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Cosmological interpretation of JWST observations

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Abstract. Observational data from the James Webb Space Telescope (JWST) indicate a significant number of galaxies with redshifts $z > 10$. Galaxies with record-breaking redshifts exhibit luminosities comparable to those of galaxies in the local universe, and they are small in size, measuring hundreds of parsecs, as determined within the standard cosmological model, ΛCDM. Within this framework, a satisfactory explanation for their formation and evolution has not yet been found. So, most current research focuses on revising theories of galaxy formation and evolution to align with JWST observational data. In this talk, we discuss cosmological tests based on JWST observations, which could provide an alternative explanation. High-redshift galaxies detected by the JWST exhibit brightness and large masses, yet their sizes are over 10 times smaller than those of low-redshift galaxies with comparable masses. This leads to an increase in the gravitational potential ϕ and, consequently, an increase in the velocity dispersion, which in turn results in the broadening of galaxy spectral lines, including Ly_α. Thus, their spectral lines measured by the JWST must be widened. Checking galaxy spectral line widths constitutes a new physical cosmological test, which can be conduct using the current JWST data. The high rate of star formation in those galaxies implies a high number density of ionizing photons. This leads to a significant tension with the optical depth of reionization based on the cosmic microwave background (CMB). The previously known tensions of the ΛCDM model (H_0, σ_8), along with this new inconsistency, indicate that the method of using CMB to determine cosmological parameters and the concept of *Planck* precision cosmology may require further evaluation.

Keywords: cosmology: observations, dark ages, reionization, first stars, early universe

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1 Introduction

Observations by the James Webb Space Telescope (JWST) indicate that at distances associated with high redshifts, there is a significant number of massive galaxies (with masses $> 10^{10}\,\mathrm{M}_\odot$) that formed within 500 million years of the beginning of the universe. The observed number density of massive galaxies with $z > 10$ (Finkelstein et al. 2023) does not align with the predictions made by the theory of galaxy formation. The recently published UNCOVER catalogue of JWST galaxies (Weaver et al. 2024) includes a notable number of galaxies with $z \approx 20$. This is consistent with the predictions of the ΛCDM model regarding the redshift at which the first stars and galaxies are expected to form. Therefore, at this redshift there should be much fewer galaxies, which are expected to be shapeless and small in size. The JWST observations indicate that galaxies with $z > 10$ exhibit morphological characteristics, containing significant amounts of dust and metals. They appear similar to late-universe galaxies, except their physical sizes.

Currently, most of the theories focus mainly on the search of a galaxy-formation model that would allow explaining the existence of fully developed galaxies at redshifts that correspond to the young age of the universe, as standard cosmology does not allow enough time for their formation. In our opinion, it is reasonable to explore cosmological model testing again, especially since the JWST provides great opportunities for it. The observational data available for $z > 10$ may be helpful for distinguishing between cosmological models, even considering potential noise and significant statistical uncertainties.

There are two kinds of cosmological tests that can be performed: cosmographic and physical tests (Orlov & Raikov 2016). In the next section, we focus on the cosmographic tests, and in the last Section, we discuss the physical tests.

2 Cosmographic Tests

Angular Size vs Redshift Test. For large redshifts, different cosmological models predict different galaxy angular sizes θ. Figure 1 shows a comparison of observational data and predictions from the ΛCDM and static cosmological models. The red dots indicate observational data obtained from the JWST public data, the black dots correspond to some pre-JWST observations. The references to the catalogues used for this graph are provided in our separate publication (Lovyagin et al. 2022).

The figure reveals that the ΛCDM prediction is inconsistent with observational data, unless we interpret the observed diminished galaxy sizes as the signature of galaxy evolution: the standard model assumes that galaxy sizes grow as galaxies merge with each other over the course of the universe's evolution.

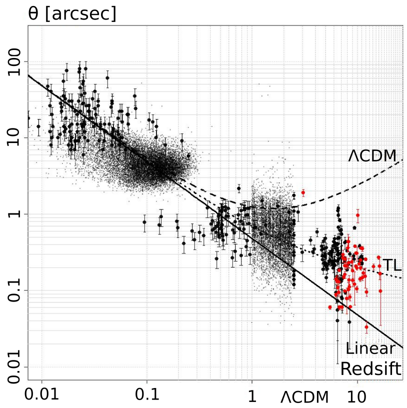

Fig. 1. Angular sizes θ of galaxies as a function of their redshifts z. The red dots indicate observational data obtained by the JWST during its first year of operation in orbit. The black dots correspond to some pre-JWST observations. The theoretical curves are calculated for a medium-sized galaxy (10 kpc) using ΛCDM model (the dashed curve, $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, $k = 0$), Zwicky's tired light (TL) model (the dotted curve) and linear Hubble's law (the solid line, $H_0 = 70$ km/s/Mpc).

It should also be noted that, within the ΛCDM model, there is an increase in the linear sizes of galaxies, as well as growth in the sizes of galaxy clusters. Several researchers have noted the presence of small protoclusters up to $z \sim 10$ in JWST surveys, e.g. Castellano et al. (2023). The preliminary assessment indicates that, according to the standard cosmological model, there may be insufficient time for such clusters to form. Additionally, the evolution of their sizes appears to align with the rate of space expansion, which is not typically expected for gravitationally bound objects. This requires additional research. The Zwicky tired-light (TL) prediction is consistent with the JWST observations, while the ΛCDM evolutionary explanation is refuted by the fact that the observed high-redshift galaxies are similar to the late-universe galaxies by their morphology, chemical composition, and dust content.

Surface Brightness Test. Most of the published works dealing with JWST imaging data determine galaxy parameters (luminosity functions, sizes, masses) by measuring Sérsic profiles. These photometric measurements may act as a proxy for Tolman's surface brightness test (Hubble & Tolman 1935; Geller & Peebles 1972). This test is based on the fact that a galaxy with a redshift z changes its surface brightness in proportional to $(1+z)^{-n}$, where $n = 4$ in the context of the ΛCDM model and $n = 1$ in a static case.

The $\propto (1+z)^{-4}$ decline in surface brightness implies that a distant ($z \gtrsim 10$) Milky Way-like galaxies cannot be observed using JWST. Observations of many galaxies at redshift $z \gtrsim 10$ indicate that, within the framework of the ΛCDM model, their physical brightness must increase rapidly with z (i.e., rapidly decrease due to evolution). This implies that the stellar population in such galaxies is many times denser than in ordinary galaxies. For this reason, the dynamical properties of these small, luminous, and massive galaxies may differ from those of ordinary galaxies in the late universe.

Galaxy Concentration Test. In the ΛCDM model, the proper volume of spherical shells with constant Δz decreases as $(1+z)^{-1}$, while it increases as $(1+z)^{2}$ in the static model. The observation of a large number of galaxies at $10 \lesssim z \lesssim 20$ (Weaver et al. 2024) implies an extremely high concentration of galaxies in the early universe within the framework of the ΛCDM model which may result in potential physical inconsistencies. This requires further investigation.

3 Physical Tests

Galaxy gravitational potential test. From the perspective of cosmographic tests such as angular size versus redshift and the Tolman test, the critical issue is the evolution of galaxy masses and linear sizes. Note that the gravitational potential of a galaxy, $\phi \propto M/r \propto v^2$, where M is the mass of the galaxy, r is its radius, and v is the linear rotation speed. The rotation speed, in turn, affects the width of the galaxy's spectral lines. Thus, we propose a new physical cosmological test — an independent determination of the evolution of ϕ in galaxies as function of increasing z though the observation of the equivalent width of spectral lines. If the ΛCDM model is correct, a dependence of the spectral line width on z should be observed, reflecting galaxy evolution, whereas in a static universe, such dependence would be absent or relatively weak (assuming slow evolution case). Preliminary analysis by Nakane et al. (2024) shows no evidence of the evolution of the gravitational potential. The complete implementation of this test is a task for future work.

Tension in cosmological parameters. Before the JWST observations, two problems with precision cosmology were already known: the H_0 and σ_8 tensions. According to the calculations (Muñoz et al. 2024), reionization is suggested to have started earlier than the standard model indicates and may have been completed by the time the galaxies observed by the JWST telescope formed. Galaxies observed by the JWST produced an excess of ionizing photons in the early universe. Consequently, the reionization process observed by JWST is currently showing a factor of 2 tension with the findings from *Planck* precision cosmology (Melia 2024). By contrast, in the slowly-evolving or static model such a problem does not occur.

At this moment, it can be observed that the determination of cosmological parameters based on the CMB (including *Planck* parameters) may warrant further verification. The H_0 – tension is resolved supportive of the value of $H_0 = 73.5\,\mathrm{km/s/Mpc}$. In this case, the corresponding age of the universe is estimated to be 12.6 Gyr (as opposed to the commonly accepted value of 13.8 Gyr from the CMB *Planck* cosmology). The galaxies with $z \approx 20$ observed by the JWST have an age of $\sim$ 160 million years, which raises questions about the feasibility of developing a physically meaningful galaxy-formation model that can account for a well-developed galaxy in such a short timeframe. This observation also prompts considerations regarding the accuracy of the universe's age as described by the ΛCDM model. The natural alternative to resolve this problem is to revise the standard cosmological model.

Infra-red galaxies. In the JWST deep fields, several new objects have also been discovered, referred to as HST-dark Infra-red Galaxies at $3 < z < 8$, including those reported by Williams et al. (2024). While the observation of such objects may have several explanations, the following has not yet been proposed in the literature. The authors propose that these galaxies could be sufficiently old that only the longest-living stars, i.e., red dwarfs, are present in them. In this case, the age of these galaxies must be much older than the age of the universe according to the standard cosmological model. This requires further investigation into the physical properties of these objects, particularly using spectroscopic methods.

4 Conclusions

The ΛCDM model with galaxy formation starting from baryonic acoustic oscillations became recognized as the standard model of "precision cosmology". The discussion of alternative cosmological models was given limited attention, although certain studies (e.g., Geller & Peebles 1972; Sandage & Perelmuter 1990) concentrated on cosmological tests. Precision cosmology relies on observations of the microwave background, which typically feature low angular resolution. In contrast, initial observations from JWST, known for its high resolving power, have revealed discrepancies with existing theoretical predictions. As a result, current discussions are focused on updating the theory of galaxy formation, which may include the role of primordial black holes, despite possible inconsistencies with CMB observations.

In the article, we highlighted the most significant contradictions between JWST observations and the standard cosmological model: cosmographic tests of angular size versus redshift, the galaxy concentration problem, Tolman's test and its physical consequences; *Planck*'s H_0, σ_8, and reionization tensions; and age inconsistencies of objects (insufficient time for the formation of observed objects in the ΛCDM-early universe and potentially overly old objects in the local universe). Although the TL model can resolve some of these contradictions, but it also known unresolved problems and discrepancies with observations. In the authors' opinion, there is currently insufficient observational data to conclusively determine the nature of cosmological redshift. However, JWST observations clearly indicate the need to revise the age of the universe significantly upwards, and suggest that a static cosmological model provides a more natural explanation for the observed results of cosmographic and physical tests. These contradictions indicate the importance to revive discussions about cosmological models and further research in this direction, including the new Galaxy gravitational potential test proposed in the article.

References

Castellano M., Fontana. A., Treu T., et al., 2023, The Astrophysical Journal Letters, 948, 2, id. L14
Finkelstein S.L., Leung G.C.K., Bagley M.B., et al., 2023, arXiv:2311.04279
Geller M.J. and Peebles J.E., 1972, ApJ, 174, p. 1
Hubble E.P. and Tolman R.C., 1935, ApJ, 82, p. 302
Lovyagin N., Raikov A., Yershov V., et al., 2022, Galaxies, 10, p. 108
Melia F., 2024, arXiv:2407.01581
Muñoz J.B., Mirocha J., Chisholm J., et al., 2024, arXiv: 2404.7250
Nakane M., Ouchi M., Nakajima K., et al., 2024, ApJ, V. 967, p. 28,
Orlov V.V. and Raikov A.A., 2016, Astr. Rep., 60, p. 477
Sandage A. and Perelmuter J. M., 1990, ApJ, 350, p. 481
Weaver J.R., Cutler S.E., Pan R., et al., 2024, ApJ Suppl. Ser., 270, p. 7
Williams C.C., Alberts S., Ji Z., et al., 2024, ApJ, 968, 1., id. 34