Objectives & Significance

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 neighbourhood. Traditional near-field cosmology studies, 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).

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. 2015/2016).

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.*

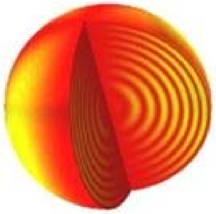

Fig. 1: Model of oscillation mode in a star.

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.*

Approach & Methodology

We base our approach on observing a large number of red giants to probe the Galaxy far beyond the solar neighbourhood. This proposal is part of the continuing K2 Galactic Archaeology Program, which was initiated at Campaign-0 and has so far been allocated a total of over 60000 stars (including Campaigns 1–10) – the largest number of allocated targets to a single K2 program. It is our intention to make similar proposals for future K2 fields in order to probe galactic directions not probed before and take advantage of K2's unique '360-degree view'.

Target selection & number of targets

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 in order 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: $-2 < [\mathrm{Fe/H}] < 0.5$ (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 targets need to be observed per campaign to obtain the required number of red giants**. Each campaign adds stars at new locations, gradually snapping our 'picture' of the

Galaxy into focus as the mission progresses. 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.

Campaign 14 is critical for boosting our sample of rare halo stars. 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).

C15 is ideally placed towards and slightly above the centre of the Galaxy. In combination with previously observed C2+11, it will allow us to study effects from bulge/bar interactions with the thick disk in great detail throughout an extended galactic latitude-dependent region. This is likely to reveal new insights to the complex dynamical history of the Galaxy’s inner region.

With C16 we will double the data on stars previously observed during C5. This will provide our best opportunity to investigate the link between any seismic detection bias and the length of the time series, which is important for calibrating biases in all other campaigns. C16 gives us the only 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 $J–K > 0.5$, $9 < V < 15$ 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 $9 < Kp < 14.5$. Stars already observed spectroscopically by APOGEE/RAVE/SEGUE 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). Now, in order to obtain an efficient and still reproducible selection of the halo stars we include a stellar sample selected by $0.5 < J–K$, $15 < V < 16$ (sorted by V magnitude but priority given to stars with reduced proper motion (in EPIC) < 5.

We refer to the summary tables in the Target List section for quantitative details of our selection. Towards the faint end of our targets, we serendipitously include 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.

Generating light curves

We will generate light curves using our own aperture photometry pipeline developed for the K2 mission. The pipeline performs dynamic automated aperture mask selection, background estimation and subtraction, and positional decorrelation to reduce effects due to spacecraft micro-slews and pointing jitter. We will compare our light curves with those in the public domain to identify which are best suited for detecting oscillations in red giants. The assessment will include light curve (post-) processing to further reduce effects such as outliers, jumps or thermal drifts, following the automated methods described in Garcia et al. (2011) and Stello et al. (2015).

Measuring asteroseismic parameters and surface properties

The measurements of the large frequency separation, $\Delta\nu$, and frequency of max power, ν_{max}, will be done using the SYD (Huber et al. 2009) and A2Z (Mathur et al. 2010) time series analysis pipelines. We further anticipate participation from other groups within KASC/TASC using independent methods, as for C1 (Stello et al. 2016). From these analyses, we create a consolidated list of results, which will be fed into the next stage of the analysis – the grid modelling. The full potential of the grid modelling will be reached when combined with data on stellar surface temperature and metallicity. Through our team's strong links to large ground-based surveys, these additional data are already available to us for a significant fraction of our targets, and will for the remainder be added as top priority on the target lists of the APOGEE, GALAH and SAGA surveys.

Grid modelling

To obtain estimates of the stellar radius, mass and age we will use the RADIUS pipeline (Stello et al. 2009). RADIUS uses seismic scaling relations and large grids of stellar models to estimate fundamental stellar parameters based on $\Delta\nu$, ν_{max}, T_{eff} and [Fe/H]. Through collaboration with KASC/TASC, we will engage a larger set of grid modelling pipelines, which will help us obtain robust results and inform typical systematic errors. As demonstrated in Stello et al. (2009) (see also Huber et al. 2012, Silva Aguirre et al. 2012 and Chaplin et al. 2013), stellar radii can be obtained to the 2–3% level and mass to 7% from grid modelling. From radius we get distances to about 5%, independent of distance. From preliminary work we expect to obtain ages to about 15–20%, but we aim to improve on that with complementary theoretical work and improved calibrations of asteroseismic scaling relations. These efforts will build on our current analysis of the sensitivity of red giant models to changes in the input physics, and on our continued calibration of seismic scaling relations using open clusters, eclipsing binaries, and interferometry (Stello et al. 2011, Brogaard et al. 2012, Huber et al. 2012, and White et al. 2013). The PI and collaborators are heavily involved in a comprehensive analysis of the sensitivity of red giant models to changes in the input physics (Miglio et al. in prep). They are also involved in the ongoing APOKASC project combining spectroscopic and asteroseismic data in the original Kepler field. A strong correlation between seismic mass and first dredge-up products, especially the carbon to nitrogen ratio, was found in APOKASC red giants (Martig et al. 2016) and generalized to spectroscopic mass diagnostics (Ness et al. 2016). We will incorporate constraints derived from the measured surface abundances in our models using methods similar to these.

Modelling the Galaxy

We will use GALAXIA (Sharma et al. 2011) and TRILEGAL (Girardi et al. 2005), two state-of-art galaxy synthesis tools, to create theoretical populations that represent the targeted stars. Comparing observations with theory will allow us to test the currently assumed physics, especially the age–metallicity and age–velocity relations that underpin the galactic models. The comparison will use our seismic results on radius, mass, and age, and T_{eff} and [Fe/H] drawn mainly from APOGEE and GALAH, and where applicable, from other surveys such as RAVE (Steinmetz et al. 2006), Gaia-ESO (Gilmore et al. 2012), LAMOST (Cui et al. 2012), and SAGA (Casagrande et al. 2014). We will also include data from ESA's Gaia mission.

Our asteroseismic analyses will determine the distances to tens of thousands of stars, which will be a major asset. Initially, we will do this using our seismically inferred stellar radii; combined with T_{eff}, this will provide a luminosity estimate at the 10% level, and distances to a precision of ~5%. We expect to improve our age estimates using complementary distances from Gaia. This will be particularly important for investigating the build-up of the thin and thick disks and the halo at the very early evolution of the Galaxy.

Impact & Relevance

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.

Understanding how galaxies evolve helps to inform our perception of the cosmos, from a cultural to a psychological level. This proposal addresses NASA's Strategic Goal 1, as defined in the 2014 Strategic Plan: "Expand the frontiers of knowledge, capability, and opportunity", including Objective 1.6: "Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars." In addition, the project directly addresses Section 3.2 of NASA's 2013 Astrophysics Roadmap: "Archaeology of the Milky Way and Its Neighbors."

The high precision and high 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 red giants. Our program takes full advantage of K2's unique '360 degree' field-of-view capability by probing the Galaxy along the ecliptic over the course of subsequent K2 campaigns; 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.

Plan of work

The work outlined here is a large multi-national coordinated effort. It comprises the primary research for PI Stello, who holds a 4-year Australian Research Council Fellowship to work on the asteroseismology of red giants to perform galactic archaeology investigations.

Key milestones

- We expect the first phase of the project (generating light curves) to complete three months from the date pixel data are made public [D+3mth].
- Subsequent completion of time series analysis to extract $\Delta\nu$, and ν_{max}, of all red giants in our sample including compilation of the consolidated values [D+6mth].
- K2 targeting is an identified priority for APOGEE and GALAH, and we expect to have spectra for approved targets by the time the K2 data are obtained.
- Completion of the following grid modelling, including consolidating results [D+8mth].

- Compare estimated radii, masses and ages with population synthesis models of the Galaxy (initial results expected after four months) [D+12mth].

Management structure

The collaboration behind this proposal comprises large parts of the KASC/TASC `red giant' working groups, asteroSTEP (a collaboration merging expertise on galaxy and stellar evolution with asteroseismic techniques), APOKASC (a collaboration between KASC and APOGEE focussed on merging asteroseismic data from the old Kepler field with ground-based infrared spectroscopy), and GALAH (a large project on the AAT in Australia to obtain spectra of up to 1mio stars in the southern hemisphere). In addition to the PI and Co-Is, the 31 participants that have committed time to this project are listed in the proposal's Program Specific Data (Section IX, question 9).

Dennis Stello (PI): is the overall coordinator of the project. Stello was among the early pioneers in applying seismology to study red giants. He was co-creator of the SYD pipeline designed to extract seismic parameters from Kepler data, and he led the first demonstration of asteroseismic grid modelling techniques. He will use his existing software to determine the seismic inferred stellar properties. As part of the KASC/TASC chairing group, Stello will liaise with these consortia on efforts where expertise and capabilities can be efficiently utilised within the broader seismic community including independent time series analyses and grid modelling, which has been common practise during projects aimed at the Kepler and CoRoT fields**.**

Marc Pinsonneault (Co-I): is the primary link to the APOGEE consortium, which will provide surface temperatures and metallicities for the stars in our northern fields. These data will be crucial for the grid modelling process to obtain precise estimates of the stellar properties. Marc Pinsonneault led similar work within APOKASC (Pinsonneault et al. 2014). [Funding receiver]

Ken Freeman (Co-I): is the senior leader of the GALAH project on the AAT. GALAH serves a similarly important role as APOGEE, but with an emphasis on stars towards the south. Ken will be responsible for providing stellar surface temperatures and metallicities to the project.

Andrea Miglio (Co-I): is the leader of the asteroSTEP collaboration, and has been a pioneer in using seismic measurements to probe stellar populations in the Galaxy. He will be responsible for coordinating comparisons between our observed stellar properties and those found from simulations of the Galaxy in close collaboration with Co-I Sanjib Sharma and Leo Girardi.

Derek Buzasi (Co-I): is the brainchild of the resurrection of NASA's WIRE satellite and developed the software to generate light curves from its star tracker. He will lead the work on creating our K2 light curves in coordination with KASC-wide efforts. [Funding receiver]

Savita Mathur (Co-I): is the co-developer of the A2Z time series analysis code and has been a central part of the team that generated corrected light curves for KASC in the past. She will work closely with Rafael Garcia (Saclay) and Co-I Buzasi to provide light curves optimised for seismic purposes, and she will take part in the time series analysis. [Funding receiver]

Sanjib Sharma (Co-I): is the developer of the GALAXIA population synthesis code. He will work with Co-I Ken Freeman and Joss Bland-Hawthorn (Uni. of Sydney) on target selection for the GALAH survey and with Co-I Miglio on comparing our observations with galaxy models.

Value-added community resources

The value-added community resources that this project will deliver are described under SECTION IX – Program Specific Data, Question 7 (Data Management Plan), and supporting letters from MAST are attached to the proposal.

Even though no formal commitment was sought or made to provide value-added community resources for the initial K2 campaigns (C1-3), we are committed to do so anyway. A preliminary set of seismic results from C1 was made available earlier this year on the public K2 Galactic Archaology Program website (www.physics.usyd.edu.au/~k2gap). The full seismic data set of C1 has just been published through the K2 Galactic Archaology Program Data Release 1, which includes the K2 GAP DR1 paper by Stello et al. (accepted Dec 2016). The light curves and seismic results will be made public on MAST (see attached letters of support from MAST). We are currently in the process of doing that for DR1. Results from subsequent campaigns are expected to follow swiftly hereafter now that we have the necessary understanding of the data and the analysis process.

Target list

The target lists are not provided in this document due to the large number of targets proposed. Instead we give more informative target list summary tables for each campaign illustrating the order of each subsample that we target.

Campaign-14

Sample	V~Kp+0.35	N_target	N_giant	Giant_fraction
SPEC		117	117	1.00
2MASS	9.0 < V < 15.0	5775	1733	0.30
2MASS	15.0 < V < 16.0 + rpm	6829	1776	0.26
2MASS	15.0 < V < 16.0	9859	1873	0.19
2MASS	15.0 < V < 16.0	12070	2052	0.17

Campaign-15

Sample	V~Kp+0.35	Field	N_target	N_giant	Giant_fraction
SPEC			1971	1971	1.00
2MASS	9 < V < 15.0	1-2	3700	3034	0.82
2MASS	9 < V < 14.5	3-6	5402	3943	0.73
2MASS	9 < V < 14.5	7-10	7275	5020	0.69
2MASS	9 < V < 14.5	rest	10974	7023	0.64

Campaign-16

Sample	V~Kp+0.35	N_target	N_giant	Giant_fraction
SPEC		234	234	1.00
2MASS	9.0 < V < 15.0	4208	2314	0.55
2MASS	9.0 < V < 15.0	8058	2901	0.36
2MASS	15.0 < V < 16.0 + rpm	10110	3033	0.30
2MASS	15.0 < V < 16.0	16572	3314	0.20

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

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