

Space-based vs. Ground-based telescopes with Adaptive Optics (AO)¹

Advances in technology make it possible to partially correct the wavefront errors caused by the Earth's atmosphere that blur ground-based astronomical images. *Adaptive Optics* is a technique to detect and correct these errors in real time, yielding sharper images that approach the physical limits (called the *diffraction limit*) of large telescopes, thus decreasing the advantage previously enjoyed by the Hubble Space Telescope. Current AO systems are limited to infrared wavelengths, and operate over less than 1% of the sky. While rapid progress is expected with continued investments in AO and large telescopes, even under the most optimistic assumptions, AO from the ground will not replace the capabilities of Hubble.

Some of the most exciting research in astrophysics demands the space-based (Hubble) capabilities:

- Finding and obtaining precise measurements of very distant supernovae to help understand the nature of the "dark energy" that is causing the universe to accelerate.
- Measuring the spatial structure of solar systems in the process of formation.
- Seeing galaxies in formation less than one billion years after the big bang.
- Studying the atmospheres of planets in other solar systems.

Why is Hubble so critical, when we now have much larger ground-based telescopes?

- Ground-based adaptive optics today only works at infrared wavelengths.
- Achieving Hubble-quality images at optical wavelengths is more than 10 years away and not even the focus of current AO development for astronomy. Projections indicate that the optical images obtained from the largest telescopes in 2015 will have an image quality no better than Hubble's before the optics corrected the spherical aberration of the primary mirror.
- Hubble is sensitive to all wavelengths from the ultraviolet to the near infrared. Many of these wavelengths are blocked by the atmosphere and inaccessible from Earth.
- Despite advances in image quality, the sensitivity of groundbased telescopes is limited by the enormously greater foreground radiation from the Earth's atmosphere. On a moonless night, the sky at 0.7 microns is eight times brighter from the top of Mauna Kea in Hawaii than it is from Hubble. At 1.5 microns it is 600 times brighter.
- Hubble images are stable. Even with AO, the atmosphere causes quality to vary in images taken with ground-based telescopes (with position and time), making precise measurements extremely difficult. Hubble stability is the main reason it is used to detect the atmospheres of extra-solar planets such as Osiris.

¹ A summary prepared by the scientific staff of the Space Telescope Science Institute, which is Operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS5-26555. Please direct questions or comments to Henry Ferguson (ferguson@stsci.edu).

- Observations with AO require relatively bright guide stars to correct for atmospheric turbulence. This currently limits applications to less than 1% of the sky. Even in the observable areas, AO image quality degrades rapidly with distance from the guide star. At optical wavelengths, AO would correct fields of view 100 to 1000 times smaller than Hubble's.

There are some research areas where ground-based telescopes with adaptive optics will be better than Hubble, but these represent a small fraction of present-day observing programs. For example infrared studies of the center of the Milky Way may be better done with groundbased AO, and so-called "extreme" AO systems may soon become competitive in infrared imaging of disks and planets around nearby stars. AO from large telescopes may generally surpass Hubble for observations of bright targets in small fields in the infrared. Much of today's astronomical research requires observations at shorter wavelengths, where AO remains uncompetitive with Hubble. Even in the infrared, most of the cosmological research proposed for the infrared channel of Hubble's WFC3 camera could not be carried out from the ground because the targets are too faint and the required fields of view are too large.

Ground-based telescopes (with or without AO) are nevertheless the workhorses for research projects where image quality is less critical or where the relatively bright sky is not the factor that limits the signal-to-noise ratio. However, Hubble completely dominates large-field, diffraction-limited studies of faint astronomical targets, such as searches for galaxies in the early universe. It will remain unique for discovering supernovae at great distances needed to study the dark energy driving the acceleration of cosmic expansion. Dark energy is considered by many to be the greatest puzzle in all of physics. Hubble contributions are complementary to ground-based research, because measurements of the effects of dark energy require measurements of both nearby targets and very faint distant targets. Observations of the nearby galaxies and supernovae are best done using the large fields of view provided by ground-based telescopes *without* AO, while Hubble is essential for precise measurements of very faint and distant targets.

Ground-based telescopes have surpassed Hubble for many kinds spectroscopic measurements at optical and infrared wavelengths. Spectroscopy from space is crucial for research requiring high spatial resolution (e.g. searching for black holes), low backgrounds (e.g., confirming the redshifts of the most distant supernovae), or ultraviolet wavelengths. *Progress in understanding the universe demands both kinds of facilities.*

The comparison in 2010

Vigorous research programs in the technique of Multi-Conjugate Adaptive Optics (MCAO) are underway at major observatories. We can expect the first facility tests on large telescopes in 2005-2006. The technique in principle allows correction of wider fields of view, but the necessity of having multiple guide stars will limit the fraction of sky that can be observed. This is particularly troublesome for studies of the distant universe, which require observations out of the plane of our galaxy, where the density of

useful guide stars is much lower than average.

Natural guide stars may be supplemented by laser beacons. Even with laser beacons, it is expected that natural guide-stars will be required to compensate for image motion. Studies from the European Southern Observatory (ESO)² suggest that a system of five lasers and three natural guide stars may allow Hubble-quality imaging *in the infrared* (at 1.2 microns) over up to 35% of the sky in fields of view one-quarter the size of the WFC3 camera planned for installation on Hubble in 2006. Performance degrades rapidly at shorter wavelengths. At best 4% of the sky will be available at 0.8 microns. Good AO performance will be achieved in fields of view about 1% of the size of Hubble's at optical wavelengths, and about 20% of the Hubble WFC3 field of view in the infrared.

The comparison in 2015

By 2015 ground-based telescopes with mirrors 100 feet in diameter may be reaching first light. Examples include the California Extremely Large Telescope (CELT) the Giant Segmented Mirror Telescope (GSMT), and the ESO Overwhelmingly Large Telescope (OWL). These are ambitious projects. The cost estimate for CELT is \$700M – comparable to a major NASA satellite.

The larger mirrors will offer sharper images in the infrared. By collecting more photons, larger mirrors also make it possible to use fainter guide stars for AO correction, making more of the sky accessible. However, none of the groups planning AO systems for these telescopes currently advertise being able to achieve Hubble clarity at optical wavelengths. Without full wavefront correction, stellar images will tend to have a sharp central core encompassing less than 10% of the light and a diffuse halo with more than 90% of the light, with an appearance to Hubble's images before the optics were repaired. Full correction is likely to be achieved over extremely small fields of view at optical wavelengths, even in the 2015 timeframe.

Technical Details

Today's AO systems typically work by deforming mirrors with hundreds of actuators to compensate for the turbulence in the atmosphere. Measurements of the image quality and corrections must be made tens to hundreds of times per second. Correction of images at optical wavelengths on large telescopes will require thousands of actuators. Aside from the computational challenge, the required measurements are fundamentally limited by the number of photons per second that can be gathered from the guide stars. There is no such limitation for Hubble.

Laser beacons reflect back from only one or two layers in the atmosphere, probing the turbulence along the line of sight to that layer. The laser traverses the atmosphere twice, over a slightly different path than the astronomical target of interest. Thus partial correction is possible, but perfect correction is nearly impossible. The imperfections

² Viard, E., et al., 2000, *Concept and performance of multiple laser guide stars for 8 m class telescopes*. In: Adaptive Optical Systems Technology. Ed. P. L. Wizinovich. Proc. SPIE, 4007, 94-105.

severely limit the expected performance at optical wavelengths. Furthermore, corrections at short wavelengths take significantly more laser power than corrections at long wavelengths – scaling as wavelength to the power of -3.6. Laser beacons capable of acting as guide stars for MCAO at optical wavelengths are beyond the current state of the art.

Image quality is typically characterized by the "Strehl ratio." A perfect image has a Strehl ratio of 100%. Hubble images have a Strehl ratio of 80% at visible wavelengths (approximately 0.5 microns). The best AO systems on large telescopes in 2015 will likely have Strehl ratios of less than 10% at 0.5 microns. (For comparison, today's AO systems today typically deliver Strehl ratios of 15% at 1.2 microns less than 50% of the time over 1% of the night sky. Hubble delivers a Strehl ratio of 98% at the same wavelength.)

Of historical interest: Early images from Hubble before the correction for spherical aberration had a Strehl ratio of 15%, comparable that achieved by AO systems operating today at 1 micron.

Another measure of image quality is the radius of a circle that encloses one-half the light received from a star. For Hubble, the radius of this circle is 0.05 arcseconds at 0.5 microns. When averaged over fields of view comparable to Hubble's, this radius is likely to be 0.3 arcseconds in the best conditions with the best AO systems on large telescopes in 2015.

Achieving near Hubble-quality images at optical wavelengths over more than 1% of the sky by 2015 would require major breakthroughs:

- in deformable-mirror technology, to allow 5000-25000 actuators,
- in algorithms and computational speed to allow corrections many times per second,
- in the laser power to allow high levels of correction at optical wavelengths, and
- in the conceptual designs of AO systems, to measure turbulence at multiple layers.

Conclusion: *Ground-based telescopes are an essential tool for astronomy, but will not surpass Hubble's optical imaging performance by 2015.*

Further reading:

Dekany, R., Nelson, J. E., and Bauman, B., 2000, *Design Considerations for CELT Adaptive Optics*, Proc. SPIE, 4003.

Schneider, G., et al., 2002, *Domains of Observability in the Near Infrared with HST/NICMOS and (Adaptive Optics Augmented) Large Ground-Based Telescopes*, A summary study solicited by STScI in preparation for HST cycle 12.

http://nicmosis.as.arizona.edu:8000/REPORTS/NICMOS_AO_WHITEPAPER.html

Web pages:

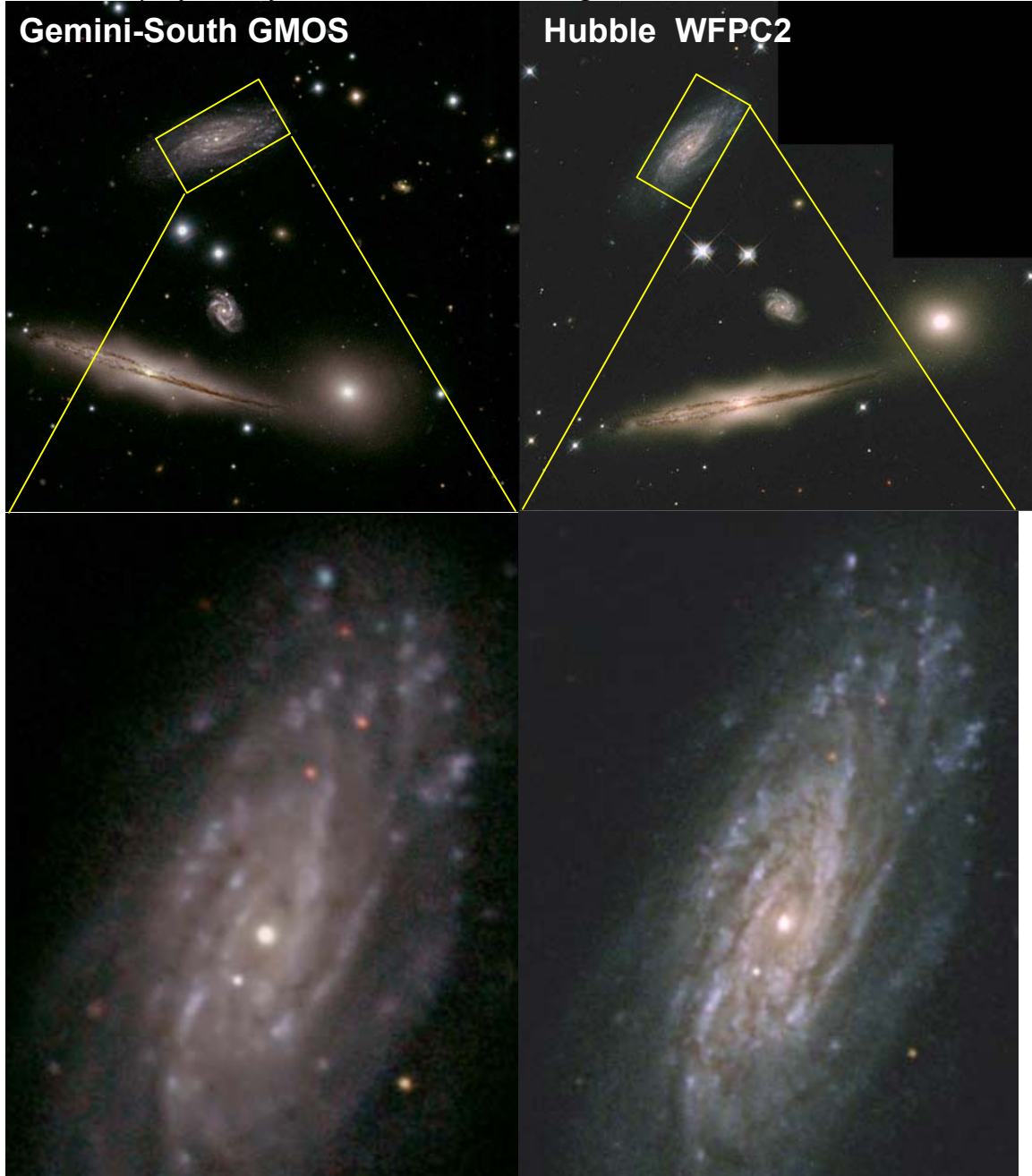
Center for Adaptive Optics: <http://cfao.ucolick.org>

Center for Astronomical Adaptive optics: <http://caao.as.arizona.edu/>

ESO MCAO: <http://www.eso.org/projects/aot/mcao/mcao.html>

Image Comparison – State-of-the art optical images without AO

The Gemini-South image of Hickson Compact Group 87 shown below (left) appears to “rival the view from space,” as reported in the press. The Gemini image was taken in extraordinarily good optical seeing, but without adaptive optics. Viewed at a distance, the Hubble and Gemini images indeed look similar. However, it is important to realize that Hubble’s forté is in providing detail, as illustrated in the enlargements below. *The Advanced Camera for Surveys (ACS), installed in 2002, has improved Hubble’s optical resolution by a factor of two over the WFPC2 image shown here.*



The second comparison, below, shows two images from the Great Observatories Origins Deep Survey. The image on the left was obtained by the Subaru 8-meter telescope in more typical observing conditions (1.1 arcsecond “seeing”) from atop Mauna Kea. The image on the right is from the Hubble ACS. All of the objects seen in the image are distant galaxies. The highly distorted object near the center may be an on-going collision between two or more galaxies.

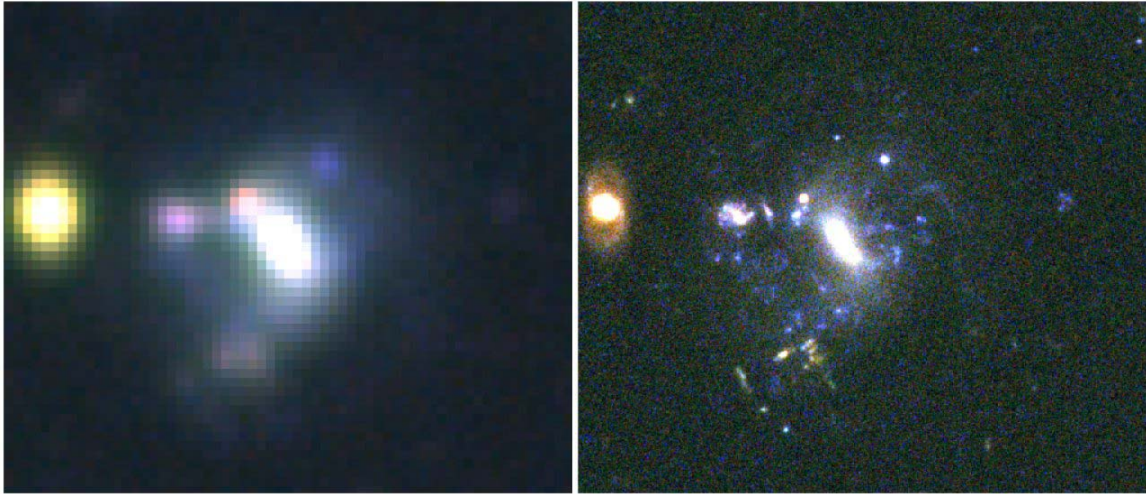
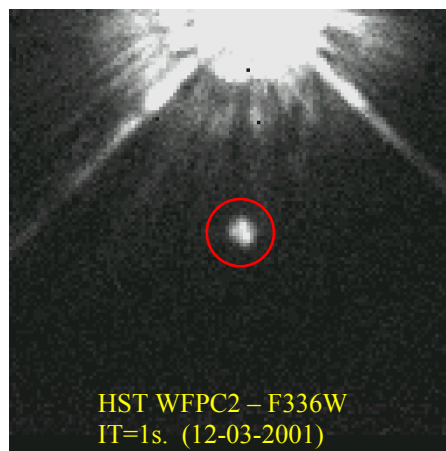
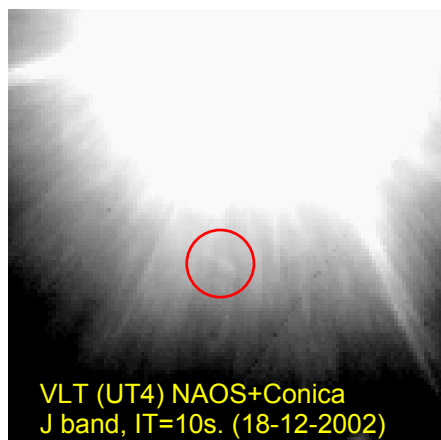


Image Comparison: State-of-the-art images with AO

The two images below show views of a protoplanetary disk (circled) near the bright star θ Orionis C, in the center of the Orion nebula. The disk is being destroyed by the overwhelming ultraviolet radiation from the star. The image on the left was taken with AO in good conditions by the European Very Large Telescope (VLT). It is at a wavelength of 1.1 microns. The image at right was taken by Hubble at ultraviolet wavelengths. In spite of the excellent image quality of the VLT image, the protoplanetary disk is nearly lost in the glare of the nearby star.



The two images below show the dust disk around the young star HD141569, as it appears in the infrared from Hubble (left) and with adaptive optics from the Hale telescope on Mt. Palomar (right). Such disks are expected to be the birthplace of planets. Studying these disks is extremely challenging from Hubble or from the ground, because the bright light of the star must be heavily suppressed in order to see the disk. (The black cross in image A and the black region in the center of image B are due to the occulting optics in the telescope used to suppress the starlight. The radial spokes in the Hubble image are artifacts of the optics.)

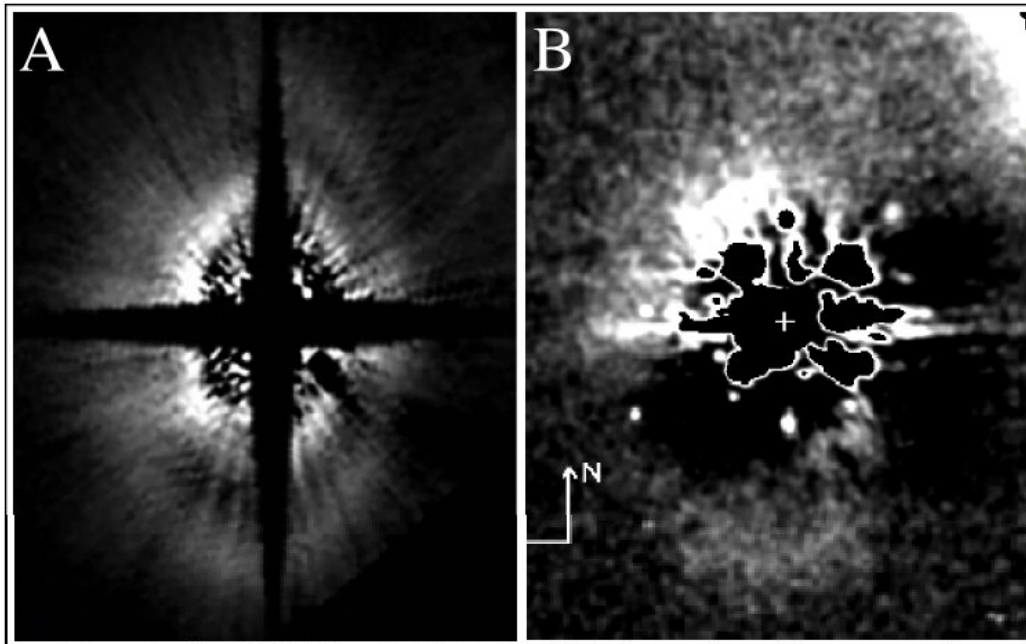
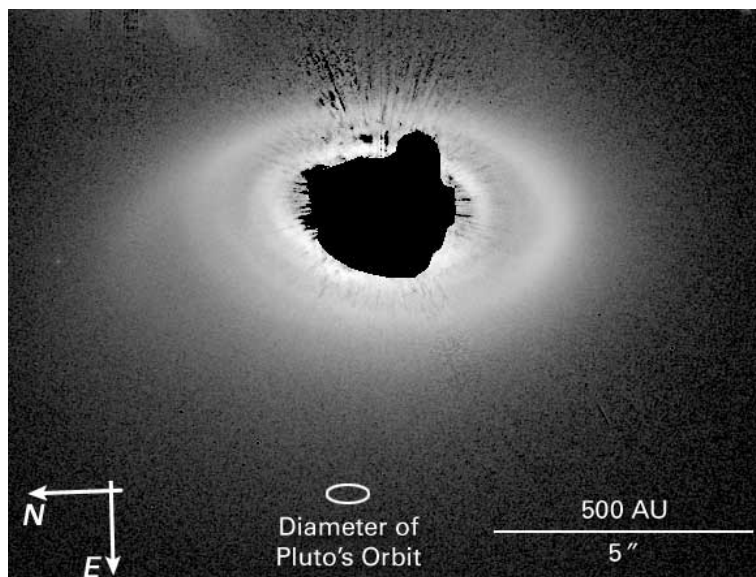


Figure 14. NICMOS (A) and PALAO (B) PSF-subtracted near-IR coronagraphic observations of the HD 141569A circumstellar disk.

The image at right shows the same disk at optical wavelengths (rotated by 90 degrees) as seen by the Hubble Advanced Camera for Surveys. The black region in the center is due to the occulting optics. The non-uniform brightness of the disk provides interesting clues to the dynamics of such solar-systems in formation.



As a final comparison, four views of the planet Uranus are shown. Clockwise from the upper left, the images are (1) a view at optical wavelengths from the Hubble ACS, (2) a view at infrared wavelengths from the Hubble NICMOS instrument, (3) a view in the infrared from the Keck telescope with adaptive optics, and (4) a view in the infrared from the Subaru telescope with adaptive optics.

