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Cosmic Chronometers: A Model-Independent Route to H(z) and Implications for the Hubble Tension

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Abstract. The Hubble constant (H0) has always had a significant difference between the measurement results of the early universe and the late universe. This difference is called the Hubble tension, which directly challenges the standard ΛCDM cosmological model. Although the local H0 value can be accurately determined by using the distance ladder method of Cepheid variable stars and Type Ia supernovae, the observation results of cosmic microwave background radiation are often low. Therefore, it is crucial to develop independent detection methods to identify potential system errors or find new physical mechanisms.The cosmic timer (CC) method provides a novel alternative. By analyzing the age differences of massive and passively evolved galaxies, it directly determines the Hubble parameter H(z) without using a model-dependent method. This article reviews the observational and theoretical basis of CC technology, elaborates on the strict criteria for selecting galaxies as reliable cosmic timers, and especially emphasizes the necessity of ancient massive galaxy groups that are not affected by the formation of recent stars. We further discussed the spectral age determination tools, including the physical origin of age-sensitive absorption characteristics and D4000 break, and their application in deriving differential age. With the upcoming data released by DESI, Euclid and JWST, it is expected that the cosmological timer will reach a percentage level of accuracy, thus providing cross-verification of the history of cosmic expansion and the nature of Hubble tension.

Keywords: Galaxies evolution, stellar population, Cosmology

1. Introduction

In 1929, Edwin Hubble proved that the farther the galaxy is from us, the faster it moves away from us. This phenomenon is not only the first evidence of the expansion of the universe, but also proves the Big Bang theory. In 1998, scientists discovered that the Type Ia supernova (SNe Ia) was darker than expected at long distances, indicating that the expansion of the universe was accelerating. This discovery introduced the concept of dark energy, and based on this, the ΛCDM model was produced. In this model, the cosmological constant (Λ) leads to the accelerated expansion of the universe in the later stage, and cold dark matter (CDM) controls the formation of the cosmic structure. Another key parameter of this model that needs to be studied is the Hubble constant (H_0), which measures the current expansion rate of the universe.The most commonly used method for measuring H_0 is the distance ladder method. This method uses the Cepheid variable star to calibrate

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the true brightness of the Type Ia supernova. Type Ia supernovae are used as standard candles because they come from similar exploding white dwarfs with mass reaching the Chandrasekhar limit. Astronomers use the Phillips relation to adjust the brightness to obtain an accurate distance (D_L). By combining these distances with redshift measurements, scientists can estimate the density of matter (Ω_m) and the density of dark energy (Ω_Λ). However, there is a significant difference (more than 4σ) between the value of the Hubble constant H_0 obtained by this method and the value obtained from early cosmic data (such as cosmic microwave background radiation (CMB) measured by Planck satellites) [1]. The H_0 value given by Planck satellite data is about 67.4 km/s/Mpc [1], while the value given by the distance ladder method (SH0ES) is about 73–74 km/s/Mpc [2].This difference is called Hubble tension, which prompts scientists to develop new methods to avoid uncertainty in distance ladder methods or CMB models. Cosmic timer (CC) technology is such a method, which measures the expansion rate H(z) by observing the age difference of ancient massive galaxies [3, 4]. This method is basically independent of the cosmological model and does not require assumptions about dark energy, spatial curvature or early cosmic physics.

2. The cosmic chronometer principle

The Friedmann–Lemaître–Robertson–Walker metric assumes that the universe is uniform in all directions, and the Hubble parameter H(z) is closely related to the change of cosmic time with redshift:

$$\mathrm{H}\left(\mathrm{z}\right)=-\left(\frac{1}{1+\mathrm{z}}\right)\left(\frac{\mathrm{dz}}{\mathrm{dt}}\right)$$

In order to measure dz/dt, we need a set of "cosmic clocks", that is, celestial bodies that are at different times and can be accurately compared. Massive galaxies that formed most of their stars early and later evolved passively without new stars are typical examples of such clocks. By selecting galaxy groups with similar evolutionary history and measuring the age difference Δt within the smaller redshift range Δz, we can estimate the differential age relationship:

$$\mathrm{H}\left(\mathrm{z}\right)\ \approx\ -\left(\frac{1}{1+z}\right)\left(\frac{\mathrm{dz}}{\mathrm{dt}}\right)$$

This method only uses the relative age difference, not the absolute age of the universe, so there is no need to rely on a specific cosmological model. Therefore, many systematic errors related to the absolute age or distance measurement of the universe can naturally be reduced.

3. Galaxy selection and observational criteria: ensuring purely passive evolution

Accurate cosmic chronometer (CC) measurement requires careful selection of samples. This can ensure that the age difference in the sample stems from the expansion of the universe, not the difference within the galaxy group [3, 4]. Our main selection target is the ancient and inactive star population.

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3.1. Why choose massive, old galaxies

Galaxy formation models and observations reveal a process called "downsizing" [5]. The most massive galaxies ($\log(M^*/M_\odot) \approx 10.5–11$) quickly form stars at high redshift ($z > 2$) and quickly run out of gas. These galaxies are usually located in dense areas and change very little over time. Their light mainly comes from old stars, so they are good indicators of time. In contrast, low-mass galaxies have long and irregular star formation histories, so they are not reliable as cosmic clocks.

3.2. Mitigating contamination from young stellar populations

Even a small number of young stars ("frosting") will make the brightness-weighted age appear younger, resulting in errors in H(z) measurements [3, 4]. In order to avoid this situation, the cosmic chronometer (CC) research adopts strict selection rules:· Morphology and color: Choose elliptical galaxies or early-type galaxies, or galaxies located on the red sequence in the color-magnitude diagram [5]. For galaxies with little recent star formation, the red sequence is a tight correlation between color and brightness.· Emission line diagnostics: Nebular emission lines (e.g. [O II] λ3727, Hα, [O III]) show the radiation of short-lived massive stars. Galaxies must have very weak or no such emission lines (equivalent width <1–2 Å) to be included in the scope of research. This excludes galaxies that have formed stars in the past 10^8 years [3, 4].· Specific star formation rate (sSFR): Only galaxies with sSFR $< 10^{-11}$ yr^{-1} are selected to ensure that the star formation rate is very low relative to the total stellar mass [3, 4].· Uniformity: In order to reduce data dispersion, the sample is limited to a narrow range in terms of velocity dispersion, stellar mass and environment [3, 4].Key survey projects with the required high-quality spectroscopy and imaging data include SDSS [6], BOSS [6], and future data from DESI [7], Euclid [8], and JWST [9].

4. Age-dating techniques: spectroscopic clocks and the 4000 Å break

Scientists use the Stellar Population Synthesis (SPS) model to determine the age of the galaxy. The model will generate a comprehensive spectrum based on the star formation history (SFH), initial mass function (IMF) and chemical composition of the galaxy.

4.1. Formation of age-sensitive spectral features

• Balmer Absorption Lines (like Hβ and Hδ) happen when electrons in hydrogen jump from the n=2 level to higher energy levels. These lines are strong in A-type stars, which live about 0.1 to 1 billion years. As a group of stars gets older, the stars that leave the main sequence have less mass, so there are fewer A-type stars. This makes the Balmer lines get weaker over the first few billion years. As demonstrated in the SPS models of Bruzual & Charlot (2003) [10], the strength of the Hβ line can be used to tell the age of star groups that are in the middle of their life, but this also depends on how much metal is in the stars, an uncertainty further quantified by Conroy et al. (2009) [11].

• Metal Lines (such as Mg b, Fe λ5270, and Fe λ5335) come from the atmospheres of cool, low-mass stars called K and M giants. As the star group gets older, more light comes from these red giant stars, making the metal lines stronger over time. The stellar population models of Bruzual & Charlot (2003) [10] and the high-resolution models of Maraston & Strömbäck (2011) [12] show how these features evolve. By looking at both Balmer lines (which show age) and metal lines (which show age and metal content), we can tell the difference between a star group's age and its metal content.

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4.2. The 4000 Å break (D4000)

The most reliable way to tell the age of stars in galaxy studies is the 4000 Å break. This is a clear jump in galaxy light caused by many metal absorption lines on the blue side and less light before 4000 Å because ionized metals block it in cool stars. The study by Balogh et al. (1999) [5] established the D4000 break as a key age indicator in galaxy evolution studies.

• Definition: The D4000 index is the ratio of average light in the red area to the average light in the blue area. The usual narrow-band D_n4000 is:Blue band: 3850–3950 Å (rest-frame)Red band: 4000–4100 Å (rest-frame)

• Measurement: After adjusting D4000 to the rest-frame, we measure directly from the light of the galaxy. Because it uses a wide band instead of a narrow line, it can work well even if the data is a little noisy or the instrument resolution is low. The SPS models of Bruzual & Charlot (2003) [10] show that as the star ages, this break becomes stronger, but it also depends to some extent on the metal content, an uncertainty further explored in the high-resolution models of Maraston & Strömbäck (2011) [12].In the study of galaxy age, scientists pay attention to the differences in age indicators (such as ΔD4000 and ΔHβ) between galaxies near redshift. This method, pioneered by Moresco et al. (2012) [3], helps to reduce the error caused by calibration differences in the model.

5. Systematic uncertainties: a hierarchical assessment

The accuracy of H(z) measured by the cosmic chronometer is affected by the following important problems, which are from large to small:

• The biggest problem: different stellar population synthesis models

Different stellar population synthesis models use different data and methods to represent the life stages of stars, especially for TP-AGB stars. As shown by Bruzual & Charlot (2003) [10], Conroy et al. (2009) [11], and Maraston & Strömbäck (2011) [12], this will lead to a 10-20% deviation of the age of the stellar population. To solve this problem, scientists use a variety of models (such as BC03 [10], M11 [12], FSPS [11]) and observe the age differences between galaxy groups with similar redshifts, rather than the exact age. This differential approach, as applied in Moresco et al. (2012, 2016) [3, 4], helps to eliminate common errors.

• A very big problem: age-metallicity degeneracy

Young stars rich in metal may look like older stars with less metal abundance in light. This degeneracy was characterized in the SPS models of Bruzual & Charlot (2003) [10]. To solve this problem, scientists check parameters sensitive to metal abundance (such as [MgFe]', Mgb/⟨Fe⟩) and select galaxies with similar velocity dispersion (velocity dispersion is related to metal abundance and mass) [3, 4]. This can ensure that their metal abundance history is relatively close.

• Medium and other problems: a small number of new star outbreaks ("Frosting")

A small number of residual star formation (less than 1% of mass) will make the stars look younger. The sample selection criteria established by Moresco et al. (2012, 2016) [3, 4] address this by eliminating galaxies with emission lines ([O II], Hα) and using special methods to observe the light of old and new stars.

• Smaller problem: the difference in the initial mass function (IMF) at the time of the birth of the star

The mixture of stellar masses at the birth of a star will affect its brightness and mass. As discussed by Conroy et al. (2009) [11], this will lead to a slight difference in the calculation of the age of the stellar population. However, the cosmic chronometer method focuses on changes over

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time, so it is less affected. Usually, only a simple initial mass function is used, or only a small amount of adjustment is made.

6. Conclusion

Many studies have used cosmic chronometers to accurately measure H(z) in the redshift range from 0 to about 2. Moresco et al. (2012) [3] and Moresco et al. (2016) [4] obtained about 30 H(z) data points using red-sequence galaxies. When they use Gaussian processes to estimate H_0, the value obtained is about 68–69 km/s/Mpc. The latest data from BOSS [6] and DESI [7] support a history of cosmic expansion consistent with the lower values supported by the Planck satellite [1].Different from Type Ia supernovae or Baryon Acoustic Oscillations (BAO), which measure distance by cumulative expansion history,

$$D_{L(z)} = \left(\frac{c}{H_0}\right)(1+z)\int \frac{dz^{'}}{E\left(z^{'}\right)}$$

The cosmic chronometer (CC) method directly measures the cosmic expansion rate H(z). Therefore, it has the following obvious advantages:No distance ladder required: CC measurement is absolute, so there is no need for parallax or Cepheid variable star calibration. It avoids problems such as brightness changes or dust blocking the standard candles, which affect the distance ladder measurements of the SH0ES team (Riess et al., 2022) [2]. It does not depend on the early universe model: As demonstrated by Moresco et al. (2012, 2016) [3, 4], the H(z) value of CC only comes from the behavior of the galaxy in the later stage. In contrast, the CMB estimate of H_0 from Planck Collaboration (2020) [1] depends on a specific early universe model (such as a flat ΛCDM model with normal neutrinos). If the values of CC and CMB do not match, it may mean that there is a new physical phenomenon in dark matter or gravity, rather than an error in the early cosmic physics model.At present, the noise of CC data is greater than that of supernovae or CMB data, but usually shows a lower H_0 value (~68 km/s/Mpc), consistent with the findings of Moresco et al. (2016) [4] and Planck Collaboration (2020) [1]. If the better CC data in the future, from upcoming surveys such as DESI [7], Euclid [8], and JWST [9], is consistent with CMB but seriously inconsistent with the local distance measurement results ($H_0 > 73$) from SH0ES [2], it means that the problem lies in the local distance measurement error or our misunderstanding of the early universe.

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