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 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 initial campaign 1 results already demonstrated clear seismic detections (Stello et al. 2015).

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.*

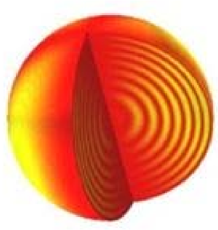

Fig.1: Model of oscillation mode in a star.

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

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 11 provides a unique opportunity to probe the Galactic bulge without as much crowding as C9, and our target list will also include cluster stars, which will be important calibrators. Campaign 12 is critical for boosting our sample of rare distant halo stars. Obtaining their seismic distance has the potential to constrain the dark matter halo. We can now capitalise on the known improved K2 pointing since C3 to reach more distant stars for this purpose (Mathur et al. submitted). With C13 we will probe the radial gradient of the Galactic outer disk, which provides our best opportunity to test the Galaxy models at large radial distances.

Our bulk selection follows that of previous campaigns, based purely on 2MASS colour and magnitude. Here we select stars having $J–K > 0.5$, $9 < V < 14.5$ 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 $9 < Kp < 14.1$. Stars already observed spectroscopically by APOGEE/RAVE/SEGUE (about 500 stars in each campaign) 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 we demonstrated with C1 data, Stello et al. 2015).

Now, in order to obtain an efficient and still reproducible selection of the halo stars in C12 we include two additional stellar samples, one to capture the 'bright' halo stars, and one to capture the faint halo stars. The bright sample comprises stars with $0.5 < J–K$, $14.5 < V < 16.0$ (sorted by V magnitude but priority given to stars with reduced proper motion (in EPIC) < 5. Photometric errors start to increase beyond V=16.0 in 2MASS, hence we use the SDSS bands for the faint sample, which also provide the photometric *l*-colour metallicity indicator to select halo stars more efficiently. The faint sample is a composite of stars, which all have $16 < r < 17$ and $0.5 < (g–r) < 0.7$, and either *l*-colour > 0.1 or reduced proper motion (in EPIC) < 5, to target distant halo giants. We give higher priority to the faint sample (~1000 stars) over the bright sample (~1500 low proper motion stars plus ~8000 purely colour-selected stars) to ensure we obtain data for the most distant halo stars.

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 science 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.

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

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]. At the time of pixel data release we anticipate our pipeline is ready and tested on previous K2 data, and light curves should be generated with minimal campaign-specific modifications required.
- 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].

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. The publication of the asteroseismic results for all our campaign 1 targets is imminent, and the light curves and seismic results will be made public on MAST alongside that publication (see attached letters of support from MAST). Results from subsequent campaigns are expected to follow swiftly hereafter now that we have the necessary understanding of the data and the analysis process.