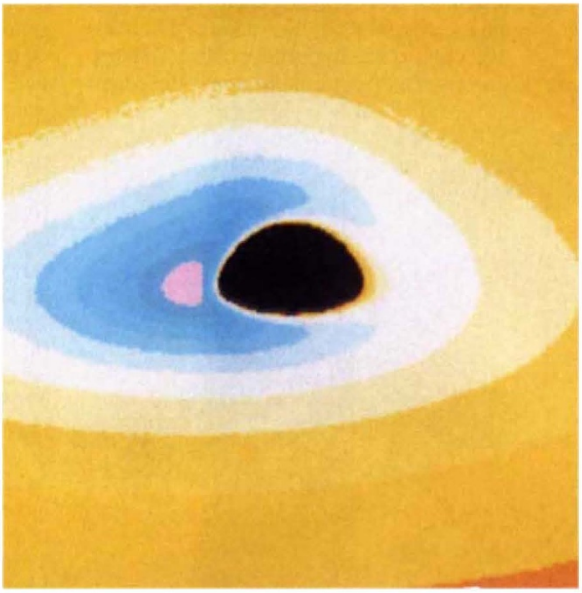
Seeing and believing

Jules P. Halpern

THE most productive year yet for the pursuers of black holes has been crowned by a long-awaited discovery that represents the closest we have come to actually seeing one. On page 659 of this issue[1], Tanaka *et al.* report that a severely distorted emission line, seen in the X-ray spectrum of a Seyfert galaxy, is of exactly the right shape to be coming from the innermost regions of an accretion disk around a supermassive black hole. The bright, 'active' nucleus of a Seyfert galaxy is thought to be powered by the gravitational potential energy of material spiralling slowly inwards through an accretion disk, into a black hole of more than a million solar masses. The shape of an emission line from such a structure — in this case the Kα fluorescent line of iron at an energy of 6.4 keV (wavelength 1.94 ångströms) — provides the most direct evidence for the enormous velocity approaching the speed of light, and other manifestations of the strong gravitational field that controls the appearance of the disk in the immediate neighbourhood of the black hole's 'event horizon'.

If one could view an accreting black hole in visible light, it would look something like the accompanying figure[2]. The rotating accretion disk, rather than appearing as the symmetric annulus around a dark centre that it really is, looks distorted. The gravity of the black hole bends the rays of light passing around it. Also, the side of the disk moving towards the observer looks brighter than the side moving away, a result of the so-called headlight effect for rapidly moving sources of light. With colour vision, we would see the Doppler shift, with the approaching side of the disk blue, and the receding side red.



Simulated picture of an accretion disk around a black hole, from ref. 2, viewed at an angle of 20° above the disk plane. The sense of rotation is left side approaching and right side receding. The observed temperature, shown in false colour, ranges from $<3\times10^6$ K (orange) to $>1.2\times10^7$ K (violet).

We will probably never see this picture directly because, at the great distances of the galaxies, the accretion disk, which is comparable in size to the Solar System, is too small to be resolved. Nevertheless, the iron Kα line seems to be confined to the inner accretion disk where conditions are uniquely suited to its production. Spectroscopic measurements of its profile (intensity versus wavelength) can be even more revealing of the black hole's extreme properties than a visible image, because the spectrum contains information about the velocity of the material in the disk as well as the time dilation (gravitational redshift) that causes the atoms' clocks to run slower in the gravitational field of the black hole. Theoretical predictions of the line profile corresponding to this picture have been discussed optimistically for the past six years or so[3]. Advances in X-ray spectroscopy put into practice by the Japanese–American satellite ASCA, and dedicated long exposure times, made possible the corresponding observational discovery reported by Tanaka *et al.*[1].

Both the inclination angle of the accretion disk to the line of sight, and its radius relative to the radius of the black hole's event horizon, are determined by fitting the spectrum to a simple model. One might try to dream up alternative explanations for the peculiar shape of the line that do not involve a black hole, but I agree with the authors that the detailed properties of this particular spectrum are difficult to rationalize in any other way. Just about the only quantity that has not been measured by this observation is the mass of the black hole, for the simple reason that material falling in has the same velocity no matter what the black hole's mass is. It is probably 10^7 solar masses, and future, more sensitive instruments should be able to measure it because time variability of the line profile can reveal the absolute size of the disk, which is proportional to the mass of the black hole and possibly only a few light-minutes in radius. With the acquisition of higher quality data, it may even be possible to learn whether or not the black hole itself is rotating, not to mention details of accretion disk structure never seen before.

The search for a proof of the existence of supermassive black holes has long followed two complementary paths. The first method is the one described above, which now appears to have reached fruition. The second method is an older one. It involves observation and modelling of galactic rotation and random velocities using the starlight spectrum in the centres of nearby, non-active galaxies such as Andromeda and NGC3115, in order to deduce the presence of dark, gravitating mass that cannot be accounted for by the amount of starlight present. The existence of black holes of 10^7–10^9 solar masses has been inferred in this way[4]. More recently, this stellar dynamics method has been applied in a simplified form to the observations of maser emission with radio interferometers[5] and visible line emission with the Hubble Space Telescope[6], using the apparently circular orbits of these sources to demonstrate the need for supermassive black holes in regions as small as one light year across at the centres of active galaxies.

The two methods are orthogonal in the following sense. The X-ray emission line offers the opportunity to 'see' a black hole through the unique relativistic effects of strong gravity; but because the emission arises from gas, which is susceptible to forces other than gravity, it cannot prove rigorously that a black hole is responsible. The stellar dynamics method, on the other hand, is immune from the effects of non-gravitational forces. However, it demonstrates the existence of a supermassive black hole without seeing it, because it operates in a region far larger than any in which general relativity could produce observable effects that are distinct from ordinary newtonian gravity. Perversely, we can either see a black hole, or prove it exists, but not both! Which method is more satisfying is ultimately a matter of taste. Probably because of this fundamental complementarity, practitioners of either approach hardly ever acknowledge the others. Perhaps they will — starting now. □

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