Boötes-I, Segue 1, the Orphan Stream and CEMP-no Stars: Extreme Systems Quantifying Feedback and Chemical Evolution in the Oldest and Smallest Galaxies

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Galactic satellite galaxies provide a unique opportunity to map the history of early star formation and chemical evolution, the baryonic feedback on gas and dark matter, and the structure of low-mass dark matter halos, in surviving examples of the first galaxies. We are using VLT–FLAMES spectroscopy to map the kinematics and chemical abundances of stars in several ultra-faint dwarf spheroidal galaxies and the enigmatic Orphan Stream in the Halo. Two paths of early chemical enrichment at very low iron abundance are observed directly: one rapid and carbon-rich (CEMP-no), one slow and carbon-normal. We deduce long-lived, low-rate star formation in Boötes-I, implying insignificant dynamical feedback on the structure of its dark matter halo, and find remarkably similar kinematics in the apparently discrete systems Segue 1 and the Orphan Stream.

With the discoveries from the Sloan Digital Sky Survey, the galaxy luminosity function has been extended down to luminosities three orders of magnitude below previous limits in recent years. Remarkably, these extremely low luminosity objects, the dwarf spheroidal (dSph) galaxies with total luminosities as low as 1000 $L_\odot$, comparable to a moderate star cluster, are quite unlike star clusters — they are real galaxies. Fortunately, with their very few red giants but more populous main-sequence turn-off stars, they are within range of detailed study, with considerable efforts currently underway at the Very Large Telescope (VLT) and Keck.

These lowest-luminosity galaxies provide a unique opportunity to quantify the formation and chemical enrichment of the first bound structures in the Universe. At present, there are no convincing models for the origin and evolution of these extreme objects — observations lead the way. The ultra-faint dSphs certainly have extreme properties. They are clustered in groups on the sky, their velocity dispersions are tiny — no more than 3–4 km/s at the lowest luminosities — yet the objects themselves are very extended, with half-light radii of hundreds of parsecs, implying extreme dark matter dominance. Their chemical abundances are also extreme, with dispersions of several dex, and containing stars down to [Fe/H] = –4. There are hints that they are associated with, or possibly entangled in, kinematic streams and superimposed on — or in — the tidal tails of the more luminous Sagittarius dSph (Sgr) galaxy.

The lowest luminosity dSphs do not look like the tidal debris of larger systems, they look like the most primordial galaxies of all. Arguably even more interesting than their relevance as galaxy building blocks is to understand the objects themselves. Are they the first objects? Did they contribute significantly to reionisation? What do they tell us of the first stars? What was the stellar initial mass function (IMF) at near-zero metallicity? How are the faintest dSphs related to more luminous dSphs and the Milky Way galaxy?

In order to address these questions, we are obtaining VLT FLAMES observations using both the spectrographs GIRAFFE and UVES, with exposures of up to more than 15 hours, of member stars of the most enigmatic of the ultra-faint systems. These targets include: the lowest luminosity system Segue 1 (Belokurov, 2007a; see Simon et al. [2011] for a detailed Keck study) and the Orphan stream (Belokurov et al., 2007b), both of which are at similar distances to the bifurcated tidal tail of Sgr (Ibata, Gilmore & Irwin, 1994); the common-distance and similar-velocity pair Leo-IV and Leo-V (Belokurov et al., 2008); and the inner regions of Boötes-I (Belokurov et al., 2006b), a surviving example of one of the first bound objects to form in the Universe, providing a touchstone to test the chemical evolution of the earliest low-mass stars.

Our FLAMES GIRAFFE and UVES spectra are beginning to quantify the kinematics and abundance distribution functions in these systems, including several element ratios, providing the first quantitative study of what we find to be survivors of truly primordial systems that apparently formed and evolved before the time of reionisation. Our target fields are summarised in Figure 1.

Segue 1 and the Orphan Stream

Segue 1 is the lowest luminosity galaxy known. It has a wide abundance range, including hosting a very carbon-enhanced metal-poor star with no enhancement of heavy neutron-capture elements over Solar ratios (called a CEMP-no star: c.f., Norris et al. [2010a] for our VLT study and Beers & Christlieb [2005] for the definitions of metal-poor star subclasses). Such stars, which are like those in the Milky Way Halo field, are suspected to be successors of the very first supernovae — see below. The velocity distribution measured in Segue 1, which is consistent with the Keck study of Simon et al. (2011), shows a very narrow distribution, consistent with a dispersion of less than 4 km/s. In spite of this low dispersion, Segue 1 is completely dark-matter dominated, with a mass-to-light ratio in excess of 1000. The velocity distribution function, in which Segue 1 has its radial velocity near V = 200 km/s, also indicates the presence of stars from the Sagittarius tidal stream (at V = 0 km/s), which is at a very similar distance, and stars in a cold kinematic structure with radial velocity V = 300 km/s. This cold highest-velocity

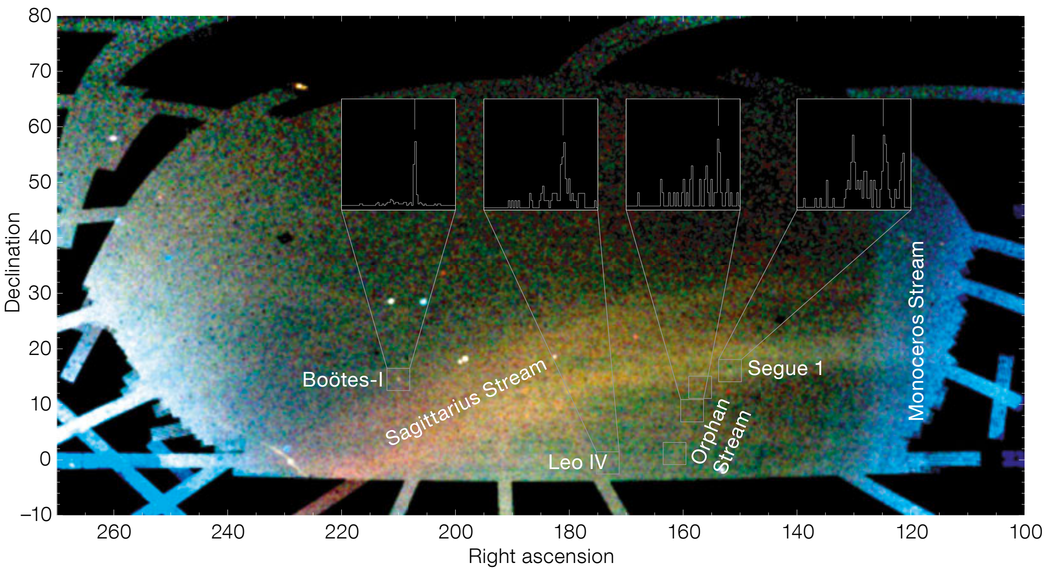

Figure 1. The background shows the "Field of Streams" (Belokurov et al., 2006a), the distribution of turn-off stars observed by the Sloan Digital Sky Survey, statistically colour-coded by distance with the bluer colour showing more nearby, the redder more distant streams. The fields observed for this project by the VLT are marked in grey, with representative velocity distributions indicated. The velocity distribution for Boötes-I is marked by its extreme narrowness. The low surface brightness Orphan Stream is very evident in velocity space, again with very low velocity dispersion. Segue 1 shows three distinct velocity peaks, corresponding to the Sgr Stream, Segue 1 itself, and the "300 km/s" stream, evident only in velocity space.

stream is not yet well defined, and remains under study.

The Orphan Stream provides another example of a Halo stream, although in this case it has a sufficiently high surface brightness to allow it to be traced over more than 60 degrees of arc. The perigalacticon of the Orphan Stream orbit passes close to Segue 1, and hence to the Sagittarius tidal tail. As Figure 1 illustrates, the internal velocity dispersion in the Orphan Stream is unresolved at the resolution of the observations, being less that 3–4 km/s. The Orphan Stream and Segue 1 kinematics and distance, the latter determined from main-sequence turn-off fitting, provide an interesting illustration of the complexity of the outer Galactic Halo. Both Segue 1 and the Orphan Stream have similarly low internal velocity dispersions. Remarkably, at the Orphan Stream's closest approach to Segue 1, both have the same Galactocentric distance (within uncertainties), which is also the same as the local Sagittarius tail, being separated by only a few kiloparsecs (kpc) at most. Even more bizarrely, at the point of closest approach, the orbit of the Orphan Stream has exactly the same Galactocentric radial velocity as does Segue 1. Is this coincidence, or evidence of a common history?

The analysis of Simon et al. (2011) suggests that Segue 1 is contained inside its tidal radius, and is a robust, albeit small and faint, galaxy, which just happens to be passing through a busy part of the outer Galaxy. The metal-poor ([Fe/H] = –3.5) CEMP-no star Segue 1-7, which we have studied with the VLT, lies almost four half-light radii from the centre of Segue 1, while all the other well-studied members are inside 2.3 half-light radii (70 pc). Does this hint at tidal truncation of an earlier, much larger (and more luminous?) predecessor? Segue 1 is very deep inside the Galactic tidal field, well inside the (disrupting) Sgr dSph, and the Large Magellanic Cloud–Small Magellanic Cloud pair, with their gaseous tidal stream. All the dSph galaxies that are not deep in the Galactic tidal field have much larger half-light radii (Gilmore et al., 2007). We also have the remarkable similarity (indeed, near identity) of the distances and radial velocities of Segue 1 and the Orphan Stream as further clues. In spite of searching, we have not (as yet) found any trace of any extra-tidal Segue 1/Orphan Stream member stars, or a physical link between the systems: there are no identified stars with appropriate velocities in the spatial region between the Orphan Stream peri-galacticon and Segue 1. Are they just ships passing in the dark night? The hunt for enlightenment continues.

Boötes-I

Boötes-I provides an example of a complementary case: an apparently normal, extended dSph galaxy (half-light radius 240 pc), at 60 kpc Galactocentric distance, whose special features are its low surface brightness and low total luminosity ($M_V = -6$). Boötes-I has low mean metallicity (with a range from [Fe/H] = –3.7 to –1.9) and hosts a CEMP-no star that we have studied with the VLT ([Fe/H] = –3.3; Norris et al., 2010b). Our GIRAFFE spectra have been analysed for a kinematic study (see Koposov et al., 2011). Using careful data reduction techniques, Koposov et al. (2011) showed that GIRAFFE spectra obtained in single one-hour observing blocks over several years can be combined to deliver radial velocities with an accuracy floor approaching 0.1 km/s. From this study we demonstrated that Boötes-I has a smaller velocity dispersion than suggested by previous studies. We showed the kinematics to be best described by a two-component system, a majority with dispersion 2.5 km/s, and a minority with dispersion as high as 9 km/s, or by a single dispersion of 4.6 km/s. Our preferred interpretation is that the apparent multi-component kinematic structure may reflect orbital anisotropy inside Boötes-I. Our observations to date are limited to the central regions, so further study at larger radii is required to clarify the situation.

There are key issues in early galaxy evolution which can be resolved by the analysis of chemical element distributions. These include the early stellar high-mass IMF, star formation rates at very

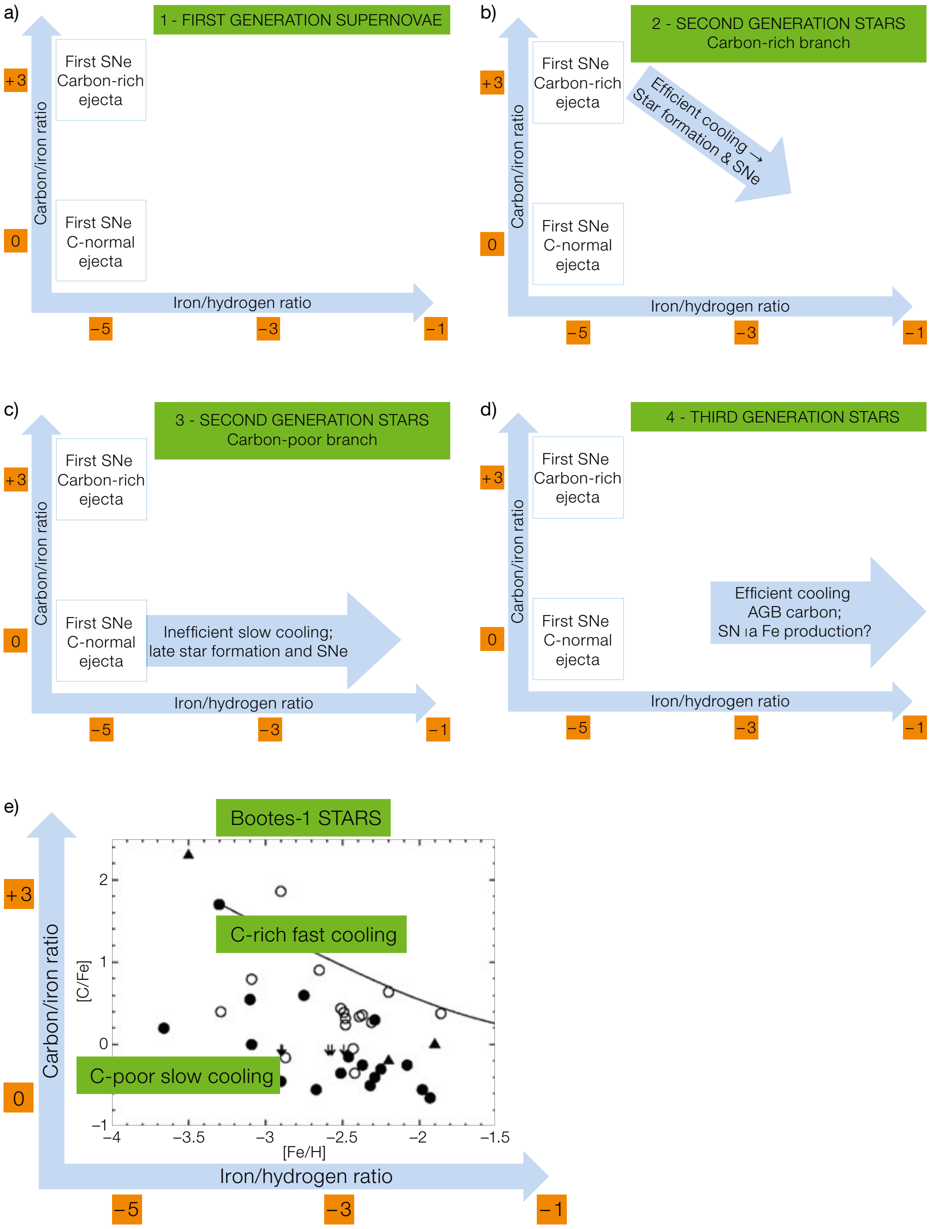

Figure 2. A schematic diagram of the two star formation and evolutionary paths evident at the lowest abundances. The very first stars, apparently of high mass, generate two patterns of chemical enrichment — carbon-enhanced and carbon-normal (Figure 2a). This difference may correspond to different progenitors, or may simply be spatial inhomogeneity from a single SN. The carbon-enhanced material very rapidly cools, apparently forming stars with a wide range of masses, including SN progenitors, which generate standard Galactic Population II abundances (Figure 2b). This process continues until the carbon abundance in the ISM is diluted to the Solar value, when [Fe/H] ~ –3. The lower carbon abundance ISM does not take part in this enrichment process, but on a slower timescale stars are formed, again with a wide range of masses and an apparently standard IMF (Figure 2c). This enrichment path also eventually reaches [Fe/H] = –3. The whole ISM is now sufficiently enriched for efficient cooling, so that chemical evidence of the evolutionary path is now lost (Figure 2d). Should either path correspond to sufficiently slow star formation, SNe Type Ia will generate low [α/Fe] at this stage. The correspondence of this model with data from stars in Boötes-I (circles) and Segue 1 (triangles) is shown in Figure 2e.

early times, and their consequences, and feedback on baryonic gas and the dark matter potential well. Our UVES observations of Boötes-I address these points directly (Gilmore et al., 2013).

α-elements and the IMF

The α-elements, together with a small amount of iron, are created and ejected by core-collapse supernovae, on timescales of less than 10^8 years after the formation of the supernova progenitors.

Enhanced ratios of α-element/Fe above the Solar values are expected in stars formed from gas that is predominantly enriched by these endpoints of massive stars. Thus chemical abundances in the stars formed within the first 0.5 Gyr after star formation began will reflect the products of predominantly core-collapse supernovae.

Although we see hints of a declining α-element abundance, suggestive of a resolution of the duration of the chemical evolution of Boötes-I, this is not formally significant in our present sample. The observed lack of scatter in these element ratios at a given [Fe/H] requires that: (i) the stars formed from gas that was enriched by ejecta sampling the mass range of the progenitors of core-collapse supernovae (SNe); (ii) the supernova progenitor stars formed with an IMF similar to that of the Solar neighbourhood today; and (iii) the ejecta from all SNe were efficiently well-mixed. Both the first and last points set an upper limit on how rapidly star formation could have proceeded, since: the star formation regions need to populate the entire massive-star IMF, the stars need sufficient time to all explode, and the gas needs time to mix the ejected enriched material. All these steps must occur before substantial numbers of low-mass stars form.

The observed lack of scatter in the α-element abundance ratios requires that the well-sampled IMF of core-collapse supernova progenitors is invariant over the range of time concerned and/or the iron abundance. This can be expressed as a constraint, from the scatter, on the variation in slope of the massive star IMF, assuming that the ratios reflect IMF-averaged yields. A scatter of 0.02 dex constrains the variation in IMF slope to be 0.2. The overall agreement between the values of the elemental abundances in Boötes-I stars and in the field of the Halo implies the same value of the massive star IMF that enriched the stars in each of the two samples, although our formal limit on this IMF slope is only agreement within a slope range of 1.

The Galactic Halo and Boötes-I (and Segue 1) display a large range in carbon abundance at low metallicity. For iron abundances greater than about [Fe/H] = –3.2, excess carbon enhancements above the solar [C/Fe] ratio are consistent with carbon production in asymptotic giant branch (AGB) companions (called CEMP-r/s stars, which have apparent contributions of both rapid (r) and slow (s) nucleosynthetic processes; Beers & Christlieb, 2005). At lower values of [Fe/H], excess carbon is commonly seen, but is inconsistent with AGB production: rather the CEMP-no stars are more likely to have formed from gas enriched by non-standard supernovae (such as "mixing and fallback" supernovae), or by the winds from rapidly rotating massive stars. In both cases the supernova progenitors were massive stars formed from primordial material — the first stars.

CEMP-no stars

Our discovery of CEMP-no stars in the two dwarf galaxies Segue 1 and Boötes-I is strong evidence for their self-enrichment from primordial material. The carbon over-abundance reflects the yields of the very first generation of supernovae or massive stars. This provides an opportunity to consider the evolutionary history of the extremely carbon-enriched, iron-poor interstellar medium gas in these galaxies.

A key piece of information is that the most iron-poor star currently known in Boötes-I is not carbon-enhanced. Carbon-enhanced and carbon-normal stars co-exist at the same low iron abundance within the same system (and in the Galactic field Halo; c.f. Caffau et al., 2011). This provides direct evidence that carbon enhancement is not required for very low-iron abundance gas to cool and form low-mass stars. The additional information we consider here is that CEMP-no stars are not found at [Fe/H] greater than –2.5, either in the field Halo or in dwarf spheroidal galaxies.

Given the amplitude of the [C/Fe] and [Mg/Fe] values in CEMP-no stars, one must also explain why stars are not found with intermediate C and Mg excesses at higher [Fe/H]. Apparently the highly C- and Mg-enriched ISM does not survive to mix with "normal" enriched ISM and form more stars with moderate CEMP-no enrichment. Rather, the cooling efficiency of the highly carbon-enriched material must be sufficiently great that all of it cools and forms (the surviving) low-mass stars mixing with "normal" SNe ejecta before [Fe/H] reaches –3 dex. That is, our Boötes-I data provide direct evidence for two discrete channels of chemical enrichment at very low iron abundances.

With our current knowledge of stars in Boötes-I, there is no direct chemical evolution track (assuming standard yields of carbon and iron) between the CEMP-no stars and the carbon-normal stars with [Fe/H] < –3. This means that at very low iron abundance there is no one-to-one relationship between [Fe/H] and the time since the first SNe. This conclusion is summarised in Figure 2, which shows the chemical evolutionary enrichment sequence deduced from our UVES study, and its consistency with observations. The CEMP-no stars form rapidly out of gas enriched by only one generation of SNe and most likely prior to the onset of effective mixing. This results in a small mixing length, spatial inhomogeneity and a large scatter in elemental abundance ratios.

Such a scenario requires that the gas within which the CEMP-no stars form can cool and be locked up in low-mass stars very rapidly, and with high efficiency, so that material with this abundance pattern is removed from the system at early times. This picture is consistent with models of the formation of very metal-poor low-mass stars which appeal to enhanced cooling due to carbon. It may well be that the CEMP-no material resulted from a very small number of (Population III?) supernovae, possibly only one.

A surviving primordial galaxy

Our metallicity and elemental abundance data show that Boötes-I has evolved as a self-enriching star-forming system, from essentially primordial initial abundances. This allows us uniquely to investigate the place of CEMP-no stars in a chemically evolving system, as well as to limit the timescale of star formation in this dSph. The low elemental abundance scatter requires low star formation rates, allowing time for SNe ejecta to be created and mixed over the large spatial scales relevant. This is further evidence that Boötes-I survived as a self-enriching star-forming system from very early times. It also implies that only unimportant amounts of dynamical feedback between the star formation in Boötes-I and its dark matter halo can have occurred. Boötes-I is indeed a surviving primordial system, ideal to investigate the earliest stages of star formation, chemical enrichment and dark matter properties.

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