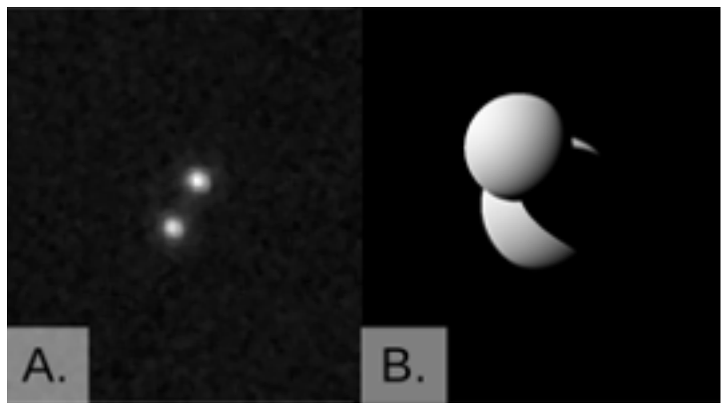
CS486C – Senior Capstone Design in Computer Science

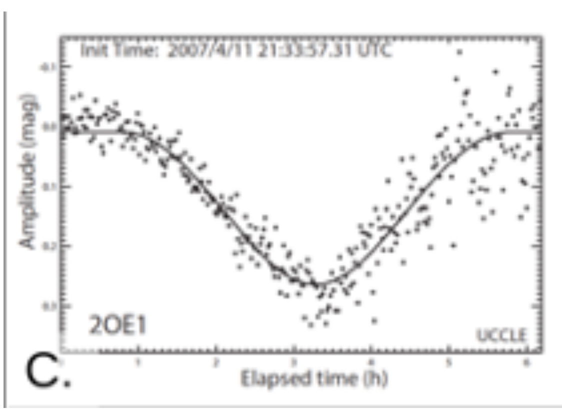
Project Description

Project Title: Complex Asteroid shapes in Modeling of Binary Asteroid Systems	
Sponsor Information: LOWELL OBSERVATORY 125 YEARS | 1894 - 2019	Dr. Will Grundy, Astronomer Dr. Audrey Thirouin, Astronomer grundy@lowell.edu ; thirouin@lowell.edu Lowell Observatory, Flagstaff

Project overview:



Asteroids are leftover debris from the formation of planets. Their study can explain the solar system's configuration and also the distinct characteristics of Earth that enabled life to emerge and thrive there. They are also a potential threat to life on Earth. Asteroids are challenging to study since they are much smaller than planets and they are far too numerous to send spacecraft to explore more than just a tiny sample of them. Remote methods are essential. But even an asteroid so distant that it is just a point of light in the telescope can reveal a lot about itself. This is especially true for a binary asteroid – a pair of asteroid objects in tight orbit around each other. The changing shadows the two cast onto one another cause variations in overall brightness over time (what we call a "lightcurve") that carries information about the sizes, shapes, and mutual orbit of the pair. Although this sounds straightforward enough, it is actually quite challenging to invent techniques for deducing information about the binary asteroid from its observed lightcurve. Overall, this is what is called a *non-linear inverse problem*, a class of problem that is encountered throughout science and technology. In simplified terms, the overall approach to solving these problems is to use a computer model of the system of interest, where you can (as parameters) adjust features of interest (like size, orbital rate, etc.), and use that model to compute the lightcurve for the modeled system. You then compare these computed lightcurves to the actual observed lightcurves while varying the model parameters and, when you get a match, you have figured out the dynamics of the real system. More specifically, we start with a "forward model" in the form of a three-dimensional model of a pair of orbiting asteroids that is ray-traced to compute a model lightcurve. We then search through the space of possible input parameters, running the model for each to produce model lightcurves, and try to match that to the observed lightcurve of the target system. Various algorithms can be used to optimize this search for the set of input parameters that provides the best match between model lightcurve and actual observations; obviously the trick is to find ways to tune the process to quickly find the best match *without* exhaustively covering the (large!) parameter space.



Previous Capstone teams have created a forward model for this problem and also implemented a non-linear least squares inversion method as one "smart" way to guide exploration of the parameter space. But application to real-world data calls for one key additional capability in the forward model: the ability to work with more complex mathematical shapes than spheres. This is needed because most asteroids have non-spherical shapes. Non-spherical shapes of various functional form can provide better approximations to the shapes of real asteroids. A simple example is the oblate spheroid, in which the polar radius is somewhat smaller than the equatorial radius. A more general form is the triaxial ellipsoid. Functional forms derived from the physics of equilibrium fluid bodies are even better, since they are consistent with the physics of the system (mass, density, rotation rate, tidal deformation). Arbitrarily complex shapes can also be represented as collections of triangular facets, but this quickly becomes very expensive computationally so it is desirable to focus first on representing the shapes with simple mathematical functional forms.

The overall aim of this Capstone project is to design, test, and add a new module to the existing forward modeling system that supports modeling of more complex non-spherical shapes, and provides integration and interface features that allow scientist users to add complex shapes as a dimension that can be enabled/explored by the forward modeling system. Specifically:

Key features of this envisioned project include:

- Creation of a new module within the existing modeling engine, that implements more complex functional forms for the shapes for the binary asteroids.
- A bare bones proof of concept will add a simple triaxial ellipsoid shape. A more complete implementation will enable users to select fluid equilibrium shapes and/or adjust various parameters of the new shapes in a more fine-grained way (such as by setting the density as the free parameter, and deriving the shape accordingly, under the assumption of fluid equilibrium).
- An alternate approach could be to represent the shapes with collections of triangular facets, but to get the necessary performance, that would almost certainly require a GPU implementation rather than a more generic CPU implementation. A stretch goal will be to explore this option with a basic implementation, and doing some initial trials to better understand the computational power it would need.

Knowledge, skills, and expertise that will be developed:

- No specific astronomy or mathematical knowledge is required; sponsors will serve as technical advisors for these aspects.
- Getting familiar with the existing software and associated documentation and discussion with sponsors.
- Programming skill in C++ and experience with Doxygen.
- Familiarity with Linux/Windows computing environments.
- Gain competence in scientific computing and inverse problems.
- Understanding of ray tracing algorithms.

Equipment requirements:

- There is no specific hardware required for this project, just a standard Linux software development environment.
- Existing code and documentation will be provided by the sponsor.

Deliverables:

- The software module described, implemented in C++ and fully documented. Integrated into existing system infrastructure.
- Fully functioning new major version of software, tested and deployed in the Lowell computing environment.
- User Manual for configuring and operating the software updated to account for new features.
- A report describing the design and implementation of the new features and their integration into the software infrastructure, written for the target audience of a future developer.
- Professionally-documented source code, delivered as a repository in GitHub or as a zip or tar archive.