Letter to the Editor

Do the lensing cross-sections of faint galaxies cover the whole sky?

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Abstract. Very deep galaxy surveys have revealed a considerably large population of faint galaxies, which leads to the speculation that all distant objects are moderately magnified by the gravitational lensing effects of galaxies (Fried 1997). In this letter, we present a simple estimate of the lensing amplitudes by all galaxies up to redshift $z = 2$ in terms of galaxy merging and answer the question whether the sky is fully covered by the lensing cross-sections of galaxies. It is shown that, as a result of the combination of the increase of galaxy number and the decrease of galaxy velocity dispersion with lookback time, less than $\sim 1/10$ of the sky to $z = 2$ can be moderately affected by the galaxy acting as lenses with magnification $\mu > 1.1$. This conclusion is independent of the galaxy limiting magnitude. In other Words, no matter how high the surface number density of faint galaxies becomes, it is unlikely that their lensing cross-sections of $\mu > 1.1$ can cover the whole sky.

Key words: gravitational lensing – galaxies: general

1. Introduction

It is indeed not a novel idea to suggest that all the distant objects may be affected by the gravitational lensing of the matter clumps between the sources and the observer. Three decades ago, Barnothy and Barnothy (1968) proposed that all the quasars were nothing but the gravitationally magnified images of Seyfert galactic nuclei. Press and Gunn (1973) showed that the probability of the occurrence of gravitational lensing in an $\Omega = 1$ universe is nearly unity. Unlike the previous speculations for which there was apparently a lack of both convincing observational and theoretical supports, the current argument is based on the numerous and unprecedented deep galaxy surveys which have revealed a considerably large population of faint galaxies (Metcalfe et al. 1996; references therein). Using the surface number

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density of faint galaxies down to $R = 26$, $1.93 \times 10^{15}/\square°$, Fried (1997) derived a projected mean distance between galaxies to be $8''.2$, which led him to the conclusion that all the high redshift ($z > 1$) objects are moderately magnified by a factor of 1.1–1.5 due to gravitational lensing by the intervening galaxies. Indeed, this was a natural and plausible consequence, provided that all the faint galaxies were at $z \approx 0.5$ and had a mean velocity dispersion $\sigma \approx 200$–300 km s^{-1}.

Nonetheless, spectroscopic redshifts have not been available for most of the faint galaxies to date. Namely, we do not yet know where these faint galaxies are. For instance, the faint blue galaxies might be the star-forming galaxies at moderate redshift of $z \sim 0.4$ (e.g. Broadhurst et al. 1992) or at high redshifts of $z \sim 2$ (Metcalfe et al. 1996). While the dispute regarding the merging rate has existed for several years, it is generally agreed that galaxy mergers may play an important role in the formation and evolution of galaxies. At least, the merging model provides a good fit to the faint galaxy number counts. It is particularly noted that the merging alters significantly the redshift and velocity dispersion distributions of galaxies. What is the optical depth due to gravitational lensing for a distant source if the redshift and velocity dispersion information for the faint galaxies according to the prediction of galaxy merging is employed ? Can the sky be fully covered by the lensing cross-sections of galaxies if faint galaxies are neither peaked at $z \sim 0.5$ nor distributed randomly in redshift space ? We would like to answer these questions by modeling the galaxy matter distribution as the simplest singular isothermal sphere and the galaxy evolution as merging. Rix et al. (1994) and Mao & Kochanek (1994) have presented a sophisticated treatment of how galaxy mergers affect the various aspects of statistical lensing. Here we focus on the specific issue of the lensing covering of galaxies over the sky.

2. Galaxy lenses as a result of merging

Following the idea of Broadhurst et al.(1992), we assume that the galaxy merging only increases the galaxy number with

increasing lookback time, whilst maintaining the proportion of different types (E, S0, S) of galaxies, their respective K-corrections and luminosity function shapes. Under these hypotheses, the present-day galaxy luminosity function can be written as

$$\phi_i(L_0, 0)dL = \phi^*(L_0/L_i^*)^{-\alpha} \exp(-L_0/L_i^*)d(L_0/L_i^*), \qquad (1)$$

where i indicates the $i-$th morphological type of galaxies: i=(E, S0, S). The luminosity function at redshift z in the merging model is thus

$$\phi_i(L, z) = \phi_i(L_0, 0)f(z), \qquad (2)$$
$$f(z) = \exp\{-Q[(1 + z)^{-\beta} - 1]/\beta\}. \qquad (3)$$

Here $f(z)$ is representative of the time-dependence of evolution of the luminosity function, Q is the merging rate and β is the ratio of the Hubble time H_0^{-1} to the age of the universe. The galaxy luminosity L at z is relevant to both the mering rate and the history of the star formation rate. For a matter dominated flat universe of $\Omega_0 = 1$, $\beta = 1.5$, while matching the galaxy number counts gives roughly $Q \approx 4$. This scenario of galaxy merging can account for both the redshift distribution and the number counts of galaxies at optical and near-infrared wavelengths (Broadhurst et al. 1992). If we further model the galactic halo by an isothermal sphere which is characterized solely by its velocity dispersion σ, σ at z will be reduced by a factor of $f(z)^\nu$ with respect to its present-day value σ_0 since the galaxy mass as a result of merging would decrease with lookback time. In particular, ν is close to 1/4 (Rix et al. 1994).

The surface number density of faint galaxies to $R = 26$ obtained by Fried (1997) from the deep observations of the fields around three quasars is $1.93 \times 10^5/\square^\circ$, in good agreement with the previous surveys(e.g. Metcalfe et al. 1996). This yields a mean alignment distance of $4''.1$ between the line-of-sight and the faint galaxies, i.e. $7.3\,h^{-1}$ kpc in linear size if the galaxy is at $z = 0.5$, where h is the Hubble constant in unit of 100 km/s/Mpc. Indeed, assuming that the faint galaxies seen at $R = 26$ have a mean velocity dispersion of 200 km/s and are located at $z \sim 0.5$, we can easily estimate that any background sources at $z \sim 1$ will be gravitationally magnified by a factor of $\mu > 1.1$. So, Fried (1997) argued that it is a purely observational fact that the distant objects must be lensed by foreground galaxies.

Using the empirical formula between the luminosity L_0 and central velocity dispersion σ_0 of local galaxies $L_0/L_i^* = (\sigma_0/\sigma_i^*)^{g_i}$ with $\sigma_i^* = (225, 206, 144)$ km/s and $g_i = (4, 4, 2.6)$ for $i = (E, S0, S)$ galaxies (see Fukugita & Turner 1991), we can compute from eq.(1) the morphological composition $\{\gamma_i\}$ of galaxies by requiring $\sigma_0 = 200$ km/s. It turns out that $\{E : S0 : S\} = (62, 37, 1)$, i.e., the galaxies with $\sigma_0 > 200$ km/s following the Schechter luminosity function eq.(1) are mainly composed of the E/S0 populations. As numerous surveys have shown that the spirals are in the majority in the universe ($\sim 70\%$), the oversimple assumption of Fried (1997) regarding the velocity dispersion $(200 - 300$ km/s) for all the faint galaxies has overestimated their contributions to gravitational lensing. Furthermore, the velocity dispersion of distant galaxies becomes smaller relative to that of local galaxies in terms of galaxy merging, which also leads to a decrease of lensing magnification. As a consequence, if the faint galaxies observed by Fried (1997) are L^* spirals at $z \approx 0.5$, the lensing magnification of a background source at $z = 1$ would reduce to $\mu \approx 1.03$.

3. Lensing cross-sections

We now estimate the total lensing cross-sections of galaxies with redshifts ranging from 0 to z_s for the distant sources like quasars. For simplicity, we still employ the singular isothermal sphere for the galaxy matter distribution and the evolutionary scenario of galaxy merging. The lensing cross-section for magnification greater than μ by a single galaxy at z_d is simply $\pi\theta_E^2/(\mu - 1)^2$ where $\theta_E = 4\pi[\sigma(z_d)^2/c^2](D_d D_{ds}/D_s)$ is the Einstein radius with D_d, D_{ds} and D_s being the angular diameter distances to the galaxy, to the distant source and from the galaxy to the source, respectively. The total lensing cross-section by all the galaxies is

$$p(z_s, > \mu) = F\,T(z_s)\,\frac{1}{(\mu - 1)^2}, \qquad (4)$$

in which

$$F \equiv 16\pi^3 \frac{\phi^*}{cH_0^3} \sum_i \gamma_i \sigma_i^{*4} \Gamma(-\alpha + 4/g_i + 1), \qquad (5)$$

and

$$T(z_s) \equiv \int_0^{z_s} (1 + z_d)^3 \left(\frac{\tilde{D}_d \tilde{D}_{ds}}{\tilde{D}_s}\right)^2 f(z_d)^{1-4\nu} d\tilde{r}_{prop}, \qquad (6)$$

where the symbols with a hat of tilde are the corresponding parameters in units of c/H_0, and dr_{prop} is the proper distance within dz of z. Except for the factor of $1/(\mu - 1)^2$, eq.(4) identifies the eq.(6) of Rix et al. (1994) for $\Omega_0 = 1$, in which they concluded that the total optical depth to multiple images is quite insensitive to merging. This can be easily shown in terms of eq.(4) by noticing that $\nu \approx 1/4$. Taking $\nu = 1/4$ and the galaxy morphological composition $\{\gamma_i\} = (12\%, 19\%, 60\%)$ (Postman & Geller 1984) and utilizing the numerical result of F found by Fukugita & Turner (1991) and the result of T found by Turner et al. (1984), we have

$$p(z_s, > \mu) = 0.047 \times \frac{1}{(\mu - 1)^2} \frac{4}{15} \frac{[(1 + z_s)^{1/2} - 1]^3}{(1 + z_s)^{3/2}}. \qquad (7)$$

A straightforward computation yields $p(1, > 1.1) = 3\%$ and $p(2, > 1.1) = 10\%$, i.e., the total lensing cross-sections of $\mu > 1.1$ by all the galaxies even to $z_s = 2$ cannot cover the whole sky at all ! It is important to note that this conclusion is independent of the limiting magnitudes of the surveys which may reveal a remarkably high surface density of galaxies. Also, our computation has probably overestimated the lensing cross-sections of galaxies in the sense that a biasing factor of $\sqrt{1.5}$ between the velocity dispersion of stars and of dark matter particles is employed by Fukugita & Turner (1991) in obtaining T

for E/S0 galaxies. If such a correction of velocity biasing is unnecessary (e.g. Kochanek 1994), the total lensing cross-section of galaxies $p(z_s, > 1.1)$ reduces to $(2\%, 6\%)$ for $z_s = (1, 2)$.

4. Conclusion

The merging model provides an increasing galaxy number and a decreasing galaxy mass with lookback time, which can relatively easily account for the observed high surface number density and the redshift distribution of galaxies in the deep surveys (Broadhurst et al. 1992). At least, it works equally well as other models (see, for examples, Yoshii & Sato 1992; Metcalfe et al. 1996). In the scenario of galaxy mergers, the gravitational lensing of distant sources (e.g. quasars) by galaxies is affected by the following two factors: (1)There will be more galaxies as lenses as one goes back in time; (2)The galaxy masses, and equivalently the galaxy velocity dispersion, will decrease with lookback time. The first factor will alter significantly the galaxy redshift distributions and enhance the lensing amplitude, while the second one reduces the lensing cross-sections. A combination of these two factors gives rise to an optical depth to gravitational lensing that is roughly independent of the galaxy mergers [eqs.(4)-(6); see also Rix et al. 1994; Mao & Kochanek 1994].

As a consequence, despite the fact that a considerably high surface number density of faint galaxies is detected in the deep surveys, the total lensing cross-sections of galaxies towards a distant source are still rather small, and can never fully cover our sky up to $z = 2$. The claim that all the high redshift ($z > 1$) objects are moderately magnified by galaxies (Fried 1997) arises from the oversimple assumptions about the galaxy redshifts and velocity dispersions $(200 - 300$ km s$^{-1})$ at high redshifts. We find that the maximum lensing covering by galaxies to $z = 2$ is only 10%, and this number is likely to reduce to 6% for a more realistic galaxy distribution. Other more sophisticated models of galaxy evolution should be employed in order to give a better estimate of the lensing covering by the faint galaxies over the sky.

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