Modeling the History of Astronomy: Ptolemy, Copernicus, and Tycho

BERRY COLLEGE

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ABSTRACT: The Copernican Revolution is an astronomy course for non-science majors at Berry College. The course begins with simulated observations of the night sky and then proceeds to an examination of several historical models that were proposed to explain these observations. This poster describes how students actively engage with computer simulations to gain a deep understanding of the Ptolemaic and Copernican models of our solar system. Students then have the opportunity to model their own unique planetary system. Each student receives a personalized Easy Java Simulations program depicting the motion of a "Sun" and several planets against background stars. Students make the measurements they need and then construct both Ptolemaic and Copernican models for their system. Students also investigate the relationships between the Ptolemaic, Copernican, and Tychonic models and evaluate these models in the context of early 17th Century knowledge of astronomy and physics. More information is available at http://facultyweb.berry.edu/ttimberlake/copernican/.

Observing the Sky

Students make simulated observations of the night sky using **Stellarium**. They are guided to discover the following observational facts:

- The Sun drifts eastward relative to the stars along a great circle on the Celestial Sphere. The Sun completes one circuit around this path, known as the *Ecliptic*, in a one *sidereal year*.
- The five visible planets (Mercury, Venus, Mars, Jupiter, and Saturn) move relative to the stars and the Sun. *Elongation* measures the angle between a planet and the Sun on the sky. If a planet is at 0° elongation it is in *conjunction*, at 90° it is in *quadrature*, and at 180° it is in *opposition*.
- The five visible planets generally drift eastward and remain near the Ecliptic, though they can be found slightly above or below. The time for a planet to complete one circuit along the Ecliptic is its *zodiacal period*.
- The Sun periodically moves eastward past each planet. The time between one pass and the next is that planet's *synodic period*.
- Occasionally the planets move westward (in *retrograde* motion) for a short time before resuming their eastward motion. The time between successive retrogrades is equal to the planet's synodic period.
- Mercury and Venus are never more than 28° and 48°, respectively, from the Sun. They are in conjunction during the middle of their retrograde motion. These planets are known as *inferior planets*.
- Mars, Jupiter, and Saturn can attain any elongation. They are in opposition during the middle of their retrograde motion. These planets are known as *superior planets*.
- The planets vary in brightness. Mars, Jupiter, and Saturn are brightest when in retrograde (Mars dramatically so). Venus is slightly brighter when it is in retrograde.

After discovering these facts and learning the appropriate vocabulary, students are given a personalized simulation of a fictitious solar system. (Each system has all planets orbiting in a common plane in circles with the central star at the center.) Students must identify planets, classify each planet as inferior or superior, and measure the following:
- sidereal year,
- (average) zodiacal period of each planet,
- synodic period of each planet,
- maximum elongation of each inferior planet,
- time from opposition to quadrature for each superior planet.

Ptolemaic Modeling

Students use the **Inferior Ptolemaic** and **Superior Ptolemaic** Easy Java Simulations (EJS) models to explore a simplified version of the Ptolemaic system in which each planet moves uniformly counterclockwise on a circle called the *epicycle* and the center of the epicycle moves uniformly counterclockwise along a circle called the *deferent*. The deferent is centered on Earth. The Sun moves uniformly counterclockwise on a circle centered on Earth. Students discover the following relationships between this theory and the observational data:

- The period of the epicycle center's motion around the deferent must equal the planet's zodiacal period.
- The period of the planet's motion around the epicycle (measured relative to the deferent) must equal the planet's synodic period.

- The center of an inferior planet's epicycle must remain on the Earth-Sun line in order to keep the planet near the Sun in the sky.
- For superior planets, the line from the center of the epicycle to the planet must always be parallel to the Earth-Sun line in order to ensure that the planet retrogrades at opposition.
- For an inferior planet, the ratio of its epicycle radius to its deferent radius is given by
$$R_e/R_d = \sin\theta$$
where θ is the planet's maximum elongation. The geometry is illustrated in Figure 1.

Figure 1: Ptolemaic geometry for an inferior planet at maximum elongation.

- For a superior planet the formula for this ratio is more complicated, but the ratio can be computed from the planet's zodiacal period, its time from opposition to quadrature, and the length of the sidereal year.

Once they understand how the Ptolemaic model is constructed, students can evaluate the model.
- The model, with the relations detailed above, can match the observational data.
- Although the ratio of a planet's epicycle to its deferent is fixed, there is no set scale for relating the size of one planet's orbit to another. Even the order of the planets is not determined in the Ptolemaic system.
- The model automatically makes a planet brighter when it is in retrograde, because at that time it will be closer to Earth.
- Retrograde can be synchronized to opposition/conjunction, but only by adding the constraints described above. These constraints do not occur automatically and they are somewhat mysterious.
- Planets come in two varieties which follow very different rules. There is no explanation for why this is the case.
- Planets move around an empty point in space.

After exploring the simplified Ptolemaic model of our solar system, students can develop a Ptolemaic model for their personalized fictitious solar system using the observational data they collected earlier.

Copernican Modeling

Students use the **Copernican System** EJS model to explore a simplified version of the Copernican system in which each planet moves uniformly counterclockwise on a circle centered on the Sun. Students discover the following relationships between this theory and the observational data:

- Planets are naturally classified as inferior or superior depending on whether their orbit is smaller or larger than Earth's, respectively.
- The period T_e of Earth's orbit is one sidereal year.
- The period T_p of a planet's orbit is given by
$$T_p = \left(T_e^{-1} \pm T_s^{-1}\right)^{-1}$$
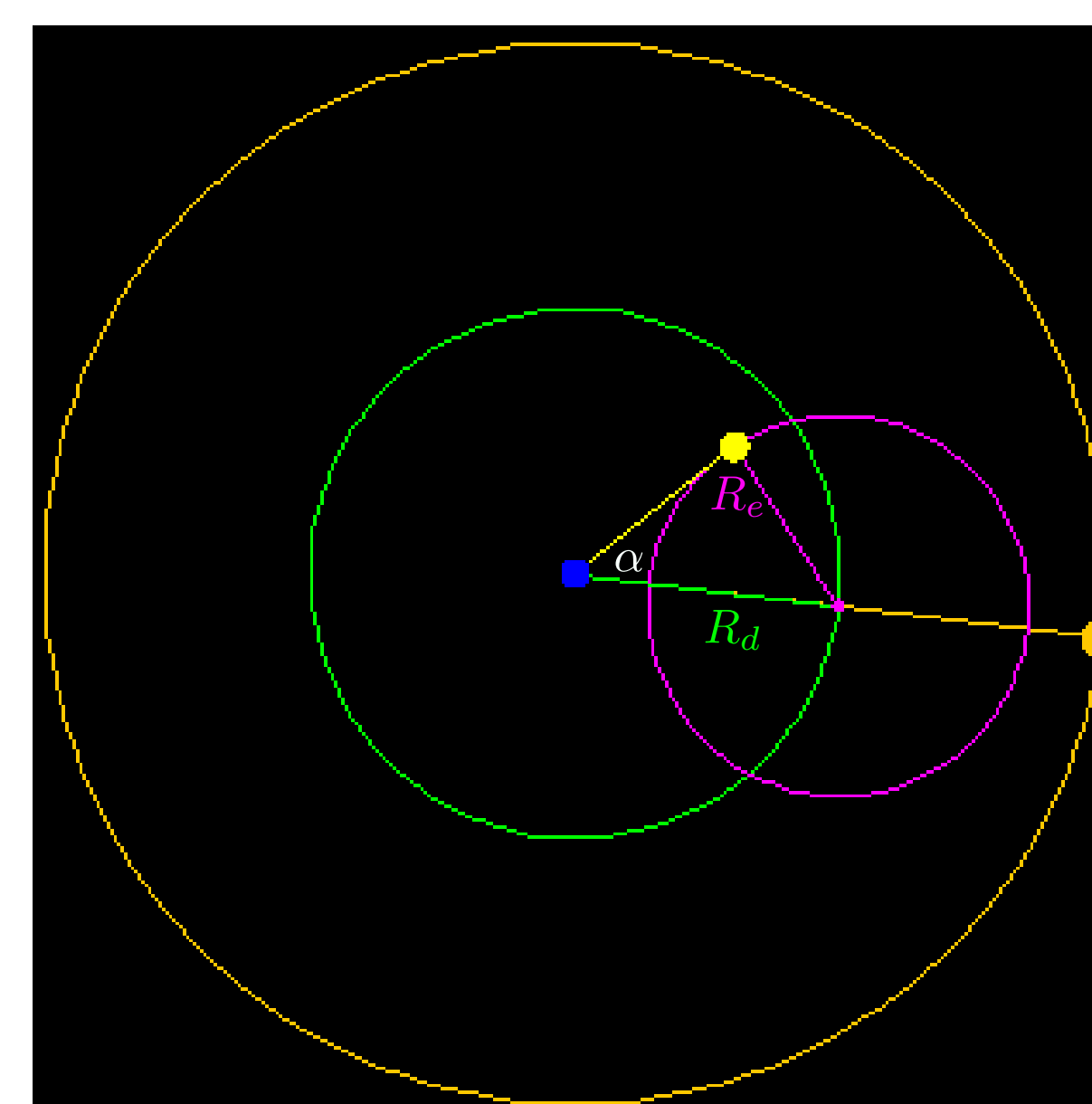where T_s is the planet's synodic period (+ for inferior, - for superior).

- For an inferior planet, the ratio of the planet's orbital radius to that of Earth is given by
$$R_I/R_E = \sin\theta$$
where θ is the planet's maximum elongation. The geometry is illustrated in Figure 2.

Figure 2: Copernican geometry for an inferior planet at maximum elongation.

- For a superior planet the formula for this ratio is more complicated, but the ratio can be computed from the planet's orbital period, time from opposition to quadrature, and the length of the sidereal year.
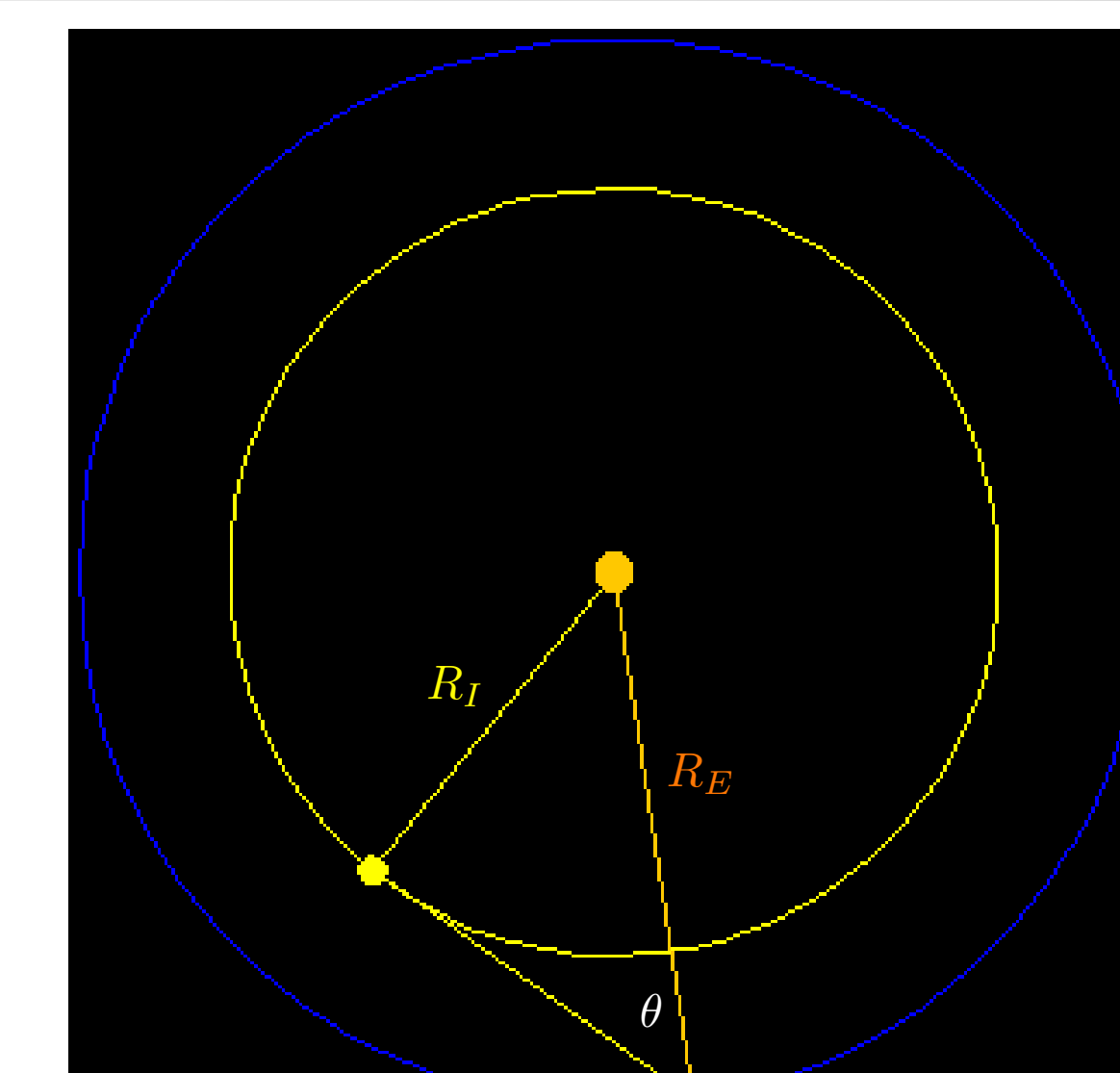
Once they understand how the Copernican model is constructed, students can evaluate the model.
- The model correctly reproduces the observational data without any special constraints.
- The model produces retrograde motion in a natural way when Earth passes, or is passed by, another planet. Retrograde motion is automatically synchronized to conjunction/opposition and also automatically occurs when the planet is closest to Earth (and thus brightest).
- The sizes of all planetary orbits are fixed relative to Earth's orbit. This provides a unique ordering for the planets from Mercury nearest the Sun to Saturn farthest from the Sun.
- The model provides a natural explanation for the distinction between inferior planets with orbits smaller than Earth's, and superior planets with orbits larger than Earth's.
- All planets orbit around a physical body: the Sun. Planets closer to the Sun orbit at greater speeds and thus have shorter orbital periods.

After exploring the simplified Copernican model of our solar system, students can develop a Copernican model for their personalized fictitious solar system using the observational data they collected earlier.

Ptolemy, Copernicus, and Tycho

The Tychonic theory is basically a Copernican theory with a stationary Earth. The **Ptolemy Copernicus Tycho** EJS model illustrates the geometric equivalence of the three simplified theories (see Figure 3) and shows:
- For inferior planets the Ptolemaic epicycle is the Copernican orbit of the planet, while the Ptolemaic deferent is an image of the Copernican orbit of Earth.
- For superior planets the Ptolemaic epicycle is an image of the Copernican orbit of Earth, while the Ptolemaic deferent is the Copernican orbit of the planet.

Resources
- **Stellarium**: www.stellarium.org
- EJS models: **Inferior Ptolemaic, Superior Ptolemaic, Copernican System,** and **Ptolemy Copernicus Tycho** all available from *Open Source Physics* at www.compadre.org/osp/.
- Personalized solar system simulations and activity handouts available at facultyweb.berry.edu/ttimberlake/copernican/.
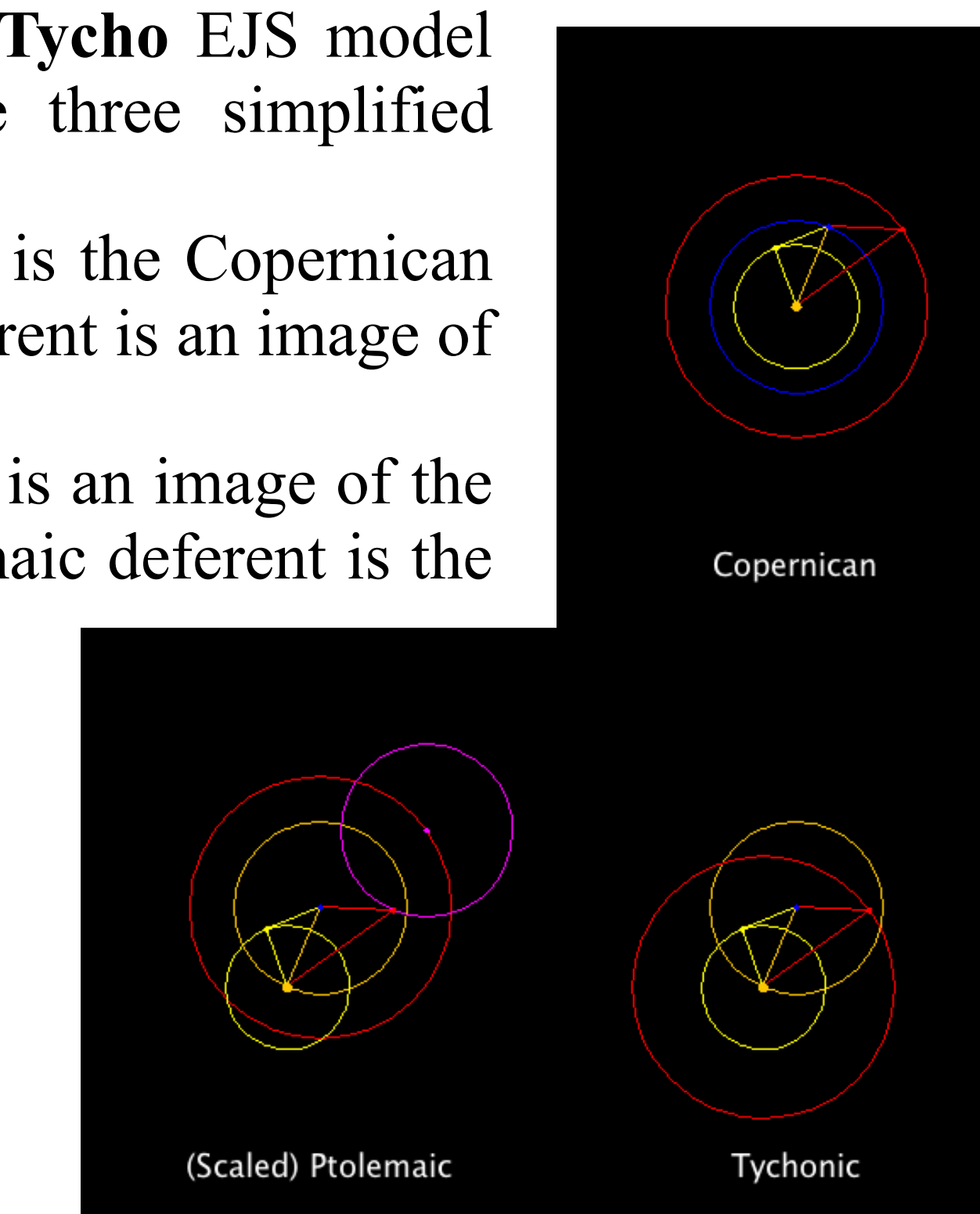

Figure 3: Comparison of Ptolemaic, Copernican, and Tychonic systems.