H0LiCOW - Lens Mass Model of HE 0435-1223 and Blind Measurement of Its Time-delay Distance for Cosmology

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Gravitational lens time delays provide a one-step method to determine the Hubble Constant, H_0. This method is independent of the cosmic distance ladder [1] and serves as a test of systematic effects in individual H_0 probes. This method rests on the fact that light rays from the source take different paths through space-time to each of the image positions. These paths have different lengths and traverse different gravitational potentials before reaching the observer, leading to an offset in arrival times. If the source is variable, the delays can be measured by monitoring the images. The measured time delays can be used to calculate the time-delay distance, $D_{\Delta t}$, a combination of angular diameter distances among the observer, lens and source. $D_{\Delta t}$ is primarily sensitive to H_0 with weaker dependence on other parameters.

The H_0 Lenses in COSMOGRAIL's Wellspring (H0LiCOW) [2] project is modeling five lensed quasars with measured time delays to obtain a robust constraint on H_0 to < 3.5 % precision. The first two lenses have been analyzed [3,4], and analysis of the third lens, HE 0435-1223 (hereafter HE0435), has now been completed [5].

HE0435 is a quad-image lens for which accurate time delays have been measured [6]. We have wide-field imaging and spectroscopy to characterize mass projected along the line of sight [7,8], which can bias the inferred $D_{\Delta t}$ if unaccounted for. We have deep *HST*/WFC3 observations in the F160W filter, along with archival *HST*/ACS imaging in F555W and F814W, for modeling the lens system. This deep, high-resolution imaging is crucial in order to use the full surface brightness distribution of the extended quasar host galaxy as constraints. We have also measured the lens galaxy's velocity dispersion with Keck/LRIS, which helps to break degeneracies in the mass model. We try a range of models with different assumptions such as the parameterization of the mass profile, the region over which the lensed images are fit, etc. to test for systematic effects. Our final result combines the distributions from all of these models.

Throughout our analysis, we blind the $D_{\Delta t}$ and H_0 values by subtracting the median from the distributions. This allows us to evaluate the precision and relative offsets of these distributions and their correlations with other parameters without seeing the absolute value. This is done to remove confirmation bias and the tendency of experimenters to stop investigating systematic errors when they obtain an answer consistent with the "expected" result. After finalizing our analysis and coming to a consensus among the coauthors, we unblind the results and do not make any further changes to the models.

From our analysis, we determine the time-delay distance to be $D_{\Delta t} = 2612^{+208}_{-191}$ Mpc. For a flat ΛCDM cosmology, we constrain the Hubble constant to be $H_0 = 73.1^{+5.7}_{-6.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. We combine this result with the first two H0LiCOW lenses to obtain a 3.8 % constraint of $H_0 = 71.9^{+2.4}_{-3.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ for flat ΛCDM, in good agreement with the latest distance ladder results [1] and in tension with *Planck* (Planck Collaboration 2016).

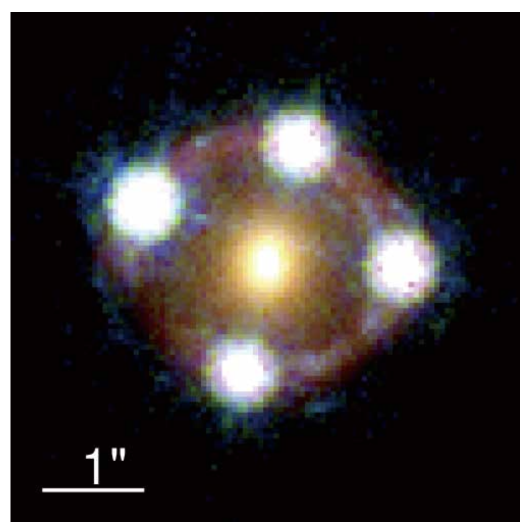

Figure 1: Multicolor *HST* image of HE0435.

References

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