
19. How many exoplanets?

THE DISCOVERY OF the first exoplanets (i.e. planets beyond our own solar system) was a major landmark in astronomy. The first discoveries, in 1995, were proof that planets indeed existed around other stars, and that they might even be rather common.

The principle of detecting exoplanets by observing their transit across the face of their host star dates back to at least the mid-19th century, when the prolific Irish scientific writer Dionysius Lardner suggested it as one of five explanations for periodic variable stars in his 1851 *Handbook of Natural Philosophy and Astronomy*.

The idea is simple enough: careful observations of a star's brightness should show periodic dips if an orbiting planet transits the star. But it is hugely challenging in practice: for a period of 1 year (as Earth), transits will be rare, and observations over a long time would be needed to establish its periodicity as a result of multiple transits.

The problems are compounded by the need for suitable orbital alignment with the line-of-sight to the Earth, and for the tiny drops in brightness expected in the majority of realistic cases.

IN 1938, David Belorizky from Marseille Observatory argued that *'stellar photometry with 0.01 mag precision will provide the means of discovering the existence of other planetary systems'*.

In 1952 Otto Struve remarked: *'It is not unreasonable that a planet might exist at a distance of 1/50 astronomical unit. Its period around a star of solar mass would then be about 1 day.'* This is somewhat surprising because, at the time, the shortest orbital period of any known planet was just 88 days, for Mercury. Why did Struve speculate about planets with an orbital period of only 1 day? But his remark was prescient, for the first planet discovered, 51 Peg b, had an orbital period of just 4 days.

Even before the detection of the first exoplanet in 1995, and before the first transiting exoplanet was seen in 1999 (HD 209458 b), the method was considered to be one of the most promising means of detecting planets of Jupiter mass, with the detection of Earth-class planets quickly seen as being within its capabilities.

In the past two decades this method of detecting and characterising planets has flourished, through numerous impressive ground-based monitoring programmes, and through dedicated space telescopes, notably CoRoT, Kepler, and TESS. As of February 2021, and of more than 4300 exoplanets now known, the transit method has discovered around 3300, the majority of these being with NASA's Kepler satellite, operated between 2009–18.

As of the same date, 824 planets had been discovered from their host star's 'radial velocity' (or Doppler shift), which oscillates back and forth along the line-of-sight as a planet orbits around it.

A further 106 have been discovered by the difficult technique of 'gravitational microlensing'. And just one very massive planet has been discovered by astrometry.

In 2018, Exoplanet Encyclopedia compiler Jean Schneider, of the Observatoire de Paris (Meudon), was justified in stating that *'Nowadays the most powerful method to detect extrasolar planets is the transit method'*.

ASTROMETRY WAS ALSO recognised as being a possible way of detecting exoplanets. At the same time that Lardner was mentioning the transit technique, Captain W. S. Jacob, at the East India Company's Madras Observatory, had been measuring the astrometric orbit of 70 Oph. In 1855, he reported that anomalies in the orbit made it 'highly probable' that the system contained a planetary body. He was wrong.

The method has continued with a checkered history to this day. Claimed detections, all later proven to be false, included those of Thomas See, in his measurements of binary star orbits at the Lowell 24-inch telescope near Mexico City in the 1890s; and Erik Holmberg, who suspected that Proxima Centauri was orbited by a planet (in 1938), and similarly 70 Oph (in 1943).

In 1943 Kaj Strand, later Scientific Director of the US Naval Observatory, 1963–77, reported his results for 61 Cyg: *'The only solution which will satisfy the observed motions gives the remarkably small mass of...16 times that of Jupiter... Thus planetary motion has been found outside the solar system.'* Strand was also wrong.

Lengthy disputes surrounded extensive ground-based observations of Barnard's star, for which two planetary mass bodies with periods of 12 and 20 years were proposed by Peter van der Kamp in 1963. All of these, and a few others, were later shown to be false.

But these efforts, though unsuccessful, should be given due credit: the measurements were challenging because of the tiny angles to be measured, and were plagued with difficulties as a result. But it nevertheless shows how, already more than a century ago, some understood the issues, and made efforts to find exoplanets.

IN THE EARLIEST DISCUSSIONS of space astrometry that I have found, from 1964, Paul Couteau and Jean Claude Pecker, of the Nice Observatory, considered the search for planetary systems. The Hipparcos space mission was originally proposed by Pierre Lacroute in the late 1960s, adopted by the European Space Agency in 1980, and operated between 1989–1993. Exoplanet science didn't figure in its original scientific objectives, although a search for Jupiter-like companions to nearby stars using the Hipparcos data was later suggested by Wilhelm Gliese, of nearby star compiler fame, in 1982.

Following the announcement of the first three exoplanets discovered by radial velocities (47 UMa, 70 Vir, and 51 Peg) in 1995, I used the pre-publication Hipparcos data to place upper limits on their masses (Perryman et al., 1996). Orbits for a few others were later measured by Hipparcos and the Hubble Space Telescope.

IDEAS FOR Gaia began to take shape around this time. A first design, Roemer, was proposed by Danish astronomer Erik Høg and Swedish astronomer Lennart Lindegren. It was developed in a form to measure all billion stars to 20 mag, with photometry and radial velocities, by Lennart Lindegren and myself. In subsequent years, large teams worked to submit a detailed proposal to ESA's advisory committees, and it was adopted by ESA's Science Programme Committee in 2000.

More than 100 scientists contributed to the enormous scientific case for Gaia, and these specialist contributions were assembled by Tim de Zeeuw of the Leiden Observatory and myself, running to 100 pages of the overall 360-page scientific and technical proposal.

The case for exoplanets occupied five of those pages back in 2000. With a young researcher, Ana Colorado, I made the first estimates of the numbers that Gaia would detect based on a rather simple model: counting the number of stars of suitable spectral type out to 200 pc, taking into account the estimates of planet occurrences known at the time, and using estimates of the accuracies achievable by Gaia as a function of star magnitude.

We concluded that 10 000–50 000 Jupiter-like planets should be detectable, and discussed the implications for the deeper studies of these (and multi-planet) systems.

Incidentally, in my role as ESA's project scientist for Gaia, we argued at the time of selection, in 2000, that it could be developed and launched in 2012. This impressively challenging mission was duly launched in 2013.

MORE CAREFUL ESTIMATES of the numbers of planets detectable by Gaia were made before launch, using improved models of the instrument and its sky scanning, improved estimates of planetary occurrences, and improved models of data analysis and orbit fitting.

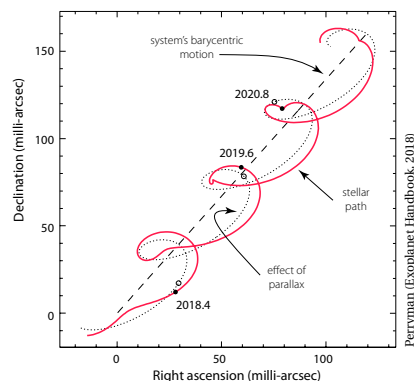
Amongst these, detailed simulations including orbit fitting were made by Casertano et al. (2005) who concluded that some 8000 giant exoplanets (of 1–3 times the mass of Jupiter, orbiting F, G, and K-type stars) should be detectable by Gaia astrometry.

Later estimates extended the host stars to a broader range of spectral types, distances, and magnitudes, using the best estimates of exoplanet frequency distributions, and detailed simulations of the Gaia instrument and its scanning of the sky (Perryman et al. 2014).

We found that some 21 000 Jupiter-mass long-period planets should be discoverable out to distances of 500 pc for the nominal 5-yr mission (including some 1000–1500 around M dwarfs out to 100 pc), rising to some 70 000 for a 10-yr mission. The planets that Gaia should discover in large numbers – Jupiter-like planets, in Jupiter-like orbits – will not be the sort of habitable planets that are so keenly targeted by exoplanet scientists today. But they will clearly signal planetary systems that are, perhaps, very much like our own, with a Jupiter-like sentinel orbiting far out from the star capturing potentially hazardous objects left over from the system's formation.

Amongst these should be 25–50 transiting planets with periods in the range 2–3 years, perfectly placed for detailed studies of their atmospheres through follow-up transit measurements from the ground.

THE MOST POWERFUL method of detecting extrasolar planets today is without doubt the transit method, as emphasised by Jean Schneider. But planet detection through astrometry, recognised as a remarkable opportunity for Gaia already 25 years ago, and more than two decades in preparation and execution, may prove to be the most powerful in just a few years from now!



Simulated star–planet motion on the sky

Perryman (Exoplanet Handbook, 2018)