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The Impact of CoRoT and *Kepler* on Eclipsing Binary Science

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Abstract. The CoRoT and *Kepler* space missions have opened a new era in eclipsing binary research. While specifically designed for exoplanet search, they offer as by-products the discovery and monitoring of variable stars, in great majority eclipsing binaries (EB). The missions are therefore providing thousands of EB light curves of unprecedented accuracy (typically a few hundred parts per million, ppm), with regular sampling (from 1^{s} to 29^{m}), extending over time spans of months, and with a very high duty cycle (> 90%).

Thanks to this excellent photometry, research topics as asteroseismology of EB components are quickly developing, and physical phenomena such as doppler boosting, theoretically predicted but extremely difficult to observe from the ground, have been unambiguously detected. We present the main properties of the Corot and *Kepler* EB samples and briefly review the highlights of the missions in this field.

Keywords. binaries: eclipsing, stars: oscillations, surveys

1. CoRoT and *Kepler* space missions

CoRoT† (COnvection, ROtation and planetary Transits) is a French-led international "small" space mission launched in December 2006. The mission is devoted to the achievement of two parallel "core programs," asteroseismology and extra-solar planet search, which require the same type of observations, i.e. high accuracy photometry and long continuous monitoring. These programs are carried out in two contiguous "seismo" and "exo" fields, with a 27 cm telescope and four CCDs of 1.3° × 1.3° on the sky. After launch each field was covered by two CCDs, the observations were performed in Long and Short runs lasting, respectively, ∼ 150 and ∼ 30 days, and for each run up to ten bright ($5.7 > V > 9.5$) seismo-targets and up to 12000 exoplanet targets ($11.5 > V > 16.5$) were observed. Unfortunately, the number of observed targets dropped to half after the loss in March 2009 of one of the two data processing units. That event induced as well a

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† The CoRoT space mission was developed and is operated by the French space agency CNES, with participation of ESA's RSSD and Science Programmes, Austria, Belgium, Brazil, Germany, and Spain; complete information is available at http://corot.oamp.fr

change in observing strategy (shorter "Long" runs of $\sim$ 80 days have also been scheduled to increase the total number of targets).

CoRoT has provided high-accuracy (10^{-3}–10^{-4} mag) photometry of about 140,000 stars in a broad bandpass spanning 370 − 1000 nm. Chromatic information was also obtained for exo-planet targets brighter than $V = 15$.

Only a handful of EBs were observed in the seismo-field, as binaries are in general rejected in the target selection process. Sometimes, however, binarity is discovered by CoRoT itself (e.g., Maceroni *et al.* 2009). The standard sampling of the seismo field is $32^{\rm s}$, the fast one $1^{\rm s}$, yielding light curves with hundred thousands or millions of points and a point-to-point deviation of the order of 10^{-4} mag.

Most CoRoT EBs are exo-field targets, which are sampled at a standard rate of $8^{\rm m}$ or a fast one of $32^{\rm s}$. The light curves contain from 8000 to 300,000 points. An estimate of the white noise level as function of target R-magnitude (Aigrain *et al.* 2009) yields 0.5 mmag for $R = 12$ and 2 mmag for $R = 15$.

The classification of variable stars in the exo-fields is performed by the CoRoT Variability Classifier (CVC, Sarro *et al.* 2009, Debosscher *et al.* 2009), which provides a probabilistic classification in 29 different variability classes. Independent, and somehow different, lists of binaries have also been published for the first runs by the exoplanet search teams (Carpano *et al.* 2010, Cabrera *et al.* 2009, Carone *et al.* 2011) containing the EBs rejected by the planet search algorithms or subsequent follow-up observations.

So far nineteen different fields have been observed by CoRoT (and the data of the first ten are public†), the results we present in this paper, however, refer mainly to $\sim$ 400 EBs from the first CoRoT runs (IRa1, LRc1, LRa1) as for these fields EB samples from both CVC and exoplanet search are available.

CoRoT's trail is being widened by the *Kepler* space mission, thanks to its higher performance instrumentation and longer monitoring of targets. *Kepler*, NASA Discovery mission #10, was specifically designed to discover Earth-size planets and is in operation since March 2009. The details of the mission can be found elsewhere (e.g., Borucki *et al.* 2010, Koch *et al.* 2010). In short, *Kepler* monitors $\sim$ 156,000 stars of interest (preferentially late type dwarfs) in a field of view extending over 105 deg^2 in the Cygnus - Lyra region. The standard photometry sampling is $29.4^{\rm m}$ ("long cadence") but up to 512 stars can be observed in "short cadence" mode ($59^{\rm s}$). The effective dynamic range is 7–17 *Kepler* magnitudes (K_p, in a broad bandpass from 425 to 900 nm). The target continuous monitoring can last up to the mission lifetime (the programmed 3.5 years or longer in case of extension). The estimate of the instrument performance after launch (Koch *et al.* 2010) indicates that the design goal (a photometric precision of 20 ppm for a 6.5 hr exposure of a G2-type $V = 12$ target) is close to being achieved.

Kepler data are delivered in "Quarters" (Q0, Q1, ..., Qn), typically three months long (a quarter ends when the spacecraft rolls to re-align its solar panels). Quarter Q10 is currently in progress, the first quarters (Q0–Q3) are publicly available‡.

In addition to the exoplanet core program, scientific programs devoted to the asteroseismology of *Kepler* targets have been devised and outsourced to the European *Kepler* Asteroseismology Consortium (KASC), which maintains its own archive (KASOC). Subscription to this Consortium (open to collaboration) allows access to all the KASC data.

A comprehensive catalog of 1832 *Kepler* EBs, detected in the first two quarters Q0-Q1, has been published by Prša *et al.* (2011) and updated with the addition of Q2 data by Slawson *et al.* (2011). The current version contains 2165 eclipsing or ellipsoidal binaries.

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† the Archive is mantained by the CoRoT Data Center at IAS, http://idoc-corot.ias.u-psud.fr/
‡ available from the Multimission Archive at STScI (MAST) http://archive.stsci.edu/Kepler/

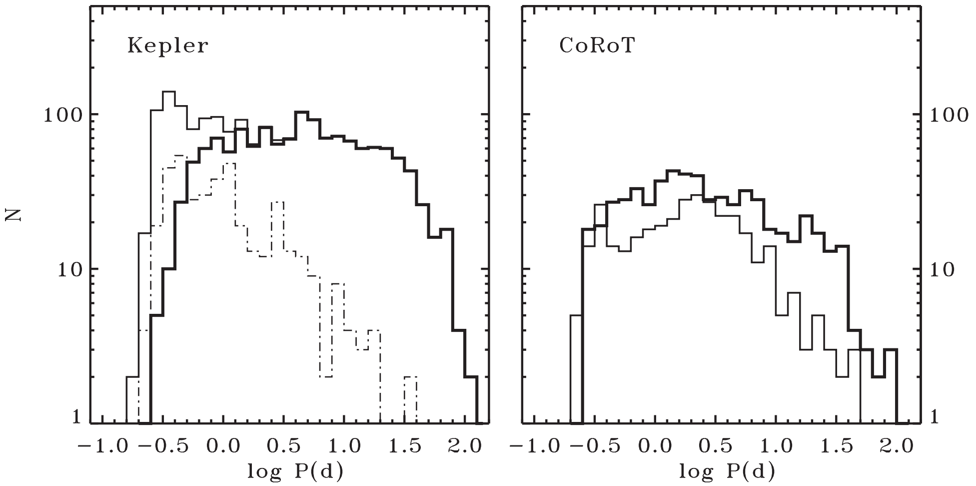

Figure 1. The period distribution of *Kepler* and CoRoT binaries. Left panel, thin line: all systems of Q0-Q2, thick line: detached and semidetached binaries only. For comparison the distribution of OGLE-I binaries with I< 16.5 is shown (dotted-dashed line), its quick decline is due to period dependent selection effects, affecting shorter periods for a ground based survey. Right panel, thin line: CVC sample (IRa1, LRa1, LRc1 fields), thick line: exoplanet sample for the same fields. The difference is related to the adopted filtering methods (see text).

2. CoRoT and *Kepler* eclipsing binaries

CoRoT and *Kepler* have provided light curves of unprecedented precision, sampling and extension. All these assets contribute to the increase of EBs frequency, which is about twice the value typical of ground-based surveys, as EBs with eclipses of smaller amplitude and shorter fractional eclipse duration are detected; see the comparison of CoRoT EB sample with that of OGLE-I in Maceroni (2010). The EB frequency of the first CoRoT fields is 1.2% of all targets. A similar, slightly larger, value of 1.4% is found by Slawson *et al.* (2011) for the first *Kepler* Quarters.

The higher efficiency of discovery of the space missions is evident as well in the orbital period distributions in Fig.1, showing different subsamples of EBs and a comparison with OGLE-I EBs of magnitude I > 16.5.

The difference between the CoRoT sample from CVC and that from exoplanet search is due to the different filter applied to extract binaries. The Fourier-based CVC algorithm fails more frequently for longer period narrow V-shaped eclipses, especially if additional (quasi-) sinusoidal variability is present (the target is classified in another variability class). On the other hand the exo-planet algorithms, designed to detect U-shaped variations, misses short period (W UMa type) binaries. The CVC algorithm has been recently improved, to better handle binary extraction, so one can expect better agreement between the two sources for the following fields.

In both figures, and more markedly in the *Kepler* sample one, the log P distribution shows an almost flat behavior for periods larger than 1^d. Besides, the histograms suggest that the higher the precision, the more complete the sample for low amplitude detection, and the wider the "plateau" of the distribution. A flat log P distribution, implying no preferred length scale for the formation of short-period binaries (Heacox 1998) is in agreement with the results of Mazeh *et al.* (2006) for a quite different sample (LMC B-type EBs).

3. CoRoT and *Kepler* highlights

It is obviously impossible to concentrate in a few pages a comprehensive review of CoRoT and *Kepler* results of relevance to close and eclipsing binaries. However, already a few highlights will provide an idea of the outstanding achievements of both missions.

Eclipsing binaries with pulsating components. Most EBs light curves of *Kepler* and CoRoT present additional variability on the top of eclipses. This is often due to surface inhomogeneities (stellar activity) but another frequent cause is intrinsic stellar pulsation, which is monitored continuously and on long time spans. Pulsations undoubtedly make the analysis more complex, but add valuable information from an independent source. In a close binary, moreover, the influence of tides on surface stability can also be studied.

A good example is the case of CoRoT (seismo) target HD 174884 (Maceroni *et al.* 2009), an unusual eccentric eclipsing binary with twin B-type components but eclipse depths differing by factor of $\sim$ 100. The analysis of the light curve of a few hundred ppm precision allowed to detect pulsations with amplitude of a few hundred ppm and frequencies exact multiples of the orbital one (8 and 13 f_{orb}), which were interpreted as tidally excited pulsations.

Another interesting system is CoRoT 102918586, whose light curve is shown in Fig. 2 together with the Fourier spectrum after subtraction of the EB model, see Maceroni *et al.* (2010) for a description of the method. It is as well an example of the difficulties in the analysis when pulsations and eclipses are of comparable amplitude. The first analysis – presented in the above-mentioned paper and based on the CoRoT photometry alone – assumed a configuration with two very similar F0 dwarfs in a circular orbit and a period $P \simeq 8.78^{\rm d}$. The short fractional eclipse duration implied, however, very small fractional radii of the components (and no tidal deformation). On the other hand the light curve residuals, after subtraction of the binary model, contained harmonics of the orbital period, difficult to explain in terms of tidally excited pulsations, the stars being spherical and in circular orbit. The subsequent acquisition of high-resolution time-resolved spectroscopy has solved the issue: the true orbital period is half the value from photometry; the system is still formed by similar components (SB2) but the orbit is eccentric, and because of orientation in space only one eclipse is observed. The harmonics of the orbital period derived from the out of eclipse shape of the binary light curve, while

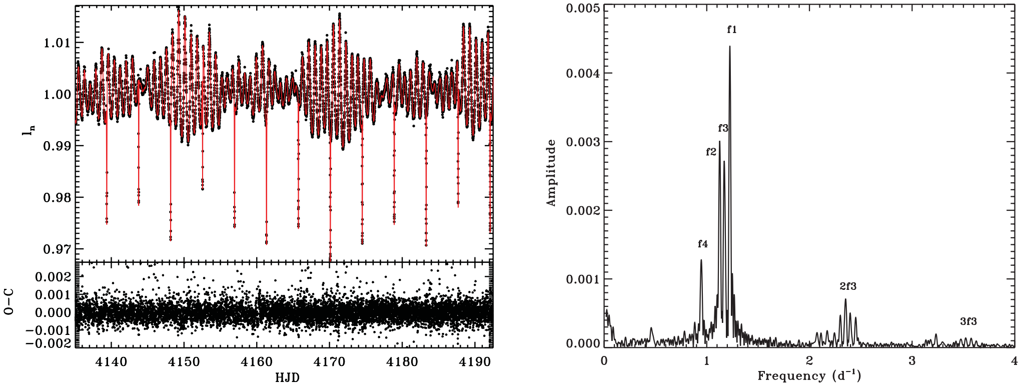

Figure 2. Left: The white-light lightcurve of CoRoT 102918586, time is in HJD-2450000, the continuous line is the fit (eclipsing binary model + pulsations), the lower box shows the corresponding residuals. Right: the power spectrum of the lightcurve after subtraction of the EB model. The main pattern (a multiplet of five frequencies around $f3 = 1.1713$ c/d), repeats at $2 \times f3$ and $3 \times f3$. Frequency $f4$ is $f3 - f_{orb}$.

the analysis of the pulsations suggests the presence of a γ Dor primary component and a rotational splitting of a $\ell = 2$ gravity mode. A complete analysis of this interesting system will be presented elsewhere (Maceroni *et al.* 2011, in preparation).

In the case of solar-like pulsations (present as well in red giants) an estimate of "asteroseismic" mass and radius is possible based on the properties of the power spectrum (frequency of maximum power and large frequency separation) combined to effective temperature from spectroscopy and to scaling laws (Kjeldsen & Bedding, 1995). This is especially valuable in the red giant case, where the estimate from classical methods is problematic. CoRoT has first detected solar-type oscillations in red giants (De Ridder *et al.* 2009), and among the first *Kepler* discoveries is that of a long period ($\sim 400^{\rm d}$) eclipsing binary with a pulsating red giant component (Hekker *et al.* 2010), which is a promising milestone of such studies.

The *Kepler* satellite also implied the discovery of several compact binaries among its fast pulsators. Kawaler *et al.* (2010) found two compact binaries with gravity-mode pulsations superposed to an irradiation effect typical of sdB stars with a close M-dwarf companion. The orbital periods are less than half a day such that seismic sounding should become possible in the future, once the noise level of the data can be brought down to such a level that tidal and/or rotational splitting can be disentangled from period spacings of the modes. An even more interesting case is 2M1938+4603, an extremely rich pulsating sdB star in a $0.126^{\rm d}$ period binary with an eclipsing dM companion (Østensen *et al.* 2010). This star is a hybrid pulsator in that it reveals numerous pressure and gravity modes, offering the potential to probe both the outer layers and the inner core if the modes can be identified.

New discoveries: beaming binaries, tidal brightening. An exciting *Kepler* result is the clear detection of the relativistic beaming effect in the light curve of two targets: KPD 1946+4340 and KOI-74 (Bloemen *et al.* 2011, van Kerkwijk *et al.* 2010).

Beaming (also known as Doppler boosting) is a signature of the component radial velocity in the light curve. This takes the form of a modulation of measured flux according to the radial velocity difference, weighted by the component contribution to the total flux. It is, therefore, best observed in systems with components of very different spectral characteristics. When one star dominates the total flux the beaming effect measurement along the orbit provides information equivalent to that obtained from the radial velocity of a single lined spectroscopic binary.

The effect was predicted by Loeb & Gaudi (2003) and Zucker *et al.* (2007) but its small amplitude (of the order of a few hundreds ppm for systems with periods of a few days) prevented detection in EBs before *Kepler*. For both detections the radial velocity amplitude from beaming is in excellent agreement with that derived from spectroscopy. KPD 1946+4340 and KOI-74 are the first members of the new class of "beaming binaries". The beaming effect has as well been detected in the light curve of CoRoT-3, a 22 Jupiter-mass object, orbiting an F3-star (Mazeh & Faigler 2010).

Another remarkable, ever-observed, effect is the "tidal brightening" characterizing the light curve of KOI-54, a strongly eccentric ($e = 0.83$) *non-eclipsing* system with two similar A-type components and orbital period of $41.8^{\rm d}$ (Welsh *et al.* 2011). The light curve shows regular brightenings of a few mmag amplitude and tidally excited pulsations at high harmonics of the orbital frequency (90 and 91 f_{orb}). The orbital phenomena are interpreted as due to tidal distortion and irradiation at periastron. Several systems with brightenings and eclipses are found in the *Kepler* data and will provide new insights in tidal phenomena.

Tertiary eclipses. Finally, it is worth mentioning the *Kepler* discovery of a few triple (or multiple) systems showing tertiary eclipse events. The intersting case of HD 181068, a compact hierarchical triple system with a red giant component, has been fully analyzed by Derekas *et al.* (2011) and appears elsewhere in this volume. Another remarkable object, KOI-126 (Carter *et al.* 2011), shows eclipses from a closer pair formed by two M-dwarfs ($P=1.7^d$) and from this close pair and a wider 1.35 $M_\odot$ third component ($P=33.9^d$).

4. Conclusions

The exploitation of CoRoT and *Kepler* data will require many years, and, for sure, many exciting discoveries are still to come. The quality of the data is a formidable challenge for theoretical models and for the analysis tools, which have to be adapted to comply with the unprecedented accuracy of the data. Besides the excellent photometry has to be complemented by other observations (e.g., spectroscopy, interferometry, multicolor photometry) to take full advantage of its potentials, tasks requiring both time and manpower. The CoRoT community and KASC-WG9 (the working group on EBs) welcome collaboration to fully exploit these gold mines.

References

Aigrain, S., *et al.*, 2009, *A&A*, 506, 425
Bloemen, S., *et al.*, 2011, *MNRAS*, 410, 1787
Borucki, W. J., *et al.*, 2010, *Science*, 327, 977
Cabrera, J., *et al.*, 2009, *A&A*, 506, 501
Carpano, S., *et al.*, 2009, *A&A*, 506, 491
Carone, L., *et al.*, 2011, in preparation
Carter, J. A., *et al.*, 2011, *Science*, 331, 562
Debosscher, J., *et al.*, 2009, *A&A*, 506, 519
Derekas, A., *et al.*, 2011, *Science*, 332, 216
De Ridder, J., *et al.*, 2009, *Nature*, 459, 398
Heacox, W. D. 1998, *AJ*, 115, 325
Hekker, S., *et al.*, 2010, *ApJ*, 713, L187
Kawaler, S. D., *et al.*, 2010, *MNRAS*, 409, 1509
van Kerkwijk, M. H., Rappaport, S. A., Breton, R. P., Justham, S., Podsiadlowski, P., & Han, Z. 2010, *ApJ*, 715, 51
Kjeldsen, H. & Bedding, T. R. 1995, *A&A*, 293, 87
Koch, D. G., *et al.*, 2010, *ApJ* (Letters), 713, L79
Loeb, A. & Gaudi, B. S. 2003, *ApJ*, 588, L117
Maceroni, C., *et al.*, 2009, *A&A*, 508, 1375
Maceroni, C. 2010, *ASP-CS*, 435, 5
Maceroni, C., Cardini, D., Damiani, C., Gandolfi, D., Debosscher, J., Hatzes, A., Guenther, E. W., & Aerts, C. 2010, *arXiv* 1004.1525
Mazeh, T., Tamuz, O., & North, P. 2006, *Ap&SS*, 304, 343
Mazeh, T. & Faigler, S. 2010, *A&A*, 521, L59
Østensen, R. H., *et al.*, 2010, *MNRAS*, 408, L51
Prša, A., *et al.*, 2011, *ApJ*, 141, 83
Slawson, R. W., *et al.*, 2011, *arXiv* 1103.1659
Sarro, L. M., Debosscher, J., López, M., & Aerts, C. 2009, *A&A*, 494, 739
Welsh, W. F., *et al.*, 2011, *arXiv* 1102.1730
Zucker, S., Mazeh, T., & Alexander, T. 2007, *ApJ*, 670, 1326