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Review

Emerging technology for astronomical optics metrology

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ABSTRACT

Next generation astronomical optics will enable science discoveries across all fields and impact the way we perceive the Universe in which we live. To build these systems, optical metrology tools have been developed that push the boundary of what is possible. We present a summary of a few key metrology technologies that we believe are critical for the coming generation of optical surfaces.

1. Introduction

Next generation space and ground based astronomical optics are bringing about exciting developments in our scientific understanding of the Universe in which we live. From solar science, exoplanet detection, to dark matter and first light investigations, the scientific community around the world is pushing the limits of our fundamental knowledge through astronomical optics. To build the next generation of telescopes, which will enable this work, new metrology methods and tools have been developed. We (see Vitae for brief description of the authors) believe that recognizing and highlighting some key emerging technology in this area will be beneficial for the scientific community.

1.1. Science motivation

Before discussing the recent developments in the field of astronomical optics metrology, we want to provide some motivation for why the tools were developed by discussing the exciting science that they are enabling. We hope that this will serve to put the technology in the larger context of how astronomy, fundamental science, and physics exist in a synergistic relationship with the optics community.

In the 2010 decadal survey report from the U.S. National Academies, *New Worlds, New Horizons in Astronomy and Astrophysics (NWNH)* [1], the most important science questions that should be addressed are identified and a prioritized listing of the major missions and facilities that are needed to realize the science goals is provided. Among the highest priority missions and facilities are the James Webb Space Telescope (JWST), the Wide Field Infrared Survey Telescope (WFIRST), the Large Synoptic Survey Telescope (LSST), and a Giant Segmented Mirror Telescope (GSMT). Each of these facilities, performing close to their theoretically achievable limits, will provide previously unobtainable observational capabilities, both in spatial resolution and sensitivity. Achieving this level of performance from these facilities requires cutting edge technology in both the fabrication and testing of the optical systems.

Three giant telescopes are under construction that should address the science goals identified in *NWNH* by a GSMT. They will explore the Universe with observations from mid-IR to near-UV wavelengths. The Giant Magellan Telescope (GMT), with an effective 24.5 m diameter primary mirror, will be located at the Las Campanas Observatory in Chile. The Thirty Meter Telescope (TMT) is currently planned for either Mauna Kea, in Hawaii, or the Canary Islands. The Extremely Large Telescope (ELT) is being built in Chile by the European Southern Observatory (ESO). Each of these observatories has challenging science and technical requirements that when met will enable these facilities to yield spectacular results.

The images we display in Fig. 1 are examples of how critical achieving the highest spatial resolution in the science images can be to realizing the science goals. To study the disks of debris and gas around distant stars from which planets form (e.g. Fig. 1(a)) and to image the exoplanets themselves (e.g. Fig. 1(b)) requires sub arc second spatial resolution and high contrast imaging. The ability to realize such images of the faint companions of the much brighter stars around which the planets orbit is enabled by adaptive optics systems.

NASA's 2.4 m Hubble Space Telescope (HST) revolutionized our ability to study the detailed structure of extremely distant galaxies. Observed behind foreground clusters of galaxies, the great mass of the foreground cluster amplifies and magnifies the images of the back ground galaxies. However, this "strong lensing" also distorts the images, see Fig. 2(a), requiring exquisite optics that enable the intrinsic properties of the galaxies to be well measured. NASA's 6.5 m JWST, scheduled for launch in October of 2018, will improve our ability to detect and study substructure in distant galaxies as shown in Fig. 2(b) because the optics

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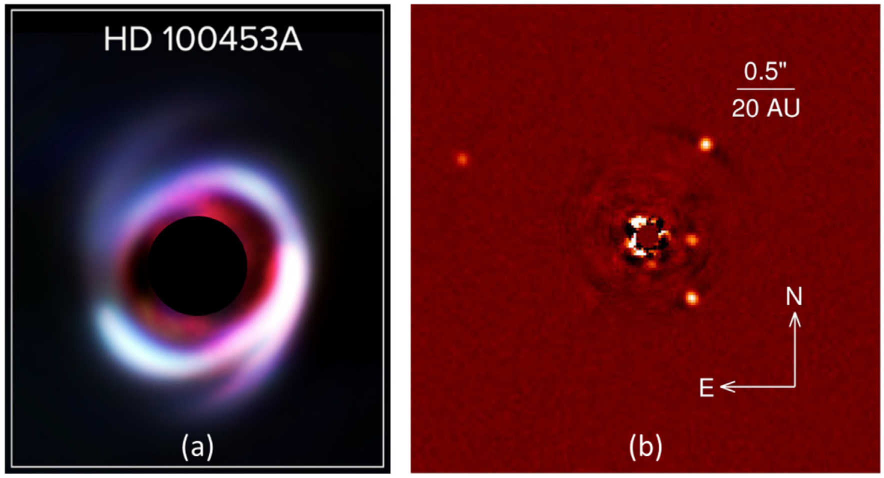

Fig. 1. Science images enabled by adaptive optics systems: (a) A double-armed spiral image in a planet-forming disk around the young star HD100453 using a coronagraph and an extreme adaptive optics system (VLT/SPHERE) as reported in Wagner et al. [2]. This unusual disk structure is most likely driven by a stellar companion outside the disk or a massive planet within the disk. Image credit: K. Wagner (Univ. Arizona), (b) exoplanet detection around HR 8799 imaged with the LMIRCam of the Large Binocular Telescope [3]. Image credit: P. Hinz (Univ. Arizona).

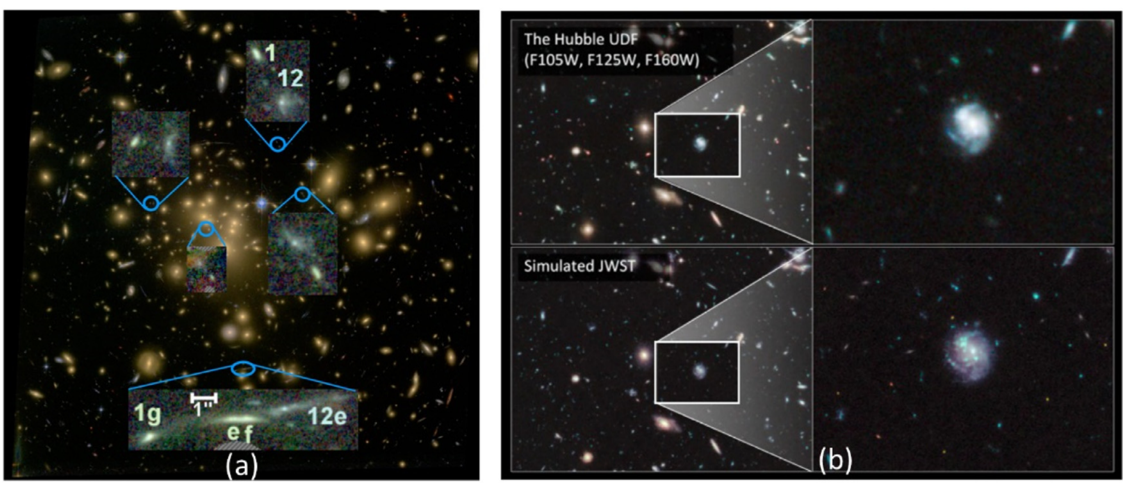

Fig. 2. Improving image quality through larger and more exquisite optics: (a) strong gravitational lensing distorts images in the Hubble Space Telescope (HST) [4], which contain information that the next generation of telescopes such as the James Webb Space Telescope (JWST) will resolve. Image credit: B. Frye (Univ. Arizona), (b) simulation of the improved resolution capabilities of the JWST compared to the HST [5]. Image credit: STSCI.

for the telescope will allow the theoretically achievable improvement in resolution provided by the larger primary mirror of JWST.

The giant ground based telescopes now being constructed: 25 m Giant Magellan Telescope (GMT), 30 m Thirty Meter Telescope (TMT), and 39 m ESO Extremely Large Telescope (ELT) will provide images of the highest spatial resolution, comparable or better to the interferometric imaging now being made, of bright targets, by the Large Binocular Telescope Observatory from Mount Graham in Arizona with its 23 m baseline. In Fig. 3(b), the exquisite 0.02″ image of Jupiter's moon IO reveals remarkable details of the surface, including hot spots from Io's volcanic activity. Images with this kind of spatial resolution, but with the full collecting area of the giant telescopes under construction, will be transformative to our study of the entire Universe, from exoplanets to the most distant galaxies.

2. Emerging metrology

The science goals of the next generation telescopes are enabled in part by unique optical surfaces. Testing the optical surfaces requires precision, accuracy, and many times, new metrology methods. Each novel technology enables a critical aspect of the optical surface to be measured, and therefore fabricated. One reason the optical surfaces of the next generation telescopes are challenging to measure is because the science dictates more complex optical specifications. At the same time, the surfaces are also becoming more aspheric, and therefore require non-traditional test methods. In order to produce magnificent results while imaging through the Earth's atmosphere, improvements in the metrology for adaptive optics are also critical for enabling the science. A few key innovations in the field of metrology for astronomical optics will be presented to provide an overview of the technology in the hopes that the community may benefit from learning about the ideas and advances that others have produced.

2.1. Full spectrum measurement

Typical optical surface specifications may include peak-to-valley (PV), root-mean-square (RMS) surface errors, number of fringes across the aperture, or even Zernike term departures from nominal. However, for the highest quality, super-polished optical surfaces used for solar science, such as the Daniel K. Inouye Solar Telescope (DKIST), the traditional specification methods do not ensure low enough scattering, or high enough imaging performance, which is effected by spatial frequencies across the entire spectrum. The spatial frequencies present on the optical surface will directly map into the Point Spread Function (PSF)