

Andrea Miglio

European Research Council Established by the European Commissio

TESTING STELLAR EVOLUTION IN CLUSTERS USING ASTEROSEISMOLOGY AND GAIA

a simple plan

testing stellar models using Gaia + asteroseismology + spectroscopy in controlled environments

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2

new data for when the feast is over? ideas for a space mission dedicated to asteroseismology of clusters

TESTING STELLAR MODELS

clusters as probes of the MW's structure, chemical and dynamical evolution:

age inference via isochrone fitting

-
- mapping photospheric abundances to those of the ISM at birth
-
- inferences rely heavily on models of stellar structure and evolution

e.g.

TESTING STELLAR MODELS

clusters as probes of the MW's structure, chemical and dynamical evolution:

- age inference via isochrone fitting
- mapping photospheric abundances to those of the ISM at birth

-
- inferences rely heavily on models of stellar structure and evolution

e.g.

clusters ideal environments to expose shortcomings of stellar models

TESTING STELLAR MODELS

constraints brought by the detection of solar-like oscillations

- (too) many examples to choose from, I will limit to red giant stars, considering additional
	-
	- extra mixing, Li production?
		- products of mass transfer / merger
		-

key processes that are being tested/calibrated a.

b. clusters as benchmarks for the asteroseismic distance, mass, and age scale

mixing from convective cores (e.g. in RC stars)

first dredge-up efficiency

mass loss rotation

TESTING STELLAR PHYSICS

cause for this may be assumed to this may be assumed to this may be assumed to this may be assumed number of t
This may be a stricted number of the limited number of the limited number of the limited number of the limited

 s in the cluster, or to the cluster, or to the three RC stars for α stars for α stars for α

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 Γ figure 1. Red-clump stars in NGC6791 and NGC6791 and NGC68191 and NGC6819 in Γ See also Montaiban et al. 2013, Bossini et al. 2015, Constantino et al. 2015 see also Montalban et al. 2013, Bossini et al. 2015, Constantino et al. 2015

dashed line shows M models computed with slightly M models computed with slightly \mathcal{M}

200

220

240

~10% overmassive stars

TESTING STELLAR PHYSICS

the test is a set of frequencies at which spikes have been

4.0

$\frac{1}{\sqrt{2}}$ the feature in the frequency-separations which, ex- $\mathsf{I} \vdash \mathsf{S} \mathsf{I} \mathsf{I} \mathsf{N} (\neg \mathsf{S} \mathsf{I} \vdash$ $\mathbf{t} \leftarrow \mathbf{t} \$ testing stellar physics

Figure 3. Colour-magnitude diagram of the observed giants in

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Figure 3. Colour-magnitude diagram of the observed giants in

Handberg et al. 2017

4.0

guesses. The relation which needs to be iteration which needs to be iteration which needs to be iteratively solved

NGC6819

a Li-rich1.6 M_{sun} RGB star \mathbf{g} is the presentation of \mathbf{g} Stars which have depressed dipole modes cannot be ϵ . This was a few stars were instead in the stars were instead in the stars were instead in stars were instead in the stars were instead in

Carlberg et al. 2015 Anthony-Twarog et al. 2013

likely products of binary interaction / coalescence hinary interaction / coalescence ence at the frequence of the high-frequence the third is variated that $\frac{1}{2}$

T_{F} for the frequence of Γ by definition, the asymptotic period spacing is uniform in dipole" stars, are stars with *‹*max . 60µHz and power spectra medicine are very reminiscent of main-sequence stars. Each very reminiscent of main-sequence stars. Each v testing stellar physics

Handberg et al. 2017

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Carlberg et al. 2015 Anthony-Twarog et al. 2013

*‹*mix ƒ *‹^p* +

arctan arctan

q tan

≠ *Á^g*

, (8)

likely products of binary interaction / coalescence hinary interaction / coalescence ence at the frequence of the high-frequence the third is variated that $\frac{1}{2}$

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 \mathbf{c}

comparing the measured position relative to the theoretical

Handberg et al. 2017

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comparing the measured position relative to the theoretical

TESTING STELLAR PHYSICS

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 -0.5

Rain et al. 2021

Leiner&Geller 2021

Jadhav & Subramaniam 2021

TESTING STELLAR PHYSICS

G

Jadhav & Subramaniam 2021

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- use all info available (chemical composition, surface rotation, seismic inference on internal structure)

evidence for overmassive stars in the field see e.g. Fuhrmann 2011, Martig 2015, Chiappini 2015, Jofré et al 2016, Izzard et al. 2017, 2018, Silva-Aguirre 2018, Miglio et sl.2021

4 A. Miglio et al.: PLATO *as it is*: a legacy mission for Galactic archaeology

gal (Gira α) synthetic population representation representation representation representation representative of α

4 A. Miglio et al.: PLATO *as it is*: a legacy mission for Galactic archaeology

gal (Gira α) synthetic population representation representation representation representation representative of α

Hyades

MS EB+ seismology of ε Tau Brogaard et al. 2021

consistency checks: issue with parallax?

Hyades

Gaia EDR3 parallax: 22.37 ± 0.17 mas *consistency checks: issue with parallax?*

Age: 0.9 ± 0.1 (stat) ± 0.1 (sys) Gyr

MS EB+ seismology of ε Tau Brogaard et al. 2021

/ µHz]

pectral density [ppm

 $\boldsymbol{\alpha}$

L2 *A. Miglio et al.* clusters as BENCHMARKS

Figure 1. CMD of NGC 6791 (left-hand panel) and NGC 6819 (right-hand panel). Photometric data are taken from Stetson, Bruntt & Grundahl (2003) and Hole et al. (2009), respectively. RGB stars used in this work are marked by open squares and RC stars by open circles. See Section 3.2 for a description of the Downloaded from https://academic.oup.com/mnras/article-abstract/419/3/2077/1064418 by guest on 18 November 2018 $\bigcap_{i=1}^n$ is information on $\bigcap_{i=1}^n$ information $\bigcap_{i=1}^n$ able, which is usually the case for field stars, equations (1) and (2) may be solved to derive *M* and *R* (see e.g. Kallinger et al. 2010; $\bigcap \Lambda \wedge D$ but, by searching solutions for *M* and *R* in grids of evolutionary clusters as BENCHMARKS

$$
\frac{M}{M_{\odot}} \simeq \left(\frac{\nu_{\text{max}}}{\nu_{\text{max},\odot}}\right)^3 \left(\frac{\Delta \nu}{\Delta \nu_{\odot}}\right)^{-4} \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}}\right)^{3/2},
$$
\n
$$
\frac{M}{M_{\odot}} \simeq \left(\frac{\Delta \nu}{\Delta \nu_{\odot}}\right)^2 \left(\frac{L}{L_{\odot}}\right)^{3/2} \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}}\right)^{-6},
$$
\n
$$
\frac{M}{M_{\odot}} \simeq \left(\frac{\nu_{\text{max}}}{\nu_{\text{max},\odot}}\right) \left(\frac{L}{L_{\odot}}\right) \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}}\right)^{-7/2},
$$
\n
$$
\frac{M}{M_{\odot}} \simeq \left(\frac{\nu_{\text{max}}}{\nu_{\text{max},\odot}}\right)^{12/5} \left(\frac{\Delta \nu}{\Delta \nu_{\odot}}\right)^{-14/5} \left(\frac{L}{L_{\odot}}\right)^{3/10}.
$$

used to compute a weighted average mass for stars belonging to the stars belonging to the stars belonging to t

Figure 1. CMD of NGC 6791 (left-hand panel) and NGC 6819 (right-hand panel). Photometric data are taken from Stetson, Bruntt & Grundahl (2003) and Hole et al. (2009), respectively. RGB stars used in this work are marked by open squares and RC stars by open circles. See Section 3.2 for a description of the $\bigcap_{i=1}^n$ is information on $\bigcap_{i=1}^n$ information $\bigcap_{i=1}^n$ able, which is usually the case for field stars, equations (1) and (2) may be solved to derive *M* and *R* (see e.g. Kallinger et al. 2010; $\bigcap \Lambda \wedge D$ CLUSTERS AS BENCHMARKS

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$$

Table 2. Average mass of stars on the RGB estimated using diagram ϵ and ϵ

• revisiting M4

HAYDN

High-precision AsteroseismologY of DeNse stellar fields

Andrea Miglio^{1,2,3} \bullet · Léo Girardi⁴ · Frank Grundahl⁵ · Benoit Mosser⁶ · **Nate Bastian7** ·**Angela Bragaglia3** · **Karsten Brogaard5,8** ·**Gael Buldgen ¨ ⁹** · **William Chantereau⁷** · **William Chaplin¹** · **Cristina Chiappini10** · Marc-Antoine Dupret¹¹ · Patrick Eggenberger⁹ · Mark Gieles^{12,13} · **Robert Izzard14** ·**Daisuke Kawata15** · **Christoffer Karoff⁵** ·**Nadege Lagarde ` ¹⁶** · **Ted Mackereth1,17,18,19** ·**Demetrio Magrin⁴** ·**Georges Meynet9** · **Eric Michel²⁰** · **Josefina Montalbán**¹ · Valerio Nascimbeni⁴ · Arlette Noels¹¹ · **Giampaolo Piotto²¹** · **Roberto Ragazzoni4** ·**Igor Soszynski ´ ²²** · **Eline Tolstoy23** · **Silvia Toonen1,24** ·**Amaury Triaud1** · **Fiorenzo Vincenzo1,25**

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Abstract

Exteroseismology **Keywords** Stars: low-mass · Globular clusters · Galaxy: bulge · Galaxies: dwarf · Asteroseismology

In the last decade, the *Kepler* and CoRoT space-photometry missions have demonstrated the potential of asteroseismology as a novel, versatile and powerful tool to perform exquisite tests of stellar physics, and to enable precise and accurate characterisations of stellar properties, with impact on both exoplanetary and Galactic astrophysics. Based on our improved understanding of the strengths and limitations of such a tool, we argue for a new small/medium space mission dedicated to gathering high-precision, high-cadence, long photometric series in dense stellar fields. Such a mission will lead to breakthroughs in stellar astrophysics, especially in the metal poor regime, will elucidate the evolution and formation of open and globular clusters, and aid our understanding of the assembly history and chemodynamics of the Milky Way's bulge and a few nearby dwarf galaxies.

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?

.. is there a need for better data?

PART 2

Experience Assumption of the Astronomy $f(10.1007/s10686-021-09711-1$ ESA VOYALARTICLE
HAYDN

ORIGINAL ARTICLE

Check for

HAYDN: THE CONTEXT

the space photometry revolution: discovering the potential of asteroseismology

high-precision stellar physics B.

internal rotational profile

stellar interiors and their evolution accessible to our investigations

• chemical composition gradients

• density stratification

HAYDN: THE CONTEXT

CoRoT, *Kepler*-K2

• TESS PLATO

- have demonstrated the potential of asteroseismology (in clusters)
- observational strategy not optimised for stellar / galactic science
- designed primarily for planet searches: wide field, bright targets, large pixel sizes

HAYDN: THE CONTEXT

CoRoT, *Kepler*-K2

• TESS PLATO

- have demonstrated the potential of asteroseismology (in clusters)
- observational strategy not optimised for stellar / galactic science
- designed primarily for planet searches: wide field, bright targets, large pixel sizes
	- overcoming these limitations i.e.
	- obtaining *Kepler*-like observations in crowded stellar fields
		- breakthroughs in stellar and Galactic science

having now a better understanding of the strengths and limitations of asteroseismology, we can propose a mission design that will lead to breakthroughs in three broad areas:

- \bullet
	- SG1
	- SG2
	- SG3

assembly history and chemical evolution of the Milky Way's bulge and few nearby dwarf galaxies.

high-precision stellar astrophysics, especially in the metal poor regime

evolution and formation of stellar clusters

haydn: science goals

SG1 high-precision stellar astrophysics: need to perform tests in controlled environments, i.e. stellar open and globular clusters

haydn: science goals

SG1 high-precision stellar astrophysics: need to perform tests in **controlled environments**, i.e. stellar open and globular clusters

haydn: science goals

- Transport of chemical elements in the stellar interior
- Core rotation and transport of angular momentum
- Mass loss on the RGB
- Occurrence of mergers / products of binary evolution
- Tests of fundamental physics

high-precision tests of stellar models, especially in the metalpoor regime (early Universe)

evolution, formation and dynamics of stellar clusters SG2

haydn: science goals

- Globular clusters formation from absolute ages
- **•** Origin of multiple populations
- Measuring helium content in GCs with asteroseismology
- Redistribution of angular momentum from inclination of stellar spin axes

NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration Acknowledgment: J. Mack (STScI) and G. Piotto (University of Padova, Italy)

47 Tuc

extracted: blue, solar-like oscillations are detectable; yellow, information on the gravity-model periodical pe spacing can also be inferred; and green, rotationally split pulsation modes can be measured, hence haydn: mission profile extracted: blue, solar-like oscillations are detectable; yellow, information on the gravity-mode period spacing can also be inferred; and green, rotationally split pulsation modes can be measured, hence information on the internal rotational profile can also be inferred. We assume a mirror diameter is 90cm

all science objectives achievable with D=90 cm and a the duration of the observations (*right panel*). all Science Odjectives achievable with D-30 chi and a combination of 6-24 months-long runs all science objectives achievable with D=90 cm and a

haydn: mission profile

- ultimate tool to tests stellar physics \bullet
- infer precise, accurate ages \bullet

PART2: SUMMARY

- ultimate tool to tests stellar physics
- infer precise, accurate ages

 \bullet

simple mission concept would overcome limitations of past/current/planned missions

- high-precision stellar astrophysics SG1
- evolution and formation of stellar clusters SG2
- assembly history of the Milky Way's bulge and dwarf galaxies. SG3

PART2: SUMMARY

relevance and potential of asteroseismology demonstrated by CoRoT, *Kepler*

- ultimate tool to tests stellar physics
- infer precise, accurate ages

 \bullet

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simple mission concept would overcome limitations of past/current/planned missions

- high-precision stellar astrophysics SG1
- evolution and formation of stellar clusters SG2
- assembly history of the Milky Way's bulge and dwarf galaxies. SG3

PART2: SUMMARY

promote development of the next generation of stellar models

Final recommendations from the Voyage 2050 Senior Commi�ee

Voyage 2050 Senior Commi�ee: Linda J. Tacconi (*chair*), Christopher S. Arridge (*co-chair*), Alessandra Buonanno, Mike Cruise, Olivier Grasset, Amina Helmi, Luciano Iess, Eiichiro Komatsu, Jérémy Leconte, Jorrit Leenaarts, Jesús Martín-Pintado, Rumi Nakamura, Darach Watson.

Voyage 2050

May 2021

Global astrometry in the near IR as described in Section 2.2.2 would have a much broader impact as it would tackle various aspects of the above questions, as well as additional important open questions regarding the **ESA chooses future** science mission themes

11/06/2021 9077 VIEWS 103 LIKES

As trometry has significantly contributed to our understanding of the Universe, from the smallest scales of the smallest scales o

3 Potential Scientific Themes for Medium Missions

3.1.8 High Precision Asteroseismology $M_{\rm eff}$ missions are a key component of ESA's Science σ

SCIENCE & EXPLORATION

Asteroseismology is one of the most powerful tools for probing the structure of stars. It uses the variability of the light from the star produced by its pulsation modes to constrain the interiors of stars. Its final aim is to determine the physical properties and the internal structure of stars, such as how temperature, pressure, density, speed of sound, and chemical composition vary with radius. In the last decade, the research field of asteroseismology has experienced a revolution with the operation of several space missions whose main aim has been the detection of exoplanets, for example *Kepler*. determine the physical properties and the internal structure or stars, such as now temperature, pressure, achsity, speed of sound, and enermear composition vary with radius. There fast accauc, the research neid of telescope apertures and what orbital mass and what or interpretation or several space missions misse main anni mission, and can also require compromises on payload, instrument resolution, sensitivity, or time resolution.

A Medium mission designed to carry out pure asteroseismology would characterise stars in a wider range of (relatively homogeneous) stellar environments such as dwarf galaxies or the Galactic bulge, as well as Red Giant Branch stars that are relatively close to the Sun. Such missions would provide key information on stellar physics that would allow testing of stellar evolution models, especially when 2-D and 3-D modelling become widely implemented. Furthermore, and in combination with *Gaia* and large ground-based spectroscopic surveys, they would provide new insights into the star formation history and different phases of the assembly of the Milky Way. *Vermess and the first indirect exampless* has returned the first indirect evidence of one of the first indirect evidence of one o

Understanding how star formation proceeds in galaxies remains one of the major goals in the theory of

characterisation as planetary bodies.

https://www.asterochronometry.eu/haydn

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high-precision asteroseismology in dense stellar fields

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Patrick Eggenberger Mark Gieles Rob Izzard Daisuke Kawata Christoffer Karoff Nadege Lagarde Ted Mackereth Demetrio Magrin Georges Meynet Eric Michel

Josefina Montalbán Valerio Nascimbeni Arlette Noels Giampaolo Piotto Roberto Ragazzoni Igor Soszynski Eline Tolstoy Silvia Toonen Amaury Triaud Fiorenzo Vincenzo