studying manoeuvrability offers a way of testing evolutionary hypotheses about the limits of manoeuvring capabilities. Such a method can also be used to uncover how the geometric properties and range of motion affect stability (the bird's tendency to return to equilibrium after a disturbance) without the need for extensive flight tests and observations.

The study's key findings provide insight into the effect of wing morphing on the location of the bird's centre of gravity; offer a way to estimate the contribution of various bird components to the rotational characteristics in different directions of movement (termed pitch, yaw and roll); and enable an assessment of birds' ability to shift from stable to unstable flight and vice versa.

Harvey *et al.* show that the centre of gravity remains nearly constant over the whole range of possible elbow and wrist angles. The contribution of wing morphing to the rotational inertia in the pitch is minimal compared with the contributions of the tail, torso and neck. By contrast, morphing the wing, especially the elbow angle, strongly affects the roll and yaw inertia. This could imply that, during flight, birds favour moving their elbow joint to induce a change in roll angle and speed.

By exploring the full range of motion for the elbow and wrist joints, Harvey and colleagues present a large parameter space that allows conclusions to be drawn about how the overall wing shape affects inertial properties. However, crucially, it relates the parameter space to insights about aerodynamic efficiency, stability and manoeuvrability.

Often, just as in the case of aircraft design, there are trade-offs between efficiency and manoeuvrability. The most efficient aeroplane configurations, such as those of gliders, have reduced manoeuvrability, whereas configurations that are more manoeuvrable, such as those of fighter jets, tend to be less efficient. Earlier work[2] indicates that birds might control this trade-off between efficiency and manoeuvrability by changing their elbow angle.

However, it is unclear whether birds have evolved towards having more stable or more manoeuvrable flight capacity. A metric used to assess the pitch stability of an aircraft or a bird is known as the static margin. This is defined as the distance between the centre of gravity and the neutral point, which is the point at which the aerodynamic forces act. A positive static margin, indicating that the neutral point is behind the centre of gravity, suggests a more stable and less manoeuvrable configuration, whereas a negative static margin (with the neutral point in front of the centre of gravity) indicates a configuration that is unstable, but highly manoeuvrable.

Previous work[3] suggests that birds are evolving towards becoming more manoeuvrable and less stable (in the direction of a more-negative static margin). Harvey and colleagues' key finding is that although the centre of gravity remained nearly constant for the full range of the elbow and wrist angles analysed, there was a notable shift in the neutral point. Such a shift caused the static margin to vary. Indeed, 77% of the species analysed can shift from a stable to an unstable configuration and vice versa. This suggests that evolutionary pressures on the range of motion of the wings maintain birds' ability to transition between stable and unstable flight. This is a powerful finding, because it indicates that not only can birds adapt their wing geometry to trade efficiency for manoeuvrability and vice versa, but they can also modulate and vary the level of in-flight manoeuvrability.

Examining the wing shape of birds, and relating this feature to flight-related characteristics, provides insight into the physics and evolutionary pressures governing avian flight. It might also enable key principles to be distilled for developing superior bioinspired, unmanned aerial vehicles. Such vehicles might adapt their wing shape across missions to maximize efficiency, stability or manoeuvrability under various operational conditions.

Aimy Wissa is in the Department of
Mechanical and Aerospace Engineering,
Princeton University, Princeton,
New Jersey 08540, USA.
e-mail: awissa@princeton.edu

1. Harvey, C., Baliga, V. B., Wong, J. C. M., Altshuler, D. L. & Inman, D. J. *Nature* **603**, 648–653 (2022).
2. Harvey, C., Baliga, V. B., Lavoie, P. & Altshuler, D. L. *J. R. Soc. Interf.* **16**, 20180641 (2019).
3. Smith, J. M. *Evolution* **6**, 127–129 (1952).

The author declares no competing interests.

Astronomy

A stellar clock reveals the history of the Milky Way

Timothy C. Beers

A brief stage in stellar evolution offers a precise means of dating stars in the Milky Way. The ages, compositions and motions of these stars all pinpoint the dynamical processes involved in the Galaxy's formation. **See p.599**

The broad-brush picture of how and when the stars in our Galaxy came together has been a topic of active research since the early 1950s[1]. Much can be learnt about this process by looking at the chemical composition of stars, which is, in turn, determined by the 'birth date' of a star – the precise time at which it formed from the chemical elements in its vicinity. But such precision requires a remarkable timepiece, and it turns out that the subgiant phase of a star's evolution offers the most precise stellar clock available. On page 599, Xiang and Rix[2] use this method to report the ages of almost a quarter of a million subgiant stars in the inner halo and disk of the Milky Way – revealing the sequence of events that took place to form our Galaxy.

> **"When low-mass stars have no core hydrogen left to burn, they are forced to seek alternative means of avoiding collapse."**

The first clues about the Milky Way's formation emerged from studies of the composition of stellar atmospheres, which revealed heavy elements with a wide range of abundances that differed from that of the Sun[3]. These abundances are often parameterized by a quantity known as metallicity, which is the logarithm of a ratio that compares the number density of iron in a given star, divided by that of hydrogen, to the same relative densities for the Sun. The most prominent structure in the solar neighbourhood, the disk of the Milky Way, was shown to be populated mainly by stars with metallicities close to that of the Sun, whereas roughly one in 1,000 local stars exhibited substantially lower metallicities, down to less than one per cent of the solar level[4]. These stars were recognized as being part of the halo of the Galaxy.

A more detailed picture of the structure of the Milky Way began to emerge in the 1980s, with the recognition that the disk comprises at least two populations: a thin disk, which includes the Sun, and a thick disk, which is more extended vertically[5,6]. Both populations seem to be in rapid rotation around the

Galactic Centre, but they differ in their average metallicities. Stars in the thin disk have metallicities close to that of the Sun, whereas those in the thick disk have values that are around four times lower[7]. Later, detailed studies of thick-disk stars showed that a small fraction of them have metallicities that are lower still – at least 150 times lower than that of the Sun[8,9]. The halo itself was shown to comprise at least two populations, the inner halo and outer halo, which have different kinematic and chemical properties[10,11]. One thing was clear: complexity reigns throughout the Milky Way.

The advent of the European Space Agency's Gaia satellite mission brought exquisitely precise data for more than a billion stars throughout the Galaxy, greatly refining analyses of the disk and halo populations[12]. These data provide astrometric measurements, including the distance to each star, as well as the stars' angular motion on the sky. When combined with data from large-scale spectroscopic surveys such as the Sloan Digital Sky Survey[13] and the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST)[14] survey, the Gaia data allow astronomers to identify and characterize the origin of the different structural elements in the disk and halo with confidence.

On the strength of these data, close associations have been made between halo stars and those located in the remnants of smaller galaxies, such as the Sagittarius dwarf galaxy[15]. The interactions between some of these satellite galaxies and the disk populations, as well as details of stellar migration within them, could account for the galaxies' observed complexity.

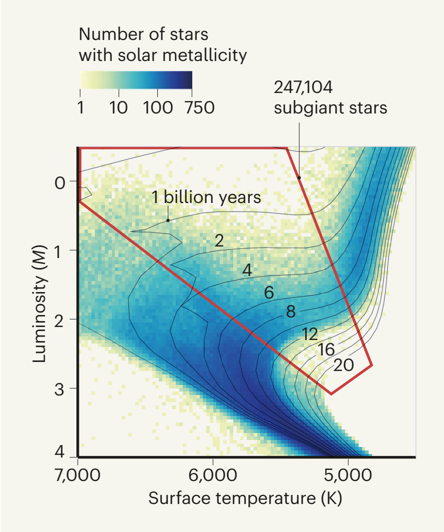

Figure 1 | Dating subgiant stars in the Milky Way. Xiang and Rix[2] determined the ages of stars in the subgiant phase of evolution – which occurs when a star runs out of core hydrogen – as a means of understanding how the Milky Way formed. By plotting luminosity (measured in *M*, absolute magnitude) against surface temperature, using data obtained by the European Space Agency's Gaia satellite mission and the Large Sky Area Multi-Object Fibre Spectroscopic Telescope survey, the authors first derived estimates of metallicity (a logarithmic ratio of iron to hydrogen number density), measured relative to the Sun. Precision ages for 247,104 subgiant stars could then be obtained by comparison with theoretical isochrones (lines that represent stars of similar ages and metallicities) at that metal abundance corresponding to ages of between 1 billion and 20 billion years. . (Adapted from Fig. 1 of ref. 2.)

But even with this deluge of information, a crucial missing piece remained. Astronomers needed a tool with which to determine the ages of large numbers of individual stars in the halo and disk systems, so as to produce a chronology of the multiple events leading to the Milky Way as it is observed today. Because a star forms from the gas in its immediate environment, it records a snapshot of the elemental abundance of that gas at the place and time of its birth. And the abundances of elements at the surface of low-mass stars do not change over their long lifetimes. So, by determining the age – or, more accurately, the birth date – of each star, the history of the assembly of the Galaxy can be reconstructed.

For many decades, astronomers have developed estimates of stellar ages using various approaches, with increasing confidence and precision. All such methods rely on our understanding of the process of stellar evolution – how a star changes its structure over its lifetime as the hydrogen fuel in its core gradually becomes depleted through the process of nuclear fusion. When low-mass stars such as the Sun have no core hydrogen left to burn, they are forced to seek alternative means of avoiding collapse.

One such way involves releasing gravitational potential energy through contraction of the stellar core, a process that marks the beginning of a stage known as the subgiant phase. This phase is very brief – typically lasting millions of years – and it ends when the star enters the giant phase of its evolution, when ignition of hydrogen in a shell surrounding the core drives a rapid expansion of its outer layers. The subgiant phase enables the most precise estimate of a star's age, because its luminosity is directly correlated with its age. But because the subgiant phase is so short, these stars are difficult to find.

Xiang and Rix took advantage of the plethora of data captured by Gaia and LAMOST to identify stars residing in this very brief phase. A diagram of stars' luminosity plotted against their surface temperature can be directly compared with theoretical isochrones (lines that represent stars of similar ages at a given metallicity), and these isochrones can be used to date stars – particularly when the isochrones are well spaced, as is the case in Xiang and Rix's data (Fig. 1). Once the metallicity of a star is known, the position of its isochrone indicates its age. This enabled the authors to pinpoint the birth dates of 247,104 subgiant stars, and to obtain a more precise clock than had previously been available for most stars.

By combining this approach with measurements of the abundance of chemical elements on the stars' surfaces, and their motions in the Galaxy, Xiang and Rix were able to distinguish between the multiple stellar populations and the environments in which individual stars formed. They found evidence that the thick disk began to form around 13 billion years ago, just 800 million years after the Big Bang. Their data also imply that assembly of the inner Galactic halo ended two billion years later.

With an innovative approach to estimating the birth dates of stars, Xiang and Rix have succeeded in helping us to better understand how our Galaxy formed. And the approach is scalable, which means that, as data for larger samples of stars in the Milky Way become available, this picture will come into even sharper focus.

Timothy C. Beers is in the Department
of Physics, University of Notre Dame,
Notre Dame, Indiana 46556, USA.
e-mail: tbeers@nd.edu

1. Roman, N. G. *Astrophys. J.* **112**, 554–558 (1950).
2. Xiang, M. & Rix, H.-W. *Nature* **603**, 599–603 (2022).
3. Chamberlain, J. W. & Aller, L. H. *Astrophys. J.* **114**, 52–72 (1951).
4. Beers, T. C. & Christlieb, N. *Annu. Rev. Astron. Astrophys.* **43**, 531–580 (2005).
5. Yoshii, Y. *Publ. Astron. Soc. Jpn* **34**, 365–379 (1982).
6. Gilmore, G. & Reid, N. *Mon. Not. R. Astron. Soc.* **202**, 1025–1047 (1983).
7. Gilmore, G. & Wyse, R. F. G. *Astron. J.* **90**, 2015–2026 (1985).
8. Morrison, H. L., Flynn, C. & Freeman, K. C. *Astron. J.* **100**, 1191–1222 (1990).
9. Chiba, M. & Beers, T. C. *Astron. J.* **119**, 2843–2865 (2000).
10. Carollo, D. *et al. Nature* **450**, 1020–1025 (2007).
11. Carollo, D. *et al. Astrophys. J.* **712**, 692–727 (2010).
12. Helmi, A. *Annu. Rev. Astron. Astrophys.* **58**, 205–256 (2020).
13. Yanny, B. *et al. Astron. J.* **137**, 4377–4399 (2009).
14. Zhao, G., Zhao, Y.-H., Chu, Y.-Q., Jing, Y.-P. & Deng, L.-C. *Res. Astron. Astrophys.* **12**, 723–734 (2012).
15. Ibata, R. A., Gilmore, G. & Irwin, M. J. *Nature* **370**, 194–196 (1994).

The author declares no competing interests.