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Adaptive optics: Observations and prospects for studies of active Galactic Nuclei

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ABSTRACT

These lectures take a look at how observations with adaptive optics (AO) are beginning to influence our understanding of active galactic nuclei (AGN). By focussing on a few specific topics, the aim is to highlight the different ways in which enhanced spatial resolution from AO can aid the scientific analysis of AGN data. After presenting some background about how AO works, I will describe a few recent observations made with AO of QSO host galaxies, the Galactic Center, and nearby AGN, and show how they have contributed to our knowledge of these enigmatic objects.

1. Introduction

Adaptive optics (AO) serves two purposes. It is an enabling technology for even more complex instrumentation such as IR/optical interferometry. But it is also an important technique in its own right. At near-infrared wavelengths (1–5 μm) it allows one to improve the spatial resolution of ground-based telescopes by an order of magnitude from 0.5 to 1″ to the diffraction limit, which for an 8-m class telescope in the H-band (1.6 μm) is about 40 mas. AO has applications in many areas of astronomy because it not only increases a telescope's sensitivity for unresolved sources, but it also reduces crowding problems in dense fields, and sharpens our view of the morphologies and kinematics of extended objects. In these lectures, the impact that adaptive optics is having on studies of Active Galactic Nuclei (AGN) is discussed with particular reference to three topics that span scales from <1 pc in the innermost region of our Galactic Center, through 10 c scales in nearby AGN, to kpc scales in QSO host galaxies at high redshift. By studying these different aspects and combining what we can learn from different spatial scales, we can gain a more holistic view of the structures comprising AGN and the physical processes governing how they are fuelled.

2. Adaptive optics overview

It is only by understanding the basic ideas behind adaptive optics that one can make the best use of it. This section therefore begins by looking at the effect that atmospheric turbulence has on a propagating wavefront. By making the approximation that the turbulence occurs in a thin layer at a fixed height, it addresses how adaptive optics can correct these aberrations. And it provides the tools needed to make simple quantitative statements about the impact of adaptive optics on a series of observations. Some ways in which the major limitations are being overcome are briefly considered.

2.1. Atmospheric turbulence

The atmosphere is a dynamically active structure which constantly has energy injected into it, either through heating (e.g. direct sunlight or re-radiation from the ground) or via convection currents and wind shear. These effects occur on scales of several tens of metres (the outer scale, L_0), and the energy is gradually transferred to smaller scales, until it is dissipated on scales of a few millimetres (the inner scale, l_0). This leads to local variations in the temperature and density of the air, and hence in its refractive index n. It can be quantified statistically using the structure

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function which describes the difference in n between a location r' and another location separated from it by r. For Kolmogorov statistics, the refractive index structure function is defined in terms of an average – denoted $\langle\ \rangle$ – over all possible r' and r. It takes the form

$$D_n(r) = \langle [n(r') - n(r' + r)]^2 \rangle = C_n^2 r^{2/3} \tag{1}$$

where C_n^2 is the refractive index structure constant. It is notable that the $r^{2/3}$ here is the origin of all the $\frac{1}{3}$ powers in expressions associated with adaptive optics. As it stands, this expression implies that the refractive indices at two points decorrelate ever more as the separation between the points increases. But this is true only as long as $r < L_0$ (e.g. for 2-m or 4-m telescopes). Instead, the decorrelation reaches a maximum at $r = L_0$, and the effect of this can be measured even on an 8-m telescope. As a result, the van Karman model is more often used. This is the same as the Kolmogorov model, but takes into account the inner and outer scales.

The impact that $D_n(r)$ has on a wavefront propagating down through the atmosphere is described using the phase structure function

$$D_\phi(r) = 2.91 \left(\frac{2\pi}{\lambda}\right)^2 (\sec\zeta)^{5/3} \int_0^\infty C_n^2(h)\mathrm{d}h \tag{2}$$

a good derivation of which is given by Roddier (1981). In this equation, ζ is the angular zenith distance at which one is looking, since the $C_n^2(h)$ profile is defined vertically through the atmosphere. In the most simple approximation, one can think of the atmosphere as a single thin 'phase screen', which induces a relative (phase) delay between two different points on a wavefront that depends only on the lateral separation of those points.

An important quantity to introduce here is Fried's parameter r_0 (Fried, 1965), which describes the coherence length of the atmosphere and is defined as

$$r_0 = 0.185\ \lambda^{6/5} (\sec\zeta)^{3/5} \left(\int_0^\infty C_n^2(h)\mathrm{d}h\right)^{-3/5} \tag{3}$$

Put in simple terms, r_0 is the size of aperture (e.g. telescope mirror) across which a wavefront can, for practical purposes, be considered unperturbed. In fact, the variance σ^2 of the resulting wavefront aberrations over a circular aperture of diameter D can be expressed in terms of Fried's parameter as

$$\sigma^2 = 1.030 \left(\frac{D}{r_0}\right)^{5/3} \tag{4}$$

Thus 'unperturbed' means having only 1 rad^2 of variance. The immediate conclusion one can draw from this equation is that turbulence limits the resolution of a telescope to λ/r_0 instead of λ/D. Other important parameters can be derived from r_0, two of which are the coherence timescale τ_0 and the isoplanatic angle θ_0. However, note that in reality these parameters are much less well correlated than implied here.

The coherence timescale can be thought of as the temporal equivalent of r_0, and is related to the time taken for the wind to blow across a cell of size r_0. Specifically, it is the time over which the variance of a wavefront changes by 1 rad^2. It is defined assuming Taylor's frozen flow hypothesis which asserts that temporal changes in the turbulence along a line of sight are due only to the lateral shift of an otherwise fixed phase screen. It is given as

$$\tau_0 = 0.314 r_0 / V_{wind}$$
$$\text{where } V_{wind} = \left[\int_0^\infty C_n^2(h) v^{5/3}\mathrm{d}h \Big/ \int_0^\infty C_n^2(h)\mathrm{d}h\right] \tag{5}$$

where v is the wind velocity as a function of height, and hence V_{wind} is a weighted mean wind velocity.

The isoplanatic angle is related to the angular size of r_0, which depends on the weighted mean distance H to the phase screen that we are using to approximate the atmosphere. Specifically, it is the angular distance between two lines of sight which causes the wavefront variance to change by 1 rad^2, and is defined as

$$\theta_0 = 0.341 r_0 / H$$
$$\text{where } H = \sec\zeta \left[\int_0^\infty C_n^2(h) h^{5/3}\mathrm{d}h \int_0^\infty C_n^2(h)\mathrm{d}h\right]^{3/5} \tag{6}$$

As we shall see later, the three parameters above form the basis for estimating the wavefront variance due to the atmosphere: r_0 and τ_0 describe the ambient atmospheric conditions and hence how well the AO system is likely to perform, while θ_0 describes how much the performance will degrade as one moves off-axis from the guide star. They all depend on $C_n^2(h)$, so that some knowledge of the turbulence profile (refractive index structure constant) through the atmosphere is needed. Various models for how $C_n^2(h)$ varies with height are available, each typically including a strong ground layer and then more moderate turbulence distributed in layers up to a height of 10–20 km. Direct measurements of $C_n^2(h)$ now typically form a crucial part of the site characterisation for any modern telescope.

2.2. Impact of a perturbed wavefront

After passing through the atmosphere, a wavefront that was originally planar will be corrugated. As such, the normal vectors at different points – i.e. the direction in which the photons are propagating – are no longer parallel. The direct result is that they can no longer be brought to focus at a point, and instead form a blur. This is quantified by the point spread function (PSF), which is the image produced by an optical system of an unresolved source. If a plane wavefront propagates through a circular entrance aperture (pupil) and is focussed by perfect optics, the image will be an Airy function which shows clear diffraction rings. Mathematically, the pupil and PSF are related via the optical transfer function (OTF) which describes how well different spatial frequencies are transferred through the optical system. The OTF is the autocorrelation of the pupil, and the PSF is the Fourier transform of the OTF. As Fig. 1 shows, for a circular pupil, the OTF is very nearly a conical function. A strongly perturbed wavefront will yield only a more diffuse PSF, which is often characterised by a Gaussian function (albeit with broader wings). In this case, the OTF is also approximately Gaussian, and shows that high spatial frequencies are not transmitted through the imaging system (i.e. the atmosphere).

2.3. A simple adaptive optics system

To flatten a wavefront that has been corrupted by the atmosphere, an AO system must include a wavefront sensor (WFS) to measure the shape of the wavefront and a deformable mirror (DM) with which to apply the corrections (although for practical purposes the global slope, or tip-tilt, is usually corrected by a separate flat mirror). What happens can be seen in Fig. 2. The perturbed wavefront is reflected from the initially flat DM into the WFS. Here, the shape of the wavefront is measured, and a real-time computer turns these measurements into a set of commands (i.e. voltages) which are sent to the DM. The DM can now correct the shape of the wavefront to be what it was a short time previously (at least to the limits of the WFS sensitivity and mechanical ability of the DM). Thus, what remains is only a small residual wavefront aberration due to changes since the previous measurement was made. It is this residual aberration that is now measured by the