THE KAVLI PRIZE

ASTROPHYSICS PRIZE 2020 EXPLANATORY NOTES

Black holes as galactic engines

Black holes are among the most enigmatic objects in the universe. Created by imploding massive stars, they are so dense that the gravitational field around them completely warps space-time and prevents even light from escaping their clutches. Anything that passes their event horizon is lost from view forever. And yet we know that black holes exist. That's because the vast amounts of energy given off in their vicinity generate signals that we can intercept, even if those signals take millions of years to reach us.

Andrew Fabian, an astronomer at Cambridge University in the UK, has spent his life studying the signals that arrive in the form of X-rays. In particular, he has scrutinised the X-rays emitted by supermassive black holes at the centre of very bright galaxies, revealing that those black holes play an intimate role in the life of galaxies and clusters of galaxies.

Figure 2: The active galaxy NGC 1275 is a well-known radio source (Perseus A) and a strong emitter of X-rays due to the presence of a black hole in the center of the galaxy. Credit: X-ray: NASA/CXC/IoA/A.Fabian et al.; Radio: NRAO/VLA/G. Taylor; Optical: NASA/ESA/Hubble Heritage (STScI/AURA) & Univ. of Cambridge/IoA/A. Fabian

A supermassive black hole can be up to billions of times more massive than the Sun, its immense gravity sucking in vast amounts of gas from surrounding space. Because most of that gas arrives off-target having travelled a long way, it overshoots the black hole slightly and then gets pulled back – putting it on a spiral trajectory. The result is a thin "accretion disk" surrounding the black hole within which particles collide and give off energy, much of it at X-ray frequencies.

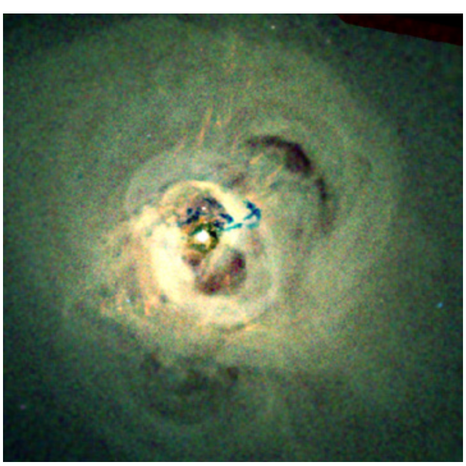
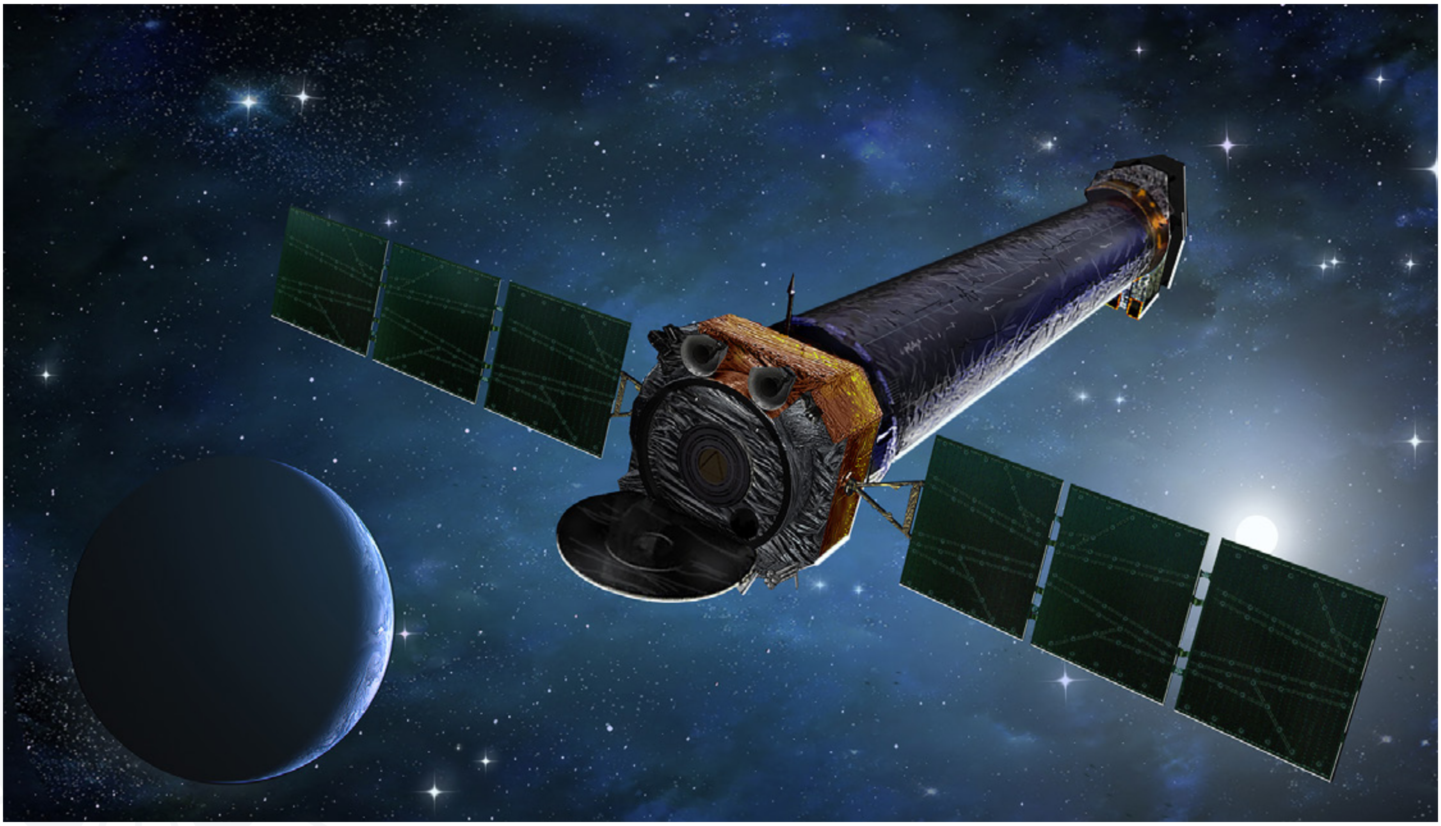


Figure 1: An X-ray image from NASA's Chandra satellite showing heated gas surrounding the centre of the vast Perseus galaxy cluster. Photo: © NASA/CXC/IoA/A.Fabian et al.

These cosmic X-rays can't be seen on Earth because they are blocked by the atmosphere. So scientists instead observe them from space. Having first measured the emission from a black-hole-like source known as Cygnus X-1 in the early 1970s, researchers have since launched a series of ever more sophisticated X-ray satellites.

In 1995, Fabian and colleagues reported having found tell-tale signs of a black-hole powered accretion disk in X-rays gathered by a Japanese-American mission known as the Advanced Satellite for Cosmology and Astrophysics. They discovered that a peak in the energy spectrum due to the emission of X-rays by iron within several very bright galaxies was broader and at slightly lower frequencies than expected. They interpreted this as an effect of Einstein's general theory of relativity, an effect that had been predicted by Fabian and other



Andrew Fabian and colleagues have used NASA's Chandra observatory, seen here in an artist's impression, to make detailed studies of the Perseus galaxy cluster

Credits: NASA/CXC & J.Vaughan

researchers a few years earlier – that time close to a powerful source of gravity slows down when measured from outside.

Building on that research, Fabian found it was possible to measure two distinct sets of X-rays emitted close to a black hole – those generated by the accretion disk directly as well as others produced by very hot electrons close to the black hole that bounce off the disk before travelling out across space. By measuring the short time delays between the two emissions he and his collaborators were able to map the accreting gas and measure the black hole's rate of spin.

But Fabian has also used X-ray data to study the effect of black holes over much greater distances. Indeed, he posed and then found a solution to a problem that has kept astronomers busy for decades – where does intergalactic gas in clusters of galaxies get its energy from? The gas between galaxies in certain bright clusters should be cool enough that it clumps together to form new stars. But astronomers observe no such star formation and measure the gas to be millions of degrees hotter than it ought to be without an extra source of energy.

Fabian and co-workers found clues to help solve the mystery in several X-ray images of the Perseus cluster taken by NASA's Chandra satellite in the first few years of this century. These images showed a range of features within the cluster, including dark patches and ripples of brightness, spaced 30,000 light-years apart, emanating from a central dark region.

Fabian reckoned that these features were created as a result of energy being transferred mechanically from a central black hole to the surrounding gas. The idea was that the dark regions are bubbles formed when jets of material shooting out from the black hole at right angles to the accretion disk push against the gas. The huge pressure generated then propagates outwards as a series of sound waves that heat up the gas.

That work earned Fabian a place in the Guinness Book of Records for having discovered "the deepest note in the universe" – a B-flat, 57 octaves below middle C (a sound, it was pointed out, that no-one would be able to hear). But the research also underlined the central role that black holes play in the lives of galaxies, in this case by generating negative feedback that limits both their own growth and that of surrounding stars. It might also explain why the mass of supermassive black holes is tied to the mass of their host galaxies, as has been observed.

This idea of black-hole feedback is now widely accepted. What's more, Fabian has found that black holes in less massive galaxies than those at the centres of clusters also transfer energy, but do so more directly. In this case, their intense X-rays and ultraviolet radiation simply push dusty gas out of the host galaxy.

A number of details about these processes still remain to be filled in, including the extent to which the spin of a black hole contributes to the heating. But these details aside, says Kavli astrophysics committee chair Viggo Hansteen of the University of Oslo, there is now no doubt that black holes are the central engines heating intergalactic gas. "Every time you solve a problem others emerge," he says. "But the central problem of 'what is heating the gas?' is solved."

By Edwin Cartlidge