PERSPECTIVE

Galactic Paleontology

Eline Tolstoy

Individual low-mass stars have very long lives, comparable to the age of the universe, and can thus be used to probe ancient star formation. At present, such stars can be identified and studied only in the Milky Way and in the very closest of our neighboring galaxies, which are predominantly small dwarf galaxies. These nearby ancient stars are a fossil record that can provide detailed information about the physical processes that dominated the epoch of galaxy formation and subsequent evolution.

One of the major successes in astronomy over the past century must be our very detailed and fundamental understanding of stars, and specifically the way they live out their lives, burning hydrogen into helium and producing heavier elements such as carbon, nitrogen, and oxygen. We also understand how stars end their lives—either as supernova explosions, producing much heavier and more exotic elements in the process (such as iron, calcium, magnesium, and titanium), or slowly fading away as white dwarfs that contribute almost nothing to the universe beyond a few photons.

The work of Ejnar Hertzsprung and Henry Norris Russell, at the beginning of the last century, showed that the colors and luminosities of individual stars form distinct sequences for different groups of stars. The physical reasons could not be understood until the work of Hans Bethe in the 1930s, which explained nuclear burning processes inside stars. He showed that these color and luminosity trends were evolutionary sequences, which depend on the age and mass of a star. This physical understanding means that we can use these sequences to determine the ages of individual stars by measuring their luminosities. From these sequences we know that low-mass stars, like our Sun, have lifetimes comparable to the age of the universe. If such stars formed in the early universe, then they will still be around today, in more or less the same state as they were then, representing living fossils of past star formation. This provides a powerful tool to measure when and how many stars were formed at different ages of the universe, back to the earliest times (1, 2) (Fig. 1). Thus, for all galaxies that are near enough to be resolved into individual stars (e.g., the Sculptor dwarf spheroidal galaxy, Fig. 2) down to the faint magnitudes of the lowest-mass stars [about 10 parsec distance (3), or the boundaries of our Local Group (4)], we can determine detailed star formation histories star by star, going back to the first low-mass stars (5, 6). It is only by resolving individual stars that we can pick out the few faint fossil remnants of the most ancient stellar population, and use their properties to understand the link between the formation of the first stars and the first galaxies.

During the 1950s, the work of M. Burbidge, G. Burbidge, W. Fowler, and F. Hoyle provided a further critical advance in our understanding of nucleosynthesis. They explained how (and which) chemical elements can be produced in a variety of different conditions, including the interiors of stars and supernovae, throughout the universe. This means that it is only as part of the life cycle of stars that all chemical elements in the universe heavier than helium (and some lithium) are formed. Over time, with each successive generation of stars and their supernova deaths, the gas in galaxies, from which new stars form, becomes more enriched in heavy elements.

The outer region of stars, the photosphere, contains the remnants of the gas from which the star originally formed. Because the properties of the photosphere are largely unaffected by the internal processes of nuclear burning going on in the core of the star, the gas trapped there can be considered a fossil record of the gas properties of the galaxy at the time the star formed and can be used to trace its chemical evolution.

In the 1920s, thanks to recent advances in quantum mechanics, Cecilia Payne was able to determine how to interpret the absorption lines seen in the spectra of stars in terms of the abundances of different chemical elements in the photosphere. She realized that the multitude of iron absorption lines in the spectrum of our Sun (and all other stars) does not imply high iron content, but merely the fact that iron has numerous possible quantum mechanical transitions (which produce spectral lines). Proper treatment of the probability of line formation shows that these lines do not correspond to a high fraction of iron. In fact, she found that all stars contain mainly hydrogen and helium, with only a tiny fraction (less than 2%) of all the other elements. The abundance of the chemical elements found in a star's photosphere is referred to as the star's metallicity (astronomers call all elements heavier than helium "metals"). Low-metallicity stars formed from gas that had not been very much enriched by previous generations of stars, and thus they are presumed to be older than higher-metallicity stars.

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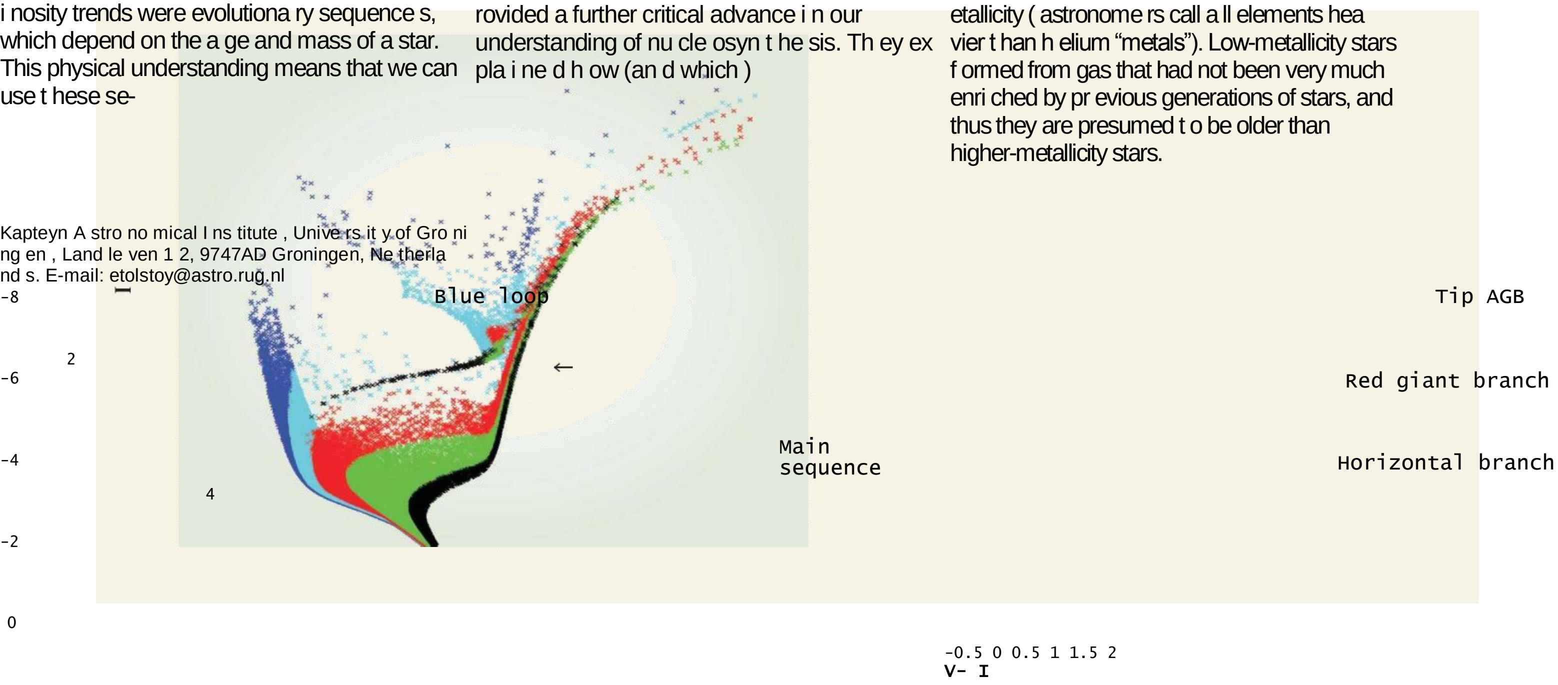
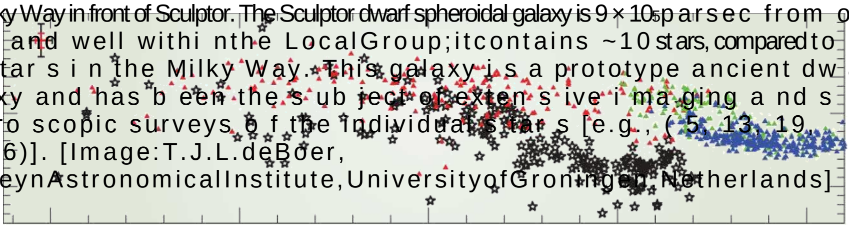


Fig. 1. The theoretical color-magnitude diagram (or Hertzsprung-Russell diagram) made from stellar evolution models, in the filters V (visual) and I (red), for a galaxy that has formed stars constantly for the last 13 billion years. Each data point represents an individual star. The stars are color-coded according to their age: blue, stars <300 million years old; cyan, 300 million to 1.1 billion years old; red, 1.1 billion to 3 billion years old; green, 3 billion to 8 billion years old; black, >8 billion years old. Also labeled are a few key stellar evolution phases that clearly mark the presence of stellar populations of different ages. The Red Giant Branch contains stars >1 billion years old, which makes it a poor age discriminator, whereas on the Main Sequence (the longest phase in a stellar lifetime when hydrogen is fusing to form helium in the core) the different ages of stellar populations are nicely spread out. The Horizontal Branch (an almost horizontal sequence of stars at I ~ 0), only contains stars > 10 billion years old and is thus an unequivocal indicator of the presence of an ancient stellar population. The upper Main Sequence and Blue Loop stars are uniquely identified with very young stellar populations (<1 billion years old), and the extended Asymptotic Giant Branch (AGB) above the tip of the Red Giant Branch is a mix of intermediate-age stellar populations. This color-magnitude diagram was made using the IACstar synthetic computation code (2).

4Fig. 2. A true color image (35 arc min by 35 arc min) of the Sculptor dwarf spheroidal galaxy taken with the NOAO CTIO Blanco 4-m telescope and MOSAIC camera. All the small blue and red dots are individual stars. Some of the brighter stars (with a red fuzzy halo) are foreground stars in the halo of the Milky Way in front of Sculptor. The Sculptor dwarf spheroidal galaxy is 9×10^5 parsec from our Sun and well within the Local Group; it contains ~10 stars, compared to ~10^{11} stars in the Milky Way. This galaxy is a prototype ancient dwarf galaxy and has been the subject of extensive imaging and spectroscopic surveys of the individual stars [e.g., (5, 13, 19, 23–26)]. [Image: T.J.L. de Boer, Kapteyn Astronomical Institute, University of Groningen, Netherlands]



5Fig. 3. Abundance measurements of iron ([Fe/H]), with increasing metallicity going from left to right, and alpha-elements ([a/Fe], an average of calcium, magnesium, and titanium) for individual stars in the Milky Way (triangles) and a diverse sample of dwarf galaxies within 2.5 × 10 parsec of the Milky Way (star symbols). About half of the dwarf galaxy measurements come from the Sculptor dwarf spheroidal galaxy shown in Fig. 2. The Milky Way symbols are color-coded according to whether their kinematics suggests membership in the halo (red), the thick disk (green), or the thin disk (blue) [(5, 8, 9, 12–14, 24, 27, 28) and references therein].

The average error bars on the measurements are given in the top left hand corner, in red for the Milky Way stars, and in black for the dwarf galaxy stars. The errors for the Milky Way stars are on average smaller than those for the dwarf galaxy measurements.

Our detailed understanding of stellar properties means that today we can use photometric and spectroscopic studies of individual stars in our Milky Way and other nearby galaxies to trace the history of star formation throughout the universe, back to the first low-mass stars that may have formed even before the first galaxies (7–9). Extensive surveys (10) have found small samples of extremely metalpoor stars, which are presumably the oldest and formed at very early times. The lowest-metallicity star ever found anywhere in the universe is an otherwise unremarkable star in the halo of the Milky Way, with an iron abundance $\sim 3 \times 10^{-9}$ that of the Sun (11). So far no zero-metallicity star has been found. This implies that the very first stars must have been more massive, and thus much shorter lived, than our Sun. Extremely metal-poor stars have also been found in nearby dwarf galaxies (12–17), although their properties are generally distinct from those of the metal-poor stars found in the Milky Way (Fig. 3).

One of the fundamental tenets of the currently favored theory of galaxy formation and evolution, called hierarchical structure formation, is that a series of mergers combined smaller structures (dwarf galaxies) to form the large galaxies we see today, such as the Milky Way (18). The chemical properties of the individual stars found in different galaxies can show whether they have had a common history within the Local Group. By comparing the abundance properties of the individual stars in the Milky Way to those in the surrounding swarm of dwarf galaxies, we can see whether such small galaxies could have combined to form the Milky Way, and can gain some information about the time scale over which this could have occurred.

Relative to the Milky Way, dwarf galaxies appear to show more scatter in abundance ratios, as well as a much slower enrichment of alpha elements (Fig. 3). It remains an open question exactly how well the distribution of extremely low-metallicity stars in dwarf galaxies compares to that in the Milky Way, as at present the samples of these stars (represented on the left side of Fig. 3) are still rather small (13, 14, 19). The abundance patterns of the individual stars that make up the different components of the Milky Way (halo, thin/thick disk, bulge) (Fig. 3) show evidence of coherent large-scale star formation that allows all the components of the Milky Way to efficiently enrich with metals, often very rapidly. This suggests that large galaxies can retain the enriching products of supernovae explosions and can rapidly build up metals in the disk, bulge, and halo. In contrast, the small dwarf galaxies we observe today in the Local Group have had a wide range of star formation histories and do not contain very metal-rich stars, such as those typical of the Milky Way disk or bulge (5). This strongly suggests that in low-mass dwarf galaxies, star formation is never a continuous process; it is instead liable to progress in fits and starts, probably because the galaxies are so small that the energetic effects of star formation tend to disrupt the gas (from which stars form) so severely that only a very low level of star formation can allow the galaxy to remain bound (20, 21). This difficulty for small galaxies to retain gas, and the products of star formation, results in a slow buildup in metallicity (22). This very irregular and inefficient mode of star formation also leaves its mark in the stellar abundance pattern of a range of chemical elements (5, 7)(Fig. 3).

A comparison between the abundance patterns of stars in the Milky Way and dwarf galaxies indicates that large and small systems evolve differently. This means that the bulk of the Milky Way stellar mass cannot have come from the merging of other galaxies, but that most stars must have formed from gas within the Milky Way. This restricts merging as a dominant process to redshifts, $z > 5$, which corresponds to a time when the universe had been forming stars for 1 billion years or less. It is not yet

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possible to know whether our Milky Way and its environment are typical, and therefore how general this conclusion is. The next logical step is to extend the comparison to individual stars in M31 and its surroundings, but this must wait for a highr esolution spectrograph on the next generation of extremely large telescopes. We also need to obtain larger samples of stellar abundances in our Milky Way and surrounding dwarf galaxies. The future of these kinds of study is promising, as large surveys on ever larger telescopes can train their mirrors on ever more distant resolved stellar systems.

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3. The parsec is a commonly used measure of distance in astronomy corresponding to the distance from the Sun to an object that has a parallax of 1 arc sec. This is equivalent to ~3.26 light years or 3.1×10^{13} km.
4. The group of galaxies that includes the Milky Way and where all galaxies are bound together by gravity. It comprises around 50 small- to medium-sized dwarf galaxies, two large spiral galaxies (the Milky Way and M31), and two smaller spirals (the Large Magellanic Cloud and M33). It has a very irregular shape, but it is 2×10^{6} parsec at its broadest extent.
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Acknowledgments: This was written while I was a visitor at l' Observatoire de la Cote d' Azur, and I am grateful for the support of the visitor program there. Supported by a VICI grant from the Netherlands Organization for Scientific Research. I thank F. Fraternali, V. Hill, and E. Starkenburg for comments and discussion.

10.1126/science.1207392

REVIEW

The Cosmic History of Star Formation

James S. Dunlop

Major advances in observational astronomy over the past 20 years have revolutionized our view of cosmic history, transforming our understanding of how the hot, smooth, early universe evolved into the complex and beautiful universe of stars and galaxies in which we now live. I describe how astronomers have used a range of complementary techniques to map out the rise and fall of star formation over 95% of cosmic time, back to the current observational frontier only ~500 million years after the Big Bang.

The cosmic history of star formation is our own history, or at least our prehistory. It is only through the lives and deaths of successive generations of stars that the atomic composition of the universe has been enriched (albeit only slightly) to contain atoms such as carbon, oxygen, and nitrogen, atoms that are essential for organic-based life. The past history of star-formation activity even affects today's financial markets, with the seemingly ever-rising price of rare commodities such as gold being due, in large part, to the rarity and brevity of the violent supernova explosions in which all gold was originally forged.

The formation of one particular star, our Sun, has of course been especially important to us, as it provides all the energy to power life on Earth. Fortunat

We thus live in a fairly stable and peaceful corner of the universe, and indeed our entire Milky Way Galaxy of ~100 billion stars appears to be evolving gently and steadily, forming stars at the relatively modest rate of ~3 solar masses per year. However, there are many pieces of evidence to suggest that the universe was once a much more violent place, with stars being formed at a much higher rate than is seen around us today. At the same time, we also know that, at very early times, in the so called "dark ages," there can have been no stars at all until the inferno following the Big Bang cooled to a temperature that allowed the first clouds of primordial gas to collapse. Charting the cosmic history of star-formation activity, from the first stars to the present day, has thus long been a fundamental goal of astronomy.

How to Measure Star-Formation History

Astronomers are fortunate in having four independent lines of evidence through which to map out the past history of star formation in galaxies.

otherwise we probably wouldn't be here), this energy source is remarkably stable and long-lived. The geological evidence from within the solar system indicates that the Sun has been burning for ~5 billion years, and astronomers now understand enough about stellar evolution to be confident that the Sun will burn for a similar amount of time again, before expanding into a red giant en route to eventual death as a white dwarf stellar remnant.

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Fig. 1 As shown by the Hubble Space Telescope image of the elliptical galaxy ESO 325-G004 (left), massive galaxies in the n
lmingly dominated by old red/yellow stars formed more th
show little evidence of recent star-formation activity. By con
nerally continue to form stars in the present day, as show
clusters, red clumps of ionized hydrogen gas, and dark reg
shown in the Hubble Space Telescope image of the spira

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