Stars to eyes by adaptive optics

Observational astronomers have for centuries complained of ‘bad seeing’. For, after all their trouble figuring and polishing lenses and mirrors to a fraction of a wavelength of light, the stars mock their efforts by twinkling and dancing to the whim of the turbulent air.

Sir Isaac Newton thought the problem forever insoluble. In *Opticks* (1730, fourth edition) Newton writes, unusually for him in English rather than Latin:

“If the Theory of making Telescopes could at length be fully brought into Practice, yet there would be certain Bounds beyond which Telescopes could not perform. For the Air through which we look upon the Stars, is in a perpetual Tremor; as may be seen by the tremulous Motion of Shadows cast from high Towers, and by the twinkling of the fix’d Stars. But these Stars do not twinkle when viewed through Telescopes which have large apertures. For the Rays of Light which pass through divers parts of the aperture, tremble each of them apart, and by means of their various and sometimes contrary Tremors, fall at one and the same time upon different points in the bottom of the Eye, and their Trembling Motions are too quick and confused to be perceived severally. And all these illuminated Points constitute one broad lucid Point, composed of those many trembling Points confusedly and insensibly mixed with one another by very short and swift Tremors, and thereby cause the Star to appear broader than it is, and without any trembling of the whole. Long Telescopes may cause objects to appear brighter and larger than short ones can do, but they cannot be so formed as to take away that confusion of the Rays which arises from the Tremors of the Atmosphere.” (pages 110–111)

Newton concludes that:

“The only Remedy is a most serene and quiet Air, such as may perhaps be found on the Tops of the highest Mountains above the Gроссer Clouds.”

This has, indeed, proved quite successful; but now there are new remedies that Newton could not have anticipated. He could have conceived of putting a telescope in an orbit around the Earth, way beyond the atmosphere. The Hubble would have delighted, though it would not have fundamentally surprised him. But correcting the dynamic ever-changing tremor of the air with a flexible mirror would have been astonishing beyond belief. Yet this is what is now done—to attain the theoretical limit to resolution with apertures of several metres diameter—with adaptive optics (Roddier 2001).

Earth-based telescopes have obvious advantages over orbiting instruments. It is now possible to take full advantage of their size, accessibility, rigidity, and relatively low cost for many kinds of observations.

Harnessing powerful computing with precision engineering, this is a wonder of our time. The atmosphere is, of course, opaque to much of the optical spectrum, and clouds are a bother now just as they were to Newton. One can’t have everything; but over the last ten years this new intelligence of technology has opened eyes to the Universe as never before. True, it is used for artificial electronic eyes; but the results of this new vision are fed to human eyes and brains. Is the next step computer-astronomers?

How does adaptive optics work? It depends on a reference, which can be a laser beam directed as an artificial star into the sky; a wavefront analyser, based on an array of micro-lenses; a low-noise CCTV; a flexible mirror, with a number of fingers operated
by actuators to modify its shape; a high-speed computer, or sometimes a neural net which learns what to do. What it does, is to compensate the disturbance with a dynamic reverse transfer function. How beautiful.

These new developments are of rather special interest to me as I tried a very different solution to the astronomical 'seeing' problem in the 1960s. This worked rather like a human astronomer opening a shutter whenever the image was clear and its major features in their statistically correct places. But human reaction time makes this an impossible task. Our device built up an image photographically from successive snapshots, using analogue autocorrelation to select moments of minimum disturbance (Gregory 1964, 1974). Might there be a case for combining the two methods, if adaptive optics has its best moments? In any case, a comparison would be interesting.

Sir Isaac Newton complained of the perpetual tremor of the air, giving bad seeing. But there is also perpetual tremor in the eye itself. Does this give bad seeing? Not only does the eye as a whole move, continually and uncontrollably, but the lens within is for ever hunting for best focus, or 'accommodation' as for some unknown reason we call it. The lens searches for focus by hunting around the optimum, because the sign of the error (focused too near or too far) is not available for correction in the right direction. So the eye's lens has to hunt blindly around the optimum; even though our technological intelligence can solve this problem in a camera that even a professor can afford to buy.

Recently, the astronomer's technique of adaptive optics has been turned around, to look into the eye itself. With an artificial star shone onto the retina for reference, it is now possible to correct the eye's inner turbulence—so individual cone cells of the living human retina can be seen (Glanc et al 2002). This improved ophthalmoscope should help surgery and aid assessment of retinopathy, as in diabetes. The technique is being developed for tomography to see deep into the retina.

Apart from its obviously important clinical uses, it gives a direct objective measure of the dynamic disturbance in the eye. It turns out that the ocular disturbance is more than the design limits of correction by the flexible mirror used by Glanc et al (2002). It is surprisingly large; but should we be surprised? Are there not entoptic phenomena that tell us this, by observation from inside? These do need to be interpreted. This is a controversial issue, which I raise again in the light of this new technique of adaptive optics.

Visual jazzing

When Donald MacKay produced his ray figure (MacKay 1957), he thought the 'jazzing' effect of repeated lines was due to the high informational redundancy of this and other examples. Surely, several of us queried his information-theory interpretation at the time, while admiring its ingenuity and conceptual elegance. Could a surfeit of redundancy really do this? Why were high contrast and close line spacing necessary? No doubt I was not alone in thinking of MacKay's ghostly 'chrysanthemum' shapes as moiré patterns, produced by the repeated lines beating with their transient afterimage.

One can see this objectively by sandwiching 'overhead' transparencies of the MacKay rays. To see the transient afterimage operating in this way, a transparency may be placed on a selected time-constant phosphor, such as an oscilloscope screen. It beats with this artificial afterimage; though, of course, one must be careful to distinguish what is going on with the phosphor, from the transient afterimage in one's own eye.

With considerable daring (for Donald MacKay was a formidable character) I wrote to him suggesting this alternative explanation, with the observation that the jazzing disappeared when his ray pattern was viewed stabilised on the retina as a long-lasting afterimage, from an electronic flash. He tried it but disagreed. He saw jazzing in the long-term afterimage and I didn't.
It was essential to use a fixation light, in otherwise complete darkness, at the
centre of the ray pattern, to ensure accommodation and to have the figure in the fovea.
It turned out (he showed me this) that Donald used quite a bright, red fixation light,
which illuminated the figure before the flash. This set up the jazzing, before the flash.
With infinite cunning I had avoided this with a half-silvered mirror at 45° to place
the fixation light optically in the centre, and at the same distance, without illuminating
the figure. Whether Donald accepted the observation with this modification I never dis-
covered. For fear of displaying upstart arrogance, I did not publish it at the time,
around 1958. It also turned out (from much later observations) that the jazzing is much
reduced by viewing the figure through a pinhole, even when the illumination is
increased to compensate the loss of light (Gregory 1993, 1995). This, of course,
increases the eye’s depth of field, and so minimises disturbing effects (including
dynamic astigmatism) of movements of the lens.

This issue remains controversial. Semir Zeki has taken a very different view, favouring
a cortical explanation, direct activation of the visual motion region V5, for the jazzing
of the MacKay rays and other examples, such as Leviant’s beautiful *Enigma* picture
(Zeki 1994, 1995; Zeki et al 1993). This issue is surely quite important. Is the jazzing
of MacKay’s rays and of op art evidence of bad seeing, from disturbance within the
normal eye? If so, can adaptive optics improve normal vision: Can cortical movement
mechanisms really be directly stimulated by these static patterns? If so, what is so
special about these patterns, to make the cortex respond as though there is movement?
Questions are all very well, but surely we can find answers where there are such
dramatic and readily controlled phenomena.

Richard Gregory

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NB. The Internet has news of the new Gemini South telescope on the summit of Cerro
Pachón in the Chilean Andes, at 2737 metres. Together with its identical twin of the
Gemini North telescope in Hawaii, they stride the equator, so they see the entire sky.
With 10 times the light-gathering power of the Hubble space telescope, with their
adaptive optics they will produce images as sharp as those from space. Unlike the
Hubble orbiting telescope, they can be visited by nurturing astronomers at any time.
The web addresses are: [http://physicsweb.org/article/news/6/1/12](http://physicsweb.org/article/news/6/1/12); [http://news.bbc.co.uk/hi/english/sci/tech/newsid_1765000/1765896.stm](http://news.bbc.co.uk/hi/english/sci/tech/newsid_1765000/1765896.stm)