

# In Retrospect: Kepler's *Astronomia Nova*

**Jack J. Lissauer** explains how the great astronomer's insight into planetary orbits is still revealing new views of the Universe four centuries on — from extrasolar Earths to black holes.

## **Astronomia Nova**

by Johannes Kepler

First published 1609.

The 2009 International Year of Astronomy commemorates the 400th anniversary of two great discoveries: Galileo Galilei's detection of Jupiter's four major moons and the publication of Johannes Kepler's monumental book *Astronomia Nova*. In this 1609 work, Kepler demonstrated that planets follow elliptical paths about the Sun, a breakthrough that set up his famous three laws of planetary motion, still fundamental to physics and astronomy today.

*Astronomia Nova* introduced the first two of Kepler's three laws: first, that each planet moves on an elliptical path, with the Sun at one focus; and second, that a line connecting any planet to the Sun sweeps out area at a constant rate — which implies that a planet moves faster when it is nearer the Sun. In 1618, he deduced his third law, which relates the motions of the planets to one another: the ratio of the orbital period squared and the mean distance from the Sun cubed is the same for each planet.

The full title of Kepler's treatise, in translation, notes the significant role that measurements of the orbit of Mars had in the deduction of his laws: *New Astronomy Based upon Causes, or Celestial Physics Treated by Means of Commentaries on the Motions of the Star Mars, from the Observations of Tycho Brahe, Gent.* Observations of the red planet were key because its orbit is more eccentric than any other planet apart from Mercury, which is close to the Sun and difficult to observe. Kepler was also familiar with Mars because he was given accurate data on its motion when he was hired to assist the great astronomer Tycho Brahe in 1600. The inclusion of 'physics' in the title signifies Kepler's mathematically and physically rigorous approach to the problem — one that is familiar to any modern scientist but not to natural philosophers of his era. Kepler's thinking was far ahead of that of most of his contemporaries.

In the same year that *Astronomia Nova* was published, the heliocentric model of the Solar System was only just verified. The concept that Earth and other planets orbit the Sun is credited primarily to Nicolaus Copernicus, who published his theory in 1543, more than 60 years before Kepler's book, although the idea itself dates back at least as far as the Greek

astronomer and mathematician Aristarchus of Samos, who lived in the third century BC. Galileo's discovery of four moons orbiting Jupiter using a telescope confirmed that Earth wasn't the centre of the Universe around which everything in the celestial domain revolves.

Kepler was the first to realize that orbits are better described by ellipses traversed at non-uniform speed than by combinations of 'perfect' circular motions on which orbits had hitherto been modelled. Like a modern data analyst, he incorporated all of the observations with their inherent measurement errors in an attempt to fit a model. His weaving together of observations and mathematical models into a physical theory was a vanguard for future studies.

Kepler's revolutionary model was accurate enough to predict the transits of the inner planets Mercury and Venus across the Sun's disc, which were first observed in 1631 and 1639, respectively. Thus it is fitting that Kepler's name today graces the first space mission dedicated to searching for planets beyond our Solar System using a similar method. Launched on 7 March this year, the Kepler spacecraft's telescope will continuously monitor the light from more than 100,000 stars looking for planetary transits over a period of at least three-and-a-half years. When a planet passes between its star and the telescope, once per orbit, the star dims measurably.

Because large planets orbiting close to their

stars block more light, such planets are easiest to detect using the transit method. Hence, to date, all of the planets discovered in this way from the ground are larger than Uranus and have orbital periods of less than 10 days. But the clear view and unbroken observations available from space mean that the Kepler mission should detect smaller and more distant planets, notably Earth-like bodies with one-year orbital periods around Sun-like stars. Even smaller planets orbiting near their stars will be detectable, as will more distant planets that are larger than Earth.

Since Kepler deduced his laws, there have been many advances in our knowledge of planetary orbits, Isaac Newton's theories of motion and gravity being the most substantial. The trajectories of planets — and the Sun — can be perturbed by the gravitational pulls of other planets and moons. Deviations of the motion of Uranus from that explained by Newton's model led to the discovery of Neptune in 1846. By contrast, irregularities in the motion of Mercury were explained only by a completely new theory of space-time and gravity, Albert Einstein's general theory of relativity, published in 1915.

As astronomy has expanded its horizons, the application of Kepler's laws has led to even stranger discoveries. Invisible dark matter is needed to explain the fast orbits of gas in the outskirts of spiral galaxies — these orbital speeds exceed the predictions of Kepler's third law, which implies that an object with a large orbit should move slowly. And, by contrast, the Keplerian behaviour of the orbits of stars in our Galaxy's centre has revealed the existence of a supermassive black hole at the core of the Milky Way.

Kepler was an early champion of the application of reason to our understanding of the Universe. He wrote in his introduction to *Astronomia Nova*: "I prove philosophically not only that the Earth is round ... not only that it is contemptibly small, but also that it is carried along among the stars." Four hundred years later, it is striking that we are still using his laws to measure planetary systems that lie far from our own.

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Johannes Kepler's 1609 book outlined his first two laws of planetary motion.

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