JWST Research Progress on "Little Red Dots" in the Early Universe Pre-print

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Abstract

High-redshift surveys conducted by the JWST have revealed a unique class of compact red objects known as "Little Red Dots" (LRDs). LRDs exhibit compact morphologies, with spectral energy distributions (SEDs) characterized by a V-shaped structure in the ultraviolet-visible bands and extreme reddening in the rest-frame optical regime. Some LRD spectra are accompanied by broad Balmer emission lines, suggesting the potential presence of low-luminosity active galactic nuclei (AGN). However, LRDs exhibit weak radiation in the X-ray and far-infrared bands; thus, traditional AGN models struggle to fully explain their observed characteristics.

This paper reviews the primary findings on LRDs based on recent JWST photometric and spectroscopic studies, systematically summarizing their photometric features, spectroscopic properties, and statistical distributions. Furthermore, it summarizes the current major physical models for LRDs, including: (1) dust-obscured AGN, referring to low-luminosity active galactic nuclei subject to significant dust extinction; (2) super-Eddington accretion, where black holes grow at rates exceeding the Eddington limit, thereby influencing the SED morphology; (3) extreme starburst galaxies, which possess intense star formation activity accompanied by strong dust extinction; and (4) composite models of AGN and starburst galaxies.

Full Text

Preamble

Discovery of "Little Red Dot" Objects in the Early Universe

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Abstract

High-redshift surveys conducted by the James Webb Space Telescope (JWST) have revealed a unique class of compact red objects known as "Little Red Dots" (LRDs). These objects are characterized by their compact morphologies and spectral energy distributions (SEDs) that exhibit a distinct V-shaped structure in the ultraviolet-to-visible range, followed by extreme reddening at the rest-frame optical wavelengths. A subset of LRDs displays broad Balmer emission lines in their spectra, suggesting the presence of low-luminosity Active Galactic Nuclei (AGNs). However, their relatively weak emission in X-ray and far-infrared bands poses a challenge for traditional AGN models, which struggle to fully explain these observed characteristics.

This paper reviews the latest photometric and spectroscopic research on LRDs, systematically summarizing their photometric features, spectral properties, and statistical distributions. Furthermore, we categorize the primary physical models currently proposed to explain the nature of LRDs, which include: (1) Dust-obscured AGNs, representing low-luminosity active galactic nuclei subjected to significant extinction by interstellar dust; (2) Super-Eddington accretion, where black holes grow at rates exceeding the Eddington limit, potentially explaining their compact morphologies; (3) Extreme starburst galaxies, characterized by intense star formation activity accompanied by heavy dust extinction; and (4) Hybrid models that combine elements of both AGNs and starburst galaxies.

Keywords

Galaxies; Active Galactic Nuclei (AGN); Star Formation; High Redshift; James Webb Space Telescope (JWST)

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1 Introduction

Since its successful launch in 2021, the James Webb Space Telescope (JWST) has rapidly become a leading instrument in astronomy, particularly for early universe research, thanks to its exceptional resolution and sensitivity in the optical and infrared bands. It has delivered a series of revolutionary breakthroughs and findings regarding the formation and evolution of the universe. Among the many groundbreaking discoveries made by JWST, a class of mysterious objects widely present in the early universe (redshift $z \gtrsim 4$) has garnered significant attention. In the early stages of JWST operations, Labbé et al. [?] first reported a category of unique objects characterized by compact morphologies, blue rest-frame ultraviolet (UV) spectra, and significant reddening in the rest-frame optical bands. These objects have been descriptively named "Little Red Dots" (LRDs) by astronomers. Their unique characteristics have sparked a surge of related research in the less than two years since their discovery. As more photometric and spectroscopic observation missions are conducted, various research teams are working to reveal the true nature of these compact red objects.

Initially, because LRDs exhibit significant reddening in the rest-frame optical band and some sources show broad Balmer emission lines, some researchers speculated that these objects might be dust-obscured active galactic nuclei (AGNs). Studying high-redshift AGNs is crucial for understanding the formation and growth mechanisms of black holes in the early universe. AGNs are among the most powerful energy sources in the universe, driven by rapidly accreting supermassive black holes (SMBHs) at their centers, which influence the evolution of host galaxies by releasing immense radiation and material outflows. Typical AGNs exhibit X-ray emission and an infrared power-law spectrum generated by accretion disk heating; their observational characteristics vary with the line of sight and can be classified into Type 1 and Type 2, with Type 1 typically showing broad emission lines. Based on these properties, traditional AGN identification methods usually rely on X-ray detection, infrared colors, and spectroscopic diagnostics. However, most LRDs discovered by JWST lack X-ray detections, the origin of their blue-skewed UV radiation remains unclear, and their spectral features differ from those of low-redshift AGNs. Furthermore, LRDs exhibit characteristics suggesting unusually large black hole masses. These differences in characteristics have sparked extensive research and discussion regarding the nature of LRDs, suggesting that the properties of high-redshift AGNs may be more complex than those in the local universe. Therefore, in-depth study of LRDs not only helps identify potential high-redshift AGNs but also provides key observational evidence for exploring seed black holes in the early universe and their co-evolution with host galaxies.

Based on the latest JWST observation data, this paper will systematically explore the physical properties of LRDs, including their photometric characteristics, spectroscopic features, and statistical properties in the high-redshift universe. Furthermore, we will discuss the formation mechanisms of LRDs and provide an outlook on how future, more in-depth observations can help us understand the role of these objects in cosmic evolution.

2.1 JWST Observational Instrumentation

The James Webb Space Telescope (JWST) was developed through a collaboration between the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Canadian Space Agency (CSA), and was successfully launched on December 25, 2021. As the successor to the Hubble Space Telescope (HST), JWST features a larger aperture (a 6.5 m primary mirror) and enhanced infrared observation capabilities, enabling deep observations in the near-infrared (NIR) and mid-infrared (MIR) bands. Its four primary scientific instruments—the Near-Infrared Camera (NIRCam), the Near-Infrared Spectrograph (NIRSpec), the Mid-Infrared Instrument (MIRI), and the Near-Infrared Imager and Slitless Spectrograph (NIRISS)—cover a wavelength range of 0.6 to 28.5 μm, providing a wealth of data for studying the formation and evolution of galaxies. As the primary imager for JWST, NIRCam also possesses spectroscopic capabilities, with a wavelength coverage of 0.6 to 5.0 μm, providing critical data for the study of early galaxies.

NIRCam utilizes a dual-module design, where each module contains both short-wavelength (SW) and long-wavelength (LW) channels, allowing for simultaneous observations across different wavelengths. Furthermore, its extremely high imaging sensitivity (reaching the nano-Jansky level) enables the detection of exceptionally faint, high-redshift galaxies, providing essential data for galaxy research during the Epoch of Reionization (EoR).

In this study, a large number of galaxies that appear red in the rest-frame optical bands were successfully identified through NIRCam' s wide-field imaging and high-sensitivity infrared color analysis. NIRSpec serves as the primary spectrograph for JWST, covering a wavelength range of 0.6 to 5.3 μm and offering multiple spectroscopic modes ranging from low to high resolution. By employing a revolutionary microshutter array (MSA), NIRSpec is capable of observing hundreds of galaxies simultaneously. This significantly enhances observational efficiency, making it an ideal tool for large-scale galaxy spectroscopic surveys.

The Integral Field Unit (IFU) of NIRSpec provides three-dimensional spectroscopic data, enabling astronomers to resolve the internal gas kinematics and chemical composition of galaxies. The spectra of these objects typically exhibit strong Balmer transitions and dust attenuation features. JWST/NIRSpec provides high signal-to-noise ratio (SNR) spectra, allowing astronomers to further analyze whether these galaxies are in a phase of intense star formation or if they harbor growing supermassive black holes. As the only mid-infrared instrument covering the 5–28 μm band, MIRI offers unique observational capabilities for studying dust-obscured galaxies. In galaxy research, MIRI' s high sensitivity allows astronomers to study galaxies at high redshift. By analyzing MIRI' s mid-infrared spectra, researchers can further probe star formation activity and the chemical composition of the gas within these systems.

2.2 Advantages of JWST in Identifying Little Red Dots

Under the deep observations provided by JWST, the identification and certification of these sources currently rely primarily on methods such as color indices, continuum slopes, and emission lines. The color index method is based on the fact that "Little Red Dots" (LRDs) typically exhibit significant reddening features in the rest-frame optical band. Utilizing NIRCam multi-band photometric data, this method effectively identifies high-redshift galaxies while excluding contamination from low-redshift dust-extinguished galaxies. In contrast, previous instruments were limited by their wavelength coverage and could not provide corresponding photometric bands for high-redshift objects; furthermore, ground-based telescopes suffer from limited sensitivity in near-infrared photometry due to atmospheric absorption.

The wavelength coverage of JWST NIRCam from 0.6 to 5.0 μm ensures the measurement of key features, such as the Lyman break and Balmer break, thereby enhancing the reliability of photometric source selection. The continuum slope method is based on the unique characteristic of LRDs, which appear red in the rest-frame optical band but blue in the ultraviolet (UV) band. High-sensitivity near-infrared photometric data allow astronomers to fit continuum slopes across multiple bands and, combined with spectroscopic data, more accurately characterize the spectral properties of these galaxies. Compared to single-color selection, the spectral slope fitting method utilizes more complete spectral information, reducing uncertainties caused by measurement errors in individual bands and improving identification precision. Additionally, research has identified a class of LRDs with extremely strong Balmer emission lines, where the equivalent width (EW) can exceed $1,000$ Å. These may be candidates for Broad Line Regions (BLRs) and could play a significant role in the reionization process of the early universe. Consequently, the selection of emission-line sources has also become an effective method for identifying LRDs.

3 Observational Characteristics and Physical Properties of LRDs

The high sensitivity of the JWST has enabled the detection of many high-redshift faint galaxies that were previously unidentified, with the discovery of "Little Red Dots" (LRDs) representing a significant breakthrough. These objects exhibit compact, point-source characteristics in the JWST/NIRCam bands and show significantly red color indices in the rest-frame optical regime. This class of objects was first identified by Labbé et al. (2023), whose research utilized color index criteria to select a population of "red massive galaxies" at $z \sim 7-9$ that appeared to possess extremely high stellar masses ($M_* \sim 10^{10} M_\odot$) accompanied by substantial dust extinction ($A_V > 3$).

3.1.1 Point-Source Dominated Morphological Features

Morphologically, these objects primarily manifest as compact, point-source structures. [FIGURE:1] displays a subset of the sources discovered in the CEERS field by Kocevski et al. (2025). Three-color composite images were synthesized from JWST/NIRCam filter data; as shown in the figure, these sources exhibit distinctly red colors and highly compact morphologies.

The point-source structure of a galaxy typically implies that its emission is dominated by a compact, concentrated component, such as an Active Galactic Nucleus (AGN), a dense stellar cluster, or a seed black hole in the early universe. Statistical results indicate that the median effective radius (R_e) of these galaxies is approximately 150 pc, a value at least an order of magnitude smaller than the typical size of local galaxies of comparable mass. Furtak [?] utilized the gravitational lensing effect of the galaxy cluster A2744 to discover an object at high redshift with an effective radius smaller than 35 pc. This indicates that some of these objects are highly compact.

3.1.2 V-shaped Spectral Energy Distribution

Spectral analysis serves as a critical tool for investigating the physical properties of these sources. Overall, Little Red Dots (LRDs) exhibit a blue spectrum in the rest-frame ultraviolet (UV) but transition to a steep red continuum in the rest-frame optical, resulting in a unique V-shaped spectral energy distribution (SED). This characteristic likely involves the combined effects of young stars, dust-obscured starburst activity, and AGN. The reddening observed in the rest-frame optical can be interpreted either as a dust-obscured AGN continuum or as dust-rich star-forming activity.

Using data from the Systematic Mid-infrared Instrument Legacy Extragalactic Survey (SMILES), [**?**] found that the flux upper limits for most LRDs in the mid-infrared (MIR) suggest that these objects are not generally dominated by strong AGN activity. Their SEDs tend to flatten after a rest-frame wavelength of $\lambda \sim 5\mu$m, consistent with the typical stellar radiation peak. [**?**] further noted that the observed colors of LRDs are bluer than those of typical heavy dust-obscured quasi-stellar objects (QSOs), which are dominated by hot dust torus radiation at $\lambda > 5\mu$m.

3.2.1 Broad Balmer Emission Lines

Spectroscopic observations from JWST have revealed that approximately 20% to 30% of LRDs exhibit broad Balmer emission line features. The Full Width at Half Maximum (FWHM) of these emission lines is generally around $1,000$ km/s, with some sources reaching up to $3,000$ km/s. For instance, Kokorev et al. (2023) reported that the $H\alpha$ emission line in UNCOVER-18594 possesses a broad component with a significance exceeding 10σ. [FIGURE:1] illustrates the fitting of the $H\alpha$ emission line for source ID:73488. These line widths are consistent with the characteristics of Type 1 AGNs, suggesting that LRDs are likely candidates for dust-obscured AGNs.

3.2.2 X-ray Properties

Despite the fact that most selected sources are located within deep X-ray survey coverage areas—such as the 7Ms Chandra Deep Field South (CDFS)—the X-ray detection rate remains extremely low. Even for sources exhibiting broad-line features, many remain undetected. Stacking analyses of the entire sample have yielded only marginal detection signals.

The low X-ray detection rate may be related to a high covering factor; specifically, the presence of a significant amount of neutral gas surrounding the LRDs could suppress the X-ray radiation from the central engine. Research by [**?**] indicates that the X-ray radiation from LRDs is significantly weaker than that of low-redshift AGN; the upper limits for X-ray luminosity are approximately 1 dex lower than expected.

3.2.3 Low Ultraviolet Luminosity

Compared to general galaxies and previously discovered high-redshift ($z \sim 6$) quasars, LRDs exhibit relatively low ultraviolet (UV) luminosities. [FIGURE:1] illustrates the UV luminosity function at redshift $z \sim 5$. The UV luminosities of the LRD sample are primarily concentrated within the range of $\mathrm{M_{uv}} \in [-21, -17]$. The number density of LRDs at low UV luminosities is significantly higher than previously expected, approximately 10 to 100 times higher than results reported by [**?**] at similar redshifts.

3.3.1 Mass Characteristics

Due to the characteristic broad Balmer emission lines, research typically employs local virial black hole mass estimators. Specifically, mass estimation is performed based on the broadening and luminosity of the $H\alpha$ line:

$$\lg(M_{\mathrm{BH}}) = 6.60 + 0.47 \lg\left(\frac{L_{\mathrm{H}\alpha}}{10^{42}}\right) + 2.06 \lg\left(\frac{\mathrm{FWHM}_{\mathrm{H}\alpha}}{1000}\right)$$

The results indicate that the black hole masses are primarily distributed within the range of 10^6 to $10^8 M_\odot$. In the high-redshift universe, the M_{BH}/M_* ratio can reach as high as $10\% - 100\%$, deviating significantly from the local 0.1% ratio. This suggests that the formation and growth of black holes may be more closely related to mass accretion processes rather than being solely influenced by the star formation rate.

4 Physical Interpretations of Little Red Dots

4.1.1 Dust-Obscured AGN Model

The dense point-source structure and extreme reddening in the optical bands support the dust-obscured AGN hypothesis. Spectroscopic studies have demonstrated that approximately 80% of candidates exhibit broad emission lines consistent with a Broad Line Region (BLR). However, the distribution of LRDs on the BPT (Baldwin-Phillips-Terlevich) diagram reveals that most of these objects fall within the region occupied by local star-forming galaxies rather than typical AGNs. This may suggest that their narrow emission lines are dominated by star-formation activity within the host galaxy, while the central AGN is heavily obscured.

4.1.2 Seed Black Hole Models

The black hole mass estimates suggest that seed black holes in the early universe grew at a rate significantly faster than the mass accumulation of their host galaxies. Current theoretical models are categorized into light seeds (from Population III stars) and heavy seeds (from direct collapse of gas clouds). The lack of X-ray emission and optical variability in LRDs may be explained by super-Eddington accretion, where high-velocity outflows and high-density plasma obscure or upscatter X-ray photons.

Figure 4

Figure 1: Figure 4

4.2 Starburst Galaxy Model

Extreme reddening and significant Balmer breaks suggest that LRDs could be highly obscured starburst galaxies. Pérez-González (2024) indicated that LRD colors are bluer than predicted by typical dust-shrouded AGN models. The luminosity in the rest-frame near-infrared is relatively flat, consistent with a stellar radiation peak. Current research increasingly favors a composite model where an AGN influences the infrared and broad-line features, while young stars and dust dominate the ultraviolet and optical radiation.

5 Summary and Outlook

JWST' s exceptional infrared sensitivity has identified over 300 LRD candidates at $z > 4$. These objects exhibit compact morphologies, V-shaped SEDs, and broad Balmer emission lines, yet they show weak X-ray and far-infrared emission. Future research will involve statistical analyses of larger samples from upcoming missions like Euclid and the Roman Space Telescope. High-resolution spectroscopic analysis and joint multi-wavelength observations will be crucial to resolving the debate over their physical nature and understanding the co-evolution of galaxies and black holes in the early universe.

Figures

Source: ChinaXiv —Machine translation. Verify with original.