Asteroseismology of the Open Clusters NGC 6791, NGC 6811, and NGC 6819 from 19 months of Kepler photometry

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Collaborators:
Kepler Asteroseismic Science Consortium Members
• Highlights in OCs NGC 6791, 6811 & 6819
  Mass and Age, $T_{\text{eff}}$ and Metallicity, Mass loss, Rotation, Membership study

• What we expect from Red Giants
  RGB Oscillations
  Asteroseismic parameters and their relation to stars’ fundamental properties

• Ensemble results from 19 months photometry
  $\varepsilon$ and C-D diagrams, Ensemble échelle diagrams, Linewidths, Period spacings of mixed dipole modes
Section 1

Highlights in Open Clusters
OCs General Properties

  **NGC 6791** extremely old
  Average mass of RGB stars:
  \( M_{\text{RGB}} = 1.15 \pm 0.02 \, M_\odot \)
  Age: \( \sim 8.3 \, \text{Gyr} \)

  **NGC 6819** middle aged
  Average mass of RGB stars:
  \( M_{\text{RGB}} = 1.68 \pm 0.03 \, M_\odot \)
  Age: between 2 and 2.4 Gyr

**Mass & Age**

Adapted from Stello et al. 2011b
OCs General Properties

  with eclipsing binaries
  **NGC 6791** extremely old
  Average mass of RGB stars: $M_{\text{RGB}} = 1.15 \pm 0.02 \, M_\odot$
  Age: $\sim 8.3$ Gyr

  with asteroseismic grid fitting
  **NGC 6819** middle aged
  Average mass of RGB stars: $M_{\text{RGB}} = 1.68 \pm 0.03 \, M_\odot$
  Age: between 2 and 2.4 Gyr

- **NGC 6811** young, only red clump (RC) stars
  Average mass of RC stars: $M_{\text{RC}} = 2.35 \, M_\odot$
  Glushkova, E. V. et al, AstL, 25, 86
  Age = $0.7 \pm 0.1$ Gyr

Mass & Age

__Highlights in Open Clusters__
- What we expect from Red Giants
- Ensemble results from 19 months photometry
- Conclusions
OCs General Properties

**Metallicity**


- **NGC 6791** metal rich
  \[\frac{\text{Fe}}{\text{H}} = 0.29 \pm 0.03 \text{ (random)} \pm 0.07 \text{ (systematic)}\]


- **NGC 6819** solar metallicity
  \[\frac{\text{Fe}}{\text{H}} = 0.09 \pm 0.03\]

Bruntt et al. 2012
Molenda-Zakowicz et al. 2013

- **NGC 6811** \sim{} solar metallicity

**Mass loss**


- Direct estimates of mass loss rates for NGC 6791 and NGC 6819

- **NGC 6791** significant mass loss
  \[\Delta M = 0.09 \pm 0.03 \text{ (random)} \pm 0.04 \text{ (systematic)} M_\odot\]

- **NGC 6819** no mass loss
  \[\Delta M = -0.03 \pm 0.04 M_\odot\]

**Rotation**


- Study of stellar rotation in **NGC 6811**
  Periods \sim{} 11 days in early K-type
Membership study


- Membership study of the Red Giants from color-magnitude diagrams (CMD)
- Identification of targets with evidence of RGB oscillations


- Amplitude estimates for oscillations in the three OCs

Our sample of 115 Red Giants observed by Kepler

60 RGs for **NGC 6791** (RGB and RC)
5 RGs for **NGC 6811** (only RC)
50 RGs for **NGC 6819** (RGB and RC)
Section 2

What we expect from Red Giants

...see also Josefina’s talk
Pressure modes (p modes) (Solar-like Oscillations)

Vandakurov 1968; Tassoul 1980; Gough 1986

\[ \nu_{n,\ell} = \Delta \nu \left( n + \frac{\ell}{2} + \epsilon \right) - \delta \nu_{0,\ell} \]
Pressure modes (p modes)
(Solar-like Oscillations)

Vandakurov 1968; Tassoul 1980; Gough 1986

\[ \nu_{n,\ell} = \Delta \nu(n + \ell/2 + \epsilon) - \delta \nu_{0,\ell} \]

\[ \Delta \nu \propto \sqrt{\rho} \]

\[ \nu_{\text{max}} \propto g/T_{\text{eff}} \]

as the star evolves

\[ l = 3, m = 1 \]

\[ l = 3, m = 2 \]
**Pressure modes (p modes)**
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Stochastic excitation and damping
**Pressure modes (p modes)**
(Solar-like Oscillations)

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Small frequency spacings \( \delta \nu_{01} \)

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Adapted from Corsaro et al. 2012b

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Adapted from Stello et al. 2013

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RGB Oscillations

Gravity modes (g modes)
(Radiative cores)

- As the star evolves p modes ↓ in frequency
- As the star evolves g modes ↑ in frequency
- From subgiant phase of evolution Mixed modes are generated (mostly dipole modes)

Stello, D. (2012; ASPC 462, 200)
Gravity modes (g modes)

(Radiative cores)

- As the star evolves p modes \(\downarrow\) in frequency
- As the star evolves g modes \(\uparrow\) in frequency
- From subgiant phase of evolution Mixed modes are generated (mostly dipole modes)

\[\text{Mixed modes} + \text{p modes} = \text{Oscillations in Red Giants}\]

Period spacing \(\Delta P\)
Sensitive to core structure and composition

Adapted from Stello et al. 2013
Asymptotic parameters

- From ensemble analysis (hundreds of RGs) observed with Kepler we have:
  - Tight correlation between $\delta \nu_{02}, \delta \nu_{01}$ and $\Delta \nu$
  - $\varepsilon$ is a function of fundamental stellar parameters (Mass, Radius)


Adapted from Huber et al. 2010
Period Spacings


- $\Delta P$ as a way to distinguish between He-core and H-shell burning RGs


Adapted from Bedding et al. 2011

Adapted from Mosser et al. 2012

Really powerful tool for constraining the evolutionary stage of Red Giants
Section 3

Ensemble results from 19 months photometry
Why Cluster RGs?

- Exploiting the common properties of cluster stars
- Ensemble analysis of asymptotic parameters (AARG code)
- Period spacings analysis
- 19 months of continuous photometry observations with Kepler

(1) More stringent results on asymptotic quantities
(2) Deeper comprehension of the physics behind
(3) Possibility for detailed modeling of the stars
• Verified log-relation by Mosser et al. 2011
\[ \epsilon = (0.601 \pm 0.025) + (0.632 \pm 0.032) \log \Delta \nu \]

• Very good agreement with the results by Kallinger et al. 2012 (Kepler) and Mosser et al. 2011b (CoRoT) on field RGs

• Power-law relation provides another reliable law
\[ \epsilon = (0.681 \pm 0.017) \Delta \nu^{0.261 \pm 0.014} \]

Adapted from Corsaro et al. 2012
Adapted from Corsaro et al. 2012

C-D diagrams for $\delta \nu_{02}$

• Highlights in Open Clusters
• What we expect from Red Giants
• Ensemble results from 19 months photometry
• Conclusions

Padova, 23rd September 2013

C-D diagrams for $\delta v_{01}$

Adapted from Corsaro et al. 2012


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Evidence for **mass dependence**. We correlate the slope $b$ of the linear fit in the C-D diagram to mass:

$$b_{02} = (0.138 \pm 0.012) + (-0.014 \pm 0.008) \left( \frac{M_{\text{RGB}}}{M_{\odot}} \right)$$

$$b_{01} = (-0.073 \pm 0.012) + (0.044 \pm 0.008) \left( \frac{M_{\text{RGB}}}{M_{\odot}} \right)$$

- Qualitatively agreement with theoretical results by Montalban et al. 2011
Ensemble échelle diagrams

NGC 6791

Mixed dipole modes more pronounced in Clump stars

Broadening of $l = 2$ ridges for RC stars - Mixed quadrupole modes

Adapted from Corsaro et al. 2012


Padova, 23rd September 2013

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Ensemble échelle diagrams

- Highlights in Open Clusters
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Linewidths are related to damping of the modes

Adapted from Corsaro et al. 2012
Exponential correlation between linewidths and $T_{\text{eff}}$ (even for cooler stars) - **One law only from MS to RG stars**

\[
\Gamma = \Gamma_0 \exp \left( \frac{T_{\text{eff}} - 5777 \text{ K}}{T_0} \right) \mu\text{Hz}
\]

$\Gamma_0 = 1.39 \pm 0.10 \mu\text{Hz}$

$T_0 = 601 \pm 3 \text{ K}$

- Temperature estimates for the three clusters from (V - K) color
- Exponential correlation between linewidths and $T_{\text{eff}}$ (even for cooler stars)

Adapted from Corsaro et al. 2012


- Highlights in Open Clusters
- What we expect from Red Giants
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Highlights in Open Clusters

What we expect from Red Giants

Ensemble results from 19 months photometry

Conclusions

Adapted from Corsaro et al. 2012

\[ \Delta P_{\text{obs}} - \Delta \nu \]
• 53 RGs, where $\Delta P_{\text{obs}}$ could be measured


• Some of them are standing outside the expected regions: discussion of **14 special cases**
  (AGB stars, Binaries, Blue Stragglers, Evolved Clump stars)
Conclusions

- Log-relation $\varepsilon$-mean density of the stars confirmed and improved also for cluster RGs and new power law relation tested

- First evidence for mass dependence of small spacings $\delta\nu_{02}$ and $\delta\nu_{01}$ in cluster RGs (in qualitative agreement with predictions)

- Different behaviour of RC stars in C-D diagrams relative to their RGB counterparts (theoretical models for post He-flash phase are required)
Conclusions

- **New exponential law for linewidths** as a function of temperature

- **53 Red Giants** could be classified in their evolutionary stage

- Period spacing analysis revealed **14 stars** to be **at a different stage of evolution** than anticipated from the CMD - **Very interesting for modeling!**

- **6 evolved RC stars** to be modeled theoretically
Funding for this Discovery mission is provided by NASA's Science Mission Directorate. The authors would like to thank the entire Kepler team, without whom this investigation would not have been possible.

We thank all the KASC members contributing to this work:


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Thank you for your attention!
Evidence for a systematic difference in temperature of the two clusters

Linewidths increase with temperature (in agreement with Huber et al. 2010 and Kallinger et al. 2012)

RC stars have larger linewidths because of higher temperatures

Adapted from Corsaro et al. 2012
## Interesting targets list

### Outliers $\Delta P_{\text{obs}}$

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Adapted from Corsaro et al. 2012

### Other interesting cases

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Adapted from Corsaro et al. 2012
**KIC 2436593** RGB star belonging to NGC 6791

\[ \nu_{\text{max}} = 111.64 \, \mu\text{Hz} \]

\[ \Delta \nu = 9.64 \, \mu\text{Hz} \]

\[ \epsilon = 1.238 \]

\[ \delta \nu_{02} = 1.178 \, \mu\text{Hz} \]

\[ \delta \nu_{01} = 0.078 \, \mu\text{Hz} \]

\[ \Delta P_{\text{obs}} = 54.7 \, \text{s} \]

Adapted from Corsaro et al. 2012
Mass loss


- Direct estimates of mass loss rates for NGC 6791 and NGC 6819

- Mass correction to the $\Delta v$ scaling relation for clump stars

- **NGC 6791** significant mass loss
  \[ \Delta M = 0.09 \pm 0.03 \text{ (random)} \pm 0.04 \text{ (systematic)} \, M_\odot \]
  \[ M_{\text{RC (corrected)}} = 1.15 \pm 0.03 \, M_\odot \text{ (2.7 \% corr.)} \]

- **NGC 6819** no mass loss
  \[ \Delta M = -0.03 \pm 0.04 \, M_\odot \]
  \[ M_{\text{RC (corrected)}} = 1.65 \pm 0.04 \, M_\odot \text{ (1.9 \% corr)} \]
Section 4

Discussion of interesting targets
Interesting targets list

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Outliers $\Delta P_{\text{obs}}$

- **A, B, C, D** unexpected position in the $\Delta P_{\text{obs}}-\Delta \nu$ diagram
- **A, B** are likely to be binary stars, with one component RGB and another faint less-evolved component (suggested by their lower B-V color)

Adapted from Corsaro et al. 2012

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**Highlights in Open Clusters**

- What we expect from Red Giants
- Ensemble results from 19 months photometry
- Discussion of interesting targets

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Outliers $\Delta P_{\text{obs}}$

- A, B, C, D unexpected position in the $\Delta P_{\text{obs}}$-$\Delta \nu$ diagram
- C, D have a high mass estimate and are likely to be evolved blue straggler stars (BSS) as suggested by Rosvick, J. M., & Vandenberg, D. A. 1998, AJ, 115, 1516

Adapted from Corsaro et al. 2012


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Other interesting cases

- **KIC 2437589** misclassified from CMD
  Higher mass than other RGB (1.7 M$_\odot$)
  Suggestion by Brogaard et al. 2012 for BSS in the RGB phase
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- **6 likely evolved RC stars** - Show masses of RC stars but lower $\Delta \nu$. Hence larger radii

- **KIC 9716522** ($\Delta P_{\text{obs}} = 154 \, \text{s}$) is an AGB  
  as suggested by Stello et al. 2011b from CMD

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Linewidths and $T_{\text{eff}}$

- Linewidths of 800 RGs appear to increase with increasing $\Delta v$

- Linewidths correlate well with $T_{\text{eff}}$, both from Kepler and CoRoT

- Linewidths increase with the logarithm of $\Delta v$

- No evident correlation of linewidths with $T_{\text{eff}}$ for RGs observed with CoRoT (5 months)