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The Keplerian revolution of variable stars

L. MOLNÁR[1]

(1) Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, H-1121 Budapest, Konkoly Thege Miklós út. 15-17, Hungary, molnar.laszlo@csfk.mta.hu

Abstract: The Kepler space telescope was conceived as an exoplanet statistics mission, but it turned out to be so much more. It has revolutionized many aspects of stellar astrophysics, ranging from pulsating stars to binaries and cataclysmic variables. Moreover, it has matured the field of asteroseismology, and, to quote Arthur Eddington from a century ago, finally allowed us to "obtain certain knowledge of that which is hidden beneath substantial barriers:" the insides of stars. In this short review, I present a few examples of the ways we achieved these breakthroughs.

Introduction

Almost a century ago, the great astronomer, Arthur Stanley Eddington, started his book, "The Internal Constitution of Stars", by addressing the scale of the problem in understanding stars:

"At first sight it would seem that the deep interior of the Sun and stars is less accessible to scientific investigation than any other region of the Universe. Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden beneath substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?" (Eddington, 1926)

Although the quote suggests that the problem seemed impenetrable by him at the time, it should be noted that Eddington then went on to explain that two things do escape the interior of stars, namely, gravity and light. However, these two messengers still carry only very limited information.

Therefore, we can assume that Eddington would be very pleased with the advances of stellar astronomy since his time: with the advent of helio- and asteroseismology, we found a third messenger from the insides of stars, namely, stellar oscillations (see, e.g., Deubner & Gough 1984). (A fourth one would be neutrinos, of course, but observations are currently limited to the Sun itself, see, e.g., Suzuki (2000), and references therein.) And with the advent of space-based, high-precision observations, especially with the *Kepler* space telescope, asteroseismology itself matured to a diverse and prolific field within astronomy.

A brief history of Kepler

A photometric space mission called *FRESIP* (FRequency of Earth-Sized Inner Planets) was envisaged in the early 1990's by Bill Borucki and his colleagues, based on their pioneering scientific and engineering work in the late 1980's. The mission, later renamed to *Kepler*, would search for transiting exoplanets by monitoring, initially tens of, in later proposals, hundreds of thousands of stars, continuously. The same observations would then be used for asteroseismology to characterise the planet hosts. The mission proposal was rejected by NASA four times, before finally accepting it as a Discovery mission in 2000. The telescope was launched in 2009, and went on to observe the original *Kepler* field-of-view for four years. A detailed summary of the development history, characteristics, and first results of the mission was written by Borucki (2016).

But in 2013, disaster struck: a second reaction wheel of the spacecraft failed, making stable pointing of the telescope impossible. Not all was lost, however, and after some frantic work, a new, ingenious mission was proposed. In the K2 mission, the telescope would point parallel to the Ecliptic plane, instead of perpendicular to it, to distribute the incoming sunlight as evenly as possible for extended periods of time, to minimize the unbalanced torque exerted by the radiation pressure of the Sun. The mission would also change fields-of-views about every 80 days to keep the Sun to the side of the telescope. Initial testing commenced in early 2014, and soon the K2 mission officially started (Howell et al. 2014). In hindsight, it is fair to say that what seemed as a tragedy at first, might have been the best thing that could possibly happen to the mission, as the new K2 fields opened up many new ways to do science with the space telescope (the sky coverage of the missions is shown in Fig. 1). Just one important aspect is that whereas the original *Kepler* mission looked at exoplanet statistics of often faint and distant targets, K2 can search for planets around nearby stars more effectively. And these planets, such as K2-18b (Benneke et al. 2017) will very likely be among the first targets of the James Webb Space Telescope.

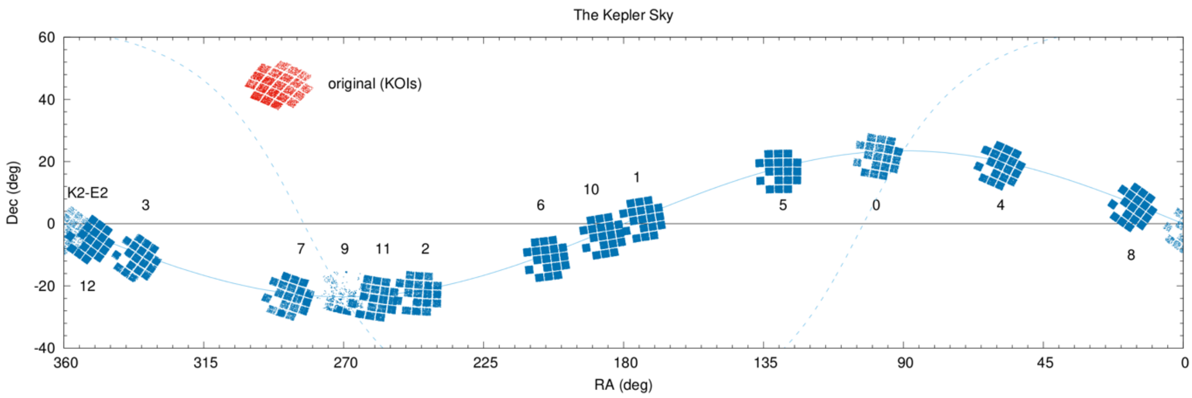

Figure 1: The sky, as observed by the *Kepler* and K2 missions. Blue dots represent the targets observed by K2 until Campaign 12. In case of the original mission only the *Kepler* Objects of Interest (KOI) are shown. Updated version of the figure used by Molnár, Szabó & Plachy (2016).

The asteroseismic revolution

Solar-like oscillations (SLOs) are the low-level brightness and radial-velocity variations of stars that are not classical pulsating stars, e.g. the oscillations do not form coherent standing waves. They are caused by convective motions inside the star that continually excite these evanescent modes. Observing the SLOs can be crucial to understand these stars, as the parameters of the oscillation spectra can be much more sensitive to the properties of the star, such as age, mass, radius, than regular spectral line parameters. And these parameters are important not only for stellar astrophysics, but also for exoplanet science, as basically all planetary parameters and their respective uncertainties are derived from the properties of its star. Therefore, a better handle on the stellar radius, for example, translates into a more accurate estimation of the bulk density and composition of its exoplanets.

Detecting the oscillation spectra of stars and deducing their global parameters and inner structure remained largely a promise until the arrival of space photometric missions. Successful ground-based observations were limited to a handful of stars only, and the interpretation was hindered by the potential confusion between alias peaks (caused by gaps in the data) and avoided crossings of different modes (deviations from the expected separations between the frequency peaks). A summary of early results was provided by Bedding and Kjeldsen (2003).

The landscape fundamentally changed with the launch of the first asteroseismic space telescopes, especially the French-led CoRoT mission (Baglin et al. 2006). Still, these observations were mostly limited to red giant stars whose oscillation amplitudes are one two orders of magnitude larger than that of main-sequence stars (Kallinger et al. 2010, Mosser et al. 2011).

Main-sequence stars and planet hosts

While detecting thousands of exoplanet candidates down to sub-Earth sizes was a huge accomplishment in itself by the *Kepler* mission, many of those candidates benefitted strongly from the asteroseismic analyses of their host stars (see, e.g., Silva Aguirre et al. 2015). One excellent example for constraining stellar and planetary parameters is the Kepler-93 system, where the mass of the star was determined to an accuracy of 3.6%, and the radius of the single transiting planet to 1.3% (Ballard et al. 2014). The latter, based on the combination of optical and infrared data from the *Kepler* and *Spitzer* space telescopes, translates to an absolute uncertainty of only 120 km. Another great example is the Kepler-444 system that hosts five small, sub-Earth planets, and asteroseismology revealed that it is older than 11 billion years, e.g., it is 2.5 times older than the Sun and has seen most of the 13.8-billion-year long history of the Universe (Campante et al. 2015).

Another interesting aspect of the asteroseismic analysis is that the relative amplitudes of the oscillation modes depend on the inclination of the rotational axis star. Since the inclination of a transiting exoplanet is confined to a small range, such measurements can reveal spin-orbit misalignments between stars and their respective exoplanets (Campante et al. 2016).

But main-sequence stars can be of importance on their own right, not just as exoplanet hosts. A prime example is the nearby, bright visual binary star, 16 Cyg A and B. Both stars were observed during the prime mission of *Kepler*. Independent model fits to their asteroseismic data indicated that the two stars have the same age (7.0 ± 0.3 Gyr) and chemical composition (Metcalfe et al. 2012, 2015). This is the result we expect from a binary star that is assumed to born from the same molecular cloud, at the same time, but it is reassuring that the results actually confirm this theory. Since the two stars are bright and relatively close to the Sun, it was also possible to measure their radii directly, via optical interferometry. The results agreed with the asteroseismic radii, indicating that the asteroseismic models that are based on the Sun are valid for other main-sequence stars as well (White et al. 2013).

The K2 mission also brought about the first ever asteroseismic detections of main-sequence stars in open clusters: oscillations of two members of the Hyades were identified by Lund et al. (2016).

Red giants

While stellar oscillations revealed a wealth of information about main-sequence stars, the modes we can observe are limited to the stellar envelope, because the pressure modes observable at the surface only penetrate the star to a certain depth. Gravity modes propagate within the core, but they diminish before reaching the surface, and hide the information they might carry. The *p*- and *g*-modes are also separated by oscillation frequencies. However, as stars start to evolve away from the Main Sequence, their cores contract and their envelopes expand, raising and lowering the limiting frequencies for g- and p-modes, respectively. Soon the two frequency domains start to overlap, and so-called mixed modes start to appear: modes that propagate a predominantly *g*-modes in the core, but may penetrate into the envelope and continue with the same frequency but as predominantly *p*-mode oscillations. Therefore, mixed modes are able to carry information about the core right out to the stellar surface and thus to our instruments, finally allowing us to really peer behind Eddington's substantial barriers.

P- and *g*-modes can be distinguished in the oscillation spectra based on their separation: while *p*-modes of consecutive order are separated (more or less) by equal frequency spacings, *g*-modes are separated by equal period spacings. Given the required sensitivity, e.g., by *Kepler*, one only has to disentangle the two interlaced combs of peaks (Beck et al. 2011). This method was then applied to separate two kinds of red giants in the initial *Kepler* observations. Some red giant stars are burning hydrogen in their shells surrounding their contracting, but not yet burning core. Other ones are already burning the Helium in their cores. Now, these stars look remarkably similar from the outside, and are notoriously hard to separate via conventional spectroscopy, complicating the studies of stellar populations and mass loss, for example. Since their cores are different, their *g*-mode spacings are also different (~50 s versus 100-300 s), and with *Kepler*, we were able to actually separate them for the first time (Bedding et al. 2011).

What else can we uncover about the interiors of red giants? Quite a lot, it turns out. A long-standing problem of stellar evolution is the transport of angular momentum inside stars. Basic physics principles tell us that the contracting cores of red giants should speed up. But when we finally get to see those cores as white dwarfs, they rotate relatively slowly again, in the order of days, meaning that the must have lost much of their core angular momentum. *Kepler* confirmed that this is indeed the case: the cores and envelopes of larger, e.g. more evolved stars rotate faster and slower, respectively (Deheuvels et al. 2014). However, soon after, the core rotation rates start to decrease (Mosser et al. 2012). Clearly, *Kepler* showed that our general picture on the evolution of red giant and red clump stars are correct: we only have to pin down the exact mechanism(s) that could transport the angular momentum away at the right rate.

Blue giants

Data from *Kepler* provided many surprising discoveries over at the hot side of the Hertzsprung-Russell diagram as well. Massive O- and B-type stars possess numerous physical processes that complicate their understanding. Here not the envelopes, but the cores of stars are convective, and they can be able transport and mix in fresh fuel from the bottom of the envelope into the core. Therefore, without the understanding of processes like convective overshoot, effects of fast rotation, magnetic fields, mixing, etc., even simple questions such as the lifetimes of these stars remain hard to answer. The original *Kepler* field was more or less limited to B-type stars only, but with the start of the K2 mission, we are now able to study the variations of the rare O-type stars as well (Buysschaert et al. 2015).

We have known for a long time that many B-type stars pulsate. High-precision observations revealed that several stars are in fact hybrid pulsators: they exhibit both β Cephei- and SPB (Slowly Pulsating B)-tye variations that originate from *p*- and *g*-mode pulsations, respectively (Balona et al. 2011). Given enough observable pulsation components, their modelling is analogous to that of solar-like oscillations: precise *Kepler* data led to the detailed analysis of several B-type stars (see, e.g, Pápics et al. 2014). One very intriguing finding that I selected to highlight is the possible presence of counter-rotating envelopes. While the internal rotation of stars can be complicated, as we have seen in red giant stars, we at least assume that the whole rotates in one direction. However, asteroseismic modelling indicated that B stars may experience counter-rotation between the core and the envelope, with layers that are essentially standstill within the star (Triana et al. 2015).

Another study showed periodic variations in many B-type stars, even for those that do not pulsate. These are likely caused by rotational variations, implying that these stars possess starspots generated by stellar magnetic fields (Balona 2016). However, since the envelope of B-type stars is not convective, these magnetic fields must originate from mechanisms different from the dynamo that operates in solar-type stars.

RR Lyrae and Cepheid stars

The first observations of *Kepler* revealed just how biased the gound-based observations can be. RR Lyrae stars pulsate with a characteristic timescale of half a day, which means that consecutive cycles are very hard to observe. As such, we had to wait until the arrival of continuous space-based photometry to discover the presence of period doubling in fundamental-mode RR Lyrae stars (Kolenberg et al. 2010, Szabó et al. 2011). The observations of the *Kepler* (and also, *CoRoT*) missions transformed our understanding of RR Lyrae stars. They are no longer seen as simple radial pulsators, but rather as stars with intricate dynamics between various modes that are further complicated by the presence of the Blazhko effect (see, e.g., Molnár et al., 2012, Benkő et al. 2014, Moskalik et al., 2015, Plachy et al., 2014, Szabó et al. 2014). However, despite the recent progress in the theoretical understanding of RR Lyae stars, and the emergence of new, promising proposal, such as the radial mode resonance hypothesis (Buchler & Kolláth 2011) an unambiguous explanation of the Blazhko effect is yet to emerge.

The field-of-view of the original mission included only a single, fundamental-mode Cepheid. Nevertheless, the analysis of the data set revealed many new details about this star. The *Kepler* observations of V1154 Cyg showed short-term variations in the pulsation and slower, low-amplitude modulation cycle. The data was precise enough to detect the granulation noise in the star, the first time for a Cepheid star. However, no signs of solar-like oscillations were found, suggesting that the pulsation inhibits or at least quenches other oscillation modes, even though granulation, an thus a convective layer is present in the envelope of the star (Derekas et al. 2012, 2017).

And across the HR diagram

It is impossible to account for all the discoveries *Kepler* made over the years in this short review, covering virtually all ranges of the HR diagram. It observed the rotational variations of brown dwarfs (Scholz et al. 2015) and M dwarfs (Davenport et al. 2015).

Observations of pulsating subdwarf and white dwarf stars also revealed surprising new findings. The differences between the *p*- and *g*-modes in the pulsating subdwarf B star KIC 3527751 indicate that the core of the star rotates almost three times slower than the outer envelope. This is the first indication of radial differential rotation in an sdB star (Foster et al. 2015). Some pulsating white dwarfs were found to show peculiar, repeating outbursts during which both the average brightness and the pulsation amplitude of the stars increase (Bell et al., 2015, Hermes et al. 2015). The duration of these outbursts is typically several hours, and thus they were easy to confuse with atmospheric extinction variations from the ground, and the lack of detection so far. The origin of these bursts is still a matter of debate.

Analysis of δ Scuti stars revealed convective motions can plausibly excite not only non-coherent, solar-like oscillations, but coherent pulsations as well (Antoci et al. 2014). With the K2 mission, of δ Scuti-type pulsations can be exploited even further. Stars may evolve through the instability strip not only as they leave the main sequence but as they evolve towards it. Pre-main sequence pulsators can be then used to examine the inner structure of very young stars via asteroseismic analysis (Ripepi et al. 2015, Zwintz et al. 2015).

The baseline of the original mission was also long enough to provide new insights into yellow and red supergiants. Analysis of the single RV Tau-type star displayed intricate changes in the pulsation amplitude and the order of low- and high-amplitude cycles (Bódi et al. 2016). A combined analysis of all M giants indicated that the transition from solar-like oscillations to pulsations occur at periods about 10 days, where the amplitudes start to grow faster than the scaling relation of the oscillation amplitudes (Bányai et al. 2015).

The extremes

The prosperity of the results delivered by the *Kepler* mission can also be illustrated by the extremes of the observations carried out. The faintest targets the mission has observed are in the *Kp* = 21-22 mag range, and include extragalactic RR Lyrae stars and supernovae (Molnár et al. 2015). The continuous temporal coverage of the mission was invaluable to detect the earliest stages of supernova explosions, including the shock breakout before a II-type event, and the non-detection of reflected light form a Ia-type supernova that suggested a merging white dwarf pair as progenitor (Garnavich et al. 2015, Olling et al. 2015).

Observations of very bright stars are hindered by the increasing saturation of the CCD modules. The saturation can be compensated by various means, such as collecting all saturated pixels, or using the smear data for science (Pope et al., 2016). And then, for stars in the *Kp* = 3-4 mag range, the reflection halo from the optical surfaces around the image of the stars can be exploited. This latter method was used to detect the variation of the O-type star HD 188029 that was located between the CCD modules during the original mission (Aerts et al., submitted). Halo photometry was also used to reconstruct the light variations of the brightest members (the seven sisters) in the cluster Pleiades (White et al., submitted). The difference between the faintest and brightest targets of *Kepler* is about 18 mag, a flux difference in excess of 10^7.

Conclusions

In this review, I presented a sample of discoveries from the *Kepler* and K2 missions to illustrate the rich and diverse accomplishments achieved with the space telescope so far. The mission has not only enriched the field of exoplanet research (Coughlin et al. 2016), but also provided an answer for the question Eddington proposed a century ago. Asteroseismology, employing high-precision time series photometry, has finally provided us with a tool to "obtain certain knowledge of that which is hidden beneath substantial barriers". And the work will be continued even after *Kepler* exhausts its fuel in 2018. The American TESS mission will provide us with data from the bright stars all around the sky. The first SONG telescope has finally, after a long wait, delivered the first results, collecting precise radial velocity measurements of bright stars from the ground (Grundahl et al. 2017). And in the next decade, the European PLATO mission will build on the legacy of *Kepler*, and expand the field of asteroseismology even further.

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