Using Asteroseismology to Measure Masses of Evolved Stars in M4

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Motivation & Background

Asteroseismology provides a new avenue to study stellar evolution and globular cluster (GC) formation. Using photometry from the *K2* mission [1], we have measured asteroseismic masses for 39 evolved stars in the GC M4 and found the integrated mass loss along the red giant branch (RGB) and red horizontal branch (RHB). M4 remains the only GC for which it is possible to measure mass loss with the current available photometry. This study reports the largest ever seismic analysis of GC stars, and the first detection of oscillations in early asymptotic giant branch (EAGB) stars in GCs.

Solar-like oscillations in globular cluster stars have only been observed once before [2], where eight stars were analysed in M4. We were interested if we could achieve a larger sample of observed solar-like oscillators in M4, and obtain their masses. Due to the short observing periods in *K2,* instrumental noise and the clustering of the field which resulted in low signal-to-noise (SNR), detecting seismic signatures was difficult for GC stars.

Mass loss rates of evolved stars remains a major uncertainty in stellar modelling. As mass is a defining factor on the subsequent evolution of the star, it is important that we accurately understand and constrain this phenomenon. By obtaining accurate masses of stars in different evolutionary phases, total mass loss along each branch can be quantified. Combining the seismic mass equation [3,4] and the Stefan-Boltzman law, 4 mass equations were used in this study:

$$\left(\frac{M}{M_\odot}\right) \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^{3}\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2} \quad (1)$$

$$\left(\frac{M}{M_\odot}\right) \simeq \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{2}\left(\frac{L}{L_\odot}\right)^{3/2}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{-6} \quad (2)$$

$$\left(\frac{M}{M_\odot}\right) \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)\left(\frac{L}{L_\odot}\right)\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{-7/2} \quad (3)$$

$$\left(\frac{M}{M_\odot}\right) \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^{12/5}\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-14/5}\left(\frac{L}{L_\odot}\right)^{3/10} \quad (4)$$

From this study, we discovered a weak bi-modal mass distribution along each branch. We aim to determine if the bi-modality reflects the multiple populations of M4. If the mass difference is confirmed to track the multiple populations, then this is strong independent evidence for the inferred He differences between populations. This He variation will correspond to different population ages, which supports the hypothesis that the sub-populations in a GC are different generations.

Background Photo Source: ESO Imaging Survey

Kepler Telescope Image Source: NASA

Mass Loss Results

Using photometric temperatures and bolometric luminosities, accurate masses for all 39 targets (28 RGB, 7 RHB and 4 EAGB) were found using Eqs 1-4. A comparison of the average RGB, RHB and EAGB masses from each seismic mass equations is shown in Fig 1. The most precise and accurate masses were calculated from Eq. 3.

Using the mean masses calculated from Eq. 3, an integrated mass loss on the RGB and RHB was determined as follows

$$\Delta M_{RGB} = \overline{M}_{\rm RGB} - \overline{M}_{\rm RHB} = 0.18 \pm 0.04\, M_\odot$$
$$\Delta M_{RHB} = \overline{M}_{\rm RHB} - \overline{M}_{\rm EAGB} = 0.04 \pm 0.06\, M_\odot$$

The mass difference on the RGB was consistent with the expected mass loss of 0.2 solar masses from models [5]. The RHB result suggests that there is a small amount of mass loss along the RHB. However, this is not statistically robust due to the small sample of EAGB stars.

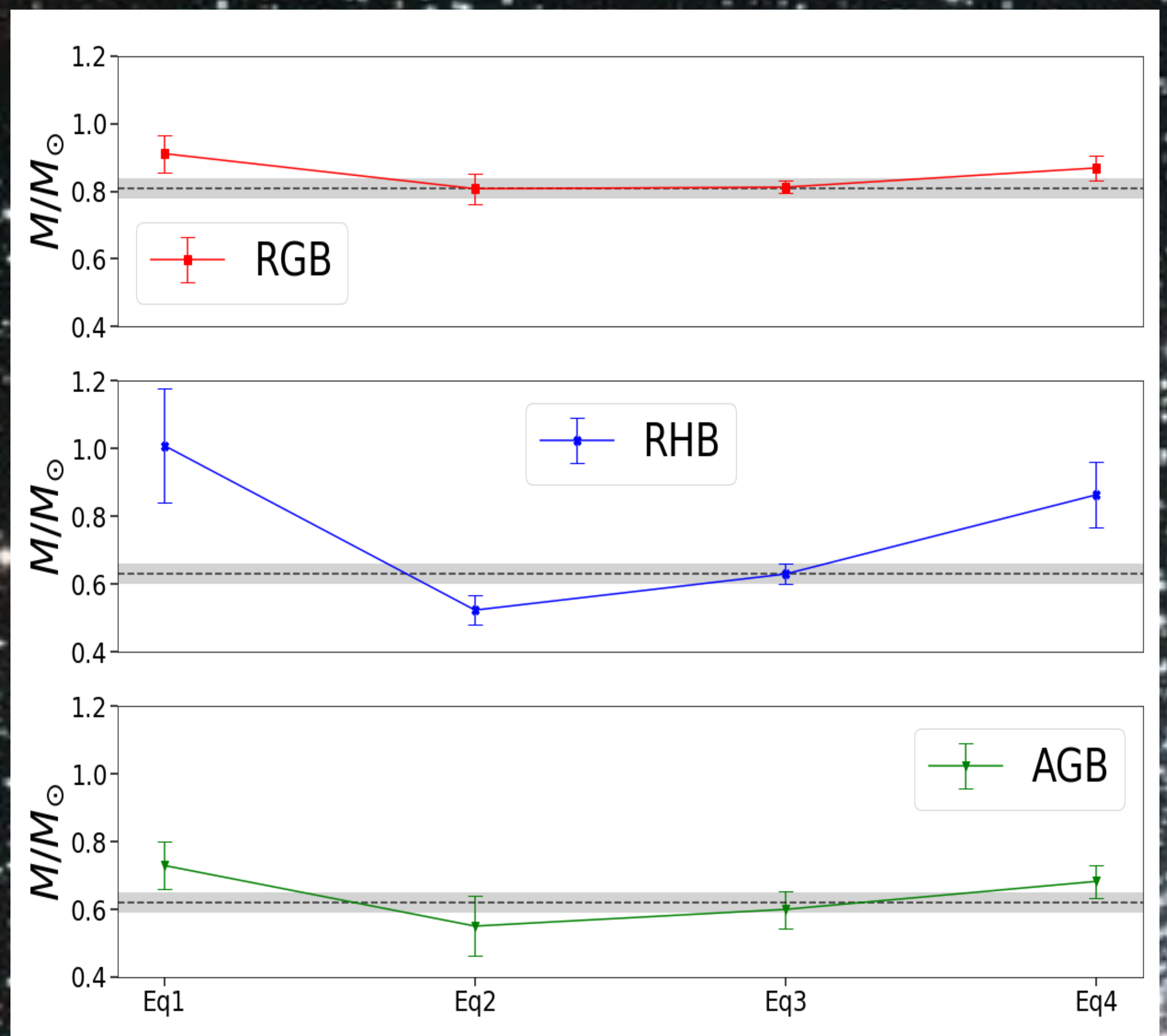
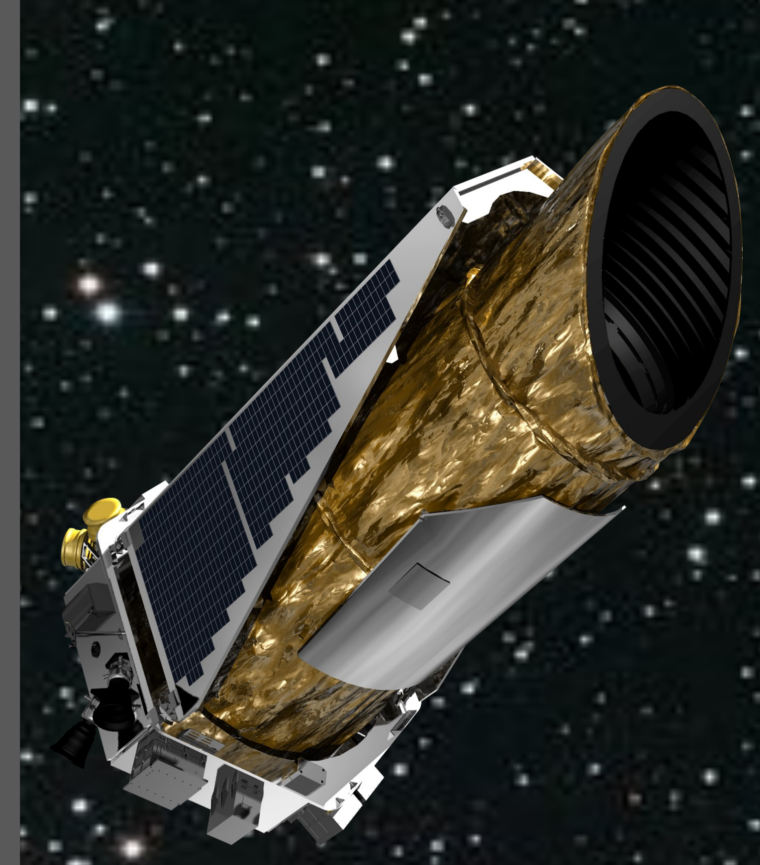


Fig. 1: Average masses calculated from seismic mass equations for each evolutionary stage. Error bars are the 1σ standard error on the mean. The dashed grey lines represent the expected mass for that evolutionary stage and the grey shaded area represents ±0.03 from the expected value which was estimated from models. Eq 3 can be observed to be the best performing equation.

Bi-Modal Mass Distribution

In our study, we observed a weak mass bimodality in the our RHB sample (bottom panel of Fig 2). In contrast, the expected small mass difference (~0.04 solar masses [5]) on the RGB was not detectable and we do not observe a bimodality (top panel of Fig 2). This is due to the error bars on our RGB masses. However, the mass dispersion of the RGB sample was higher than expected, consistent with a hidden mass variation.

Chemical abundance information can help distinguish between sub-populations. If mass bimodalities are associated with sub-population membership, the light elemental abundances (eg. C, N, O, Na and He) should correlate with mass. As a test, we used a subset of our RGB sample which overlapped with the study [6], to classify stars into 'Na-rich' (logϵ(Na)>5.25; also known as SP2) and 'Na-poor' (logϵ(Na)<5.25; also known as SP1), and compare the averages masses (see Fig. 3). We find a weak signal of mass difference between the Na-rich and Na-poor samples. This is interesting considering we could detect nothing in Fig 2. Future works will include obtaining spectroscopic measurements of light elements for our stars to confirm a correlation between our bi-modal mass distribution and the multiple populations in M4.



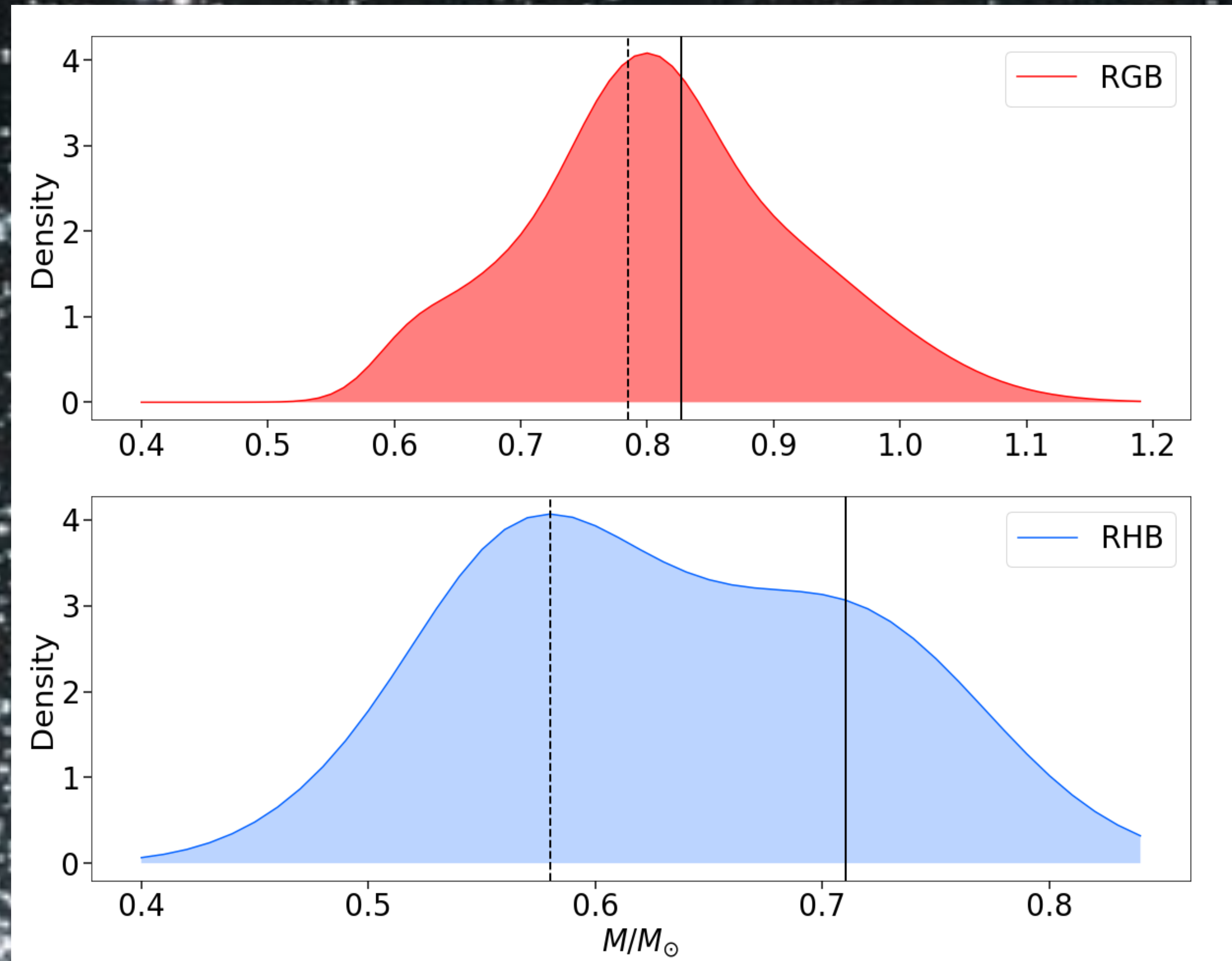


Fig. 2: Gaussian kernel density estimation (KDE) histograms showing the seismic mass distributions. The errors on the mass estimates were used to define the histogram bin widths. Vertical lines represent the expected masses for SP1 (solid) and SP2 (dashed), based on detailed models [6]. The top panel is the RGB sample. No bimodality is found, since the mass difference is within the uncertainties. The dispersion is larger than expected, hinting at mass variation. The bottom panel is the RHB sample. This shows a potential bimodal mass signal. We find that the broad distribution is not consistent with a single population.

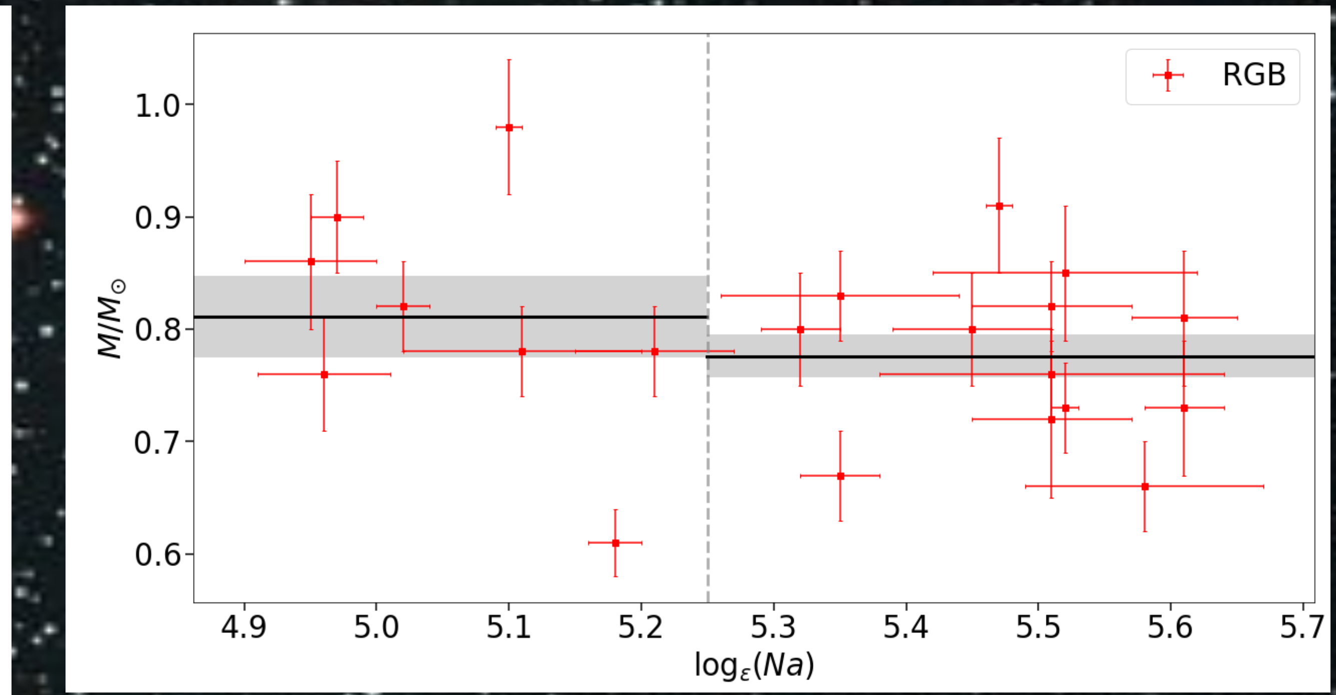


Fig. 3: Estimated masses against sodium abundances for an overlapping 21 RGB stars with [6]. The RGB sample is separated into the two sub-populations as indicated by the grey dashed line. The solid horizontal black lines represent the average mass for each sub-population and the grey shaded region is the 1σ standard error on the mean. A marginal decrease in mass can be seen between the two sub-populations. This difference is exactly as expected – the SP1 (Na-poor) stars have a larger masses on average than SP2 (Na-rich) stars.

References

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