The LAMOST-Kepler Project: A Model of Win-Win Astronomical Cooperation

— An Interview with Peter De Cat

When astrophysicist Peter De Cat from the Royal Observatory of Belgium visited Xinglong Observatory in 2008, he learned from his Chinese colleague FU Jianning that LAMOST, the new 4m-aperture, 5 degree field-of-view telescope capable of acquiring 4,000 stellar spectra at a time, would be open to the Chinese community only. "What a pity," he thought. However, when his research with NASA's Kepler satellite went deeper, De Cat felt the urge to bring LAMOST in. The significance of such a space-ground combination is huge, and mutually beneficial. "Not only the more than 500 colleagues from the Kepler community can benefit from LAMOST data for their research, the intensive monitoring of this part of the sky also serves as a test bed for the performance of LAMOST itself," the project chair claimed. In the following interview with *BCAS*, De Cat looks back on how the collaboration was born, grew and prospered, and envisions the tasks to be fulfilled in a second round of LAMOST-Kepler survey starting from 2015.

BCAS: How did the LAMOST-Kepler project come into being in the first place? How do you see the significance of such a collaborative effort?

De Cat: I started to collaborate with Prof. FU Jianning in 2007, at that time for the project "rotation and pulsation in main-sequence gravity mode pulsators". For this project, we selected a few stars for intensive case studies to find out if there is direct observational evidence for the influence of rotation on the pulsations of two classes of pulsating stars.

We therefore used telescopes from all over the world to collect our data. One of them was the 2.16-m telescope of the Xinglong Observatory in China. The best way for a detailed study of the pulsations of a star is by collecting time series of high-resolution spectroscopy. It is well known that if you send the light of the Sun through a prism, the light will be split into all the colors of the rainbow. Each individual color corresponds to an electromagnetic wave with a unique wavelength. In high-resolution spectroscopy, this principle is applied to the light of a star, but in a very detailed way. Because the atmosphere of a star is composed of a mixture of chemical elements, the electromagnetic spectrum of a star shows what we call "absorption lines". At well-defined wavelengths, that are unique for each chemical element that the atmosphere of the star contains, we receive less light than what we would expect for a star that doesn't have these chemical elements in its atmosphere.

As the atmosphere of a pulsating star is moving all the time, these chemical elements are moving too. Because of the Doppler effect, the corresponding absorption lines will be deformed and are constantly changing in time. We can study these so-called line profile changes to find out which pulsations are causing them. Once we know the frequency and the type of the observed pulsations, we can compare them to those that are predicted by theoretical calculations. These calculations have some unknowns for which we can only guess their value. These parameters are linked to the internal structure and composition of the star and to the physical processes that are ongoing in their interior.

So, the pulsations of a star give us in an indirect way some information of its interior because the frequency spectrum of the pulsations is a fingerprint of the stellar interior. We are actually listening to the songs that the stars are singing. The song of the star is defined by its internal structure and composition and by the physical processes that are ongoing in its interior. This sound is unique, just like the sound of each music instrument is uniquely determined by the shape and the material the instrument is composed of. The study of stellar pulsations to have a look inside stars is what we call "asteroseismology". The

Figure 1 Position of the 42 CCDs of the Kepler space mission on the night sky. (Credit: C. Roberts)

desire to apply asteroseismic techniques to stars is the main driving force for both the project I mentioned before and for the LAMOST-Kepler project.

I came to the Xinglong observatory twice for observations: a first time in October 2008 for four nights and a second time in April 2009 for six nights. During these missions, I visited Prof. FU and he talked to me about this new 4-m telescope that was being constructed at that time and that would be capable of obtaining spectra for 4,000 stars in a circular field-of-view with a diameter of 5 degrees simultaneously. He told me that this instrument would be open to the Chinese community only. “What a pity”, I thought.

In March 2009, the Kepler space mission was launched. This mission was designed to detect Earth-like planets around solar-type stars with the transit method. Therefore, ultra-precise photometric observations would be gathered continuously, initially for three years, for thousands and thousands of stars in the “Kepler field”: a fixed field of 105 square degrees in the constellations Lyra and Cygnus (see figure 1).

The scientific observations of the Kepler mission started on May 2, 2009. I was asked to become chair of the KASC working group concentrating on the “Slowly pulsating B stars”: one of the classes of pulsating stars that we are studying in the project I mentioned in the beginning. KASC is the abbreviation for “Kepler Asteroseismic Science Consortium”. This is a community of more than 500 scientists that want to use the Kepler data for asteroseismic purposes. The ultra-precise Kepler light curves are indeed a goldmine for asteroseismic studies for pulsating stars of all types and flavors.

I also volunteered to become responsible for the gathering of ground-based follow-up data for the Slowly Pulsating B stars. These extra observations are needed because the Kepler light curves on their own are not sufficient to determine the basic parameters of the observed stars, like their temperature, gravity and chemical composition of their atmosphere. For some of these parameters, a first estimate was already available thanks to photometric observations that were obtained during the preparation phase of the Kepler mission.

All these results are collected in the so-called KIC, which stands for the “Kepler Input Catalog”. But the KIC does not contain parameters for all the targets that were being observed by Kepler, especially not for the faintest ones, and the accuracy of these values is not always good enough to be able to reach the asteroseismic goals. Compared to photometry, spectroscopic observations are much better because they can give extra information about the chemical composition, the radial velocity (the speed with which the star is moving away or towards us) and the rotation rate (the speed with which the star is spinning around its rotation axis). And then I realized: “The LAMOST is the only instrument that is capable of gathering the additional data that we need in an efficient way as it can observe up to 4000 objects at the same time.” This is especially the case for the faint targets because the brightest targets were already being observed with smaller telescopes elsewhere, in most cases on a one-by-one basis.

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Even though Prof. FU told me before that the LAMOST would only be open to the Chinese community, I took the liberty to contact him in October 2009 to discuss the basic idea I had in mind for the LAMOST-Kepler project: to gather low-to-mid resolution spectra for as many stars in the Kepler field-of-view as possible to obtain a homogeneous and accurate determination of the basic stellar parameters. Prof. FU was enthusiastic and told me that it would be possible to request observations with LAMOST in the Kepler field during the test phase and the pilot survey in 2010 and 2011 only, provided that we prepared a detailed observation proposal.

So that is what we did. I therefore contacted the 13 other sub-chairs of the KASC working groups that are responsible for the gathering of ground-based follow-up observations for the different types of pulsating stars. All of them supported the idea and together we prepared a proposal to observe 14 LAMOST fields to cover the whole Kepler field-of-view (see figure 2).

At the end of the pilot survey, only 4 of the 14 requested LAMOST fields were observed. This is partly due to the fact that the Kepler field is best visible during the summer, so in the period that the Xinglong Observatory is closed because of the monsoon. After these first two years of observations, the project was evaluated. Thanks to both the very promising preliminary results and the strong defense of Prof. FU, the importance and potential of the LAMOST-Kepler project could be demonstrated and our project received the top priority for observations from 2013 onwards, even though the general survey was already ongoing. This was unexpected but, of course, excellent news! In the meantime, all the requested LAMOST fields have been observed at least once under good conditions (see figure 2).

The importance of this collaborative effort is huge! Not only the more than 500 colleagues from the Kepler community can benefit from our data for their research, the intensive monitoring of this part of the sky also serves as a test bed for the performance of the LAMOST itself. Given the importance of this particular field-of-view, also data is being gathered with other instruments in the northern hemisphere. This is particularly true for the brighter objects, so by making sure that the observations of the LAMOST-Kepler project also include a sample of bright stars, the data obtained with other instruments can be used to improve the calibration of the LAMOST spectra and to get a better idea of the accuracy of the results obtained with LAMOST spectra.

BCAS: What did the project accomplish with its first round of survey?

De Cat: All of the requested LAMOST fields have been

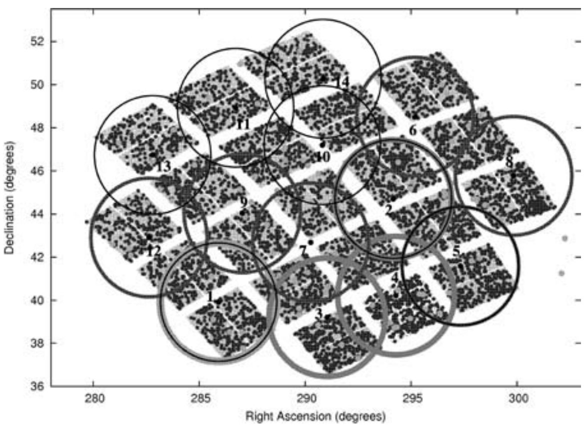

Figure 2 The targets in the Kepler field that are of scientific interest for the LAMOST-Kepler project. The black numbered dots refer to the centers of the 14 LAMOST fields that were chosen to cover the Kepler field. The LAMOST fields that have been observed in 2011, 2012, 2013, and 2014 are indicated by the circles drawn with a full line going from thick to thin and from grey to black, respectively.

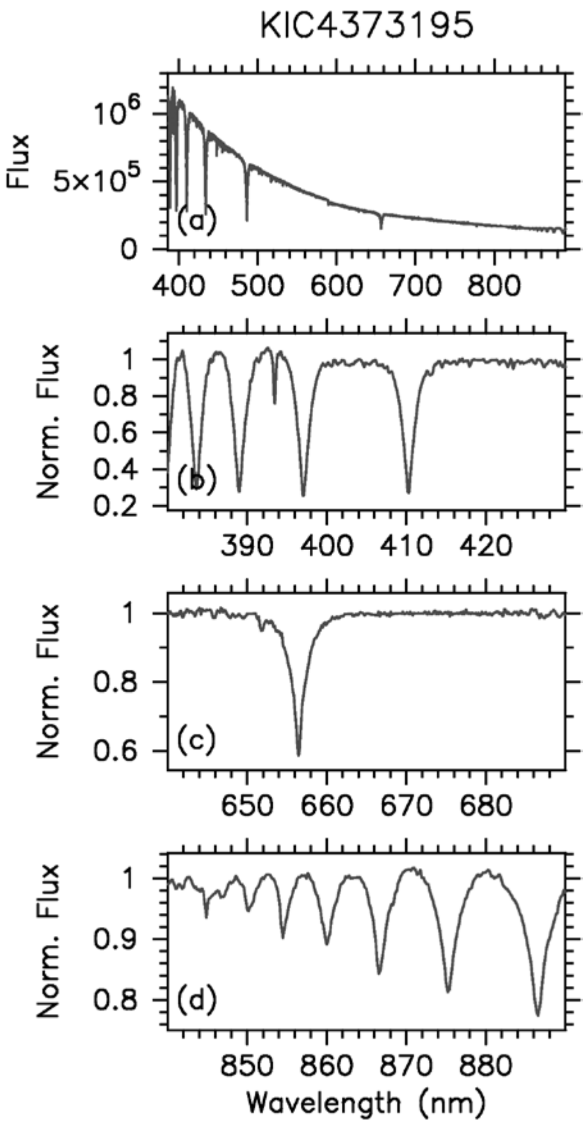

Figure 3 Example of a high-quality LAMOST spectrum for the Kepler star KIC4373195. In the different panels, we show the approximately flux calibrated spectrum in the full observed wavelength range (panel a) and the continuum-normalized fluxes in three different wavelength regions: 380-430 nm (panel b), 640-690 nm (panel c) and 840-890 nm (panel d). The spectrum reveals absorption lines that are typical for a hot star.

observed at least once by now. So far, more than 100,000 LAMOST spectra have been collected for LAMOST-Kepler project. We have data for more than 80,000 different objects of which about 17,000 do not have parameters in the KIC. In other words, we should be able to determine the basic parameters for about 17,000 objects for the first time with the LAMOST spectra! Unfortunately, the quality of not all of these spectra is good enough to guarantee reliable results. About 70% of the observed targets now have at least one high-quality spectrum such that the star can be removed from our target list (see figure 3). In total, almost 200,000 stars were observed by the Kepler mission. These targets are the most important ones for the LAMOST-Kepler project.

In May 2013, the Kepler observations ended after the failure of a second of the four reaction wheels. The spacecraft could no longer point towards the Kepler field-of-view in an ultra-stable way as before, so the exceptional precision of the light curves could not be reached any more. Of these 200,000 Kepler stars, about 20% already has a high-quality LAMOST spectrum after the first round of observations.

All the high-quality LAMOST spectra are now being analyzed by three different groups: one in China, one in Europe and one in the USA. Each of them is using an independent analysis code specifically adapted to the LAMOST spectra. The first results are very promising as the results obtained by the three teams seem to be consistent with each other for the majority of the objects. The calculations are nearly finished so the final results will be published in the very near future! I also receive requests from other colleagues that are interested in the use of the data of the LAMOST-Kepler project on a regular basis. This can be either for case studies or for global studies for particular types of stars.

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BCAS: How do you evaluate the performance of LAMOST, and the quality and scientific potential of its spectra?

De Cat: During the test phase of the LAMOST, in 2011, there were obviously some problems with the positioning of the fibers. For many fibers, we received much less flux than would be expected in the case that the fiber would be positioned exactly on the star. Moreover, there was still a lack of good standard stars that is needed for a good calibration of the spectra. Therefore, the reduction codes that are used to transform the raw LAMOST spectrum into a spectrum that is ready for scientific analysis failed to work in many cases. Only for about 15% of the fibers, the resulting LAMOST spectrum was of high quality. In the meantime, the situation has improved a lot. The pointing problems have been solved, each LAMOST field for the LAMOST-Kepler project already has a good set of standard stars and the reduction codes have been optimized.

The LAMOST is now a very well performing instrument! During the last observation season of the LAMOST-Kepler project, the percentage of fibers that lead to a high-quality spectrum almost reached the 70% level. If you take into account that 5% of the fibers is always used to observe the sky and doesn't contain an object at all, this is an extremely good result! Given its large field-of-view and the large numbers of fibers, the LAMOST has proven to be the best instrument available to gather low-resolution spectra for the determination of basic stellar parameters in an efficient, homogeneous and accurate way to characterize the stars in stellar fields in the northern hemisphere.

BCAS: Would you give a couple of examples to illustrate the scientific findings resulting from the collaboration?

De Cat: I already mentioned that one of the main results of the LAMOST-Kepler collaboration is that the basic stellar parameters are being determined for the first time for thousands of objects. And for many more objects, our knowledge of the stellar parameters is being improved. One of these basic stellar parameters is the metallicity. This is basically a measure for the amount of elements that are heavier than hydrogen and helium that are contained in the atmospheres of the stars. DONG Subo and his collaborators used 12,000 LAMOST spectra from the first two data releases and found that the metallicities of Kepler field stars as given in the KIC systematically underestimate both the true metallicity and the dynamic range of the Kepler sample. They also showed that, contrary to the KIC metallicities, the metallicities as derived from LAMOST spectra with the codes used in the Chinese group are in very good agreement with the metallicities that are derived from high-resolution spectra that are available in the literature. So the LAMOST metallicities should be preferred above KIC metallicities.

The LAMOST spectra also contain the Ca II H & K lines at 396.85 and 393.37 nm, respectively. These spectral lines can be used to measure the chromospheric activity of the observed stars. Christoffer Karoff and his collaborators used the LAMOST spectra of 7,700 main-sequence solar like stars with an effective temperature between 5,000 and 6,000 K to do this. From their analyses they concluded that, from a statistical point of view, the superflare rate of our Sun cannot be expected to be more than one every millennium. Such a superflare is a very energetic outburst that is caused by the magnetic field of the star. As a superflare can bring severe damage to our Earth, this is very good news!

BCAS: What is the plan for a second round of LAMOST-Kepler survey? What else is on the blueprint of this collaboration?

De Cat: During the second round of the LAMOST-Kepler survey we want to focus on the targets that have been observed by the Kepler mission as these targets can benefit the most from having accurate values for the basic stellar parameters. There are still more than 160,000 Kepler targets for which we don't have a high-quality LAMOST spectrum yet, so extra observation rounds are still very welcome! These targets will get the first priority.

The second priority will be given to those Kepler targets for which we already have a good LAMOST spectrum. With extra epochs it will be possible to check the consistency in the results and to search for close binaries. In close binaries, two stars are rapidly revolving around each other, so large changes in the radial velocity can be expected and these can be detected if the objects are observed on different nights. The rest of the fibers will be filled with other stars from the KIC and, if still needed, with other field stars that are not related to the Kepler mission at all. We are aware that it is unrealistic to expect that all the Kepler stars will be observed by LAMOST because the Kepler field also contains four open clusters. The star density in these clusters is simply too high to be able to observe all the Kepler targets in these clusters in a reasonable timespan. However, with a few more observation rounds, we can expect to have high-quality data for more than 80% of the Kepler stars, which would be an extremely good result!

The ultimate goal of the LAMOST-Kepler project is that the basic stellar parameters that are being derived from the LAMOST spectra will be used as basic ingredients for follow-up studies of stars that have been observed by the Kepler mission or for other stars that just happen to be in the observed field. The first such studies are already finished and we are convinced that there will be many more to come as soon as the results of the LAMOST-Kepler project become available to the astronomical community!