（別紙様式５）

変革を駆動する先端物理・数学プログラム（FoPM）

国外連携機関長期研修　報告書

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Participation in the Seventh PHOEBE Workshop at Yunnan University

I stayed at Yunnan University for two weeks and participated in the Seventh PHOEBE Workshop. The aim of this workshop was to provide participants with practical training in simulating and fitting observational data of close binary systems—such as flux variations, radial velocity variations, and other relevant features—using the software PHOEBE (PHysics Of Eclipsing BinariEs).

Background

My research focuses on searching for compact objects—such as white dwarfs, neutron stars, and black holes—in non-interacting close binary systems (Shiraishi et al. 2025). Such systems are of great importance as progenitors of X-ray binaries, Type Ia supernovae, and gravitational-wave sources, and thus play a crucial role in understanding the evolutionary pathways of compact objects. However, detached binaries composed of a normal star and a compact object are X-ray faint because they do not undergo mass transfer, and therefore only a small number of such systems have been discovered to date.

Using photometric and spectroscopic survey data from *Gaia* DR3 and TESS, I have identified a large number of candidate detached binaries consisting of a star and a compact object. These candidates are being followed up with spectroscopic observations to measure radial-velocity variations. So far, I have reported two systems that are single-lined spectroscopic binaries (SB1s) composed of a compact object and a G-type main-sequence star.
In SB1 systems, the orbital inclination and the mass of the unseen companion are degenerate, allowing only a lower limit on the compact-object mass to be determined. As a result, precise mass measurements are not possible using radial velocities alone.

One way to break this degeneracy is to use information from photometric variability. In star–compact object binaries with orbital periods of a few days, tidal forces exerted by the compact object deform the visible star, producing photometric modulations with amplitudes of about 0.1–1% at half the orbital period (ellipsoidal variations). If the amplitude of this effect can be measured from the light curve, the degeneracy between the inclination and the compact-object mass can be lifted.

However, many of the star–compact object binaries I have discovered exhibit stellar spots on the visible star, which produce rotational modulations in the light curve. Because these systems have short orbital periods, tidal locking synchronizes the stellar rotation with the orbital motion, making it difficult to disentangle ellipsoidal variations from spot-induced variability.

By using PHOEBE, it is ideally possible to simultaneously fit ellipsoidal variations and stellar spots, potentially enabling accurate measurements of ellipsoidal-variation amplitudes and, consequently, precise determinations of compact-object masses. This motivated my participation in the PHOEBE Workshop.

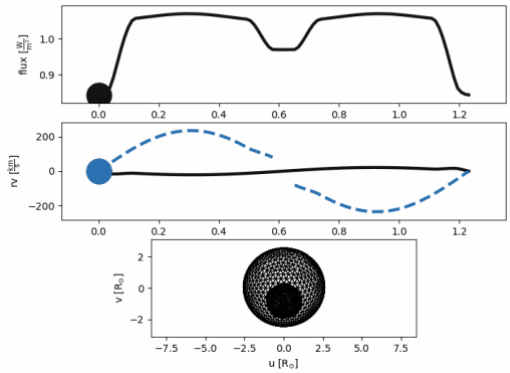


Figure # 1 The light curve and radial velocity curves of an eclipsing binary obtained by my PHOEBE simulation

PHOEBE Workshop

During the first week, I learned the physical models adopted by PHOEBE and how to simulate light curves of close binary systems. The software calculates light curves that include eclipses, irradiation effects, ellipsoidal variations (caused by tidal

deformation of stars), Doppler boosting (including special-relativistic aberration of light, time dilation, and Doppler shifts due to orbital motion), and rotational modulation caused by stellar spots. PHOEBE also accounts for limb and gravity darkening, interstellar extinction, and deviations of stellar spectra from blackbody radiation.

Through these lectures and hands-on sessions, I became able to simulate the light curves and radial-velocity curves of well-studied eclipsing binaries (Figure #1).

In the second week, I learned how to solve inverse problems—that is, how to infer the physical parameters of close binary systems from observational data. PHOEBE performs fitting in three steps: (i) estimation, (ii) optimization, and (iii) sampling.

First, PHOEBE provides rough estimates of system parameters directly from observables without using a forward model. For example, the geometry of eclipsing light curves can constrain the eccentricity, inclination, sum of fractional radii (the sum of the stellar radii divided by the semi-major axis), radius ratio, and temperature ratio. These quantities are estimated by fitting the observed light curve with simple analytic formulae or by using machine-learning techniques.

Next, PHOEBE optimizes a merit function using a forward model, such as those learned in the first week, to obtain a solution consistent with the observations. At this stage, PHOEBE employs standard optimization techniques, including the Nelder–Mead method and conjugate-gradient methods.

Finally, PHOEBE samples the parameter space around the solution using the forward model and merit function, yielding posterior distributions that can be used to estimate parameter uncertainties. For this purpose, PHOEBE supports Markov Chain Monte Carlo sampling and nested sampling.

Outcomes and Experience

By participating in this workshop, I became proficient in using PHOEBE to simulate and fit light curves of close binary systems. The skills acquired during the workshop were partially applied in a subsequently submitted paper (Shiraishi et al. 2025). In that study, we reported the discovery of a close binary consisting of a G-type star and a compact object with a mass of approximately one solar mass. We simulated the observed light curve of this system using PHOEBE and compared it with TESS observations to roughly estimate the properties of stellar spots on the G-type star.

In addition, interactions and discussions with other workshop participants were highly fruitful. In particular, I had in-depth discussions on contact binaries with researchers from Thailand, which led to the initiation of a new collaborative project. We are currently analyzing the radial-velocity data and light curves of a contact binary using PHOEBE to determine its physical parameters.

Reference

Shiraishi, Y., Hotokezaka, K., Masuda, K., et al. 2025, arXiv e-prints, arXiv:2509.12808, Accepted for publication in the Publication of the Astronomial Society of Japan

