

# Towards ensemble asteroseismology of the young open clusters $\chi$ Persei and NGC 6910

S. Saesen<sup>1</sup>, A. Pigulski<sup>2</sup>, F. Carrier<sup>1</sup>, G. Michalska<sup>2</sup>, C. Aerts<sup>1</sup>, J. De Ridder<sup>1</sup>, M. Briquet<sup>1</sup>, G. Handler<sup>3</sup>, Z. Kołaczowski<sup>2</sup>, B. Acke<sup>1</sup>, E. Bauwens<sup>1</sup>, P.G. Beck<sup>1,3</sup>, Y. Blom<sup>1</sup>, J. Blommaert<sup>1</sup>, E. Broeders<sup>1</sup>, M. Cherix<sup>4</sup>, G. Davignon<sup>1</sup>, J. Debosscher<sup>1</sup>, P. Degroote<sup>1</sup>, L. Decin<sup>1</sup>, S. Dehaes<sup>1</sup>, W. De Meester<sup>1</sup>, P. Deroo<sup>1</sup>, M. Desmet<sup>1</sup>, R. Drummond<sup>1</sup>, J.R. Eggen<sup>5</sup>, J. Fu<sup>6</sup>, K. Gazeas<sup>7</sup>, G.A. Gelven<sup>5</sup>, C. Gielen<sup>1</sup>, R. Huygen<sup>1</sup>, X. Jiang<sup>8</sup>, B. Kalomeni<sup>9</sup>, S.-L. Kim<sup>10</sup>, D.H. Kim<sup>10</sup>, G. Kopacki<sup>2</sup>, J.-H. Kwon<sup>10</sup>, D. Ladjal<sup>1</sup>, C.-U. Lee<sup>10</sup>, Y.-J. Lee<sup>10</sup>, K. Lefever<sup>1,11</sup>, A. Leitner<sup>3</sup>, P. Lenz<sup>3,12</sup>, A. Liakos<sup>7</sup>, D. Lorenz<sup>3</sup>, A. Narwid<sup>2</sup>, P. Niarchos<sup>7</sup>, R. Østensen<sup>1</sup>, E. Poretti<sup>13</sup>, S. Prins<sup>1</sup>, J. Provencal<sup>14</sup>, E. Puga Antolín<sup>1</sup>, J. Puschnig<sup>3</sup>, G. Raskin<sup>1</sup>, M.D. Reed<sup>5</sup>, M. Reyniers<sup>1</sup>, E. Schmidt<sup>3</sup>, L. Schmitzberger<sup>3</sup>, M. Spano<sup>4</sup>, B. Steininger<sup>3</sup>, M. Stęślicki<sup>2</sup>, K. Uytterhoeven<sup>13,15</sup>, J. Vanautgaerden<sup>1</sup>, B. Vandenbussche<sup>1</sup>, V. Van Helshoecht<sup>1</sup>, E. Vanhollebeke<sup>1</sup>, H. Van Winckel<sup>1</sup>, T. Verhoelst<sup>1</sup>, M. Vučković<sup>1</sup>, C. Waelkens<sup>1</sup>, G.W. Wolf<sup>5</sup>, K. Yakut<sup>1,16</sup>, C. Zhang<sup>6</sup>, and W. Zima<sup>1</sup>

<sup>1</sup> Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Leuven, Belgium

<sup>2</sup> Instytut Astronomiczny Uniwersytetu Wrocławskiego, Wrocław, Poland

<sup>3</sup> Institut für Astronomie, Universität Wien, Wien, Austria

<sup>4</sup> Observatoire de Genève, Université de Genève, Sauverny, Switzerland

<sup>5</sup> Department of Physics, Astronomy and Material Science, Missouri State University, USA

<sup>6</sup> Department of Astronomy, Beijing Normal University, Beijing, China

<sup>7</sup> Department of Astrophysics, Astronomy and Mechanics, University of Athens, Athens, Greece

<sup>8</sup> National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China

<sup>9</sup> Izmir Institute of Technology, Department of Physics, Izmir, Turkey

<sup>10</sup> Korea Astronomy and Space Science Institute, Daejeon, South Korea

<sup>11</sup> Belgian Institute for Space Aeronomy, Brussels, Belgium

<sup>12</sup> Copernicus Astronomical Centre, Warsaw, Poland

<sup>13</sup> INAF - Osservatorio Astronomico di Brera, Merate, Italy

<sup>14</sup> Department of Physics and Astronomy, University Delaware, USA

<sup>15</sup> Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot, Gif-sur-Yvette, France

<sup>16</sup> Department of Astronomy & Space Sciences, Ege University, Izmir, Turkey

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As a result of the variability survey in  $\chi$  Persei and NGC 6910, the number of  $\beta$  Cep stars that are members of these two open clusters is increased to twenty stars, nine in NGC 6910 and eleven in  $\chi$  Persei. We compare pulsational properties, in particular the frequency spectra, of  $\beta$  Cep stars in both clusters and explain the differences in terms of the global parameters of the clusters. We also indicate that the more complicated pattern of the variability among B type stars in  $\chi$  Persei is very likely caused by higher rotational velocities of stars in this cluster. We conclude that the sample of pulsating stars in the two open clusters constitutes a very good starting point for the ensemble asteroseismology of  $\beta$  Cep-type stars and maybe also for other B-type pulsators.

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## 1 Introduction

From the point of view of seismic modelling, the most important stellar parameters are masses, radii, luminosities, and effective temperatures. For single stars these parameters are usually poorly determined, especially for distant stars. On the other hand, if pulsators are members of an open cluster, the individual stellar parameters can be constrained much better. First, it can be safely assumed that the members have the same age, distance and chemical composition. In consequence, one can adopt that they are located on the

same isochrone. This helps to pinpoint stellar masses, especially if there are eclipsing binaries among cluster members that can be used to yield their masses and radii.

These considerations form a background for an *ensemble* asteroseismology of stars in open clusters, where individual pulsators need no longer be modelled independently. Through the location on the isochrone, the masses of stars and consequently their frequency spectra are closely related and can be matched simultaneously. In general, we would like to point out that this kind of modelling has great potential in terms of (i) understanding the pulsations of dif-

ferent groups of stars observed in a cluster, (ii) estimating the cluster parameters, and (iii) testing the physics, e.g., the opacities.

The possibility of ensemble asteroseismology motivated us to carry out multisite campaigns on three open clusters that were known to contain  $\beta$  Cep-type pulsators, and for which we expected to discover several more. The first cluster, NGC 3293, will not be discussed here. Preliminary results of the campaign on this cluster were presented by Handler et al. (2008). The other two clusters we selected are NGC 884 ( $\chi$  Persei) and NGC 6910. Before the campaign, two  $\beta$  Cep stars and some candidates were known in  $\chi$  Persei (Krzesiński & Pigulski 1997, 2000), four in NGC 6910 (Kołaczkowski et al. 2004).

The two open clusters,  $\chi$  Persei and NGC 6910, are different in many ways. The mass of  $\chi$  Persei is estimated to be  $3700 M_{\odot}$ , the age is about 14 Myr (Currie et al. 2010). NGC 6910 is about an order of magnitude less massive and much younger; the age of this cluster was estimated to be  $6 \pm 2$  Myr by Kołaczkowski et al. (2004). NGC 6910 is also more reddened than  $\chi$  Persei with considerable differential reddening: the range of  $E(B-V)$  colour excess amounts to 0.52–0.56 mag for  $\chi$  Persei and 1.0–1.4 mag for NGC 6910. The colour-magnitude diagrams (CMDs) for  $\chi$  Persei and NGC 6910 are shown in Figs. 1 and 2, respectively. While the main sequence of member stars can be clearly seen in the CMD of  $\chi$  Persei with only a small contamination of field stars, the CMD for NGC 6910 is severely contaminated. Due to the large (and differential) reddening, the cluster main sequence in Fig. 2 is smeared and located right of the bluest field stars.

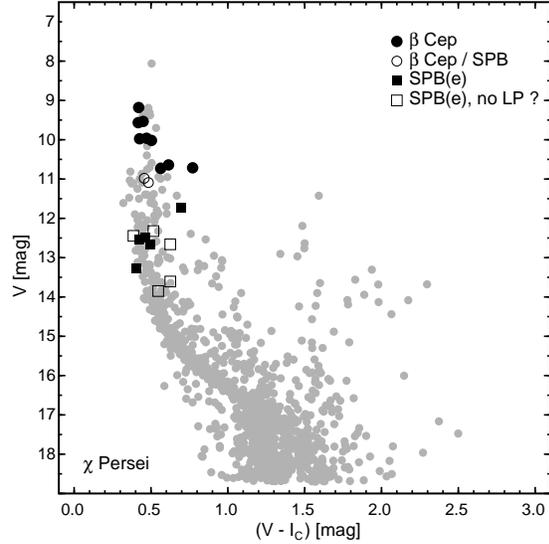
## 2 Observations, reductions and analysis

The campaign was carried out in three seasons, 2005–2007, involving about 70 observers who used 15 telescopes. For each cluster, over a thousand observing hours were obtained resulting in a detection threshold of about 0.2–0.3 mmag for periodic signals. A detailed description of the data obtained for  $\chi$  Persei was given by Saesen et al. (2010). The amount and quality of the data for NGC 6910 is very similar. For a detailed description of the calibration and reduction procedures, as well as the results of the variability survey in  $\chi$  Persei, we also refer the reader to Saesen et al. (2010).

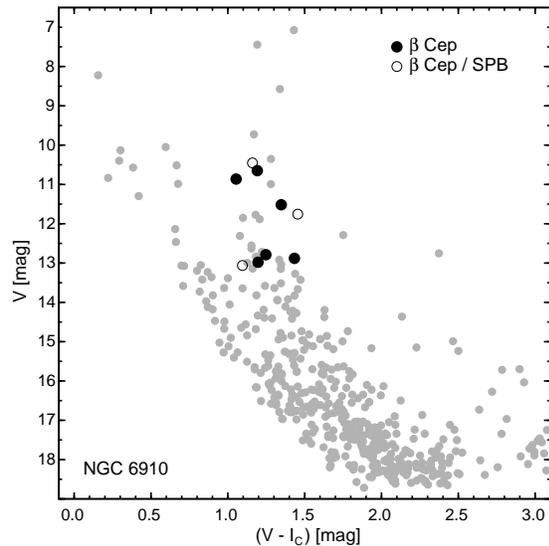
The results for NGC 6910 we are presenting here are based on the analysis of the data from only two sites, Białków and Xinglong. In terms of the amount and quality of the data, these two sites contributed mostly to the final result. The full variability survey for NGC 6910 will be published once all data are reduced and analysed.

## 3 Some results and discussion

Since we discovered many  $\beta$  Cep stars, we will focus on the differences in the frequency spectra of these stars in



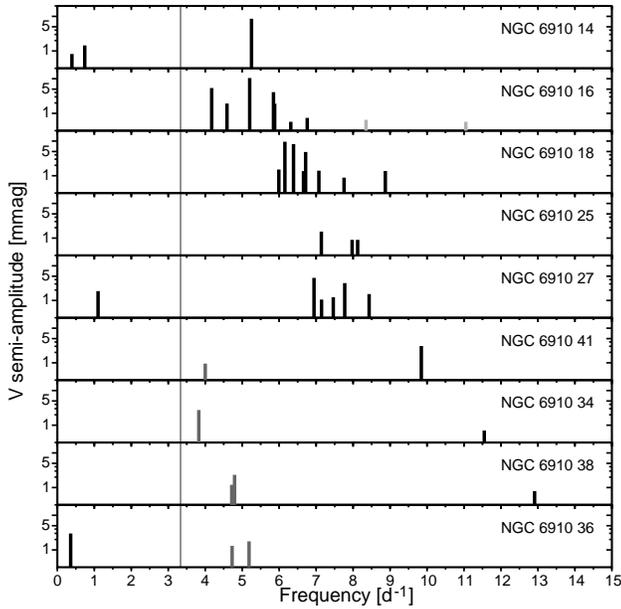
**Fig. 1** Colour-magnitude diagram for  $\chi$  Persei. The magnitudes and colours were taken from Keller et al. (2001) and Currie et al. (2010). The data were corrected for the systematic differences between these two sources of photometry. The diagram shows only those stars that were observed during the campaign. See text for the explanation of different symbols used to show variable stars.



**Fig. 2** Colour-magnitude diagram for NGC 6910. The photometry was obtained from the campaign data transformed to the standard system.

both clusters in our short discussion. However, there are other main-sequence pulsators in both clusters, in particular slowly pulsating B (SPB) and  $\delta$  Sct stars, that can also be used in seismic modelling.

In general, the separation in frequency between p and g modes in massive stars is relatively good for non-evolved stars. In the course of main sequence evolution, however, the frequencies of g modes increase eventually replacing the

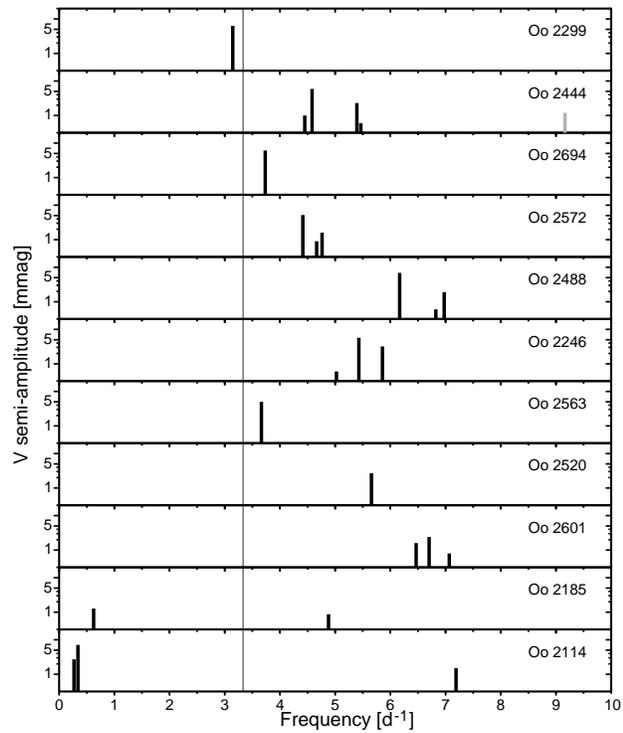


**Fig. 3** Schematic frequency spectra for nine  $\beta$  Cep stars in NGC 6910. The vertical line denotes a period equal to 0.3 d. The two light gray bars denote a combination mode and an harmonic. See text for the explanation of the dark gray bars.

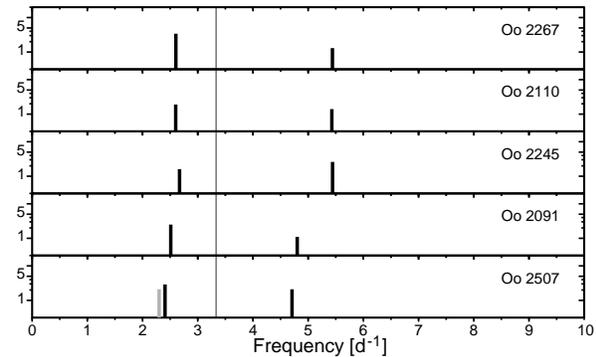
frequencies of p modes through avoided crossings. These modes are called ‘mixed’ due to their mixed character, g in the interior and p in the envelope. Although the occurrence of a p mode (or at least a mixed mode) is a prerequisite for the classification of a star as a  $\beta$  Cep-type variable, for lack of mode identification we usually use a more practical definition of a  $\beta$  Cep-type star. For example, early B-type stars showing periodic variations with periods shorter than 0.3 d can be termed  $\beta$  Cep stars (see, e.g., Sterken & Jerzykiewicz 1993). Following this definition, we classify eleven stars in  $\chi$  Persei and nine in NGC 6910 as  $\beta$  Cep stars (see Figs. 1 and 2). This makes the two clusters comparable to four other young open clusters known to be rich in  $\beta$  Cep stars: NGC 3293, NGC 4755, NGC 6231 and h Persei (NGC 869).

Accounting for differential extinction, we have plotted in Fig. 3 the frequency spectra of the nine  $\beta$  Cep stars found in NGC 6910 going from the brightest (top) to the faintest (bottom). This is also a sequence of decreasing mass. In addition, because of the same age and different masses, the sequence goes from more evolved to less evolved stars. A striking feature that can be seen in Fig. 3 is a strip of modes with increasing frequency when we go from more massive (bigger) to less massive (smaller) stars. This is exactly what is expected for p modes. Additionally, three  $\beta$  Cep stars in this cluster, NGC 6910-14, 27, and 36<sup>1</sup>, show the presence of low-frequency modes, which can be interpreted as g modes. These stars are therefore good candidate hybrid

<sup>1</sup> The numbers we use follow the Oosterhoff (1937) for  $\chi$  Persei and the WEBDA (<http://www.univie.ac.at/webda>) designation for NGC 6910.



**Fig. 4** The same as in Fig. 3 but for eleven  $\beta$  Cep stars in  $\chi$  Persei.



**Fig. 5** The same as in Fig. 3 but for five other stars from  $\chi$  Persei showing variability with periods shorter than 0.3 d.

$\beta$  Cep/SPB stars. Moreover, we see that, in the four faintest stars, another group of modes occurs (shown with dark gray bars). All they have frequencies in the range between 4 and 5.5  $\text{d}^{-1}$ . Without detailed modelling it is difficult to say if they are p or g modes; f mode(s) are also a possibility.

The frequency spectra for  $\beta$  Cep stars in  $\chi$  Persei are presented in Fig. 4. When we go from the most to the least massive  $\beta$  Cep stars in this cluster (from top to bottom in Fig. 4), the frequencies of the detected modes do not change as monotonically as in NGC 6910. The most likely explanation of this behaviour is the fast rotation of stars in  $\chi$  Persei. The projected rotational velocities,  $V \sin i$ , were measured for many stars in  $\chi$  Persei and for at least seven  $\beta$  Cep stars from our sample the values of  $V \sin i$  exceed  $100 \text{ km s}^{-1}$  (Strom et al. 2005, Huang & Gies 2006). Fast rotation re-

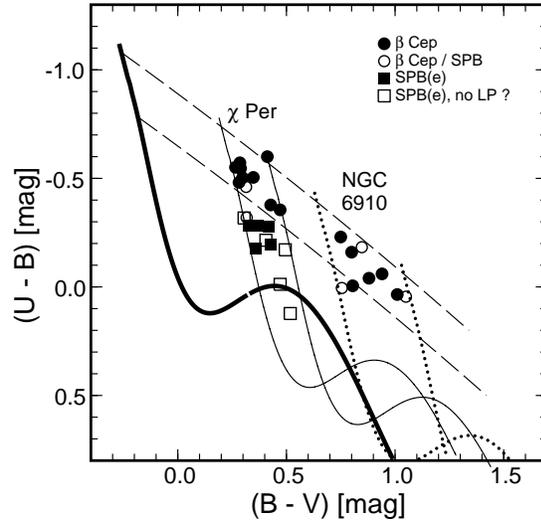
sults in considerable shifts in frequency for non-axisymmetric modes. Stars in NGC 6910 have no measurements of their rotational velocities, but there is only one Be star known in this cluster, whereas in  $\chi$  Persei 20 Be stars are known (Keller et al. 2001). This might mean that, on average,  $\beta$  Cep-type stars in NGC 6910 rotate much slower than stars of this type in  $\chi$  Persei. We also note two hybrid stars, Oo 2114 and 2185, with modes that have frequencies below  $1 \text{ d}^{-1}$ , presumably g modes.

Fast rotation in  $\chi$  Persei might also be responsible for the occurrence of several stars with periods shorter than 0.3 d which we do not classify as  $\beta$  Cep stars because, as can be judged from Fig. 6, they are mid- to late-B type stars. We divided them into two groups which are shown with different symbols in Figs. 1 and 6. The first group (shown with filled squares) consists of five stars. Their frequency spectra are shown in Fig. 5. These stars show bi-periodic variability; the period of one term is shorter than 0.3 d, the period of the other, longer. Four of the five stars have measured projected rotational velocities. They range from 150 to  $250 \text{ km s}^{-1}$ . In addition, Oo 2091 is known as Be star. According to many different observations, including ground-based data (Uytterhoeven et al. 2007), satellite data (Walker et al. 2005, Huat et al. 2009, Gutiérrez-Soto et al. 2010) and the surveys in the Magellanic Clouds (Kołaczkowski et al. 2006), this type of behaviour seems to be very common in fast-rotating stars. Their frequency spectra contain usually a large number of terms with frequencies clustering around two values; the ratio of these values is usually close to 2. Although not all five stars in  $\chi$  Persei we discussed above are known as Be stars, following Walker et al. (2005), we tentatively classify them as SPB(e) stars.

The second group consists of five other variable mid- to late-B type stars, Oo 2752, 2611, 2019, 2406, and 2228, shown with open squares in Figs. 1 and 6. However, compared to the first group, they show only terms with a period shorter than 0.3 d. If due to pulsations, the short periods can be explained by fast rotation: rotation can easily shift the frequencies of non-axisymmetric prograde g modes to the observed values. It is therefore quite possible that they are also SPB(e) stars in which long-period (LP), i.e., low-frequency term(s) are not detected due to low amplitudes.

The results of the variability surveys in  $\chi$  Persei and NGC 6910 which we partially presented here form a very good basis for the ensemble asteroseismology in both clusters. The fast rotation for  $\chi$  Persei stars is a complication, but, on the other hand, this cluster may help us to understand better the interaction between pulsations and rotation. There are two other open clusters,  $\eta$  Persei and NGC 3293, with a similar amount of data obtained during other campaigns. They are of similar age as  $\chi$  Persei and also contain many fast-rotating stars.

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**Fig. 6** The  $(U - B)$  vs.  $(B - V)$  diagram for the discussed stars in  $\chi$  Persei and NGC 6910. The thick line stands for the relation for unreddened luminosity class V stars (Caldwell et al. 1993). The two thin continuous lines denote the same relation shifted by the reddening vectors corresponding to  $E(B - V) = 0.46$  and  $0.68$  mag, a minimum and maximum reddening in  $\chi$  Persei. Similar relations for NGC 6910 are shown with dotted lines for  $E(B - V) = 0.9$  and  $1.3$  mag. Reddening lines, delimiting the range of spectral types for  $\beta$  Cep stars, are shown with dashed lines.

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