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COSMOLOGICAL PARAMETERS FROM THE SDSS DR5 VELOCITY DISPERSION FUNCTION OF EARLY-TYPE GALAXIES THROUGH RADIO-SELECTED LENS STATISTICS

Kyu-Hyun Chae[1]

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ABSTRACT

We improve strong lensing constraints on cosmological parameters in light of the new measurement of the velocity dispersion function of early-type galaxies based on the SDSS DR5 data and recent semianalytical modeling of galaxy formation. Using both the number statistics of the CLASS statistical sample and the image separation distribution of the CLASS and the PANELS radio-selected lenses, we find the cosmological matter density to be $\Omega_{m,0} = 0.25^{+0.12}_{-0.08}$ (68% CL) assuming evolutions of galaxies predicted by a semianalytical model of galaxy formation and $\Omega_{m,0} = 0.26^{+0.12}_{-0.08}$ assuming no evolution of galaxies for a flat cosmology with an Einstein cosmological constant. For a flat cosmology with a generalized dark energy, we find the nonevolving dark energy equation of state $w_x < -1.2$ ($w_x < -0.5$) at the 68% CL (95% CL).

Subject headings: cosmological parameters — galaxies: evolution — galaxies: statistics — gravitational lensing

Online material: color figure

1. INTRODUCTION

Strong lensing has been an important astrophysical tool for probing both cosmology (e.g., Refsdal 1964; Turner et al. 1984; Fukugita et al. 1992; Kochanek 1993; Chae et al. 2002, 2004; Chae 2003; Mitchell et al. 2005; York et al. 2005) and galaxies (their structures, formations, and evolutions; e.g., Keeton et al. 1997; Mao & Schneider 1998; Keeton 2001; Kochanek & White 2001; Chae & Mao 2003; Ofek et al. 2003; Rusin & Kochanek 2005; Chae 2005; Treu et al. 2006; Koopmans et al. 2006; Chae et al. 2006). Strong lensing is also potentially a useful tool to test theories of gravity (e.g., Keeton & Petters 2005, 2006).

At the time of this writing there are ∼90 galactic-scale strong lenses.[2] Parts of them form well-defined samples that are useful for statistical analyses. For example, 26 lenses from the Cosmic Lens ALL-Sky Survey (CLASS; Myers et al. 2003; Browne et al. 2003) and the PMN-NVSS Extragalactic Lens Survey (PANELS; Winn et al. 2001) form a well-defined radio-selected lens sample, and the Sloan Digital Sky Survey (SDSS; Oguri et al. 2006) has accumulated 25 galactic-scale lenses (including eight rediscoveries) so far and expect to eventually obtain a statistical sample of from 60 to 70 lenses.[3] These well-defined samples are particularly useful not only for constraining cosmological parameters such as the present-day matter density $\Omega_{m,0}$, dark energy density $\Omega_{x,0}$, and its equation of state w_x (e.g., Chae et al. 2002; Chae 2003; Mitchell et al. 2005), but also for constraining the statistical properties of galaxies such as optical region velocity dispersions (e.g., Chae 2005; Chae et al. 2006) and galaxy evolutions (e.g., Chae & Mao 2003; Ofek et al. 2003).

The sample from the completed CLASS, in particular its subsample of 13 lenses strictly satisfying well-defined selection criteria (the CLASS statistical sample; Browne et al. 2003; Chae 2003), was first extensively analyzed by Chae et al. (2002) and Chae (2003), who found $\Omega_{m,0} \approx 0.3$, assuming a flat cosmology and adopting nonevolving galaxy populations. Mitchell et al. (2005) reanalyzed the CLASS statistical sample based on the velocity dispersion function (VDF) of early-type galaxies directly derived from the SDSS Data Release 1 (DR1; Stoughton et al. 2002) galaxies (Sheth et al. 2003). However, Chae (2005) finds that the Sheth et al. (2003) VDF of early-type galaxies would imply a significantly underestimated abundance of early-type galaxies based on the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) first-year cosmology (Spergel et al. 2003) and the CLASS statistical sample. Just recently, Choi et al. (2007) have made a new measurement of the VDF of early-type galaxies based on the much larger SDSS Data Release 5 (DR5; Adelman-McCarthy et al. 2007)[4] galaxies, employing a new and more reliable method of classifying galaxies (Park & Choi 2005). The Choi et al. (2007) VDF has a much higher comoving number density of early-type galaxies and a different shape for the lower velocity part compared with the Sheth et al. (2003) VDF. The Choi et al. (2007) early-type number density is in favor of the Chae (2005) results.

The goal of this work is to improve strong lensing statistics using the SDSS DR5 VDF of early-type galaxies. Our focus shall be to put independent constraints on $\Omega_{m,0}$ and w_x assuming a flat cosmology. We consider both no evolution and a evolution of galaxies based on the prediction by a semianalytical model of galaxy formation (Kang et al. 2005; Chae et al. 2006). In § 2, we briefly describe the data and the analysis method. We present and discuss the results in § 3.

2. DATA AND METHOD

The comoving number density of galaxies as a function of velocity dispersion (σ) can be described by the modified Schechter function $\phi(\sigma)$ given by (Sheth et al. 2003; Mitchell et al. 2005)

$$dn = \phi(\sigma)d\sigma = \phi_* \left(\frac{\sigma}{\sigma_*}\right)^{\alpha} \exp\left[-\left(\frac{\sigma}{\sigma_*}\right)^{\beta}\right] \frac{\beta}{\Gamma(\alpha/\beta)} \frac{d\sigma}{\sigma}, \quad (1)$$

where ϕ_* is the integrated number density of galaxies, σ_* is the characteristic velocity dispersion, α is the low-velocity power-

[1] Sejong University, Department of Astronomy and Space Sciences, Gwangjin-Gu, Seoul 143-747, Korea; chae@sejong.ac.kr.

[2] See http://cfa-www.harvard.edu/castles.

[3] N. Inada, 2006 SDSS collaboration meeting in Seoul (http://astro.snu.ac.kr/~sdss/).

[4] The data set actually used is called DR4plus, which is very similar to the DR5.

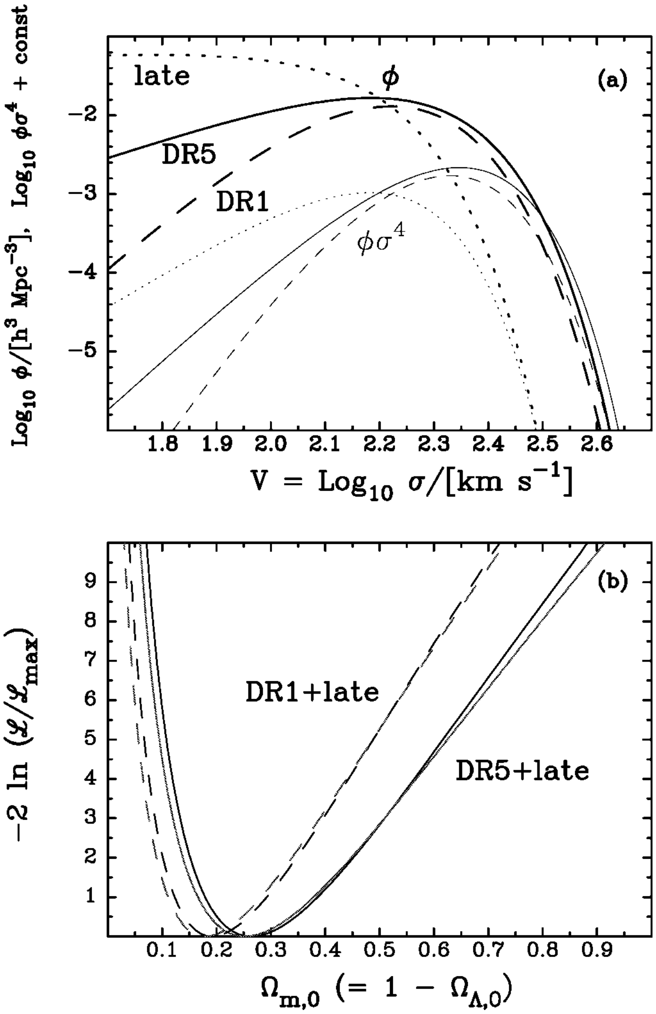

FIG. 1.—(*a*) Thick lines are the DR5 (*solid line*) and the DR1 (*dashed line*) early-type VDFs and the late-type VDF (*dotted line*). Thin lines show the behavior of $\phi\sigma^4$ (which is proportional to the differential lensing probability) for these VDFs. (*b*) Behavior of the likelihood function (eq. [7]) as $\Omega_{m,0}$ is varied for a flat cosmology with an Einstein cosmological constant. The solid (dashed) lines are based on the SDSS DR5 (DR1) VDF of early-type galaxies and the SDSS DR5 LF of late-type galaxies. The black and red curves correspond, respectively, to the cases of assuming no evolution of galaxies and the evolutions of galaxies predicted by a recent semianalytical model of galaxy formation. [*See the electronic edition of the Journal for a color version of this figure*.]

law index, and β is the high-velocity exponential cutoff index. Sheth et al. (2003; the number density being updated by Mitchell et al. 2005) found from the SDSS DR1 for the early-type galaxy population

$$(\phi_*, \sigma_*, \alpha, \beta)_{\rm DR1} = [(4.1 \pm 0.3) \times 10^{-3}\ h^3\ {\rm Mpc}^{-3},\ 88.8 \pm 17.7\ {\rm km\ s}^{-1},\ 6.5 \pm 1.0,\ 1.93 \pm 0.22], \quad (2)$$

where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-3}. This was the first direct measurement of the VDF of early-type galaxies. Just recently, Choi et al. (2007) have found from the much larger SDSS DR5

$$(\phi_*, \sigma_*, \alpha, \beta)_{\rm DR5} = [8.0 \times 10^{-3}\ h^3\ {\rm Mpc}^{-3},\ 161 \pm 5\ {\rm km\ s}^{-1},\ 2.32 \pm 0.10,\ 2.67 \pm 0.07]. \quad (3)$$

The above VDFs are intrinsic functions derived taking into account the correlated measurement errors of σ (Sheth et al. 2003; Choi et al. 2007). The DR1 and DR5 VDFs are shown in Figure 1*a*. The DR5 VDF is clearly quite different from the DR1 VDF in both the number density and the shape for the lower part of σ. This is in large part due to the improved galaxy classification scheme of Park & Choi (2005), who make use of a SDSS $u-r$ color versus $g-i$ color gradient space.

While early-type galaxies dominate strong lensing, late-type galaxies cannot be neglected. Among the radio-selected lenses with known galaxy types from the CLASS and the PANELS (see Chae 2005, Table 1), about 30% are late-types. For the late-type galaxy population, the direct measurement of the VDF is complicated by the significant rotations of the disks. We proceed as follows. We adopt the luminosity function (LF) of late-type galaxies from the SDSS DR5 (Choi et al. 2007). We turn the LF into a circular velocity function using a Tully-Fisher relation (Tully & Pierce 2000). Finally, we turn the circular velocity function into a VDF assuming that the circular velocity is proportional to the inner velocity dispersion as would be the case in an isothermal model. In principle, we can estimate all the parameters of equation (1) for the late-type population using the Tully-Fisher relation and a galaxy model. However, we leave σ_* free and determine it from the image separation distribution. Our adopted VDF for the late-type galaxy population is then

$$(\phi_*, \sigma_*, \alpha, \beta)_{\rm late} = [1.13 \times 10^{-1}\ h^3\ {\rm Mpc}^{-3},\ \sigma_*^{\rm (late)},\ 0.3,\ 2.91]. \quad (4)$$

A late-type VDF with $\sigma_*^{\rm (late)} = 133$ km s^{-1} determined from lensing in § 3 is shown in Figure 1*a*. It is interesting to note that this VDF of late-type galaxies matches relatively well that of Sheth et al. (2003), who determined $\sigma_*^{\rm (late)}$ using a Tully-Fisher relation taking into account the scatter of the Tully-Fisher relation.

The SDSS galaxy populations refer to a redshift range of $0 \lesssim z \lesssim 0.2$, while the radio-selected lenses are in the range of $0.3 \lesssim z \lesssim 1$, so that galaxy evolutions must be taken into account. Most previous works have been done with the assumption of no evolution of early-type galaxies from $z = 0$ to 1 relying on several observational arguments (see Chae 2003 and references therein) such as the fundamental plane and the color-magnitude relations. More recently, Mitchell et al. (2005) have taken into consideration galaxy evolutions using the prediction by the extended Press-Schechter model of structure formation, which is calibrated by *N*-body simulations (Sheth & Tormen 2002). We take into consideration galaxy evolutions using the predictions by a recent semianalytical model of galaxy formation (Kang et al. 2005; Chae et al. 2006) that is based on the high-resolution *N*-body simulations of Jing & Suto (2002). Specifically, we constrain the evolutions of the VDFs using the evolutions of the virial circular velocity functions used by Chae et al. (2006) assuming a power-law relation between the virial circular velocity and the velocity dispersion as given by equation (6) of Chae et al. (2006). We consider the evolutions of both the number density ϕ_* and the characteristic velocity dispersion σ_* as follows:

$$\phi_*(z) = \phi_{*,0}(1+z)^{\nu_n}; \quad \sigma_*(z) = \sigma_{*,0}(1+z)^{\nu_v}. \quad (5)$$

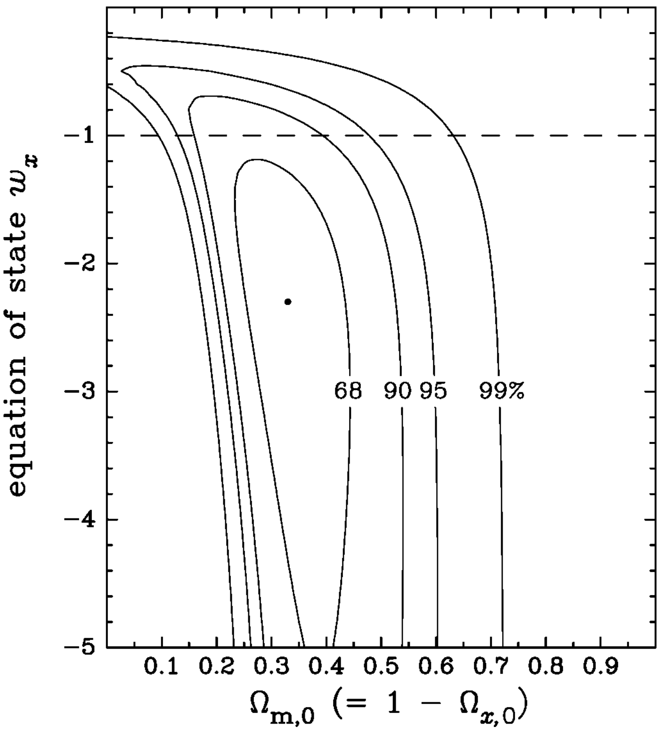

FIG. 2.—Constraints in the plane spanned by the matter density $\Omega_{m,0}$ (= $1 - \Omega_{x,0}$ in our assumed flat cosmology) and the nonevolving equation of state w_x of a generalized dark energy based on the SDSS DR5 VDF of early-type galaxies and LF of late-type galaxies through radio-selected strong lensing statistics. We have assumed the evolutions of galaxies predicted by a semianalytical model of galaxy formation.

We obtain the following best-fit parameters for the early-type and late-type galaxy populations of Kang et al. (2005):

$$(\nu_n,\ \nu_v) = (-0.229, -0.01) \text{ for early-type and } (1.24, -0.186) \text{ for late-type.} \quad (6)$$

We use all the lensing properties of the CLASS and the PANELS lenses (Chae 2005, Table 1). Specifically, we use both the image separation distribution of all "single" lenses as well as the number statistics of the well-defined CLASS statistical sample of 13 lenses. We use the same singular isothermal ellipsoid lens model and analysis method recently used by Chae (2003, 2005) and Chae et al. (2006). The likelihood function is essentially the same as that given by equation (11) of Chae et al. (2006), namely,

$$\ln \mathcal{L} = \left(\sum_j \ln \delta p_{\rm IS}(j)\right) + \left\{\sum_k \ln\,[1 - p(k)] + \sum_l \ln \delta p(l)\right\}, \quad (7)$$

where $\delta p_{\rm IS}(j)$ is the relative image separation probability, $p(k)$ is the total multiple-imaging probability due to both the early-type and late-type populations, and $\delta p(l)$ is the differential lensing probability of the specific separation, lensing galaxy type, lens and source redshifts. The only difference here is that for the lenses of unknown galaxy morphologies the image separation probability $\delta p_{\rm IS}(j)$ is calculated as a weighted sum due to the early-type and late-type galaxy populations where the weighting factors are the differential lensing probabilities for the observed specific image separations (Chae 2003, eq. [29]).

3. RESULTS AND DISCUSSION

We first consider a flat cosmology with an Einstein cosmological constant. Figure 1*b* shows the behavior of the likelihood function (eq. [7]) as the matter density $\Omega_{m,0}$ is varied. The results shown in Figure 1*b* are based on the SDSS DR1/DR5 early-type VDF (eqs. [2] and [3]) and the late-type VDF (eq. [4]). For the DR5 VDF we find $\Omega_{m,0} = 0.25^{+0.12}_{-0.08}$ and $0.26^{+0.12}_{-0.08}$ (68% CL), respectively, for the evolving (eq. [6]) and nonevolving populations of galaxies. The fitted value of $\sigma^{\rm (late)}_{*,0}$ for the late-type population is 133 and 127 km s^{-1}, respectively, for the evolving and nonevolving cases.

For the DR1 VDF we find $\Omega_{m,0} = 0.18^{+0.1}_{-0.06}$ and $0.19^{+0.1}_{-0.06}$ (68% CL), respectively, for the evolving (eq. [6]) and nonevolving populations of galaxies. The difference between the DR1 and the DR5 results can be understood from the behavior of $\phi\sigma^4$, which is proportional to the differential lensing probability, shown in Figure 1*a*. Note that our results based on the DR1 VDF differ from the Mitchell et al. (2005) results because of differences in the calculations of magnification biases and cross sections satisfying observational selection functions. For example, for the differential number-flux density relation of $|dN/dS| \propto (S/S_0)^{-\eta}$ with $S_0 = 30$ mJy, we use $\eta = 1.97$ (2.07) for $S < S_0$ ($S > S_0$), while Mitchell et al. (2005) use erroneously $\eta = 2.1$ for any S.[5] Taking into account the flux ratio limit for the doubly imaged systems in the CLASS statistical sample, namely, that the fainter-to-brighter image flux ratio must be greater than 0.1 (Browne et al. 2003; Chae 2003), Mitchell et al. (2005) find $\tilde{B} = 3.97$ using the singular isothermal sphere (SIS) model, where $\tilde{B}$ (Mitchell et al. 2005, eq. [15]) is the magnification bias times the cross section satisfying the flux ratio limit divided by the unbiased cross section. However, we find $\tilde{B} \approx 3.36$ for the SIS, taking correctly into account the CLASS observational selection functions. Another difference is that Mitchell et al. (2005) use the SIS, while we use the singular isothermal ellipsoid. For example, a lens ellipticity of 0.4 can amount to a difference of $\Delta\Omega_{m,0} \approx -0.05$ compared with the spherical case because of the variation of the magnification bias and cross section for the equal numbers of oblates and prolates (see, however, Huterer et al. 2005 for other possibilities).

The directly measured SDSS DR5 VDF of early-type galaxies is more reliable than VDFs inferred from early-type LFs using a Faber-Jackson (Faber & Jackson 1976) relation (e.g., Chae 2003) because of significant scatters in the relation (Sheth et al. 2003). The SDSS DR5 VDF is also likely to be more reliable than the DR1 VDF (Sheth et al. 2003) not only because the DR5 VDF is based on a much larger volume sample but also because it is based on a more reliable galaxy classification technique by Park & Choi (2005). Therefore, the SDSS DR5 VDF in conjunction with galaxy evolution models from a recent semianalytic model of galaxy formation (Kang et al. 2005; Chae et al. 2006) removes in large part potential systematic errors in one of the main ingredients of strong lensing statistics.

Our derived values of the matter density based on the SDSS DR5 VDF are in excellent agreement with the results from the *WMAP* and the large-scale structures in the SDSS luminous red galaxies (Spergel et al. 2003, 2006; Tegmark et al. 2004; Eisenstein et al. 2005). The SDSS lens search is eventually expected to discover from 60 to 70 strongly lensed quasars. Thus, we expect that the precision of strong lensing statistics

[5] While the lensed sources have observed flux densities $S_{\rm ob} > 30$ mJy, the magnification factor is given as an integration for the range from $S = S_{\rm ob}$ to $S_{\rm ob}/\mu_{\rm max}$, where $\mu_{\rm max}$ is the maximum possible theoretical magnification (see Chae 2003, eq. [36]). Thus, it is essential to use $\eta = 1.97$ for $S < 30$ mJy.

will improve by a factor of 2 or better in the near future (in particular if the CLASS statistical sample is combined with the SDSS sample). Furthermore, within a few decades next generation observation tools such as the Square Kilometer Array (e.g., Blake et al. 2004; Koopmans et al. 2004) will improve the precision of lensing statistics by orders of magnitude. Perhaps strong lensing statistics may play even more important roles in the future for uncovering the physical processes of galaxy formations and evolutions (see, e.g., Kochanek & White 2001; Keeton 2001; Chae & Mao 2003; Ofek et al. 2003; Chae et al. 2006).

Finally, we consider a flat cosmology with a generalized dark energy $\Omega_{x,0}$ with a nonevolving equation of state w_x. Figure 2 shows the confidence limits in the $\Omega_{m,0}$-w_x plane. We have $w_x < -1.2$ at the 68% CL ($w_x < -0.5$ at the 95% CL), so that strong lensing appears to marginally favor a supernegative equation of state (e.g., Caldwell et al. 2003). On the other hand, the *WMAP* results (Spergel et al. 2006) favor $w_x = -1$ (Einstein's cosmological constant). It is not clear at the present why lensing data appear to favor $w_x < -1$. It will be interesting to see whether this remains so with future lensing data.

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