thousand light years. The universe was known to be not older than several hundred million years without specific structures. It is only in the 1920’s that astronomers realized that galaxies exist.

With the industrial development of the twentieth century, science and technology have grown exponentially. The astronomical society has largely benefited and participated in this development which has consequently contributed to enhancing our knowledge about

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5The earth is the center of the Universe with the canopy of heaven turning around our flat planet.
the Universe. Important discoveries have been made, and it is well known at present that the universe contains many structures.

The Universe is organized in voids, which are underdense regions with a diameter up to $265 \times 10^6$ Light Years, and also in clusters and super clusters of galaxies. The clusters and super clusters are linked by filaments (see Figure 1a). Clusters consist of 10 to 1000 galaxies surrounded by a huge amount of ionized gas. Each galaxy is composed of one hundred billion of stars, in which the majority of them are rotating in a disk plane that has a diameter up to hundred thousand light years and it is surrounded by a dark matter halo. After the discovery of Hubble in the 1920's who has shown that the galaxies move away from each other at a speed which is proportional to their distance ($\sim 74$ kilometer per second and per Megaparsec, 1 per sec $= 3.26$ Light Years), the stationary universe perception changed for a universe in expansion. New theories have been proposed to explain this more complex universe.

One of the theories that has been introduced is the hot Big Bang theory. The hot Big Bang theory is a scientific concept which claims that the universe emerged from a singular extremely dense and hot point about 13.7 billion years ago (at the time $t = 0$, the temperature and the density were infinite). The Hot Big Bang is based on observations, like redshift of distant galaxies discovered by Hubble, indicating that space expands. In the beginning this theory has been controversial, but it has proved realistic when in 1964, Wilson and Penzias measured a background noise higher than the expected one while testing a new model of antenna. This disturbing signal was nothing less than the remains of the Big Bang explosion. The signal, called cosmic microwave background (CMB), corresponds to the first instant of the universe ($\sim 380000$ years old) when it became transparent to light. At a temperature of $\sim 3000$ degrees Celsius, the speed of the protons and electrons became low enough that they could stay coupled, leaving enough space to the radiation to escape. Figure 2a shows the moment the Universe became transparent. The black spots correspond to the densest regions where galaxies were most likely to form. Because of the expansion of the universe, the faint signal is highly redshifted and can be recorded at radio frequencies. A careful analysis of the temperature variations provides crucial information for estimating many cosmological parameters confirming the "Concordance Model" of cosmology. The Concordance Model is a Lambda-Cold Dark Matter model which tries to describe our Universe that has emerged from the hypothetical Hot Big Bang. This model attempts to explain cosmic microwave background observations, large scale structure observations and supernovae observations of the accelerating expansion of the universe.
At present the Concordance Model appears to be the best model of the Universe. Within this model, it has been deduced that 24% of the universe is composed of baryonic (∼4%) and non-baryonic matter, also called dark matter, and the remaining 76% of the universe is constituted of a mysterious medium called dark energy. Very little is known about the dark energy except that since about 7 billion years it dominates our universe causing the accelerating expansion of the universe. This strange medium is indeed intriguing but it is not the subject of this thesis. In the present study we focus on the dark matter instead and the tools that are used to position and estimate its quantity at different scale of the universe. To carry out such analyses we use the gravitational lensing theory.

**Gravitational Lensing as a Probe of Dark Matter**

The Gravitational Lensing theory provides powerful methods to localize and quantify dark matter. This theory is based on the influence of a gravitational well, that is produced by a mass, on the space which surrounds the massive object. A gravitational well curves the space, and any objects or electromagnetic waves which pass in the disturbed environment are deflected towards the mass. This phenomenon transforms a massive object into a (gravitational) lens for luminous sources which are localized in the background of the massive object. Depending on the strength of the lens, an observer aligned correctly with the lens and the sources, would see (multiple) images of the sources shifted and/or distorted and/or magnified (see Figure 3a). Within the gravitational lensing field, we can distinguish three different subjects: Microlensing, Strong Lensing and Weak Lensing.

In microlensing events, we observe only the images of the sources which are magnified compared to the original sources images. The source objects are extragalactic stars. Using microlensing events it is possible to study dark matter distribution which is located in compact objects such as brown dwarfs or planets.

Strong lensing events strongly distort and magnify the source images. Moreover sometimes it is even possible to observe several sources images (see Figure 3a). Such events permit for studying the mass distribution of the lenses at small scales, for determining
The weak lensing regime corresponds to the case where the magnification and the distortion of the images can hardly be observed and there are no multiple images. In that case we resort to statistical analyses to extract a weak gravitational lensing signal. Weak gravitational lensing applied to a cluster of galaxies permits to estimate the mass distribution of the cluster. When the weak lensing is applied to galaxies, we speak about galaxy-galaxy lensing. We can study the dark matter halo of the lens galaxies, their shape and the maximum radius. The study of the distant galaxies shapes slightly distorted by large scale structures, provides information about the inhomogeneous megaparsec matter distribution. To carry out such analyses, we need CCD cameras larger than those, which have been available in the last decades.

**OmegaCAM: A New Instrument Suitable for Weak Gravitational Lensing**

In order to carry out weak gravitational lensing analyses, instruments providing wide field images with a huge amount of galaxies are necessary. Such an instrument has to supply very good quality images, the optics of the telescope has to be excellent and the electronic system has to degrade the images as less as possible. The VST-OmegaCAM system fulfills these requirements. OmegaCAM is a one square degree, wide field, optical camera composed of a mosaic of 8 by 4 CCDs. In addition 4 extra CCDs are used for guiding and image analysis. The mosaic so built has 16 kilo × 16 kilo pixels with a filling factor of about 95% of its total surface. The OmegaCAM camera will be mounted on the Very Large Telescope Survey Telescope (VST) in Paranal. The CCDs are the most important components of this optical system, they have the task to collect photons which have been traveling sometimes millions of years, with the highest possible efficiency. Therefore the CCDs require specific care for their selections. Because of their high

![Figure 3a: Illustration of a gravitational lensing event. Courtesy NASA and ESA.](image-url)
efficiency in collecting (faint) light, their relative simplicity to operate, and their digital output that can be used directly by astronomers, they have become essential to carry out astronomical surveys. It is nowadays pointless to design an optical instrument without having CCDs as detectors.

CCDs, Crucial Devices for Today’s Science

What is a Charge-Coupled Device?

A Charge-Coupled Device (CCD) is an electronic component able to convert photons which strike its semiconducting material layer into electrical charges (see an example of CCD, Figure 4a). The surface of a CCD constitutes of a succession of elementary units called pixels. A CCD has, depending of its dimension, generally between 256 × 256 and 4096 × 4096 pixels. Each pixel is a capacitor made of Metal-Oxide-Semiconductor (MOS capacitor), and when an external voltages is applied correctly to it, the MOS structure creates a potential well able to store charges (see Figure 5a). A pixel has a size generally between 6 and 25 microns and it is sensitive to photons with wavelengths between 250 and 1100 nm.

How does a CCD work?

The photons which strike the silicon layer possess enough energy to liberate electrons. The electrons release is possible if the silicon is composed of two successive layers brought in contact, one n-type and one p-type layer. The electrons which are in excess in the n-type layer diffuse in the p-type layer. When photons with enough energy strike the silicon layer, electrons are released and captured by the nearest MOS capacitor which produces a potential well when voltages are correctly supplied (see Figure 5a). Depending on the wavelength of the photons, the number of produced negative charges is more or less efficient (the ratio of electrons per incident photons is called quantum efficiency). The quantity of electrons produced by the photon-electrons conversion and captured by the MOS capacitor is proportional to the incident light. The image projected on the CCD is then sampled and transformed into negative charges by the matrix of pixels, each pixel containing a certain quantity of electrons proportional to the light intensity which has reached the pixel. The time to collect photons, also called integration period, varies between a fraction of a second up to several hours. During the integration period the voltages applied to the MOS capacitor remain unchanged. Once the exposure time...
Figure 5a: Schematic View of the Basic Layout of a Three-Phase, front side illuminated CCD (back side illuminated CCDs are CCDs which receive the photons from below in this Figure). The photons come from the top of the CCDs on this Figure, cross the polysilicon electrodes and transfer their energy to electrons which are pulled out of the Si atoms. The potential wells, produced by the MOS capacitors, collect the electrons and store them. Courtesy Ian S. McLean, Electronic Imaging In Astronomy.

is complete, the transfer of charges can proceed. In the case of CCDs which have three electrodes per pixel, $O_1$, $O_2$ and $O_3$, (the charges are initially located below $O_2$, see Figure 6a and 7a), we first set the adjacent electrode, here $O_3$, to the potential level of $O_2$. Both electrodes, $O_2$ and $O_3$, have now the same potential and the charges are distributed below these two electrodes. Next, we lower the potential of the electrode $O_2$ to push the electrons which are below $O_2$ towards $O_3$. To transfer charges from one pixel to the other, three of the transfers described above, are necessary (a pixel is composed of three electrodes). An identical method is applied to the output register to transfer the charges to the output amplifier. The processes of lowering and raising the voltages are repeated as many time as necessary in order to readout the complete CCD. The way the electrodes are driven can be described in a diagram called clock pattern (see Figure 8a).

The simplicity of using the CCDs and their efficiency have changed completely the way we see our Universe nowadays and also have helped in popularizing astronomical science. At present, very nice images can be produced with a well tuned CCD even by amateur astronomer (see Figure 9a and 10a).

In This Thesis

The first part of this thesis is dedicated to the work carried out at ESO on the CCDs of the OmegaCAM camera, which is the detector instrument of the VST. Once installed on the telescope, the camera will not be dismounted except for the maintenance of the system. It is then impracticable to stop the observing in order to exchange a CCD by another one because of cosmetic reasons or an insufficient performance of that CCD compared to the other CCDs. Each device has to be fully characterized before being mounted in the CCD mosaic. To populate the mosaic of the OmegaCAM camera, 32 +
Figure 6a: Schematic View of a $4 \times 4$ matrix of pixels, Three-Phase CCD. Courtesy Ian S. McLean, *Electronic Imaging In Astronomy.*

Figure 7a: Charge-coupling in a three-phase CCD.

Figure 8a: Example of Clock pattern for the transfer of charges after an integration period for a three-phase CCD.
4 €2V 44-82-1-A57 CCDs had to be selected. Each CCD has $4102 \times 2048$ pixels and it is thinned, backside illuminated, with a specific coating on the surface in order to make it more sensitive in the blue spectra. To characterize the CCDs a complete procedure has been developed. For each CCD, we

- measure the efficiency to convert photons into electrons at different wavelengths (Quantum Efficiency),
- check the intensity’s variation among pixels at different wavelengths (Photon-Response Non-Uniformity),
- measure the noise produced by the electronic chain while the CCD is readout (Readout Noise),
- measure the gain that gives the relation between the pixel values in analog-digital units (ADUs) and the produced number of electrons (Conversion Factor),
- verify if the incident light which illuminates the CCD is proportional to the quantity of electrons produced (Linearity),
- check if the quantity of free electrons produced by the silicon crystal is within the specification (Dark Current),
- analyze the efficiency to transfer charges from one pixel to the other (Charge Transfer Efficiency),
- control the quality of pixels matrix (Cosmetic Defects). We look for:
  - Pixels which produce too much dark current compared to the rest of the pixels (Hot and Very Bright Pixels),
  - Pixels insensitive or very less sensitive to the light (Dark Pixels),
  - Pixels which do not transfer the total amount of charges while the CCD is readout (Traps and Very Large Traps),
  - Unusable columns of the CCD pixel matrix which correspond to more than ten continuous defect pixels (Bad Columns).

Based on such CCD analyses and compatibility of voltages, the devices are selected and organized into a mosaic with characteristics distributed as homogeneous as possible.

When the OmegaCAM camera is installed on the VST telescope in Paranal, it will be possible to carry out the surveys such as the Kilo Degree Survey (KiDS). KiDS is a 1500 square degree survey in 4 bands and has been developed to realize a weak gravitational
lensing study. Such an analysis requires high quality images and a huge amount of galaxies. It is expected that both criteria will be fulfilled by the VST-OmegaCAM system. To handle the huge amount of data that the VST-OmegaCAM system will produce, a new software system is built (AstroWISE). To realize weak gravitational lensing analysis, new data reduction techniques are developed.

In the second part of this thesis, the development of a new method for Point Spread Function (PSF) correction and galaxy ellipticity estimates is described. The new technique is tested and compared to a method widely used by astronomers in the gravitational lensing field, the Kaiser, Squire and Broadhurst (KSB) method. The new method based on shapelets decomposition (similar to wavelets decomposition) extends the KSB method, it is faster and more accurate theoretically than the KSB method. Using the corrected ellipticity of the galaxies, we carry out a statistical analysis in order to extract from it a cosmic shear signal which is a probe of inhomogeneous matter distribution on megaparsec scales. Furthermore, we compare the estimates of galaxy ellipticities obtained using either the shapelets or KSB method. For this purpose, we employ the 50 Fors1 images, produced by Maoli et al. (see article: Cosmic shear analysis in 50 uncorrelated VLT fields). These authors used those images to compute a significant cosmic shear signal (CSS). Initially we reproduce the calculation of the CSS of Maoli et al. using the standard methodology based on the KSB method. Next, we carry out the cosmic shear signal extraction after using the shapelets method to correct the PSF. From these two sets of data, we also carry out an identical analysis of systematic errors (same analysis carried out by Maoli et al.). No systematic errors are recorded, thus confirming that both methods provide a real cosmic shear signal. Our work validates our pipeline based on the shapelets method which will be used for future weak gravitational lensing analyzes.

Moreover, we also carry out a Galaxy-Galaxy lensing analysis on the 50 VLT Fors1 data and succeed in estimating, using two models of galaxy halos, the main characteristics of the galaxy halos located at a distance of 1-2 thousand Megaparsecs (1 parsec = 3.26 Light Years = 3.085 \times 10^{16} meters). Compared to other surveys we found similar results.

This study has shown that the methodology we developed to carry out Galaxy-Galaxy lensing analyses provides robust results and it can be used with confidence to study Galaxy-Galaxy lensing signals in the future OmegaCAM images.