to vanish. This suggests that the insurance is thinnest where human pressure is highest.

Weeks and colleagues combined large-scale bird surveys with the use of AVONET[5], a global database of the shape (morphology), ecology and location of all bird species. These characteristics can be visualized collectively when they are plotted in a multidimensional 'functional space', in which species that eat different foods, forage in different ways or move differently are far apart[2]. Each local assemblage is represented as a cloud of points in this space[6]: a broad cloud means the species in an assemblage have many distinct ecological roles, whereas a tight cluster means most species have roughly the same functions. The authors then tested how robust the distribution of points is by simulating realistic extinction scenarios – for example, removing rare species first and recording how quickly a cloud shrinks and key roles disappear. This gives a direct estimate of how resistant each assemblage is to further species loss[7].

Weeks and colleagues' analysis covers 3,696 bird species in 1,281 local assemblages, spanning intact or little-disturbed vegetation, plantations, cropland and cities. Two results stand out.

First, relative to less-disturbed sites, functional diversity and redundancy decline most sharply in farmland and intensive urban areas, where fruit and nut eaters (frugivores) and insect eaters have few surplus species, so seed dispersal and pest control rely on a small subset of birds. Second, these disturbed assemblages can seem functionally complete, in the sense that the main roles are still represented, but they are less resistant to further loss. In simulated extinctions, key roles disappear faster if assemblages are disturbed. Land-use changes can lead to assemblages that seem diverse but are functionally vulnerable.

This focus on the stability of functions, rather than on losses in species numbers alone, is what makes the study particularly useful for conservation. In practice, much of conservation work still focuses on mapping species richness or functional diversity at a single point in time.

Weeks *et al.* treat bird assemblages as dynamic systems that will continue to lose species over time, and ask how close these assemblages are to a tipping point. By analysing specific types of bird such as fruit eaters and invertebrate eaters, rather than averaging across all birds, the authors reveal connections that might otherwise be missed. Weeks and colleagues tested more than one type of extinction scenario (examining trait-based and rarity-based extinction scenarios), and assessed various metrics of ecosystem functioning – the results converge on the same answer, strengthening the findings.

There are limits to the study that matter for interpreting the conclusions. First, the authors compare places that already differ in land use, and use those differences to infer how these places might change over time. This introduces uncertainty, and many 'primary' sites have long disturbance histories, so present-day communities might already be depleted. A true time series would provide stronger evidence[8]. Second, inferring functions from bird characteristics is still an approximation[9]. For example, birds with large beaks are assumed to disperse large seeds, but seed dispersal was not directly measured. Furthermore, sampling and detectability could bias some assemblages towards common, conspicuous species; without taking this into account, some biases probably remain.

Lastly, use of the word redundancy needs care. Species with similar characteristics can often cover the same role, but they are almost never perfectly interchangeable[6,7].

The overall message is blunt. Land-use change is leaving many bird communities just a few species losses away from losing ecosystem services that people rely on, such as natural pest control and forest regeneration. Counting species is not enough. Managers and policymakers should also ask whether there are backup species for each key ecological role. This points to restoration as a practical solution. Semi-natural vegetation, forest fragments and diversified farmland can be used to rebuild redundancy for the functional roles that look the most fragile.

Future work can move in three obvious directions. Linking stability metrics to direct outcomes such as pest suppression is a useful approach. Another option is to extend this type of study beyond birds to examine other organisms[10]. Finally, it is worth investigating which restoration actions rebuild redundancy most efficiently. The goal is clear. It is time to reinforce ecological insurance before the next loss makes the gap obvious.

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Astronomy

Ultra-low-density planets seen around a young star

Valerio Nascimbeni

Measurements of the masses of exoplanets orbiting a young star have identified a system of low-density 'super-puff' planets. **See p.310**

In 1992, the first planet outside our Solar System was discovered[1]. Since then, astronomers have catalogued thousands of such exoplanets, most of which are found in planetary systems that are very different to our own. The early stages of a planetary system's evolution are pivotal in determining its structure, so observing exoplanets around young stars is crucial for understanding trends in the catalogue of mature exoplanets. On page 310, Livingston *et al.*[2] present a detailed dynamical study of a young planetary system – the roughly 20-million-year-old star V1298 Tau and its four known orbiting planets. Using observations of small perturbations in the motions of the planets, the researchers identify them as large, low-density 'super puff' planets.

From our line of sight on Earth, the orbits of the four planets around V1298 Tau are all seen edge-on. This means that they are all transiting planets, which pass in front of their host star and eclipse it at regular intervals. Astronomers have detected that the luminosity of V1298 Tau becomes slightly dimmer around every 8, 12, 24 and 48 days, which corresponds to the orbital periods of its planets, which are called V1298 Tau c, d, b and e, respectively (the letters are arranged in order of discovery).

If a planetary orbit has a transiting configuration, astronomers can measure a property

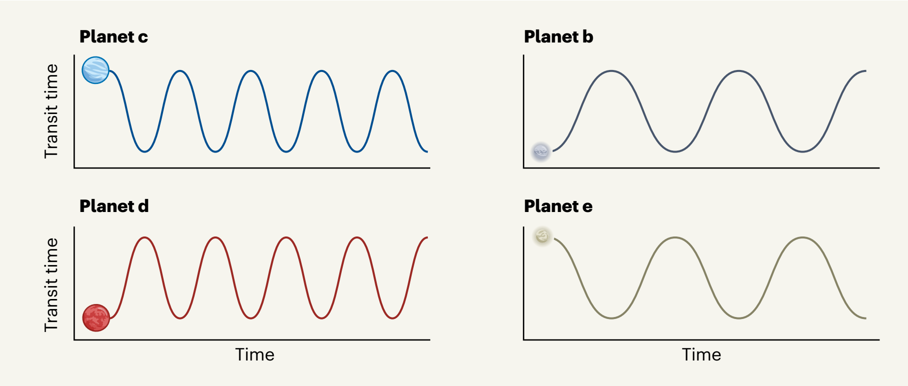

Figure 1 | Orbits of a system of exoplanets are linked in a 'resonance chain'. The star V1298 Tau is orbited by four known planets: c, d, b and e. To measure the mass of these planets, Livingston *et al.*[2] observed them transiting across the face of their host star during their orbits and measured variations in the transit times, which are caused by gravitational interactions between the planets. The ratios between the orbital times of the planets involve small integers, which means that they form a 'resonance chain' in which small gravitational perturbations can grow. The planets exhibit sinusoidal transit time variation, and the transit-time variations of c and d, and those of b and e, are anticorrelated, meaning that when the transit time of one planet in the pair was maximally delayed, the other was maximally early. The masses of the planets, as calculated using their transit-time variations, indicate that they are low-density 'super-puff' planets.

of the planet that is otherwise generally inaccessible: its radius. Combined with the planetary mass, which is measured using other techniques, the radius constrains estimates of the average density of the planet and therefore gives an indication of its inner composition and structure. V1298 Tau is an example of a compact planetary system, a common type in which the planets' orbits are packed close together – all four would fit within the orbit of Mercury, the closest planet to our Sun.

However, compact systems are usually made up of small planets that have radii up to around two or three times that of Earth, whereas V1298 Tau's planets all have radii between five and ten times the radius of Earth. Radii in this range are associated with the gas giants – planets that include Jupiter and Saturn and are made of mostly hydrogen and helium – as well as the less dense super-puff planets in which a small rocky core is surrounded by a vast atmosphere. Super-puff planets are generally less dense than the gas giants, so estimating the masses of V1298 Tau's planets is essential for understanding how this planetary system formed and how it will evolve in the future.

The gravitational pull of its planets can make a star 'wobble' relative to an observer, which shifts the detected frequencies of its light. Spectroscopic observations are commonly used to detect this motion and calculate planetary masses. However, this technique is ineffective for young stars because of changes in the star's magnetic field, which manifest as dark 'starspots' on its surface and make it more difficult to accurately measure the frequency shifts.

Livingston and colleagues used an alternative method to determine the masses of the planets in this system: the transit timing variation (TTV) technique, which searches for slight changes in the transit time of the planets that are caused by the mutual gravitational attraction between them. Because gravitational forces are proportional to mass, careful modelling of this dynamical perturbation can accurately measure planetary masses as well as other important orbital parameters. TTVs are particularly effective in systems such as V1298 Tau, in which the ratios of the orbital periods to each other are small integers (the times it takes for planets c, d, b and e to orbit the star are in the ratio 2:3:6:12). In this configuration, which is known as a resonance chain, the influence the planets have on each other's orbits grows over time, which can amplify the TTVs by orders of magnitude.

The authors observed 43 transits of V1298 Tau by its four planets and combined this with the available transit data of the system. They performed modelling to find the planetary parameters that best fit the data. Their results revealed large, nearly sinusoidal TTVs exhibited by each planet (Fig. 1). The TTVs of planets c and d had roughly the same period but were anticorrelated, meaning that when the transit of one planet in the pair was maximally delayed, the transit of the other was maximally early. The same was true for planets b and e.

The TTVs yielded reliable masses for the four planets for the first time: 5, 6, 13 and 15 Earth masses for Tau c, d, b and e, respectively. Surprisingly, these masses indicate that the planets have remarkably low average densities of between 0.08 and 0.2 times the density of water, making the V1298 Tau planets among the least dense ever discovered. This is consistent with the properties of super-puff planets – the low density can almost certainly be attributed to extended atmospheres of hydrogen and helium.

Detailed modelling using planetary evolutionary models suggested that, under reasonable assumptions, all four planets will contract over the next five billion years (about the current age of our Sun) to join the population of much denser planets that are commonly seen around mature stars. These planets generally fall into one of two categories: those that are up to around twice the size of Earth are 'super-Earths' and those that are larger than super-Earths but smaller than Neptune are 'sub-Neptunes'. The observation of the planets around V1298 Tau indicates that they are all sub-Neptunes, but the authors predict that as they evolve, some will become super-Earths. This modelling is consistent with the existence of a radius gap – the observation that there are few planets that have radii around twice that of Earth[3].

Finally, the authors traced the evolution of the V1298 Tau system back to its earliest stages, when the planets formed from a protoplanetary disk of dust and gas swirling around the young star. Their results suggest a 'boil off' scenario in which a rapid phase of dispersal of the material in the protoplanetary disk prevented the planets from growing bigger. This interpretation would fit the whole set of masses and radii of these four planets, but it predicts internal temperatures for planet b that are in disagreement with some recent spectroscopic measurements[4]. This discrepancy will require further investigation.

More generally, this work, which is limited to a single planetary system, paves the way for a wider population study of young stars that host multiple transiting exoplanets. These systems are now being increasingly represented in astronomical catalogues[5] thanks to all-sky surveys such as that conducted by NASA's Transiting Exoplanet Survey Satellite, as well as improvements in data-analysis techniques. This will provide a more comprehensive picture of how the formation of exoplanets shapes the characteristics of mature planetary systems, highlighting, for instance, how differences in chemical composition or stellar environment can influence planetary evolution.

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