Jacob Bekenstein: Quantum gravity pioneer

Jacob Bekenstein (pictured), the father of black hole thermodynamics, passed away in August. His insight, that black holes should have an entropy proportional to their area and a temperature proportional to their surface gravity, is one of the most important discoveries in modern physics. It continues to mystify researchers and shapes our current quest for a quantum theory of gravity.

This celebrated insight came out of a famous conversation between Bekenstein and his PhD advisor, John Wheeler. A hot cup of tea has entropy, as its macroscopic description admits many possible microstates. A black hole, on the other hand, has no entropy according to general relativity, being uniquely described by macroscopic quantities such as mass, angular momentum and electric charge. This, Bekenstein dubbed 'the no-hair theorem'. But Wheeler was puzzled: what happens, he asked, if I throw the cup of tea into the black hole? Initially, the entropy of the system is given by the entropy of the cup of tea, but after the tea has fallen into the black hole, the total entropy is zero because only the black hole is left. The second law of thermodynamics says that the entropy of a closed system can only increase. Has the second law been violated?

Bekenstein's answer was that the black hole must have an entropy proportional to its area, and that the black hole's increase in entropy after absorbing the cup of tea would more than compensate for the decrease in entropy of the Universe due to the disappearance of that cup of tea. Bekenstein based his insight not only on the teacup thought experiment, but also on a then recently proven theorem by Stephen Hawking: the area of a black hole can only increase. Bekenstein realized that the non-decreasing of the black hole's area was reminiscent of the second law of thermodynamics.

What is striking about Bekenstein's intuition is that he understood not only that the black hole must have an entropy which is a function of its area, but that it should be proportional to the area itself. Bekenstein reached these conclusions through a number of considerations, including the application of the second law to two merging black holes (ruling out an entropy that scales as a power of the area that is less than 1). He dismissed higher powers by considering processes changing the black hole area by a minimal amount. He was even able to come remarkably close to getting the constant of proportionality right, conjecturing that it must be close to (1/2) ln 2 in natural units.

The exact value of 1/4 was determined two years later by Hawking, who wanted to prove Bekenstein's ideas about black hole entropy wrong. Instead, Hawking showed that black holes radiated at a temperature that behaved just as Bekenstein predicted. Using Bekenstein's first law of black hole thermodynamics, this fixed the black hole entropy as its area divided by four.

Almost forty years on, this extraordinary result continues to reverberate. Any potential theory of quantum gravity should correctly predict the value of the black hole entropy. Indeed, as quantum gravity is not driven by experiment, black hole thermodynamics remains the only really solid piece of information we have in our attempts to construct it.

Likewise, popular insights into quantum gravity, such as those provided by the anti-de Sitter/conformal field theory (AdS/CFT) correspondence and the holographic principle, are directly inspired by Bekenstein's insight that the entropy of a gravitating system can scale with its area, whereas for ordinary matter, it tends to scale with the volume. Since entropy is a measure of information, this could allow information about a volume of space–time to be encoded in the boundary of that space–time.

Although ascribing entropy to black holes appeared to rescue the second law from Wheeler's famous teacup gedanken experiment, Bekenstein felt he had to go further. What if the cup of tea had so much entropy that when it was thrown into a black hole, the increase in black hole entropy was not enough to compensate for the decrease in entropy due to its disappearance? Bekenstein thus proposed an entropy bound given by a system's energy and radius, arguing that ordinary matter such as teacups cannot have too much entropy. If an object violated his entropy bound, it could be thrown into a black hole and the second law of thermodynamics would be violated.

This prompted a debate between Bekenstein and two other students of Wheeler, Bill Unruh and Bob Wald. The debate elegantly elucidated the intricacies of black hole thermodynamics, with Unruh and Wald arguing that the second law was saved by the buoyancy force produced by black hole radiation, and Bekenstein pushing for his entropy bound. Whereas the outcome of the debate suggested the entropy bound was not necessary, it is widely believed to hold, and the subject continues to inspire.

Bekenstein generally carved out his own path in his research, and was not swayed by scientific trends. When it came to explaining why the trajectories of stars in galaxies deviate from what general relativity predicts, most scientists took the view that this was due to dark matter. Bekenstein instead believed that our theory of gravity required modification, a view he advocated in the early 1980s along with Mordehai Milgrom, well before this idea become more popular. In 2004, he developed the first relativistic modification of Newtonian dynamics to account for the discrepancy. He explored the idea that the fine-structure constant and gravitational coupling constant varied over time, developed a quantum model for black holes, and most recently, developed and promoted experiments to probe the quantum nature of space–time.

Despite his radical physical intuition, and the immense influence of his ideas, he was a modest, quiet man, generous with his time, and more critical of his own work than that of others.