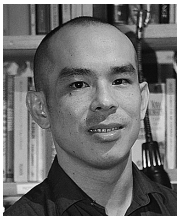
Measurement of the Hubble Constant from Lensed Quasars



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Gravitationally-lensed quasars have an observable time delay between the multiple images that can be used to determine the Hubble constant (H_0), which sets the expansion rate of the Universe. Recent observations have revealed a tension between measurements of H_0 from the early and late-Universe, presenting a challenge for cosmology. In this article, I will discuss my research that uses lensed quasars to precisely measure H_0 in an independent way.

1. Strong Gravitational Lensing

Gravitational lensing is a phenomenon that occurs when light rays emitted by a distant object (the "source") are deflected by a massive intervening object (the "lens") before reaching the observer. If the lens and source are sufficiently well-aligned, the lensing effect can produce multiple, magnified images of the source (Figure 1). This is referred to as strong gravitational lensing.

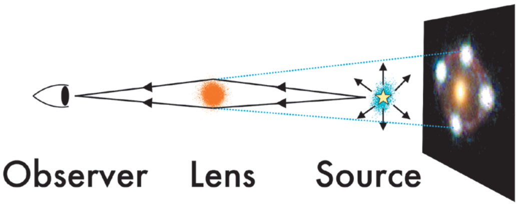

Figure 1 Diagram showing the geometry of a strong gravitational lens. Light rays are emitted by the source in all directions, and those that pass close to the lens are deflected on the way to the observer, resulting in multiple, magnified images of the source.

Strong lensing is a powerful tool for a variety of science goals. The observed lensing effect primarily depends on the total mass distribution of the lens, including both baryonic and dark matter. By fitting a mass model to the lens that can reproduce the observed image configuration, we can learn about the mass structure of the lensing object and compare it to the observed light profile. Lensing is therefore a way to probe the dark matter distribution in galaxies and clusters, including potentially the distribution of dark matter substructure. Strong lensing can also aid in studies of the background source, as the lensing effect can increase the effective flux and resolution, allowing for detailed studies of the source that wouldn't be possible without the benefit of lensing magnification.

Lensing is also sensitive to cosmological parameters, as the underlying cosmology affects the distances that light rays travel from the source to the observer. In this article, I will discuss my research that uses strong gravitational lensing to measure the expansion rate of the Universe and shed light on an emerging tension in cosmology.

2. The Hubble Tension and Time-Delay Cosmography

Our standard model of cosmology is the "flat LCDM" model, which is consistent with a variety of observations. Flat LCDM is a simple six-parameter model that assumes spatial flatness, a dark energy equation of state parameter $w=1$ (i.e., a cosmological constant), and cold (i.e., non-relativistic) dark matter.

One of the key parameters in flat LCDM is the "Hubble constant", H_0, which is the present-day expansion rate of the Universe. The Hubble constant is a relation between the distance (d) and recessional velocity (v) of an object at cosmological distances as specified by Hubble's Law [1], $v=H_0d$. Since the discovery of the expansion of the Universe, more and more precise studies have been undertaken in order to determine this parameter, which has important implications for the size and age of the Universe. In recent years, a growing discrepancy has emerged between measurements of H_0 based in the early-Universe and late-Universe [2].

2.1 Tension Between Early- and Late-Universe Measurements of H_0

The cosmic microwave background (CMB) is the radiation from the era of recombination, shortly after the Big Bang. This radiation, which has been redshifted to microwave wavelengths in the present day, encodes important information about the physical properties of the early Universe. By observing and characterizing the pattern of small temperature variations in the CMB, the *Planck* satellite has been able to precisely constrain a number of cosmological parameters. While CMB observations do not directly measure H_0, it is possible to infer H_0 by assuming an underlying cosmological model. Under the assumption of flat LCDM, the *Planck* observations tightly constrain H_0 to be 67.4 ± 0.5 km s^{-1} Mpc^{-1} [3].

It is also possible to measure H_0 directly in the local Universe by determining distances and recessional velocities to objects at cosmological distances (i.e., solving Hubble's Law for H_0). Velocities are generally easy to determine by obtaining high-resolution spectroscopy and calculating the redshift of the object. Absolute distances, on the other hand, are very difficult to measure directly outside of the Milky Way and Local Group. What is typically done is to use a direct geometric distance measurement (e.g., parallax, detached eclipsing binaries [4], megamasers [5, 6]) to calibrate a "standard candle", which is any type of object that has a constant (or standardizable) luminosity and can be seen at larger distances. These standard candles can then be used to determine their distances and infer H_0, or to calibrate even brighter standard candles to reach even greater distances, an approach known as the "distance ladder" (e.g., [7–11]).

The Supernovae, H_0, for the Equation of State of Dark Energy (SH0ES) collaboration has accurately measured H_0 using the distance ladder method. They use geometric distances to calibrate Cepheid variable stars as standard candles. These Cepheids are then in turn are used to calibrate type Ia supernovae, which are brighter standard candles that can be seen at cosmological distances.

Using this method, SH0ES measures H_0 to be 74.0 ± 1.4 km s^{-1} Mpc^{-1} [10]. This late-Universe measurement is in $>4\sigma$ tension with the *Planck* CMB result for flat LCDM.

The cause of this discrepancy, which has come to be known as the "Hubble tension", is unclear. It is possible that there are unaccounted systematic uncertainties in one or both methods, despite several reanalyses and systematics tests that have been performed. Alternatively, it may be that the flat LCDM model is incorrect, which would point toward new physics needed to explain the tension. Whatever the case may be, one of the most important complementary constraints that can be made to shed light on the Hubble tension is to have multiple, independent methods to measure H_0 in order to check for systematic errors.

2.2 Time-Delay Cosmography

Strong gravitational lensing can be used to measure H_0 through a method called "time-delay cosmography" (see e.g., [12] for a review). Light rays that are emitted from the source at the same time will arrive at the observer at different times, depending on which of the multiple light paths they take. This "time delay" between multiple images depends on a combination of the distances between the observer, lens, and source (which depend on H_0) and the gravitational potential at each image position (which can be determined from the lens mass model). By measuring the time delay and accurately modeling the mass distribution of the lens, it is possible to infer H_0 in a way that is completely independent of the CMB and the distance ladder [13].

If the background source is variable, it is possible to measure the time delay by monitoring the lensed images and comparing their light curves. Quasars are ideal sources for this purpose, since they are bright and variable on short timescales. We can look for variations in the flux of the quasar over time, which will appear in the different images at different times due to the time delay effect.

A complicating factor in time-delay cosmography is the effect of mass along the line of sight (LOS) to the lens and source. Galaxies and clusters projected along the LOS will induce small perturbations on the light rays as they travel through space, which can lead to a biased estimate of H_0. These perturbations, which are quantified by a term called the "external convergence", k_{ext}, need to be accounted for (e.g., [14, 15]).

Although the theory behind time-delay cosmography has been known for a long time ([13]), past attempts to constrain H_0 using this method have suffered from large systematic uncertainties in various aspects of the analysis, including poorly-sampled light curves, low-resolution imaging data, simplistic mass model assumptions, and ignoring LOS effects. With modern facilities and instrumentation, along with developments in computing power and data analysis techniques, it is now possible to overcome these issues and make time-delay cosmography a competitive probe of cosmology.

3. H0LiCOW / TDCOSMO

The H_0 Lenses in COSMOGRAIL's Wellspring (H0LiCOW; [16]) collaboration (now called TDCOSMO) has performed a detailed analysis of several strongly-lensed quasars to infer H_0. Using a large volume of multi-wavelength data from various facilities and state-of-the-art analysis techniques, we are able to improve on all aspects of past time-delay cosmography efforts and constrain H_0 to a precision comparable to other techniques.

3.1 Time Delay Measurement

H0LiCOW uses time delays measured from a dedicated monitoring campaign, primarily by the Cosmological Monitoring of Gravitational Lenses (COSMOGRAIL; [17–19]) project. Using a variety of small telescopes, COSMOGRAIL has been

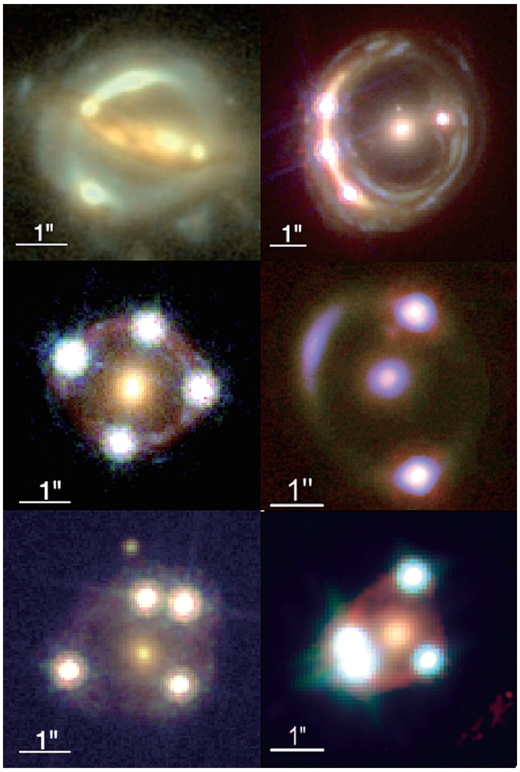

Figure 2 Multicolor images of the six lensed quasars used in the H0LiCOW analysis. The images are created using two or three imaging bands in the optical and near-infrared from *HST* and/or ground-based AO data. The lenses are (from left to right, top to bottom) B1608＋656, RXJ1131−1231, HE0435−1223, SDSS 1206＋4332, WFI2033−4723, and PG 1115＋080.

monitoring several lensed quasars for years in order to measure their light curves. We also make use of monitoring data in the radio with the Very Large Array (VLA) [20].

With regular sampling cadence and well-tested curve shifting techniques [19, 21], we are able to accurately measure the time delays in a systematic way. Observing for multiple seasons is necessary to overcome the effects of microlensing by stars in the lens galaxy, which can mimic features in the light curve. However, we have also started high-cadence monitoring [22, 23] to look for smaller, shorter-timescale variations in the quasar light curves, which has shown promising results and will allow us to obtain time delays in just a single observing season.

3.2 Lens Mass Modeling

H0LiCOW uses deep high-resolution imaging from the *Hubble Space Telescope* (*HST*) and ground- based adaptive optics (AO) to perform accurate lens modeling. The high resolution is necessary in order to subtract off the light from the lensed quasars and use the surface brightness distribution of the quasar host galaxy as additional constraints on the model. Unlike previous studies that only used the quasar image positions as constraints, the H0LiCOW lenses are constrained by hundreds of surface brightness pixels, leading to a much more accurate model. We use two primary lens modeling codes, Glee [24, 25] and Lenstronomy [26, 27], for this purpose. We have also recently performed a blind test of the consistency between these two codes [28] to test for systematics.

It is also important to have high-resolution spectroscopy of the lens galaxy to measure its velocity dispersion. This additional kinematic constraint helps to mitigate degeneracies in the lens modeling. We assume either an elliptical power-law profile or a composite (stars＋dark matter) model, both of which are physically-motivated, and marginalize over the two model families.

3.3 Mass Along the LOS

Strong perturbers that are either very massive or very close to the lens in projection need to be included explicitly as mass components in the lens model. H0LiCOW uses deep spectroscopy of LOS galaxies near the lens to determine the redshifts and velocity dispersions of perturbing galaxies, as well as to identify and characterize galaxy groups and clusters [29, 30].

In addition to these significant perturbers, the cumulative effects of all other nearby galaxies along the LOS contribute to $k_{\rm ext}$ and need to be accounted for. We use a weighted galaxy number counts method, along with cosmological simulations, to correct for this [31–34]. We take a fixed aperture around the lens galaxy and count the number of LOS galaxies above a certain magnitude limit within the aperture. We then compare this number to the same number calculated from random lines of sight from the CFHTLens Survey to determine the relative overdensity of the lens LOS to the average LOS in the Universe. We then use the Millennium Simulation [35] to pick out lines of sight that have the same relative overdensity in galaxy number counts and calculate $k_{\rm ext}$ from ray tracing in these fields [36]. This gives us a distribution of $k_{\rm ext}$ values, which we apply to our inferred H_0 in post-processing.

3.4 Blind Analysis

We carry out our analysis blindly with respect to H_0 and related quantities. In practice, this is accomplished by subtracting the median of the H_0 distribution when viewing plots and tables containing our results. This is done to prevent confirmation bias and the tendency for experimenters to stop analyzing systematic errors when they have a result that is deemed to be "correct". By blinding the results throughout the study, we must take care to be very confident in our analysis and very thorough in our systematic error checks.

When the analysis of a lens is complete, all of the primary authors of the study must agree before unblinding the result. The collaboration also agrees beforehand that whatever the resulting value of H_0, it must be published as is with no further changes to the analysis.

4. Results

From a combined analysis of six lensed quasars [24, 32, 34, 37–39], we measure $H_0 = 73.3^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1} in a flat LCDM cosmology (Figure 3) [40]. This is consistent with the SH0ES distance ladder result, but in $>3\sigma$ tension with the *Planck* CMB result.

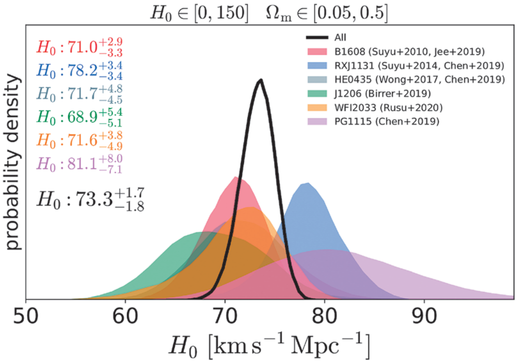

Figure 3 Marginalized H_0 for a flat LCDM cosmology with uniform priors. Shown are the H_0 posterior PDFs for the individual lens systems (shaded curves), as well as the combined constraint from all six systems (black line). The median and 16th and 84th percentiles are shown in the figure legend.

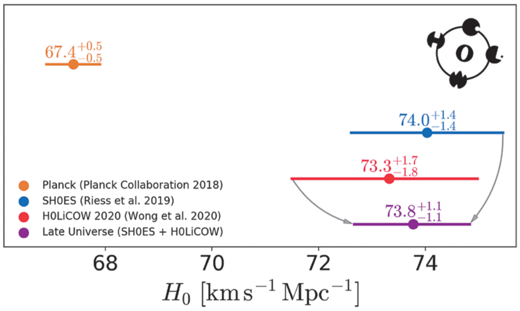

Figure 4 Comparison of H_0 constraints in a flat LCDM cosmology. The early-Universe probe is from *Planck* (orange; [3]). The late-Universe probes are the results from SH0ES (blue; [10]) and H0LiCOW (red; [40]). When combining the late-Universe probes (purple), we find a 5.3σ tension with *Planck*.

Since both the H0LiCOW and SH0ES results are late-Universe probes of H_0 that are completely independent, we can combine them in order to compare the result to the early-Universe *Planck* result (Figure 4). We find that the combination of H0LiCOW and SH0ES is in 5.3σ tension with the *Planck* CMB result, further exacerbating the Hubble tension.

Since the publication of the H0LiCOW milestone result [40], a seventh lens has been analyzed [41], bringing the tension between *Planck* and TDCOSMO to$>4\sigma$. Along with the latest SH0ES results [11], the combined TDCOSMO+SH0ES measurement is in$>6\sigma$ tension with *Planck*. Various other methods have started to show similar results as well, with early-Universe probes preferring a lower value of H_0 and late-Universe probes preferring a higher value [2]. As this tension continues to grow, the cosmological community must examine potential alternatives to a flat LCDM model. This would be a major paradigm shift in cosmology, requiring new physics to consistently explain all of the observational data.

5. Future Work

As we push toward a more precise measurement of H_0 from time-delay cosmography, we focus on addressing uncertainties in our analysis, as well as expanding our sample of lensed quasars. Although there is no statistical evidence for unaccounted random errors in our analysis [23], we must investigate potential systematic uncertainties that could lead to a bias [28, 42, 43]. One potential systematic that has arisen is our assumption of either a power-law or composite lens mass model (e.g., [44–46]). While we believe these profiles are physically-motivated, relaxing this assumption significantly reduces the precision of our result [47]. With upcoming integral field spectroscopy with the *James Webb Space Telescope* (*JWST*), we will be able to address this issue and precisely constrain the mass model [48, 49].

Lensed quasars are rare, so we will also take advantage of new and upcoming datasets to discover more of them that can be used for time-delay cosmography. I have been working on searches for strong lenses at all scales in deep Subaru telescope imaging data from the Hyper Suprime-Cam Subaru Strategic Program (HSC SSP). As co-chair of the HSC SSP Strong Lensing Working Group, I have been involved in our dedicated lens search program, Survey of Gravitationally Lensed Objects in HSC Imaging (SuGOHI). SuGOHI uses a variety of search methods [50–55], which has led to the discovery of hundreds of new lens candidates. With the upcoming Legacy Survey of Space and Time (LSST) and *Euclid* mission, we will potentially discover orders of magnitude more lenses of all types [56]. It is therefore crucial that we develop the methodologies needed to find and analyze lenses in current surveys now in preparation for this huge influx of data in the future.

6. Conclusions

We have analyzed six lensed quasars in the H0LiCOW sample (now seven with the latest TDCOSMO results) to achieve the highest-precision probe of H_0 to date from time-delay cosmography. Our inferred H_0 of $73.3^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1} in a flat LCDM cosmology is consistent with the SH0ES results from type Ia SNe calibrated by the distance ladder, but in$>3\sigma$ tension with *Planck* CMB measurements. Our constraint is completely independent of both SH0ES and *Planck*, and thus serves as an important check of systematics. Together, the late-Universe probes (SH0ES and H0LiCOW) are in $>5\sigma$ tension with the *Planck* result.

Despite efforts to explore and address systematic errors in the various methods, the tension between early- and late-Universe measurements of H_0 has only continued to grow. If unresolved, this tension may force the rejection of the flat LCDM model in favor of new physics, which would dramatically change our understanding of the Universe.

We are continuing to improve the constraints from time-delay cosmography, both by addressing systematic uncertainties and expanding the sample of lensed quasars. With upcoming *JWST* integral field spectroscopy, we will obtain precise constraints on the lens mass models, even allowing for departures from our physically-motivated assumed profiles. Moving into the future, many new lensed quasars are being discovered in large imaging surveys such as the HSC SSP, which will hopefully allow us to constrain H_0 to the $\sim$1% level in the near future.

Acknowledgement

I am extremely grateful to Sherry Suyu, who brought me into the H0LiCOW/TDCOSMO collaboration and has been a very influential mentor in my career. This work would not have been possible without the contributions of the rest of the TDCOSMO collaboration. I am also grateful for all of the collaborators I have worked with during my time in Japan, particularly those who have served as my host researchers and/or mentors: Takashi Hamana, Masamune Oguri, Nao Suzuki, and Masayuki Tanaka. I would like to thank Mayuko Mori for help with creating Figure 1. Figures 2, 3, and 4 are reproduced from [40] (Figures 1, 2, and 12, respectively).

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