Impact of Gravitational Lensing on Cosmology
Proceedings IAU Symposium No. 225, 2004
Mellier, Y. & Meylan, G. eds.

doi:10.1017/S1743921305002231

Quasar Lensing Statistics and Ω_Λ: What Went Wrong?

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Abstract. In the pre-WMAP, pre-Supernova-Ia-Hubble-diagram era, quasar lensing statistics stubbornly indicated low values of Ω_Λ. In contrast, a number of recent lensing statistics studies either find the data support the standard ΛCDM picture, or simply take the standard cosmological parameters as a given. Have the data or the analyses changed or improved, and how? I review several of the "historical" and the more recent studies, and show that there is no particular measurement, assumption, or model parameter in the old studies that was grossly wrong. Instead, at least several effects, operating together, are likely required in order to achieve agreement between the observations and the currently standard cosmology. Most likely among these effects are: a somewhat lower lensing cross section for elliptical galaxies than assumed in the past; some loss of lensed quasars in optical samples due to extinction by the lenses; and a somewhat lower-than-standard value of $\Omega_\Lambda \sim 0.6$. The agreement between recent model calculations and the results of radio lens surveys may be fortuitous, and due to a cancellation between the errors in the input parameters for the lens population and the cosmology, on the one hand, and for the source population, on the other hand.

1. Introduction

The fraction of quasars that are strongly lensed (i.e., split into multiple images) by intervening galaxies is a probe of, among other things, the volume of space between us and the quasars. Since the size of this volume depends on cosmological parameters, and in particular on the cosmological constant, Ω_Λ, measurement of the lensed fraction can constrain cosmology. Specifically, a large value of Ω_Λ gives a large volume, out to a given redshift, and hence leads to a large lensing probability, assuming a constant comoving density of lenses (i.e., galaxies). This idea was first outlined in a series by papers of Ed Turner and collaborators (Turner, Ostriker, & Gott 1984; Turner 1990; Fukugita & Turner 1991; see Kochanek *et al.* 2004 for a recent review). Figure 1 shows the increase in volume out to a source at $z = 2$, as a function of Ω_Λ, for flat geometries. A useful order of magnitude estimate for the lensing optical depth τ for sources at distance D, lensed by an intervening population with density n, and with each lens having a strong-lensing cross section σ is

$$\tau \sim n\sigma D. \tag{1.1}$$

Taking, for n, the comoving density of L_* ellipticals, 0.5×10^{-2} Mpc^{-3}, for the cross section for multiple lensing, πR_E^2, where $R_E \sim 5$ kpc is a typical Einstein radius for an L_* elliptical at $z \sim 0.5$, and a proper-motion distance to the source of about 2 Gpc, Eq. 1.1 gives a lensing otical depth of order 10^{-3}. To obtain the lensing probability, the optical depth must be corrected by the magnification bias, B, i.e., the over-representation of lensed objects in a flux limited sample of sources having a steeply rising number-magnitude relation, due to the magnification that lensing entails. For bright quasar samples, $B \sim 10$, while for radio samples B is typically a few. Thus one expects of order

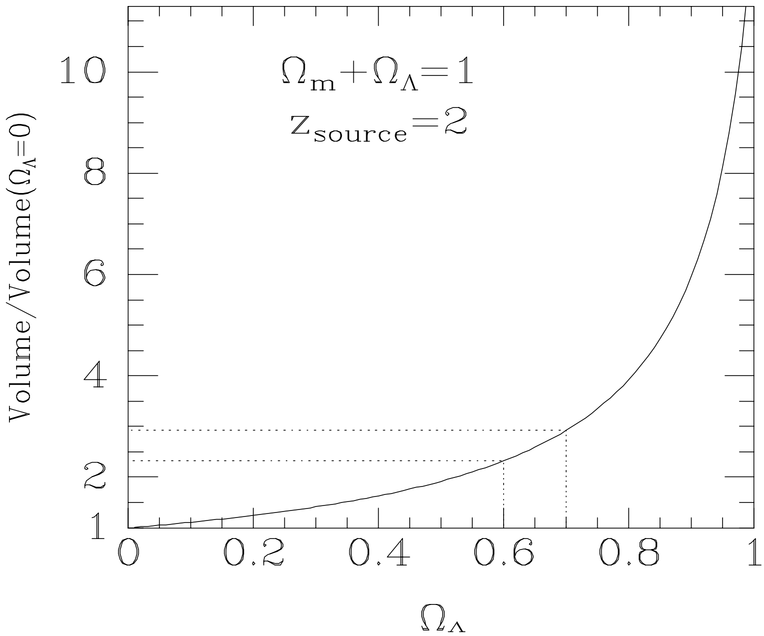

Figure 1. The volume enclosed within the radius out to a source at $z = 2$, as a function of Ω_Λ, relative to this volume for $\Omega_\Lambda = 0$, for flat geometries.

1% of bright ($\lesssim$ 18 mag) quasars, and a fraction of a few $\times 10^{-3}$ of radio samples, to be strongly lensed. Detailed calculations predict similar numbers.

2. A brief history of lensing surveys and analyses

The first large optical survey for lensed quasars that was sensitive over most of the $0'' - 3''$ range over which galaxy lensing occurs was the HST Snapshot Survey for lensed quasars (Maoz *et al.* 1993), which found that $4/502 \approx 1$ % out of a sample of luminous $z > 1$ quasars are lensed. Maoz & Rix (1993) modeled the results of this survey using a "hybrid" model for galaxies, consisting of a deVaucouleurs stellar-mass profile, combined with a cored isothermal sphere distribution representing the dark halo. They found that the observed low frequency of lensing was consistent with an $\Omega_\Lambda = 0$ Universe, and placed a 95 % confidence upper limit of $\Omega_\Lambda < 0.7$. An $\Omega_\Lambda = 0.7$ model predicted about 3 times more lensed quasars than observed. This is basically just the factor of 3 in volume between $\Omega_\Lambda = 0$ and $\Omega_\Lambda = 0.7$, shown in Fig. 1. They also showed that a singular isothermal sphere (SIS) model, with the velocity dispersions of galaxies based on the Faber-Jackson relation, gave a prediction similar to that of the hybrid model for the number and image-separation distribution of lensed quasars. Most of the following lensing statistics analyses indeed used the SIS approximation. Kochanek (1996) analyzed, assuming SIS, a somewhat enlarged sample obtained by adding results of severel ground-based surveys to the Snapshot sample. He found that 5/864 quasars that are lensed gave a 95% confidence limit of $\Omega_\Lambda < 0.66$.

These conclusions started changing when Chiba and Yoshii (1997, 1999) analyzed the same Snapshot sample. They argued that, not only do the data allow a cosmological constant, but that they actually favor it, with a best fit $\Omega_\Lambda = 0.7^{+0.1}_{-0.2}$ in the latter paper. However, this result was reached by assuming a quite "shaved" galaxy luminosity function, with normalization ϕ^* cut by half, slope α changed from -1.1 to $+0.2$, a low-mass lens cutoff, and σ^*, the velocity dispersion of an L_* galaxy, reduced by 20% compared to that used by previous calculations. At about this time, the results of two large radio surveys for lensed quasars, JVAS and CLASS (Browne *et al.* 1997, 2003), also began to be analyzed. Falco, Kochanek, & Munoz (1998), based on a 6/2500 lensed fraction among JVAS sources, concluded yet again that Ω_Λ is low, < 0.73, at 95% C.L. But several recent analyses of the final combined JVAS/CLASS results, in which $\sim$ 12/5000 of the radio sources are lensed (note that the fraction is identical to the previous 6/2500) actually get results fully consistent with the currently standard cosmology: $\Omega_\Lambda = 0.8 \pm 0.1$ (Chae *et al.* 2002, Chae 2003); $\Omega_\Lambda = 0.7 \pm 0.1$ (Mitchell *et al.* 2004).

3. Where did we go wrong?

This chain of events naturally raises the question of what went wrong with the first studies, especially the optical ones. Why did lensing statistics fail to predict the accelerating Universe before it was discovered by other means? Let us examine the various observational and theoretical inputs to the problem and attempt to locate the problem.

Data? Perhaps the results of the HST Snapshot Survey suffered from small number statistics, or from the HST mirror optical aberration (even though Maoz *et al.* 1993 showed this had little effect on the lensing detection efficiency). New surveys would then show a larger lensing fraction, as predicted by the models for the optical surveys in a Λ-dominated Universe. However, a second snapshot survey for lensed quasars with HST on a new sample has found that 3/320 quasars are lensed (Morgan 2003), i.e., still 1%!
Model Parameters? A lensing prediction requires empirical inputs for the properties of the lensing population. Let us examine each of those, as they appear schematically in Eq. 1.1.
Lens number density, n: Maoz & Rix (1993) assumed $\phi^* = 1.56 \times 10^{-2}$ Mpc^{-3} for the density of L^* galaxies. This is nearly identical to modern values: $\phi^* = 1.59 \times 10^{-2}$ Mpc^{-3} (2dF; Madgwick *et al.* 2002) and $\phi^* = 1.49 \times 10^{-2}$ Mpc^{-3} (SDSS: Blanton *et al.* 2003). More important is the number density of early-type galaxies, the dominant lenses. Here again Maoz & Rix (1993) assumed $\phi^*_E = 0.48 \times 10^{-2}$ Mpc^{-3}, compared to: $\phi^*_E = 0.45 \times 10^{-2}$ Mpc^{-3} (2MASS; Kochanek *et al.* 2001) and $\phi^*_E = 0.41 \times 10^{-2}$ Mpc^{-3} (SDSS: Mitchell *et al.* 2004). The new values would lower the predictions by only ~ 10 %, not by a factor of 3. The assumed logarithmic slope of the Schechter luminosity function, $\alpha = -1.1$, was also similar to the best current estimates for ellipticals, $\alpha \sim -0.54$ to -1.
Lens cross section: In SIS models, this parameter depends on the velocity dispersion of an L^* early-type galaxy as σ^{*4}. Thus, an overestimate of σ^* is a prime suspect for driving the lensing predictions up, and the estimates of Ω_Λ down. The early SIS studies assumed $\sigma^* = 225$ km s^{-1} for ellipticals and 206 km s^{-1} for S0s. This compares to the modern measured values for early types of 209 km s^{-1} (2MASS; Kochanek *et al.* 2001) and $\sim$ 200 km s^{-1} (SDSS; Sheth *et al.* 2003; Mitchell et al. 2004). The latter authors actually fit a modified Schechter function to the observed velocity dispersion distribution of SDSS ellipticals, so a direct comparison of the "break" velocity dispersion is difficult. Direct measurement of this distribution circumvents the need to use the Faber-Jackson relation and the luminosity function in SIS lensing statistics calculations, and is thus an important step forward (but see Kochanek *et al.* 2004, for an argument that an estimate of σ^* from the image-separation distribution of the lens sample itself is still superior). Nevertheless the peak of the cross-section-weigthed distribution of velocity dispersion, $\phi(\sigma)\sigma^4$, shown by Mitchell *et al.* (2004), is at 225 km s^{-1}, just the value assumed by

https://doi.org/10.1017/S1743921305002231 Published online by Cambridge University Press

the old studies. A SIS calculation using $\sigma^* = 200$ km s^{-1}, instead of the old values, will predict, 30-40% fewer lensed than the old calculations. This, on its own, cannot explain the factor 3 discrepancy.

Magnification bias B: The bias depends primarily on the source number-magnitude relation at each redshift, or equivalently, on the redshift-dependent luminosity function. Maoz & Rix (1993) used the following parameters for the quasar luminosity function: low-luminosity logarithmic slope $\alpha = -1.2$, high-luminosity slope $\beta = -3.6$, and break absolute luminosity $M^* = -20.25$. Modern values of these parameters (2dF, Boyle *et al.* 2000) are $\alpha = -1.63$, $\beta = -3.45$, and $M^* = -20.6$. The steepening in α will tend to raise the magnification bias. The change in β is small. The shift in M^* to higher luminosities will lower the bias, and thus tend to cancel the efect of a steeper α. Thus, a modern bias calculation for an optical sample would not obtain a result significantly different from the old ones.

Extinction? Extinction by dust in the lens galaxies, could, in principle, select against lensed quasars in optical surveys, leading to artificially low observed lensing rates. However, the magnitude of this effect was studied by Falco *et al.* (1999) using the color differences between lensed images in radio-selected and optically selected lensed quasars. They found that dust could reduce the number of optically selected lensed quasars by $\sim 10 - 30$ %. Again, this effect alone would not bring the predictions for an $\Omega_\Lambda = 0.7$ Universe in line with the observed lensing fraction.

Galaxy Evolution? Naturally, if the lensing population were to disappear or to become ineffective as one goes to higher redshift, this would lower the observed number of lenses. However, Rix *et al.* (1994) already showed that, if one breaks up elliptical galaxies into smaller building blocks, as one goes to higher redshifts, and if the merging process occurs in a physically reasonable way, the total expected number of lenses changes little. Since there are then more lenses along the line of sight, but each with a lower mass, the main effect is on the image separation distribution, with more small-separation lenses and fewer large-separation lenses. More recently, Ofek, Rix, & Maoz (2003) used the observed distribution of lensing galaxy redshifts in 17 known lensed quasar systems to limit the allowed amount of evolution in σ^* of early-type galaxies. They found that the lens galaxy redshifts are consistent with no evolution out to $z = 1$, independent of cosmology. At 95% C.L., $\sigma^*(z = 1) > 0.63\sigma^*(z = 0)$. This lack of evolution in the elliptical population out to $z \sim 1$ is consistent also with the results of other studies, based on number counts, colors, etc.

Ellipticity? Clustering? Most lensing statistics models have assumed circularly symmetric mass distributions for the lenses (see Chae 2003, for an exception), and have ignored clustering of the lenses. The impact of lens ellipticity and clustering were recently studied by Huterer, Keeton, & Ma (2004) and Keeton & Zabludoff (2004), who found that their influence is small, and in the direction of increasing the lensing efficiency. Thus, including these effects would actually slightly raise the predicted frequency, and hence would lower the deduced values of Ω_Λ.

Cosmology, after all? It is evident from Fig. 1 that the volume test, which was a main original motivation for lens surveys, is most powerful for very high values of Ω_Λ. But clearly, even changing Ω_Λ from the canonical 0.7 down to, e.g., 0.6 will reduce the volume, and hence the lensing rate, by 20%. Such a value of Ω_Λ is still consistent with the SN-Ia and CMB measurements. Indeed, Sullivan *et al.* (2003) have derived SN-Ia Hubble diagrams, separated by morphological type of the SN host, based on HST imaging. For SNe-Ia in ealy-type hosts, which are least susceptible to extinction uncertainties, the best fit is $\Omega_\Lambda = 0.5 \pm 0.1$.

4. Why do the radio surveys get it "right"?

All of the recent lensing statistics analyses have been based on the JVAS/CLASS radio surveys. The rationale has been that these surveys provide larger statistical samples, and are free of the extinction effects that may influence optical samples. These advantages would then lend credibility to the latest analyses, which give results consistent with the concordance $\Omega_\Lambda = 0.7$ cosmology. However, several problems with the radio surveys must be noted. First, while the no-extinction advantage is real and important, it is the number of lensed systems, not the number of sources surveyed, that determine the statistical power of the sample. There are about a dozen lensed systems in the JVAS/CLASS statistical sample, which is similar to the 11 or 12 lenses in the combined large optical surveys, e.g., the two HST snapshot surveys and several ground-based surveys (see Morgan 2003). Second, a shortcoming of the radio surveys has been, and remains, the poor characterization of the source population, in terms of redshift distribution and luminosity function. These two uncertainties lead to uncertainties in the optical depth and in the magnification bias, respectively. (Indeed, different assumptions about the source population are behind the different conclusions reached from the same observed radio lensing fraction, by Falco *et al.* (1998) on the one hand, and Chae (2003) and Mitchell *et al.* (2004), on the other hand.) The poor characterization of source redshift is illustrated by the fact that 5 of the 12 lens systems in the sample analyzed by Mitchell et al. (2004) have unknown source redshifts. For the unlensed sources, a single representative redshift is assumed, and the number-flux relation is assumed to be independent of redshift. Chae (2003) has shown that, even within the context of this limited representation of the source population, uncertainties in the parameters have a strong influence on the cosmological inferences. In contrast, in bright optical surveys, the redshift of every individual source is known, and the source number-flux relations at every redshift, and at fluxes much lower than those of the sample, are well characterized. Thus, the agreement between the calculations and the observations of lensing frequency in the JVAS/CLASS radio sample, assuming very similar input parameters to those used in the old optical models, but with $\Omega_\Lambda = 0.7$, may be fortuitous. The agreement may result from a cancellation of errors, where the excess of lens systems, predicted by the assumed properties of the lensing population, is cancelled by unrealistic assumptions made for the source population. This possibility needs to be studied in more detail.

5. Conclusions

I have argued that there was nothing particularly wrong in the data of the optical lens surveys of the early 90s, nor in the input parameters of the models used to analyze them. In other words, new optical surveys have confirmed the ~ 1 % lensing fraction among the bright quasar population, and new analyses, using updated parameters for the source and lens populations, would reach similar conclusions – namely that the observed lensing fraction is lower than expected in a flat $\Omega_\Lambda = 0.7$ cosmology. Since none of the parameters or effects in the problem can, on their own, produce a factor of 3, or so, reduction in the observed lensing frequency, I conclude that a conspiracy of several effects must be at work. The most reasonable ones are that the velocity dispersion of ellipticals are somewhat lower than assumed in past studies; that, due to extinction by the lens galaxies, lensed systems are somewhat under-represented in the optical samples, compared to the no-extinction assumption; and that, perhaps, Ω_Λ is actually somehat less than 0.7. Each of these effects can lower the lensing frequency by only several tens of percents, but together they can produce the required reduction. I have also postulated

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that the agreement between the data and the models for radio lens surveys, which use basically the same input parameters for the lensing population, may be fortuitous, and due to the relatively poor knowledge of the properties of the source population. The advantages of optical surveys in terms of characterization of the source population mean that a new lensing calculation of the combined optical samples, using updated lens and source parameters, is in order.

Acknowledgements

This work was supported by the German-Israeli Foundation for Scientific Research and Development.

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