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Stereoscopy in Distant Galaxies: Exploring Techniques and Simulations

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Abstract

Stereoscopy has become an invaluable tool in the study of distant galaxies, offering insights into their three-dimensional structure and dynamics. This paper examines the various types of 3D reconstruction techniques including time stereoscopy and view stereoscopy. Additionally, it explores the use of simulations to test and compare the effectiveness of these stereoscopic techniques for distant galaxies.

1. Introduction

To understand stereoscopy, we first need to consider how depth perception functions in human vision. According to (Uematsu et al., 2024) binocular vision—where both eyes work together—plays a central role in perceiving depth. The brain, however, compensates for this by processing information from both eyes. Importantly, depth perception requires a minimum of two distinct views for the brain to construct a 3D image. The interocular distance in humans mirrors the stereo base in such systems, where two distinct viewpoints (such as cameras or telescopes) are used to reconstruct three-dimensional depth information. This paper discusses stereoscope imaging taking physiological properties of eyes as standard control. The different stereoscopic types are discussed along with simulations performed. These include stereoscopic astronomy, which expands the horizons of multiple telescopes at different distances in space images the same source. Further binocular, view, Galactocentric and time stereoscopy are discussed and simulated.

2.1 Multiple Telescopic Observations

In stereoscopic astronomy, the concept of the stereo base is critical for achieving depth perception when observing distant celestial objects. When multiple telescopes, positioned at different locations on Earth or in space, observe the same galaxy, the distance between them effectively serves as the stereo base.

2.1.1 Stereoscopy in Distant Galaxies

Binocular stereoscopy, a well-established technique in the field of astronomy, has proven to be a powerful method for studying the three-dimensional structure of distant galaxies (Genzel et al., 2020). By analyzing the disparity between two images of the same celestial object, captured from slightly different perspectives, researchers can reconstruct the depth and spatial relationships within these distant systems.

2.1.2 View Stereoscopy

View Stereoscopy leverages multi-angle imaging to create a three-dimensional representation of galaxies. This technique is particularly useful in weak gravitational lensed studies, where the shapes of distant galaxies are (albeit distorted) due to the gravitational influence of foreground mass distributions. The Euclid mission, for example, aims to conduct extensive surveys of galaxy shapes and distributions, allowing astronomers to map dark matter in the universe by analyzing these distortions (Cimatti & Scaramella, 2012; Martinelli et al., 2021).

2.1.3 *Galactocentric Stereoscopy*

Stereoscopy Using Galactocentric Velocities focuses on the kinematic properties of galaxies, providing insights into their internal dynamics and interactions. The resolved three-dimensional kinematics of distant galaxies serve as a powerful tool to trace the processes governing star formation and galaxy evolution, such as mergers and accretion (Kiessling et al., 2015). By measuring the velocities of stars and gas within galaxies, researchers can infer the gravitational influences at play, which is essential for understanding the formation of early-type galaxies in dense environments (Fan et al., 2010; Förster Schreiber & Wuyts, 2020).

2.1.4 Time Stereoscopy

This technique would involve capturing snapshots of the galaxy at different time intervals to observe changes in structure and star formation rates. The logarithmic spiral model can simulate the evolution of spiral arms over time, providing a temporal dimension to the data. By analyzing these time-sequenced images, we can assess the distribution of stellar populations, as seen in the work of Gnedin (Gnedin et al., 2010), who explored mass profiles and their implications for galaxy dynamics. By combining velocity fields with positional data, these techniques enable the interpolation of new positions, which can be used to generate stereoscopic image pairs, offering a more comprehensive view of galactic structures and their temporal evolution. Further, we explain different stereoscopic techniques in detail.

3. Material and methods

Methodology for different stereoscopic effectiveness on logarithmic spiral galaxy model:

3.1 Logarithmic spiral galaxy model

This model captures the appearance of many spiral galaxies, which often show arms that extend in a spiral pattern from the center outward. The spiral arms of these galaxies follow a specific mathematical form, which can be described by the equation of a logarithmic spiral.
The polar equation of a logarithmic spiral is:

$$r = r_0 e^{b\theta}$$

where r is the radial distance from the center, r_0 is the initial radius (the distance from the center at ($\theta=0$), θ is the angular coordinate, b is a constant that controls the tightness of the spiral: the smaller b is, the tighter the spiral).

By applying this model, we can generate synthetic observations that mimic the behavior of real galaxies, allowing us to test the effectiveness of different stereoscopic techniques.

3.2 Time Stereoscopy

Time stereoscopy holds immense potential in unveiling the intricate structures and dynamics of these celestial marvels. To illustrate the feasibility of this approach, a simulation involving the construction of two spiral galaxies was conducted as shown in Figure 1.

In the simulation, the galaxies were modelled by randomly generating points distributed along a logarithmic spiral, and the rotation of the galaxies over time, controlled by the parameter \`t\`, allowing for the capture of the galaxies at two distinct time instants. To avoid uniformity, a slight random noise was introduced in the position of the stars.

The resulting stereoscopic pair of the spiral galaxies at time A) t=0 and B) t=0.5 is depicted in Figure 1, showcasing the potential for depth perception and 3D reconstruction through this method. While the simulation demonstrates the viability of time stereoscopy for galaxy reconstruction, the practical application of this technique in reality can prove challenging due to the vast timescales and minute changes involved in the evolution of distant galaxies, which are situated millions of light-years away (Leike et al., 2021).

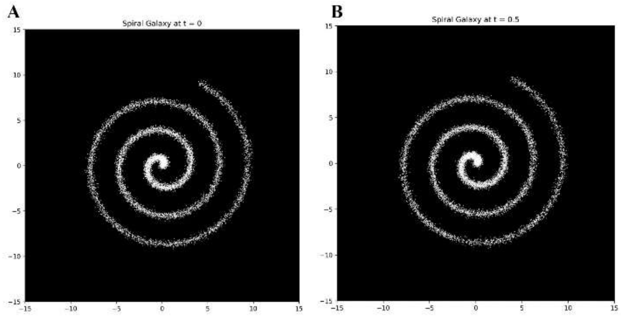

Fig. 1 Stereoscopic pair of spiral galaxies at time A) t=0 and B) t=0.5

3.2 View Stereoscopy

The technique for view stereoscopy applied is binocular stereoscopy, according to the paper (Rai et al., 2024) the 3D reconstruction of distant galaxy was attempted by forming a stereo pair, from multiple images received of the same galaxy due to gravitational lensing by galactic cluster RX J2129. A remarkable image was obtained with the James Webb Space Telescope (JWST) (Kelly et al., 2022; Lea, 2023), showing three images lensed by galactic cluster RX J2129 of a galaxy containing Type Ia supernova AT 2022riv (cf.(Morgan et al., 2001)). Due to their different path lengths, two of the three images are 320 days and 1000 days after the first. Here we move forward with a different approach, in the initial analysis, only two views were used at a time to generate stereo images, which were then rotated to minimize the angular disparity between them. To enhance the depth reconstruction, we now employ the Algebraic Reconstruction Technique (ART), commonly utilized in computed tomography (CT) to reconstruct three-dimensional images from multiple two-dimensional projections. As demonstrated by Gordon et al. (Jaman et al., 1985a), a minimum of three distinct views is required for effective 3D reconstruction. A simulation was performed using three views to reconstruct the galaxy's structure, applying ART to mitigate the limitations observed with two-view stereoscopy and to attempt a more accurate 3D representation of the galaxy.

4. Results and Discussion

Algebraic Reconstruction Techniques (ART) were introduced by Gordon, et al.(Gordon et al., 1970; Jaman et al., 1985b) for solving the problem of three-dimensional reconstruction from projections in electron microscopy and radiology. This is a deconvolution problem of a particular type: an estimate of a function in a higher dimensional space is deconvolved from its experimentally measured projections to a lower dimensional space.

ART is an iterative procedure which starts with an initial estimate of the image and then update the pixel values so that they satisfy the given projection data.

We implemented this technique by modeling a galaxy with a logarithmic spiral structure and viewing it from three distinct angles (0°, 45°, and 90°). These views were then projected onto a two-dimensional plane, as illustrated in Figure 2.

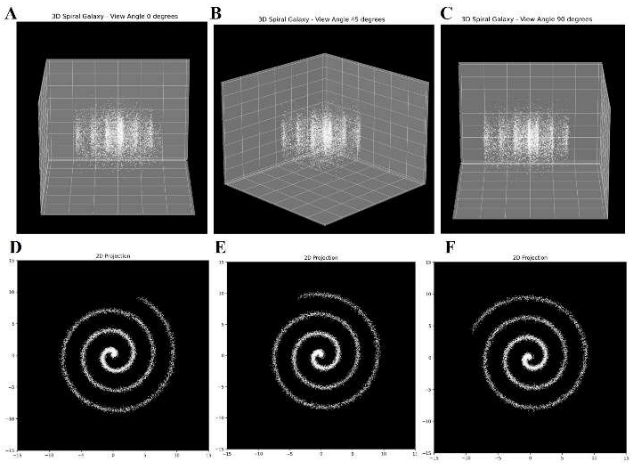

Fig.2 Images from A) to C) are the 3D view of galaxy at angles 0,45 & 90. These views when projected on a 2D planes form corresponding images D), E) and F).

The resulting 2D projections represent the three distinct views used for reconstruction. The results of this reconstruction are shown in Figure 3. From the simulation, it is evident that the 3D reconstruction closely approximates the original galaxy model, demonstrating a high degree of fidelity between the reconstructed and the true structure. This suggests that the ART algorithm is effective in recovering the three-dimensional morphology of the galaxy from multiple 2D projections, providing a reliable method for 3D reconstruction in astronomical imaging. It should be noted, however, that the quality of the reconstructed image is contingent upon the resolution of the input data. It should be noted, however, that the quality of the reconstructed image is contingent upon the resolution of the input data.

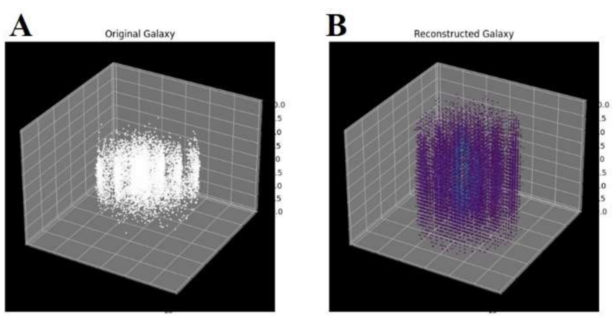

Fig. 3 Inset shows A) and B) images show the original and image reconstructed using ART algorithm respectively.

Higher-resolution images of the galaxy would significantly enhance the fidelity of the reconstruction. Additionally, increasing the number of 2D projections could further refine the accuracy of the 3D model, providing more detailed information about the galaxy's structure and reducing potential artifacts introduced by limited viewpoints.

Galactocentric velocity as an aid in 3D reconstruction

This method represents a form of time stereoscopy where, rather than using direct observations of galaxies at two distinct timestamps, we utilize their galactocentric velocities. These velocities enable us to model the positions of galaxies at a specific time t, where ‘t’ is the time at which the modeled galactic positions and the original observations can be paired stereoscopically.

In the study by Sohn et al.(Sohn et al., 2018) precise measurements of globular cluster motions within the Milky Way were employed to gain insights into their origins and to estimate the galaxy's total mass. The paper presents measurements of absolute proper motion (PM) for 20 globular clusters in the Milky Way's halo, derived from data obtained with the Hubble Space Telescope (HST). These clusters, situated between approximately 10 and 100 kiloparsecs (kpc) from the Milky Way's center, exhibit very small measurement uncertainties, around 0.06 milliarcseconds per year.

The study finds that both young and old halo clusters share similar three-dimensional velocities, which were determined by integrating existing radial velocity data. Notably, some clusters, such as NGC 6101, exhibit high tangential velocities exceeding 290 km/s, while the majority have lower tangential velocities below 200 km/s.

Thus, an SGL probe or more feasibly, a fleet of such probes would need to scan and sample this extensive region systematically, pixel by pixel. This process involves measuring the brightness of the Einstein ring at various locations to construct a resolved image of the original distant source. The challenges of this technique lie in the immense spatial scale and the need for precise measurements to reconstruct detailed images from the amplified light.

The angular resolution of the SGL is, in principle, a few times 10^{-10} arcsec at the focal region. However, this angular resolution is valid only if we were to measure the brightness of the Einstein ring around the Sun with a tiny telescope, with an aperture less than a few cm, which of course contradicts the requirement that a telescope must, at the very least, have the angular resolution to distinguish the Einstein ring from the solar disk, so it necessarily has to be a meter-class instrument. With such an instrument, the actual resolution is a lot less, maybe on the order of a few times 10^(-9) arcsec under ideal circumstances.

5. Conclusion

The review and simulation results provide an in-depth analysis of applying stereoscopy and the Algebraic Reconstruction Technique (ART) to achieve three-dimensional views of galaxies. Our findings indicate that given current temporal and resolution constraints, both time and view stereoscopy offer limited utility. However, the integration of multiple images presents a viable opportunity to enhance image quality through the ART algorithm. The most promising approach involves acquiring 6D phase space information of galactic clusters and extrapolating their positions to generate a stereoscopic pair. This technique, while offering the potential for significant improvement in reconstructing galactic structures, faces challenges related to the movement of galactic clusters and the influence of dark matter and other celestial bodies on these measurements. We aim to highlight both the potential and the current limitations of these techniques to guide future research. As Solar Gravitational Lensing (SGL) becomes a feasible observational tool and image resolution technology advances, these insights will become increasingly valuable for astronomers seeking to explore and understand distant galaxies.

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7. References

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