B. Sometimes predictions lead to new discoveries, as in the case of Neptune.

C. Sometimes predictions indicate new physics, as when general relativity is required to explain Mercury's orbit.

D. Science is a process of testing a hypothesis over many years until the community is comfortable calling it a scientific theory.

Suggested Readings:

Bennett, Donahue, Schneider, and Voit, *The Cosmic Perspective*, chaps. 3–4, 7.

Grosser, *The Discovery of Neptune*.

Hoyt, *Planets X and Pluto*.

Sagan, *The Demon-Haunted World*.

Weintraub, *Is Pluto a Planet?* chaps. 6–9.

Questions to Consider:

1. Can you think of a hypothesis that might explain the Titius-Bode rule? How would you test that hypothesis?
2. Adams predicted the existence of Neptune first, but Le Verrier published his prediction first. Who deserves credit as the discoverer?
3. Does the existence of general relativity mean that Newton's law of gravity is wrong?
4. If the testing of a hypothesis takes many years, do most scientists live to see their work elevated to the status of scientific theory?

Lecture Six

From Observational Evidence to Discoveries

Scope: The teaching of science tends to celebrate the discoveries and end products of the scientific method, despite the fact that the observations and data gathering play just as important a role. This idea is especially true in astronomy, where the basic job of creating an accurate and detailed map of the heavens has been a continuing and evolving task for thousands of years. Careful and patient surveys of the sky not only uncover new knowledge but also serve as the basis of other observations in astronomy. Since the invention of the telescope, craftsmanship in their construction has conferred advantage in making discoveries. As telescopes improved and grew larger, they reached limitations due to size, weight, and Earth's atmosphere. Advances continued through the development of instruments attached to the telescopes that, for example, disperse light into its spectrum or capture it in a photograph. Observational improvements have continually enabled scientific advances. Each stage of research—instrumentation, observation, and interpretation—has developed into a specialized field for astronomers.

Outline

I. Our big ideas about how the universe works are based on a long chain of evidence and argument.

A. The models of the solar system and physical laws are the end product of the scientific method.

B. Gathering the data to develop and support those ideas is just as critical a component of research.

C. As astronomy has developed as a science, specialization and collaboration throughout the discovery process have become more important.

D. The romantic view of a lone astronomer on a mountaintop in a solo search for answers is far from accurate.

II. The data from pre-telescopic observations were mainly concerned with positional astronomy, or astrometry.

A. The motions of the Sun and stars define the day and the year.
1. The line on the sky from north to south is called the meridian.
2. The average time between the Sun crossing the meridian is the 24-hour solar day.
3. Due to Earth's tilt and elliptical orbit, the Sun's motion across the sky varies over a year.
4. The average time between a star's crossing of the meridian is 23 hours 56 minutes, which is called the sidereal day.
5. The stars serve as a reference frame, and the positions of the Sun and planets can be related to which stars they are near or which constellation they are in.

B. Positions on the sky are defined in terms of the celestial sphere.
1. Right ascension and declination on the sky are analogous to longitude and latitude on Earth.
2. The zero point of the coordinates is the point in the sky where the Sun's path (the ecliptic) crosses the celestial equator on the spring equinox.
3. Declination is an angular measure in degrees, minutes, and seconds of arc.
4. Measuring the time of meridian crossing gave rise to right ascension being measured in hours, minutes, and seconds.

C. Star positions serve as the basis for making measurements on the sky.
1. Constellations serve only as geographical markers on the celestial sphere.
2. An important job in astronomy is to define a catalog of known star positions.
3. The position of an object is then measured relative to a known star.
4. Over centuries the positions of the stars changed, revealing the precession of Earth's rotation (the precession of the equinoxes).

D. In 2000, astronomy moved to using the International Celestial Reference System (ICRS).
1. Positions in ICRS are measured relative to 212 distant radio sources.
2. The precession of the equinoxes will not affect ICRS coordinates.

III. Telescopes extended the ability to see objects that are small, faint, and far away.

A. The two basic types of telescopes are refractors and reflectors.
1. Refractors use lenses to collect and focus light.
2. The largest refractors are limited by the length of the telescope and the weight and optical quality of the lens.
3. Reflectors use mirrors to gather light.
4. The largest reflectors are limited by the size and optical quality of the mirrors.

B. Telescopes have several important characteristics that determine their usefulness for research observations.
1. Magnification, or resolving power, is the ability to see fine details.
2. The resolution of large ground-based research telescopes is limited by the scattering of Earth's atmosphere.
3. The size of a telescope's primary lens or mirror determines its light-gathering power.
4. The quality of the optical path of the telescope can affect both the above characteristics.

C. Craftsmanship in telescope making is an important factor in scientific discovery.
1. Access to the best and largest telescopes has repeatedly enabled astronomers to make important discoveries.
2. Galileo's improvements to the spyglass brought about the birth of telescopic astronomy.
3. William Herschel discovered Uranus using his own telescopes, the finest reflectors of his time.
4. Telescope makers are an important branch of astronomers.

IV. While individual discoveries are trumpeted, one can argue that science benefits much more from general surveys of the sky.

A. Creating surveys of the sky can both reveal and enable discoveries.
1. Surveys establish a reference set of knowledge against which future observations can be compared.
2. Herschel found Uranus while doing a survey of stars.
3. Finding Uranus within historical observations allowed the problem with its orbit to be more readily identified.
4. Neptune's discovery was aided greatly by a recent, accurate star map.

5. The long and painstaking observations of surveys are important, if unglamorous, work.

B. Survey data taken for one purpose are often used for different, unrelated research.

C. A favored approach in astronomy is a targeted search.
   1. Some targeted searches use surveys to develop a list of candidates for further observation.
   2. Other targeted searches focus upon a particular region of the sky.
   3. Searches for solar system objects have often looked along the ecliptic for retrograde motion at opposition.

V. Over the years, the telescope has decreased in importance, while the instruments used with the telescope have grown in importance.

A. As telescope design encountered limitations, improvements had to come elsewhere.
   1. Telescopes gather and focus light, while instruments process and analyze the collected light.
   2. Today's best observatories are defined by both the telescopes and the instruments attached to the telescopes.

B. Sensitive detectors allow astronomers to analyze light in many ways that the human eye cannot.
   1. Prisms and other devices spread light into a spectrum for study by wavelength.
   2. Photography uses time exposures to record faint objects.
   3. Many specialized devices have been developed for astronomical observations.
   4. As an example, the blink comparator allows one to quickly switch between two observations, and it was used to discover Pluto.

VI. Astronomy has developed into a wide-ranging field with many specialties.

A. Building and running an observatory requires a dedicated team.

B. The design and fabrication of sensitive instruments demand specialized talents.

C. Observational astronomers must be careful and patient to produce high-quality data.

D. Those who interpret observations and speculate about their physical basis are called theorists.

E. Excellence across all these aspects of astronomy is generally what leads to scientific advance.

Suggested Readings:

Bennett, Donahue, Schneider, and Voit, *The Cosmic Perspective*, chap. 6.

Hoyt, *Planets X and Pluto*.

Levy, *Clyde Tombaugh*.

Shu, *The Physical Universe*, chaps. 1–2.

Weintraub, *Is Pluto a Planet?* chap. 10.

Wilson, *Astronomy through the Ages*, chaps. 2, 6.

Questions to Consider:

1. Since you can only see at most half of the sky at one time, how would you measure the relative positions of stars on opposite sides? How would you work up a global solution for positions? Would using many telescopes and many observers across the globe introduce or suppress errors?
2. Some research telescopes are many decades old. Why would professional astronomers still be using such old equipment? How can it compete with current technology?
3. Given the speed of modern communications, astronomers can collaborate with others anywhere in the world. How does this help or hinder scientific progress?