Space photometric applications in the K2 mission

NKFIH PD-116175 project

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Final scientific report

When the American Kepler space telescope broke down in 2013, many scientists feared that NASA's revolutionary astrophysical mission may had come to an abrupt and untimely end. Little did we know back then how fortunate we were. By late 2014, the telescope was back in business, and was given a new, rather experimental mission, called K2. With no pre-defined science cases in the new mission, the exploitation of the capabilities of the telescope were largely left to the scientific community. And the community responded with enthusiasm, expanding the scope of the mission into areas well beyond the telescope's original design. In 2015, I, too, formulated a research plan to explore some specific areas and use cases of the mission. Here I summarise my work over the three years and the results I obtained, as well as the new projects and initiatives that I have started based on them.

The advantages of the space photometric missions, such as MOST, CoRoT, and Kepler, have been their ability to deliver high-precision measurements almost continuously for extended periods of time, ranging from weeks to years. Kepler also had the advantage of carrying a large, 1-meter telescope that allowed it to reach faint targets. My research topics were also building on these aspects.

Photometry of large-amplitude variables

Data processing for Kepler was designed to detect small signals: shallow transits and minute stellar oscillations. I wanted to investigate stars that produce strong, and often rather fast light variations, RR Lyrae and Cepheid stars in particular. I started to work on methods to preserve both the full variation and the internal accuracy to detect small signals hiding behind the pulsations. I developed an alternate method, dubbed Extended Aperture Photometry, to process the data of these stars. Although we are still working on a final catalog of EAP light curves of these variable stars, many results for individual stars have been already published.

— I discovered granulation noise in V1154 Cyg, the only Cepheid-type star in the original Kepler mission. This is the first clear detection of such convective motions in a Cepheid. Even more interestingly, beyond the single coherent pulsation, we didn't detect any small oscillations that instead appear to be quenched. (Derekas et al., 2017 — I am a corresponding author.)

— We examined two old, type-II Cepheid stars, one of which is a member of a dense globular cluster. We clearly detected cycle-to-cycle variations in the pulsations in both stars, but the K2 observations were too short to pinpoint their origins (Plachy et al., 2017).

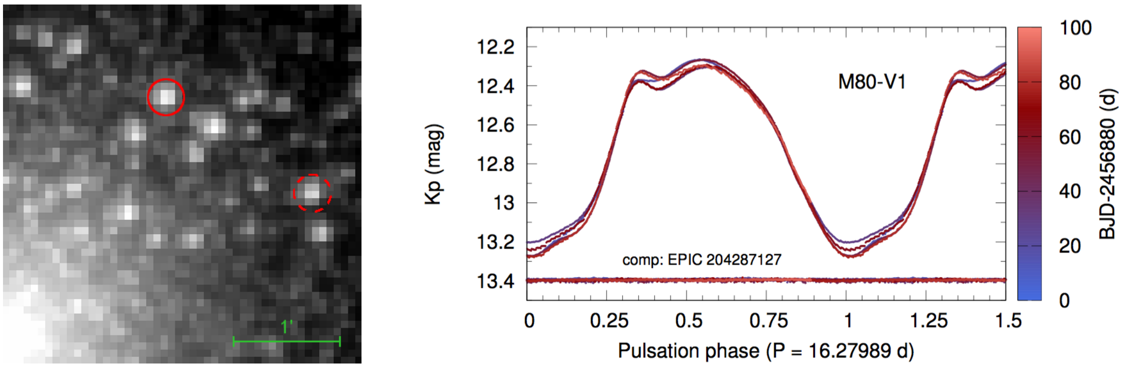

Figure 1: The type-II Cepheid M80-V1 (solid circle) and a non-variable star (dashed circle) in the globular cluster M80 in the K2 images, and the light curves I obtained (Plachy et al. 2017).

— Some preliminary results about the EAP method, such as false positive Cepheid candidates, the distribution of small additional modes in RR Lyrae stars, the behaviour of shockwaves connected to the pulsation, and a very rare, modulated double-mode RR Lyrae star were published in short publications and conference proceedings papers.

— A paper analyzing all double-mode RR Lyrae stars observed by K2, based on my EAP light curves is nearing completion: we show that virtually all of these stars exhibit very similar, low-amplitude extra modes (Moskalik et al. 2018, Nemec et al., in prep.).

— I discovered a few very peculiar stars in the globular cluster M80 whose K2 light curves are unlike normal RR Lyrae stars, yet they seem to have very similar physical properties. We started to collect spectroscopic observations with larger, ground-based telescopes, but further work will be needed to decipher the nature of these stars.

Synergies with other missions

— As Kepler/K2 wasn't able to observe certain Cepheid targets, I proposed a target for the Canadian MOST space telescope, a peculiar star that exhibits a modulated light curve. I detected period doubling for the first time in a classical Cepheid star from these data. This discovery strengthens the case that modulation and period doubling may arise from the same process (mode resonances) both in RR Lyrae and Cepheid stars (Molnár et al., 2017a).

— I joined the Data Processing and Analysis Consortium of the European Gaia mission that is mapping more than 1.5 billion stars in the Milky Way. I contributed to the second data release of the mission by validating some of the variable star detection methods. I cross-matched the Gaia candidates with the confirmed Kepler/K2 targets, and showed that the mission already performs well for single-mode pulsators, and has a completeness rate between 70-78% (Molnár et al., 2018a; Holl et al., 2018). The impact of the Gaia mission can be best demonstrated with the fact that the large consortial papers from DR1 and DR2, which I also co-authored, gathered more than 3000 citations so far.

Photometry of moving objects

A key element of the K2 mission was that the fields the telescope surveyed were distributed along the Ecliptic plane. This meant that many Solar System objects fell into the fields of view of the mission. Although Kepler was developed to observe stationary objects in the sky, it turned out that observing moving objects was not impossible with it either. In order to interpret and model the light curves of Solar System objects obtained by Kepler, I helped to form a new research group that consisted of both photometry and planetary science experts. I, together with András Pál, developed the first software pipeline to extract the brightness measurements of moving objects in the K2 mission.

Distant objects

Our initial studies, during the formulation of my research plan, suggested that Kepler is capable to detect rotational variations even in very faint objects. Although I initially planned to focus on Trans-Neptunian Objects (TNOs), we soon diversified our sample with other interesting targets: small, irregular moons of Uranus and Neptune, and some centaurs. Centaurs are thought to be former TNOs that have been perturbed inwards, and orbit, temporarily, among the giant planets, thus appear brighter for us. Our results, so far:

— An unexpectedly long rotation period for the large, unnamed dwarf planet, (225088) 2007 OR10, spanning 45 hours. Thermophysical modeling using this period and infrared measurements revealed that the dwarf planet is considerably darker, with a deep red color, and larger than previously thought, with an R=1535 km radius. This makes it the third largest dwarf planet after Pluto and Eris (Pál et al., 2016). The slow rotation rate hinted at the possibility of a moon that was later discovered by others in the Hubble images of the object.

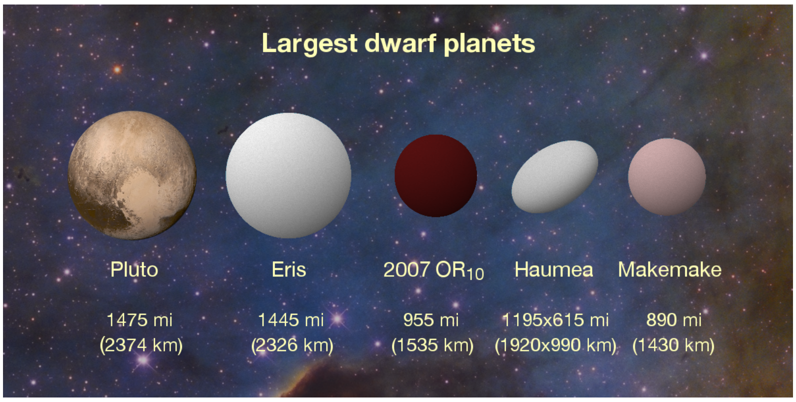

Figure 2: our press release image, showing the relative sizes and colors of the five largest dwarf planets. 2007 OR10 is as dark and red as the darkest patches of Pluto. (A. Pál/ L. Molnár, Pluto: NASA/JHUAPL/SwRI, background: Iván Éder)

— Precise light curves and detection or confirmation of the rotation rates and amplitudes of Neptune's moon Nereid, and five distant moons of Uranus. In one paper we constructed a detailed thermophysical model for Nereid, and showed that it is only slightly elongated, and likely has a rough, very cratered surface. In another paper, we argued that the irregular moons of Uranus are more similar to centaurs and TNOs than the moons of the inner giant planets, suggesting different origins (Kiss et al., 2016, Farkas-Takács et al., 2017).

— I derived rotation periods for six of the observed ten centaurs. The new values are generally longer than those that were known beforehand. Multiple of our targets with periods longer than 20 h could potentially be binary objects. This paper, led by Csaba Kiss, was submitted for review on 04/01/2019.

Trojan and main-belt asteroids

Trojan asteroids that share their orbit with Jupiter in a 1:1 resonance. I analyzed light curves of 56 members of the L4 (leading) cloud. I found that a surprisingly high fraction rotates slowly, over 2 days, and that about a quarter of the objects might actually be binary objects. The lack of fast rotators among our sample indicate less rigid, icy bodies that migrated inwards from the outer Solar System, and not outwards from the main asteroid belt (Szabó et al., 2017).

We also collected chance observations of some 1600 main-belt asteroids that crossed larger image mosaics in the K2 data. I was able to determine rotation rates for only subset of these, about 150 objects, but even this sample clearly showed that the median rotation rate of asteroids is significantly longer than what was suggested by ground-based data. I also identified objects that are tumbling around multiple axes and ones that possibly show eclipses from a secondary object (Szabó et al., 2016; Molnár et al., 2018b).

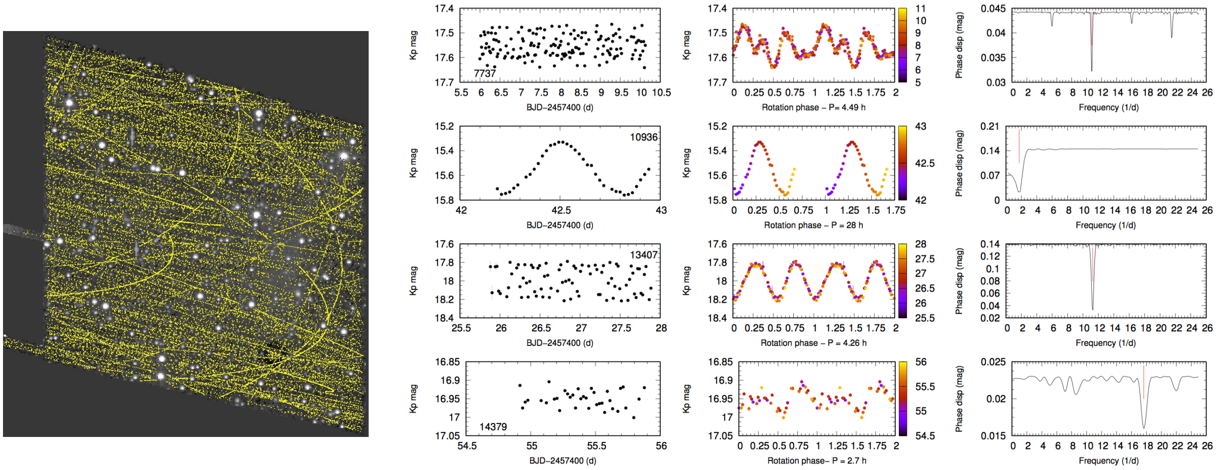

Figure 3. Left: the tracks of all known asteroids that crossed the Uranus superstamp during Campaign 8 of the K2 mission. Right: light curves, phase curves, and our phase dispersion metric I computed to detect periodicities in the data, of four different asteroids (Molnár et al. 2018b).

Towards the last K2 campaigns we proposed targeted observations of main-belt asteroids. The first result from these, a detailed spin and shape model of (100) Hekate, is ready to be submitted, as part of a larger survey (Marciniak et al., in prep.).

Faint objects and extragalactic variables

The third topic of my grant has been the detection of faint, extragalactic variable stars, at the limits of the capabilities of Kepler. Of the three topics I proposed, this turned out to be the most challenging. I was able to extract data for three RR Lyrae stars in the small dwarf galaxy Leo IV with relative ease, and those were published even before the project started. The other targets, however, were plagued with instrumental problems. Kepler experienced excess attitude changes while observing the Sagittarius stream field. I showed in our Gaia validation paper that the baseline light curves for this field can suffer both from flux loss and from blending with nearby stars. The EAP method also runs into problems with these data. While I have plans to mitigate these issues, this will require further experiments and rather intensive processing of the image data that I postponed for the sake of the other topics.

Observations of the Cepheids in the nearby dwarf galaxy IC1613 fared somewhat better. However, while this observing campaign was uneventful, the particular CCD module that covered the galaxy experienced various noise issues (rolling bands and Moiré patterns moving across the pixels). These noise sources have minor effects on brighter stars, but are comparable to the weak signals of my targets, and contaminate large parts of the light curves. I was able to measure a subsample of stars that hint at the presence of small additional modes in some of them. I presented some initial results at conferences and in a proceedings paper (Molnár et al., 2017b). However, mitigation of the noise sources to confirm any low-amplitude modes will require further processing (e.g., variable image background models).

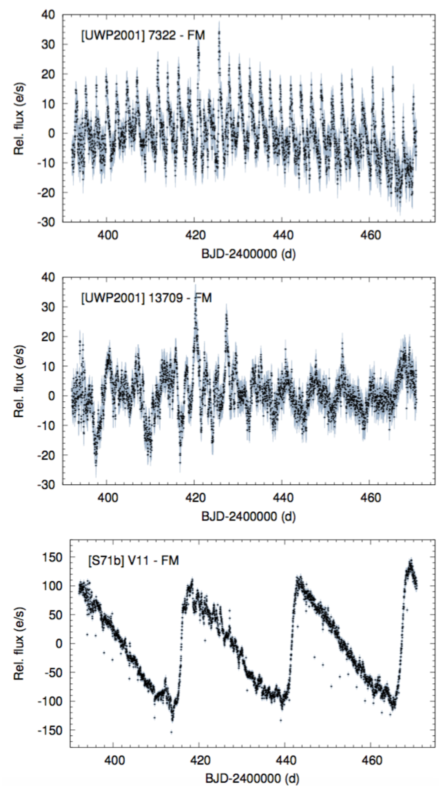

Figure 4: Light curve examples from IC1613. The middle one shows severe systematics in the first half of the campaign, distorting the pulsation signal.

I have to reiterate that this topic has been the most challenging and experimental one from the proposal. Despite the issues experienced, these problems are not prohibitive, and I expect that good results can be obtained after further work has been carried out.

Collaborations

In the research plan I proposed one longer visit to a group that works on K2 data. Instead of that, I expanded my network of collaborators through multiple shorter visits to various places (Universities of Aarhus, Leuven, Antwerp, Birmingham, and Leiden). In 2017-18, these were often connected to the TESS Data for Asteroseismology workshops where we started to prepare for mass processing and analysis of data from the TESS mission, the successor of Kepler.

During the project I supervised one BSc and one MSc thesis connected to the grant.

We also continue to work on moving objects that cross the fields of view of TESS, and published a simulation of the expected yields from the mission, and adapting the K2 pipeline to work with TESS data (Pál et al., 2018).

Dissemination of the results

Over the three years I authored 30 papers directly connected to the grant, 13 of those in journals with impact factors. I was first or corresponding author in 12 (4 with IF) of them. I gave two invited review talks, and presented numerous contributed talks and posters at various conferences, including a contributed talk during the IV. Kepler and K2 Science Conference at NASA Ames Research Center.

We successfully submitted a press release to NASA under the title "2007 OR10: Largest Unnamed World in the Solar System", a rare achievement for researchers working in Hungary. Our K2 results about 2007 OR10 gained widespread international interest when they appeared at NASA and JPL.

I submitted two English press releases about two other papers at the science news aggregator site phys.org under the titles "Kepler has caught hundreds of asteroids" and "Kepler watched a Cepheid star boil". I was featured in the Hungarian journal *Élet és Tudomány* as researcher of the week in late 2016, and authored an article about the conclusion of the K2 mission in late 2018. My results were further publicized in three online articles at csillagaszat.hu [1, 2, 3], and one Hungarian press release at mta.hu.

Grants and awards, achievements

The papers connected directly to my project collected 165 citations since 2016.

I was honored with the *Junior Prima Award* in Hungarian Sciences in 2016. I received the Excellent Researcher of the CSFK Awards in 2017 and 2018.

I successfully applied for a Bolyai Research Scholarship alongside my project, and then for the MTA Premium Postdoctoral Scholarship to continue my research after this grant has expired.

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The full bibliographic database of the grant can be accessed here, in the SAO/NASA Astrophysics Data System: https://ui.adsabs.harvard.edu/#user/libraries/0sArM6jtSkOuk5Z92CnWfA.

A summary page of my results: http://www.konkoly.hu/KIK/PD116175.html.

Budapest, 18/01/2018

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