

21. Measuring exoplanet radii

THE FIRST EXOPLANETS, by which we mean planets beyond our own solar system, were discovered only in 1995. But by the time of the first Gaia data release, DR1, in September 2016, more than 3000 were known.

Many of the first exoplanet discoveries were identified through radial velocity measurements of their host star. This is possible because the velocity of the star oscillates backwards and forwards (along the line-of-sight to the Earth) as the planet orbits around it.

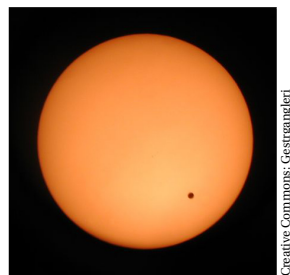
To be clear, all planets, whether those in our solar system or in others, do not orbit the centre of the *star*, but rather the *centre of mass* of the entire planetary system. This means that a star hosting one or more planets orbits this centre of gravity as well, albeit with a relatively small orbital amplitude often lying within the star's own physical boundary. So the existence of a planet orbiting a star shows itself as a tiny change in radial velocity of the star, and with the same period as the orbiting planet. All this is possible even though the planet itself is quite invisible from Earth.

MANY OF THE planets known by 2016 were actually discovered by the 'transit method'. NASA's Kepler satellite, launched in 2009, has been foremost in discovery numbers, although other instruments (such as the HAT and WASP telescopes on the ground, along with the French CoRoT satellite launched in 2006, and the NASA TESS satellite launched in 2018) have all contributed.

Like all transit searches, Kepler could only detect planets whose orbits lie *edge-on* to the sight-line from the Earth, on the alert for periodic dips caused by a planet happening to transit across the stellar disk. If the planet's orbit is inclined to this sight-line by more than a degree or so, it will escape detection by this method.

The Kepler mission transformed the field of exoplanet research, not only because of the very significant numbers of exoplanets discovered (more than 3000), but even more so because of the richness and unexpected nature of the planetary system architectures, and the deep insights into a very broad range of physical phenomena that have been gained from their study.

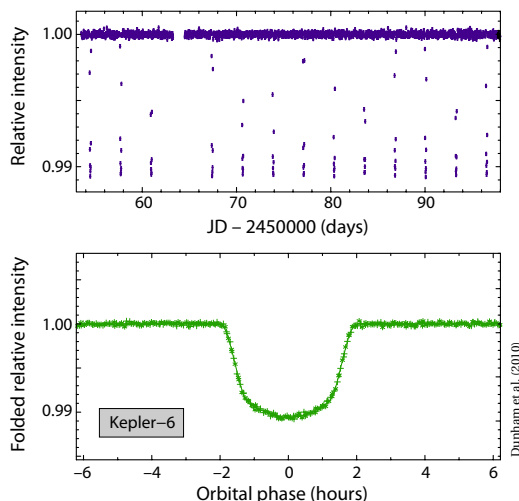
For nearly four years, the Kepler satellite locked on to one region of the sky, and monitored the brightness of some 150 000 stars, with measurements of each star every few seconds. The principles are the same as those used by Earth-based observers to watch the spectacular transit of Venus across the face of our Sun, in June 2004 and June 2012.



Transit of Venus, 8 June 2004

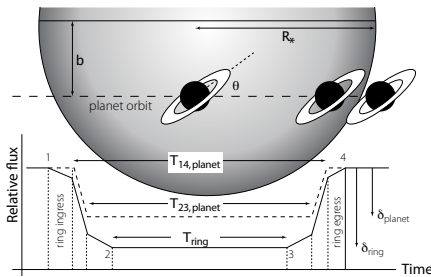
The orbits of Venus and Earth are both slightly elliptical, and both slightly inclined to the mean orbital plane of all the solar system planets, such that Venusian transits occur only every 100 years or so, seen from Earth.

Watch any star for long enough (and with a sensitive instrument), and if it is orbited by planets, and if these planets orbit edge-on to our line-of-sight, regular dips will occur at the period of the planet's orbit. Multiple planetary systems will show a family of such dips (at different periods) if they too orbit close enough to the line of sight. This shows the data for Kepler-6 over 50 days (top). When 'folded' at the planet's period of 3.2347 days, the transit shows up clearly in the light curve (bottom).



EXOPLANET TRANSITS, observed with high accuracy, with suitable timing accuracy, and preferably in multiple spectral bands, can yield astonishing insights into the planetary system. The brightness drop as the planet transits is determined by the ratio of the planet's projected area to that of its host star, so if we can estimate the star's radius (for example, from theoretical models for a given star type) we can deduce the planet's radius. If we can measure the star's radial velocity amplitude, we can infer the planet's mass. And given its mass, and its radius, we can estimate its density.

From light curves in different spectral bands we can probe the planet's atmosphere. If there are multiple planets, we can assess the system's stability, and any interactions between them. Such observations, supported by theoretical work, provide information on planetary tides, on their atmospheric conditions, on their origin, and even on the presence of planetary moons.



ACCURATE PLANETARY radii are of great importance for many reasons. Together with the planet's mass, it provides an estimate of its average density, allowing a broad categorisation of its nature, i.e. whether the planet is a gas giant (like Jupiter or Saturn), an ice giant (like Uranus or Neptune), or a rocky planet (like Earth or Mars). Combined with information about their periods and host star properties, this leads to great insights into both the physics of planetary atmospheres and interiors, and the physics of planet formation and evolution.

But there is a serious problem, which is that the mass and radius of a transiting planet cannot be measured directly. Rather, it depends, through the transit measurements, on the assumed mass and radius of its host star. Although we cannot determine these directly either, it turns out that transit measurements do provide a direct estimate of the *density* of the star!

So, how have estimates of the mass and radius of the host star been obtained up to now? Here, the theory of stellar evolution comes to the rescue. It is known that a star of a given temperature, chemical composition, and density cannot have an arbitrary mass and radius. Rather, these three parameters together fix the luminosity and age of the star, and in turn its radius and mass. While not direct, this approach has typically provided good estimates of the properties of the system.

But we can go further: measurement of the star's flux over a broad spectral range yields the star's total (or bolometric) flux, and in turn the star's angular radius, via its 'effective temperature'. It requires just one more step to realise that an accurate distance to the star allows the star's *angular* radius to be converted to a *linear* radius, and for the star's linear radius to be used in the planetary transit measurements to yield the planet's radius.

The path just described is certainly somewhat tortuous, but can be easily summarised: the accurate distance to a star, measured by Gaia, allows the radius of a transiting exoplanets to be determined directly!

JUST SUCH a piece of work, entitled '*Accurate empirical radii and masses of planets and their host stars with Gaia parallaxes*', was submitted to the *Astronomical Journal* by Stassun et al. (2017).

The authors published the radii of 116 stars that host transiting planets, determined using only direct observables – the bolometric flux at Earth, the effective temperature, and the parallax provided by the Gaia first data release. Although the typical uncertainties on the planet and star radii and masses, of around 10–20%, are generally a little larger than previously published (model-dependent) accuracies, they have the important advantage of being, for the first time, purely empirical.

Although the application to planetary radii is particularly forceful, their method (based on flux, temperature, and parallax measurements) yields the radius of a star whether it is orbited by a planet or not. Indeed, Stassun et al. (2017) also estimated stellar radii for more than 350 000 stars whose Gaia DR1 parallaxes were measured to better than 10%. These, along with even better Gaia distance accuracies in the future, will be of great value across many areas of stellar structure and evolution.

AS FAR AS I could make out, the work by Stassun et al. (2017) was the first refereed publication, outside of the Gaia scientific teams, to make use of the Gaia DR1 parallaxes. The timing merits a comment: the Gaia DR1 data was released on 14 September 2016. And their paper, making use of the published parallaxes, was submitted to the *Astronomical Journal* later that day!

THE CONTRIBUTION of Gaia to the determination of exoplanet radii provides an excellent example of science working together and advancing across different domains. The field of exoplanetary science has exploded over the past 25 years, driven by fundamental questions such as the origin of our own solar system, and the possible existence of life elsewhere in the Universe.

Who would have foreseen, 20 years ago when Gaia was accepted by ESA, that it would find immediate application in this area of exoplanet science? And which exoplanetologists, at the birth of the field in the 1990s, could have imagined that they would be demanding accurate star distances as key ingredients for their models?