Galactic archaeology on a grand scale – C17-19

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1 Summary

The project will dramatically advance our knowledge about the Milky Way. With major ramifications for the evolution theory of all spiral galaxies, the research will provide a self-consistent picture of the stellar age distribution for tens of thousands of stars in the Milky Way, revealing the first precise timeline for how the Galaxy formed and evolved. The proposal aims to achieve this by observing a sizable number of colour-magnitude selected oscillating red giants to probe the Galaxy using the fossil imprint in its stars far beyond the solar neighborhood. This is a continuing program running since Campaign-0 probing Galactic directions not probed before, taking full advantage of K2's '360-degree view' along the ecliptic. The high precision and 30-min sampling rate of K2 data are crucial for the project. No other current mission can provide data that will allow us to detect oscillations in large numbers of distant red giants.

2 Scientific Justification

Unravelling the evolutionary history of the Milky Way has been a long-standing problem in contemporary astrophysics, and understanding this history will have significant ramifications for our insight into how other galaxies form and evolve. The critical step will be to make precise measurements of the fundamental properties of stars – the building blocks and the source of galactic chemical evolution – something we currently have achieved only in the solar neigh-bourhood. Traditional near-field cosmology, or galactic archaeology, have been limited by the indirect way the crucial stellar parameters, age and mass, can be inferred for distant stars.

The Kepler and CoRoT missions have revealed an exciting new opportunity for progress: red giants are high-amplitude oscillators, and the analysis of their light curves can yield asteroseismically-determined **radii**, **masses**, and **ages**. The radius, hence distance, places a star accurately in the Galaxy, the mass reveals the mass function and, in combination with composition, provide precise ages for red giants. This has tremendous potential for expanding our view into how the Galaxy formed and evolved. However, the data from Kepler and CoRoT are insufficient: they sample only a very limited portion of galactic real estate, and a lack of well-described selection criteria for their stellar samples limits our ability to faithfully compare theoretical Milky Way models with observations (Chaplin et al. 2011, Sharma et al. 2016).

K2 provides an enormous opportunity to overcome this hurdle. *The thrust of this proposal is to combine K2 data from a large and carefully-selected stellar sample with ambitious ground-based observations, and include state-of-the-art stellar and galactic modelling calculations*. The project will complement traditional spectroscopic and photometric diagnostics with those derived from the rapidly emerging field of asteroseismology. Applying asteroseismology to obtain the radii, masses and ages of a large ensemble of stars across the Galaxy will enable us to determine much more accurately the fundamental physical processes that led to the present-day Milky Way. Our campaign 1 results already demonstrated clear seismic detections (Stello et al. 2015, 2017).

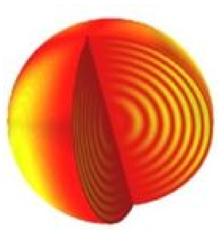

Fig.1: Model of oscillation mode in a star.

Asteroseismology is based on the elegant notion that the oscillations of an object can teach us about its physical properties; the power of this approach in the case of the Sun has been strongly demonstrated (Christensen-Dalsgaard, 2002). Convective surface motion excites sound waves, causing the star to oscillate in many modes simultaneously (Fig. 1). The frequencies depend on the physical properties of the stellar interior, such as density, temperature and composition. *Measurements of stellar oscillation frequencies combined with spectroscopy, which provides stellar surface properties, therefore yield crucial information about mass, radius, and age that have proven very difficult to obtain for field stars in the past.*

With the launch of the space missions CoRoT and particularly Kepler, red giant asteroseismology went wholesale. Crucially for the project, the detection of oscillations in large ensembles of intrinsically luminous and hence distant red giant stars (Hekker et al. 2011, Stello et al. 2013) enable the probing of stellar populations in the Galaxy (Miglio et al. 2009, 2013).

'Galactic archaeology' is a field in astrophysics that studies galaxy evolution through fossil evidence from the stellar relics of ancient star formation (Freeman & Bland-Hawthorn, 2002). The field has recently gained significant traction thanks to ambitious programs aimed at measuring the chemical composition of more than a million stars, including the Australian GALAH survey led by Freeman and Bland-Hawthorn and the US-led APOGEE survey; both observing substantial fractions of giant, which will therefore complement seismic data.

Central to galactic archaeology – and the overall aim of this proposal, is to address the following critical questions facing our current paradigms for galactic evolution: (1) is the halo made entirely of debris of small accreted galaxies, or does it include stars born in-situ in the Milky Way, (2) how is the thick disk formed, and (3) what do the age–metallicity and velocity–metallicity relations look like at large distances from the Sun. A recent gathering of world experts in galaxy evolution and asteroseismology (Sesto, Italy, 2013) has singled out the need to obtain precise stellar ages – which asteroseismology can provide – as the most important issue in the field of galactic archaeology. *Resolution of the above issues is likely to have profound consequences for a wide range of fields in astrophysics.*

3 Target Selection

The goal of galactic archaeology is to understand both the initial conditions (where and when each star is born) and the complex processes governing the evolution (the interaction of each star with the rest of the Galaxy) leading to the present day Milky Way. This problem can be formulated by five stellar observables: position, velocity, age (from seismology), and metallicity – the latter a tracer of galactic radius at birth. In the ideal case one would want to sample the entire parameter space defined by our five observables to translate that into a complete picture of the origin of the stars and their galactic evolution. This would require of order 1 million stars (Freeman & Bland-Hawthorn 2002). If the number of stars available is much less, as in our case with K2, one needs to invoke additional assumptions such as exploring a limited set of parameters or using parametric forms for certain physical relationships.

With the K2 Galactic Archaeology Program we aim at projecting the full parameter space into few dimensions such that we can explore key aspects of galactic evolution, in particular the age-metallicity distribution and age-velocity distribution and their variation in galactic radius, R, and height above the plane, Z. For this we require about 5,000-7,000 (oscillating red giant) stars each at about 15 unique R and Z regions within the galaxy, which breaks down to roughly 5,000 oscillating red giants on average per K2 campaign. These numbers are based on our expected observational uncertainties on age (20% or 0.08 dex) and metallicity (0.1dex), and the need to critically sample the parameter range spanned by the Galaxy, age: 1–13.7 Gyr (14 bins), metallicity: $-2 < [Fe/H] < 0.5$ (25 bins) by at least 15 stars per bin, which translates to a S/N ratio above 3.8 (Poisson statistics). Each campaign field has different giant yields; hence **5,500 to 15,000 of our proposed targets need to be observed per campaign to obtain the required number of red giants**. If fewer stars per campaign are allocated to the program, we would need to project the parameter space to fewer dimensions – consequently our conclusions would become more model dependent.

Campaigns 17 and 19 are critical for boosting our sample of rare halo stars near the northern and southern galactic caps, respectively. Understanding the distant halo star population has the potential to constrain the dark matter halo. Contrary to previous halo-favourable campaigns (e.g. C1), we can now capitalise on the known improved K2 pointing since C3 (resulting in Kepler-like, noise levels) to reach the faint and most distant halo stars (as done using Kepler data by Mathur et al. 2016).

C18 is well placed towards and slightly above the Galactic anti-centre, which in combination with C13, makes it particularly valuable to test the Milky Way models in the radial direction. This is likely to reveal new insights to the complex dynamical history of the Galaxy's radial migration.

All three campaigns allow us to double (for C17/19) and even triple (for C18) the data on stars previously observed in C5, C6, C12, and C16. This will be crucial for investigating the link between any seismic detection bias and the length of the time series, which is important for calibrating biases in all other campaigns. These campaigns give us the opportunity to do this in a completely self-consistent way, without reliance on simulations or inferred extrapolation from Kepler data.

Our bulk selection follows that of previous campaigns, based purely on 2MASS colour and magnitude. Here we select stars having $J–K > 0.5$, $9 < V < 16.5$ and sort them by V magnitude (brightest at top) derived as $V = K + 2*((J–K) + 0.14) + 0.382*\exp(2(J–K–0.2))$, approximately ranging $9 < Kp < 16.0$. Stars already observed spectroscopically by APOGEE/RAVE/SEGUE or with previous seismic detections are placed at the top of the list. **Our simple colour-magnitude cut is absolutely crucial for the science goals** because it (1) ensures a well-described selection function, (2) aid efficient ground-based follow up, (3) and constitute the sweet spot for K2 to clearly detect and resolve oscillations in red giants without imposing significant detection bias (as shown by Stello et al. 2015).
We refer to the summary tables in the Target List section for quantitative details of our selection. Towards the faint end of our targets, our selection function serendipitously includes a significant number of dwarfs of great value to other K2-driven science programs including planet searches around cool stars, stellar rotation, activity, and binarity. We therefore strongly advocate the target allocation "goes down" in our target list as far as possible because it ensures a reproducible selection function for all investigations using these data – a win-win situation to the broader K2 community.

4 Long-Term Legacy Value

Our program takes full advantage of K2's unique '360 degree' field-of-view capability by probing the Galaxy along the ecliptic; this will provide data from vastly different stellar populations within all four main components of the Milky Way – the thin and thick disks, the halo and the bulge. Our strong links to large industrial scale spectroscopy surveys makes our targets top priority for intense ground-based follow up. These aspects ensure that the resulting data set arising from this program will be of great use for the broader community in future studies, leading to a long-lasting legacy of the K2 mission.

We will continue to deliver our value-added products to the community via MAST(archive.stsci.edu/prepds/k2gap/) as we did for our Data Release 1 (DR1) results (Stello et al. 2017), including light curves optimized for red giant asteroseismology, frequency power spectra, and asteroseismic parameters. An additional six campaigns of seismic results are expected to be on MAST following our DR2 within a few months (Zinn et al. in prep). Our associated ground-based program K2-HERMES has already obtained high-resolution spectra of nearly 50,000 of our galactic archaeology targets, and the first data release of atmospheric parameters is about to be published (Sharma et al. submitted). We expect these data to go on MAST as well, just like we have done for the TESS-HERMES survey (archive.stsci.edu/prepds/tess-hermes/).

5 References

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6 Target Table

Here, we give target list summary tables for each campaign illustrating the order of each subsample that we target.

Campaign-17

Sample	V~Kp+0.35	N_target	**N_giant**	Giant_fraction
SPEC/SEIS		1714	**1714**	1.00
2MASS	9.0 < V < 14.0	3718	**1971**	0.53
2MASS	14.0 < V < 15.0	7398	**2959**	0.40
2MASS	15.0 < V < 16.0	15244	**4116**	0.27
2MASS	16.0 < V < 16.5	21907	**4430**	0.21

Campaign-18

Sample	V~Kp+0.35	N_target	**N_giant**	Giant_fraction
SPEC/SEIS		1946	**1946**	1.00
2MASS	9.0 < V < 14.0	5263	**3105**	0.59
2MASS	14.0 < V < 15.0	9822	**4027**	0.41
2MASS	15.0 < V < 16.0	20065	**4615**	0.23

Campaign-19

Sample	V~Kp+0.35	N_target	**N_giant**	Giant_fraction
SPEC/SEIS		1264	**1264**	1.00
2MASS	9.0 < V < 14.0	3453	**1727**	0.50
2MASS	14.0 < V < 15.0	7398	**2589**	0.35
2MASS	15.0 < V < 16.0	14436	**3032**	0.21
2MASS	16.0 < V < 16.5	20766	**3323**	0.16

N_target, N_giant, and Giant_fraction are cumulative.
In the above, we define a cool star as a giant if 1.9 < log g < 3.5 (giants with larger log g will not show oscillations in long cadence data).