

# High-Resolution Astronomical Imaging: Resolving Close Binaries and Stellar Surfaces via Optical Coherence

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## Abstract

Due to the diffraction limit of conventional telescopes, the angular resolution of single-aperture instruments in the visible band is typically restricted to  $\sim 0.02$  arcseconds, which hampers the effective resolution and imaging of close binary systems and stellar surface features. To overcome this limitation, optical interferometry has emerged as a powerful technique for high-resolution astronomical imaging, grounded in optical coherence theory and the van Cittert–Zernike theorem. By employing key technologies such as telescope arrays, baseline synthesis, closure phase calibration, and  $u$ – $v$  plane sampling, milli-arcsecond angular resolution can be achieved, enabling precise determination of orbital parameters in close binaries, as well as accurate measurements of stellar masses and radii, while allowing direct imaging of stellar magnetic activity features such as starspots and faculae. Observational approaches are generally divided into model-fitting and image-reconstruction methods, each with distinct advantages and limitations. Nevertheless, ground-based interferometry remains constrained by atmospheric turbulence, sparse  $u$ – $v$  plane coverage, limited sensitivity, and high computational complexity. Looking ahead, future developments are expected to focus on space-based interferometers, large-scale interferometric arrays, and artificial intelligence-assisted image reconstruction. These advancements not only enrich the fundamental database of stellar physics but also provide high-precision observational support for studies of stellar evolution, binary dynamics, and exoplanetary systems.

## Keywords

optical interferometry, stellar imaging, image reconstruction, coherence, close binary system

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## 1. Introduction

In modern astronomical research, stars serve as the fundamental building blocks of galaxies, and their masses, radii, luminosities, surface activity characteristics, and the dynamical properties of binary systems constitute essential foundations for investigating stellar evolution, galaxy formation, and the evolution of cosmic structures. Given the vast distances between stars and the Earth, most stellar angular diameters are on the order of milliarcseconds. In contrast, the angular resolution of conventional telescopes in the visible band is typically limited to approximately 1 arcsecond by the diffraction limit, making them inadequate for observing fine structures. In practice, stars appear as unresolved point sources, preventing the effective resolution of close binary systems, the precise determination of spatial positions and orbital parameters, and the identification of key features such as starspots, surface brightness inhomogeneities, and atmospheric

activity, which have long constrained detailed studies of stellar physics and binary systems. To overcome the observational bottleneck imposed by the diffraction limit, optical interferometry has gradually matured based on the principle of light coherence. Rather than relying on extremely large single-aperture telescopes, this technique synthesizes light signals collected by multiple small-aperture telescopes arranged in an array, exploiting the coherence of light waves to construct ultra-long baseline observation systems capable of achieving milli-arcsecond angular resolution, thereby significantly surpassing the resolution limits of conventional single telescopes [1]. Over several decades of development, optical interferometry has transitioned from theoretical conception to practical engineering application, becoming a mainstream technology in modern high-resolution astronomical observations, with wide-ranging applications in stellar angular diameter measurements, binary system dynamics, and imaging of stellar surface magnetic activity [2]. While existing reviews have described the fundamental principles and early applications of optical interferometry, a systematic integration of key techniques—such as  $u$ - $v$  plane sampling, closure phase calibration, and image reconstruction algorithms—as well as their applications in close binary parameter inversion and imaging of stellar surface magnetic activity, remains lacking. Targeted analyses of practical limitations, including atmospheric turbulence, sparse  $u$ - $v$  coverage, and limited detection sensitivity, are also insufficient. Accordingly, this paper focuses on high-resolution stellar imaging, systematically reviewing optical coherence theory, the van Cittert–Zernike theorem, interferometric measurements, model-fitting, and image reconstruction, integrating existing technological advances and representative applications, analyzing limitations, and outlining future directions to provide a reference for related research.

## 2. Theoretical Background

The realization of high-resolution astronomical optical interferometric imaging is fundamentally grounded in the theory of light coherence and the framework of interferometric measurements, with the underlying principles, observational techniques, and performance metrics forming the theoretical foundation of this work. In this chapter, we systematically outline the technical framework and theoretical underpinnings of astronomical optical interferometric imaging from four key perspectives: coherence theory, fundamental interferometric observables, imaging resolution characteristics, and representative observational facilities.

### 2.1 Theory of Light Coherence and the Van Cittert–Zernike Theorem

The fundamental prerequisite for implementing optical interferometry is light coherence, which can be classified into temporal and spatial coherence. In astronomical interferometric observations, spatial coherence plays the dominant role, describing the degree of phase correlation of light fields arriving from different spatial locations at the observation point. Only when spatial coherence is sufficiently high can the light signals received by multiple telescopes form stable and detectable interference fringes. For distant, extended light sources such as stars, the coherence distribution can be accurately described by the van Cittert–Zernike theorem. The theorem states that for a distant, incoherent, extended source, the complex degree of coherence  $\gamma_{12}(\mathbf{b})$  between two points  $P_1$  and  $P_2$  on the observation plane is directly related to the two-dimensional Fourier transform of the source's brightness distribution  $I(\boldsymbol{\theta})$ , and its standard mathematical expression is given by:

$$\gamma_{12}(\mathbf{b}) = \frac{\iint I(\boldsymbol{\theta}) \exp(-i \frac{2\pi}{\lambda} \mathbf{b} \cdot \boldsymbol{\theta}) d\boldsymbol{\theta}}{\iint I(\boldsymbol{\theta}) d\boldsymbol{\theta}}$$

In the above expression,  $\mathbf{b}$  denotes the baseline vector formed by the two telescopes,  $\lambda$  is the observing wavelength, and  $\boldsymbol{\theta}$  represents the angular position vector on the source plane [3]. The theorem indicates that the complex degree of coherence produced by a distant, extended source on the observation plane is uniquely determined by the Fourier transform of the source's brightness distribution [3]. The van Cittert–Zernike theorem provides a rigorous theoretical foundation for astronomical interferometry: by quantitatively measuring the complex degree of coherence under different baselines and wavelengths, and subsequently applying an inverse Fourier transform, one can reconstruct the angular scale, brightness profile, and spatial distribution of the target object, thereby providing theoretical feasibility for interferometric reconstruction of stellar surface structures [3].

## 2.2 Fundamental Interferometric Observables: Complex Visibility and Closure Phase

In practical astronomical interferometric observations, due to limitations imposed by atmospheric turbulence, instrumental errors, and other factors, researchers do not directly measure the phase of light waves. Instead, they focus on measuring two core physical quantities: complex visibility and closure phase [1]. As a key parameter in interferometric observations, the complex visibility characterizes variations in fringe contrast and amplitude and is directly related to the van Cittert–Zernike theorem. Its mathematical expression is given by:

$$V(\mathbf{b}) = \frac{\iint I(\boldsymbol{\theta}) \exp(-i \frac{2\pi}{\lambda} \mathbf{b} \cdot \boldsymbol{\theta}) d\boldsymbol{\theta}}{\iint I(\boldsymbol{\theta}) d\boldsymbol{\theta}}$$

In the above expression,  $V(\mathbf{b})$  represents the complex visibility, which encodes both the fringe contrast (amplitude  $|V(\mathbf{b})|$ ) and phase variations (phase  $\arg(V(\mathbf{b}))$ ), and can be directly used to reconstruct the angular scale, structural features, and brightness distribution of the target object. It serves as a key diagnostic for distinguishing between point sources, binary systems, and complex extended sources [1]. The introduction of the closure phase is intended to eliminate the effects of common-mode phase errors, such as atmospheric piston variations and instrumental delays [2]. For a closed baseline triangle formed by three telescopes (baselines  $\mathbf{b}_{12}$ ,  $\mathbf{b}_{23}$ ,  $\mathbf{b}_{31}$ ), the closure phase  $\Phi_{cl}$  is defined as the cyclic sum of the phases measured along the three baselines:

$$\Phi_{cl} = \phi_{12} + \phi_{23} + \phi_{31}$$

Here,  $\phi_{ij}$  denotes the phase measured on baseline  $\mathbf{b}_{ij}$ . Phase errors  $\Delta\phi_i$  introduced by atmospheric turbulence, instrumental imperfections, and other factors appear in the same form across the three baselines, and therefore:

$$\Phi_{cl} = (\phi_{12} + \Delta\phi_1 - \Delta\phi_2) + (\phi_{23} + \Delta\phi_2 - \Delta\phi_3) + (\phi_{31} + \Delta\phi_3 - \Delta\phi_1) = \phi_{12} + \phi_{23} + \phi_{31}$$

It is evident that the closure phase automatically cancels out common-mode phase errors introduced by atmospheric turbulence and instrumental effects, retaining only the intrinsic phase information of the target object, thereby significantly enhancing observational stability and measurement reliability [2]. In ground-based interferometric observations, high-precision image reconstruction critically depends on the accurate acquisition and analysis of closure phases [1,2].

## 2.3 Angular Resolution, Baselines, and U–V Plane Coverage

In an optical interferometric measurement system, the maximum baseline of a telescope array directly determines the angular resolution of the system, with baseline length being proportional to resolving power; the longer the baseline, the more effectively fine spatial structures of celestial objects can be resolved [1]. In observations at optical and infrared wavelengths, interferometric systems with baselines ranging from a few meters to several hundred meters can achieve ultra-high angular resolution on the order of milli-arcseconds, meeting the requirements for detailed observations of stellar surface features and close binary systems [1]. Observational data obtained from interferometric measurements are typically sampled in the  $u$ – $v$  plane [1]. The  $u$ – $v$  plane encodes the spatial frequency information of the target object, and the more complete the coverage and the denser the sampling points, the richer the reconstructed image in retained detail and the lower the level of imaging artifacts [1]. Conversely, sparse or uneven  $u$ – $v$  plane coverage can lead to blurred image contours, spurious light spots, and distorted target morphology, severely compromising measurement accuracy and imaging reliability [1]. Therefore, the design of  $u$ – $v$  plane coverage is a core factor in evaluating the performance of an interferometric system [1].

## 2.4 Modern Optical and Infrared Interferometric Arrays

To meet the observational requirements for fine structures of celestial objects, most of the world's leading high-resolution interferometric facilities operate in the optical and infrared bands. Large interferometric arrays such as CHARA, VLTI, and NPOI represent the core observational instruments in this field [4]. These interferometric facilities consist of multiple movable telescopes networked together, allowing dynamic

adjustment of baseline lengths and orientations, thereby effectively expanding u-v plane coverage and providing a robust data foundation for subsequent high-precision image reconstruction [4].

Different arrays exhibit distinct baseline configurations and observational capabilities:

- CHARA Array: Baselines up to 300 m, operating from optical to near-infrared wavelengths, achieving a limiting angular resolution of approximately 0.5 mas in the near-infrared, and excelling in high-resolution imaging of stellar surfaces [4].
- VLTI Array: Maximum baselines of 200 m, equipped with multiple interferometers and adaptive optics modules, enabling high-resolution observations in the mid-infrared [5].
- NPOI Array: Flexible baseline configurations with a maximum baseline of about 430 m, primarily operating in the optical band, offering unique advantages in measuring orbital parameters of close binary systems.

Most modern interferometric arrays are equipped with adaptive optics systems that can compensate in real time for wavefront distortions induced by atmospheric turbulence under all-weather conditions. This effectively mitigates the inherent limitations of ground-based observations, improving image clarity while enhancing the sensitivity to faint astrophysical signals [5]. Thanks to flexible baseline layouts and adaptive optics correction, contemporary interferometric arrays can perform long-term, uninterrupted, reliable, and high-precision imaging of a wide range of targets, including stars, binary systems, circumstellar dust disks, and active galactic nuclei [4,5].

### 3. Literature Review

Advances in high-resolution optical interferometry have opened new avenues for stellar physics research. This chapter systematically reviews the progress and technological breakthroughs in the field, focusing on two primary observational targets. The first is the analysis of close binary systems and the measurement of fundamental stellar parameters, where interferometric techniques have become the high-precision standard for determining key physical properties such as stellar mass and radius. The second is stellar spot imaging and image reconstruction algorithms, where optimized computational methods enable direct observation of complex surface activity features, including starspots and faculae. These developments are driving a paradigm shift in stellar physics, from the measurement of individual parameters toward the detailed characterization of stellar surface structures and the exploration of dynamic processes.

#### 3.1 Close Binary System Analysis

Compared with traditional observational methods, which struggle to resolve the angular separation and position angle of close binary systems and can only infer orbital information indirectly through spectroscopic variations, optical interferometry allows the direct acquisition of spatial structure information. Combining geometric model fitting with dynamical orbital calculations enables the high-precision determination of fundamental stellar parameters such as mass and radius. The pioneering breakthroughs in stellar parameter measurements date back to 1967, when Hanbury Brown and colleagues systematically measured stellar angular diameters using an intensity interferometer, laying the experimental foundation for subsequent observations [9]. In 1999, Söderhjelm combined Hipparcos astrometric data with ground-based interferometric measurements, significantly improving the precision of binary orbital and mass determinations [10]. In 2010, Torres et al. demonstrated that interferometric measurements greatly surpass traditional methods in accuracy, providing crucial data for stellar evolution models [6]. Duchêne and Kraus [8] highlighted that high-resolution interferometric observations substantially enhance the detection completeness of multiple star systems, and more recently, Montargès et al. [7] employed interferometric data to analyze Betelgeuse's dimming event, showcasing the technique's unique advantages for observing transient phenomena. Over the past five years, VLTI/GRAVITY, with its high sensitivity, high dynamic range, and closure-phase imaging capability, has achieved a series of breakthroughs in binary star analysis, direct exoplanet imaging, and stellar surface imaging algorithms. These results can be categorized into three system types: massive binaries, low-mass binaries, and close binaries hosting exoplanets. In massive binaries, VLTI/GRAVITY's large-scale survey of Wolf-Rayet systems in the Milky Way revealed a deficiency of long-period binaries, providing new observational constraints for massive star evolution, stellar wind interactions, and progenitor models of gravitational wave

sources, while the Araucaria Project, combining GRAVITY data, improved binary mass measurement precision to 0.03%, offering high-precision calibration for stellar evolution models [11,12]. In low-mass binaries, long-term astrometric monitoring of the nearby M-dwarf binary GJ 65 precisely determined orbital parameters and dynamical masses and identified a candidate Neptune-mass exoplanet from the residuals, providing a key case for planet formation and evolution in close binary environments, while interferometric observations of the microlensing event ASASSN-22av achieved the first direct resolution of multiple images in a double-lens system, enabling independent high-precision mass determination of red dwarf binaries [13,14]. In close binaries hosting exoplanets, upgraded GRAVITY, with higher sensitivity and stability, allows direct imaging of young gas giants within the protoplanetary disk, yielding precise orbital and photometric data and providing direct observational evidence for planet formation, migration, and dynamical interactions under binary gravitational potentials [15]. At the same time, leveraging closure-phase measurements and optimized image reconstruction algorithms, GRAVITY has realized high-resolution surface imaging of long-period variable stars and young stellar objects; by integrating regularization and global optimization methods, imaging artifacts caused by sparse  $u$ - $v$  coverage are effectively mitigated, substantially enhancing the analysis of stellar surface activity, atmospheric pulsations, and circumstellar structures [16,17].

In summary, over several decades of development, optical interferometry has evolved into a mature, systematically structured methodology encompassing a complete research workflow: data acquisition, model fitting, parameter inversion, error analysis, and evolutionary constraints. It combines efficiency, stability, and high precision, establishing itself as an indispensable core technique in modern stellar physics and providing a solid foundation for studies of stellar evolution and fine-scale astrophysical structures [6,8,9]. The new generation of instruments, exemplified by VLTI/GRAVITY, has further advanced close binary research, moving beyond traditional orbital parameter determination to detailed characterization of multiple system types and direct imaging of exoplanets, continuously providing high-precision observational support for stellar physics, binary dynamics, and exoplanetary science.

### 3.2 Starspot Imaging

Unlike close binary systems, which have relatively simple structures and can be modeled through parametric fitting, the brightness distribution on stellar surfaces is inherently complex. It includes typical activity features such as starspots and faculae, as well as fine-scale structures like bright bands and asymmetric patterns, whose activity cannot be captured by simple geometric models. Accurate reconstruction of these surface details requires algorithms that extract high-fidelity information from sparse interferometric observations. In the study of stellar magnetic activity and interferometric imaging, Schrijver et al. [18] were the first to combine high-resolution interferometric data with stellar magnetic field studies, revealing a direct relationship between magnetic regions and photospheric brightness distribution, thereby providing critical observational evidence for in-depth investigations of stellar magnetic activity and surface structures. In 2012, Baron and collaborators organized an international interferometric imaging “beauty contest” to systematically evaluate the performance of various image reconstruction algorithms on both simulated and real observational data. This effort provided authoritative guidance for selecting optimal reconstruction methods in actual observations and strongly promoted the standardization and formalization of interferometric imaging techniques [19]. Subsequently, with continuous upgrades of observational instruments and algorithms, researchers have effectively addressed challenges posed by sparse  $u$ - $v$  coverage and observational noise through techniques such as regularization, compressed sensing, and multi-source data joint inversion, enabling reliable reconstruction of stellar surface structures from limited data [19]. Among these methods, the CLEAN algorithm, a classical tool in interferometric imaging, iteratively removes the influence of the dirty beam to recover the target structure [19]; the MIRA algorithm, based on compressed sensing theory, leverages the sparsity of stellar surface distributions to enhance imaging resolution [19]; and regularized reconstruction tools such as SQUEEZE and IRBIS introduce various prior constraints (e.g., smoothness, entropy) to achieve stable surface reconstruction even with low signal-to-noise ratio data. These methods each emphasize different aspects—computational efficiency, resolution enhancement, and noise robustness—providing flexible solutions for stellar surface reconstruction under diverse observational scenarios [19].

To date, optical interferometric imaging has enabled high-resolution surface observations of various types of stars, allowing detailed characterization of activity features such as starspots and faculae, while effectively capturing structural variations induced by stellar rotation [18,19]. Leveraging this technique, researchers have

overcome the inherent limitations of traditional observations, providing the first direct and intuitive views of stellar surfaces beyond the Sun. These achievements represent a significant leap in stellar physics, shifting the research focus from merely fitting fundamental parameters to an in-depth exploration of stellar surface activity patterns and the underlying mechanisms of dynamical evolution [19].

## 4. Discussion & Synthesis

Building on the theoretical framework and literature review presented earlier, this chapter provides a systematic and comprehensive discussion of the core applications and existing technical limitations of optical interferometric imaging. On the one hand, it emphasizes a comparative analysis of the two primary data processing approaches—model fitting and image reconstruction—highlighting their respective applicability, key advantages, and inherent limitations, and clarifying how they can complement each other in practical observational applications. On the other hand, it systematically examines the technical bottlenecks in ground-based interferometric observations, including atmospheric turbulence, sparse  $u$ - $v$  coverage, sensitivity constraints, and the complexity of data processing, providing targeted insights and perspectives to guide future technological optimization and research directions.

### 4.1 Methodological Comparison Between Model Fitting and Image Reconstruction

In the processing of high-resolution interferometric data, model fitting and image reconstruction represent two core methodological approaches, each with distinct applicability and performance characteristics. Model fitting is particularly suitable for targets with simple structures and parametrically describable morphologies, such as close binary systems and symmetric stellar disks [1]. Its advantages include high computational efficiency, clear physical interpretation of fitted parameters, robust stability, and the ability to achieve high-precision measurements with limited observational data. However, its limitations are also prominent: it cannot recover complex surface features of the target, produces only discretized parameters based on the chosen model, and lacks full two-dimensional imaging capability [1]. In contrast, image reconstruction is better suited for targets with complex or non-uniform structures, such as stellar surface starspot distributions, circumstellar dust disks, and jet features [19]. Its main strength lies in producing direct, visual two-dimensional images of the target, fully preserving spatial structural details and providing direct evidence for the study of asymmetric or irregular objects. Nevertheless, image reconstruction imposes stringent requirements on observational conditions and algorithm performance, necessitating sufficient data quantity, comprehensive  $u$ - $v$  coverage, and stable reconstruction algorithms; otherwise, it is prone to noise and sparse sampling effects, which can lead to imaging artifacts or structural distortions [19].

In practical interferometric data analysis, a combined application of model fitting and image reconstruction is a more common and efficient processing approach. Typically, model fitting is first employed to rapidly and efficiently obtain key physical parameters of the target, providing reliable constraints for subsequent data analysis. Based on these parameters, image reconstruction techniques are then applied further to verify the target's structural details and symmetry features, thereby establishing a complete analytical chain from parameter inversion to structural characterization. This combined approach fully leverages the strengths of both methods while compensating for their respective limitations, resulting in research outcomes that are more reliable and comprehensive, with respect to both parameter accuracy and structural resolution [1,19].

### 4.2 Limitations and Future Prospects

Although optical interferometry has achieved breakthroughs in stellar physics and related research areas, it still faces a series of technical limitations and practical challenges under current ground-based observing conditions, which, in turn, drive continuous methodological and technological innovation. One major issue is atmospheric turbulence, which disrupts the coherence of incident light wave phases, degrading fringe contrast and measurement stability; even partial correction via adaptive optics cannot fully eliminate these systematic effects [2,5]. To address this, next-generation interferometric arrays are integrating advanced adaptive optics with fringe tracking techniques to perform real-time phase compensation and mitigate atmospheric disturbances [11,12]. Some projects are exploring ground-space hybrid observing schemes to circumvent low-altitude atmospheric effects. A second limitation is sparse  $u$ - $v$  plane coverage: constraints on the number of telescopes, array geometry, and observing time windows prevent complete and uniform sampling, leading

directly to blurred reconstructions, imaging artifacts, and structural distortions [2]. Solutions include optimizing telescope layouts and extending baseline lengths to increase spatial sampling diversity [11], as well as employing image reconstruction algorithms based on compressed sensing and regularization, which utilize the sparsity of stellar surface distributions to compensate for missing samples and significantly improve imaging quality under low-coverage conditions [16,17]. Third, limited sensitivity constrains the observation of faint or distant targets, restricting both the quantity and type of accessible objects [5]; this is being addressed in new facilities through larger-aperture telescopes, higher-efficiency near-infrared detectors, narrow-band filtering, optimized integration strategies, and multi-band joint observations to enhance detection of low-luminosity targets [12,13]. Finally, the complexity of data processing poses a practical challenge, as image reconstruction algorithms require extensive parameter tuning and optimization, with automation and robustness still in need of improvement, placing high demands on users' expertise and technical skills [2,5]. To overcome this, more robust automated pipelines are being developed, incorporating deep learning for initial model generation and parameter optimization, while standardized processing frameworks are promoting data interoperability and method reuse across different arrays [14,17]. Overall, the current limitations of optical interferometry represent both challenges and opportunities for future advancement. With continued progress in adaptive optics, array design, algorithm development, and detector technology, these issues are expected to be progressively alleviated, enabling higher-resolution and broader-coverage observations of stellar surfaces [11,12,15].

## 5. Conclusion

Optical interferometry, based on the fundamental principle of optical coherence, effectively overcomes the diffraction limit of traditional single-aperture telescopes by combining multiple telescope baselines, achieving ultra-high angular resolution at the milliarcsecond level. This provides a critical technical pathway for high-resolution stellar observations. The technique offers irreplaceable advantages and applications in key areas of stellar physics, including the precise determination of close-binary parameters, the analysis of stellar surface structure, and the imaging of circumstellar environments. At present, ground-based optical interferometry still faces practical challenges, including atmospheric turbulence, incomplete  $u$ - $v$  plane coverage, limited sensitivity, and the high complexity of reconstruction algorithms. With ongoing advancements in large-scale interferometric arrays, the gradual implementation of space-based interferometry projects, and the deep integration of compressed sensing, regularization, and deep learning into image reconstruction, high-resolution astronomical imaging is expected to continue evolving toward higher angular resolution, enhanced sensitivity, multi-band coordinated observations, and automated data processing. By enabling more precise measurements of binary parameters, clearer imaging of stellar surface structures, and more comprehensive observational samples of stellar evolution, optical interferometry will continue to provide high-precision support for stellar physics, binary star dynamics, and exoplanet studies, thereby driving fundamental astronomical research to new heights.

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