further subdivided into seven biomes, of which 'tropical or subtropical forests' is the first and so designated T1. Assignment to the tropical or subtropical lowland rainforests functional group completes the identification as T1.1 for one possible ecosystem. A tropical dry forest (Fig. 1a), distinguished by tall trees, many of which shed leaves during a relatively rain-free dry season, is in the same realm and biome as a tropical rainforest, but a different functional group (T1.2). A succulent semi-desert (Fig. 1b) would be classified as T5.2 (5 for the 'desert' biome and .2 for the 'succulent semi-desert' functional group). An underground freshwater flooded mine system (Fig. 1c) would be in the subterranean–freshwater (SF) realm. Specifically, it would be in SF2.2, which is the second (.2) functional group of the second biome of this realm — subterranean–freshwater in a human-generated landscape.

Two features of IUCNGET stand out as especially valuable. First, this system is truly comprehensive. Most of the previous classification schemes limited themselves to terrestrial[3] or marine[4] biomes only. Equally crucially, IUCNGET did not ignore human-created biomes — sites associated with farming, mines and so on are all included. This is arguably the first schema with which one could pick any point on the globe where life is found and map it back to one of the 110 functional groups.

Second, although the emphasis on both vegetation structure and processes has always been implicit in the idea of biomes, IUCNGET brings this combination front and centre. IUCNGET has a model (see Fig. 1 of ref. 1) with five categories of processes (resource drivers, ambient environment/climate, disturbance regimes, biotic interactions and human activities) that generate the defining ecosystem properties (for example, vegetation structure, vegetation seasonality, productivity, biomass and diversity).

This way of bringing processes to the forefront is particularly exciting. The link between climate and biomes has long been known[5,6] at a basic level, and an earlier, simpler effort[7] to make this connection has been extolled as providing one of ecology's most key generalities[8]. IUCNGET goes beyond just climate to include the four other categories of processes, and estimates the relative importance of the different processes for each of the 110 functional groups (see Fig. 3 of ref. 1). This required a colossal effort and a good deal of boldness in summarizing a vast amount of scientific literature. The authors almost certainly claim some generalities that will probably ultimately be proved false, but that in itself is useful — IUCNGET contains hundreds of hypotheses for ecologists to get excited about, test and prove or disprove.

The exercise of classifying biomes could easily seem like a highly detailed dive into ecological minutiae. Who but a bureaucrat gets excited about notations such as SF2.2? But we strongly suggest that these efforts, especially as epitomized in IUCNGET, are a major step towards generality in both applied and basic ecological research.

On the applied side, IUCNGET enables a move away from the individual tracking of each of the approximately 9,000,000 species living on Earth and towards identifying common processes that allow us to better predict how a biome will be affected by humans, and how human benefits (termed ecosystem services) derive from different biomes. It should also enable a transfer of knowledge about successful management practices between locations within a biome. The building of biome inventories also furthers the goal of the United Nations Convention on Biological Diversity of conserving ecosystems[9].

On the basic-research side, IUCNGET offers a way to start moving ecology past a crippling lack of generality that has arisen because of the complex reality of the dozens of forces acting on an ecosystem, ranging from predation to soil pH. Instead, IUCNGET moves ecology towards where scientists must end up — making and testing general, but conditional, claims regarding which processes are most crucial in which contexts[10–12].

Brian J. McGill and **Stephanie N. Miller** are in the School of Biology and Ecology and at the Mitchell Center for Sustainability Solutions, University of Maine, Orono, Maine 04473, USA.
e-mails: mail@brianmcgill.org; stephanie.miller1@maine.edu

1. Keith, D. A. *et al. Nature* **610**, 513–518 (2022).
2. *Domesday Book, or, The Great Survey of England of William the Conqueror A.D. MLXXXVI* (Ordnance Survey Office, 1862).
3. McMahon, G. *et al. Environ. Manage.* **28**, 293–316 (2001).
4. Spalding, M. D. *et al. BioScience* **57**, 573–583 (2007).
5. Holdridge, L. R. *Science* **105**, 367–368 (1947).
6. Köppen, W. in *Handbuch der Klimatologie* (eds Köppen, W. & Geiger, G. C.) 1–44 (Gebrüder Borntraeger, 1936).
7. Whittaker, R. H. *Communities and Ecosystems* (Macmillan, 1975).
8. Keddy, P. A. *Trends Ecol. Evol.* **9**, 231–234 (1994).
9. United Nations. *Convention on Biological Diversity* (UN, 1992).
10. MacArthur, R. H. *Geographical Ecology: Patterns in the Distribution of Species* (Princeton Univ. Press, 1972).
11. Schoener, T. W. in *Community Ecology* (eds Diamond, J. D. & Case, T.) 467–479 (Harper & Row, 1986).
12. Winemiller, K. O., Fitzgerald, D. B., Bower, L. M. & Pianka, E. R. *Ecol. Lett.* **18**, 737–751 (2015).

The authors declare no competing interests.

Astronomy

The gas about a famous quintet

Julia Blue Bird

A highly sensitive observation has revealed a large, diffuse gas feature centred on the galaxy group Stephan's Quintet — prompting a revision of our understanding of gas dynamics in the outer regions of galaxy groups. **See p.461**

The first dazzling images captured by the James Webb Space Telescope included a view of the galaxy group Stephan's Quintet[1]. Stars are often observed at the wavelengths accessible to optical and infrared instruments, but the gas in galaxies can be observed with ground-based radio telescopes, such as the Five-hundred-meter Aperture Spherical Telescope (FAST) in China. And it turns out that the gas in Stephan's Quintet has just as compelling a story to tell as do its stars. On page 461, Xu *et al.*[2] report using FAST to discover a gas feature, associated with the quintet, that lends weight to scenarios suggesting that objects outside the group might have influenced its formation history.

Galaxy groups are among the largest gravitationally bound structures to have been detected in the cosmic web of clusters, groups, filaments and voids that makes up the Universe[3]. Stephan's Quintet is located in the constellation Pegasus and seems to be an assembly of five galaxies. In fact, one of the five is much closer to us than are the others; the remaining four form the first compact group of galaxies ever discovered[4], a feat accomplished in 1877 by the French astronomer Édouard Stephan[5].

The group is so compact that the galaxies in it have started to interact. It lies around 92 million parsecs from Earth, a distance that is reasonably close in cosmic terms, at least compared with galaxies at distances of billions of parsecs. This proximity provides scientists with a front-row seat for witnessing interactions between galaxies and processes that are fundamental to galaxy evolution — and FAST is one of the key players in facilitating their observations.

With high sensitivity and substantial sky coverage[6], the 19-beam receiver of the telescope granted Xu *et al.* observations of

Figure 1 | A diffuse gas structure around Stephan's Quintet. Xu *et al.*[2] used the Five-hundred-meter Aperture Spherical Telescope to observe a large, diffuse feature of atomic-hydrogen gas associated with a group of galaxies known as Stephan's Quintet. The gas is thought to be related to a debris field produced by past interactions between members of the group, and could shed light on possible scenarios for the group's evolution. These scenarios implicate an atomic-hydrogen source (NGC 7320a) that could have passed through the group, or a nearby galaxy (Anon 4) that might have collided with one of the group's galaxies. Xu and colleagues' observations provide constraints for simulations aimed at understanding how galaxies interact.

atomic-hydrogen gas spanning a region of 30 square arcminutes, centred on Stephan's Quintet (Fig. 1). It also enabled these observations to be around 100 times 'deeper' than previous similar observations[7,8], where depth is measured by the hydrogen column density, which quantifies the amount of matter between an observer and an object. This increased depth allowed the authors to detect a large diffuse gas structure in the vicinity of the group, measuring around 600 kiloparsecs.

Hydrogen gas is the raw fuel for star formation, because atomic hydrogen on the outskirts of galaxies flows inwards and turns into molecular hydrogen, then, ultimately, into stars. Atomic-hydrogen gas is the least bound component of galaxies and is therefore the easiest to spread around during interactions. The distribution and velocity of the diffuse atomic-hydrogen gas that Xu and colleagues detected suggests that the gas is probably related to the debris field produced by past interactions involving the core members of the group.

A comprehensive understanding of the properties of the quintet essentially depends on how accurately its interaction history is known, but this history is very complex, because it involves so many objects. Previous observations[3,8] of the five galaxies have revealed distorted shapes, sweeping tails of gas and stars, as well as widespread waves of gaseous and stellar debris owing to gravitational interactions during close encounters between the galaxies. But theoretical models[9,10] based on these observations have been unable to agree on how Stephan's Quintet formed, even though it is one of the most well-studied galaxy groups. This might be related to the inability of previous observations to detect features associated with interactions that occurred in the earliest stages of the group's formation, which typically have low surface brightness.

> **"Atomic-hydrogen gas is the least bound component of galaxies."**

Knowledge of the evolution of galaxies has progressed over the past few decades, with increasingly sensitive observations and ever more-sophisticated simulations[11,12]. Cosmological simulations attempt to mimic galaxy formation, modelling a broad array of physical processes over billions of years, and across large swathes of space. Observational data, such as Xu and colleagues' results, help to constrain the physics that serves as an input to these simulations.

The authors also detected radiation at wavelengths associated with atomic hydrogen, coming from a source known as NGC 7320a in the neighbourhood of Stephan's Quintet. This source is implicated in one possible scenario for how the galaxies in the group might have interacted to generate the diffuse gas structure discovered by Xu and co-workers. This scenario suggests that NGC 7320a passed through the centre of the quintet around 1.5 billion years ago, pulling out a tail of gas that developed into the diffuse feature.

An alternative scenario is that the feature is the product of a high-speed head-on collision between another intruding galaxy, called Anon 4, and one of the core galaxies in the group, triggering an expanding wave of gas. Both scenarios are analogous to case studies simulated by other groups[13,14], and will be explored in future simulations using models that will benefit from the details of Xu and colleagues' observations.

The exquisite sensitivity of FAST enabled the detection of this tremendous gas structure. The depth of the observation allowed Xu *et al.* to ascertain that the structure is associated with debris created early in the history of Stephan's Quintet. But the exact mechanism of how the structure arose remains to be determined, and thus further studies of the group's long and complex history will be eagerly awaited, and no doubt informed by the findings reported by the authors. Improved understanding of the formation of Stephan's Quintet – one of the most famous multi-galaxy systems – is a key step towards a comprehensive picture of how galaxies evolve while they are interacting with their neighbours.

Julia Blue Bird is at the National Radio Astronomy Observatory, Socorro, New Mexico 87801, USA.
e-mail: jbluebir@nrao.edu

1. Pontoppidan, K. M. *et al. Astrophys. J.* **936**, L14 (2022).
2. Xu, C. K. *et al. Nature* **610**, 461–466 (2022).
3. Voit, G. M. *Rev. Mod. Phys.* **77**, 207–258 (2005).
4. Moles, M., Marquez, I. & Sulentic, J. W. *Astron. Astrophys.* **334**, 473–481 (1998).
5. Stephan, M. E. *Mon. Not. R. Astron. Soc.* **37**, 334–339 (1877).
6. Jiang, P. *et al. Res. Astron. Astrophys.* **20**, 64 (2020).
7. Borthakur, S. *et al. Astrophys. J.* **812**, 78 (2015).
8. Duc, P.-A., Cuillandre, J.-C. & Renaud, F. *Mon. Not. R. Astron. Soc. Lett.* **475**, L40–L44 (2018).
9. Renaud, F., Appleton, P. N. & Xu, C. K. *Astrophys. J.* **724**, 80–91 (2010).
10. Hwang, J.-S., Struck, C., Renaud, F. & Appleton, P. N. *Mon. Not. R. Astron. Soc.* **419**, 1780–1794 (2020).
11. Conselice, C. J. *Annu. Rev. Astron. Astrophys.* **52**, 291–337 (2014).
12. Naab, T. & Ostriker, J. P. *Annu. Rev. Astron. Astrophys.* **55**, 59–109 (2017).
13. Duc, P.-A. & Bournaud, F. *Astrophys. J.* **673**, 787–797 (2008).
14. Michel-Dansac, L. *et al. Astrophys. J.* **717**, L143–L148 (2010).

The author declares no competing interests.