Autoreferat w języku angielskim

Summary of professional accomplishments

1) Name and surname: **Tobias Cornelius Hinse**

2) Degrees with name, place, year and title of PhD thesis

i) Bachelor of Science (B.Sc.) in Physics-Astronomy awarded by the University of Copenhagen, Faculty of Science, Copenhagen, Denmark, June 2001.

ii) Master of Science (M.Sc.) in Astronomy awarded by the University of Copenhagen, Faculty of Science, Copenhagen, Denmark, August 2006.

iii) Doctor of Philosophy (Ph.D.) in physical science in the field of astronomy and awarded by Queen's University Belfast, Belfast, United Kingdom, December 2010. Thesis title: „*Dynamical aspects of jovian irregular satellites*''.

3) Information on employment

i) From January to June 2006: IDA (Instrument Center for Danish Astrophysics) Student Research Assistant, Niels Bohr Institute, University of Copenhagen, Denmark.

ii) From January to December 2011: Postdoctoral Research Scientist at Korea Astronomy & Space Science Institute, Daejeon, South Korea.

iii) From January 2012 to December 2013: KRCF Young Scientist Research Fellow (awarded by the Korea Research Council of Fundamental Science & Technology), Korea Astronomy & Space Science Institute, Daejeon, South Korea.

iv) From January 2014 to August 2015: KASI Research Fellow, Korea Astronomy & Space Science Institute, Daejeon, South Korea.

v) From September 2015 to June 2018: Senior Research Scientist, Korea Astronomy & Space Science Institute, Daejeon, South Korea.

vi) From July 2018 – present: Senior Research Scientist, Chungnam National University, Department for Astronomy & Space Science, Daejeon, South Korea.

4) The scientific achievement, in accordance with art.16 paragraph 2 of the Act of March 14th, 2003, concerning the scientific degrees and titles (Dz. U. item no. 882, 2016, with amendments in Dz. U. item no. 1311, 2016)

a) Title of scientific achievement

Dynamical Aspects of Transiting and Circumbinary Extrasolar Planetary Systems

b) List of publications constituting the scientific achievement (author/authors, title, date, journal, publisher name)

H1.
Hinse, **T**. **C**., Lee, J. W., Goździewski, K., Haghighipour, N., Lee, C.-U., Scullion, E. M., „*New light-travel time models and orbital stability study of the proposed planetary system HU Aquarii*", 2012, MNRAS, 420, 3609
Impact-factor of the journal in the year of publication: 5.521
Citations to the article according to ADS[†]: 45 (17. February, 2019)

H2.
Horner, J., **Hinse**, **T**. **C**., Wittenmyer, R. A., Marshall, J. P., Tinney, C. G., „*A dynamical analysis of the proposed circumbinary HW Virginis planetary system*", 2012, MNRAS, 427, 2812
Impact-factor of the journal in the year of publication: 5.521

† Source: NASA Astrophysical Data Service (ADS): http://adsabs.harvard.edu/abstract_service.html

Citations to the article according to ADS†: 44 (17. February, 2019)

H3.

Hinse, **T**. **C**., Lee, J. W., Goździewski, K., Horner, J., Wittenmyer, R. A., „*Revisiting the proposed circumbinary multiplanet system NSVS 14256825*", 2014, MNRAS, 438, 307
Impact-factor of the journal in the year of publication: 5.107
Citations to the article according to ADS†: 17 (17. February, 2019)

H4.

Lee, J. W., **Hinse**, **T**. **C**., Youn, J.-H., Han, W., „*The pulsating sdB+M eclipsing system NY Virginis and its circumbinary planets*", 2014, MNRAS, 445, 2331
Impact-factor of the journal in the year of publication: 5.107
Citations to the article according to ADS†: 20 (17. February, 2019)

H5.

Hinse, **T**. **C**., Haghighipour, N., Kostov, V. B., Goździewski, K., „*Predicting a Third Planet in the Kepler-47 Circumbinary System*", 2015, ApJ, 799, 88
Impact-factor of the journal in the year of publication: 5.909
Citations to the article according to ADS†: 14 (17. February, 2019)

c) Description of the scientific objectives and the research results presented in the scientific achievement, together with the discussion of their possible applications

Introduction

One of the most advancing fields within astronomy & astrophysics research is the discovery and characterization of *extrasolar planets*. The detection of the first planet outside the solar system was announced over two decades ago (Mayor & Queloz 1995). During this time our understanding of the nature of planetary systems has experienced an increased boost and is likely to continue in the future, revealing surprising and fascinating results of other worlds and perhaps, allows the detection of life beyond the boundaries of the solar system.

The detection history of planets took a major leap forward with the discovery of HD 209458b, the first transiting „*hot Jupiter*" (Charbonneau 2000; Henry et al. 2000) with an orbital period of a few days. This time the photometric technique was utilized in combination with spectroscopic observations of the host-star, enabling the first-time measurement of the planet's absolute *mass* and *radius* resulting in an estimate of mean-density allowing to empirically distinguish between the population of hot Jupiter's, terrestrial-sized lava- and rocky-worlds, to ice-giants and cold gas-giant extrasolar planets.

Observation and detection of circumbinary extrasolar planet

Today, we know of the existence of nearly four-thousand[1] confirmed planets orbiting stars different from the Sun. Their detection relies on various powerful astrophysical observation techniques, while also submitted to observational biases and limitations. For example, the microlensing technique (Udalski et al. 1995; Bond et al. 2004) is sensitive to planets on wide orbits probing the outer region of planetary systems, starkly complementing the statistical population of close-in hot Jupiter planets. The most successful effort responsible for the detection of almost all currently known extrasolar planets is utilizing the *Kepler* space telescope (Borucki et al. 2010) discovering a multitude of transiting planets on intermediate-range orbits with periods spanning ~1 – 300 days. The resulting planet population opened up the field of statistical demographics analysis and planet population synthesis (Mordasini et al. 2009) to test competing planet formation and dynamical evolution theories.

Perhaps one of the most surprising discoveries made by the *Kepler* telescope was the detection of planets around binary star systems. Most of the planets detected by *Kepler* are orbiting solar- to late-type *single* stars. However, the majority (~60%) of the Galactic stellar population reside within gravitationally bound pairs of stars (Duquennoy & Mayor 1991) as binary or multiple stellar systems. Doyle et al. (2011) announced the first-time discovery of Kepler-16b: a Saturn-sized transiting planet orbiting an eclipsing binary system. Since then *Kepler* discovered ten circumbinary planetary systems including Kepler-47, a transiting two-planet system (Orosz et al. 2012a). These recent findings on the occurrence frequency of

1 NASA Exoplanet Archive: https://exoplanetarchive.ipac.caltech.edu/

transiting circumbinary planets suggests that on the order of several million circumbinary planetary systems could exist within the Milky Way galaxy (Welsh et al. 2012).

Interestingly, in their work on Kepler-47, Orosz et al. (2012a) pointed out the possibility of the presence of an additional planet. Their claim was based on a single transit-event that cannot be explained by the two transiting planets. In a follow-up study Hinse et al. (2015, **H5**) investigated a three-planet scenario within the frame-work of the fully-interacting five-body problem. The authors found several stable regions for a third planet to exist. In a most recent study Orosz et al. (2019, AJ, submitted) presents a new compilation of all existing photometric data (Quarter 1 through 17) of Kepler-47 and conducted a complete re-analysis considering multi-planet model scenarios. As a highlight, a third planet was detected within Kepler-47 rendering the inferred orbital architecture to be globally stable for several tens of millions of years.

In the pre-*Kepler* era, the discovery history of circumbinary planetary systems originates in the field of astrophysical timing measurements in combination with long-term ground-based photometric observations of eclipsing binary stars and pulsars (Pribulla & Rucinski 2006; Pribulla et al. 2012). The most prominent examples are *i*) the *„pulsar planets"* detected by pulsar timing (Wolszczan & Frail 1992) of the rapidly rotating neutron star PSR 1257+12 from measured anomalies of the pulsation period and *ii*) the inference of companions around V 391 Pegasi from measuring arrival times of stellar (*p*-mode) pulsations (Silvotti et al. 2007, Silvotti et al. 2018). However, most of the population of unseen planetary- and sub-stellar-sized circumbinary companions were inferred from photometric monitoring of binary eclipse events exhibiting anomalous period variations. The underlying detection technique is based on the *light-travel time effect* (LTTE or sometimes denoted as LTT, Irwin 1952, 1959) in which the regular eclipses of the binary system is used as a reference clock. Timing anomalies – or period-changes – are then introduced in the presence of additional massive bodies altering the total centre of mass of the system. This circumstance gives rise to periodic time delays in the observed mid-eclipse times. The LTTE/LTT effect renders a one-dimensional optimization problem, which can be solved via least-squares minimization or maximum likelihood techniques. From measuring the mid-eclipse times accurately allows the derivation of parameters describing the underlying orbital architecture of the system. The amplitude, K, of the timing anomaly depends on the distance (or period as $K \propto P^{2/3}$) and mass ($K \propto M$) of the orbiting companion (Pribulla et al. 2012). An increased sensitivity is achieved for binary systems with a small total mass ($K \propto (M_1 + M_2)^{-2/3}$). Therefore, and contrary to the radial-velocity method, the eclipse timing technique is sensitive to massive companions on long-period orbits around low-mass eclipsing binary pairs, thereby providing an opportunity to probe planet/companion demographics and formation theories in the outer region of circumbinary systems comprised of late-type stars. The notorious disadvantage of the LTTE/LTT technique is the apparent necessity of collection of timing measurements spanning a substantial number of eclipse epochs in order to characterize the true period of the companion(s). Furthermore, only a lower-limit mass estimate of the companion is inferred for non-transit/eclipse events. However, *Kepler* was successful in detecting period variations for the eclipsing binaries Kepler-34 and Kepler-35 (Welsh et al. 2012) where the two circumbinary planets were inferred from transit and eclipse timing measurements. The period variations were caused by significant perturbations of the planets on the binary orbit. While the *Kepler* mission was decommissioned in late 2018, efforts in recent years, involving coordinated longitude-distributed ground-based sky-monitoring programmes on the northern (Pribulla et al. 2012; DWARF[2]) and southern hemispheres (Konacki et al. 2012; SOLARIS[3]) have been initiated with the purpose to follow-up existing and detect new timing anomalies of late-type eclipsing binary pairs.

As of today, most announcements of ground-based detected circumbinary planets/companions are controversial and previously drawn conclusions on their orbital nature are subsequently revised with *i*) the acquisition of new photometric data and/or *ii*) as a result of more careful and detailed modelling work using existing published data within the literature in combination with a necessary requirement of long-term orbital stability and consideration of possible alternative effects that could cause timing anomalies.

2 DWARF, http://www.ta3.sk/∼pribulla/Dwarfs/
3 SOLARIS, http://projektsolaris.pl/en/homepage/

The circumbinary planetary problem – reconciling theory with observations

Most announcements of circumbinary companions via LTTE/LTT are based on the compilation of historic photometric archive data often in combination with newly acquired modern charged-couple device (CCD) as well as photo-electric (PE) measurements. The improved precision in photometric measurements allowed a more accurate determination of timing events. Depending on the particular type of eclipse nature, CCD and PE observations typically allows a timing accuracy of around ±10 seconds (Pribulla et al. 2012) in order to detect a ~10 M_{Jup} companion on a 10 – 20 year orbit (Ribas et al. 2006). Although great care in the data reduction and subsequent analysis is made, most data sets are inhomogeneous involving various telescopes with data acquired under varying sky-condition resulting in photometric data of more or less varying quality.

In a dedicated sky-monitoring effort Deeg et al. (2000) was the first to study the eclipse times of the CM Dra system and announced a Jupiter-mass circumbinary planet in a ~1000 day orbit. Based on subsequent observations this finding could not be confirmed and in a follow-up analysis Deeg et al. (2008) revised their initial work proposing a Jupiter-mass planet in a ~19 yr orbit around the two red dwarf stars. This work was again *disputed* by Morales et al. (2009) who derived absolute properties of CM Dra from good-quality photometric and spectroscopic observations. They were *unable to confirm* the period variations acclaimed by Deeg et al. (2008), but measured a non-zero eccentric orbit of the binary which could be attributed to a perturbing massive companion preventing the binary orbit to fully circularize via tidal effects (Murray & Dermott 2000). An alternative mechanism to explain the observed orbital eccentricity of the binary could be found via eccentricity pumping due a circumbinary disk (Vos et al. 2015). The true nature of CM Dra still remains to be fully understood.

Less controversial is the detection of a giant planet (~6 M_{Jup}) orbiting the short-term eclipsing system – a AM Herculis-type cataclysmic variable – DP Leo (Schwope et al. 2002, Qian et al. 2010, Beuermann et al. 2011). In all three studies, agreement was found on the measured period variation being consistent with the interpretation of a giant planet in a moderately eccentric orbit with a period of ~28 years.

The first two-planet circumbinary system from eclipse timing measurements was proposed by Lee et al. (2009a). Presenting newly-acquired photometric data, the authors argued for the existence of two planetary-sized bodies around the short-period eclipsing binary HW Vir composed of a sdB and M dwarf star. The two bodies were found to have a mass of ~9 and ~19 M_{jup}, for the inner and outer body, respectively. Orbital periods were measured to be ~9 and ~16 years. *Some controversy exist for this system as well*. In a study by Horner, Hinse et al. (2012, **H2**) the system's long-term orbital stability was scrutinized. The authors found the proposed companions by Lee et al to *follow highly unstable orbits* with disruption time-scales on the order of a few thousand years. Too short to lend credibility of the existence of the system. The reason being a near-orbit crossing architecture in the Lee et al. (2009a) model solution. In order to *reconcile the observed period variations with a multi-planet system* Horner, Hinse et al. (2012) proposed an alternative scenario for the orbital architecture for which the outer planet follow a significantly wider orbit, albeit the unsatisfactory caveat of being poorly constrained by data due to the short observational base-line.

The first circumbinary multi-body planetary system for which the problem of orbital stability was noted is concerned with the HU Aqr eclipsing binary system. Qian et al. (2011) claimed the detection of two massive companions of planetary nature. This *finding was soon questioned* by Horner et al. (2011) raising *doubt about their existence* as the two proposed planets were found to be on collision-paths considering various possible architectures within the observational parameter uncertainties. Interestingly, long-term orbital stability was found for the outer planet in a retrograde orbit. This scenario, however, seems physically not plausible, since planets are believed to form from the same rotating circumbinary disk (Pierens & Nelson 2008). Other studies (Horner et al. 2013, QS Virginis) unequivocally demonstrated that the proposed planets simply cannot exist as a result of large mutual perturbations. In a follow-up study Hinse et al. (2012, **H1**) attempted to *find alternative orbital architectures that could be reconciled with the requirement of orbital stability* of the planets within HU Aqr. Stable orbital architectures were found for best-fit models with lower eccentricity of the outer planet – a result that was also found in Horner et al. (2012) for the NN Serpentis companions. The authors carried out extensive Monte Carlo simulations in an attempt to thoroughly explore the underlying parameter space for best-fit models while imposing an orbital stability requirement as an additional constraint on the fitting process (Goździewski, Konacki & Maciejewski, 2005). Orbital stability problems of similar nature were also encountered for the eclipsing systems NSVS 14256825 (Hinse et al. 2014, **H3**) and the NY Vir (Lee, Hinse et al. 2014, **H4**). In the former work Hinse et al. (2014) demonstrate that a Bayesian analysis does not provide a final answer to these problems and this technique is still subject to limitations set by observational data. Often, in the modelling of astrophysical signals, Bayesian-based models are considered to provide close-to-final answers and are at times given a too high credibility in terms of the conclusions drawn from such analysis. In the work **H4** we present new timing measurements from photometric observations of the pulsating sdB + M dwarf binary system and found that the most likely explanation of the detected period variations is due to two planetary companions. However, as in previous cases, also this *system is rendered to be unstable* and we present nearby stable solutions in form of isolated stability islands that exist in the vicinity of the best-fit model within the orbital parameter space.

Additional non-gravitational mechanisms are capable of causing period-variations in addition to circumbinary companions. These mechanisms are associated with mass-loss/transfer, magnetic wind-breaking, gravitational radiation or magnetic interaction. The latter is known as the Applegate effect (Applegate 1992) and introduces period changes as a result of the star's oblateness change due to a varying magnetic torque. Stellar mass-loss also introduces a re-distribution of mass causing an alteration in the binary period. All of these effects (Hilditch 2001) account for period-variations usually on the order of decades and are usually summarized as a binary-period damping parameter (β) in timing-modelling work (Goździewski et al. 2012). In an attempt to distinguish secular non-gravitational effects from period variations introduced by unseen companions one can estimate the magnitude of each individual contribution. For example, for the HU Aqr system Schwarz et al. (2009) noted that the amplitude of period variations is too large to be caused by the Applegate mechanism. Further, in the study by Lee et al. (2009a) the authors found a secular period change most likely caused by angular momentum loss due to magnetic stellar wind breaking. Often these secular effects on the period-variation are modelled in conjunction with suspected unseen companions.

Scientific contribution to the field of circumbinary extrasolar planets

In the following, I present in some more detail original ideas and independent research results (**H1** - **H4**) that aim to address and present solutions of fundamental problems related to the data modelling of circumbinary planetary systems, detected from photometric eclipse timing and transit measurements. As a research highlight, I present the theoretical prediction of a third transiting circumbinary planet around the Kepler-47 stellar binary system (**H5**). A third planet was indeed found and its detection is currently under review and awaits publication in the near future. For several years, since the announcement of planetary-type bodies by Lee et al. (2009a), there are *conclusions in the literature that cannot be reconciled with fundamental theoretical requirements* concerning the orbital stability of these systems. The scientific objective of this project is to achieve a more detailed understanding of aspects of data modelling based on timing-measurements. Throughout this project, I attempt to find the problematic root-cause of the highlighted mismatch between observations and theory and always aimed to advance this field by bridging new analysis methods that otherwise found application elsewhere within the astronomical literature. Previous studies were found to lack a critical and rigorous treatment in terms of data analysis techniques and adequate derivation of parameter uncertainties resulting in unbacked and hasty discovery claims. I aimed to increase the scientific standard and rigour by which timing data should be treated as part of the underlying modelling process to draw more strict conclusions on the nature of the observed phenomena.

A fundamental assumption in most of my research approach is that mutual planetary perturbations by gravitational interactions are considered to be small resulting in the assumption of a light-travel time model to be an adequate first-order approximation to measured timing anomalies. Based on the current citation metrics, the outlined research project may be judged to have had a lasting direction-changing impact within the literature of circumbinary planets/companions raising attention to central issues not addressed previously. The exoplanet field in general has advanced with excessive speed over the past five to ten years, and at times, one must admit, it is straining to keep track with an ever accelerating development of this research area. Nevertheless, this field is hugely captivating and has my continuous scientific attention and desire to uncover and bring forward the true nature of these distant worlds.

This project was initiated in 2011 as a result of starting a seven-year post-doc period at the Korea Astronomy & Space Science Institute (KASI). During this time a total of 11 peer-reviewed papers have been produced within the field of circumbinary companions as my main research focus. Additional secondary research activities outside the field of circumbinary planets was carried out as well. During the post-doc years, I published a total of 105 peer-reviewed publications.

The research work presented here was initiated and carried out by me, as part of an international collaboration[4] involving scientists from (but not limited to) South Korea, UK, USA, Australia and Poland. A substantial part of the presented scientific results were obtained from numerical calculations using a high-performance computing-cluster based in South Korea and operated by KASI (KMTNet, PLUTO & POLARIS clusters). Further, the SFI/HEA super-computing facility at the Irish Centre for High-End Computing (ICHEC) in the Republic of Ireland (via access-grant obtained with courtesy from the Armagh Observatory, UK), the „Beehive" computing cluster (Armagh Observatory) and computing facilities at the Centre for Scientific Computing at the University of Sheffield (UK) were used for executing large-scale numerical computations producing a significant amount of the results presented here. Other computing facilities such as the EPIC supercomputer operated by the University of Western Australia were also utilized.

In addition, photometric follow-up observations were obtained using international observing facilities located in Chile (DK 1.54m, ESO/La Silla) and South-Korea (1.8m, BOAO; 1.0m, LOAO; 0.6m, SOAO and 0.7m, CbNUO) to partially acquire new timing measurements of eclipsing binaries for which we suspect period changes caused by additional unseen massive companions. Individual (as PI) as well as collaborative (as co-I) observing proposals[5] resulted

4 whose members I am deeply grateful to for valuable contributions and scientific discussions / guidance
5 Partially obtained from the „*Observational Surveys of Variable Objects*" (co-PI), as well as the „*Transit-timing variations of unseen companions and follow-up of eclipsing binaries*" (PI) & MiNDSTEp projects carried out at the Korea Astronomy & Space Science Institute, South Korea.

in the awarding of a total of more than 250 nights of which ~30% resulted in useful data of sufficient scientific quality. The work presented here is still in-progress and therefore a significant amount of acquired observational data and results from numerical simulation have not yet been published and are currently awaiting a future analysis.

Revisiting HU Aquarii: Reconciling timing data with orbital stability requirements (H1)

The initiation of this research paper was motivated as a result of the study by Horner et al. (2011) who for the first time critically addressed the observational claims made by Qian et al. (2011) and pointed out the problem of orbital long-term stability of circumbinary planetary systems. Horner et al. (2011) presented compelling theoretical evidence, by considering a large range of initial conditions as part of a dynamical analysis, allowing the authors to conclude that the two planets in HU Aquarii (HU Aqr), as described by Qian et al. (2011), are unlikely to exist.

My contribution (Hinse et al. 2012, **H1**) to this developing field was inspired by the concepts presented in Goździewski, Konacki & Maciejewski (2005) who imposed orbital stability requirements as an additional observational constraint as part of the data modelling process. This is an example of applying a methodology from the literature to a new scientific problem, in an attempt to illuminate/resolve existing scientific issues. This approach seems plausible and may help to reconcile observations with the essential necessity of long-term stability of acclaimed planetary systems in general. Using a qualitative probabilistic argument, it seems unlikely that Qian et al. (2011) are reporting HU Aqr to be a planetary system which is currently undergoing a dramatic large-scale disruption, while being in the process of dissolving as a result of gravitational perturbations.

In this work we aim to find a more plausible orbital architecture that best describes the timing data while also being conform with orbital stability requirements. We carried out various LTTE/LTT models to the complete timing data set. In parallel to the fitting process, we performed a stability analysis of different configurations which best describe the observations. To be more general, in an attempt to avoid parameter correlation bias, we extended the models by Qian et al. (2011) to systems that also allow the inner planet to attain an eccentric orbit. We argue there is neither observational evidence or constraints nor theoretical arguments for perfect circular orbits within a planetary system.

For our analysis, we compiled the combined eclipse egress timing data set from works of Schwope et al. (2001), Schwarz et al. (2009) and Qian et al. (2011). A total of 113 timing measurements were obtained for HU Aqr which span the time between April 1993 and May 2010, which covers approximately 17 years. All (HJD/UTC) timing measurements have been transformed to the solar system barycentre using BJD time format stated in the TDB time standard. The LTTE/LTT model implemented followed the formalism outlined in Irwin (1952). Here, the stars of the binary are assumed to represent one single object with a total mass equal to the sum of the masses of the two stars. We show the best-fit model in Fig. 1A.

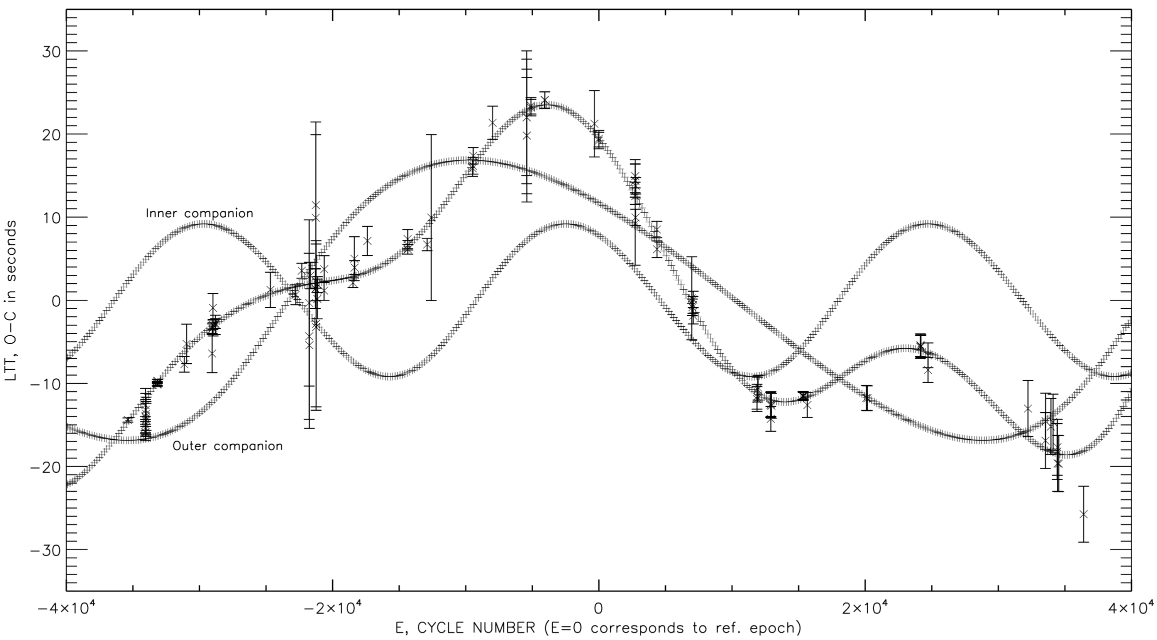


Fig. 1A: *Example of a statistically significant best-fit model of a two-planet LTTE/LTT model with χ^2=1.43 for the HU Aqr system. The individual LTTE/LTT signals of the two companions are superimposed and denoted explicitly. Timing data were taken from the literature (Schwope et al. 2001, Schwarz et al. 2009, Qian et al. 2011). The figure is reproduced from Hinse et al. (2012, Fig. 2,* ***H1****).*

For the least-squared fitting process, we used the Levenberg-Marquardt (LM) minimization algorithm as implemented in the IDL[6] routine MPFIT (Markwardt, 2009). This routine

6 https://www.harrisgeospatial.com/docs/using_idl_home.html

attempts to minimize the sum of weighted residuals squared (χ^2) between the model and the observed timing measurements. The final software implementation was tested extensively and submitted various sanity checks as part of the collaboration within which this project was carried out. As part of this process, errors in the code were identified and subsequently rectified, ensuring a validation of final results. In particular this is concerned with the determination of the minimum mass of the circumbinary companions from an iterative algorithm for the solution of the underlying mass-function.

In order to require stability of a given model, we treated the requirement of dynamical stability as an „observable''. We then carried out an extensive search based on a Monte Carlo approach of the underlying orbital parameter space using the help of various computing facilities. The result of a Lomb-Scargle period analysis (Lenz & Breger 2005) provided reasonable estimates of the orbital periods. After each successful convergence towards a solution from the LM minimization procedure, we tested the resulting fitted parameters for the following stability conditions:

(*i*) $a_1 < a_2$,

(*ii*) $q_2 - nR_H^{(2)} > Q_1 + nR_H^{(1)}$ (with $n = 1, 2$),

where q_2 is the pericenter for the outer planet and Q_1 is the apocenter for inner one, $R_H^{(k)}$ is the modified Hill radius of the *k*-th planet and a_k denotes the semi-major axis of the orbit. From the two above-mentioned stability constraints, the first condition simply demands a hierarchical system with the size of the inner planet's orbit always being smaller than that of the outer body. For eccentric orbits, we use the „spacing parameter'' n (with $n = 1$) to quantify a stability condition. The second condition essentially demands the outer planet's pericentre distance to be always larger than the inner planet's apocentre. This condition is clearly violated for the case of the planetary orbits in HU Aqr as proposed by Qian et al. (2011). In an attempt to avoid close encounters, the condition is augmented by demanding the spacing between the planets to be a multiple of their respective Hill radii.

The experiments were based on over 100,000 randomly distributed initial guesses. For each converged initial guess with $\chi^2 < 10.0$, we recorded the resulting χ^2, the initial guess parameters and the final converged model parameters as returned by the LM algorithm. This generated a population of best-fit models for which a subset respects the imposed orbital stability constraints as outlined earlier.

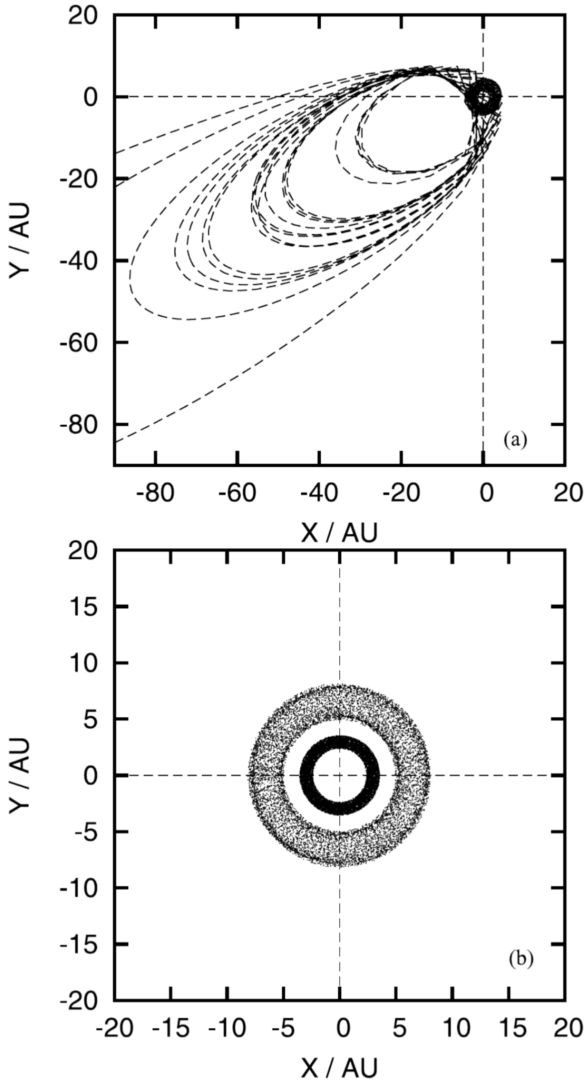


Fig. 1B: *Results from direct orbital stability integrations with and without considering best-fit models in conjunction with stability constraints. The top panel (a) exemplifies an unstable temporal time evolution and the bottom panel (b) shows a stable architecture as plausibly required to lend physical significance to the existence of the system. The figure is reproduced from Hinse et al. (2012, Fig. 3,* ***H1****).*

We then directly examined the orbital stability of our best-fitting model using the orbital integration package MERCURY[7] (Chambers, 1999). We carried out integrations for two

7 https://github.com/4xxi/mercury

scenarios: *i*) the nominal parameters for the best-fitting model with ($\chi_r^2 = 1.43$) and *ii*) an optimistic scenario, where we considered the lower limit in masses and eccentricity and upper limit in the semimajor axis for both companions. The systems were integrated for a time span of 10,000 years. Fig. 1B shows the result of two orbit integrations.

The nominal parameters scenario shows orbital instability of at least one of the planet companion, that resulted in its eventual escape. The optimistic scenario, on the other hand, resulted in a relatively stable orbital architecture when compared with the former. We also carried out long-term orbit integrations to assess the system's stability over secular time-scales. The presented work was concluded by presenting a subset of best-fit model parameters that respects the requirement of orbital stability. This approach was novel and provided a new impetus within the field of circumbinary planetary systems.

As of February 2019 the total number of citations to **H1** is 45. As a highlight of the latest development in this research field concerned with the HU Aqr system, we point towards the works presented in Goździewski et al. (2015) who revisited the HU Aqr planetary hypothesis. In summary, the authors presented new timing measurements from photometric observations acquired between 2011 and 2014 from ground-based telescopes. Detailed modelling work, including mutual gravitational perturbations between all massive objects, in conjunction with orbital stability requirements allowed the authors to rule out co-planar two-planet configurations and pointed towards the possibility that the putative HU Aqr planetary system may be much more complex: the period variations may be driven by oscillations of the gravitational quadrupole moment of the secondary binary, as predicted by the Lanza et al. (1998) modification of the Applegate mechanism. In a theoretical follow-up study this conclusion was further corroborated by Völschow et al. (2016) who argues that the HU Aqr eclipsing system is presently in an energy state allowing for the on-going operation of the Applegate mechanism providing a more plausible explanation of the observed period variations.

Scrutinizing the proposed HW Virginis circumbinary planetary system (H2)

With the progression of the project's literature study within the field of circumbinary planetary systems and massive companions, it became evident that the underlying data analysis methods, previously applied to astronomical timing data of eclipsing systems, is lacking scientific rigour and analytic thoroughness. While the remaining field of astrophysical planet discoveries and their statistical validation is rapidly advancing, the treatment of circumbinary systems from ground-based observations seems not to follow the same level of analysis standards. Further, at times, assumptions are made that have minimum backing in form of observational evidence or theoretical justifications. Often, the recorded data forming the main body of evidence, is not scrutinized or questioned in an attempt to identify possible flaws. Some examples are as follows. The parameter uncertainties presented in Lee et al. (2009a) are derived from the best-fit co-variance matrix, which is prone not to reflect reliable estimates of those quantities by not accounting for the possibility of parameter correlations. For many years, direct numerical Monte Carlo techniques (Press et al. 1992; Bevington & Robinson, 1992) have been developed allowing to derive relatively more robust parameter uncertainties. Furthermore, parameter correlations and the possibility of unconstrained parameters by observational data, is rarely discussed or highlighted in the literature. In addition, Beuermann et al. (2012a) in their analysis of HW Vir base their work on certain assumptions about the orbit of the inner companion for which little justification is provided.

The missing strictness by which data analysis is conducted, from a scientific point of view, *is* highly unsatisfactory. Data analysis methods and techniques exist that are well-established and can be applied with relatively little effort (Hughes & Hase 2010). Especially, when proclaiming new discoveries of planets or in an attempt of confirming the existence of previously claimed planets/companions in follow-up studies, such techniques should find their application.

This study, **H2**, was carried out as part of a mutual Korean-Australian international collaboration within which initial ideas and gained expertise were shared and discussed, with the scientific goal to scrutinize the proclaimed planets within the HW Vir system.

Lee et al. (2009a) announced the discovery of a two-planet circumbinary planetary system around the eclipsing system HW Vir, which features a subdwarf primary, of spectral class B and a red dwarf companion displaying mutual eclipses with a period of around 2.8 hrs. The outer planet, attributed to a companion of mass $M\sin I$ = 19.2 $M_{\rm Jup}$, had a period of 15.8 yr and a semi-amplitude of 88 sec., while the second inner planet, was attributed to a companion of mass $M\sin I$ = 8.5 $M_{\rm Jup}$, with a period of 9.1 yr and a semi-amplitude of 23 sec.

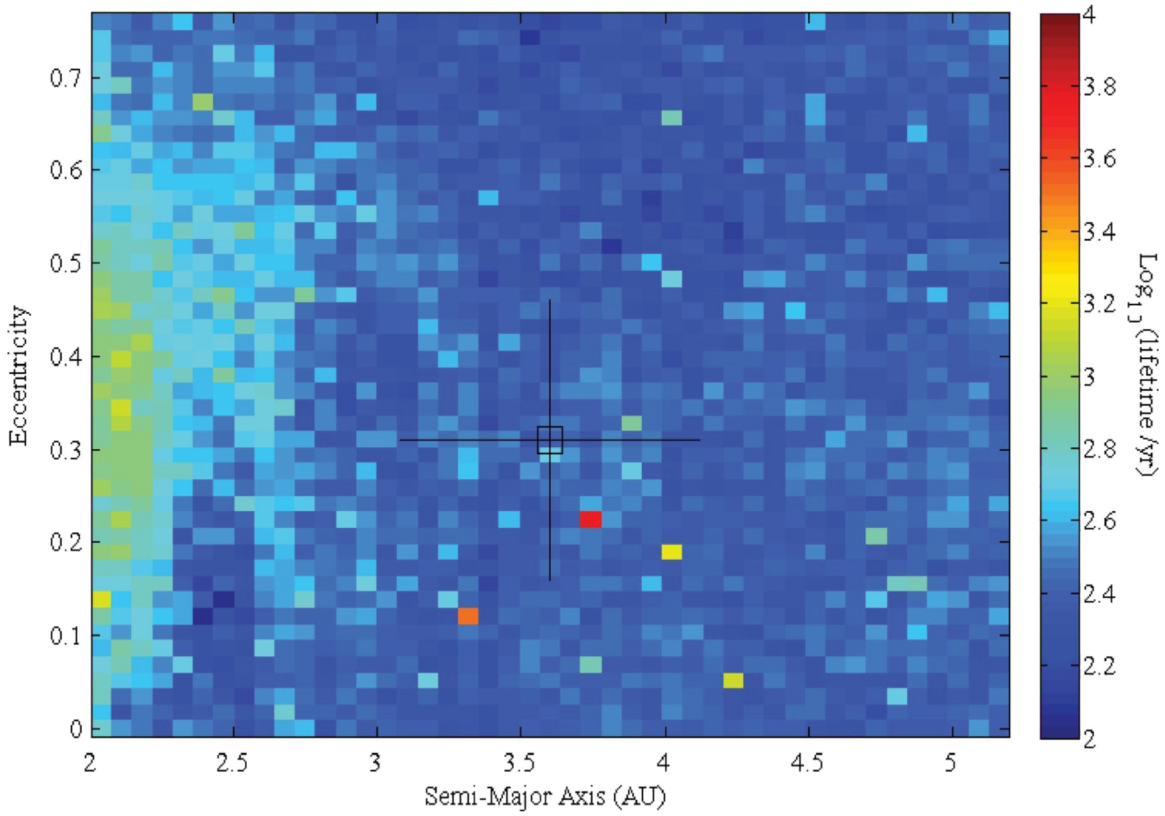


Fig. 2A: *Result of a detailed stability / life-time calculation of the planetary system HW Vir considering the semi-major axis-eccentricity (a,e) space of the inner companion. The central cross mark the best-fit (a,e) and their ±1σ confidence intervals, as proposed by Lee et al. (2009a). The system's survival life-time is colour-coded with blue indicating very short life-time periods. The figure is reproduced from Horner, Hinse et al. (2012, Fig. 1, **H2**).*

The fitting results by Lee et al. (2009a) are alarming: both planets are massive, in the regime that borders gas giants and brown dwarfs, and occupy highly eccentric orbits, allowing orbit crossing architecture, and with a separation that guarantees mutual close encounters and, thus, is very likely subject to dynamical instabilities.

In the first part of **H2**, in an attempt to assess the dynamical stability of the proposed planets, we performed a large number of direct orbit integrations. We employed the hybrid integration algorithm (with some modifications) as implemented within MERCURY (Chambers 1999) and followed the evolution of the planetary system for a maximum period of 100 Myr. The hybrid formalism developed by Chambers (1999) allows a reliable integration of eccentric orbits. In order to examine the full range of possible orbital solutions (parameter ranges covered the published 1σ confidence intervals), we considered a large grid (45 *x* 45 *x* 15 *x* 3 grid in $a - e - \omega - M$ space) of architectures for the HW Vir planetary system. We found the Lee et al. (2009a) system of planetary orbits to be extremely unstable as demonstrated in Fig. 2A. This finding, similar to HU Aqr, cast serious doubt on the physical reality. At least the orbital architecture, as proposed by Lee et al. (2009a), are not standing up to the requirement of long-term stability.

We then asked the question „*is it possible to find a best-fit LTTE/LTT model which renders the system to be stable?*". After all, Lee et al. (2009) presented convincing arguments that the detected period changes are most likely explained by additional companions. Therefore, in the second part of **H2**, we carried out large-scale numerical Monte Carlo experiments to thoroughly search the underlying model-parameter space for stable planetary systems. The underlying modelling technique is based on the method outlined in Hinse et al. (2012, **H1**). To further advance this field, and to address the problem of estimating reliable parameter uncertainties, we implemented the boot-strapping algorithm (Press et al. 1992) which has found wide acceptance within astronomical data analysis problems to determine the underlying parent distributions of the model parameters, assuming normally distributed timing measurements. Further, we chose to focus to examine the possibility of parameter correlations. Surprisingly, the search for a new model resulted in the determination of a set of parameters, that were found to be different from those proposed by Lee et al. (2009a). As a highlight, and partly based on the results from our boot-strap simulations, we were able to quantitatively demonstrate the period of the outer planet to be unconstrained by the data. We could convincingly show that a simple and straight-forward application of a Lomb-Scargle period analysis does not provide sufficient evidence for the existence of particular periodicities that might be present in a given time-series data set. This result was further, and independently, supported by our parameter correlation study. In Fig. 2B we show a selection of parameter correlations of the the two-planet LTTE/LTT model. In each panel we superimpose the 1, 2, and 3σ confidence levels for the best-fit model. Qualitatively as well as quantitatively, the adopted timing data is constraining very well the binary period and reference epoch.

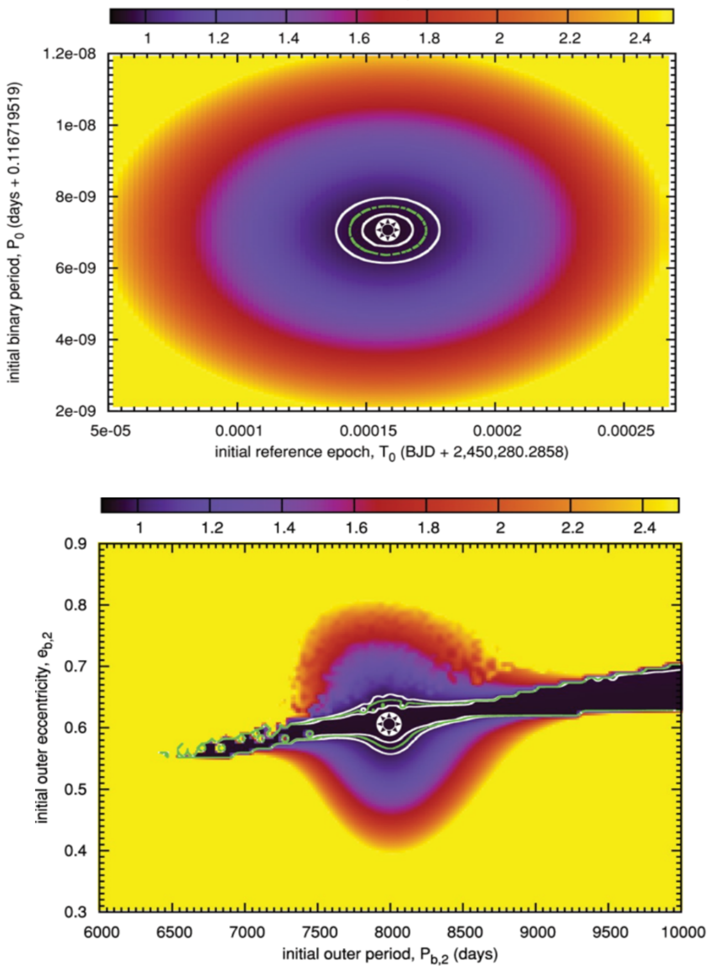


Fig. 2B: *Excerpt of results of a comprehensive parameter scan of χ^2 over orbital elements. The best-fit model is marked by a star-like symbol. Contour-curves mark the 1, 2, and 3σ confidence regions around the best-fit model. Top panel: reference epoch vs binary period; Bottom panel: orbital period vs eccentricity of the outer planet. The figure is reproduced from Horner, Hinse et al. (2012, Fig. 5,* ***H2****).*

Both parameters represent the linear ephemeris of the eclipsing binary forming part of the adopted model. However, the outer planet's period (and a consequence of Kepler's third law the semi-major axis) and orbital eccentricity is clearly demonstrated to be unconstrained by the data. The result shows, that best-fit models with equally statistical significance (within 1σ confidence level), but with dramatic different physical properties, emerge forward as equally valid possibilities, in order to explain the observational data.

To break this degeneracy one would need photometric data in form of a transit event in front of the binary components (very unlikely) and/or obtain additional timing measurements from future monitoring and follow-up observations. In a third and last part of this analysis, we investigated the stability of our newly determined architecture. Since a detailed re-analysis of the observational data for the HW Vir system yields a new orbital architecture, different from the one proposed in Lee et al. (2009a), it is interesting to consider whether that new solution offers a better prospect for dynamical stability. We therefore repeated our earlier dynamical analysis using the new orbital solution by following the same methodology in carrying out direct integrations of orbits to determine the system's life-time as a function of best-fit orbital parameters. As was the case for the original orbital solution proposed in Lee et al. (2009a), very few of the tested planetary systems survived for more than 1000 yr, with just 0.029% of the sample, surviving for more than 3000 yr, and just three systems surviving for more than 10000 yr. It seems almost certain that the proposed planets in the HW Vir system simply do not exist – at least in orbits resembling those that have been presented by Lee et al. (2009a) or in Horner, Hinse et al. (2012, **H2**).

The results and highlighted problems presented in Horner, Hinse et al. (2012, **H2**) have had an impact in the literature. As of February 2019 the total number of citations to this work is 44. As a highlight of the latest development concerned with the HW Vir system are the following results. Bours et al. (2016) present new timing measurements from photometric data obtained as part of a long-term monitoring programme. The authors provide evidence for the most probable cause for period variations for HW Vir is driven by the Applegate mechanism with induced magnetic cycles of the secondary component causing a variation of the binary orbit resulting in period variations. The likely cause of the orbital change in HW Vir, as a result of the Applegate mechanism, was further supported in the works by Pullet et al. (2018). The authors also highlight the complexity of HW Vir type binaries where the secondary component is faint and hence obstructs a more detailed characterisation. Finally, in a recent study, interesting measurements of the pulsating component of HW Vir were presented using high-precision *Kepler* (Borucki et al. 2010) photometry. The authors were able to measure pulsation properties which in turn allowed them to establish additional constraints on the physical properties of the pulsating component.

Critical review of the proposed NSVS 14256825 circumbinary planetary system (H3)

In continuation of the analysis of the putative planetary system around HW Vir, we have then turned our attention to a similar case of the proposed planets orbiting around the NSVS 14256825 binary star system (Hinse et al., 2014, **H3**).

In a recent work, Almeida et al. (2013) interpreted observed eclipse timing variations of the post-common envelope binary NSVS 14256825 (period of ~0.11 days) as being the result of a pair of LTTE/LTT effect introduced by two unseen circumbinary companions. The authors employed a Monte-Carlo Markov-Chain (MCMC) / Bayesian approach in their data analysis of the timing measurements. Proposed companions are of planetary nature, with orbital periods ~3.5 and ~6.7 yr, and masses of ~3 M_{Jup} and ~8 M_{jup}, respectively. However, a recent study by Wittenmyer et al. (2013) reveals that the proposed planetary system would be dynamically unstable on very short time-scales. This result motivated us to initiate a research project with the aim to conduct a critical review of the work by Almeida et al. (2013) in an attempt to find a best-fitting set of parameters that could explain the observed eclipse timing variations while simultaneously yield a long-term stable configuration as an initial working hypothesis.

As the basis of this work, we consider the same timing data set as published in Almeida et al. (2013). We have carried out two independent analyses based on the following data sets. Data set I: data as presented in Almeida et al. (2013). This data set spans the period from 2007 June 22 to 2012 August 13, corresponding to an observing baseline of around 5 years. Data set II: same as in Data set I, *plus three data points* (primary eclipse) from Beuermann et al.

(2012b). The second data set spans the period from 1999 June 10 to 2012 August 13, corresponding to an observing baseline of around 13 yr. The aim of considering the second data set is to investigate the effects of the additional timing data on the overall best-fitting solution.

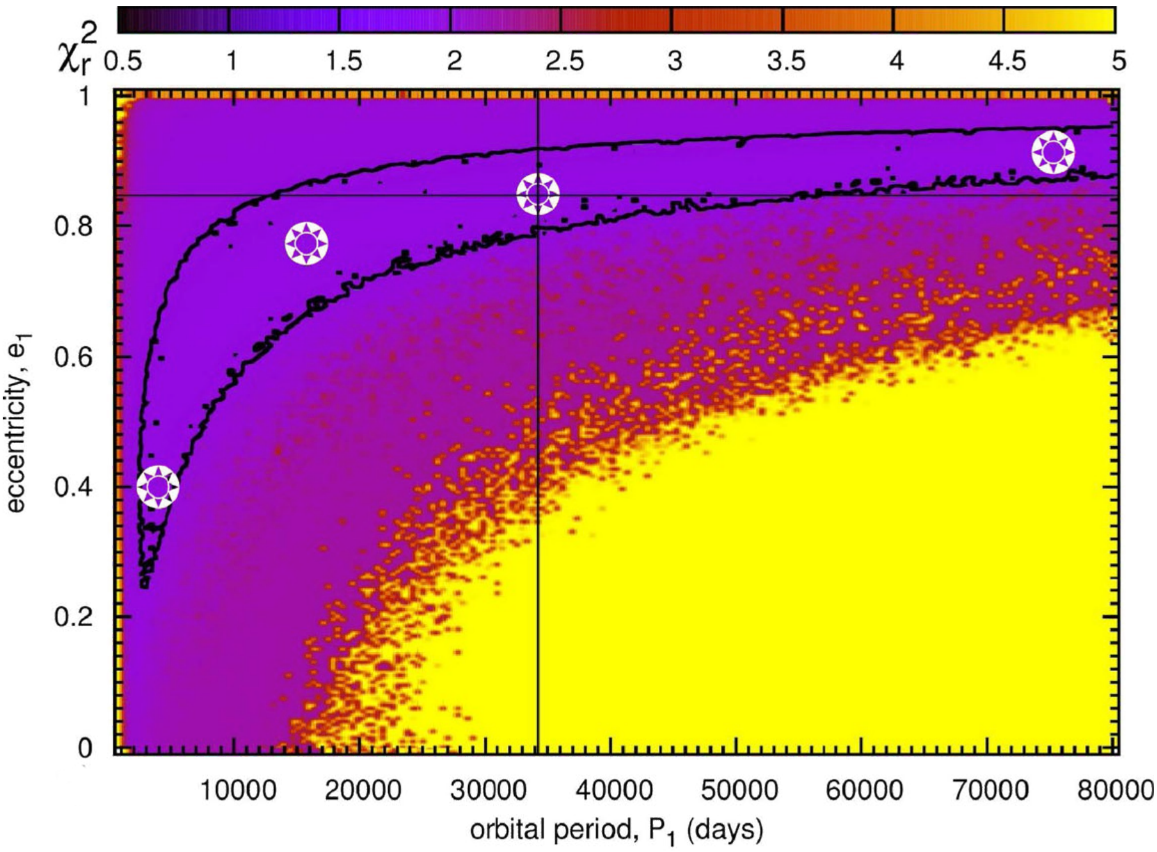
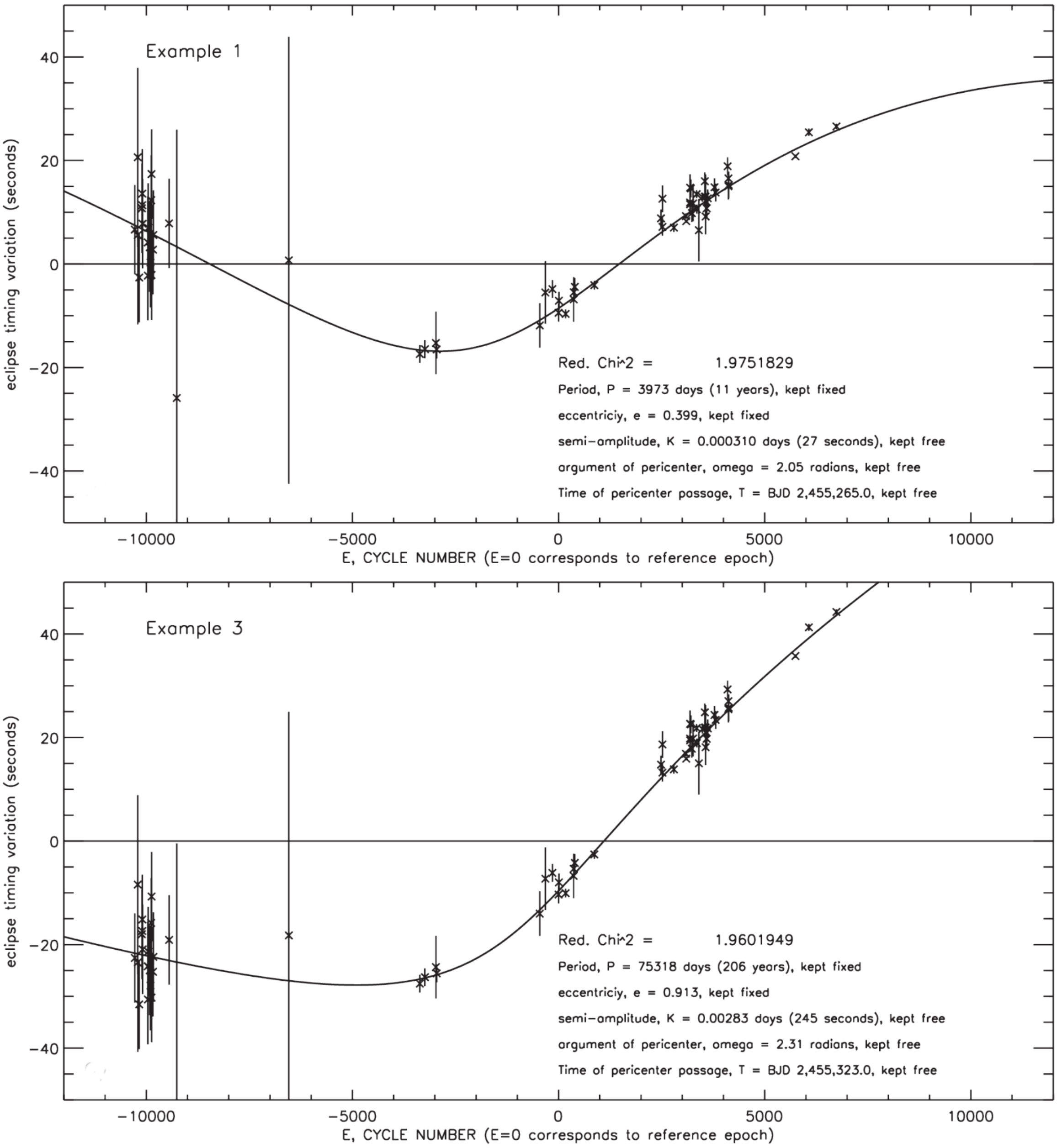


Fig. 3A: *Calculation of two-dimensional joint-confidence region obtained by calculating χ^2 for a range of orbital periods and eccentricity around the best-fit model (cross-hair) of the inner proposed companion. The black contour curve marks the 1σ confidence level (with $\Delta\chi^2$ = 2.3, 68.3% level). Three additional (P_1, e_1) pairs of test-parameters (marked by star-like symbols) have been studied in some more detail. The figure is reproduced from Hinse et al. (2014, Fig. 10, **H3**).*

We use the formulation of the LTTE/LTT effect based on Jacobian coordinates, as in Goździewski et al. (2012). Here, we assume the binary to be a single massive object with mass equivalent to the sum of the two component masses. In the case of a single companion, the Jacobian based description of the one-companion LTTE/LTT effect is equivalent to the formulation given in Irwin (1952, 1959). For consistency, we tested our results for the presently (Jacobian) derived LTTE/LTT formulation using the procedure detailed in Irwin

(1952), and obtained identical results. A best-fit model is found via least-squares minimization based on an extensive search of the underlying parameter region. As a first result, by including the three extra timing measurements presented in Beuermann et al. (2012b), we were able to improve the fundamental ephemeris of the eclipsing binary.



<u>Fig. 3B</u>*: Results (excerpts) of calculating various models as depicted in Fig. 3A. All models calculated have a χ^2 statistic within the 1σ confidence limit while the underlying model parameters exhibit vast differences. The figure is reproduced from Hinse et al. (2014, Fig. 11,* ***H3****).*

To reliably assess the validity of a two-companion model, we first considered a one-companion model. Our period analysis yielded a shortest period of around $P_1 \sim 7$ yr, with a semi-amplitude of $K_1 \sim 0.000231$ days. We therefore searched for a best-fitting solution in a narrow interval around these values by seeding over 500,000 initial guesses. The best-fitting solution was $\chi^2 = 1.98$. Again, in an attempt of rigorously study parameter correlations, we have explored the χ^2 function in the vicinity of the best-fitting parameters and determined two-dimensional joint-confidence intervals.

As a second result, we find that several parameters correlate with each other which is important to determine any parameter degeneracies. We find that the 1σ confidence level in the (P_1, e_1)-space spans over a large region in period (P_1) and eccentricity (e_1) values. We then re-calculated the χ^2 space on a grid of (P_1, e_1) considering a larger interval in the two parameters. The result of this effort are shown in Fig. 3A and suggests that the best-fit model is likely to reside within a local minimum. To quantitatively demonstrate a clear parameter degeneracy, we investigated in some more detail three additional models each having equal statistical significance as the $\chi^2 = 1.98$ best-fit model. An excerpt of results is shown in Fig. 3B demonstrating vastly differing orbital architectures, suggesting with high confidence that the observed timing measurements do not provide strict constraints on the underlying model parameters. The most likely cause is the short baseline of measured mid-eclipse times. A necessary consequence is that parameter uncertainties derived from either the best-fit co-variance matrix or from a direct boot-strap approach is inconsequential and meaningless for unconstrained problems. We therefore caution about the blind application of MCMC-based Bayesian method as a quantitative means to infer some physical properties about a planetary system with the assumption that such advanced methods automatically provide reliable results on its own. At the heart of all statistical inferences is the observational evidence. The results presented in Almeida et al. (2013) are likely to suffer strongly from a local minimum as demonstrated in Hinse et al. (2014, **H3**). Finally, an analysis of the residuals of the best-fit one-companion model revealed that the resulting root-mean-square scatter (~5s) of timing measurements around the best-fit model is on the same order as the mean timing uncertainty of the applied data. The detection confidence of a second component in the NSVS 14256825, as proposed by Almeida et al. (2013) is therefore marginal to minimum, allowing us to concluded that the Bayesian models in Almeida et al. (2013) proposing a second planet is likely the result of fitting noise.

The results presented in Hinse et al. (2014, **H3**) had some impact on the literature. As of February 2019 the total number of citations to Hinse et al. (2014, **H3**) is 17. The most significant advances are as follows. Nasiroglu et al. (2017) presents 83 new timing measurements of NSVS 14256825. The authors found a significant quasi-periodic period variation and explained its likely cause either by a light-time effect or the action of the Applegate mechanism within the M-dwarf secondary via magnetic cycles. Based on an energy-budget argument the latter effect can be ruled out allowing the authors to propose the presence of a ~15 M_{Jup} brown dwarf orbiting the binary on a moderate eccentric orbit with period ~10 years.

Two circumbinary planets around the eclipsing system NY Virginis? (H4)

Most of the research results presented up until now are based on compiled photometric data as published in the literature. In an attempt to get new timing data in the quest to search for additional companios to binary star systems, we have obtained telescope time as part of an observational follow-up monitoring project. Various binary star systems were included in the list of targets each previously known to exhibit significant period variations. The scientific goal is to further characterize the physical nature of these systems. The eclipsing system NY Virginis (NY Vir) was part of a photometric long-term monitoring programme. Here, we present the results of new photometric follow-up observations and discuss their implications for the possibility of two circumbinary planets around the NY Vir eclipsing system (Lee, Hinse et al. 2014, **H4**).

New photometric observations of NY Vir were taken on 17 nights from 2011 January to 2014 May in order to collect additional eclipse timings. We used CCD cameras (upgraded during the time period) and Cousins *I* filters attached to the 1.0-m reflector at Mt. Lemmon Optical

Astronomy Observatory (LOAO) located in Arizona, USA. The instruments and reduction methods for the FLI IMG4301E and ARC 4K CCD cameras are the same as those described by Lee et al. (2009b). In order to make an optimal artificial comparison source during our observing runs, we monitored a few tens of stars imaged on the chip at the same time as the eclipsing pair. Five useful field stars were selected and combined by a weighted average. The difference magnitudes between the variable and the artificial reference star were computed. We determined a total of 19 new timing measurements of the primary eclipse using the Kwee & van Woerden (1956) method. Timing measurements of the secondary eclipse were discarded in our analysis due to a larger uncertainty. The final differential light curves from each observing season are shown in Fig. 4A.

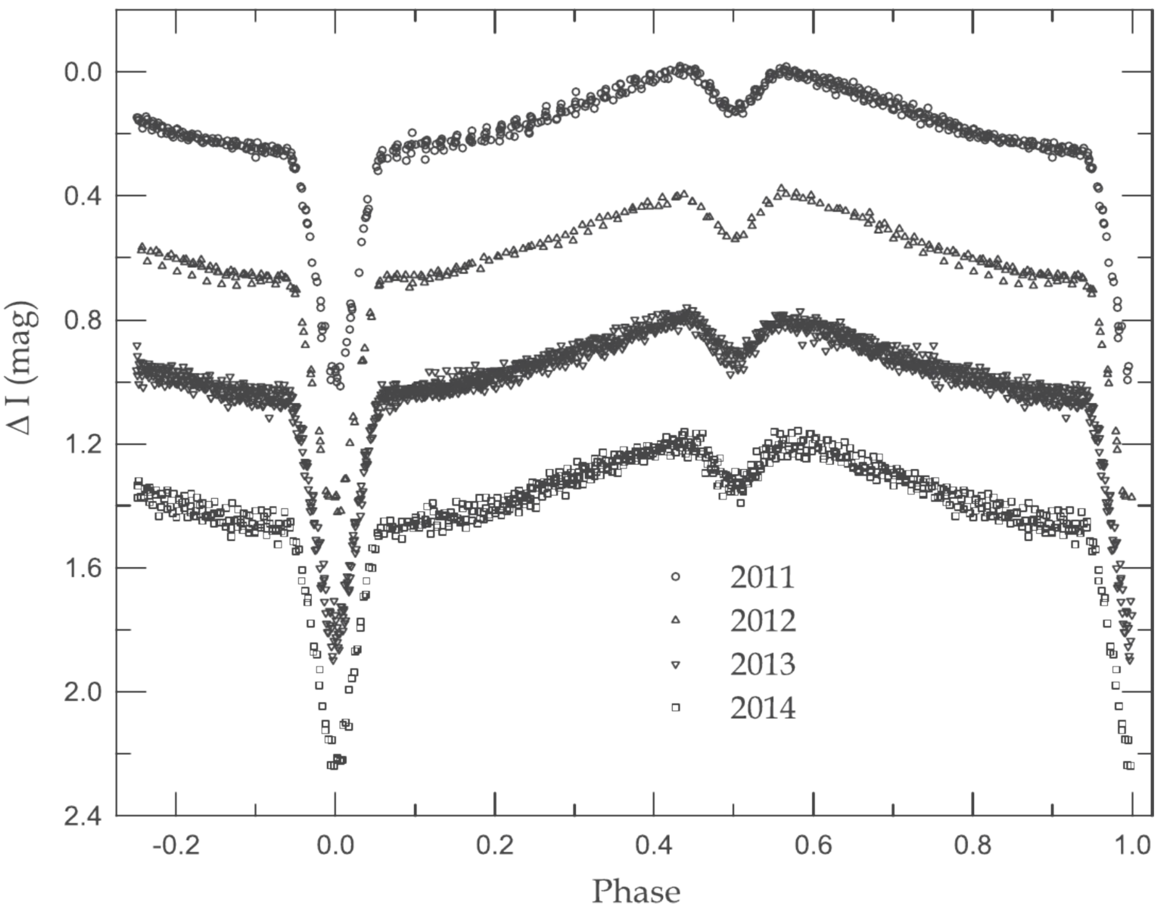


Fig. 4A: *Light curves (differential Cousins I-magnitude vs orbital phase) of HW Vir as obtained from the 1.0m LOAO reflector over a time period of four year. For the timing analysis only the primary mid-eclipse times (phase = 0.0) were used. The figure is reproduced from Lee & Hinse et al. (2014, Fig. 1, **H4**).*

In a previous study Qian et al. (2012) found that the orbital period has varied through a combination of a downward parabola (d*P*/d*t* = $-3.36 \cdot 10^{-9}$ d yr^{-1}) and a sinusoid with a period of ~8 yr and a semi-amplitude of ~6 seconds. They suggested that the sinusoidal variation could be produced by an LTTE/LTT effect due to a circumbinary planet in this system with a minimum mass of ~2.3 M_{Jup} and the parabolic change may be a part of an additional period modulation due to the possible presence of a fourth object.

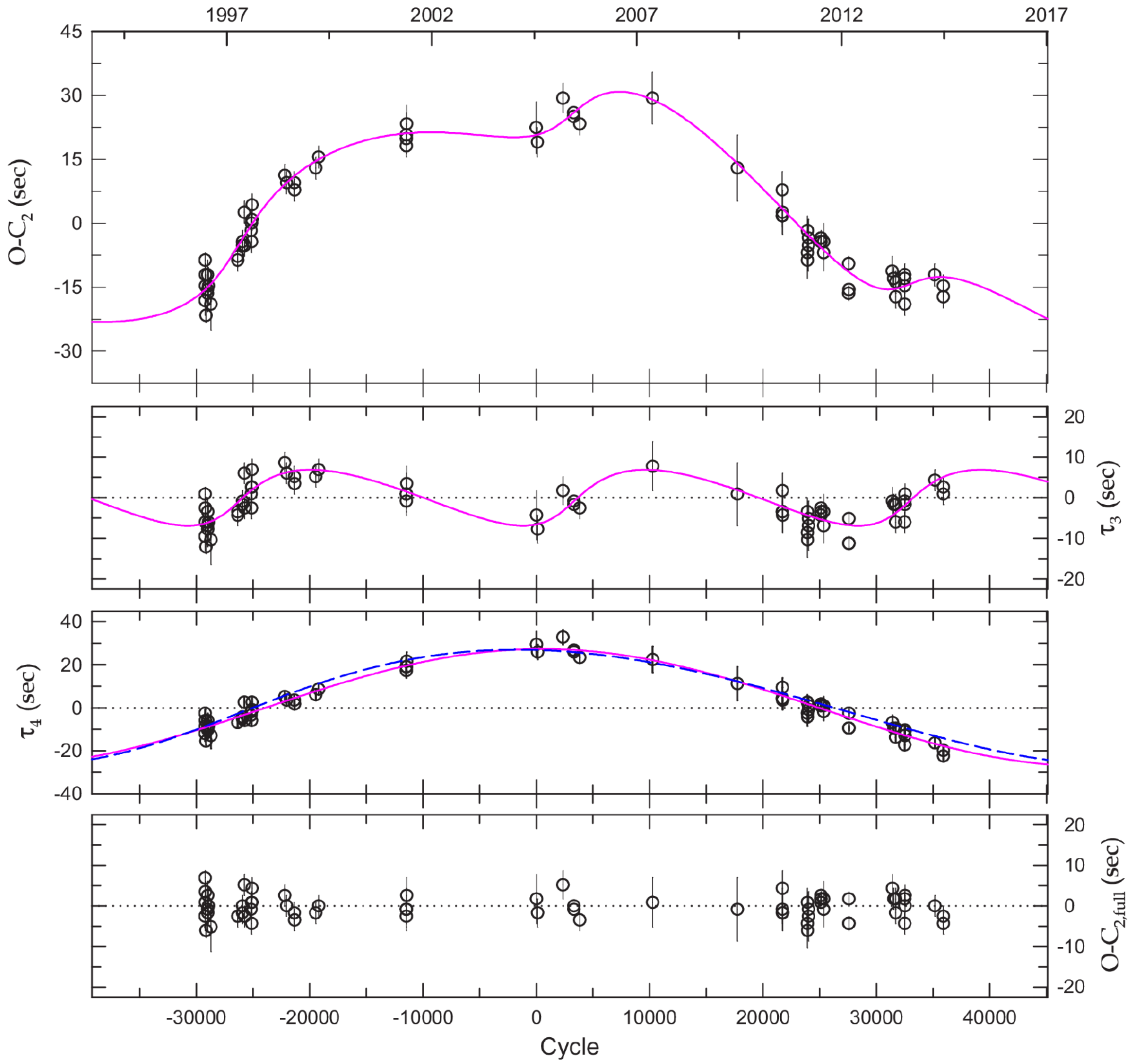


Fig. 4B: *Period variations for the HW Vir system. Top panel: Best-fit two-LTT model to measured eclipse times. Middle two panels from top to down: individual LTT signals for the inner and outer companions, respectively. Bottom panel: final residuals after subtracting the two components with a root-mean-square scatter of ~ 3 seconds. The figure is reproduced from Lee, Hinse et al. (2014, Fig. 3,* ***H4****).*

In the first step, we modelled the primary eclipse epochs by a quadratic least-squares fit resulting in a downward parabolic curve to the data. However, the quadratic ephemeris does not sufficiently follow all observed timings qualitatively revealing the *O* - *C* residuals to oscillate with a semi-amplitude of ~0.0001 days (~8 seconds). This implies that the period change of the eclipsing pair could be explained by a combination of a long-term period decrease and a short-term oscillation as shown in Fig. 4B.

In order to examine a circumbinary companion in the system as the possible cause of the periodic variation, we have chosen to apply a LTTE/LTT model (Irwin 1952) via a Levenberg-Marquardt minimization process to determine the ephemeris and orbital parameters. This approach was different from the work by Qian et al. (2012) who applied a pure sine-curve model to the data. Further, we determined the parameter uncertainties from Monte Carlo bootstrap-resampling experiments. For this, we generated 50,000 bootstrap-ensembles to generate synthetic data sets and used the best-fitting model as our initial guess for each data set.

Following the spectroscopic and light-curve analysis performed by Kilkenny (1998) the downward parabolic curve cannot be explained by a mass transfer between the binary components because the eclipsing pair is a very detached system and both stars are close to spheres. Hence, the long-term period decrease at a rate of $-3.36 \cdot 10^{-9}$ d yr^{-1} can be interpreted as angular momentum loss (AML) corresponding to $dJ/dt = -1.38 \cdot 10^{35}$ (cgs units). Possible mechanisms for AML are gravitational radiation and/or magnetic braking in the cool secondary. We computed the AML rate for each mechanism in a procedure identical to that for HW Vir (Lee et al. 2009a). The theoretical rate for gravitational radiation is $-1.01 \cdot 10^{33}$, (cgs units) which is about two orders of magnitudes smaller than the observed value, while the AML rate for the latter is $-2.07 \cdot 10^{35}$ (cgs units). This result renders it likely that the secular period decrease of NY Vir is mainly produced by AML due to magnetic stellar wind braking. However, another mechanism may be invoked to explain the secular change. Alternatively, it is possible that the observed quadratic term is part of a second LTTE/LTT effect due to the existence of a more distant circumbinary object. Accordingly, the times of minimum light were fitted by a two-LTTE/LTT ephemeris model. The results pointed towards two circumbinary companions with mass ~2.8 $M_{\rm Jup}$ and ~4.5 $M_{\rm Jup}$ and periods of ~8 and ~27 yr, respectively.

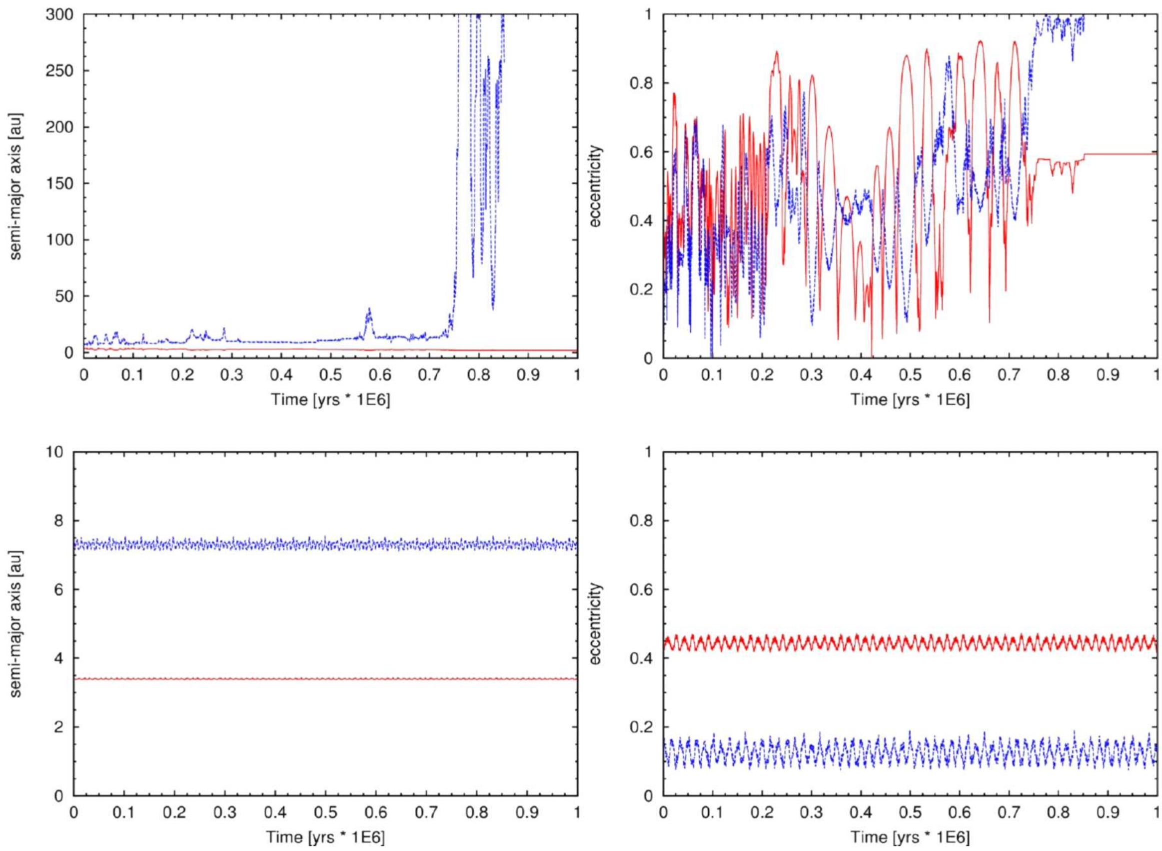


Fig. 4C**: Time evolution of semi-major axis (left panels) and eccentricity (right panels) for the proposed two-planet (red: inner; blue: outer) system over 1 million years. Top panels: chaotic and unstable dynamics. Bottom panels: quasi-periodic and stable orbital dynamics. The figure is reproduced from Lee, Hinse et al. (2014, Fig. 4,* ***H4*).*

In light of previous announcements of possible circumbinary companions to eclipsing binaries systems, we carried out a sanity check and tested the feasibility of the derived planets to follow long-term stable orbits. We have therefore carried out a stability study for the best-fitting orbit parameters of NY Vir. Because of the moderately high orbital eccentricities we applied a variable time-step interpolation algorithm implemented within MERCURY (Chambers 1999). We computed several batches of single-orbit integrations considering various initial conditions compatible with the best-fit model. The total integration time span was 10^6 years. Giving the uncertainty in the time of pericenter passage, we started the two planets from various initial mean longitudes. Furthermore, since their masses are minimum values, we also considered various inclinations and scaled the masses of the companions accordingly. In most cases we found the system to exhibit large-scale orbital instabilities.

Instability occurs either due to ejection of one body from the system or by collision between the two planets.

In the top panels of Fig. 4C, we show the time evolution of the semimajor axes and eccentricity of the two companions. As an example we show the ejection of the outer planet after some 850,000 yr. In an attempt to study the dynamics of the two-planet system in some more detail, we have numerically explored the phase space of the outer companion in a neighbourhood of the best-fitting model. We calculated the lifetime and MEGNO[8] (Goździewski et al. 2001) index to detect chaotic/quasi-periodic regions. The results confirmed the initial single-orbit test calculations demonstrating that the best-fit two-planet model is embedded in a chaotic region. However, the calculations also detected nearby quasi-periodic islands of stability. Considering the lower bounds in orbital eccentricities within the 1σ uncertainty range we found a stable architecture rendering the system to be stable over a 1 million year integration.

The results presented here had some recent impact in the development of understanding of the period variations within the NY Vir system. As of February 2019 the total number of citations to Lee, Hinse et al. (2014, **H4**) is 20. The most significant advances are as follows. Baştürk & Esmer (2018) presented new photometric data of NY Vir extending the baseline period by three years. Interestingly, the authors also point towards the possibility of systematic errors in the timing measurements as a result of the pulsation nature of the hotter component. Currently, the effect of stellar pulsations on the time of minimum light is not investigated in detail. On the other hand pulsations might be used to infer the presence of massive companions (Silvotti et al. 2007). Further, in a recent study, Song et al. (2018) presented additional photometric data of NY Vir. Although their conclusions are not decisive on the nature of the period variations, their study discusses critically certain aspects of modelling techniques that has been neglected in previous studies.

8 Mean Exponential Growth Factor of Nearby Orbits

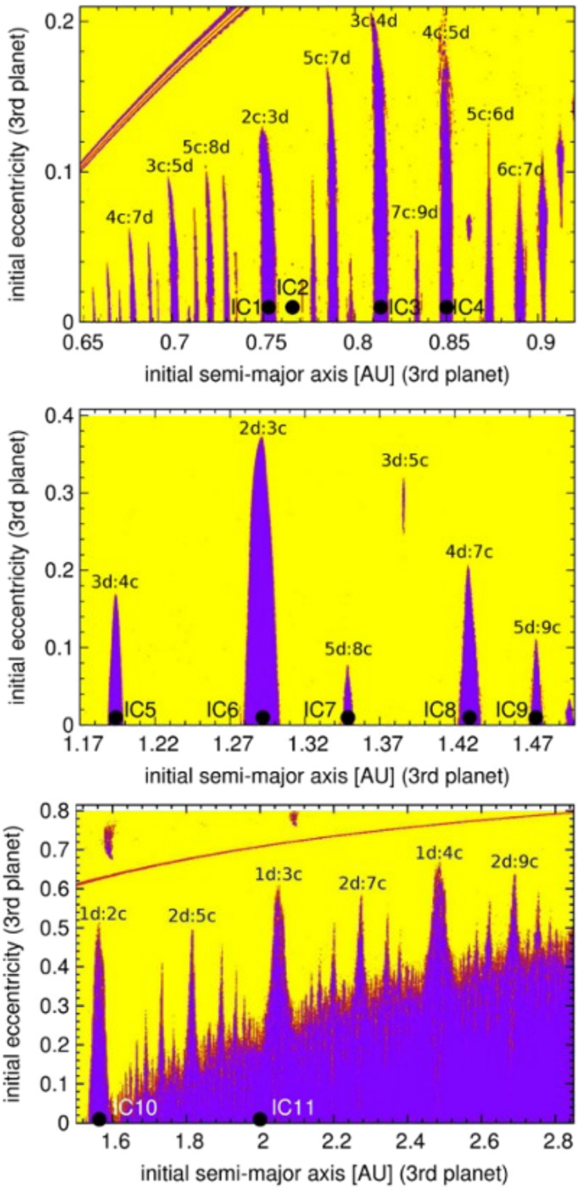
Predicting a third planet in the Kepler-47 circumbinary system (H5)

Strong evidence of planet formation around binary star systems is provided from recent photometric observations using the *Kepler* (Borucki et al. 2010) space telescope. In the past few years several circumbinary single-planet systems were detected (Doyle et al. 2011, Orosz et al. 2012b, Welsh et al. 2012, Kostov et al. 2013; 2014 and Welsh et al. 2015) predominantly using the transit method. In some cases the mass and orbital properties of the planets are favourable to sufficiently introduce gravitational perturbations in the orbit of the central binary, enabling the measurement of eclipse period variations.

One particular highlight from *Kepler* was the discovery of Kepler-47 – a transiting circumbinary two-planet (Kepler47b and Kepler-47c) system. The fact that this system harbours two planets is a strong indication that circumbinary planets can indeed form in multiples. In the Kepler-47 system, the existence of a third planet was speculated in the 2012 discovery paper (Orosz et al. 2012a) in an attempt to account for an unexplained dip-like feature present in the photometric measurements of this binary (detected at time BJD = 2,455,977.363 during a conjunction of the primary star). The most significant event, a single 0.2%-deep transit, was detected that could not be explained by adopting a two-planet photo-dynamical model.

In the study by Hinse et al. (2015, **H5**) we test the three-planet hypothesis and provide predictions of locations where a third planet could be found. Our approach is to numerically investigate the global dynamics of the five-body system (two stars + three planets) to identify stable regions for plausible masses of the third planet. The relatively high osculating eccentricity (~0.4) of Kepler-47c, indicates that the orbital phase-space of this system is likely to exhibit highly complex dynamics.

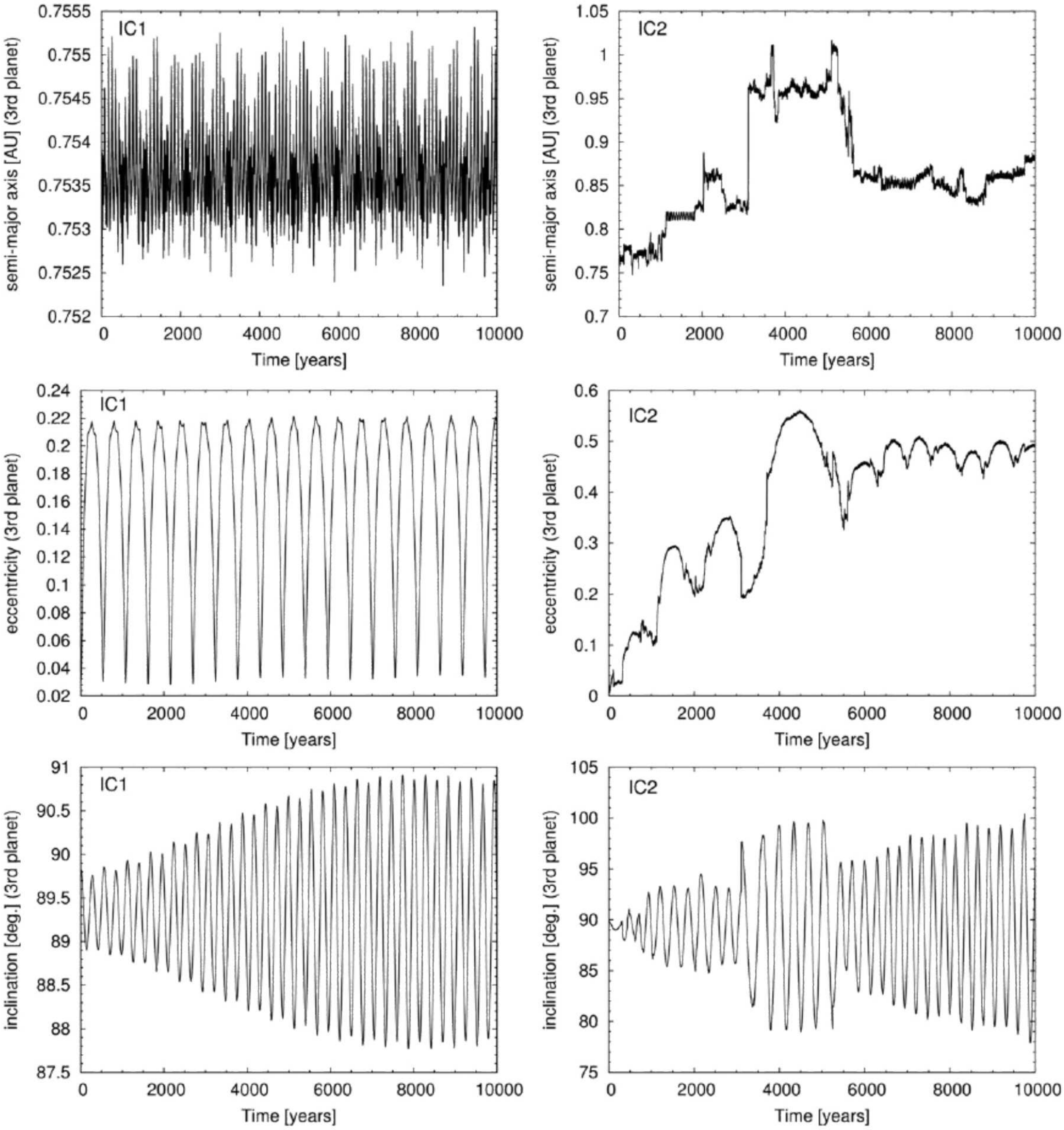
Kepler-47 is a single-lined spectroscopic binary with a ~1.0 M_{Sun} primary and a secondary with a mass of ~0.4 M_{Sun}, the period of this binary is 7.5 days. The inner planet, Kepler-47b, has a period of 50 days and a radius of ~3 $R_{\oplus}$. Orosz et al. (2012a) estimated that the mass of this planet is 7 - 10 $M_{\oplus}$. The outer planet, Kepler-47c, has an orbital period of ~303 days with a radius of ~4.6 $R_\oplus$. The authors estimated a plausible mass in the range 16 - 23 $M_\oplus$. The unexplained transit event had an observed duration of ~4.15 hrs. In their discovery work, Orosz et al. (2012a) suggested that, if this transit-like event was due to a third planet, given its depth of 0.2%, the planet must have a radius ~4.5 Earth-radii.



<u>Fig. 5A</u>: *Dynamical MEGNO maps of the third hypothetical planet within the Kepler-47 circumbinary planetary system. Yellow colour denotes chaotic dynamics and blue indicates quasi-periodic orbits. The locations of mean-motion resonances are indicated. Several black dots denote initial conditions (IC1 - IC11) that were investigated in detail as discussed in Hinse et al. (2015,* ***H5****). The figure is reproduced from Hinse et al. (2015, Fig. 2,* ***H5****).*

Our numerical investigation adopted both accurate single-orbit integrations as well as the application of the MEGNO technique (Goździewski et al. 2001). Numerical calculations were carried out using dedicated super-computing facilities. We started our stability analysis by adding a putative third planet and calculate MEGNO over a grid in semi-major axis and eccentricities of the third planet while keeping the osculating orbits of the two known planets at their best-fit values. The third planet was considered massless as well as massive with mass compatible with the observed transit depth from which a radius is derived and the use of empirical mass-radius calibration relations (Kane & Gelino, 2012).

The orbits of all planets were considered to be co-planar as a plausible assumption. First results are shown in Fig. 5A. We found three regions (with a weak dependence on investigated masses of the putative planet) where a hypothetical third planet can maintain a quasi-periodic orbit: *i*) a region in the vicinity of Kepler-47b, *ii*) a region between the two known planets, and *iii*) the region exterior to the orbit of Kepler 47c. The second region was found to be characterized by the presence of orbital mean-motion resonances between the outer planet (c) and the putative planet (d). The quasi-periodic nature for certain orbits is indicative for stable regions. Low-eccentricity orbits for the third planet are most favourable to render the system globally stable. Single-orbit numerical integrations of the five-body system were used to test the long-term time evolution of particular third-planet orbits. We contrast several initial conditions where the third planet is started on a quasi-periodic but also in chaotic orbits. For example, in Fig. 5A the 2c:3d mean-motion resonance between the putative and the outer planet is shown to offer a stable orbital architecture. A long-term time evolution of a test integration (IC1) is then compared with a nearby orbit shown to exhibit some degree of chaotic dynamics (IC2). The result of single long-term integrations are shown in Fig. 5B where we plot the semi-major axis, eccentricity and orbital inclination of the third planet vs time. The quasi-periodic nature of the 2c:3d mean-motion resonance is demonstrated. Long-term time evolution was also probed in several of our integrations considering time spans of 10 million years.



<u>Fig. 5B</u>: *Time evolution of orbital elements of the hypothetical planet for two different initial conditions IC1 (left) and IC2 (right). This demonstrates an example of quasi-periodic and chaotic dynamics. The figure is reproduced from Hinse et al. (2015, Fig. 3,* ***H5****).*

In an attempt to constrain the possible location of the hypothetical planet we made use of the measured time of transit duration. The transit duration is a strong function of the size of the orbit. For this we calculated transit duration (TDV) and transit timing variations (TTV) induced by the third planet considering various orbital architecture for which a stable time evolution was found. We implemented an algorithm for the numerical determination of transit events from direct orbit integrations. During the integration steps, we monitor the on-sky projected position of the planet (r_{sky}) relative to the primary star. The time of ingress t_1 and egress t_2 are determined from an iterative process, when $|r_{sky} - (R_A + R_{pl})| < 10^{-15}$.

The mid-transit time is then calculated from $t_1 + (t_2 - t_1)/2$. A linear regression is then used to calculate the variations in the transit times. The transit duration is calculated from $(t_2 - t_1)$. We calculated the durations of the transits of the third planet for various quasi-periodic orbits and compared with the measured (~4.15 hrs) transit duration of the putative planet. Because of the mutual interactions between planets, the duration of the transits of the third planet will vary from one transit cycle to another. We found several transit events in which the duration of the transit of the third planet to be comparable to that of the observed unexplained single transit (~4.15 hrs). For instance, from integrating IC1, one of the transits had a duration of 4.16 hrs.

In conclusion of this research we were able to identify regions where a third massive planet could render the overall five-body planetary system to follow a stable architecture. We made use of the observed transit duration of the putative transit-like signal as an observational constraint to narrow down its possible orbits. Recent developments: In a recent paper Orosz et al. (2019) the authors presents a re-analysis of all recorded photometric *Kepler* data for Kepler-47 and announced the discovery of a third planet with orbital property to be within the two previously detected planets. As a consequence of parameter correlations, their best-fit model now renders all three planets to be on near-circular orbits consistent with orbital eccentricities observed for single-star multi-planet systems. This results suggests that some aspects of formation and migration mechanisms of planets are shared between single and multiple star planetary systems.

Summary

The five research papers (**H1 – H5**) presented here are part of a larger series of publications (published after the award of the PhD degree) all concerning aspects of circumbinary multi-body dynamics and related data modelling techniques. In particular, my focus was on circumbinary extrasolar planetary systems which recently experienced an increased scientific awareness as a result of the discoveries of planets around binary star systems by the *Kepler* space telescope. Most of the population of circumbinary planets around short-period eclipsing binaries were detected from ground-based observations. Shortly after starting this project, I noticed that this field seriously suffers from major concerns related to certain system's orbital long-term stability and the inferences made from the observational data. The results presented in (**H1** – **H4**) critically address existing short-comings in the used methodology and applied data analysis techniques within the field of circumbinary extrasolar planetary systems. In each publication, I presented a more rigorous and critical treatment of the observational data, to provide new ideas and incitement, in the hope to change the, at times sloppy, data analysis practices previously found in the literature. Too often, discoveries are prematurely claimed on the ground of relatively weak data processing and related discussions of limitations of applied underlying methods. As a highlight of this research project is the theoretical prediction of a third circumbinary planet in the Kepler-47 system. This was presented in **H5**. The discovery work of an additional planet, Kepler-47d, is currently under review. I am co-authoring the discovery paper contributing with global dynamics calculations. The publications presented here are chosen to reflect my scientific contributions to this newly emerged research field over the past eight years. As a result of my review of the latest development in the literature, I noticed a change in the quality of research with increased attention to scientific thoroughness and stringency. The number of citations to each publication in **H1** – **H5** reflects the significance of this research project to the astronomical/astrophysical research community. Finally, I declare, that the presented research was conducted to the best of my scientific knowledge and abilities.

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5) Discussion of other scientific achievements

After the award of PhD degree I moved to the Republic of Korea to start post-doctoral research activities at the Korea Astronomy and Space Science Institute (7.5 years) and Chungnam National University (since July 2018). The main focus of research was the detection and dynamical characterisation of massive companions in stellar binary star systems. In addition, as a result of my active involvement in the international MiNDSTEp (http://www.mindstep-science.org/) collaboration, I continued to organize the photometric follow-up observation of transiting extrasolar planets using the Danish 1.54m telescope at the ESO/La Silla observatory in Chile. This project was then extended to also involve Korean-based telescopes as part of a Korean-USA-Chinese-Turkey collaboration of telescope networks. Further, as part of a two-year (2014 / 2015) research and education (R&E) teaching activities, I also initiated the installation of the first professional double-station optical video-detector of meteor/fireballs in South Korea. Finally, as a result of my participation of the

Sagan Summer School Workshop over several years, I was involved in smaller research projects related to the microlensing technique for the detection of extrasolar planets and the dynamics of so-called S-type planets in stellar binary systems.

Installation of a sky-monitoring camera system for the detection of meteors

In reaction of a March 2014 atmospheric meteor event (Jin-ju fireball) in South Korea, I initiated the installation of a proto-type camera system for the optical detection of meteors and fireballs.

Fig. 6A: *Double-station sky-monitoring camera system for the optical detection of meteors and fireballs in South Korea (left panel: BOAO site; right panel: SOAO site). The figure is reproduced from Hinse et al. (2017, Fig. 2).*

This project formed the main part of a 2014 / 2015 research and education program between Korea Astronomy and Space Science Institute (KASI) and the Daejeon Science Highschool (DSHS). At the time of the Jin-ju fireball event no similar system existed in South Korea. The system consists of a total of six cameras deployed on two different mountain tops. Each camera station is made up of three cameras with individual orientations chosen in order to have overlapping field of views. This setup allows the measurement of the three-dimensional trajectory for events observed simultaneously from two different camera vantage points. Fig. 6A shows the two camera systems at BOAO and SOAO observatories. The baseline between the stations is around 100 km. In general, the hardware and software setup is identical for maintenance reasons. The optical components are comprised of a WATEC 902-H2 high-frame rate video-camera in combination with a *f*/1.2 lens.

Different field of views were chosen in order to determine the limiting magnitude and detection rate as a function of focal length. Details of the sky-monitoring system were described in Hinse et al. (2017). For accurate orbit determination the software system was kept synchronized in time. The results were as follows. During a 2.5 year period of operation a total of 1886 meteor events were recorded. A total of 113 double-station events were detected and their orbits analysed. Both asteroid and cometary type meteor events were determined.

Dynamics of circumbinary sub-stellar companions in binary star systems

The light-travel time effect (LTTE/LTT) was also applied to systems for which measured period variations of the central eclipsing binary points towards the presence of sub-stellar mass circumbinary companions. The question of long-term orbital stability and viability of these systems is a necessary condition to substantiate their existence.

Several eclipsing binary systems have been proposed for which additional bodies are held responsible for the detected period variation. In the work by Hinse et al. (2012) we addressed the recent claims for two sub-stellar M-dwarf companions around the eclipsing binary SZ Herculis (Fig. 6B). A similar study was concerned with detected period variations for the RZ

Draconis system (Hinse et al. 2014). For these systems we carried out a re-analysis of the measured timing data. The goal was to find LTTE/LTT model parameters that support long-term orbital stability for these systems. In all cases, we found the underlying four-body system to be extremely unstable with maximum life-times of less that ~1000 years.

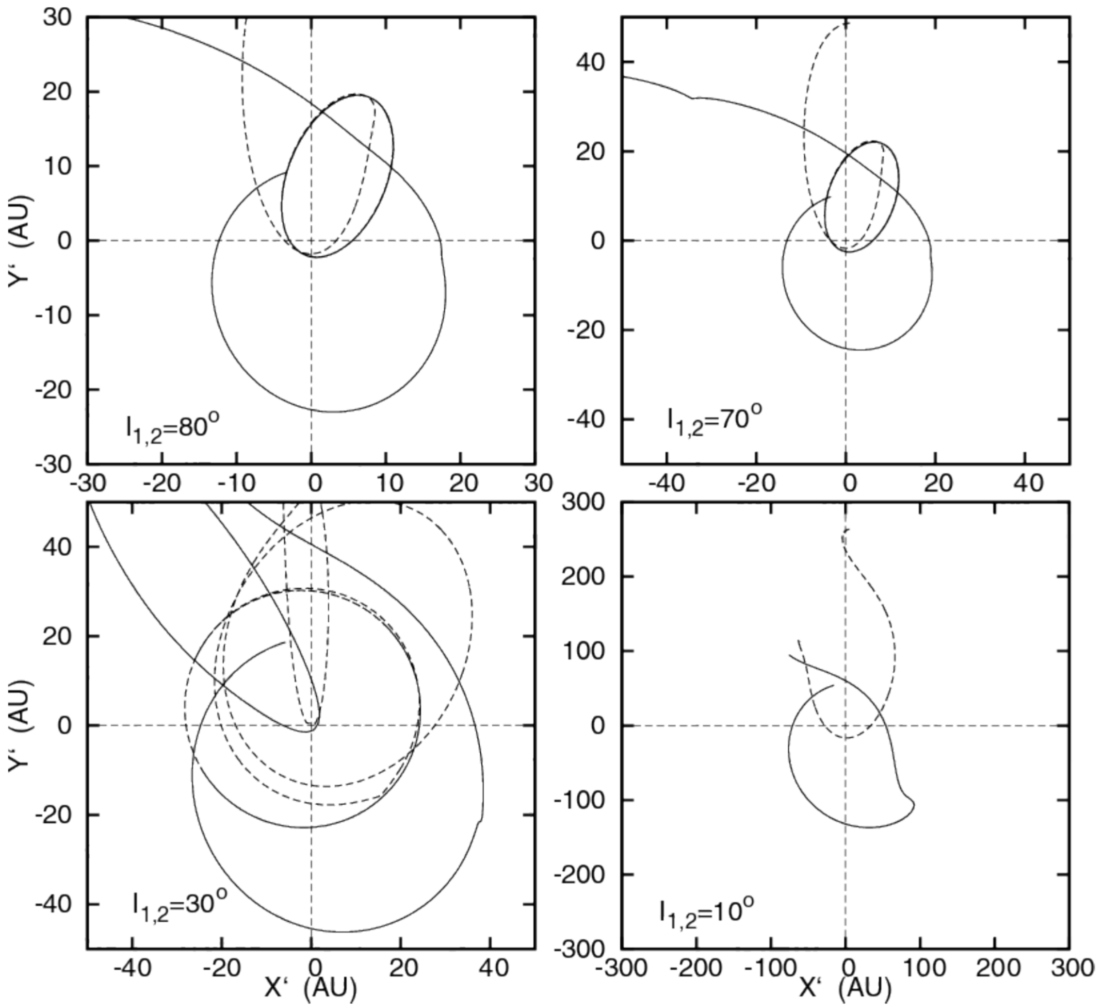

***Fig. 6B**: Examples of unstable orbits numerically explored for the proposed SZ Herculis quadtruple stellar system. The initial orbits of the two companions were assumed co-planar. Various orbital inclinations were examined. In all cases we found the systems to be highly unstable. The figure is reproduced from Hinse et al. (2012, Fig. 5).*

Dedicated dynamical stability studies of circumbinary systems were also carried out. In Horner et al. (2013) we investigated in detail the dynamical time evolution of the proposed brown dwarfs orbiting the BD+202457 eclipsing system. Also in this case we found highly unstable architectures considering the full range of parameter uncertainties. A similar study was carried out by Hinse et al. (2014) considering the SW Lyncis system where we concluded unstable orbits for the proposed companions on very short time-scales. The LTTE/LTT modelling work presented above has one major short-coming. The model assumes single Keplerian orbits neglecting mutual gravitational interactions. In an attempt to rectify this current and future work is in progress to calculate the light-travel time effect based on a few-body numerical model. Perhaps the inclusion of mutual perturbations might open up a window towards rendering these systems to follow stable orbits.

Dynamics of S-type extrasolar planets in binary star systems

Extrasolar planets were also detected to orbit one star in a binary system. These are called satellite-type planets. As part of a USA-Korea collaboration we investigated the dynamical properties of such planets. We used numerical techniques to study chaotic and quasi-periodic orbits to assess their stability. Three different stability criteria were considered: *i*) Hill-stability, *ii*) Maximum-Lyapunov Exponent and *iii*) the MEGNO index. We compared these techniques for their resemblance applied to the γ Cep and HD 196885 planetary systems (Satyal, Quarles & Hinse 2013) and found quantitatively good agreement. In the second paper (Satyal, Hinse et al. 2014) we investigated the effect of the Kozai resonance for a planet within HD196885 and applied the MEGNO technique to explore the underlying dynamics allowing us to determine parameter regimes for which the Kozai resonance is most effective.

Discovery of circumbinary planetary systems from *Kepler* photometry

In a collaboration with Veselin B. Kostov, I participated in research resulting in the discovery of circumbinary transiting planets (Kepler-64, Kepler-47, Kepler-413, Kepler-453) using high-precision *Kepler* photometry. This research was initiated during the 2012 Sagan Summer School Workshop. A fundamental problem in the modelling of transit timing variations was the inclusion of mutual perturbations of the orbits from all bodies involved.

My contribution was the implementation of a numerical multi-body code capable of integrating the equations of motion and determine the eclipse and mid-transit times of the binary pair and circumbinary planets (Fig. 6C). This resulted in the co-discovery of the circumbinary planetary systems Kepler-64 (KIC4862625 or PH-1) and Kepler-47 (Kostov et al. 2013). This project was later extended to also include the calculation of global dynamics using the MEGNO technique (Kostov et al. 2014; 2016). This resulted in the membership of the Kepler Eclipsing Binary Working Group (http://keplerebs.villanova.edu/members) for which I have carried out additional dynamical calculations concerning the stability of orbits of newly discovered circumbinary planets (Welsh et al., 2015; Orosz et al., 2019).

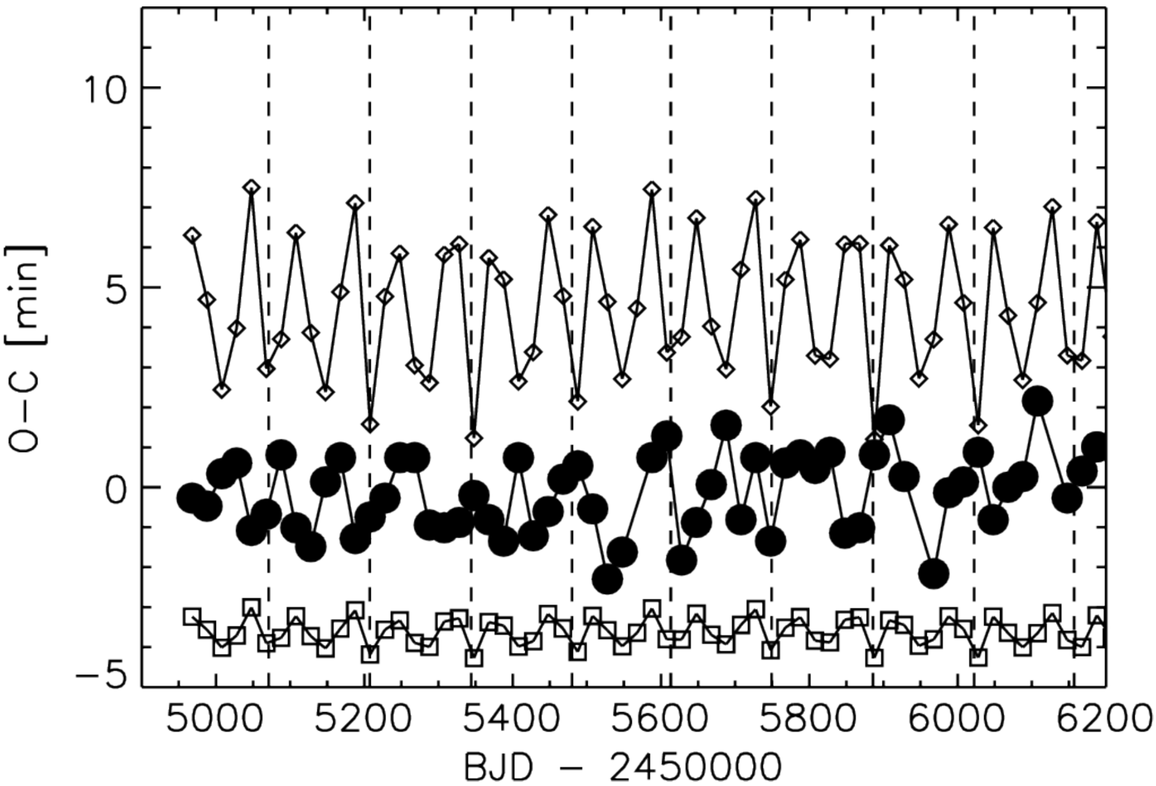

Fig. 6C: *Eclipse timing variations (O - C vs time) of the primary eclipses of KIC 4862625 (Kepler-64 or PH-1) as caused by a circumbinary planet with different mass. The timing variations (various symbols) were calculated from a three-body code. Measured eclipse timings are shown as vertical lines. The figure is reproduced from Kostov, McCullough, Hinse et al. (2013, Fig. 6).*

Photometric follow-up observations of transiting extrasolar planets

In 2008 I initiated a collaboration with John Southworth with the scientific goal to conduct photometric follow-up observations of transiting extrasolar planets from the southern hemisphere (Southworth, Hinse et al. 2009a). This project is part of the MiNDSTEp (http://www.mindstep-science.org/) collaboration using the Danish 1.54m telescope at the ESO/La Silla observatory in Chile. This project is currently still active (Southworth, Hinse et al. 2012). As an example, Fig. 6D shows the light curve of WASP-25 (Southworth, Hinse et al. 2014) as observed from various telescopes, including the Danish telescope.

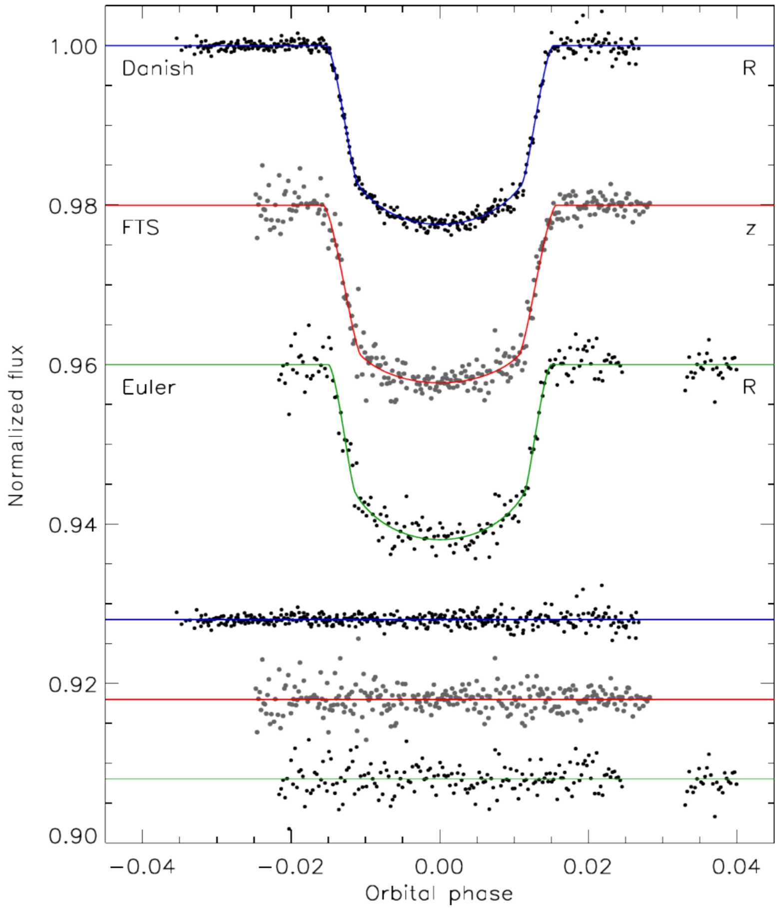

Fig. 6D: *Transit light curves for WASP-25. The data shown in the top part is obtained from the Danish 1.54m telescope. Data from additional telescopes were acquired as well. The bottom part shows the residuals between data and best-fit model. The figure is reproduced from Southworth, Hinse et al. (2014, Fig. 6).*

Traditionally, transiting planets are discovered as a result of dedicated ground-based sky-monitoring projects (WASP, Super-WASP, HAT, TrES projects). Often, the quality of photometric data is poor, but sufficiently good to meet initial detection criteria. At the beginning the class of hot Jupiters was uncovered and with increased observation baseline long-period planets were gradually detected.

From the transit light curve (Fig. 6D) the radius-ratio between the planet and stellar radius is derived as one of the model parameters. In particular, the radius-ratio is directly proportional to the transit depth. Consequently, the higher the photometric precision the more accurate the radius-ratio is measured. In combination with an accurate measurement of the stellar radius (usually from spectroscopy) the planetary radius is determined (Southworth, Hinse et al. 2009a, Southworth, Hinse et al. 2009b).

The photometric precision by which a ground-based telescope can measure the stellar flux is to a large part determined by scintillation noise (Southworth, Hinse et al. 2009a; Hinse et al. 2015) which again is depending on the atmospheric condition of the sky (turbulent vs laminar motion). Other hard-ware related sources of errors are present as well. This is usually quantified by the signal-to-noise ratio. One method to increase the signal is to apply the telescope defocus technique allowing significant prolonged exposure times of the star without saturation of the CCD chip. For the 1.54m telescope we routinely obtain a photometric precision with a mean-scatter of less than a milli-magnitude for a V ~ 12 star resulting in the measurement of planetary radius to within a few percent.

In 2008, I carried out the first few practical tests of this technique. In subsequent years, I managed and assisted in data reduction and light curve modelling. This also included thesis advisory work related to transiting planets (Harpsøe, Hardis, Hinse et al. 2013). Furthermore, this technique was also successfully applied in a collaboration work with Turkish colleagues using the TUG 1.0m telescope (Baştürk, Hinse et al. 2014).

The frequent measurement of precise transit light curves potentially enables the detection of additional planets orbiting the host star. From accurate measurement of the mid-transit time, the transit timing-vatiation technique (Haghighipour et al. 2013) can be used to infer period variations of the transiting planet caused by a perturbing planet. This technique is powerful. Non-transiting planets can be detected and in addition, upper mass limits of the additional planet can be inferred from the magnitude of the measured period variation. In an attempt to improve the characterisation of transiting planets and measure period variations, I recently joined a China-USA lead collaboration (TEMP[9] collaboration) involving various international observing facilities including Korea-based telescopes (Wang et al. 2018a, Wang et al. 2019b). My contribution to this project is to plan and schedule observing time of future transit events to acquire photometric data of transiting planets from South Korea (Wang et al. 2019a). In addition, I carry out numerical calculations using a large-scale computing cluster to determine upper mass limits of an additional planet based on observational constraints from measuring period variations for a given system (Wang et al. 2019c). Planetary systems for which the two planets participate in an orbital mean-motion resonance are especially interesting. For such special configurations the detection probability of additional planets is increased significantly via an increased period variation compared to nearby orbits. The dynamical calculations also allows the detection of the location of these resonances in the phase space from the application of the MEGNO technique. This effort has resulted in a series of publications of which two are currently in the review process (Wang et al. 2019a, 2019b).

Dynamics of Solar System small-body ring systems

As part of my supervision activities for Jeremy Wood I have contributed to his research work both as a co-supervisor and research collaborator. The research is concerned with the dynamical evolution and stability of Solar System small-bodies and the dynamics of their ring-system. This resulted in a series of three papers (Wood et al. 2017, Wood et al. 2018a, Wood et al. 2018b) during the time period from 2015 to mid-2018. The work was inspired by the discovery of a ring system around Chariklo known to belong to the population of Centaurs. The work is based on a statistical analysis as a result of detailed numerical simulations of test-particles and their long-term time evolution under the gravitational perturbations of the Sun and four giant planets. Both the orbit of Chariklo and satellite system was considered. The particle simulations were accompanied by detailed dynamical maps using the MEGNO technique to explore the underlying phase-space structure. In summary, the main result from this research demonstrated that close encounters between Chariklo and the giant planets have insignificant influence on the ring-structure stability. The orbit of Chariklo itself was found to be long-lived with an injection-time into the Centaur population

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occuring within the last 9 million years. We also found an indication for prolonged life-times for Centaur clones near the orbital resonances with Neptune.

Theoretical investigation into measuring the microlensing parallax from space

This research originated from my year-long activities within photometric follow-up observations of microlensing events towards the Galactic bulge. As a result of my participation at the 2017 Sagan Summer School Workshop, I initiated a research collaboration with Drs E. Bachelet and R. Street. Within microlensing theory the mass-distance degeneracy can be broken by measuring the same microlensing event from two different positions. This is called the microlensing parallax effect. In the paper Bachelet, Hinse & Street (2018) we investigated systematically the magnitude and uncertainties (via a Fisher matrix analysis) of the parallax effect for various space-based observatories including an observing station located on the surface of the moon. For the parallax effect to be significant a relatively long base-line is needed between the two observing stations. We paid particular attention to the detection of microlens parallax as observed by NASA's WFIRST (in planning) space telescope. As a result we outline short-comings of the Fisher matrix analysis for the parallax uncertainty estimation and provide quantitative guidelines related to microlensing parallax modelling.

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