Gravitational Lensing and the Hubble Deep Field

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Abstract.
   We calculate the expected number of multiply-imaged galaxies in the Hubble Deep Field (HDF), using photometric redshift information for galaxies with $m_I < 27$ that were detected in all four HDF passbands. A comparison of these expectations with the observed number of strongly lensed galaxies constrains the current value of $\Omega_m - \Omega_\Lambda$, where Ω_m is the mean mass density of the universe and Ω_Λ is the normalized cosmological constant. Based on current estimates of the HDF luminosity function and associated uncertainties in individual parameters, our 95% confidence lower limit on $\Omega_m - \Omega_\Lambda$ ranges between -0.44, if there are no strongly lensed galaxies in the HDF, and -0.73, if there are two strongly lensed galaxies in the HDF. If the only lensed galaxy in the HDF is the one presently viable candidate, then, in a flat universe ($\Omega_m + \Omega_\Lambda = 1$), $\Omega_\Lambda < 0.79$ (95% C.L.). These limits are compatible with estimates based on high-redshift supernovae and with previous limits based on gravitational lensing.

INTRODUCTION

The Hubble Deep Field (HDF; [1]) is the deepest optical survey that has been performed to date, allowing detailed studies of the galaxy redshift distribution and the global star formation history. Galaxies in the HDF have redshifts which are estimated to range from 0.1 to 5, with a large portion having redshifts between 2 and 4. Such galaxies have a significant probability of being strongly lensed.

The combination of high resolution and deep exposures in multiple colors provides a rich ground for gravitational lens searches, and it was expected that the HDF would contain between 3 to 10 lensed galaxies, based on the number of lensed quasars and radio sources in other surveys [2]. Instead, a careful analysis of the HDF [3] has revealed a surprising dearth of candidates for lensed sources. In fact, the best estimate is either 0 or 1 lensed sources in the entire field, although very faint images with small angular separations may have escaped current analyses. This lack of lensing has led to suggestions (e.g., Ref. [3]) that the HDF data may be incompatible with the high probability of lensing expected in a universe with a large cosmological constant.

Here, we calculate the expected number of detectable, multiply-imaged galaxies in the HDF for different cosmological parameters, and we constrain these parameters by comparing the expectations with the observations. Further details of our calculation can be found in Ref. [4].

EXPECTED NUMBER OF LENSED GALAXIES

In order to calculate the number of lensed galaxies in the HDF, we model the lensing galaxies as singular isothermal spheres (SIS) and use the analytical filled-beam approximation (e.g., Ref. [5]). We also include the effects of "magnification bias" due to a magnitude limit of point-source detection in the I-band. To describe the foreground lensing galaxies, we assume that the brightness distribution of galaxies at any given redshift is described by a Schechter function. We use the redshift-dependent luminosity function given in Ref. [6] to describe the foreground galaxies.

The background galaxies are described by magnitude and redshift distributions given in two photometric redshift catalogs [6,7]. These catalogs are complete to an I-band limiting magnitude of 27 and contain a total of 848 galaxies. In Figure 1, we show the estimated photometric redshifts of the HDF galaxies according to Ref. [6] (*left panel*) and Ref. [7] (*right panel*) versus I-band magnitude. Even though the redshift distribution is different for the two catalogs — because redshifts are estimated using two different techniques — our constraints on cosmological parameters are almost the same for either catalog.

CONSTRAINTS ON COSMOLOGICAL PARAMETERS

In Figure 2, we show the expected number, $\bar{N}$, of strongly lensed sources in the HDF as a function of Ω_m and Ω_Λ, using the photometric redshift catalog of Ref. [6]. A universe dominated with Ω_Λ has a higher number of multiply-imaged sources than the number in a universe dominated with a large Ω_m. As shown in Fig. 2, $\bar{N}$ is essentially a function of the combined quantity $\Omega_m - \Omega_\Lambda$. This degeneracy in the lensing probability permits us to constrain $\Omega_m - \Omega_\Lambda$ rather than Ω_m or Ω_Λ separately.

We constrain the quantity $\Omega_m - \Omega_\Lambda$ by comparing the observed and expected number of lensed galaxies in the HDF and by using a Bayesian likelihood approach [4]. We consider cases in which either 0, 1 (the best estimate from observations), or 2 lensed sources are found in the HDF, for lens search programs that have been carried out to an I-band limiting magnitude of $m_{\lim} = 28.5$.

If there are no lensed galaxies in the HDF, then at the 95% confidence level $\Omega_m - \Omega_\Lambda > -0.44$, so that in a flat universe $\Omega_\Lambda < 0.72$. If there is one lensed galaxy in the HDF, our constraint depends only slightly on the galaxy redshift, estimated to be between 1 and 2.5 [3]. If the galaxy redshift is 1, then $\Omega_m - \Omega_\Lambda > -0.52$, implying $\Omega_\Lambda < 0.76$ in a flat universe. If instead the galaxy redshift is 2.5,
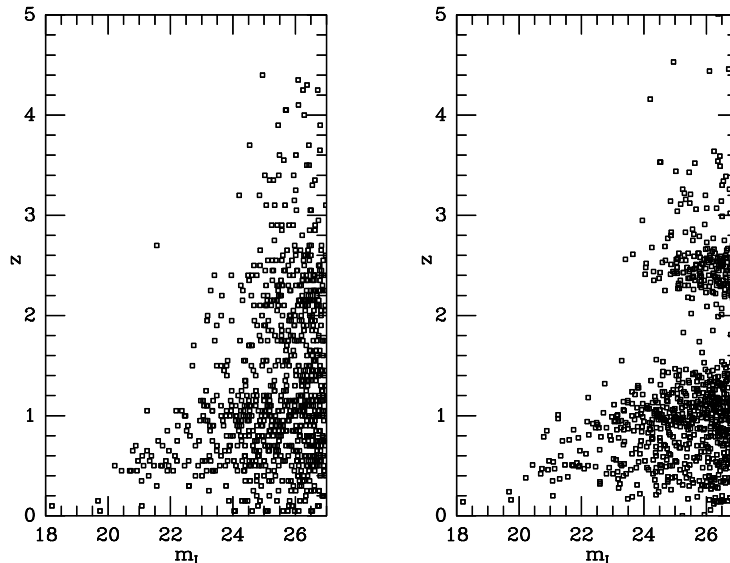
FIGURE 1. Redshift-magnitude distribution of 848 galaxies with I-band magnitude < 27 in the HDF. The plot shows the estimated photometric redshifts in the catalogs of Ref. [6] (*left panel*) and Ref. [7] (*right panel*) versus I-band magnitude. Both catalogs appear to trace the same redshift distribution, with two peaks ($z \sim 0.6$ and 2.3). However, there is a lack of galaxies in the Ref. [7] catalog between $z \sim 1.5$ to 2.2. This is the same range in redshift where no spectroscopic redshifts are currently available for the HDF.

then $\Omega_m - \Omega_\Lambda > -0.58$, and hence $\Omega_\Lambda < 0.79$ in a flat universe. If 2 strongly lensed galaxies are present in the HDF, $\Omega_m - \Omega_\Lambda > -0.73$ at the 95% confidence level. These limits are compatible with estimates based on high-redshift type Ia supernovae [8] and with previous limits on the cosmological constant based on gravitational lensing [9,10].

In Ref. [4], we discussed some of the systematic uncertainties in our calculation, the largest of which are due to effects of reddening and extinction on (optical) lens search programs. Such effects tend to reduce the number of observed lenses, and hence could lead to a systematic underestimate of the upper bound on the cosmological constant. We allowed m_{lim} to vary by as much as 1 magnitude to indicate the possible scope of such an effect: we find that our upper bound on Ω_Λ increases by about 0.06.

We find that using photometric redshifts from two different catalogs [6,7] yields results that are almost indistinguishable. Thus, we have shown that photometric redshifts can be used to estimate the expected number of lensed galaxies in the HDF with reasonable accuracy. This bodes well for the upcoming Southern Hubble Deep Field redshift catalog that is expected in the near-future. The Southern HDF will double the number of high redshift galaxies and will increase the expected number of gravitationally lensed galaxies. The actual number of lensed sources will lead to stronger constraints on $\Omega_m - \Omega_\Lambda$.
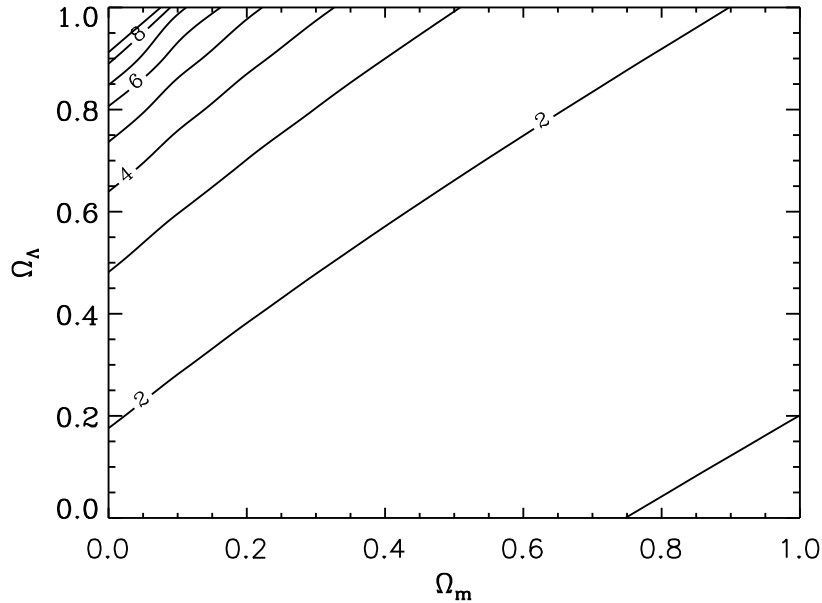
FIGURE 2. Expected number of multiply-imaged galaxies, $\bar{N}$, in the HDF, as a function of Ω_m and Ω_Λ. $\bar{N}$ is constant along lines of constant $\Omega_m - \Omega_\Lambda$, allowing for direct constraints on this quantity. Shown here is the expected number based on the redshift catalog of Ref. [6], and for lens search programs that have been carried out to an I-band limiting magnitude of $m_{\mathrm{lim}} = 28.5$.

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