A MEASUREMENT OF THE COSMOLOGICAL CONSTANT USING ELLIPTICAL GALAXIES AS STRONG GRAVITATIONAL LENSES

MYYNGSHIN IM, RICHARD E. GRIFFITHS, AND KAVAN U. RATNATUNGA
Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218
Received 1996 February 29; accepted 1996 August 20

ABSTRACT

We have identified seven (field) elliptical galaxies acting as strong gravitational lenses and have used them to measure cosmological parameters. To find the most likely value for \( \Omega_m (= \Omega_{\text{matter}}) \) and \( \Lambda \), we have used the combined probabilities of these lens systems having the observed critical radii (or image deflection) for the measured or estimated values of lens redshifts, source redshifts, and lens magnitudes. Our measurement gives \( \Lambda = 0.64 \pm 0.20 \) if \( \Omega_m + \Lambda = 1 \), and the \( \Omega_m = 1 \) model is excluded at the 97% confidence level. We also find, at the 68% (\( \Omega = 0 \))–82% (\( \Omega = 0.3 \)) confidence level, that an open universe is less likely than a flat universe without nonzero \( \Lambda \). Except for the possibility of strong perturbations due to cluster potentials and the systematic overestimation of the lens magnitudes, other possible systematic errors do not seem to influence our results strongly: correction of possible systematic errors seems to increase the significance of the result in favor of a nonzero \( \Lambda \) model.

Subject headings: cosmology: observations — cosmology: theory — galaxies: elliptical and lenticular, cD — gravitational lensing

1. INTRODUCTION

Recently, nonzero cosmological constant (\( \Lambda \)) models have found increased popularity (e.g., Ostriker & Steinhardt 1995) owing to the problem of the age discrepancy implied by the latest Hubble Space Telescope (HST) measurements of the Hubble constant: the ages of globular clusters are apparently larger than the age of the universe predicted by the standard \( \Omega_m = 1 \) model favored by standard inflationary theory (e.g., Freedman et al. 1994; for a brief overview of these arguments, see Rees 1996).

In order to measure \( \Lambda \), it has been suggested that strong gravitational lenses might be used, i.e., isolated galaxies or clusters of galaxies for which the gravitational potential results in multiple imaging of a background object (Paczyński & Gorski 1981; Aliko & Anderson 1986; Gott, Park, & Lee 1989). Following these suggestions, the use of the lens number counts (or the optical depth) was advocated since this is very sensitive to \( \Lambda \) (Turner 1990; Fukugita, Futamase, & Kasai 1990; Fukugita et al. 1992). Maoz & Rix (1993) and Kochanek (1996) have applied this method, obtaining upper limits of \( \Lambda \leq 0.7 \).

Kochanek (1992) has also suggested the lens redshift method, which, compared with the method based on lens counts, requires less presumptions about the properties of lenses and sources, properties that might bias the lens counts considerably (Helbig & Kayser 1996; Kochanek 1992; Fukugita & Peebles 1995). Taking into account the selection effects that were neglected in his early study (Kochanek 1992; for a discussion on this selection effect, see Helbig & Kayser 1996), Kochanek (1996) finds \( \Lambda < 0.9 \) at 2\( \sigma \) with a peak at \( \Lambda = 0.4 \). However, the estimated value of \( \Lambda \) in Kochanek (1996) is sensitive to the detection threshold, which is not well understood, and thus it cannot be considered very seriously at the present stage.

It has been recognized that the mean splitting of the lensed images alone is useful for studies of the dynamical properties of lens galaxies, but not for the measurement of \( \Lambda \) (Turner, Ostriker, & Gott 1984, hereafter TOG84; Fukugita et al. 1992). However, when the mean separation is used together with other information such as the lens redshift, the lens magnitude, and the velocity dispersion of the lens galaxy, then the mean separation does become sensitive to \( \Lambda \) (Paczyński & Gorski 1981; Gott et al. 1989; Kochanek 1992; Miralda-Escude 1991). In this Letter, we will try to measure \( \Lambda \) using a method we call the “lens parameter method,” which is basically similar to those discussed in the above references.

2. LENS PARAMETER METHOD

The commonly observed parameters for gravitational lenses are the lens redshift (\( z_L \)), the source redshift (\( z_S \)), the mean deflection of the lensed object (or similarly the critical radius \( \theta_{\text{crit}} \)), the lens magnitude (\( m_L \)), and the source magnitude (\( m_S \)). For some systems, one or two of these observational parameters may be missing. How sensitive is \( \theta_{\text{crit}} \) to \( \Omega_m \) and \( \Lambda \) for a given set of \( z_L, z_S \), and \( m_L \)? To calculate \( \theta_{\text{crit}} \), we will adopt the singular isothermal sphere (SIS) model for the lens, along with the filled beam approximation (see § 4), and the Faber-Jackson relation (Faber & Jackson 1976). The Faber-Jackson relation relates the velocity dispersion (\( \sigma \)) of E/S0 galaxies to their luminosities (\( L \)): \( \sigma = \sigma_0 (L/L_0)^{0.7} \). Here, we adopt \( \sigma_0 = 225 \) km s\(^{-1} \), \( \beta = 0.25 \) and \( m_{SBF} = -19.9 + 5 \log (h) \).

Then \( \theta_{\text{crit}}(z_L, z_S, m_L) \) can be expressed as

\[
\theta_{\text{crit}} = \frac{4\pi \sigma_0}{c^2 \Phi} d(z_S, z_L) [d(0, z_L)(1 + z_L)^2]^{1+2\beta} /d(0, z_S) 10^{-0.8\beta(m - M_S - K(z) - E(z) - 25)},
\]

where \( d(z_1, z_2) \) is the angular size distance between the redshifts \( z_1 \) and \( z_2 \) in Mpc, \( m \) is the total apparent magnitude of the lens galaxy, \( K(z) \) and \( E(z) \) are the \( K \)-correction and the evolutionary correction, respectively, for the lens galaxy. The \( (E + K) \) correction is important, and to calculate it we will use the 1 Gyr burst model of Bruzual & Charlot (1993) at the formation redshift \( z_{\text{form}} \) = 10. This \( (E + K) \) correction is consistent with the results from the HST Medium Deep Survey (MDS) on the evolution of the luminosity function of elliptical galaxies (Im et al. 1996), which shows a brightening in luminosity by about 1 mag looking back to \( z \sim 1 \).
Figure 1 shows the $\theta_{\text{crit}} - z_s$ relation for the strong gravitational lens systems HST 12531–2914 and HST 14176 + 5226, taking parameters from Ratnatunga et al. (1995). The two curves show the model predictions under the adoption of different cosmological parameters, and the horizontal line shows the observed value (the source redshift is unknown). The value of $\theta_{\text{crit}}$ is quite sensitive to $\Lambda$ when values are known for $z_L$, $z_S$, and $m_L$. However, the uncertainty in the prediction is about a factor of 10$^{0.15}$, which arises mainly from the uncertainties in the Faber-Jackson relation and in the apparent lens magnitude. Hence, a single lens system such as HST 12531–2914 cannot be used alone to measure $\Lambda$. In order to set a useful limit on $\Lambda$ with this method, a sample of at least five lenses is required (e.g., see Kochanek 1992).

In order to combine the information on cosmological parameters from all available lenses, we therefore construct a likelihood function that is the product of the probability of each lens having the observed value of $\theta_{\text{crit}}$ for the given values of $z_S$, $z_L$, $m_L$, and the cosmological parameters. This probability $p(\theta_{\text{crit}})$ is defined as

$$p(\theta_{\text{crit}}; z_L, z_S, m_L, \Omega_m, \Lambda) \sim \int G(\theta_{\text{crit}}[z_L, z_S, m(z)], \sigma_0) \times G(z_L, z_S, \sigma_{z_L})G(m(z), m_L, \sigma_{m_L}) dz,$$

where $\sigma_0$ is the dispersion in the predicted $\log_{10}(\theta_{\text{crit}})$ due to the uncertainty arising from the Faber-Jackson relation, together with other minor uncertainties, $\sigma_{z_L}$ is the uncertainty in $z_L$, and $\sigma_{m_L}$ is the uncertainty in $m_L$. $G(x, x_0, dx)$ is the Gaussian function with the mean of $x_0$ and the dispersion of $dx$. We adopt $\sigma_0 = 0.14$ (or in terms of magnitude, $\sigma \approx 0.7$), which is a combination of the uncertainties arising from the Faber-Jackson relation ($0.65 \times 2 = 0.13$; de Zeeuw & Franx 1991), $M_\bullet(0.3 \times 0.2 = 0.06$; Marzke et al. 1994; Loveday et al. 1992), and the $E + K$ correction ($0.5 \times 0.2 = 0.1$; Im et al. 1996). When $z_S$ is not available (HST 12531–2914), we also integrate equation (2) over $z_S$, assuming a uniform distribution in redshift space.

Finally, the likelihood function can be written

$$L = \prod_j p_{\text{norm}}(\theta_{\text{crit}}; z_L, z_S, m_L),$$

where $p_{\text{norm}}$ is the normalized probability of equation (2).

We did not adopt the $(3/2)^{0.5}$ factor (hereafter TOG factor) suggested by TOG84 in order to account for the possible difference between the velocity dispersion of the underlying dark matter and the luminous material. Recent studies show that this factor is not necessary (Kochanek 1993, 1994; Bremer & Sanders 1993; Franx 1993). Independently, we also checked the necessity of the TOG factor by considering the mean image splittings (see §4).

The advantage of this method over the previous methods is the explicit use of the lens magnitude and the $E + K$ correction, of which the latter has been observationally constrained only recently (Im et al. 1996; Faber, Djorgovski, & de Carvalho 1996; Bender, Ziegler, & Bruzual 1996; Barrientos, Schade, & Lopez-Cruz 1996). These measurements enable us to make a reasonably good estimate of the dynamical properties of each lens galaxy. The probability of each individual lens having its unique configuration can then be calculated based on these individual properties, so that we do not have to use statistical measurements (e.g., the luminosity function) that may decrease the dependence on the cosmological parameters when they are averaged over large numbers of objects. Although our method is, in principle, not as sensitive to the value of $\Lambda$ as is the lens number count method (e.g., Fukugita et al. 1992), the latter method is possibly subject to greater uncertainties (see §4). Our method is slightly more susceptible to a small change in one of the input parameters, but, in common with the lens redshift method, we have a smaller number of parameters than the lens count method. In this respect, our method has an edge over the latter. In particular, the properties of lens galaxies at high redshift ($z \gtrsim 1.5$) are highly uncertain. They could be dusty enough that the result from the lens counts might be biased against the nonzero $\Lambda$ model (Fukugita & Peebles 1995). In contrast, the lens parameter method uses lensing galaxies that lie at $z \lesssim 1$ (see §3), and the method is thus less affected by the unknown properties of high-redshift galaxies.

3. SAMPLE SELECTION

Gravitational lenses are selected using the following criteria:

1. The strong lensing must be caused by a single galaxy lens. For example, we do not include 2016–+112 in our sample since there are two lensing galaxies in this system. Also, we have excluded lens systems that are clearly influenced by strong perturbations due to cluster potentials (e.g., 0957 + 561, B1422 + 231).

2. It must be known that the lens galaxy is likely to be elliptical. For example, we do not include B0218 + 357 in our study since there is good evidence that the lensing galaxy is a spiral or a late-type galaxy (Patnaik et al. 1993).

3. The apparent magnitude and the redshift of the lens galaxy must be known or estimated to reasonable accuracy.
TABLE 1

| Name                  | $m_L$(total) | $z_L$ | $z_S$ | $\theta_{\text{sec}}$ | References |
|-----------------------|--------------|-------|-------|------------------------|------------|
| HST 14176+5226 ....... | $I = 19.71 \pm 0.05$ | 0.81  | 3.4 (7) | 1.51 | 1, 2                  |
| HST 12531-2914 ....... | $I = 21.82 \pm 0.05$ | 0.7 ± 0.1 | <5 | 0.65 | 1                     |
| PG 1115+080 ..........  | $R = 18.36 \pm 0.3$ | 0.29  | 1.72  | 1.10 | 3, 4                  |
| MG 1654+1346 ........... | $R = 18.4 \pm 0.3$ | 0.25  | 1.74  | 1.05 | 5                     |
| CLASS 1608+656 ........| $R = 19.7 \pm 0.3$ (K ≈ 16) | 0.63  | 1.39  | 1.05 | 6, 7                  |
| 0142-100 .............. | $R = 19.36 \pm 0.10$ | 0.49  | 2.72  | 1.10 | 8, 9                  |
| MG 0414+0534 .......... | $I = 21.22 \pm 0.15$ | 1.2 ± 0.4 | 2.64 | 1.05 | 10, 11, 12            |
| B0218+357* ............ | $R = 20.0 \pm 0.3$ | 0.68  | 0.94  | 0.35 | 13                    |

* Spiral galaxy lens.

REFERENCES.—(1) Ratnatunga et al. 1995; (2) Crampton et al. 1996; (3) Weymann et al. 1980; (4) Kristian et al. 1993; (5) Langston et al. 1989; (6) Myers et al. 1995; (7) Fassnacht et al. 1996; (8) Surdej et al. 1987; (9) Falco 1995; (10) Hewett et al. 1992; (11) Lawrence et al. 1995; (12) Schechter & Moor 1992; (13) Patnaik et al. 1993.

Accurate values for $m_L$ and $z_L$ are important for estimates of the dynamical properties of the lens galaxy.

4. For lens candidates that do not have a measured value for $z_S$, we select only those that show distinctive features such as rings or crosses.

We find that there are seven strong gravitational lenses that meet these selection criteria in the published literature, including objects found in our HST surveys (Table 1). B1422+231 is excluded from this list because of the possible cluster perturbation as well as the ambiguity in the lens redshift ($z_L = 0.64$ from Hammer et al. 1995 vs. $z_L \approx 0.4$ from Impey et al. 1996). For MG 0414+0534, there have been speculations that the source redshift of the system is $z = 1.00$ (Lawrence, Cohen, & Oke 1995), suggesting that the $z \approx 1$ measurement pertains to the lens galaxy (Surdej & Soucail 1994). We have analyzed the archived HST observations of this system and find a preliminary result of $R_{F675W} - I_{F814W} = 1.5 \pm 0.2$ for the lens galaxy (Ratnatunga et al. 1997), suggesting that $z_L = 1.2 \pm 0.4$, consistent with the previous estimates of $z_L = 1$, and hence we will adopt $z_L = 1.2 \pm 0.4$ for this system. Finally, we have subtracted a few tenths of a magnitude from some of the quoted lens magnitudes in the literature, in order to correct for the total apparent magnitude. When the uncertainty in the lens magnitude is not quoted in the relevant reference, errors of about 0.3 mag are assigned to these lens galaxies.

4. RESULTS AND DISCUSSION

In Figure 2, we present the relative likelihood of our measurement against $\Omega_m$ for two cases of cosmological interest: (i) $\Omega_m + \Lambda = 1$ and (ii) $\Lambda = 0$. Both likelihood functions are normalized with the maximum likelihood of case (i), and direct comparison of cases (i) and (ii) is possible using Figure 2. When a flat universe is assumed—case...
We find that $\Lambda = 0.64^{+0.15}_{-0.20}$, and we exclude the $\Omega_m = 1$ model with 97% confidence. Also, a universe with $\Lambda \gtrsim 0.9$ is excluded at the 95% confidence level. If $\Lambda = 0$ is assumed—case (ii)—then $\Omega_m \approx 0$ is favored. The difference in the likelihood function between a flat universe with $\Lambda = 0.64$ and an open universe with $0 < \Omega < 0.3$ is about 0.5–1. Hence, a flat universe with nonzero $\Lambda$ is favored over an open universe at 68%–82% confidence.

Our result is only marginally consistent with the previous estimate of $\Lambda < 0.7$ based on the lens counts, which strongly favored the zero $\Lambda$ flat universe (Kochanek 1996; Maoz & Rix 1993). To see what might have caused the disagreement between our result and the previous results, we have investigated the possible systematic errors in our analysis and these are listed below.

4.1. The Filled Beam Approximation versus the Empty Beam Approximation

To relate redshift to distance, the filled beam approximation assumes that light rays propagate through smoothly averaged spacetime. In reality, spacetime is inhomogeneous, and therefore the filled beam approximation may not be correct (e.g., Fukugita et al. 1992). To see how our result could be affected by the filled beam approximation, the analysis was repeated adopting another extreme assumption, namely the empty beam approximation. We find that the latter approximation does not change our result significantly, but strengthens our finding slightly in favor of the nonzero $\Lambda$ model.

4.2. Singular Isothermal Sphere versus Softened Isothermal Sphere

We can also assume different mass models for the lens rather than the SIS model. Recent studies show that the SIS model may be too simple to adequately describe the mass of E/S0s (Lauer 1988; Krauss & White 1992), although the size of the core radius may be small enough to be negligible (Wallington & Narayan 1993). If the softened isothermal sphere is used, the predicted $\theta_{\text{crit}}$ will be a bit smaller than the predicted $\theta_{\text{crit}}$ with the SIS model. In Figure 1, this means that the predicted lines need to be shifted down along the $\theta_{\text{crit}}$ axis, making the $\Omega_m = 1$ flat model more inconsistent with the prediction. The adoption of the softened isothermal sphere model will thus strengthen our result.

4.3. Morphological Misclassification

In our analysis, we have assumed that each lens galaxy is an E/S0. This assumption may be wrong, and to estimate the bias introduced by treating a spiral galaxy lens as an elliptical galaxy lens, we repeated our analysis with the inclusion of one known spiral lens system (B0218+357) treated as an E/S0 lens. This caused the result to be strongly biased in favor of the $\Lambda = 0$ model, because of the small predicted $\theta_{\text{crit}}$ of the spiral lens system, a result similar to the issue discussed in §4.2. Thus, if one of the seven lenses we used was actually a spiral galaxy rather than an elliptical, then the correction of it would only strengthen our result.

4.4. Wrong Lens Magnitude

Because the lens galaxy is much fainter than the lensed object in some cases, there is a possibility that the lens magnitudes are not well determined. Systematic overestimate of the lens magnitudes by more than 0.6 mag can bias the result against the $\Omega_m = 1$ model. Recent HST observations provide clues as to the accuracy of the ground-based estimates of lens magnitudes. The preliminary result by Falco (1995) from the HST observation of 0142–100 gives an aperture magnitude of $R_{F675W} = 19.66 \pm 0.01$ for the lens galaxy, while the original measurement by Surdej et al. (1987) is $R = 19$. For MG 0414+0534, our preliminary analysis of the HST observation shows $I \approx 21.4 \pm 0.15$ for the lens galaxy (Ratnatunga et al. 1997), agreeing with the previous estimate of $I \approx 21.08–21.36$ from the ground (Schechter & Moore 1992). On the other hand, Impey et al. (1996) find $m_p = 21.5 \pm 0.3$ in $V$ for the lens galaxy of B1422+231. The ground-based estimate is $r = 21.8 \pm 0.6$ for this object (Yee & Ellingson 1994; Yee 1995). At $z = 0.4$, $V - r \sim 1$ for E/S0 galaxies, thus the observed ground-based lens magnitude for this system disagrees with the HST observation by about 1 mag. These three examples may indicate that the early ground-based measurements are not very accurate. Errors seem to go both ways, and hence there may be no systematic overestimate of the lens magnitudes. But there are only seven lenses in our sample, and it may be premature to say that there are no systematic errors in the lens magnitudes.

4.5. The TOG Factor

With the TOG factor included, we find that the peak of the likelihood function shifts to the region where both $\Omega_m$ and $\Lambda$ are very small, where our test becomes quite insensitive to the cosmological parameters. However, many studies have shown in different ways that the TOG factor is not needed (Kochanek 1996, and references therein). In order to confirm earlier findings, we analyzed the mean image deflections of the known lens systems with the known source redshifts. Using criteria (1) and (2) described in §3, we find that there are 11 lens systems available for this analysis (see Table 1 in Keeton & Kochanek 1995). For these systems, we calculated the ratio $\theta_{\text{crit,obs}}/\langle \theta_{\text{crit}}(z) \rangle$. Since $\langle \theta_{\text{crit}}(z) \rangle$ is fairly independent of the cosmological parameters (TOG84; Fukugita et al. 1992), the average of 11 $\theta_{\text{crit,obs}}/\langle \theta_{\text{crit}}(z) \rangle$ values will be about 1 if the TOG factor is not necessary and about 1.5 if the TOG factor is appropriate. We find an average value of $1.0 \pm 0.1$, confirming that the TOG factor is not necessary. In order to test the TOG factor independently, the study of strong lenses at low redshift ($z < 0.1$) might be fruitful, since their lens parameters are then insensitive to the cosmological parameters. An optical survey that covers a large fraction of sky (e.g., SDSS) should be able to find a statistically significant number ($\sim 100$) of such lenses.

4.6. Cluster Perturbation

Since elliptical galaxies preferentially live in a cluster environment, the gravitational potential of the lens may include a cluster component. The strong cluster perturbation generally increases the mean image deflection, and hence we tried to exclude such lenses from our study (See criterion [1] of §3). Nevertheless, we cannot completely exclude the possibility that some of the lenses in our sample include a considerable amount of cluster perturbation. If that has happened, our result could be biased against the $\Omega_m = 1$ universe. To understand the possible contribution to the image splitting from the cluster potential, detailed modeling of the lens systems is desired using high-resolution images from the HST, or else radio observations.
4.7. Source Redshift for HST 14176 + 5226

Crampton et al. (1996) have recently published a tentative source redshift for the lens system HST 14176 + 5226. A strong emission line is found at 5324 Å, along with a possible weak emission feature at 6822 Å. The strong emission line is very likely to be Lyα at z = 3.39 if the weak emission feature at 6822 Å is real, and the latter can then be identified as C IV 1549. If the 6822 Å feature is not real, then the source object could be located at a redshift lower than z = 3.4. If z < 3.4 for the HST 14176 + 5226, then the predicted θₚ will be reduced. This would bring the peak of the likelihood function toward the large Λ value, strengthening the result in favor of the nonzero Λ model (see Fig. 1).

4.8. E + K Correction

The adopted E + K correction assumes a formation redshift z_for = 10 with a 1 Gyr burst of star formation. We find that the E + K correction is most sensitive to the value of z_for, and insensitive to the other parameters. If we adopt z_for > 10, then the result changes insignificantly toward the zero Λ model. If z_for < 10, the result changes in favor of the nonzero Λ model, and the change is significant when z_for < 2. If z_for = 1.5, Λ could be as large as Λ ≈ 0.8.

If our result is an overestimate in the value of Λ, then there must have been a large systematic overestimate of the lens magnitudes and/or there are strong cluster perturbations. On the other hand, if the lens counts have led to an underestimate in the value of Λ, then that could have been caused by: (1) the dusty nature of high-redshift elliptical galaxies (see § 2 for more discussion); (2) a decrease in the E correction is most sensitive to the value of z_for, and insensitive to the other parameters. If we adopt z_for > 10, then the result changes insignificantly toward the zero Λ model. If z_for < 10, the result changes in favor of the nonzero Λ model, and the change is significant when z_for < 2. If z_for = 1.5, Λ could be as large as Λ ≈ 0.8. If our result is an overestimate in the value of Λ, then there must have been a large systematic overestimate of the lens magnitudes and/or there are strong cluster perturbations. On the other hand, if the lens counts have led to an underestimate in the value of Λ, then that could have been caused by: (1) the dusty nature of high-redshift elliptical galaxies (see § 2 for more discussion); (2) a decrease in the number density of ellipticals as a function of look-back time, as expected if most elliptical galaxies were created via major merging events (Im et al. 1996, 1997; Baugh, Cole, & Frenk 1996; Kauffmann, Charlot, & White 1996); and/or (3) other uncertainties in the properties of lens galaxies, such as the LF and the dynamical properties of the low-mass ellipticals. Future HST observations of faint galaxies, as well as the accumulating redshift data from ground-based telescopes, will hopefully put stringent constraints on elliptical galaxy evolution at z > 1. These data will possibly give us indications as to why the results from the lens counts have strongly favored the zero Λ model, while our result strongly rejects the flat universe with Λ = 0. It is noteworthy that neither method strongly rejects the low Ω universe.

5. CONCLUSIONS

We have described and applied the lens parameter method to measure cosmological parameters using strong gravitational lenses. Using seven strong lenses each with an identified lens galaxy, we find that a model universe with Ω = 0.65 and low Ω is favored and that the flat model with Ω = 0 is excluded at greater than 95% confidence. A universe with low Ω and Λ = 0 can be marginally excluded with respect to the flat universe with a nonzero Λ at 68%–82% confidence. Our result is not biased in favor of a nonzero Λ model due to any conceivable systematic errors, except for possible strong perturbations from cluster potentials, and systematic overestimate of the lens magnitudes. Future HST observations should uncover new lens systems with measurable lens properties suitable for this kind of study, and they should also provide a better understanding of the known lens systems. We should therefore be able to get a stronger constraint on Λ in the near future.

The HST Medium Deep Survey is funded by STScI grants GO2684 et seq. We would like to thank the other members of the Medium Deep Survey Team at JHU, especially Eric J. Ostrander for his efforts on retrieving and reducing the archival HST data. We are grateful to Emilio Falco for providing the lens magnitudes of 0142–100 system. We also thank Chris Kochanek, Howard K. C. Yee, Joel Primack, and Stefano Casertano for useful discussions and communications, and Mark Subbarao and the anonymous referee for helpful comments on the manuscript.

REFERENCES

Alock, C., & Anderson, N. 1986, ApJ, 302, 43
Barrientos, L. F., Schade, D., & Lopez-Cruz, O. 1996, ApJ, 460, L89
Baugh, C. M., Cole, S., & Frenk, C. S. 1996, MNRAS, submitted
Bender, R., Ziegler, B., & Bruzual, G. 1996, ApJ, 463, L51
Bremer, T. G., & Sanders, R. H. 1993, A&A, 274, 96
Bruzual, G. A., & Charlot, S. 1993, ApJ, 405, 538
Burke, B. F. 1990, in Lecture Notes in Physics, 360, Gravitational Lensing, ed. Y. Meillier, B. Fort, & G. Soucail (Berlin: Springer), 127
Crampton, D., Le Fevre, O., Hammer, F., & Lilly, S. J. 1996, A&A, in press de Zeeuw, T., & Franx, M. 1991, ARA&A, 29, 239
Faber, S., & Jackson, R. 1976, ApJ, 204, 668
Falco, E. 1995, private communication
Fassnacht, C. D., et al. 1997, ApJ, in press
Franx, M. 1993, in Galactic Bulges, ed. H. Dejonghe & H. J. Habing (Dordrecht: Kluwer), 243
Freedman, W. L., et al. 1994, Nature, 371, 757
Fukugita, M., Futamase, T., & Kasai, M. 1990, MNRAS, 246, 24P
Fukugita, M., Futamase, T., Kasai, M., & Turner, E. L. 1992, ApJ, 393, 3
Fukugita, M., & Peebles, P. E. J. 1995, Princeton preprint
Gott, J. E. III, Park, M.-G., & Lee, H. M. 1989, ApJ, 338, 1
Helbig, P., & Kayser, R. 1996, A&A, in press
Hammer, F., et al. 1995, A&A, 298, 737
Hewitt, J. N., et al. 1992, AJ, 104, 968
Kochanek, C. S. 1996, ApJ, 473, in press
Krauss, L. M., & White, M. 1992, ApJ, 394, 385
Kristian, J., et al. 1993, AJ, 106, 1330
Langston, G. I., et al. 1989, AJ, 97, 1283
Lauer, T. 1988, ApJ, 325, 49
Lawrence, C. R., Cohen, J. G., & Oke, J. B. 1995, AJ, 110, 2583
Loveday, J., Peterson, B. A., Efstathiou, G., & Maddox, S. J. 1992, ApJ, 390, 338
Maoz, D., & Rix, H.-W. 1993, ApJ, 416, 425
Marzke, R. O., Geller, M. J., Huchra, J. P., & Corwin, H. G. 1994, AJ, 108, 437
Miralda-Escude, J. 1991, ApJ, 370, 1
Myers, S. T., et al. 1995, ApJ, 447, L5
Ostriker, J. P., & Steinhardt, P. J. 1995, preprint
Paczynski, B., & Gorski, K. 1981, ApJ, 248, L101
Palmer, M. A., Djorgovski, S. G., & de Carvalho, R. R. 1996, ApJ, 456, L79
Patnaik, A. R., et al. 1993, MNRAS, 261, 435
Ratnatunga, K. U., Ostrander, E. J., Griffiths, R. E., & Im, M. 1995, ApJ, 453, L5
Ratnatunga, K. U., et al. 1997 in preparation
Rees, M. 1996, in Proc. First RESCUE Symp., The Cosmological Constant and the Evolution of the Universe, ed. M. Fukugita (Tokyo: Universal Academy Press), 1
Schechter, P. L., & Moore, B. 1992, AJ, 105, 1
Surdej, J., & Soucail, G. 1994, in Gravitational Lenses in the Universe, ed. J. Surdej, D. Frapont-Caro, E. Gosset, S. Refsdal, & M. Remy (Liege: Université de Liège), 153
Surdej, J., & Soucail, G. 1987, Nature, 329, 695
Turner, E. L. 1990, ApJ, 365, L43
Wallington, S., & Narayan, R. 1993, ApJ, 403, 517
Weymann, R. J., et al. 1980, Nature, 285, 641
Yee, H. K. C. 1995, private communication
Yee, H. K. C., & Ellingson, E. 1994, AJ, 107, 28