Gravitational Lensing of High Redshift Sources

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Abstract.   The combination of deep exposures and high resolution offered by telescopes in space allows the detection of lensing over a wide range of source redshifts and lens masses. As an example, we model a lens candidate found in the southern Hubble Deep Field. The system consists of a source galaxy lensed into an arc, $0.''9$ from an elliptical galaxy. The photometric redshift of 0.6 for the lens galaxy implies a mass-to-light ratio of 15 in solar units, out to three effective radii. This lens system may be a preview of the large number of lensed high-redshift galaxies that will be detected with the Next Generation Space Telescope (*NGST*). When *NGST* is launched in the next decade, some of the earliest galaxies and quasars in the Universe may be observed. Popular models of structure formation imply that at a given observed flux, roughly 3% of redshift > 5 sources are multiply imaged. Thus, *NGST* should detect several lensed objects in each field of view. In addition, *NGST* will be a valuable tool for weak lensing measurements, as long as it can resolve the background galaxies. We estimate the angular size distribution of high redshift sources within hierarchical models of structure formation and find that most will be resolved by *NGST* even at $z > 10$.

1.   Introduction

As detailed throughout these proceedings, gravitational lensing studies have yielded a wealth of information on galaxies. As technological advances in astronomy lead to the discovery of new populations of sources, the techniques of strong and weak gravitational lensing can be applied in order to study these source populations and their lenses.

The extraordinary resolution of the Hubble Space Telescope (*HST*) has allowed for the first time the detection of lenses where both the source and the deflector are "normal" optically-selected galaxies. Ratnatunga et al. (1995) discovered two such lenses. The Southern Hubble Deep Field (HDF-S, Williams
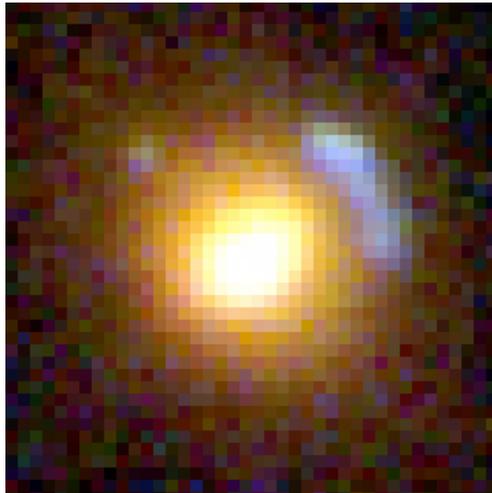
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Figure 1. A region taken from the public release of the HDF-S (Williams et al. 1999). It shows the lens galaxy, the arc to its NW, and the dot to its NE. The figure measures $3\rlap{.}''2$ on a side.

et al. 1999) is a more recent set of deep *HST* exposures. The best candidate lens, noted by the HDF-S team, consists of a blue arc about $0\rlap{.}''9$ from an elliptical galaxy. In §2 we report on a detailed study of this arc. Additional details can be found in Barkana, Blandford, & Hogg (1999).

Despite the achievements of *HST*, detecting the earliest galaxies requires the superior infra-red sensitivity planned for the Next Generation Space Telescope (*NGST*; Ferguson 1999). In §3 we explore the ability of *NGST* to extend gravitational lensing studies well beyond their current limits (see Barkana & Loeb 1999 for the complete details). Lensing rates are expected to increase with source redshift. Sources at $z > 10$ will often be lensed by $z > 2$ galaxies, whose masses can then be determined with lens modeling. In addition, the expected increase by 1–2 orders of magnitude in the number of extended sources on the sky, due to observations with *NGST*, will dramatically improve upon the statistical significance of existing weak lensing measurements.

2. A possible gravitational lens in the HDF-S

Figure 1 shows the candidate gravitational lens, HDFS 2232509–603243. The $V \sim 22$ mag elliptical galaxy fits a de Vaucouleurs profile with an effective radius $r_e = 0\rlap{.}''31$. Comparison of the colors of the elliptical with HDF galaxies with known redshifts suggests that its redshift is roughly $z = 0.6$. The $V = 25$ mag arc separates into four distinct components, labeled A, B, C and D, going clockwise around the arc. We model components A, B and D as three images of a common source. We do not model component C, which can be easily produced if the source is extended, or the dot, which we assume is a separate source.

The image positions can be fit by simple lens models, i.e., a singular isothermal halo with ellipticity or with shear. Alternatively, a constant mass-to-light

ratio model (based on the resolved image of the lens galaxy) also provides a fit when combined with a small external shear. However, with all the models a good fit is obtained only with a substantial shear produced by objects lying to the NE or SW. There are several galaxies $\sim 20''$ to the SW and others $\sim 35''$ to the NE, and these could contribute the required shear if spectroscopic redshifts confirm the presence of galaxy groups.

Assuming the photometric lens redshift of $z \sim 0.6$ gives the lens a luminosity of $\sim L^*$. Lens models imply a mass-to-light ratio of ~ 15 in solar units, and a velocity dispersion of ~ 280 km s^{-1}. Spectroscopy of this lens system should easily yield a lens redshift, and may yield a stellar velocity dispersion and an arc redshift.

3.   Gravitational Lensing with $NGST$

Numerous galaxies and mini-quasars at redshifts $z \gtrsim 5$ will likely be imaged with $NGST$. We apply semi-analytic hierarchical models of galaxy formation to estimate the rate of multiple imaging of these sources by intervening gravitational lenses. Popular CDM models for galaxy formation yield a lensing optical depth of $\sim 1\%$ for sources at $z \sim 10$. The expected slope of the luminosity function of the early sources (as estimated by Haiman & Loeb 1998) implies an additional magnification bias of ~ 5, bringing the fraction of lensed sources at $z = 10$ to $\sim 5\%$. Thus, the estimated number of detected multiply-imaged sources per field of view of $NGST$ is roughly 5 for $z > 10$ quasars, 10 for $z > 5$ quasars, 1–15 for $z > 10$ galaxies, and 30–200 for $z > 5$ galaxies. These ranges in the numbers of galaxies arise from the uncertain efficiency with which cooled gas is converted to stars at high redshift. Observations suggest that this efficiency η lies between 2% and 20%.

Lensed sources may be difficult to detect if their images overlap the lensing galaxy, and if the lensing galaxy has a higher surface brightness. In order to compare the surface brightness of source galaxies to that of lens galaxies, we calculate the redshift evolution of the mean surface brightness of galaxies detected by $NGST$, with results shown in Figure 2 (left panel). Although the surface brightness of a background source will typically be somewhat lower than that of the foreground lens, the lensed images should be detectable since they are offset from the lens center and their colors are expected to differ from those of the lens galaxy. These helpful features are evident in the case of the HDF-S lens of §2.

Weak lensing requires that background sources be resolved. Figure 2 (right panel) shows the distribution of galaxy sizes at various redshifts. Although the typical size of sources decreases with increasing redshift, $NGST$ should resolve at least 60% of the $z > 10$ galaxies that it will detect, and an even larger fraction of galaxies below redshift 10. This implies that the shapes of these high redshift galaxies can be studied with $NGST$, and thus the high resolution of $NGST$ is crucial in making the majority of sources on the sky useful for weak lensing studies.

In conclusion, the field of gravitational lensing is likely to benefit greatly over the next decade from the combination of unprecedented sensitivity and high angular resolution of $NGST$.
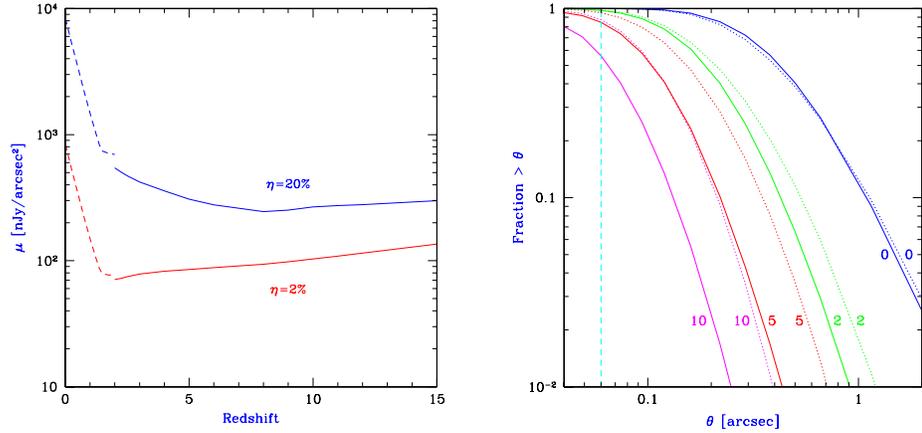
Figure 2.   The left panel shows the mean surface brightness μ of galaxies, averaged over the *NGST* wavelength band, for source galaxies (solid lines) and for lenses (dashed lines). In each case, the upper and lower curves assume a star formation efficiency $\eta = 20\%$ and $\eta = 2\%$, respectively. The curves in the right panel show the fraction of galaxies with diameters larger than θ, for $\eta = 20\%$ (solid lines) and $\eta = 2\%$ (dotted lines). Different curves consider sources with $0 < z < 2$, $2 < z < 5$, $5 < z < 10$, and $z > 10$, with the lower limit indicated. The *NGST* resolution is $0''\!.06$ (dashed line).

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