What AO can Deliver to the Astronomer Today – and what an Astronomer Would Like to Find in the Software Toolbox

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Abstract: Over the past few years high-resolution imaging with adaptive optics has become an important technique with a wide variety of applications in Solar System physics, stellar astronomy, and extragalactic research. Much of the recent progress can be attributed to a few key factors: the growing number of astronomers who have access to user-friendly AO systems, improvements in the limiting magnitude for wavefront sensing, and the availability of accessories for coronography, polarimetry, and Fabry-Perot imaging. The development of adequate software tools for the reduction of AO data will be an important requirement for the continued success of adaptive optics. A comprehensive data reduction toolbox should contain routines for basic image processing, data visualization, determination of the point spread function, and deconvolution. The toolbox should be accompanied by a cookbook with worked-out examples and data analysis recipes. The strong dependence of AO system performance on environmental conditions argues for flexible (queue) scheduling; appropriate planning and simulation tools are then needed. The combination of integral field spectroscopy with adaptive optics will pose new challenging data analysis problems.

1. Introduction

After years of technical development, testing of prototype instruments, and experimentation with observing and calibration procedures, adaptive optics has now started to fulfill its promise to produce unique astronomical results. A wide variety of problems from various astronomical disciplines have been addressed by observations with adaptive optics, and the number of publications based on theses observations has steeply increased over the past few years. Consequently, adaptive optics features prominently in the plans for the large new telescopes with apertures of 8 to 10 m diameter; the first of these instruments at the Keck II Telescope will set a new standard for angular resolution. The next step forward is expected from laser guide star systems, which will increase the sky coverage dramatically. However, adaptive optics cannot be everything for everybody. Ideally, one would like to get:

- diffraction-limited imaging over the whole sky
- large field-of-view
- high dynamic range
- operation at visible and infrared wavelengths
- high throughput, small thermal background
- flexible spectroscopic capabilities
- hassle-free and efficient operation
- simple calibration and data reduction
- little dependence on weather conditions.

Unfortunately, the realities of adaptive optics are different. The systems available to astronomers today give:

- relatively poor sky coverage with natural guide stars
- a field of a few tens of arcseconds limited by anisoplanatism
- limited dynamic range, artifacts
- degradation towards shorter wavelengths
- light loss and enhanced background due to complicated optical systems
- very limited spectroscopic capabilities
- overhead for calibration and optimization of the control loop
- often complex calibration and data reduction, which can limit the productivity
- strong dependence on site and weather conditions.

Hardware improvements (e.g., laser guide stars, adaptive secondary mirrors, AO systems with more actuators and larger bandwidth, spectrographs specifically designed for the use with AO) will undoubtedly contribute to closing the gap between the astronomers' dreams and the realities imposed by technical limitations and by the characteristics of atmospheric turbulence. It is equally important, however, to develop software tools that enable the observer to take full advantage of the capabilities of current and future instruments. In this article, I will briefly survey some recent astronomical results obtained with AO, and describe some of the software needs that should be addressed in the near future.

2. Astronomical Results from Observations with Adaptive Optics

The scientifically most productive AO systems to date are the facility instruments at ESO's 3.6 m telescope on La Silla (ADONIS, and its predecessors COME-ON and COME-ON+) and at the Canada-France-Hawaii Telescope (PUEO), as well as two systems (with 13 and 36 elements, respectively) built at the University of Hawaii. These four systems – and a few others – have produced so many results over the last two or three years that it is now possible to hold a full one-week conference with an emphasis on astronomy with adaptive optics, rather than AO technology. Consequently, any review has to be restricted to a few representative examples in each field. In addition, and beyond pure counting of publications based on AO, two interesting trends should be pointed out. First, many groups are now combining AO observations with other data, either from HST (e.g. Brandl et al. 1996, Close et al. 1997a, Stapelfeldt et al. 1998, Stecklum et al. 1998), from ground-based spectroscopy (e.g. Brandner et al. 1997, Thatte et al. 1997, Stockton et al. 1998), or from other sources. Second, AO is now used to address a wide variety of different problems, in fields ranging from Solar System physics to observations of high-redshift objects. Both trends indicate that adaptive optics has made the transition from a highly specialized technique (that could be used only by equally specialized observers) to an indispensable tool with a broad range of applications.

In our own Solar System, the planets, their moons, and the small bodies all are interesting objects for observations with adaptive optics. AO images of Neptune have been used to monitor the cloud activity; they have also provided the first infrared observation of Neptune's moon Proteus (Roddier et al. 1997). Jupiter and Saturn can be observed by using one of their moons as a guide object, or with a laser guide star. The latter method has been used for multi-spectral imaging of these planets, including observations of the SL/9 impact sites on Jupiter (Glenar et al. 1997). AO data on Saturn's moon Titan reveal complex surface features; albedo measurements and spectrally resolved data can be used to constrain the surface composition and the surface area that may be covered with lakes or oceans of liquid hydrocarbons (Combes et al. 1997). Asteroids can be described to first approximation by triaxial ellipsoids; the shape and orientation of these bodies can be extracted from high-resolution images. Repeated AO observations of Ceres and Vesta, combined with HST imaging, speckle interferometry, and lightcurve analysis, have been used to determine their dimensions and rotation poles (Drummond et al. 1998).

Adaptive optics is a very useful tool for studies of binary stars, because it increases the accessible separation range down into the sub-arcsecond regime, and because it provides enhanced sensitivity for the detection of faint companions through the concentration of light in a diffraction-limited core. Photometry of the individual components in binaries can be used to establish their spectral types (ten Brummelaar et al. 1996), and orbital parameters can be derived from repeated measurements of the same binary system (Drummond et al. 1995). In the case of pre-main-sequence binaries (Brandner et al. 1995, Schöller et al. 1996), such observations are required to determine the evolutionary status of the system and to search for the presence of circumstellar material. Surveys of large samples of stars (Bouvier et al. 1997) have become possible with reliable AO systems, which can observe dozens of stars per night. Such surveys are needed to obtain a statistical estimate of the binary frequency, i.e., a count of stars that are members of multiple systems. The comparison of binary frequencies in different stellar populations (e.g., in stars near the Sun, in the Pleiades cluster, and in star-forming associations such as the Taurus-Auriga region) can then help us answer the question about the environment in which most low-mass stars are born.

Young stars are formed through the collapse of dense clouds of interstellar matter. These gas clouds block the visible light from sites of ongoing star formation; infrared observations are therefore required to search for very young objects in suspected star-forming regions (Currie et al. 1996). With high angular resolution it is possible to obtain images of circumstellar disks (Close et al. 1997b, Stapelfeldt et al. 1998). Accretion from these disks is an essential aspect of the star formation process as we understand it today. A particularly interesting case are disks or rings around pre-main-sequence binary stars (Roddier et al. 1996, Close et al. 1998). In some cases, however, very complex geometries are found (Koresko et al. 1997), and the interpretation of the AO images is far from straightforward. The formation of stars is frequently accompanied by mass-loss in the form of collimated outflows or jets, which emit in the $(\mathrm{v} = 1-0)\,\mathrm{S}(1)$ transition of H_2 at $2.121\,\mu$m. The hot molecular gas forms emission knots and filamentary structures, which have been studied in unprecedented detail by Fabry-Perot imaging with adaptive optics (Quirrenbach & Zinnecker 1997). Massive young stars interact even more strongly with their environment. Their intense radiation ionizes the surrounding gas to form an H II region, and it can evaporate disks around other stars nearby (McCullough et al. 1995, Stecklum et al. 1998). Reflection nebulae, which are formed when light from young stars is scattered off the circumstellar material, can best be observed with polarimetric imaging (Close et al. 1997a). Fragments of the molecular clouds left over from the star formation process can also be studied in the light of the $2.121\,\mu$m line of H_2; small clumps of gas with a density contrast of at least ten have been found in this way (Rouan et al. 1997).

During their quiet lives on the main sequence, most stars are surrounded by very little material; advanced AO technologies will be required to detect clouds analogous to the Solar Zodiacal disk around other stars. Some main-sequence stars, however, have much more massive dust disks. The prototypical object in this class, β Pictoris, has been observed with the coronograph of ADONIS (Mouillet et al. 1997). In later phases of their evolution, when the supply of hydrogen is exhausted, many stars shed a large fraction of their mass through intense winds and form beautiful nebulae, whose structure can be elucidated by imaging with adaptive optics (Beuzit et al. 1994b, Roddier et al. 1995, Brandner et al. 1997).

High angular resolution is of utmost importance for observations of crowded fields, such as dense clusters of stars. What appears to be a supermassive single star in conventional images, may turn out to be a dense cluster when observed with sub-arcsecond resolution (Heydari-Malayeri & Beuzit 1994). A prominent example is R136, the central region of 30 Doradus in the Large Magellanic Cloud. More than 1000 stars have been detected and classified in the central $12\farcs8 \times 12\farcs8$ of R136 (Brandl et al. 1996). A similar number of stars has been found in AO observations of NGC 3603, the most massive optically visible H II region in the Galaxy (Eisenhauer et al. 1998). Many stars with one Solar mass or less are detected in the immediate vicinity of the central cluster of high-mass stars, which shows that regions of massive star formation are also prolific nurseries for low-mass stars. Other prominent examples of very dense fields are found in the bulge of our Galaxy and near the Galactic Center; adaptive optics has been used to study the stellar populations in a field in Sagittarius (Bedding et al. 1997), and in the innermost parsec of our Galaxy (Davidge et al. 1997b).

In relatively nearby galaxies, adaptive optics can be used to resolve individual stars, as demonstrated for the nucleus of the Andromeda galaxy (Davidge et al. 1997a). A little further from home, observations of the nuclear regions in active galaxies can benefit tremendously from adaptive optics. It is possible, for example, to distinguish between the "true" compact nucleus and more extended starburst regions in ultraluminous infrared galaxies (Knapen et al. 1997, Lai et al. 1998). In addition to increasing the angular resolution of imaging and spectroscopy, AO can help in the registration of images taken at different wavelengths since the tip-tilt sensor provides a positional reference in the visible wavelength range, while the location of the infrared emission can be measured with the science camera. This technique has been applied to the Seyfert galaxy NGC 1068 (Quirrenbach et al. 1997b); it provides information that is essential for understanding the interplay between dust, gas, stars, and the Seyfert nucleus (Thatte et al. 1997). Last but not least, AO has started to fulfill its great promise for spatially resolved observations of galaxies and quasars at intermediate and high redshift. Images of galaxies in a cluster at redshift $z = 0.42$ have been used for a morphological classification of the detected objects (Beuzit et al. 1994a). Quasar host galaxies have been resolved with AO at $z = 0.5$ (Bremer et al. 1997), $z = 1$ (Hutchings et al. 1998), and at $z = 2$ (Aretxaga et al. 1998). Tidal interaction with a companion has been inferred for a $z = 0.3$ quasar (Stockton et al. 1998). Finally, the lensing galaxy has been found with adaptive optics for a doubly imaged quasar (Crampton et al. 1998).

From this brief survey of the literature, it is clear that today adaptive optics can deliver unique data for a wide variety of astronomical applications, when high spatial resolution in the near-infrared is required. The progress during the last few years can be attributed to a number of factors: the accessibility of user-friendly systems for a growing number of astronomers, the improvements in limiting magnitude for wavefront sensing by PUEO and the University of Hawaii systems, which make full use of the good site characteristics on Mauna Kea, and the availability of accessories such as Fabry-Perot etalons, coronographs, and polarizers. In the near future, AO systems at the 8 m and 10 m telescopes will open a whole new range of possibilities by improving the resolution by another factor of 3.

It should also be pointed out that nearly all of the results mentioned above have been obtained with natural guide stars; the few exceptions are all from observations with the Rayleigh laser guide star system at Starfire Optical Range. Recently, however, three groups have reported image improvement using sodium guide stars at astronomical telescopes: the system at the 3 m Shane Telescope at Lick Observatory built by Lawrence Livermore National Laboratory (Max et al. 1997), the University of Arizona system at the Multiple Mirror Telescope (Lloyd-Hart et al. 1998), and the ALFA instrument at the 3.5 m telescope on Calar Alto built by the Max-Planck-Institutes for Extraterrestrial Physics and for Astronomy (Quirrenbach et al. 1997a, Davies et al. 1998). None of these laser systems has been routinely operated for astronomical observing programs yet. The experience gained so far shows that achieving good correction and stable calibration is considerably more complicated with laser beacons than with natural guide stars. Nevertheless, within the near future we should expect to see the the first astronomical results enabled by AO with sodium laser guide stars.

3. Reduction of Adaptive Optics Data: the Toolbox Approach

The reduction of astronomical data can be addressed in two different ways: either by pipeline processing, or with an interactive toolbox. The pipeline approach means that all data from an instrument are processed with a standard procedure, in a fairly automated way. This requires well-understood and uniform data with predictable characteristics; the data taking and calibration procedures have to be standardized to provide the necessary inputs for the pipeline. The great advantages of this strategy are ease of use even for inexperienced observers, quick results, and uniform quality of the final data products, which is necessary for archiving. For these reasons, pipeline processing is widely used for spacecraft data, and is also being implemented for ground-based data from large national and international observatories. However, it is (currently) hardly suitable for the reduction of adaptive optics data. First of all, the quality of AO data – as measured e.g. by the Strehl ratio – varies strongly with wavelength, brightness of the reference source, angular distance from the reference, and seeing (see e.g. Rigaut et al. 1998). Second, the requirements for different scientific projects may vary widely: detection of close point-like companions or extended structure, crowded-field photometry, astrometry, polarimetry, coronography and Fabry-Perot imaging each have their own difficulties. For most data sets, some form of deconvolution is necessary; experimentation with different deconvolution methods is often required to recognize deconvolution artifacts. Furthermore, the calibration of the point spread function can be done in a variety of different ways, either from a point source within the field-of-view, or by periodically offsetting to a reference star, or from wavefront sensor data (Véran et al. 1997). When the field of interest is so large that anisoplanatism is important, it may be necessary to use local point spread functions in smaller sub-fields (Eisenhauer et al. 1998). For these reasons, a more flexible approach than pipeline processing is needed.

A data reduction toolbox contains a set of loosely related routines, which together provide all capabilities needed to process the data. It is up to the user to decide which tools are most appropriate for a given scientific project, and how they should be used. This ensures a maximum of flexibility, but requires more competent users than pipeline processing. Since the individual routines in the toolbox are comparatively simple and independent from each other, it is also relatively easy to add user-supplied procedures for specific purposes. Unlike a pipeline, which has to be carefully designed in its entirety from the beginning, a toolbox can grow over time from ad-hoc solutions for individual problems into a more comprehensive set of general data reduction routines. This makes the toolbox approach attractive for distributed development. Many individuals can contribute procedures that they have written for their own research interests, such as an optimized mosaicing procedure, a sophisticated psf-fitting routine, or an implementation of a new deconvolution algorithm. This may be the most realistic and efficient path to a data reduction package that meets the requirements of the growing user community of facility AO instruments. A few conditions have to be met, of course: agreement on a software platform (perhaps IDL, at least initially), willingness to share data reduction software, adherence to common standards (which should be kept as simple as possible), and commitment to providing essential documentation.

The AO data reduction toolbox should ultimately provide every routine needed to transform the raw data from the telescope into end products for astronomical interpretation and publication. The first steps consist normally of basic image processing, such as sky subtraction, flat-fielding, dead pixel correction, re-centering, co-adding, and mosaicing. These operations are not specific to adaptive optics, and suitable tools can be found in several astronomical and general-purpose image processing packages. The next task is frequently determining the psf; in the case of a "large" field, angular anisoplanatism may necessitate the use of different point spread functions in smaller sub-fields. Depending on the astronomical program, and on the brightness of the wavefront reference source, the information about the psf may come from different sources: from one or several stars in the field, from observations of psf calibrator stars interleaved with those of the science target, or from wavefront sensor data. These observing modes should all be supported by the toolbox; in many cases some experimentation is needed to determine the "best" psf. A fairly large number of different algorithms have been used to actually perform the deconvolution of AO data; Shift-and-add, Fourier inversion, Wiener filtering, Clean, Richardson-Lucy, Maximum Entropy, and the Pixon method are among the most popular. These algorithms are all prone to produce artifacts of various kinds; comparing the results of several methods is therefore a good way of checking the reality of features that are revealed by deconvolution but not obvious in the raw images. The steps of psf determination and deconvolution can be combined in a single algorithm (blind or myopic deconvolution); here the psf is estimated directly from the data, which increases the dynamic range in the deconvolved image (Christou et al. 1997). In addition to these general imaging procedures, the toolbox should contain software for more specific tasks, such as photometry, astrometry, reduction of Fabry-Perot sequences, and polarimetry. In cases when it is known that the structure of the source can be described by a few parameters (e.g., binary stars, or barely resolved asteroids, which can be represented by triaxial ellipsoids), it is more efficient to fit these parameters directly, than to measure them from deconvolved images. The application of this strategy to crowded-field photometry has lead to the development of the Plucy algorithm, in which the image is decomposed into an ensemble of point sources (defined by their positions and fluxes) on top of a smoothly varying background (Hook & Lucy 1994). In addition to these data processing procedures, one should not forget visualization tools, which are essential components of any interactive package.

4. The Need for an Adaptive Optics Cookbook

As more and more astronomers view adaptive optics as a tool they might want to use for their own research, the expertise about the capabilities of AO systems, about observing procedures, and about data reduction has to be disseminated to a growing number of potential users. Most astronomers will probably not want to become technical experts, but they want to know how they can make optimum use of available systems for their specific purposes. Worked-out examples and test data sets taken from observing projects carried out by a knowledgeable AO user would be of tremendous help for novices. They could familiarize themselves with calibration strategies and data reduction procedures by tracing the steps that have already lead to a result published in the astronomical literature. In particular, a picture gallery of typical deconvolution artifacts, and a collection of "traps and pitfalls" would help new users to interpret their data; unsubstantiated claims of spectacular results based on faulty data analysis could hopefully be avoided. This would require that some AO experts take the time to document in detail how they have processed their data, including all the dead ends encountered on the way. Some guidance can already be obtained from the Adonis and Pueo web pages, and more work along these lines could be done as part of the "functional duties" of astronomers working at the national and international observatories. Over time, a collection of assorted data reduction recipes could thus be generated from the experience with individual astronomical projects. This collection could finally grow into a comprehensive adaptive optics cookbook, which would be part of the data reduction toolbox.

5. Making Good Use of Telescope Time

Observations with adaptive optics depend much more heavily on the "weather" conditions than most other astronomical projects. The degree of correction achieved on axis varies strongly with the seeing parameters r_0 and τ_0, and the corrected field size depends on the isoplanatic angle θ_0. In addition, the performance of laser guide star systems is influenced by the column density of the sodium layer in the mesosphere. Fluctuations of the effective height of this layer affect the relative focus of the laser guide star and astronomical targets. Dust and haze increase the low-altitude backscatter from sodium beacons; this problem can be so bad that the laser has to be switched off altogether. Since all these environmental factors have such a strong influence on the quality of the data, and therefore on the feasibility of specific astronomical projects, it is very beneficial to use flexible scheduling (also known as queue scheduling) for AO projects. Each observer has to specify a set of conditions under which the planned observations are feasible; the telescope scheduling is done nearly in real-time, and the observation with the highest priority among all those that are possible under the prevailing conditions is actually carried out. When the circumstances are too bad for any AO observations (e.g., when the seeing gets worse than a certain limit), the telescope time can still be used with other instruments.

For the successful implementation of flexible scheduling for adaptive optics, a number of conditions have to be met. An obvious prerequisite is that the relevant atmospheric parameters are monitored reliably. This is routinely done at many observatories for r_0 (or equivalent measures of the seeing), but rarely for the other factors influencing AO performance. It is possible, however, to measure the turbulence and wind profiles of the atmosphere, e.g. with SCIDAR (SCIntillation Detection And Ranging). This gives nearly complete information on the actual atmospheric turbulence characteristics; site monitors based on the SCIDAR method or similar techniques should be operated at every AO site. For AO systems with laser guide stars, the sodium column density should also be monitored. This could perhaps be done by continuously performing high-resolution spectroscopy of a very bright star without intrinsic or interstellar sodium absorption; the equivalent width of the sodium D lines in such a star is a direct measure of the mesospheric sodium column density.

For effective queue scheduling it is also necessary that the observers can predict the final result of their observations for a given set of environmental conditions. Since this "final result" is normally obtained only after psf determination and deconvolution, these processes should be included in the modeling of the observations. This means that the data reduction toolbox should possess the capabilities to perform a complete reduction of simulated data sets. In this way one could, for example, see how changes in the seeing affect the accuracy of crowded-field photometry or the detectability of faint close companions. The simulations can be based on semi-empirical approaches, which make use of libraries of point spread functions observed with a given system under known conditions, or of (realistic) parameterized models of the psf. While providing the astronomer with such a unified interface to planning of the observations and to data reduction will take a lot of work, the benefits of making optimum use of the telescope time should certainly justify the effort.

6. Three-Dimensional Data Reduction Challenges

The combination of adaptive optics with integral field spectroscopy holds great promise for several areas of astronomy, including observations of galactic nuclei and high-redshift galaxies. The reduction of data from these instruments will pose new challenges, which are not encountered in AO imaging. The reformatting of three-dimensional data cubes on two-dimensional detectors results in a complicated data format. Spatial and spectral flatfielding have to be applied separately; detector non-uniformity and cross-talk between adjacent pixels are more annoying because of the scrambling of the data cube on the detector. The signal-to-noise ratio may vary strongly between spectral channels, for example in emission line objects or due to increased thermal background at longer wavelengths in the K band. On the other hand, the point spread function varies only mildly and predictably with wavelength. This means that optimum methods have to be devised for the three-dimensional determination of the psf (as a function of wavelength), and for the deconvolution of data cubes.

Furthermore, the limited number of pixels requires compromises between spectral resolution and coverage, spatial sampling, and field-of-view. For example, the real estate on an infrared detector with 2048×2048 pixels may be allocated to 2048 spectral and 2048 spatial channels. Nyquist sampling of the J-band psf at a 10 m telescope would thus result in a field-of-view of only $\sim 0\farcs5$. To get a reasonable field of at least a few arcseconds, one therefore has to deal with severe undersampling of the psf. This problem can be alleviated by obtaining multiple exposures shifted by a fraction of the pixel size. This micro-stepping (or dithering) technique recovers some of the information lost by the poor sampling. It has successfully been applied to HST images, but it has to be determined how well it will work through the strongly varying atmosphere. An alternative strategy is the combination of spatially undersampled data cubes with properly sampled direct images in a joint deconvolution process. Here some effort is needed to determine under which conditions the spectral and spatial constraints are sufficiently strong for a successful retrieval of the diffraction-limited information in every wavelength channel. These new algorithms, and appropriate tools for the visualization of three-dimensional data, have to be added to the data reduction toolbox when integral field units become available at telescopes equipped with adaptive optics.

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