Searching for extrasolar planets through precise stellar velocity measurements

Planets of Multiple Suns

Dr. Maciej Konacki searches for extrasolar planets in complex systems containing multiple stars

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Although the possible existence of extrasolar planets, similar to the Earth or different, has intrigued astronomers for centuries, it was only in the early 1980s that the technical capacity to discover them emerged

Planets orbiting another star are hard to find for two basic reasons: firstly, planets shining with reflected light range from a billion (in the visible range) to a million (in infrared) times weaker than their parent star; secondly, the angular distance in the sky between a star and its orbiting planet is very small owing to the large distance between a terrestrial observer and any star other than the Sun. Consequently, we are left with so-called indirect methods - instead of seeking out planets directly, we must keep a close eye on stars themselves to detect possible planets' influence on their behavior.

The three basic types of measurement methods in astronomy focus on the brightness, position, and velocity of a celestial body. Measuring a star's velocity (or more precisely its radial velocity) is the most effective method of planet detection. Of 240 known planets orbiting other stars, over 90% have been discovered by measuring the radial velocity of stars. To be able to discover planets in this way, we have to measure velocity with an order of precision of 10 m/s. For instance, Jupiter's presence in the Solar System makes the Sun move around the centre of mass of the two-body system and change its velocity with an amplitude of 12 m/s and a period of 12 years. Because astronomers determine stellar velocity using spectroscopy (measuring spectral shifts associated with the Doppler effect), such high-precision measurements only became possible in the early 1980s thanks to the development of methods cleverly coping with the instability of spectrographs applied in astronomy. Before that, the precision of measurements was only 1 km/s.

Hot Jupiters

The first extrasolar planet orbiting a Sun-like star (51 Pegasi) was detected as recently as in 1995. The discoverers, Michel Mayor and Didier Queloz, were the first to prove the existence of a planet orbiting a Sun-like star, and moreover this planet appeared unusual. This 51 Pegasi planet now belongs to a numerous group of "hot Jupiters," i.e. gigantic planets circling their stars in very tight orbits. The planet of Pegasi 51 orbits its star within just 4 days (its whole year therefore lasts just 4 days). This discovery has forced us to revise the theories of how Jupiter-like planets form.

Planets in multiple star systems - if we mange to confirm their existence - pose a great challenge to contemporary theories of planet formation

The standard model of the formation of gigantic Jupiter-like planets was called the core accretion model. It assumed that from the protoplanetary disk surrounding a young star, consisting of gas, dust and ice, the solid core of a planet first formed, later acquiring a gaseous envelope by gas accretion from the disk. In this model the core of a Jupiter-like planet must form far from the star, at a distance of several astronomical units, beyond the so-called "snow line" where the protoplanetary disk contains a sufficient amount of ice to make a massive solid core. The planet orbiting 51 Pegasi, however, is only 0.05 AU from its star. How is this possible? Currently this fact is explained in terms of the migration of young planets within the protoplanetary disk. According to this theory, Jupiter-like planets actually come into being far away from the star, then move toward it to become "parked" in tight, short-period orbits.

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For some reason this migration has not taken place in the Solar System – our gigantic planets are situated far away from the Sun. In the Universe, however, planet migration must be a frequent phenomenon since as many as 20% of known planets orbiting other stars are hot Jupiters.

Hot Jupiters have spurred the rapid advancement of methods to seek and characterize planets as a branch of astrophysics. Systematic searching for planets began in the early 1980s. Canadian researchers Bruce Campbell, Gordon Walker, and Stevenson Yang focused their efforts on looking for Jupiter-like planets, i.e. circling stars in long-period orbits. They concentrated on observing a small sample of stars for many years. If only they had opted for the crazy approach of looking for gigantic planets in short-period orbits, the first extrasolar planets would have been discovered 25 years ago. The precision of their measurements would have more than sufficed to find hot Jupiters! Our awareness of our own Solar System generalized to other planetary systems, however, limited our imagination in searching for other planets.

Incidentally, Swiss researchers Mayor and Queloz were likewise not looking for hot Jupiters – they discovered the planet orbiting 51 Pegasi while studying short-term stellar activity, although at the same time they were ambitiously searching for "normal" Jupiters using the same instrument!

Dreams of "another Earth"

We owe most of our current knowledge of extrasolar planets to precise measurements of stellar velocity. Among these planets, we have discovered many with very eccentric orbits (i.e. elliptical rather than circular). The orbits of the planets in the Solar System are essentially similar to circles. There are several explanations for this noncircularity of extrasolar planet orbits. One of them envisages significant gravitational interaction between young planets, leading to increased eccentricity of their orbits. But here again, it appears that for some reason these processes did not play an important role in the formation of the Solar System. We can even risk saying that the planetary systems discovered so far are completely different from our own. It should be stressed, however, that until recently the precision of measurements has only enabled us to discover big, massive planets with relatively short orbital periods,

The candidate for a planet in the HD 188753 trinary star system has been already been given the name Tatooine, derived from the *Star Wars* films. This was the name of Luke Skywalker's home planet, with two rising suns

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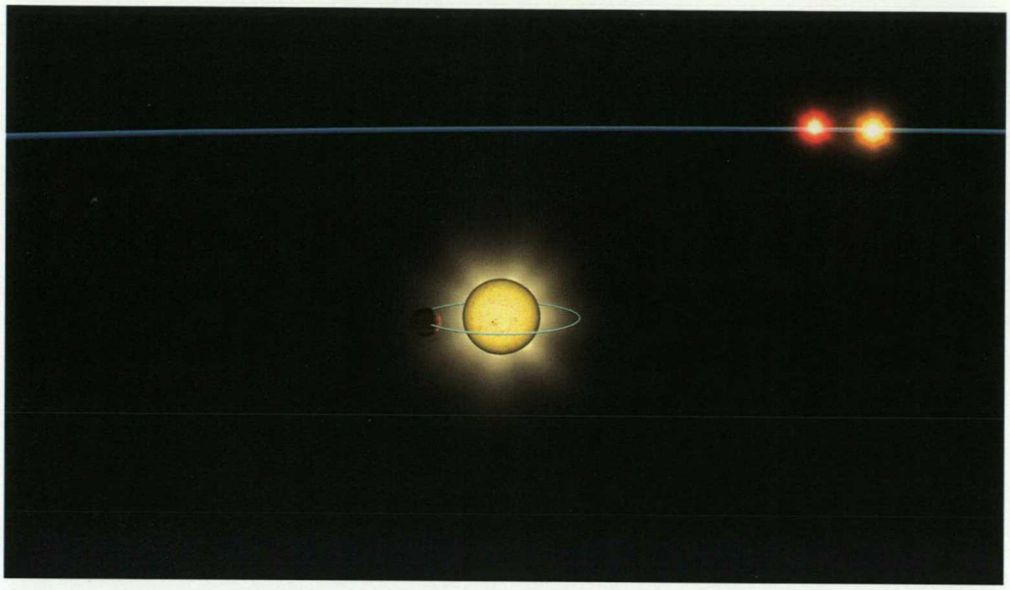

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The only "safe" place in a trinary star system, where the orbit of a planet is not constantly altered by the companion stars, is situated near the major star in the system. However, the most popular theories of planet formation cannot explain how a planet could form in such a position

and the discovery of planets with parameters similar to any in our Solar System has been impossible. Observations techniques must be further refined before we can detect "another Earth." For the time being we have to be content with looking for planets with masses comparable to the Earth's but circling not very massive stars in short-period orbits. These two factors ensure that the amplitude of alterations in stellar velocity caused by the planet reaches the order of 1 m/s, i.e. the current level of measurement precision. If we actually want to find another Earth, we need precision on the order of 10 cm/s, which still remains to be achieved.

Metals and planets

The most interesting outcome of planetary research in recent years has been the discovery of a relation between the probability of planet formation around a star and the star's metallicity. In astronomy, metallicity measures the content of elements heavier than hydrogen and helium in a given star, for which the metallicity of the Sun provides a convenient benchmark. Research has shown that about 5% of Sun-like stars have planets. Yet planets exist in the case of as many as 30% of stars with metallicity 3 times higher than that of the Sun and 0.3% of stars with metallicity 3 times lower. In other terms, the likelihood of planet formation is greater the more content of elements heavier than hydrogen and helium was present in the matter from which the star and planets emerged. Since this conclusion is based largely on investigations into known Jupiter-like planets, it also bears upon to the theory of their formation. It seems to point to the accuracy of the core accretion model, as heavier elements facilitate the formation of the solid core of a Jupiter-like planet. This is significant since there is also a competitive (though highly unorthodox) model, in which Jupiter-like planet formation is caused by gravitational instability of the protoplanetary disk, through the collapse of fragments of the disk (thus more or less in the same way as stars form).

Multiple star systems

At present, discovering yet another planet is not sufficient to make a significant contribution to the astrophysics of extrasolar planet systems. Observation programs are nowadays designed to test or even to undermine different aspects of the theory of planet formation. It is in this spirit that the present author searches for planets in complex binary or multiple star systems.

Most stars in the Sun's galactic surroundings are binary or even multiple stars - i.e. systems of stars bound together gravitationally. When we randomly choose a star in the sky at night, the likelihood of it being a binary or trinary star is 60% and more complex systems are not rare. These configurations are so small and remote that they appear to be single stars when observed with the naked eye, although the fact that they are multiple can be seen clearly through a telescope.

Due to technical problems with measuring the velocity of binary stars using the spectroscopic technique with a precision sufficient to find planets, investigations have so far focused on single stars. This difficulty stems mostly from the fact that the spectrum we obtain is the combination of the spectra of the stars constituting the binary or multiple star system. Indeed, that is why planet-hunters have simply avoided star systems - but despite such an approach it appears that around 40 known planets orbit stars in binary or even trinary star systems! However, in such cases the stellar companions of stars with planets are so remote (in the sky and physically) that they can be treated (and observed) as if they were single.

A planet of three suns?

In 2003, the present author developed a technique to measure stellar velocity in tight multiple star systems and began to search for planets in such systems using the 10-meter Keck I telescope in Hawaii. In 2006 the program was continued using the European (Italian) 3.5-meter TNG telescope in the Canary Islands. The program resulted in the discovery of the first candidate for a trinary-system planet, orbiting the main star of the HD 188753 system.

The search for such planets is important as they may significantly verify the theory of planet formation. It should be noted that the influence of *close* stellar companions in the protoplanetary disk (from which the planet must be formed) around the main star is destructive in nature. In the HD 188753 system, the protoplanetary disk would be gravitationally "trimmed" by the companion stars to a size a bit larger that the Earth's orbit. Thus if the existence of a planet in the HD 188753 system is confirmed by further observations, this planet will pose a great challenge to the existing theories. Other planets discovered within the framework of this program still remain to be confirmed and published. Moreover, in 2-3 years' time, the SALT telescope (which Poland can use for 10% of the observation time) will be equipped with a spectrograph enabling us to search for such planets in the Southern hemisphere as well. The hunt for planets undoubtedly requires patience, but the results often exceed our greatest expectations. ■

Further reading:

Konacki M. (2005). Precision radial velocities of double-lined spectroscopic binaries with an iodine absorption cell. *Astrophysical Journal, 626*, 431.

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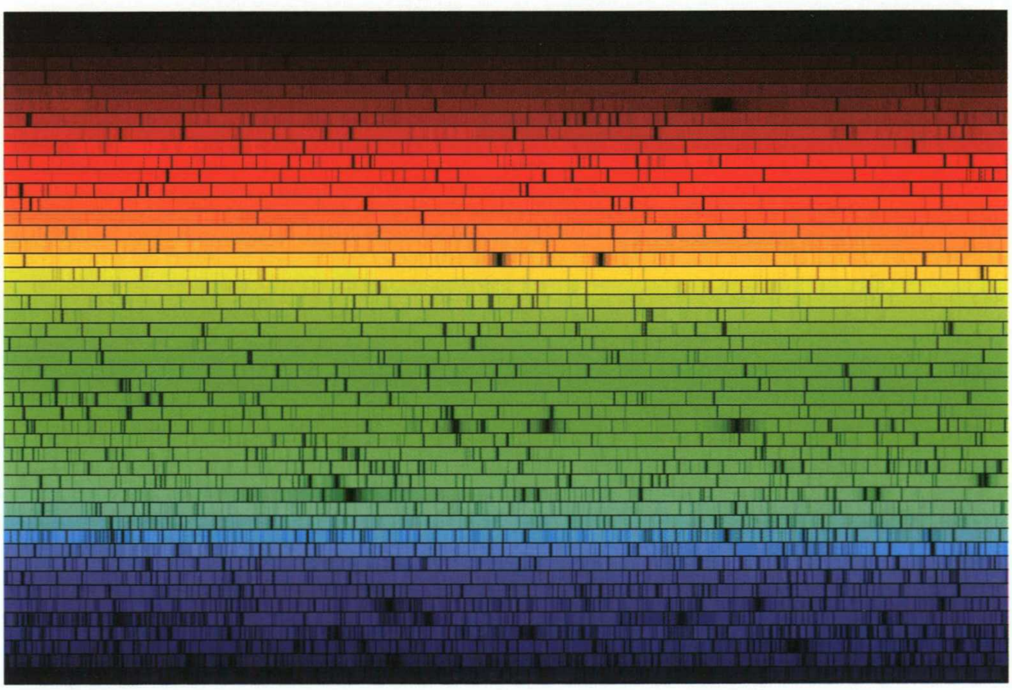

Astronomers determine the velocity of stars using spectroscopy, by measuring the shifts of their spectra associated with the Doppler effect