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HIGH-Z GALAXIES THROUGH GRAVITATIONAL LENSING

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RESUMEN

La gravedad es el motor clave de la evolución del universo y de la formación de sus principales estructuras: las galaxias, cúmulos de galaxias y filamentos. La gravedad es también una herramienta muy valiosa para explorar el universo a alto corrimientos al rojo a través del efecto relativista de las lentes gravitatorias. Los potenciales gravitatorios de los cúmulos de galaxias convierten a estos objetos en poderosos telescopios cósmicos que magnifican la señal de galaxias con alto corrimiento al rojo. En este trabajo presentamos un proyecto para estudiar tales galaxias con el *Gran Telescopio Canarias* (GTC) y el instrumento OSIRIS. Describimos el fenómeno de lente gravitatorio, enfatizando el caso del régimen fuerte en cúmulos de galaxias. A continuación mostramos una aplicación de los códigos numéricos para estudiar el cúmulo MS2137.3-2353. Finalmente discutimos el uso del *Gran Telescopio Milimétrico* (GTM) para hallar candidatos de galaxias lenteadas a muy alto corrimiento al rojo.

ABSTRACT

Gravity is the key engine for the evolution of the universe and the formations of its main structures: galaxies, clusters of galaxies and filaments. Gravity is also an invaluable tool for exploring the universe through the relativistic effect of gravitational lensing. The gravitational potentials of clusters of galaxies turn these bodies into powerful cosmic telescopes which enhance the signal from high-redshift galaxies. In this paper we present a project to study such galaxies with the *Gran Telescopio Canarias* (GTC) and the instrument OSIRIS. We describe the gravitational lens effect, stressing the strong regime case in clusters of galaxies. Then we show an application of the numerical codes to study the cluster MS2137.3-2353. Finally, we discuss the use of the *Large Millimeter Telescope* (LMT) to find candidates for lensed galaxies at very high redshift.

Key Words: **GALAXIES: HIGH-REDSHIFT — GRAVITATIONAL LENSING**

1. INTRODUCTION

The last decade of development in the determination of cosmological parameters (e.g., Lahav & Liddle 2004), as well as the understanding of galaxy formation and evolution in the CDM scenario (e.g., Firmani & Avila-Reese 2003), along with the modeling of gravitational lenses (e.g., Kneib et al. 2003) have provided the best conditions for observational studies of high-redshift galaxies through gravitational lenses, and tests of the cosmological paradigm.

Detecting faint, high-redshift galaxies is a challenge for modern telescopes. Many of these objects have been detected using broad-band filters and looking for candidates with a Lyman break signature. In many cases, these candidates have been confirmed through spectroscopic observations (e.g., Steidel et al. 1996,1999). The detection of high-redshift galaxies has been possible because some of them have an intense Lyα line in emission. This line can be observed using narrow-band filters to search for candidates that can then be confirmed spectroscopically. This methodology is being used in the Subaru Deep Field (e.g., Kodaira et al. 2003; Ajiki et al. 2004; Kashikawa et al. 2004; Taniguchi et al. 2005). The narrow-band technique is very efficient to detect Lyα emitters, but it has the disadvantage that it can only be applied to galaxies at the redshifts covered by the filters.

The 10-m *Gran Telescopio Canarias* (GTC) will be equipped with the instrument OSIRIS (Optical System for Imaging and low Resolution Integrated Spectroscopy). The imaging capabilities of this instrument include two tunable filters (blue and red) which can be centered at any wavelength in the range 365 to 1000 nm, and with any resolution between 300 and 1000. Thus, this instrument will have an unprecedented potential to detect Lyα emitters at any redshift between $2<z<7$.

Our aim is to study the faint, high-redshift galaxy population through the gravitational lens magnification produced by clusters of galaxies. To enhance the probability of detection for these faint galaxies,

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we plan to study the center of the clusters where the magnification is larger.

2. GRAVITATIONAL LENSING

The physical and mathematical description of the gravitational lens phenomenon has been presented in a number of book and reviews (e.g., Fort & Mellier 1994; Schneider, Ehlers, & Falco 1999; Mellier 1999; Petters, Levine, & Wambsganss 2001; Mollerach & Roulet 2002; Courbin & Minniti 2002).

Light, in the presence of a gravitational field, is deviated in a similar way as considered in geometrical optics. The images appear magnified and distorted. The image properties are described by the convergence κ, and the shear γ. The convergence is proportional to the lens surface mass density, and is responsible for the isotropic increase or decrease in size. The shear is responsible for image distortion. Together, convergence and shear produce the image magnification, which is the variation of the solid angle of the image with respect to the source. Because the light is deviated, the light beams may arrive to the observer through different optical paths, producing several images for a given source. Both gravitational delay and the different optical paths produce a net temporal delay for each of the multiple images.

Gravitational lenses do not have a focus. Thus, the image has a different size than the source would have if it were observed directly, but the *contrast* or surface brightness is conserved. The change between the solid angle from the source to the image is called *amplification*. For a given distribution of lenses, the amplification may be divergent for some source positions. The directions in the source plane along which the amplification diverges are called the caustics. The images of the caustics, i.e., the directions in the observer's sky along which a source would be seen infinitely magnified, are known as the critical lines. Objects close to these lines may show an odd number of images, some of them amplified and some de-amplified. De-amplified images are often too dim to be detected. These cases where the observer-lens-source alignment is very good and several images are formed, we call the gravitational lens *strong regime*. In this regime, the images may be seen as tangential and radial arcs. In contrast, in the *weak regime* the alignment is not so good; the images are unique and show a weak tangential distortion (arclets).

3. THE STRONG REGIME IN CLUSTERS OF GALAXIES

Gravitational arcs around the centers of the clusters are a powerful tool to estimate the cluster mass and the mass distribution. Another good estimator is the mass inferred from X-ray observations (e.g., Ota et al. 2004).

Allen (1998) and Wu (2000) found that in clusters with cooling flows, the mass estimation from gravity matched the mass estimation from X-ray observations. This was not the case for clusters without cooling flows. This situation implies that relaxed clusters that have developed a cooling flow can be described by simple, axi-symmetric models, but for dynamically active clusters these models produce discrepant estimates.

Since the first numerical simulations (Navarro, Frenk, & White 1996,1997), CDM halos have shown a central cuspy profile. However, the radial arcs require softer central profiles (e.g., Luppino et al. 1999; see also Bartelmann 1996).

Relative abundances and positions of the radial arcs in comparison with the tangential arcs can constrain the central density profile (Miralda-Escudé 1995; Molikawa & Hattori 2001; Oguri, Taruya, & Suto 2001). Unfortunately, radial arcs are difficult to detect because they are near the cluster centers, thus they can be easily be hidden by the light of the galaxies. This circumstance has prevented systematic studies of the central density profiles.

A very important application of the gravitational lens effect is to study clusters of galaxies which produce arcs from several sources at different distances. In these cases, the cluster mass distribution is of course the same, but the geometrical efficiency of the lens is different for each group of arcs. As far as this efficiency depends on cosmological parameters, it is in principle possible to deduce these parameter values from geometrical considerations (Link & Pierce 1998; Gautret, Fort, & Mellier 2000). Soucail, Kneib, & Golse (2004) have applied this technique to study Abell 2218 and have concluded that a universe with the critical mass density and without a cosmological constant is inconsistent with the observations.

The strong gravitational lens effect is very sensitive to the cluster asymmetries and thus to the interaction cross section for dark matter particles. Meneghetti et al. (2001) have found that the efficiency for the strong lens effect in clusters would drop abruptly if the interaction cross section for dark matter particles were greater than 0.1 $\mathrm{cm}^2\ \mathrm{g}^{-1}$.

Finally, the strong gravitational lens effect in clusters is frequently used as a cosmic telescope to magnify distant sources up to the photometric and spectroscopic detection limits. This is the effect that

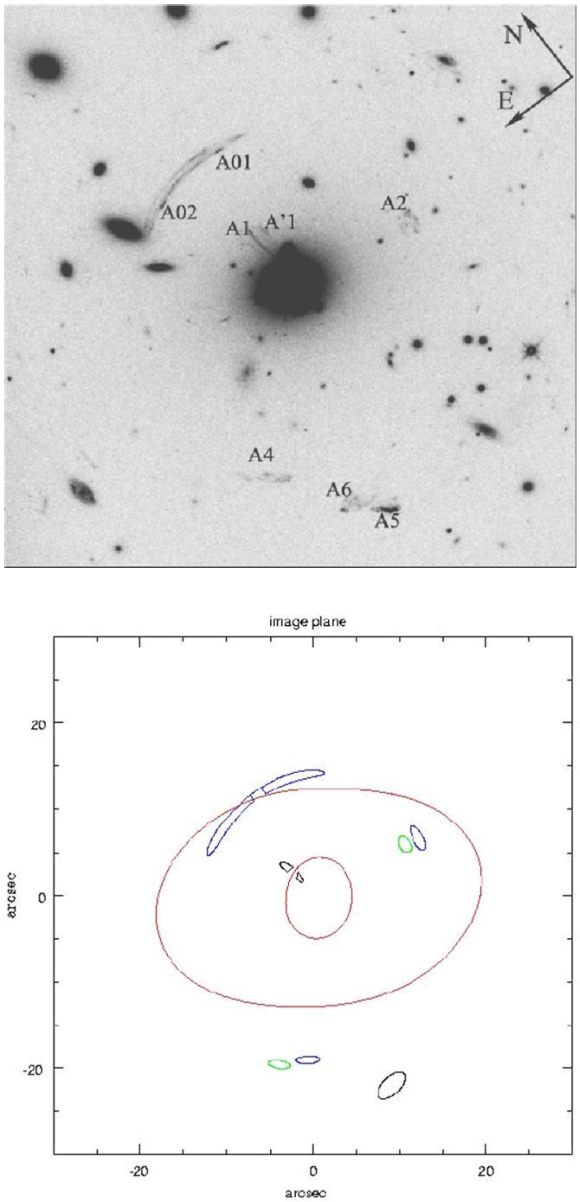

Fig. 1. The cluster of galaxies MS2137.3-2353 and its arc systems. Upper panel: the cluster and the three arc systems identified by Gavazzi et al. (2003), [A01,A02,A2,A4], [A1,A5], and [A'1,A6]. Lower panel: A model for the arc systems [A01,A02,A2,A4], and [A1,A5] obtained using the code written by Keeton (2001).

we want to use to study Lyα emitters and other high-redshift galaxies.

4. MODELS BASED ON GRAVITATIONAL LENSING

Currently, we are preparing for observations with the GTC-OSIRIS tunable filters. The instrument will be available by the end of 2006, and the first scientific data will be obtained during 2007. Preliminary work for these observations includes modeling clusters of galaxies with the codes written by Keeton (2001) and Kneib (1993). Figure 1 shows an example of one of these models for MS2137.3-2353, a cluster of galaxies at redshift z=0.313. Gavazzi et al. (2003) have identified three arc systems: [A01,A02,A2,A4], [A1,A5], and [A'1,A6], which correspond to three different objects at redshift around 1.6. For our model, we only used the first two systems (the arc system [A'1,A6] will be discussed in a future work). To search for a mass model for this cluster, we use standard lens modeling techniques as implemented in the code written by Keeton (2001). We model the central cD galaxy as an isothermal ellipsoid, and the cluster component was modeled with an NFW profile. The models are determined depending on the available data. Arc and galaxy magnitudes and positions, redshifts, galactic dispersion velocities, etc. are valuable information to refine the models.

5. MILLIMETER REGION

By the end of 2006 it is expected that the 50-m Large Millimeter Telescope (LMT) will be built, and it will become operational during 2007. This telescope will be installed on the Sierra Negra (Mexico) and operated by the Instituto Nacional de Astronomía Óptica y Electrónica. One of the aims of the telescope is to search for dust emission from very-high-redshift galaxies. The instrument BOLOCAM installed on this telescope will consist of wide-band incoherent detectors to obtain very high continuum sensitivity. The instrument is designed to operate in the 2.1, 1.4, and 1.1 millimeter bands with a resolution of 5 arcsec.

Dust emission from massive starburst galaxies has a very broad feature in the range 0.1-1000 μm which peaks in the 60-100 μm region. Combes, Maoli & Omont (1999) have shown that this feature allows a constant level of detection for the dust emission between $1<z<10$, which is also known as *negative k-correction*. Figure 2 show the sensitivity of LMT-BOLOCAM to detect dusty starburst galaxies.

We plan to use BOLOCAM to detect candidates for high-redshift lensed galaxies. The strategy is to observe clusters of galaxies and gravitational arcs with the GTC-OSIRIS. With this data, we will fit models for the cluster mass distribution. These models will include the geometric description of the critical lines. Using LMT-BOLOCAM we will search for candidates for high-redshift lensed galaxies around

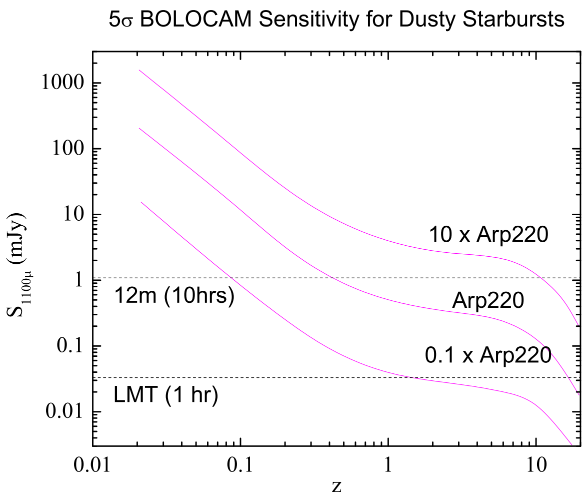

Fig. 2. Sensitivity of BOLOCAM to dusty starburst galaxies on the 12-m telescope (Kitt Peak) and the LMT as a function of redshift. Note that one hour of integration at the LMT will reveal galaxies at z = 10 with dust mass less than half of Arp220's. Figure adapted from the INAOE web page, http://www.inaoep.mx.

these critical lines. The candidates will be confirmed or rejected after follow-up observations.

6. TWIN TELESCOPES AT SPM

The project to build two 6.5-m optical telescopes at San Pedro Mártir will be an opportunity to extend this project beyond its actual scope. One of these telescopes will be dedicated to optical imaging, and the other to wide-field spectroscopy. For example, using deep imaging and the weak lensing effect, the mass distribution of the cluster of galaxies can be extended to include the outer regions (e.g., Bartelmann & Schneider 2001). Wide-field spectroscopy will easily allow us to determine the dispersion velocities of the galaxies in the cluster, and the redshift of several arcs simultaneously.

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