The High Redshift Universe with Adaptive Optics: Recent results from CFHT

David Crampton

Dominion Astrophysical Observatory, National Research Council of Canada, Victoria, V8X 3X1, Canada.

Email: David.Crampton@hia.nrc.ca

Abstract. The CFHT Adaptive Optics Bonnette (AOB) has been used to obtain high spatial resolution (0.1") observations of several extragalactic targets including the nuclei of nearby galaxies, high redshift galaxies, AGN, radiogalaxies, the host galaxies of quasars and gravitational lenses. Examples of these are discussed and the role of adaptive optics in exploring the high redshift universe is critically assessed in light of these results.

1. Introduction

The CFHT Adaptive Optics Bonnette (AOB) provides excellent correction using much fainter guide stars than previous systems so that observations of many extragalactic targets are now possible, using either a nearby reference star or the object itself. A wide variety of extragalactic objects have now been observed with AOB and some of these are used as examples to discuss some of the problems encountered and to demonstrate the potential of adaptive optics for studies of the high redshift universe.

2. The Adaptive Optics Bonnette

The CFHT AOB is based on a curvature wavefront system (Roddier et al. 1991) with 19 subapertures. A complete description of the system is given by Arsenault et al. (1994), and a comprehensive discussion of its performance by Rigaut et al. (1997). If the target is to be observed in the infrared, a dichroic is used to reflect the visible light to the wavefront sensor (WFS) while transmitting the IR light to the science detector, but if the target is to be observed in the visible, a beamsplitter must be used to send a percentage of the light to the WFS. The delivered image quality depends on the brightness of the reference star, its distance from the target, the seeing at the time of observation and the wavelength of observation. To gain an appreciation of how these variables affect the images and what can be expected, the reader is encouraged to visit the “performance meter” at http://www.cfht.hawaii.edu/manuals/aob/psf.html

To achieve FWHM ~0.12" imaging in the near-IR (diffraction-limited) and at I under median seeing conditions, the reference star must be brighter than R ~14 and within ~30" of the target. However, the system will provide good correction
on stars as faint as $R = 17$ under good seeing conditions, and the reference star can be located anywhere within the $90''$ diameter field. AOB offers considerable advantages in terms of operational efficiency, since it is literally a push-button operation that eliminates all the overhead of focussing and guiding associated with conventional observing.

The observations reported here were all made with the University of Montreal infrared camera MONICA (Nadeau et al. 1994) which was modified to give a pixel scale of $0''.034$ and hence a field of $8''.8 \times 8''.8$. This very small field is a significant handicap for many observations, as is the fact that the detector suffers from persistence problems, i.e., a bright source leaves a residual image that slowly decays with time. Since the site seeing is variable, observations of relatively bright stars usually have to be carried out in order to monitor the PSF (point-spread function). The sequence of observations of very faint sources thus has to be carefully planned to minimize such problems while adequately monitoring the PSF to attain the scientific goals. Véran et al. (1997) have recently demonstrated that statistics of the wavefront sensor signals can be used to derive an excellent model of the average PSF. This is obviously ideal in that the synthetic PSF is simultaneous with the the target observation and it obviates the requirement of directly observing the bright star.

3. Examples of Self-referencing Targets

Objects such as the nuclei of nearby galaxies, seyferts and AGN can be usually guided on directly, i.e., the nucleus is often sufficiently point-like to enable the WFS to function properly as long as there is sufficient flux. For example, guiding on the nucleus of M31 was straightforward, resulting in diffraction-limited images (FWHM = $0''.12$) of the stars in the nuclear bulge region, despite the fact that it is double with a fainter component at a distance of $\sim 0''.5$. The near-IR image quality is comparable to that of WFPC on HST, enabling accurate magnitudes and colors to be determined for a significant number of stars in the bulge (Davidge et al. 1997). During the commissioning period, other nearby galaxies, AGN and Seyfert 1 type galaxies with point-like nuclei and magnitudes in the range $m = 11–14$ (e.g., bright ones like NGC 4151 to fainter ones like NGC 6814) were observed with AOB, guiding on the bright nuclei themselves. However, guiding was not successful on more diffuse objects such as the $V = 13$ nucleus of the Seyfert 2 galaxy Mrk 266, or the large bright elliptical galaxy which hosts 3C296.

The small MONICA field complicates observations of such targets since neither the sky nor PSF stars are normally included in the frames. An accurate estimate of the PSF is essential for these sources in order to adequately subtract the effects of the bright point source from the nuclear region, so a nearby reference star of similar brightness must be monitored throughout the sequence of observations.

4. Targets with guide stars

Nearby guide stars must be used for targets which are not sufficiently concentrated or bright enough for the WFS to perform adequately. In this case, not only
are observations of the guide star itself required to monitor the PSF variations, but measurements of starfields (e.g., globular cluster fields) are also required to estimate the degradation of the PSF due to anisoplanatic effects. Steinbring (1997) has developed semi-empirical software that models this degradation over the field as a function of the seeing and produces an “off-axis PSF” that can be used to help analyse the target data. For some projects this is not important, but for the observations of quasar host galaxies, for example, it is vital. Studies of the latter are notoriously difficult due both to the faintness of the galaxy itself plus the superposition of the bright nuclear source. Some quasars have already been observed with AOB, both in the visible region (at $I$) with a CCD detector and in the near infrared (mostly at $H$). Analysis of the $z = 1.1$ quasar, 1055.3+019, which is well-resolved in both $I$ and $H$, has recently been published by Hutchings et al. (1998) who suggest that the host galaxy has been undergoing a close encounter or merger event.

The components of multiply-imaged gravitational lenses formed by galaxies in the line of sight to distant quasars typically have subarcsecond separations and consequently their study and monitoring could significantly benefit from the improved resolution offered by adaptive optics. At present, about $\sim 35$ such lenses are known (Kochanek 1997) but virtually none of them have nearby guide stars that are sufficiently bright to give good correction. One exception is SBS 1520+530, a doubly-imaged BAL quasar with a separation of $1''6$ which happens to be only $13''$ from a m$\sim$12 star. $H$ band images with FWHM = $0''15$ taken with AOB reveal the lensing galaxy $0''40$ from the fainter component, offset $0''12$ from the line joining components A and B (Crampton, Schecter and Beuzit 1997).

### 5. Registering invisible targets

Targets which are very faint, particularly those that are diffuse, often present additional problems since the MONICA field is so small that there aren’t any objects or features that can be used to register the images. In general, near-IR images have to be dithered to remove the effects of bad pixels and to improve the flat-field, offsets are often required to enlarge the area surveyed, and differential flexure between the WFS and the detector may produce additional shifts. Consequently, registering and superimposing the images is not trivial. The AOB WFS coordinates are recorded in the FITS headers and observations of star fields have been used to calibrate these positions in terms of pixel location on the detector and/or equatorial coordinates. Repeated observations of the same point source (e.g., a quasar) over several hours show that the WFS positions can be used to register frames with a dispersion of 1.4 pixels or $0''05$. Since the delivered images in the near-IR usually have FWHM $\sim 0''12$, this is clearly inadequate, so future systems should be designed with a low-order WFS incorporated close to the detector to minimize flexure and allow for sub-pixel “drizzling” and registration. Ideally, the coordinates of this WFS should allow diffraction-limited images to be registered to better than $\sim 10\%$ of their FWHM; for 8m telescopes this will be of the order of a few mas.

Although the $0''034$ pixel scale is necessary to properly sample the $\sim 0''1$ resolution delivered by AOB, many extragalactic projects would benefit from a
larger field. KIR, a new 1K×1K camera with three times higher sensitivity and a field of 36″ has just been commissioned, so registration will be easier. Even so, astrometry to the precision that is possible with 0′′.1 images will be challenging: relative positions can be measured to an accuracy of a few mas, but tying these to an absolute reference frame is difficult. Since many extragalactic targets are diffuse, a larger pixel scale would not be a disadvantage for most investigations, and the larger field would significantly improve the probability of including stars, providing even better registration and astrometry.

The jet of 3C273 is an example of an object which is barely visible, even on background-subtracted 300s exposures at $H$ and $K$. The jet is located between 11 – 21″ from 3C273 which, of magnitude R = 13, was used as the guide star for AOB. Given the small field of the detector, the jet had to be observed at two different locations along the jet and then all the frames were registered using WFS positions. Unfortunately the site seeing was poor on average and very variable (from 0′′.5 to 1′′.2) during the observations so, combined with registration uncertainties, the resulting (preliminary) image has a resolution of only ∼0′′.3. Observations with the new KIR camera should be significantly better.

6. Summary

Our experience with AOB demonstrates that adaptive optic systems can be made robust, reliable, efficient and user-friendly and will routinely deliver 0′′.1 resolution images from $I$ to $K$ with substantial gains in the visible. AOB observations of many extragalactic targets are now feasible and competitive with HST. Images of most of the objects discussed in this article can be found on the web at [http://www.hia.nrc.ca/science/instrumentation/optical/pueo2/pueo2.html](http://www.hia.nrc.ca/science/instrumentation/optical/pueo2/pueo2.html). Spectroscopic observations using instruments designed to exploit the AOB image quality are just beginning, although to obtain reasonable spectral resolution simultaneously with high spatial resolution will require adaptive optic systems on 8–10m telescopes for the majority of extragalactic targets.

References

Arsenault, R., Salmon, D.A., Kerr, J., Rigaut, F., Crampton, D., & Grundmann, W. 1994, SPIE, 2201, 883
Crampton, D., Schecter, P. & Beuzit, J.-L. 1997, submitted to AJ Davidge, T.J., Rigaut, F., Doyon, R. and Crampton D. 1997a, A.J., 113, 2094 Hutchings, J.B., Crampton, D., Morris, S.L., & Steinbring, E. 1997, submitted Kochanek, C. 1997, [http://cfa-www.harvard.edu/glensdata](http://cfa-www.harvard.edu/glensdata)
Lai, O., Arsenault, R., Rigaut F. et al, 1995, in OSA/ESO topical meeting on Adaptive Optics, ed. M. Cullum (Garching, ESO), p. 491 Nadeau, D., Murphy, D.C., Doyon, R. & Rowlands, N. 1994, PASP, 106, 909 Rigaut, F. 1997, PASP, in press, [astro-ph/9712196](http://arxiv.org/abs/astro-ph/9712196)
Roddier, F., Northcott, M. & Graves, J.E. 1991, PASP, 103, 131 Steinbring, E. 1997, in preparation
Véran, J.-P., Rigaut, F., Maitre, H. & Ronan, D. 1997, JOSA, A, 14, 11