

Figure 2 | Metabolism and mass.

a, Kleiber's law. Logarithmically, the basal metabolic rate of mammals varies with body mass as a straight line with a slope of 0.74. **b**, When expressed on a linear scale, the 3/4 scaling relationship of Kleiber's law (green line) shows total respiration rate decreasing proportionately as a function of body mass. In contrast, the isometric (slope 1.0) logarithmic scaling relationships described by Reich *et al.*¹ for vascular plants are consistent with a strictly proportional (linear) relationship between whole-plant respiration and mass. The authors also report that the intercept of the log–log scaling relationship depends on plant nitrogen. On the linear scale shown here, this translates to steep proportionality for plants in nutrient-rich greenhouse soils (red line) and less-steep proportionality for plants in nutrient-poor natural soils (blue line). Note that it is difficult to distinguish visually between isometric and 3/4 scaling lines on a linear scale, as this projection draws attention to only a limited part of the dynamic range.

et al. also report that the intercept of the scaling line differed between plants grown in the greenhouse and in the field, showing that respiration per unit mass differed systematically between these two environments.

The next observation is even more intriguing. When Reich *et al.* expressed plant respiration against the whole-plant content of nitrogen (instead of plant mass), the dissimilarity in intercept between environments entirely disappeared, but the overall scaling slope remained isometric. This suggests that the systematic difference in respiration per unit mass was caused by higher supplies of nitrogen in greenhouse compared with field environments. More importantly, across the different environments plant respiration was consistently more closely linked to variations in nitrogen than in mass. This result challenges not only the idea of a universal 3/4 scaling law, but also the notion that size alone is the dominant determinant of differences in metabolism across species. In hindsight, this need to explicitly consider nutrients might not be so surprising given that nitrogen is an essential component of enzymes such as Rubisco (responsible for carbon fixation in plants), and of proteins, chlorophyll and other biomolecules involved in plant photosynthesis and respiration.

Do the results simply imply that it is the business ends of plants — leaves and roots — in which most respiration occurs, and therefore most nitrogen is stored? In such a case, the metabolism versus nitrogen relationship might largely reflect rather pedestrian proportionate variations in crown and root volumes across individuals and species. A key issue is whether Reich and colleagues' findings extend beyond the size of tree saplings, the largest individuals sampled. Nitrogen allocation may

very well change as trees mature within natural forests and become increasingly subject to constraints of self-thinning¹⁵ and competition for nutrients¹⁶. A second question is why nitrogen emerges as such a strong correlate of metabolism, when phosphorus is generally considered the better predictor¹⁷.

Nonetheless, we find ourselves with a theory challenged. There is no question of the value

of ideas such as those of West and colleagues^{2–4}, as they dare to invoke first-principle universal mechanisms. But these new findings question a central tenet of the metabolic scaling theory — that size-dependent distribution networks exert the primary constraint on metabolic rates in vascular plants. Reich and colleagues' results¹ will spark considerable debate among ecologists and physiologists: at stake is the issue of whether there is a truly unified theory of metabolism that encompasses all organisms. ■ Lars O. Hedin is in the Department of Ecology and Evolutionary Biology, Princeton University, Princeton, New Jersey 08540, USA. e-mail: lhedin@princeton.edu

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EXTRASOLAR PLANETS

Light through a gravitational lens

Didier Queloz

A planet with a mass lower than that of Neptune has been detected as its gravity bent the light from a remote star. This lensing technique adds to our arsenal for spotting small planets outside the Solar System.

Ten years ago, Michel Mayor and I discovered the first planet outside the Solar System orbiting a Sun-like star¹. This 'exoplanet' orbits the star 51 Pegasi in 4 days and has about the same mass as Jupiter (more than 300 times that of Earth). Its existence was revealed through highly accurate measurements of a tiny 'Doppler' variation in 51 Pegasi's radial velocity — the speed at which its position changes relative to an observer. This variation is caused by the gravitational pull of an orbiting planet with a mass 1,000 times less than that of 51 Pegasi. The discovery triggered many more Doppler surveys to search for planets around nearby stars. As a result, more than 160 planets with masses ranging from ten times that of Jupiter down to that of Neptune (which

is around 17 times Earth's mass) have been found (Fig. 1).

The range of planet masses and orbital parameters that can be identified by the Doppler technique is limited both by the detection sensitivity of the technique and by the time needed to survey at least one orbital period of each planet. The largest Doppler variation is caused by planets of high mass and those on short orbits. Therefore, low-mass planets can be detected only if they are on short orbits.

On page 437 of this issue, Beaulieu *et al.*² report the use of a different technique, known as gravitational microlensing, to detect a planet with a mass less than that of Neptune. Its orbital distance is about 2 AU (1 AU, or astronomical unit, is the Earth–Sun distance),

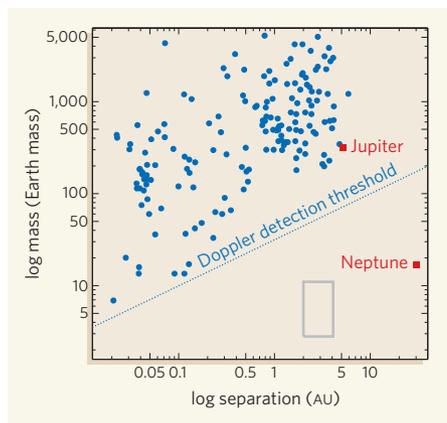


Figure 1 | Limits of the Doppler technique. Blue dots indicate the masses of the extrasolar planets found so far using the Doppler technique, plotted against their separation from their star. High-mass planets on short orbits (and so at a smaller separation) cause the greatest Doppler variation of the star's radial velocity. There is a detection threshold of accurate Doppler surveys of around 3 m s^{-1} radial velocity (blue line) below which no planet can be found using this technique. The grey rectangle indicates the region (including uncertainties) of the planet found by Beaulieu *et al.*² using the gravitational microlensing technique. The new planet is thus well below the Doppler sensitivity threshold.

which would correspond to an orbit between those of Mars and Jupiter in the Solar System. The planet's orbit is thus considerably larger than those found for planets of similarly small mass using the Doppler technique, for which the orbital distances are no more than 0.15 AU.

The evidence for Beaulieu and colleagues' planet lies in a small amplification effect that occurs when light from a remote, background star is deflected, as in the action of a lens, by the gravity of a closer, moving object as this approaches our line of sight to the star (Fig. 2). The brightness of the background star increases continuously and predictably over a period, generally a few weeks, and then decreases as the lensing object moves away again. This effect is generally caused by an intervening star, but sometimes a companion planet to this lensing star can also produce a detectable signal. In looking for such a signal, the rise in brightness corresponding to the approach of the star alerts observers to the need for more intensive observations. The aim is to detect a smaller brightness change that occurs on a timescale of around a day: the signature of an orbiting planet around the lensing star.

This planetary microlensing signal is challenging to detect. If seen and carefully traced,

however, it provides an unambiguous measurement of the mass ratio between the planet and the star, as well as supplying a measure of the separation of the planet from its star that depends on both the distance of the lensing star from Earth and its transverse velocity. The real mass and separation can then be obtained through a statistical approach. This uses a galactic model to estimate the expected distances and velocities of both the lens and the source star on the basis of the values anticipated for stars of their brightness in that sector of the sky.

From the wealth of planets found so far, we know that the frequency with which they are encountered increases with decreasing mass³. But Doppler detection of planets with masses lower than that of Neptune is still a challenge, and is restricted to planets on orbits shorter than a couple of months. The Neptune-mass planets with short-period orbits found by Doppler surveys⁴⁻⁷ suggest a relatively high occurrence of such low-mass planets orbiting normal stars. Beaulieu and colleagues' detection² further strengthens this suggestion: they argue that the probability of detecting a microlensing event from a planet such as theirs is more than ten times smaller than that of detecting an event caused by a giant planet.

Interestingly, the physical structure and formation history of this new planet, because of its orbital distance, is likely to be different from that of the closer low-mass planets discovered by the Doppler surveys. Whereas these short-period, Neptune-mass planets are likely to have migrated inwards and are now enduring the strong irradiation⁸ of their host star, causing some evaporation⁸ of their atmosphere, Beaulieu and colleagues' planet is certainly more akin to the ice giants Uranus and Neptune of our Solar System.

The discovery by Beaulieu *et al.*² demonstrates that microlensing surveys can detect sub-Neptune planets with low separations from their stars. In combination with other planet-finding techniques, microlensing surveys will play their part in eventually gathering a complete picture of planet statistics right down to the regime of rocky planets. A deeper insight into the physical models of planetary formation for low-mass giant and high-mass rocky planets will surely follow. ■

Didier Queloz is at the Observatoire de Genève, 51 chemin des Maillettes, 1290 Sauverny, Switzerland.
e-mail: didier.queloz@obs.unige.ch

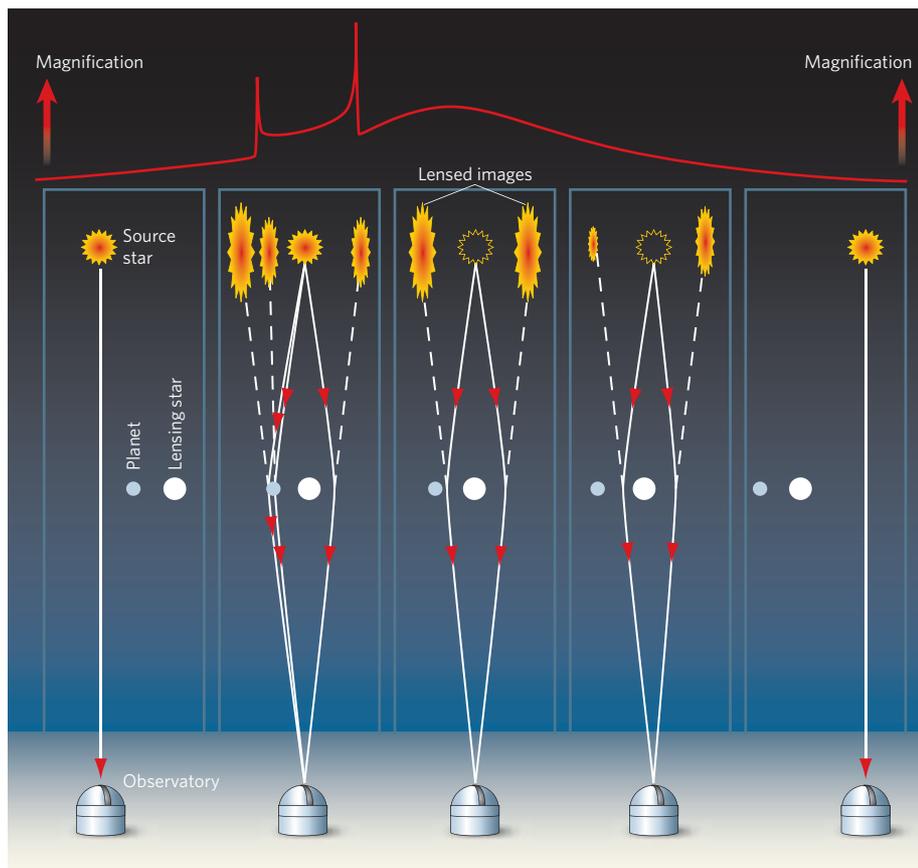


Figure 2 | Lensing planet. The gravitational microlensing effect exploited by Beaulieu *et al.*² results from the bending of space-time near an object of given mass that is predicted by Einstein's general theory of relativity. An object, such as a star, crossing our line of sight to a more distant source star will affect the light from that star just like a lens, producing two close images whose total brightness is enhanced. If the lensing star is accompanied by a planet, one can (potentially) observe not only the principal effect from the star, but also a secondary, smaller effect resulting from perturbation by the planet.

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