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ABSTRACT

The statistics of gravitational lenses are incompatible with large cosmological constants Λ and low cosmological densities Ω. The 90% confidence limits are that $\Lambda < 0.5$ in flat cosmologies, and $\Omega > 0.2$ in standard cosmologies if lenses are modeled either as singular isothermal spheres or de Vaucouleurs models. The mass distribution of elliptical galaxies is consistent with both lens statistics and stellar dynamics if the mass distribution in E/S0 galaxies is that of an isothermal sphere. Lens statistics require E/S0 galaxies modeled as de Vaucouleurs models to have blue mass to light ratios of $(22 \pm 3)h$ compared to dynamical estimates of $(10 \pm 2)h$. If E/S0 galaxies have constant mass to light ratios, galaxy dynamics and lens statistics cannot be reconciled without a serious systematic error in either the lens or dynamics calculations. Lens statistics limits the epoch of galaxy formation to $z \gtrsim 1$ and substantial merging of galaxies to $z \gtrsim 0.5$. Typical models of galaxy formation produce smaller numbers of lenses with larger separations than no evolution models, while typical models of mergers produce a constant number of lenses with smaller separations.

1. Introduction

The number of gravitational lenses found in a survey for lensed quasars is a volume test of the cosmological model because the number of lenses depends on the expected number of lens galaxies between the observer and the high redshift quasar. Compared to the theoretically favored $\Omega = 1$ flat cosmological (Einstein-DeSitter) model, both flat cosmologies with a positive cosmological constant Λ and low density $\Omega < 1$ cosmologies produce larger numbers of lenses.[1,2] Flat universes with $\Lambda = 1$ produce ten times as many lenses, and empty $\Omega = 0$ universes produce twice as many lenses as the Einstein-DeSitter model.

The number of lenses also depends on the masses of E and S0 galaxies. Spiral galaxies, despite their larger numbers, do not represent an important contribution to the expected number of lenses because of their smaller masses.[1,3,8] The number of lenses depends on σ_*^4 where σ_* is the characteristic velocity dispersion of an L_* galaxy, or M_* where M_* is the characteristic mass of an L_* galaxy. Small uncertainties in the dynamical variables lead to large uncertainties in the expected number of lenses: a 10% uncertainty in σ_* leads to a 40% uncertainty in the expected number of lenses. This sensitivity to dynamical uncertainties severely limits the utility of lens statistics to estimate cosmological models unless we can find some other, internal means of controlling the dynamical variables.

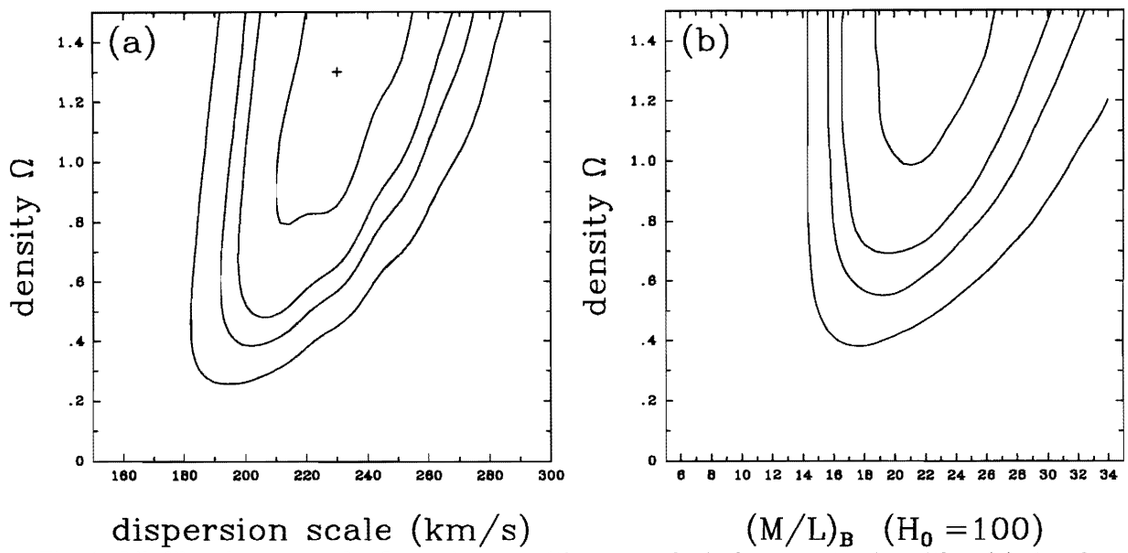

Fig. 1. Likelihood contours for flat universes with a cosmological constant using either (a) singular isothermal lenses or (b) de Vaucouleurs lenses. The likelihood contours are the 68.3%, 90%, 95.4%, and 99% confidence intervals on one parameter. The second variable is either the velocity dispersion σ_* or the blue mass to light ratio $(M/L)_*$ of an L_* galaxy. The cross marks the peak likelihood.

Fortunately, each lens we find also has a characteristic length, the image separation or critical radius of the lens. The image separation depends largely on the dynamical variables, with only a 5% variation from the cosmological model.[4] The separation depends on σ_*^2 or $M_*^{1/2}$, so by simultaneously fitting the expected number of lenses and their observed separations we can avoid the intrinsic uncertainties of galaxy dynamics. After fitting the lens data we can always go back and compare the estimates of galaxy masses from the statistical model of the gravitational lenses to the estimates of galaxy masses from traditional, stellar dynamical methods.

The evidence on radial mass distributions in E and S0 galaxies is ambiguous because of uncertainties about the isotropy of the stellar velocities. While the data is consistent with a constant blue mass to light ratio of $(M/L)_* = (10 \pm 2)h$ where $H_0 = 100h$ km s^{-1} Mpc^{-1} is the Hubble constant,[5] it is also consistent with an isothermal mass distribution with $\sigma_* \simeq (223 \pm 10)$ km s^{-1}.[6] The former has the advantage of conceptual simplicity, whereas the latter is more theoretically motivated and similar to the mass distributions predicted to hold for spirals to produce flat rotation curves. Most lens studies assumed a dispersion scale of $\sigma_* \simeq 270$ km s^{-1} based on theoretical arguments that the velocity dispersion of the dark matter should be $(3/2)^{1/2}$ larger than the central velocity dispersions of the galaxies.[1,7] This theoretical correction uses an oversimplification of the luminosity profiles, and for real E/S0 luminosity profiles there is no such correction.[6] Most theoretical studies of lenses and cosmology[1,2,8,9,10] include the correction and therefore overestimate the number of lenses by a factor of 2.25, and overestimate the image separations

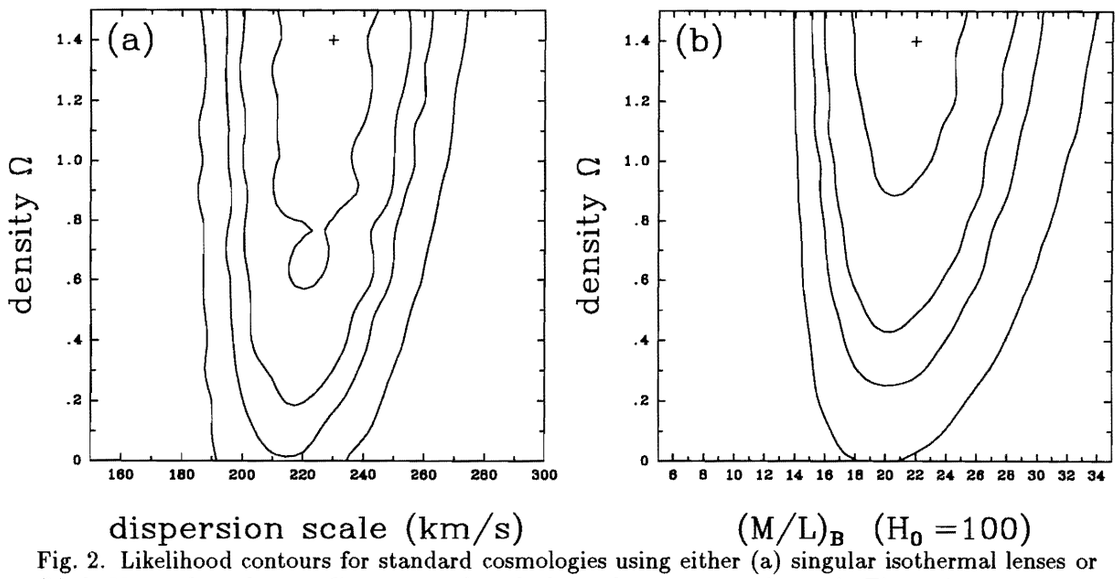

Fig. 2. Likelihood contours for standard cosmologies using either (a) singular isothermal lenses or (b) de Vaucouleurs lenses. Contours and peaks have the same meaning as in Figure 1.

by a factor of 1.5. Several studies[3,11,12] include results both with and without the correction or normalize the masses of the galaxies from the lens data.

In this paper we examine maximum likelihood models of the optical surveys for lensed quasars.[13,14,15,16] These surveys include 680 quasars and five lenses. In this paper we neglect one lens, 0957+561, which is a composite lens consisting of a galaxy and a cluster. We also include the image separations for the MG[17] and Jodrell Bank[18] radio lenses with known source redshifts. A detailed discussion of the data set is given in Kochanek.[3] We include only E/S0 galaxies (see Kochanek[3] for the effects of spirals), normalized to the local galaxy counts,[19] and galaxy type distributions.[20] We use the dynamical models summarized in Maoz & Rix[10] for the de Vaucouleurs model lenses or Kochanek[6] for the isothermal models. We adopt the quasar number counts model of Wallington & Narayan[9] which is a good fit to the quasar number counts for $1 < z < 4$ based on the form of the Boyle et al.[21] luminosity function.* We then use the maximum likelihood method for lenses[3] to examine models in the space of cosmology and the primary dynamical variable for both isothermal (dynamical variable is σ_*) and de Vaucouleurs (dynamical variable is $(M/L)_*$) models of the mass distribution in E/S0 galaxies. All the calculations include the selection functions for the different surveys detecting lenses of varying separations and flux ratios.

2. Limits on the Cosmological Constant

*We have to correct a conversion error in Wallington & Narayan[9] (also present in Kassiola & Kovner[22]) from absolute to apparent magnitudes caused by a shift between $h = 0.5$ in Boyle et al.[21] and $h = 1$ in the theoretical papers.

Figure 1 shows contours of the likelihood for flat universes with a cosmological constant, Λ. The contours are located at the 68.3% (1σ), 90%, 95.4 (2σ), and 99% confidence intervals for one degree of freedom, so that the confidence intervals on each variable are easily read from the graphs. Independent of the mass normalization and of the type of potential we use for the galaxies, we find that $\Lambda < 0.5$ at 90% confidence. The cosmological models with $\Omega = 0.2$ and $\Lambda = 0.8$ that are sometimes suggested to solve problems with structure formation are ruled out by lens statistics with more than 99% confidence. The dominant systematic uncertainties are already included by looking at two potential models and allowing the mass normalization to vary. Other potential problems like galaxy evolution can also be ruled out as a means of making a large cosmological constant consistent with lensing.[23,24] It is very unlikely that there is a systematic error in the lens calculations large enough to allow a significant cosmological constant.

3. Limits on the Cosmological Density

Figure 2 shows the contours of the likelihood for normal cosmological models as a function of the cosmological density, Ω. Because the differences between the $\Omega = 0$ and $\Omega = 1$ cosmological models are much smaller than when $\Lambda = 1$, the limits on Ω are much weaker. Most of the range is permitted simply by the expected Poisson fluctuations in the number of gravitational lenses. Nonetheless, $\Omega \simeq 1$ models are favored, and $\Omega > 0.2$ at 90% confidence. Thus lensing joins the evidence from large scale velocity flows and theoretical prejudices in favoring the Einstein-DeSitter model. The differences are, however, small enough that systematic and statistical errors could still shift the results by a significant amount. Larger lens surveys are required to reduce the statistical errors.

4. Relation To Galaxy Dynamics

We can also estimate the allowed range for the dynamical variables by fitting the velocity dispersion profiles of a sample of 37 E/S0 galaxies.[5] The details of the fitting procedures are described by Kochanek[6], and these simplified methods reproduce the results of van der Marel[5] for the de Vaucouleurs models. By comparing Figure 2 and Figure 3, it is immediately obvious that the dynamics of galaxies and lens statistics are consistent for the isothermal models and inconsistent for the de Vaucouleurs models. Maoz & Rix[10] first pointed out that the standard dynamical normalization and a constant mass to light ratio cannot fit lens statistics. This conclusion is independent of the cosmological model because it depends purely on the distribution of image separations, which is effectively independent of cosmology. In Figure 3, we can clearly quantify the magnitude of the problems: dynamics estimates that $(M/L)_* = (10 \pm 2)h$ (B band) while lens statistics requires $(M/L)_* = (20 \pm 3)h$ to fit the observed image separations. This difference is much greater than the estimated errors. In Figure 4 we show the result of combining the lens and dynamical constraints on the isothermal model.

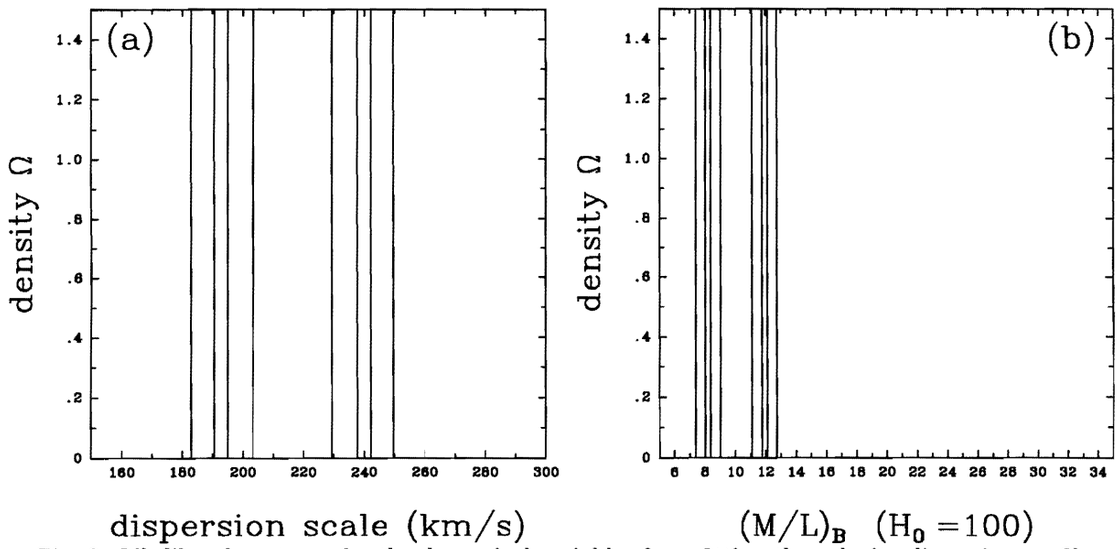

Fig. 3. Likelihood contours for the dynamical variables from fitting the velocity dispersion profiles of 37 E/S0 galaxies. The likelihood contours are the same as in Figure 1, and the peak likelihood is a vertical line near the center of the confidence limits. Note that the dynamical limits agree with the lens limits for the isothermal model in (a), but disagree with the lens limits for the de Vaucouleurs model in (b).

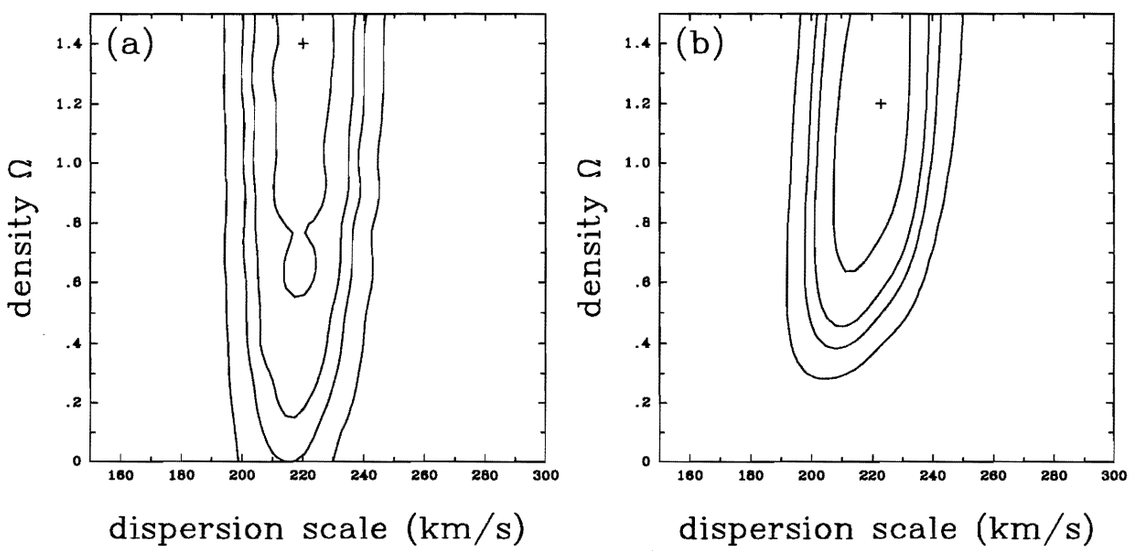

Fig. 4. Likelihood contours for flat (a) and standard (b) cosmologies for the isothermal model combining both the lens data and the dynamical data. Contours are labeled as in Figure 1. Note that by superimposing the two likelihood models we reduce the uncertainties in σ_*, but the cosmological limits do not change very much. Because of the wild disagreement of the lens and dynamical data for the de Vaucouleurs model, it does not make sense to try to combine the models.

5. Galaxy Evolution

The previous models all assumed a constant comoving density of unevolving lens galaxies. Lens statistics are most sensitive to the properties of galaxies at one half of the proper motion distance to the source ($z \sim 0.3$-0.5 typically) rather than their local properties, so galaxy evolution can strongly effect the cosmological limits. The basic principle of evolution is that if high redshift galaxies cease to be effective lenses at high redshifts due to evolution, than we can reduce the expected number of lenses and allow cosmologies that overproduce lenses in the no evolution models. The models cannot, however, examine the expected number of lenses alone – evolution models that change the expected number of lenses by a factor of two also strongly modify the expected lens separations.

Two studies[23,24] examined how the evolution of E/S0 galaxies changes cosmological limits and is in turn limited by the statistics of lenses. After an exhaustive survey of formation and merger scenarios, we concluded that no reasonable evolution scenario could allow a large cosmological constant ($\Lambda \gtrsim 0.8$). Only scenarios in which E/S0 galaxies are first formed at very low redshifts ($z \sim 0.5$) lead to significant increases in the likelihoods of these models. Even so, the models are still statistically rejectable compared to the standard cosmological models with no evolution. The very late formation times for the galaxies are also incompatible with standard galaxy formation scenarios. Merger scenarios in which the E/S0 galaxies are built up either from the locally observed spiral population or from smaller and smaller subclumps lead to little or no improvement in the models with a large cosmological constant. Most merger scenarios preserve the expected number of lenses while making their average separation smaller. The selection functions of the surveys are sufficiently sensitive to small separation lenses to make the number of detected lenses too large to allow a large cosmological constant.

6. Conclusions

Gravitational lensing is a powerful new tool for examining cosmology and the structure of galaxies. Discrimination between models is restricted by the small number of lenses in the sample. Even so, models with an interesting cosmological constant are firmly ruled out, the theoretically preferred $\Omega = 1$ models are favored over low density models, and lenses suggest that even the inner regions of E/S0 galaxies contain a significant amount of dark matter. Several new lenses are found each year, so the statistical errors will begin to decline rapidly over the next few years. The ultimate results will depend on when the problem is dominated by systematic errors (as all cosmological tests ultimately are), but a sample with a large number of lenses has many internal checks from the structure of the observed lenses to control and check the statistical model.

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