Tycho and Kepler meet in Prague (1600-01)

- Tycho needs Kepler:
  - difficult calculations to figure out orbit of Mars

- Kepler needs Tycho:
  - precision data to figure out true orbits of the planets

- Together embark on improved astron. tables (Tabulae Rudolphinae)
Johannes Kepler: The Great Theorist

- 1571 – 1630
- born into middle-class: lifelong economic struggles
- completed Copernicus agenda
- The last mystic (last scientific astrologer)
Kepler: Geography of his Life

[Map of Europe with marked regions and cities]
Europe: Deeply divided into multiple confessions
Kepler: Birth and Upbringing in Wuerttemberg

- Born 1571: Weil der Stadt (near Stuttgart)
- middle-class family
- father: a mercenary, mother: cantankerous
University Education at Tuebingen (1589-94)

- Leading Protestant University
- Undergrad (7 Liberal Arts)
- (Lutheran) Theology
University Education at Tuebingen (1589-94)

- Michael Maestlin, professor of mathematics and astronomy
- taught: Ptolemy and Copernicus
- lifelong friendship with Kepler
Neoplatonism: Search for hidden harmony

God

(William Blake, 1757-1827)

Realm of Ideas

Motion of planets

Realm of Experience
Neo-Pythagoreanism: A Universe governed by Numbers

Divine Tetractys:

1 + 2 + 3 + 4 = 10

- symbolizes the universe!
Kepler studies Theology and makes Enemies

• “Last Supper Controversy”:
  - Lutherans: Wine *is* Christ
  - Calvinists: Wine only *symbolizes* Christ
• Kepler, being a Lutheran, supports Calvinist view
• Source of great trouble, professionally and personally
Mathematician in Graz (Austria)
Mathematician in Graz

- Teacher at Protestant High School
- Styrian estate mathematician: horoscopes
Mysterium Cosmographicum

- Why are there exactly six planets?
- What determines their distances from the Sun?
- *Cosmographic Mystery* (1596)
Mysterium Cosmographicum: 5 Platonic Solids

- **Tetrahedron**: 4 vertices, 6 edges, 4 faces.
- **Cube**: 8 vertices, 12 edges, 6 faces.
- **Octahedron**: 6 vertices, 12 edges, 8 faces.
- **Icosahedron**: 12 vertices, 30 edges, 20 faces.
- **Dodecahedron**: 20 vertices, 30 edges, 12 faces.
Mysterium Cosmographicum

- planetary orbits nested between Platonic solids!
Kepler and Astrology

• One of his duties: Work out annual calendars, i.e., predict the events of the year ahead!
Kepler and Astrology

- Kepler: one of the last scientific astronomers!
- Henceforth, astronomy and astrology part company
Kepler: Fleeing the Counter Reformation in Graz
Kepler: Move to Imperial Prague

Rudolph II
- Emperor (1576-1612)

• Great Patron of Arts and Sciences (Tycho, Kepler)
Tycho’s Assistant in Imperial Prague

Benatky Castle: Tycho’s Final Domicile (1599 – 1601)

- Tycho invites upstart young Johannes Kepler!
Kepler: The Inheritor of Tycho

• After Tycho’s death (1601): Kepler moves quickly to get hold of Tycho’s data

• Emperor Rudolph II appoints Kepler to become Imperial Mathematician

• Imperial order: Complete *Rudolphine Tables*

• Kepler’s main agenda: Win the “battle with Mars”
Kepler’s Warfare with Mars

- Tycho pointed out to Kepler that orbit of Mars is particularly difficult to understand!
- Orbit of Mars shows large deviation from circularity!
The New Astronomy: The Orbits of the Planets

- **Astronomia Nova** (New Astronomy, 1609)
- Kepler’s 1\textsuperscript{st} and 2\textsuperscript{nd} Law:
  - planets move in elliptic orbits with Sun in one focus
  - law of areas
- Finally: A model that works!
- Introduce Celestial Physics
The New Astronomy: The Orbits of the Planets

• Problem: Observe (Mars-orbit) from moving platform (Earth)!

• But want to figure out orbit with respect to Sun!

• A convolved problem!
Long Process of Trial-and-Error

• Method: (1) Try given orbital geometry, and (2) compare with Tycho’s data

• All combinations involving circles, can only give accuracy of ~ 8 arcmin

• But: Kepler knew that Tycho’s data have accuracy of ~ 4 arcmin

• Thus: Reject circular orbits!

• Eventually: Try elliptic orbits with Sun in one focus!
• 1\textsuperscript{st} Law: Planets move in ellipses with the Sun in one focus!

\textbf{Semi-major axis }a\textbf{  
\textbf{eccentricity }e

\[ e = \frac{\text{Distance from center to focus}}{a} \]
Orbit of the Planets: Kepler’s 1st Law

- Ellipse is one of the three conic sections, and the circle is a special case!

(Conic sections described by Apollonius of Perga in 200 BC)
Speed of the Planets: Kepler’s 2nd Law

- Start with Sun-centered version of Ptolemy’s equant!
Speed of the Planets: Kepler’s 2nd Law

- Kepler realizes: Pseudo-equant is almost equivalent to “equal area in equal times” as seen from Sun!
Speed of the Planets: Kepler’s 2\textsuperscript{nd} Law

- 2\textsuperscript{nd} Law: A line drawn from the Sun to a planet sweeps out equal areas in equal times!
Finally solving the Problem of the Planets

• One unified framework valid for *all* planets!
  - No ad-hoc fixes allowed!

• For each planet, 2 free quantities (parameters) to choose: semi-major axis $a$, and eccentricity $e$

• It could not have been done without Tycho’s data!
**Coup-d’État in Prague (1611)**

- Emperor Rudolph deposed by his brother

- Kepler has to leave Prague
Move to Linz (Upper Austria)
Mathematician in Linz (1612-28)

- Teacher at Protestant High School
- Upper-Austrian estate mathematician: horoscopes
The Harmony of the Worlds

- *Harmonice Mundi* (Harmony of the Worlds, 1619)

- Kepler’s 3rd Law:
  \[- P^2 = a^3 \]

- full of mystical speculation
The Harmony of the Worlds

- Kepler’s 3rd Law: \( P^2 = a^3 \)
The Harmony of the Worlds

- The Music of the Spheres
- recall: Pythagoras
Rudolphine Tables (Tabulae Rudolphinae)

- improve Reinhold’s old (1551) Prutenic Tables
- based on Copernicus’ De Revolutionibus
- limited accuracy in light of Tycho’s observations
- Kepler has promised Tycho on deathbed to complete this
Rudolphine Tables (Tabulae Rudolphinae)

- *Tabulae Rudolphinae* (1627)
- based on Kepler’s new laws of planetary motion
- unprecedented accuracy (after all: Kepler’s is the correct model)
- Astronomers adopt tables first, before the theoretical works
Rudolphine Tables

- Tables: non-glamorous, but very useful!
Rudolphine Tables: The Frontispiece

- Allegory of Astronomy
Witchcraft Trial of Kepler’s Mother (1620-21)

- Kepler (successfully) defended his old mother

“Water Trial”
Kepler: Pact with the Devil (1628-30)

- Entered the employ of generalissimo Wallenstein
- Wallenstein was firm believer in astrology
- Moved to Sagan

Wallenstein, Supreme Commander of Imperial Troops in Thirty Years War
Journey’s End: Death in Regensburg (1630)
Kepler’s Epitaph:

“I measured the skies, now the shadows I measure. Skybound was the mind, eartbound the body rests”
Kepler’s role in the Scientific Revolution

**Newton** (1642-1727)
- dynamics
- law of gravity

“Standing on the shoulders of giants”

**Kepler** (1571-1630)
- celestial motion
- 3rd Law

**Galileo** (1564-1642)
- laws of free-fall
- principle of inertia
• Johannes Kepler:
  - finally solves the problem of the planets
  - break free from the old dogma of uniform circular motion
  - completes Copernican Revolution

• Kepler’s Laws of Planetary Motion
  - 1st Law: Planets move in ellipses with the Sun in one focus
  - 2nd Law: A line from the Sun to a planet sweeps over equal areas in equal time (“Law of Areas”)
  - 3rd Law: $P^2 = a^3$

• Kepler calculates *Rudolphine Tables*
  - New standard of precision