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Dark Energy Constraints from Quasar Observations

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Recent measurements of the parameters of the concordance cosmology model (ΛCDM) done in the low-redshift Universe with supernovae Ia/Cepheids, and in the distant Universe done with cosmic microwave background imply different values for the Hubble constant (67.4 ± 0.5 km/(s Mpc) from Planck vs. 74.03 ± 1.42 km/(s Mpc) Riess et al. 2019). This Hubble constant tension implies that either the systematic errors are underestimated, or the ΛCDM does not represent well the observed expansion of the Universe. Since quasars — active galactic nuclei — can be observed in the nearby Universe up to redshift $z \approx 7.5$, they are suitable to estimate the cosmological properties in a large redshift range. Our group develops two methods based on the observations of quasars in the late Universe up to redshift $z \approx 4.5$, with the objective to determine the expansion rate of the Universe. These methods do not yet provide an independent measurement of the Hubble constant since they do not have firm absolute calibration but they allow to test the ΛCDM model, and so far no departures from this model were found.

topics: cosmology, dark energy, quasars

1. Introduction

The cosmological parameters can be estimated from different sets of data at various redshifts, but if the standard lambda cold dark matter (ΛCDM) model is valid, they can always be represented by the current (zero redshift) values. The final results from the Planck mission, based on the analysis of the cosmic microwave background (CMB) do not indicate any tension with the standard model, and give the value of the $\Omega_m = 0.315 \pm 0.007$ [1] and the Hubble constant $H_0 = 67.4 \pm 0.5$ km/(s Mpc). Many of the measurements done in the local Universe ($z < 10$) are in significant disagreement with these Ω_m or H_0 values (e.g. [2]) while other measurements, also local, are still roughly in agreement with the results from Planck (e.g. the last results from gravitational waves [3]).

Therefore, various probes and methods are needed to confirm, or to reject, the hypothesis that the ΛCDM model does not describe the Universe well, and the evolving dark energy is needed instead of the cosmological constant. Quasars (QSO) are very attractive cosmological probes, since they cover a broad range of redshifts, from nearby sources (referred to as active galactic nuclei, AGN) to most distant objects at redshift above 7 [4, 5]. They also do not show significant evolution with redshift [6].

2. Two methods for using quasars in cosmology

We are currently using two methods of turning quasars into *standardizable* candles. The first method is based on the radius–luminosity relation and the second method is based on super-Eddington sources.

2.1. Method based on radius–luminosity relation for BLR

The reverberation mapping technique is based on the long-term monitoring of a source in order to determine the time response ($\tau_{\rm BLR}$) of the emission line to the continuum variations [7]. The most important result from the reverberation mapping studies is the correlation between the continuum luminosity (L) and the distance (R_{BLR}) where the emission line is emitted in the broad line region (BLR). This relation is known as the radius–luminosity relation (R–L) and it is given approximately by $R_{\mathrm{BLR}} \propto L^{0.5}$. The reverberation mapping studies require extensive use of telescope time to achieve high quality results, thus only ≈ 120 sources have been analyzed with this technique until now. Most of the monitoring is based on the optical Hβ for low-redshift sources, while for high redshift regimes, due to the Doppler shift, the monitoring is focused on the UV emission lines such as Mg II $\lambda 2800$, C IV $\lambda 1549$ and C III $\lambda 1909$.

For many years, the R–L relation showed a low scatter ($\sigma_{\mathrm{rms}} \approx 0.13$ dex) [8], which ensured its use in the determination of the black hole mass (M_{BH}). However, the inclusion of new sources, particularly those radiating close to the Eddington limit (high accretion rates), has led to a much larger scatter, clearly related with the accretion rate [9, 10]. Some corrections based on the accretion rate [11] and independent parameters such as the Fe II strength or the amplitude of variability [12–14] (in turn, correlated with the accretion rate) have been proposed to correct this effect, allowing to reduce the scatter.

Besides, the R–L relation offers the possibility to determine the luminosity independently of the redshift [15, 16], and to estimate the cosmological parameters. However, in [11] the errors for Ω_m and Ω_Λ based on available Hβ were still very large, despite the corrections for the accretion rate. In the present paper, we make the following important modifications. First, we combine the previous sample with Mg II $\lambda 2800$ reverberation-mapped sources. The new sample includes two sources monitored by us with the Southern African Large Telescope (SALT) during 6 years [17, 18]. Next, since the errors of the time delay measurement are highly asymmetric, we use the χ^2 statistics to determine the cosmological parameters, we use the method of [19] instead of a simple symmetrization of the errors.

We also modified the approach to the R–L relation in the case of the Hβ sample which is extremely heterogeneous. We treated the coefficients of this relation as arbitrary, and minimized the total χ^2 fit to a flat cosmological model, with the Hubble constant fixed at 67.5 km s^{-1} Mpc^{-1}. For the Mg II $\lambda 2800$ sample, we used the R–L parametrization given by (9) in [18], since this sample was analysed in a more uniform way. While fitting the flat cosmology model (both samples combined), we applied the sigma-clipping approach, and we removed the sources which showed a departure by more than 3 sigma from the best-fit. All the removed sources were from the Hβ sample: Mrk 493, J074352.02+271239.5, Mkn 509, MCG+08-11-011, J142103, J142043, J141123, and J142052. Thus, our total sample has now 120 objects. We then

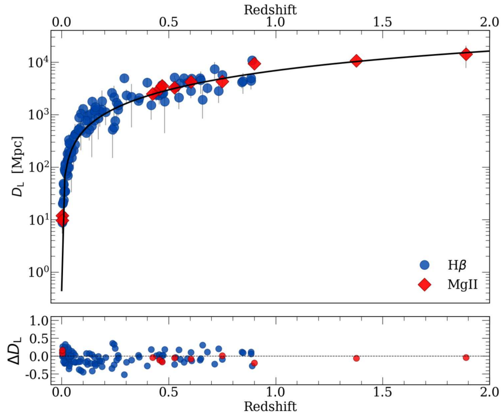

Fig. 1. Quasar Hubble diagram using the reverberation mapped sources. Blue circles and red diamonds correspond to the Hβ and Mg II $\lambda 2800$ sources, respectively. The black line marks the ΛCDM model for flat cosmology, $\Omega_m = 0.297$, $H_0 = 67.5$ km/(s Mpc). The bottom part shows the residuals.

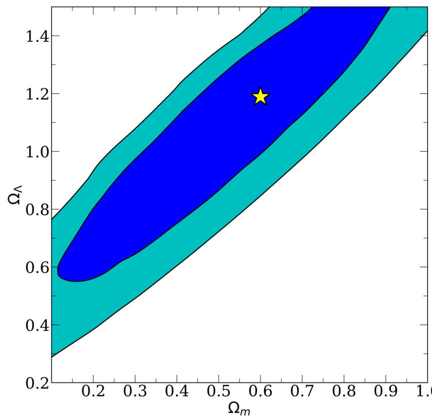

Fig. 2. Confidence contours at 68% (cyan) and 95% (blue) for Ω_m and Ω_Λ for general ΛCDM model based on χ^2 fitting where the best Ω_m and Ω_Λ are represented by the yellow symbol.

refitted the Hubble diagram. The best-fit returned the best R–L parametrization of Hβ sample as $\log(L_{5100}) = 1.489 \log(\tau_{\mathrm{corr}}) - 2.222$, where τ_{corr} is the time delay corrected by the accretion rate effect [11].

For the flat cosmology, we obtained the best-fit value $\Omega_m = 0.297^{+0.060}_{-0.054}$ (see Fig. 1). This value is fully consistent with the value 0.3153 ± 0.0073 from Planck [1] for flat cosmology, and the error in our new result is much smaller than that obtained by [11], although still much larger than from Planck. This illustrates that the method could be powerful, if the sample is more uniformly analysed from the very beginning. If we do not assume a flat cosmology, 2-D contour errors are still large (see Fig. 2), although considerably smaller than in [11]. The best-fit Planck values are well within the 1σ error, so we do not see any tension with the results based on cosmic microwave background.

2.2. Method based on super-Eddington sources

Quasars radiating close to the Eddington limit are known as xA-QSO or super-Eddington sources [20, 21]. This QSO population shows peculiar spectral and photometric properties, which differentiate them from the rest of the QSO population and make them easy to identify in catalogs like SDSS or the upcoming Vera Rubin Observatory's Legacy Survey of Space and Time (LSST). In the optical range, they are the strongest Fe II emitters and do not show a strong contribution of narrow emission lines such as [O III] $\lambda\lambda$4959, 5007 [22]. Super-Eddington sources show the strongest outflows in the high ionization lines mostly observed in the UV emission lines like C IV λ1549 or S IV λ1397 [23], although in the most extreme cases the strong radiation forces provoke the presence of outflows in low-ionization lines such as Hβ or Al III λ1860.

According to the photoionization models, their broad line regions are characterized by large densities ($n_{\mathrm{H}} = 10^{12}$–10^{13} cm^{-3}), low-ionization parameters ($\log U < -2$) and high metallicities ($Z \approx 10 Z_{\odot}$) [24–27]. In addition, super-Eddington sources also show remarkably low optical variability and time delays shorter than those predicted by the R–L relation [28]. The UV flux ratios Al III λ1860/Si III λ1892 > 0.5 and C III λ1909/Si III λ1892 < 1.0 have shown a high effectiveness as selection criteria to identify xA-QSO sources at high-redshift, while at-low redshift xA-QSO typically show Fe II/H$\beta > 1.0$ [20].

In xA-QSO, despite the rise of the accretion rate, the luminosity saturates toward a limiting value, since the accretion efficiency decreases. Thus, the ratio luminosity–black hole mass (L/M_{BH}) does not change and they can be considered as "Eddington standard candles". A similarity in the physical conditions (density, ionization parameter, metallicity) of the BLR is expected because they belong to the same population, therefore a generalization of all of them can be considered [29]. Since the low-ionization lines are less affected by the strong radiation forces, emission lines like Hβ and Al III λ1860 are excellent candidates for virial estimators. Based on these assumptions, it is possible to determine the luminosity distances independently of redshift and get an estimation of the matter and energy content in the Universe.

The previous xA-QSO sample included ≈ 200 objects at redshift $z < 2.7$ [30]. In order to increase the redshift range, we considered the most recent edition of the Sloan Digital Sky Survey Reverberation Mapping (SDSS-RM) catalog [31]. This catalog includes the automatic measurements of the most important UV emission lines for 549 sources with $44.1 < \log L_{1700} < 46.9$ ers s^{-1} at $0.9 < z < 4.3$, where $\approx$ 20% show high accretion rates, so they can be considered as super-Eddington candidates. In the xA sources, the Fe III λ1914 shows

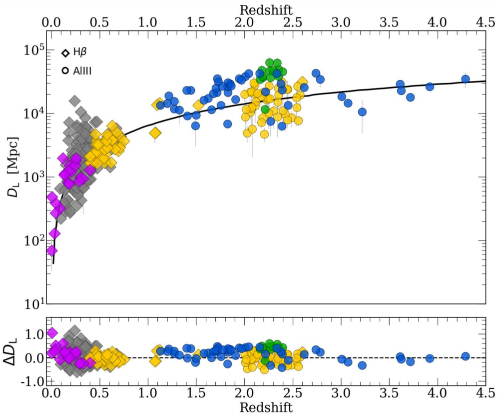

Fig. 3. Quasar Hubble diagram using the super-Eddington sources. Diamonds correspond to the measurements from the Hβ, while circles belong to UV Al III λ1860 emission line. Purple, gray, yellow, green and blue symbols correspond to the xA sources from the SEAMBH project [12, 20, 22, 25] and SDSS-RM [31] samples, respectively. The best-fit line shows the flat model, with H_0 from Planck, and best fit $\Omega_m = 0.290$.

an important contribution, hence a good deblending of the C III λ1909 and Fe III λ1914 is required. Unfortunately, the SDSS catalog does not include Fe III in their multicomponent fittings, so not all the sources satisfy the selection criteria to identify them as the xA. So for the first test, we select the sources based on the Eddington ratio ($\mathrm{L}/\mathrm{L}_{\mathrm{Edd}} > 0.2$) estimated from the Al III λ1860 based black hole mass. After removal of some objects with extreme $\mathrm{FWHM}_{\mathrm{AlIII}}$ values, our final sample includes 88 objects at $1 < z < 4.5$.

In order to determine the cosmological constant Ω_m and Ω_Λ, we combine the previous xA samples such as the super-Eddington sources from the super-Eddington accreting massive black holes (SEAMBHs) project with the most recent measurements from [25]. The quasar Hubble diagram with the super-Eddington sources is shown in Fig. 3. We adopt the scaling of the virial estimator to be consistent with Planck H_0 value, and we assume the flat cosmology. In this case, we obtain $\Omega_m = 0.290^{+0.048}_{-0.043}$, fully consistent with the Planck results despite the fact that quasars cover the redshift range from nearby sources to almost 4.5.

3. Discussion

We have presented here the most recent results based on the two methods for applying quasars to constrain the expansion rate of the Universe. Our methods, as for now, are not based on absolute scaling so they cannot predict the value of H_0.

In principle, such an absolute scaling can be achieved. For method (i), it would require an independent measurement of the dust temperature at the BLR onset, and the development of a 3D BLR model, which is in progress (see, e.g., [32]). For method (ii), we would need an absolute scaling of the radius–luminosity relation, also establishing the mean density of the BLR (see, e.g., [20, 29]). At this stage, we fixed the value of the Hubble constant at the Planck value and tested, whether the redshift dependence of the luminosity distance is consistent with the standard ΛCDM model, and whether the remaining cosmological parameters derived from quasar data are consistent with Planck values.

So far, within the available accuracy, our values of Ω_m are fully consistent with the Planck value for the flat Universe despite the fact that the second method extends up to the redshift 4.5. Thus, we do not support the claim of the tension with the standard model based on supernovae Ia with absolute scaling in turn predominantly based on Cepheid stars [33]. Our results from method (i) are consistent with the tension found by [34] since they claim to see departures only above the redshift 1.5–2, and method (i) does not go this far. As for method (ii), we have many sources up to redshift 2.5, but indeed very few above 2.5, and our method of analysis was not yet optimized by an outlier removal through sigma-clipping. Further studies are clearly needed for this method, both with the current data and eventually by increasing the number of high redshift quasars.

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