Publications of the Astronomical Society of the Pacific, **127**:1197–1203, 2015 December

Astronomical Adaptive Optics

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Received 2015 September 25; accepted 2015 October 14; published 2015 December 2

ABSTRACT. Adaptive optics is now a fully mature technique to improve the angular resolution of observations taken with ground-based astronomical telescopes. It is available at most of the major optical/IR observatories, and is planned as an integral part of the Extremely Large Telescope next generation facilities. In this mini-review aimed at non-AO specialists, we recall the history, the principle of operation, the major components, the performance, and the future of nighttime astronomical adaptive optics.

Online material: color figures

1. INTRODUCTION

Almost as soon as telescopes were invented, astronomers realized that the quality of observations was limited by atmospheric turbulence, which distorts short exposure and blurs long exposure astronomical images. Newton was the first to be quoted as realizing that clearer observations (in the sense of being less blurred) would require observing from the top of the highest mountains. He was perfectly right of course, but even on top of Hawaii's Maunakea or the Chilean mountains, the atmospheric turbulence limits the angular resolution attainable by any arbitrarily large telescope operating in the visible to the resolution achievable by a 20-cm telescope. The *angular resolution* is the size of the smallest details that can be seen in an image. If not for the atmospheric turbulence, the angular resolution of a perfect telescope would be equal to λ/D [rd]—for instance, 0.012″ when observing at a wavelength $\lambda = 500$ nm on a $D = 8$ m telescope. Instead, the atmospheric turbulence "seeing"—the size of the blurred image—is typically of the order of 1″, almost two orders of magnitude worse than what the telescope could achieve. Astronomers and engineers built larger telescopes because they gather more photons, but until the development of adaptive optics, the only remedy to the blurring problem was to send telescopes into space; a sometime necessary, but expensive, option.

2. HISTORY OF ASTRONOMICAL ADAPTIVE OPTICS

In 1953, Horace Babcock, an American astronomer, proposed the concept of adaptive optics (AO). The wavefront aberrations induced by atmospheric turbulence could be measured by a wavefront sensor and compensated for by a wavefront corrector, thereby deblurring the images in part or entirely. Babcock had already a concept in mind, and from the start had identified the limitations of the technique, including the fact that it was limited to the vicinity of stars bright enough to use as guides, in effect a very small fraction of the sky.

This remained concept until the applicable technology became mature enough. Pushed and funded by DARPA (Defense Advanced Research Projects Administration), the first defense-oriented research started in the early 1970s, and the first successful demonstration of the technology was made in 1973 in the laboratory with the Real-Time Atmospheric Compensator (RTAC), closely followed by field tests, and then by second-generation systems like CIS, installed at AMOS (Air Force Maui Optical Station) on Maui. A good description of these early endeavors can be found in Hardy (1998).

These developments advanced the state of the technology, and by the mid-1980s, AO components such as detectors, deformable mirrors, and (analog) reconstructors were available, albeit under restricted use. Having somehow heard about the DARPA AO program's success (for interesting insights, see McCray [2000]), astronomers became interested in applying this technique for astronomy. Beckers, Roddier, and Kibblewhite started a program at the National Optical Astronomical Observatories (NOAO), but the project never saw starlight and was stopped in 1987. In Europe, Léna (Paris-Meudon Observatory), Fontanella (ONERA), Merkle (ESO [European Southern Observatory]), and Gaffard (CGE) initiated an AO project named COME-ON, which was started in the wake of the VLT (Very Large Telescope) agreement when the various partners realized that AO was absolutely necessary to take full advantage of the 8 m interferometric coupling. COME-ON was a low-order system, with a 19-actuator deformable mirror (DM) and a 20-subaperture Shack–Hartmann wavefront sensor (WFS), and used a 32×32 pixel near-infrared (NIR) imager. It saw first light at the Observatoire de Haute-Provence in France in November 1989, and achieved the diffraction limit of the 1.5-m telescope in the NIR (Rousset et al. 1990). It was then moved to the ESO La Silla 3.6-m telescope where it was used successfully for several runs until 1992 (Rigaut et al. 1991), after which it had several upgrades: COME-ON+ and ADONIS (Beuzit et al. 1997). In the early 1990s, Roddier and his team at the University of Hawaii were working on an AO system based on curvature sensing, a new wavefront sensor concept that proved to be very efficient in its use of photons. The system was tested in 1992 on the University of Hawaii (UH) 2.2-m telescope at Maunakea (Roddier et al. 1991) and spawned a generation of AO instruments: Canada–France–Hawaii Telescope (CFHT) PUEO, ESO MACAO, the United Kingdom Infrared Telescope (UKIRT) AO system, Hokupa'a at Gemini, and others. See Roddier (1999) for a more detailed description of the first years of astronomical AO. In May 1991, much of the adaptive optics work that had been done by the US Department of Defence became declassified, and was later published in the literature (Fugate et al. 1994).

In the mid to late 1990s, various teams worked on demonstrating AO with laser guide stars (LGS). The Multi-Mirror Telescope (MMT) in 1995 (Lloyd-Hart et al. 1995) and the 3-m Shane telescope at the Lick observatory in 1996 (Max et al. 1997) were the first astronomical telescopes to demonstrate LGSAO, later on followed by Calar Alto. Initially, LGS AO brought only moderate image quality gains. It took many years and dedication to understand and overcome all the problems associated with LGSs. The undisputed leader in that venture is the Keck Observatory—according to Wizinowich (2013), the Keck LGS system has produced 72% of all LGS-based astronomical papers from 2004 to 2012—who closed the loop in LGS mode in 2003, followed by Gemini, the VLT, and others.

The same period saw the emergence and later on the demonstration of other key technologies such as deformable secondary mirrors (Brusa-Zappellini et al. 1999), pyramid wavefront sensors (Ragazzoni 1996), and the explosion of new concepts, such as GLAO, LTAO, MOAO, and others (see § 5).

The early 2000s marked the coming of age of AO, with it becoming mainline, producing high-impact astronomical science (see § 6) and generally finding its place between seeing-limited and space-based observatories. Observations with adaptive optics now amounts for 25% of the allocated observing time in major observatories like Keck and soon the VLT, where Unit Telescope 4 is being transformed into an adaptive telescope.

Of course, AO is much more than just nighttime astronomical AO. It started as a defense project. AO has been used with resounding success to image the surface of the Sun for almost as long as for nighttime astronomy (Rimmele et al. 2013). AO is also now a commonly used technique for medical applications, including retina and deep tissue imaging.

3. THE COMPONENTS OF AO

So what is AO really, and how can it be defined? Originally, AO was aimed at compensating atmospheric turbulence using a combination of a wavefront sensor and a deformable mirror, placed in a close-loop arrangement, to restore the diffraction limit of the optical system. The principle of a classical AO system is shown in Figure 1. Because the applications of AO have diversified so much—AO is now used in medical imaging, optical fabrication, and other applications—most of this is not true anymore. There can be one or multiple wavefront sensors, and one or multiple wavefront correctors (MCAO, MOAO); the arrangement can be either close-loop or open-loop (e.g., MOAO); and an AO system does not necessarily aim at restoring the full resolution (e.g., GLAO). However, it will generally use at least one wavefront sensor (WFS) at least one deformable mirror (DM), and some kind of reconstruction process. The following sections expand on these concepts.

3.1. Wavefront Sensors

There are many types of WFS, with various virtues and shortcomings. Some of the properties that are relevant to AO are sensitivity, linearity, achromaticity, dynamic range, spatial aliasing, computational requirements, whether it can work on extended sources, and last but not least, ease of implementation.

Because astronomical applications are almost always photon-limited, one of the most important properties is sensitivity: how effectively it makes use of the photons. For the same reason, achromaticity is also of important, although it does not apply when using laser guide stars (LGS). When using LGS, the ability of the WFS to work with extended sources is a critical property. Many—but not all—applications are in closed-loop systems; in these, dynamical range and linearity are less important because the WFS sees a residual error—hopefully small amplitude aberrations.

The most commonly used WFS in astronomical adaptive optics is undoubtedly the Shack–Hartmann WFS (SHWFS): it is achromatic, can use extended sources (albeit with a reduction of signal-to-noise ratio [S/N]), and is linear. Although it is also

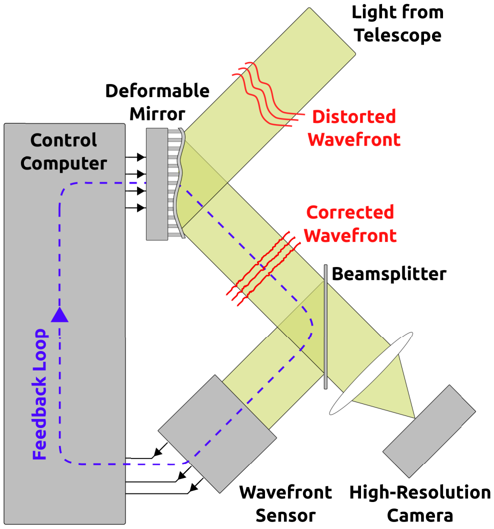

FIG. 1.—Principle of AO in a closed-loop arrangement. See the electronic edition of the *PASP* for a color version of this figure.

relatively sensitive, it is by no means the most sensitive WFS, nor the one with the lowest spatial aliasing (Guyon 2005). Importantly, they are easy to understand and implement: essentially, a SHWFS dissects a beam into many apertures (called subapertures) by using an array of lenses (called a microlens array). Each of these lenses forms a spot image. The resulting array of spots is imaged onto a detector. Resulting from the basic properties of lenses, the transverse location of one of the spot is directly proportional to the average *slope* of the wavefront in the subaperture. The overall wavefront can then be reconstructed from the *X* and *Y* slopes in each of the individual subapertures (Hudgin 1977; Fried 1977).

The high-resolution community has been experimenting, with various level of success, with new WFS concepts since the beginning of the 1990s: the curvature wavefront sensor, proposed by Roddier & Roddier (1988), makes use of extrafocal image intensity. It can be shown that it measures something proportional to the curvature of the wavefront, hence its name. It is quite efficient in its use of photons; its sensitivity can be tuned during operation to match the amplitude and spatial properties of the wavefront to analyze. Some late developments even include a dual-modulation device (Guyon et al. 2008). Curvature wavefront sensors were used with success at University of Hawaii, CFHT, ESO, and SUBARU.

Another very successful WFS is the pyramid sensor (Ragazzoni 1996; Esposito & Riccardi 2001), which can be loosely described as the 2D analogous of a Foucault knife. Pyramid WFS has been used in many systems, in particular the LBT AO systems, where, in conjunction with deformable secondary mirrors (see § 3.2), it has allowed reaching a Strehl ratio in excess of 93% in H band on an 8-m telescope.[1]

3.2. Wavefront Correctors

In all early AO systems, the telescope entrance pupil was reimaged on the wavefront corrector, which was part of a dedicated instrument. A deformable mirror (DM) is the most common form of wavefront corrector. It is generally a few millimeters to a few tens of centimeters in diameter. There are many DM technologies. The deformation of the thin membrane, or segments in some cases, can be affected by actuators, attached to the back of the mirror surface, that can be either piezoelectric (Piezostack, Xinetics/CILAS, or Curvature mirrors), magnetic (ALPAO/Microgates deformable secondary mirrors, see Fig. 2), or use solid-state Microelectromechanical systems (MEMs) technology (Boston Micromachines Corporation; IRIS-AO Inc).

A DM for astronomical AO applications has to deliver a stroke of a few microns to a few tens of microns, with bandwidth from 500 Hz to a few kHz, and with little or no hysteresis. DMs have been produced with as many as a few thousand actuators, for application in extreme AO and/or extremely large telescopes.

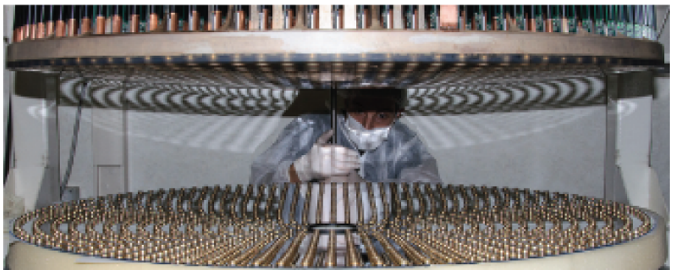

FIG. 2.—Deformable secondary mirror being assembled, showing the shell and magnets (*bottom*) and reference surface, coils, and electronics (*top*). See the electronic edition of the *PASP* for a color version of this figure.

The choice of technology is mostly driven by the application, but also by the cost and reliability. For instance, extreme AO needs many actuators but does not need to transfer a large field of view, and will generally uses compact, actuator-dense MEMs DMs. At the other extreme, for ground layer AO, which requires passing a large field of view, or when thermal emissivity is of importance, deformable secondary mirrors are preferred. Reliability and failure mode was also quite important for systems with thousand of actuators. For instance, contactless actuators, as in magnetic/coil technologies, will fail more gracefully than contact actuators.

4. LASER STARS

Because atmospheric turbulence is vertically distributed along many kilometers above ground, the light coming from different directions crosses different parts of the turbulent volume, and will thus lead to different aberrated wavefronts; this is called *anisoplanatism*. Practically speaking, for good observing sites, the phase error resulting from anisoplanatism is of the order of $\lambda/4$ for isoplanatic angle $\theta_0 \approx 7 \times \lambda^{1.2}{}''$, where λ is in microns.

Additionally, the guide star needs to be bright enough to provide enough photons in a coherence volume $r_0^2 \times \tau_0$ (the atmospheric turbulence coherence length and time), which is typically the surface of a subaperture times the WFS sampling time. That leads to the concept of *limiting magnitude*, and, when coupled with the *anisoplanatic limitation*, to the concept of *sky coverage*, which is the fraction of the sky into which AO compensation can be achieved. A typical value for sky coverage is 0.001% at $\lambda = 500$ nm and scales as λ^6, making it a few percent in the NIR.[2] This limitation is fundamental and the only remedy is to observe from sites with better seeing.

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[1] The Strehl ratio is a measure of quality of the image; a image with no aberration would have a Strehl ratio of 100%. A typical H-band image affected by atmospheric turbulence on a large telescope has a Strehl ratio of a few percent at most.

[2] This strong dependence explains why the vast majority of astronomical AO systems to date aim at compensation in the near-infrared.

Or is it? Foy & Labeyrie (1985) proposed creating artificial guide stars by using a laser to excite sodium atoms lying in a conveniently located layer, between 90 and 100 km above ground. This layer is constantly replenished by small meteorites. Its lower bound is well defined and occurs at the altitude where density is high enough for the sodium atoms to bond chemically with other species. The line used is the one that has the largest cross-section transition of sodium atoms: the 589 nm D2 line, the same one used in orange street lights. Of the many schemes to produce artificial stars suitable for AO, this one has proven to be the most successful, albeit challenging (Max et al. 1997; Wizinowich et al. 2006; D'Orgeville et al. 2012). Many telescopes are now equipped with LGS; at Maunakea, one can often spot four orange beams crisscrossing the sky. LGSs are also an integral component of all the extremely large telescopes being designed right now.

However, LGS does not come without limitations. The light from an LGS comes from a point at finite distance, and thus forms a cone which does not overlap exactly with the cylinder of light coming from an astronomical object, which is located, for all practical purposes, at infinity. This is called the *cone-effect* (Tallon & Foy 1990; Fried & Belsher 1994).

Another limitation results from the fact that the laser beam that creates the LGS has first to go up through the turbulence, which causes an unknown—or difficult to know—jitter. This essentially means that the position of the LGS cannot be used to determine tip–tilt, or global image motion (Rigaut & Gendron 1992). A natural guide star (NGS) is therefore needed to provide a fixed point of reference. It can be significantly fainter than for NGS-only AO as the full telescope aperture, opposed to a small subaperture, can be used to gather the signal.

5. THE ADAPTIVE OPTICS ZOO

In the beginning there was only AO. In the 1970s, 1980s, and early 1990s, AO was challenging enough that all the efforts were focused in making it work and convince the astronomical community to adopt it. When this was well under way, new concepts emerged, and bloomed into a full zoo: LGSAO, eXAO, GLAO, LTAO, MCAO, and MOAO to cite the main ones. As should be clear to the reader by this point, physical limitations imposed by anisoplanatism and signal-to-noise ratio in the WFS make it impossible to obtain a perfect image (Strehl ratio of 100%) over an arbitrarily large field of view. Choices have to be made. This is what all these AO variations are about, as we will see below.

Extreme-AO (eXAO) is basically AO on steroids, optimized to achieve very high correction performance (high Strehl ratio). The main application is high-contrast science, in which the interesting object or feature is angularly close (0.1–1.0″) to a much brighter object: mostly exoplanets and disks, or quasi-stellar object (QSO) host galaxies (e.g., see Fig. 3). The challenge in eXAO is that control of the very tight error budget (typically a total rms error of 60–80 nm in current systems) means that every term has to be controlled with the utmost attention. eXAO requires many actuators, and only works with NGS, as the cone effect disqualifies LGSAO. Current competitors for the detection of the first one Jupiter-mass exoplanet are GPI (Macintosh et al. 2015), SPHERE (Beuzit et al. 2008), SCExAO (Martinache & Guyon 2009), FLAO (Esposito et al. 2010), PALM3000 (Dekany et al. 2013), and MagAO (Close et al. 2013).

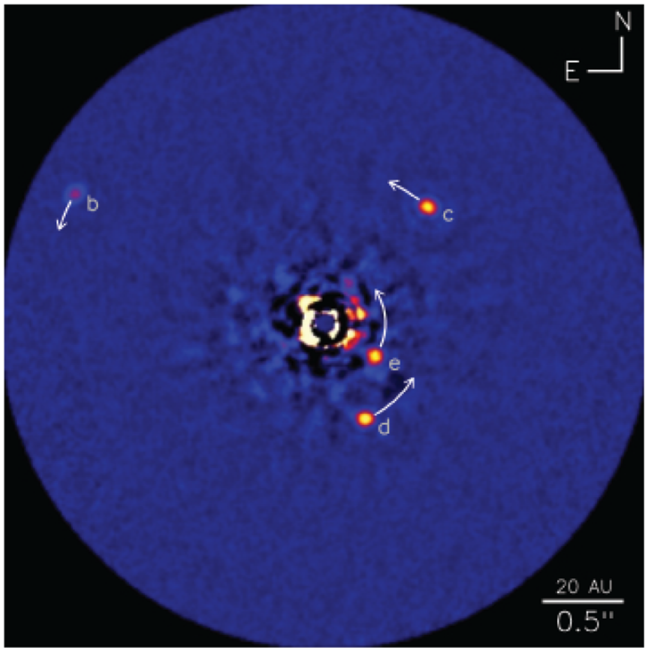

FIG. 3.—The detection and direct imaging of a planetary system around main-sequence star HR8799 (Marois et al. 2010). In 2013, out of the six planetary systems directly imaged (excluding distant planets), five had been with adaptive optics systems and one from the *Hubble Space Telescope* (F. Marchis, private communication). See the electronic edition of the *PASP* for a color version of this figure.

GLAO, or ground layer AO, is the other extreme (Rigaut 2002; Tokovinin 2004). In GLAO, only the ground layer of turbulence is corrected. Because it is in proximity to the telescope aperture, the correction of the ground layer is close to being isoplanatic, and can be applied to wide fields, of the order of 7′ to 10′. Site characterization studies, numerical simulations, and first on-sky results show that GLAO can provide a gain of 2–3 in image size, providing "super seeing" conditions most of the time, and allowing significant savings in the observing time necessary to reach a given S/N. GLAO has been demonstrated at the MMT and the LBT, and will soon be part of the ESO 8-m AO facility telescope (Arsenault et al. 2012). It is also an AO mode planned for the future ELTs.

In *LTAO*, or laser tomography AO, multiple LGSs are used to alleviate the cone effect limitation (see § 4). The LGSs are pointed in various directions, their collective cone probing the

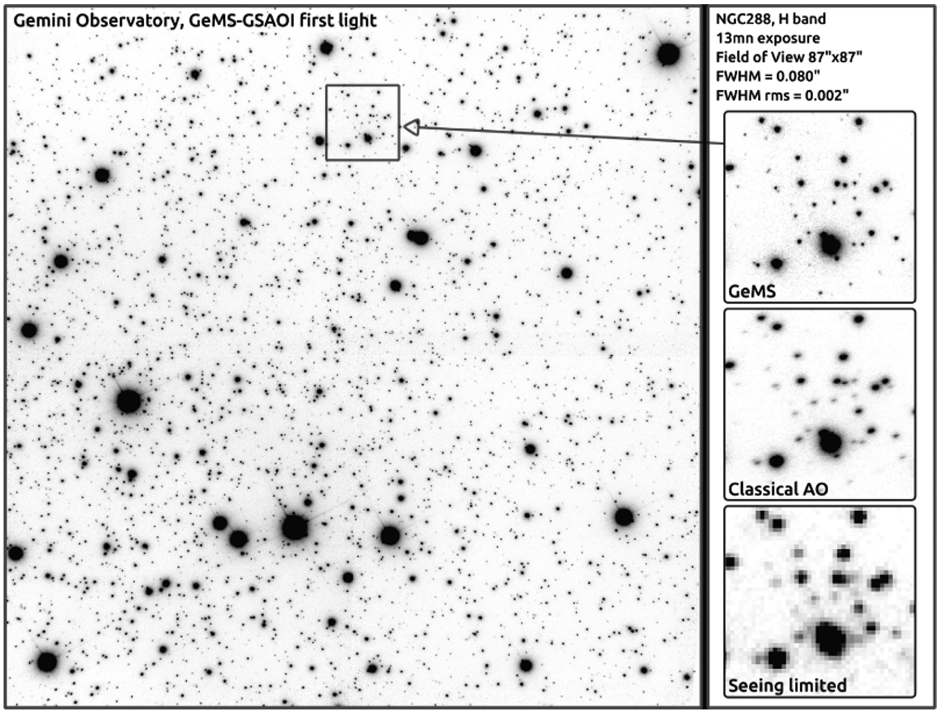

FIG. 4.—First light image of GeMS, the Gemini MCAO system, providing close to the diffraction limit images over 2′ square, an order of magnitude larger—in surface—than the isoplanatic patch at 2.2 μm.

full cylinder. The phase in the direction of the object of interest is obtained through a tomographic reconstruction process (Lloyd-Hart et al. 2006). This can lead to a high Strehl ratio, but because only one DM is used, it suffers from the same anisoplanatic limitations as classical AO.

MOAO, or multiple-object AO, is somewhat similar to LTAO in the sense that many guide stars (NGS or LGS) are used, through a tomographic process, to derive the command to apply to a deformable mirror to correct in one particular direction. The difference is that the many guide stars cover a much larger field of view—many arcminutes—and that the DM is downstream from the sensing stage; ideally integrated into a small unit starring at the astronomical object of interest and additionally including some kind of science imager or spectrograph. The intent is to have many of these DM/science instruments units to bring a multiplex advantage. One could imagine, for instance, having IFUs pointed at galaxies, each IFU also having its own integrated DM. MOAO provides small patches of good correction scattered across a large field, is well suited to, e.g., extragalactic studies. The main challenge of MOAO is related to the open-loop operation, which imposes new linearity, dynamical range, and hysteresis requirements on the WFSs and the DMs. The cost associated with multiplexing is also an issue. MOAO is planned for some of the ELTs and has been demonstrated recently at the William Herschel Telescope (Gendron et al. 2011) and Subaru (Lardière et al. 2014).

Finally, in *MCAO*, or multiconjugate AO, several DMs are “stacked” in a series to form a 3D corrector, which can then be optically conjugated to the whole turbulent volume and thus provide anisoplanatic correction (Beckers 1988; Ellerbroek 1994). The information on the 3D volume of turbulence is provided by multiple guide stars (NGS or LGS) and a tomographic processor. MCAO was demonstrated at ESO with NGSs (Marchetti et al. 2007), and more recently, at Gemini with LGSs (Rigaut et al. 2013), providing moderate Strehl (30–50%) over fields of view of nearly two arcminutes, an order of magnitude larger than with classical AO (See Fig. 4).

6. PERFORMANCE, ACHIEVEMENTS, AND THE ELT CHALLENGE

As outlined above, AO systems are designed to serve different science needs, so the performance metrics vary.

Mainstream AO systems such as NAOS (VLT), Keck-AO, or FLAO (LBT) regularly deliver images at the diffraction limit (about 40 mas at H band) with Strehl ratio in excess of 50%.

For eXAO, it is all about contrast, so Strehl is paramount, together with halo/speckle stability and suppression. Most of eXAO systems now achieve wavefront errors around 80 nm, leading to Strehl ratios in excess of 90% at 1.65 μm (H photometric band). Combined with coronagraphs and other observing techniques, GPI and SPHERE achieve contrast levels of 10^{-7} at 0.2″ from the star (Mawet et al. 2012).

Although they remain a complex and challenging technology, LGSs are becoming mainstream, and LGSAO facility systems are reaching their expected performance. Many of the new concepts have been demonstrated, and even implemented as facility systems, for instance, the Gemini MCAO system, which provides 30% H-band Strehl images over $85'' \times 85''$. LGS systems, together with significant improvements in detector technology, have also boosted the sky coverage by a large factor, getting into the 20–30% range. New projects like the Keck-NGAO aim to improve that even further (Wizinowich et al. 2008).

AO is benefiting, or even enabling, many areas of astrophysics, ranging from solar system planetary science to dynamical studies of low and mid-redshift galaxies, through exoplanets, stellar populations, and the discovery of the black hole in our own galaxy, including high-impact papers and science, of which Marois et al. (2008); Ghez et al. (2008); Genzel et al. (2010); Lagrange et al. (2009); Brown et al. (2006) are examples. Davies & Kasper (2012) give an extensive list of the science done with AO. Wizinowich (2013) provides a comprehensive journal review and counts 558 refereed papers published through 2014 using only Keck AO data (most in astronomical journals). Since 2006, 45% of Keck-II observing nights have been used for AO programs . ESO has dedicated one of the four VLTs exclusively to AO use, with the AO Facility that is coming online imminently.

The next generation of Extremely Large Telescope (ELT) relies heavily on AO, for engineering and scientific reasons. The challenges are real, and stimulated technology developments for large DMs (the European-ELT M4 DM is specified to be 2.4×2.5 m with 5316 actuators), large detectors (ESO/e2v LGSD detector is specified to be 1680×1680 pixel to be read-out at 700 Hz), and more efficient reconstruction strategies. By contrast, the sodium laser power requirements scale only moderately with the telescope diameter. In addition, these ELT AO systems require validation of concepts like LTAO or MOAO, so teams have been busy around the world building demonstrators, to be tested on the current generation of 8-m telescopes (CANARY, Raven, AOF).

Essentially all the next big questions in astronomy will need large collecting power and high angular resolution to be addressed: how galaxies assemble, how stars and planets form, and the direct imaging of extra solar systems. Challenges remain, of course, but astronomical AO likely has a bright future ahead.

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