Astronomy Labs at Williams College

Williamstown, Massachusetts

GROWTH

Global Relay of Observatories Watching Transients Happen

Stuart Vogel (Williams College ‘75) at the 1973 total solar eclipse in Kenya

Observational labs: we have always involved our students in contemporary research projects

Astronomy Survey Courses

- ASTR 101: From Suns to Black Holes (yearly)
- ASTR 102: Our Solar System and Others (alternate years)
- ASTR 104: The Milky Way Galaxy and the Universe Beyond (alternate years)

taught by Jay Pasachoff

Astronomy Survey Courses

- ASTR 101: From Suns to Black Holes (yearly)
- ASTR 102: Our Solar System and Others (alternate years)
- ASTR 104: The Milky Way Galaxy and the Universe Beyond (alternate years)

textbook: *The Cosmos: Astronomy in the New Millennium*, 4th ed. by Jay Pasachoff and Alex Filippenko, http://thecosmos4.com

ASTR 101 labs

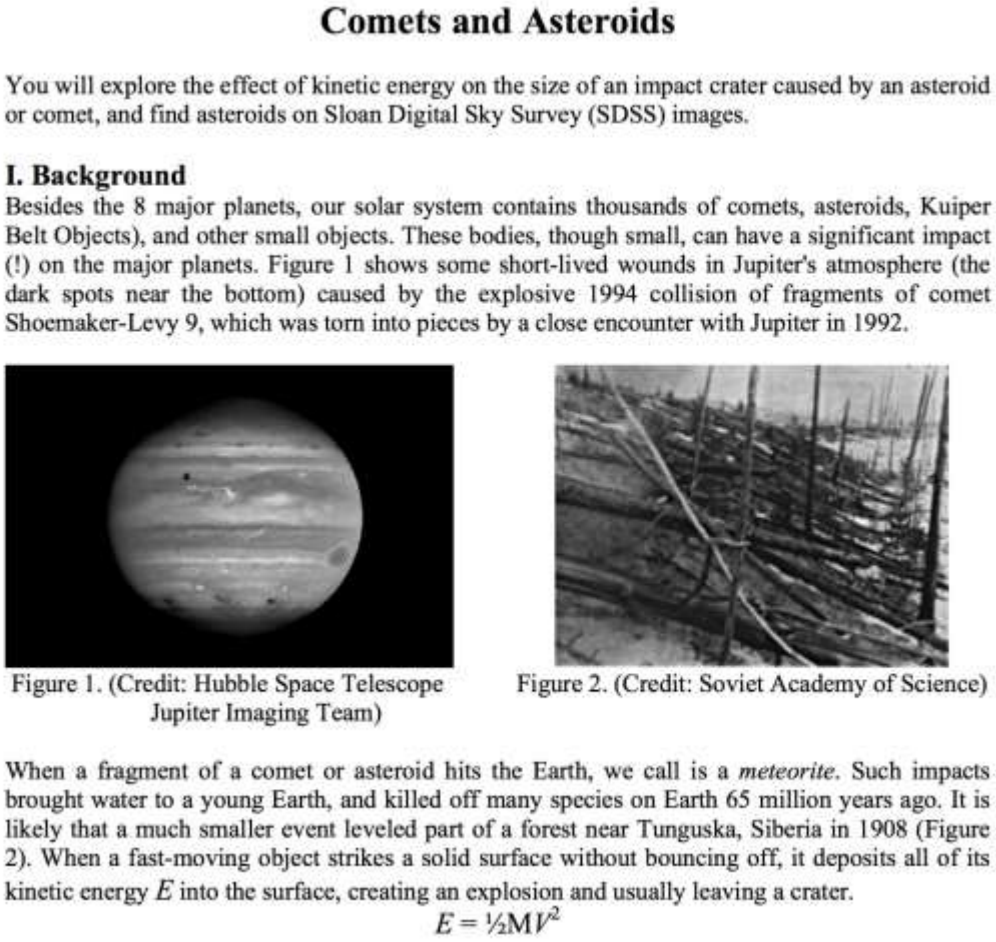
- **Lab I** Optics and Spectra T,W 9/29, 30
- **Lab II** The Virtual Sky T,W 10/6, 7
- **Lab III** Spectral Classification T,W 10/27, 28
- **Lab IV** Binary Stars T,W 11/3, 4
- **Lab V** After the Supernova T,W 12/1, 2

taught by Dr. Steven Souza

ASTR 102 labs

- **Lab I** The Virtual Sky 2/25, 26
  (*Starry Night* software)
- **Lab II** Lunar Samples 3/10, 12
- **Lab III** Transit of Venus 3/18, 19
- **Lab IV** Moons of Jupiter 4/15, 16
- **Lab V** Comets & Asteroids 5/6, 7

ASTR 102 lab



Comets and Asteroids

You will explore the effect of kinetic energy on the size of an impact crater caused by an asteroid or comet, and find asteroids on Sloan Digital Sky Survey (SDSS) images.

I. Background

Besides the 8 major planets, our solar system contains thousands of comets, asteroids, Kuiper Belt Objects), and other small objects. These bodies, though small, can have a significant impact (!) on the major planets. Figure 1 shows some short-lived wounds in Jupiter's atmosphere (the dark spots near the bottom) caused by the explosive 1994 collision of fragments of comet Shoemaker-Levy 9, which was torn into pieces by a close encounter with Jupiter in 1992.

Figure 1. (Credit: Hubble Space Telescope Jupiter Imaging Team)

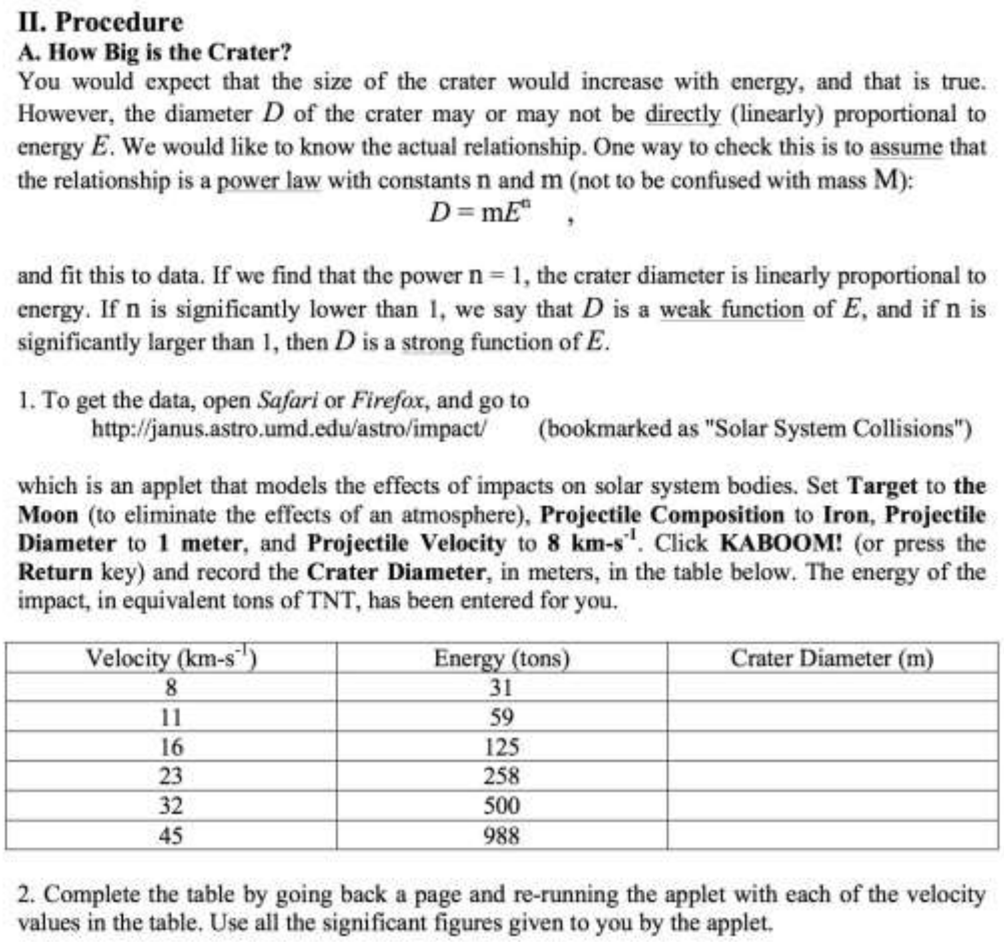
Figure 2. (Credit: Soviet Academy of Science)

When a fragment of a comet or asteroid hits the Earth, we call is a *meteorite*. Such impacts brought water to a young Earth, and killed off many species on Earth 65 million years ago. It is likely that a much smaller event leveled part of a forest near Tunguska, Siberia in 1908 (Figure 2). When a fast-moving object strikes a solid surface without bouncing off, it deposits all of its kinetic energy E into the surface, creating an explosion and usually leaving a crater.

$$E = \tfrac{1}{2}MV^2$$

labs are written and administered by Dr Steven Souza, Senior Lecturer

ASTR 102 lab



II. Procedure

A. How Big is the Crater?

You would expect that the size of the crater would increase with energy, and that is true. However, the diameter D of the crater may or may not be directly (linearly) proportional to energy E. We would like to know the actual relationship. One way to check this is to assume that the relationship is a power law with constants n and m (not to be confused with mass M):

$$D = \mathrm{m}E^{\mathrm{n}} \quad ,$$

and fit this to data. If we find that the power $\mathrm{n} = 1$, the crater diameter is linearly proportional to energy. If n is significantly lower than 1, we say that D is a weak function of E, and if n is significantly larger than 1, then D is a strong function of E.

1. To get the data, open *Safari* or *Firefox*, and go to
   http://janus.astro.umd.edu/astro/impact/ (bookmarked as "Solar System Collisions")

which is an applet that models the effects of impacts on solar system bodies. Set **Target** to **the Moon** (to eliminate the effects of an atmosphere), **Projectile Composition** to **Iron**, **Projectile Diameter** to **1 meter**, and **Projectile Velocity** to **8 km-s^{-1}**. Click **KABOOM!** (or press the **Return** key) and record the **Crater Diameter**, in meters, in the table below. The energy of the impact, in equivalent tons of TNT, has been entered for you.

Velocity (km-s^{-1})	Energy (tons)	Crater Diameter (m)
8	31	
11	59	
16	125	
23	258	
32	500	
45	988	

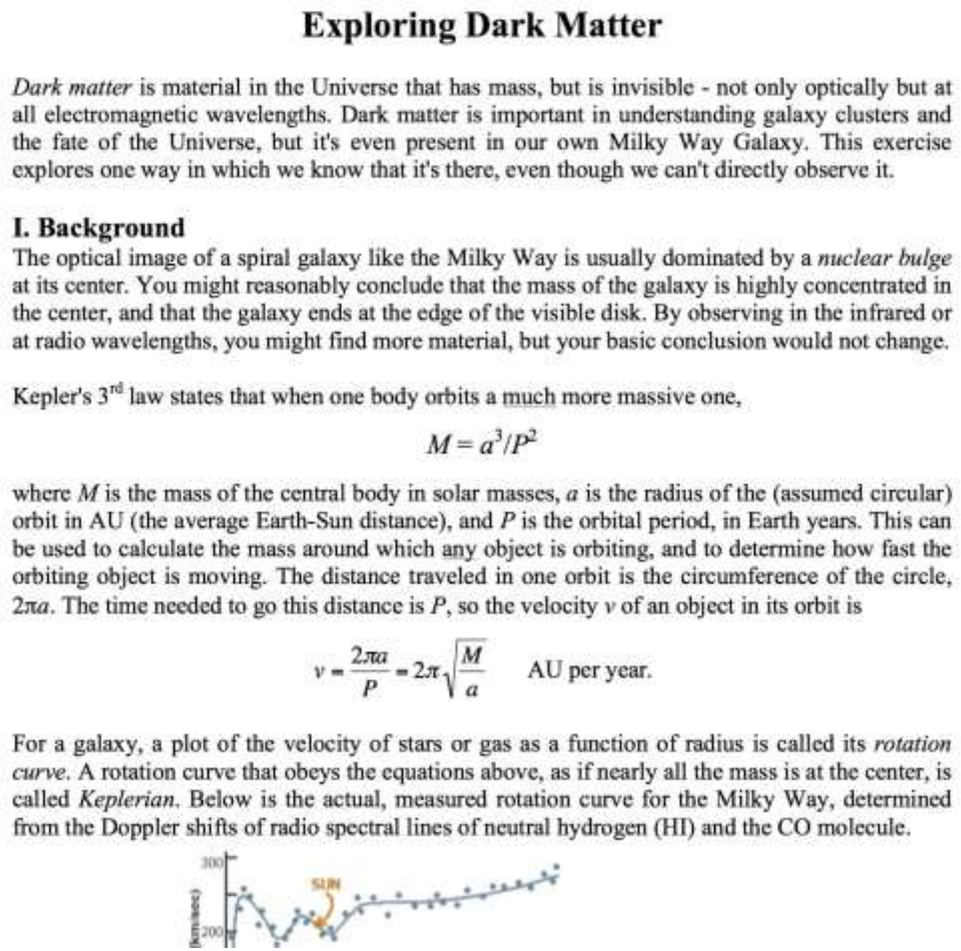
2. Complete the table by going back a page and re-running the applet with each of the velocity values in the table. Use all the significant figures given to you by the applet.

labs are written and administered by Dr Steven Souza, Senior Lecturer

ASTR 104 labs

- **Lab I** Distances in Astronomy T,W 2/17, 18
- **Lab II** The Virtual Sky T,W 2/24, 25
- **Lab III** Hubble's Law and the Expansion of the Universe T,W 3/17, 18
- **Lab IV** Galaxies, Active Galaxies and Quasars T,W 4/14, 15
- **Lab V** Exploring Dark Matter T,W 5/5, 5/6

ASTR 104 lab



Exploring Dark Matter

Dark matter is material in the Universe that has mass, but is invisible - not only optically but at all electromagnetic wavelengths. Dark matter is important in understanding galaxy clusters and the fate of the Universe, but it's even present in our own Milky Way Galaxy. This exercise explores one way in which we know that it's there, even though we can't directly observe it.

I. Background

The optical image of a spiral galaxy like the Milky Way is usually dominated by a *nuclear bulge* at its center. You might reasonably conclude that the mass of the galaxy is highly concentrated in the center, and that the galaxy ends at the edge of the visible disk. By observing in the infrared or at radio wavelengths, you might find more material, but your basic conclusion would not change.

Kepler's 3rd law states that when one body orbits a much more massive one,

$$M = a^3/P^2$$

where *M* is the mass of the central body in solar masses, *a* is the radius of the (assumed circular) orbit in AU (the average Earth-Sun distance), and *P* is the orbital period, in Earth years. This can be used to calculate the mass around which any object is orbiting, and to determine how fast the orbiting object is moving. The distance traveled in one orbit is the circumference of the circle, $2\pi a$. The time needed to go this distance is *P*, so the velocity *v* of an object in its orbit is

$$v = \frac{2\pi a}{P} = 2\pi\sqrt{\frac{M}{a}} \quad \text{AU per year.}$$

For a galaxy, a plot of the velocity of stars or gas as a function of radius is called its *rotation curve*. A rotation curve that obeys the equations above, as if nearly all the mass is at the center, is called *Keplerian*. Below is the actual, measured rotation curve for the Milky Way, determined from the Doppler shifts of radio spectral lines of neutral hydrogen (HI) and the CO molecule.

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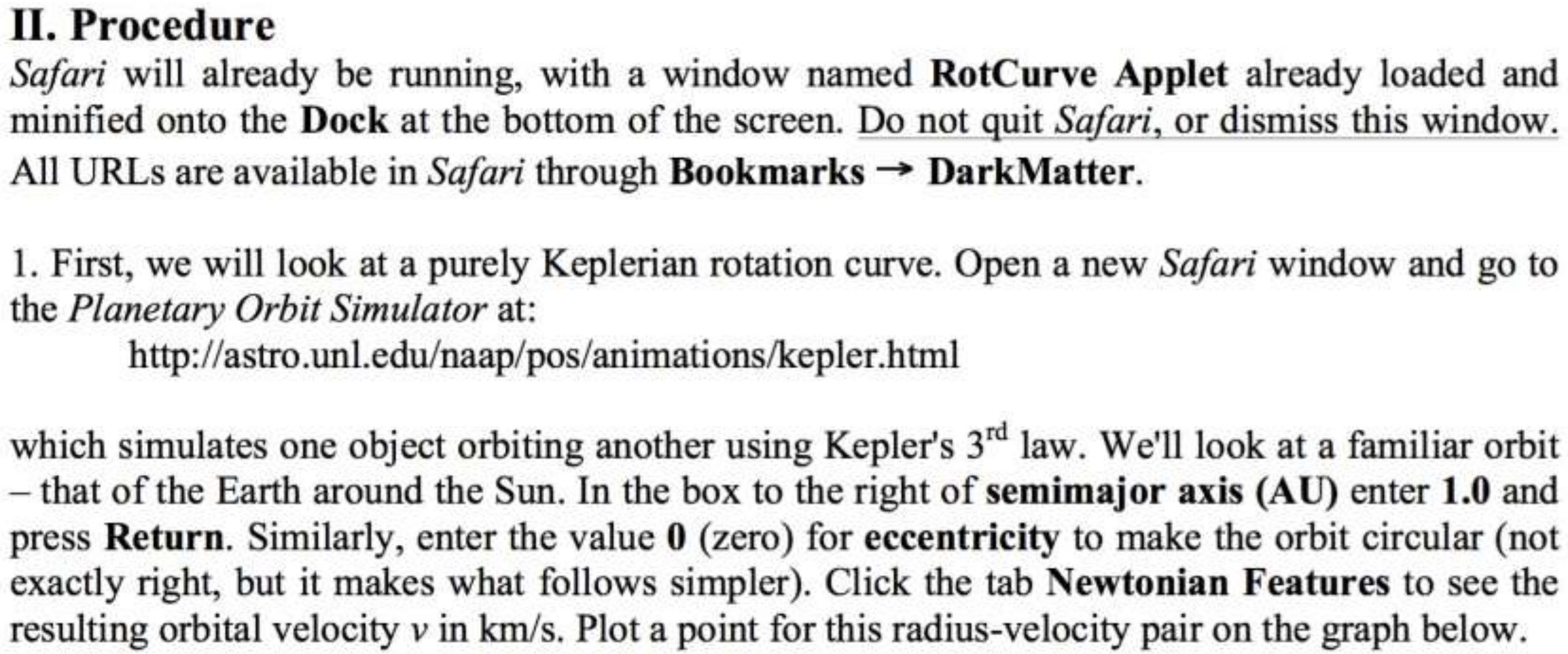
ASTR 104 lab



II. Procedure

Safari will already be running, with a window named **RotCurve Applet** already loaded and minified onto the **Dock** at the bottom of the screen. Do not quit *Safari*, or dismiss this window. All URLs are available in *Safari* through **Bookmarks → DarkMatter**.

1. First, we will look at a purely Keplerian rotation curve. Open a new *Safari* window and go to the *Planetary Orbit Simulator* at:

    http://astro.unl.edu/naap/pos/animations/kepler.html

which simulates one object orbiting another using Kepler's 3rd law. We'll look at a familiar orbit – that of the Earth around the Sun. In the box to the right of **semimajor axis (AU)** enter **1.0** and press **Return**. Similarly, enter the value **0** (zero) for **eccentricity** to make the orbit circular (not exactly right, but it makes what follows simpler). Click the tab **Newtonian Features** to see the resulting orbital velocity *v* in km/s. Plot a point for this radius-velocity pair on the graph below.

labs are written and administered by Dr Steven Souza, Senior Lecturer

For ASTR 101, 102, 104

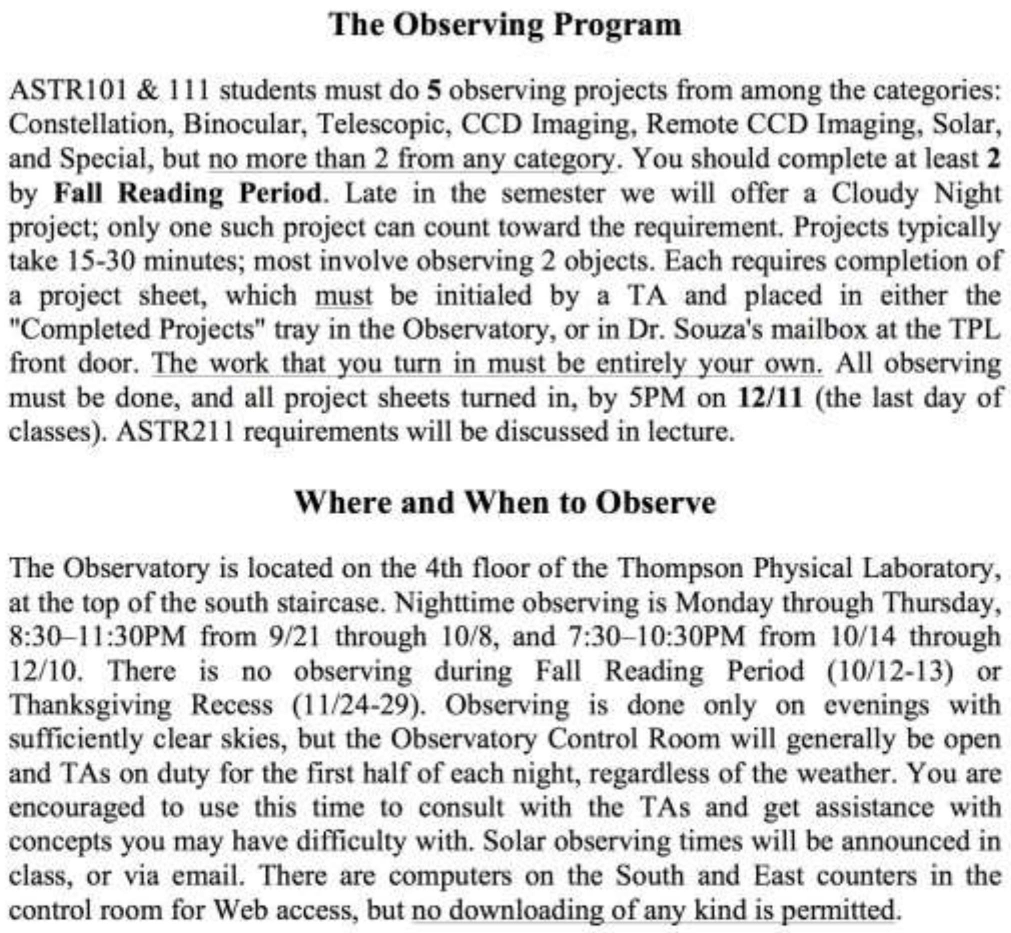
- Observing sessions will include use of the 24-inch telescope and other telescopes for nighttime observations of stars, star clusters, planets and their moons, nebulae, and galaxies, as well as use of other telescopes for daytime observations of the Sun.

For ASTR 101, 102, 104

Observing-Lab Facilities at Williams College

- a 24-inch Cassegrain telescope (manufactured by DFM Engineering, Inc.) equipped with a 3056 x 3056 pixel CCD main imaging camera (Apogee, Inc.) and a wide range of optical filters
- a recently-overhauled Optomechanics Model 10 spectrograph with a 120 x 2048 pixel CCD camera (Apogee, Inc.)
- a remotely-operated 4-inch Stellarvue apochromatic refractor and color CCD camera for wide-field imaging
- a 6-inch Meade apochromatic refractor for visual observing and planetary imaging.
- Additional instruments include a Lunt LS60T H-alpha telescope for viewing the Sun, 3- and 8-inch aperture Celestron telescopes, and a direct-view solar spectroscope. We also maintain a network of Apple computers to support observing, and other instructional and research needs.

Evening observing program



The Observing Program

ASTR101 & 111 students must do **5** observing projects from among the categories: Constellation, Binocular, Telescopic, CCD Imaging, Remote CCD Imaging, Solar, and Special, but no more than 2 from any category. You should complete at least **2** by **Fall Reading Period**. Late in the semester we will offer a Cloudy Night project; only one such project can count toward the requirement. Projects typically take 15-30 minutes; most involve observing 2 objects. Each requires completion of a project sheet, which must be initialed by a TA and placed in either the "Completed Projects" tray in the Observatory, or in Dr. Souza's mailbox at the TPL front door. The work that you turn in must be entirely your own. All observing must be done, and all project sheets turned in, by 5PM on **12/11** (the last day of classes). ASTR211 requirements will be discussed in lecture.

Where and When to Observe

The Observatory is located on the 4th floor of the Thompson Physical Laboratory, at the top of the south staircase. Nighttime observing is Monday through Thursday, 8:30–11:30PM from 9/21 through 10/8, and 7:30–10:30PM from 10/14 through 12/10. There is no observing during Fall Reading Period (10/12-13) or Thanksgiving Recess (11/24-29). Observing is done only on evenings with sufficiently clear skies, but the Observatory Control Room will generally be open and TAs on duty for the first half of each night, regardless of the weather. You are encouraged to use this time to consult with the TAs and get assistance with concepts you may have difficulty with. Solar observing times will be announced in class, or via email. There are computers on the South and East counters in the control room for Web access, but no downloading of any kind is permitted.

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Pre-major course

ASTR 111 Introduction to Astrophysics

How do stars work? This course answers that question from start to finish! In this course we undertake a survey of some of the main ideas in modern astrophysics, with an emphasis on the observed properties and evolution of stars; ASTR 111 is the first course in the Astrophysics and Astronomy major sequences. It is also appropriate for students planning to major in one of the other sciences or mathematics, and for others who would like a quantitative introduction that emphasizes the relationship of contemporary physics to astronomy.

Topics include radiation laws and stellar spectra, astronomical instrumentation, physical characteristics of the Sun and other stars, star formation and evolution, nucleosynthesis, white dwarfs and planetary nebulae, pulsars and neutron stars, supernovae, relativity, and black holes (including a discussion of the first reported detection of gravitational waves, generated during the merging of two massive stellar black holes more than a billion light-years away).

taught by Prof. Karen Kwitter

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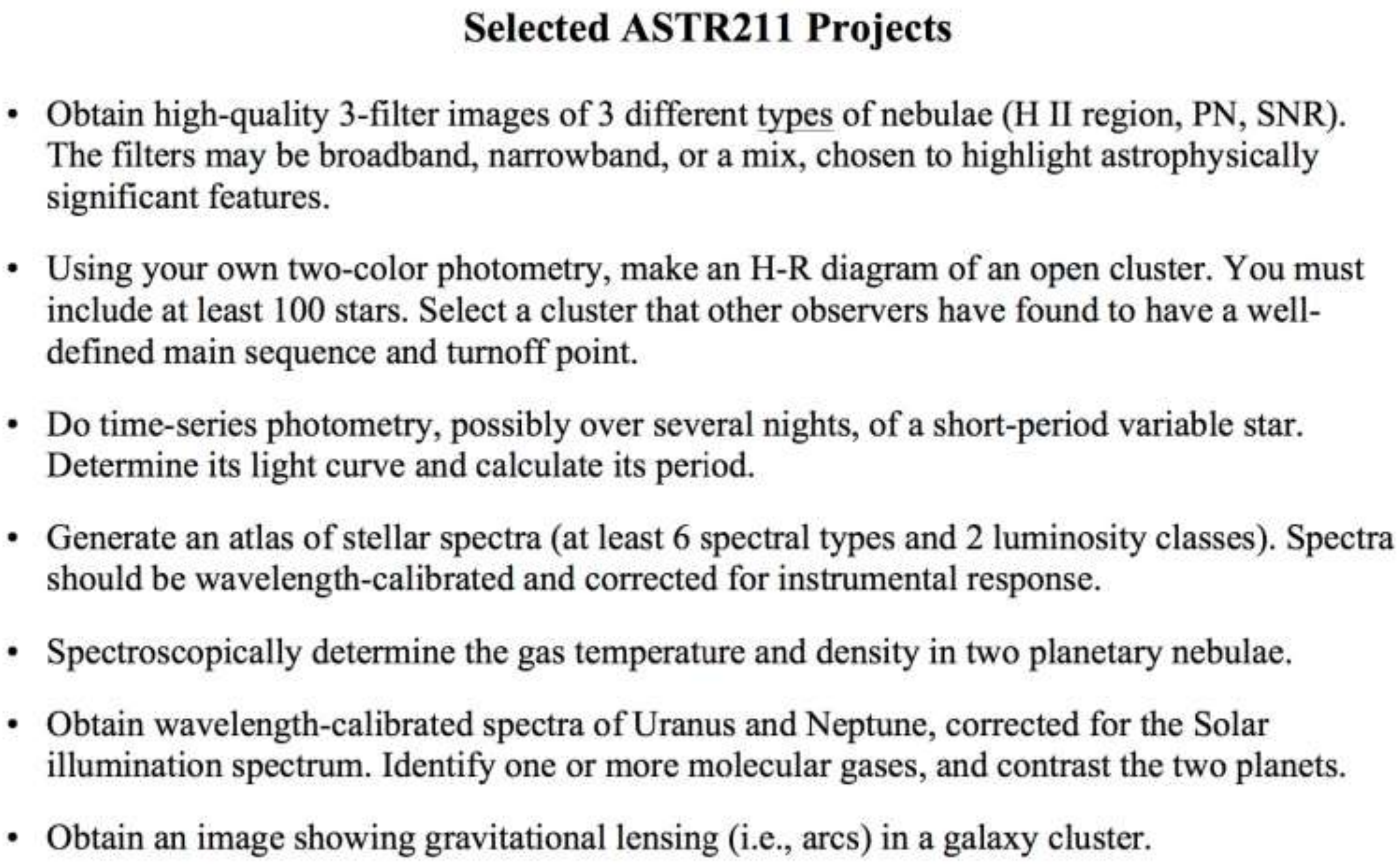
taught by Prof. Karen Kwitter

ASTR 211 Astronomical Observing and Data Analysis

- This course will introduce techniques for obtaining and analyzing astronomical data. We will begin by learning about practical observation planning and move on to discussion of CCD detectors, signal statistics, digital data reduction, and image processing. We will make use of data we obtain with our 24-inch telescope, as well as data from other optical ground-based observatories and archives. We also learn about and work with data from space-based non-optical observatories such as the Chandra X-Ray Observatory and the Spitzer Space Telescope (infrared).

taught by Karen Kwitter

ASTR 211 Astronomical Observing and Data Analysis



Selected ASTR211 Projects

- Obtain high-quality 3-filter images of 3 different types of nebulae (H II region, PN, SNR). The filters may be broadband, narrowband, or a mix, chosen to highlight astrophysically significant features.
- Using your own two-color photometry, make an H-R diagram of an open cluster. You must include at least 100 stars. Select a cluster that other observers have found to have a well-defined main sequence and turnoff point.
- Do time-series photometry, possibly over several nights, of a short-period variable star. Determine its light curve and calculate its period.
- Generate an atlas of stellar spectra (at least 6 spectral types and 2 luminosity classes). Spectra should be wavelength-calibrated and corrected for instrumental response.
- Spectroscopically determine the gas temperature and density in two planetary nebulae.
- Obtain wavelength-calibrated spectra of Uranus and Neptune, corrected for the Solar illumination spectrum. Identify one or more molecular gases, and contrast the two planets.
- Obtain an image showing gravitational lensing (i.e., arcs) in a galaxy cluster.

Keck Northeast Astronomy Consortium

virtual department with about 25 faculty members
summer research for students at each other’s colleges
fall student research symposium
Keck Foundation funds superseded by current NSF RUI

Williams, Wesleyan, Middlebury, Colgate, Vassar, Wellesley, Haverford/Bryn Mawr, Swarthmore

Keck Northeast Astronomy Consortium

a distinguished alumna of our summer-research program
at Williams College on the KNAC exchange:
Mansi Kasliwal

Williams, Wesleyan, Middlebury, Colgate, Vassar, Wellesley, Haverford/Bryn Mawr, Swarthmore

KECK NORTHEAST ASTRONOMY CONSORTIUM

COLGATE * HAVERFORD * MIDDLEBURY * SWARTHMORE
VASSAR * WELLESLEY * WESLEYAN * WILLIAMS

KNAC

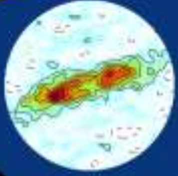
Keck Northeast Astronomy Consortium

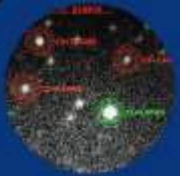
REU

Research Experiences for Undergraduates

Colgate
Haverford
Middlebury
Swarthmore
Vassar
Wellesley
Wesleyan
Williams

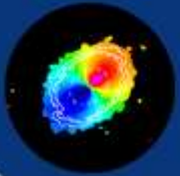
Application deadline:
February 12, 2016





Spend your summer doing astronomy research at a northeast liberal arts college!

stars & star formation
light curves
python
x-rays
observation
spectroscopy
radio
exoplanets
telescopes
ultraviolet
solar system
occultations
quasars & AGN
galaxies & ISM
cosmology
variability
theory
infrared
coding
photometry
computation
planetary nebulae

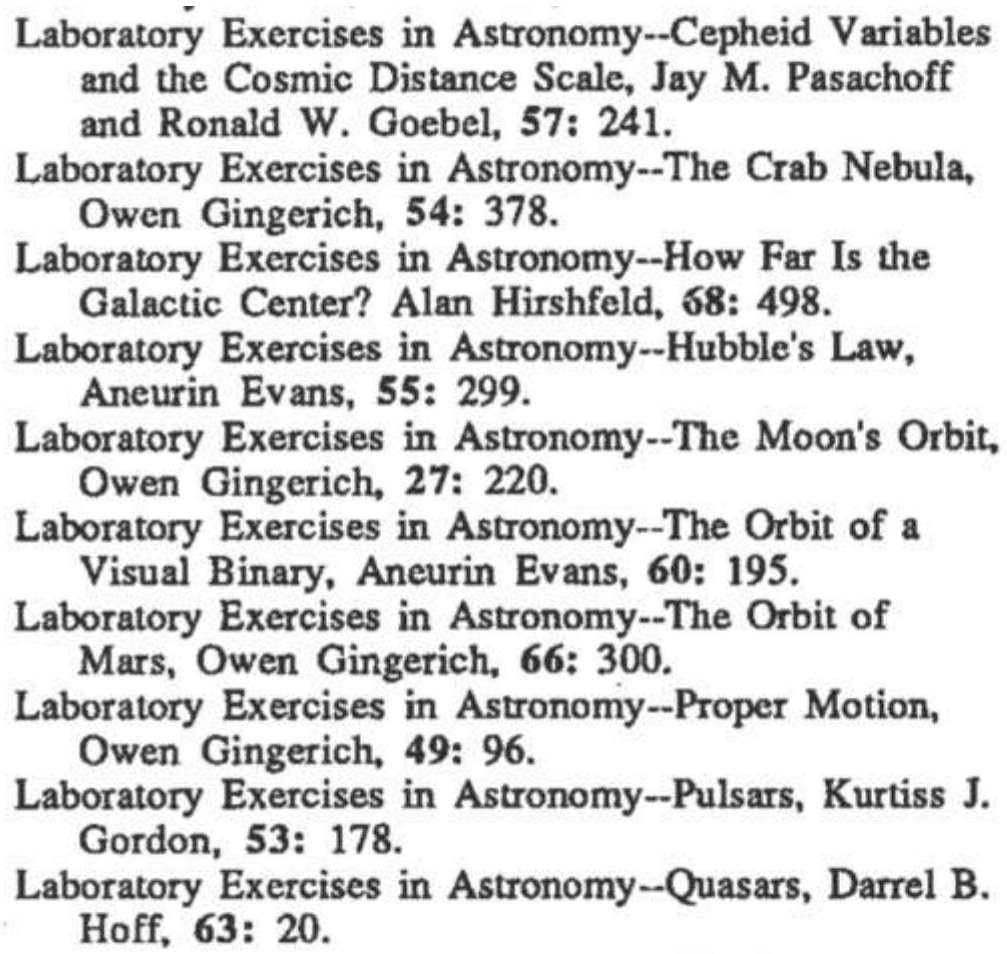


For more info & to apply: http://knac.org/

https://sites.williams.edu/scientephic/news/williams-hosts-astronomy-symposium/ - more-420

- Williams students presented on the following topics:
- **Tim Nagle-McNaughton** and **MeiLu McDermott**: “Photoionization Models of Planetary Nebula in Outer Regions of M31”
- **Marcus Hughes**: “Searching for Circumbinary Planets in K2 Data”
- **Tina Seeger**: “Developing a Methodology to Classify Io’s Mountains by Morphology”
- **Hallee Wong**: “Short Term Variability in the Open Cluster NGC 1960”
- **Allison Carter**: “Precise Measurement of the Stark Shift in the Indium $6P_{½}$ State Using Two-Step Laser Spectroscopy”
- **Becky Durst**: “Observation of the 2015 Occultation of Pluto”
- **Anneliese Rilinger**: “It’s A Tight Squeeze: Reducing Noise Levels of Quantum Correlated Squeezed Light”
- **Sarah Stevenson** : “Second Harmonic Generation and Magnetic Contrast versus Laser Intensity for Materials of interest in Spin Hall Effect Spin Current Generation”
- **Emily Stump**: “Infrared SED Decomposition of Active Galactic Nuclei”

Sky & Telescope Labs



Laboratory Exercises in Astronomy--Cepheid Variables and the Cosmic Distance Scale, Jay M. Pasachoff and Ronald W. Goebel, **57:** 241.

Laboratory Exercises in Astronomy--The Crab Nebula, Owen Gingerich, **54:** 378.

Laboratory Exercises in Astronomy--How Far Is the Galactic Center? Alan Hirshfeld, **68:** 498.

Laboratory Exercises in Astronomy--Hubble's Law, Aneurin Evans, **55:** 299.

Laboratory Exercises in Astronomy--The Moon's Orbit, Owen Gingerich, **27:** 220.

Laboratory Exercises in Astronomy--The Orbit of a Visual Binary, Aneurin Evans, **60:** 195.

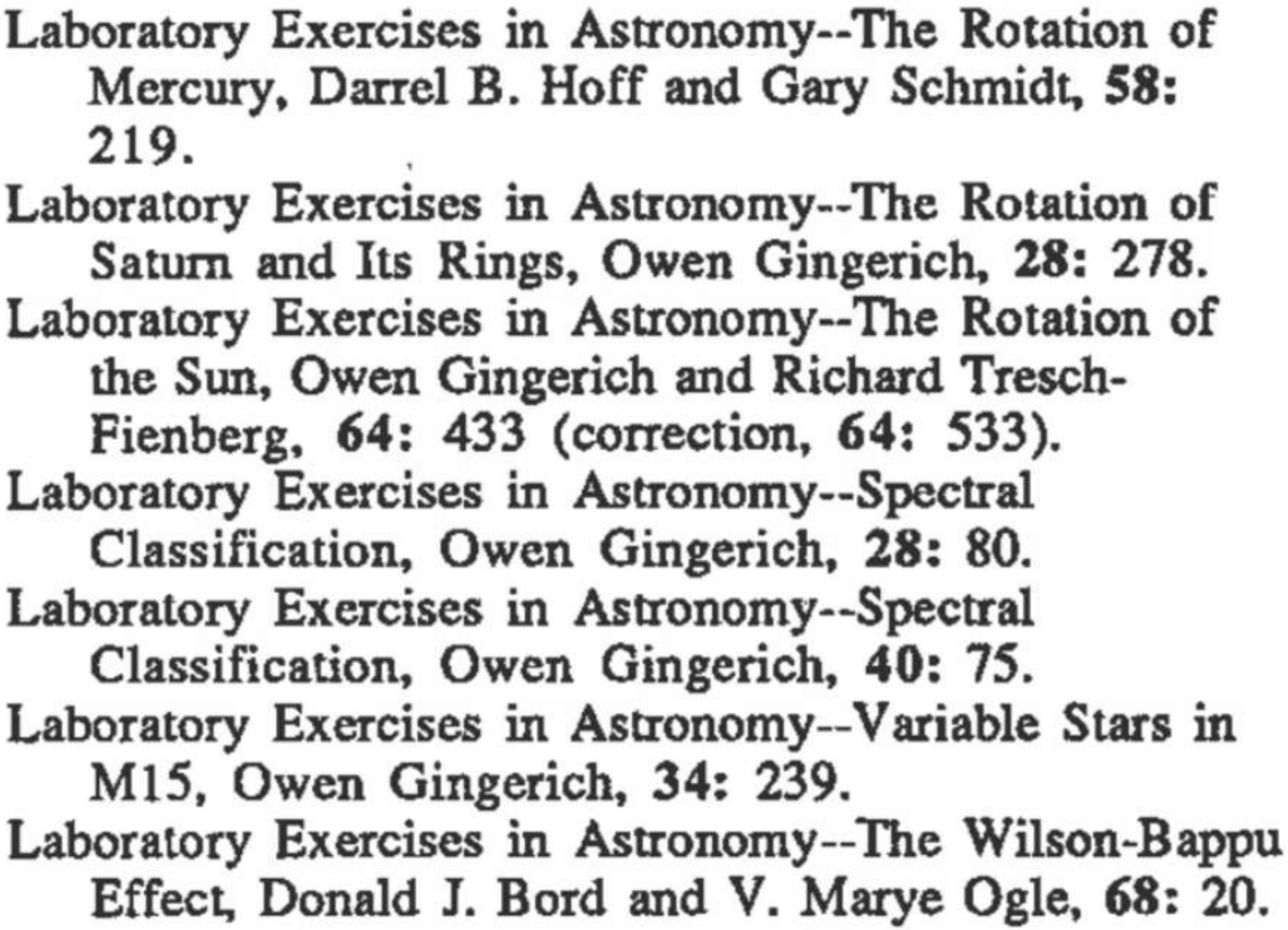
Laboratory Exercises in Astronomy--The Orbit of Mars, Owen Gingerich, **66:** 300.

Laboratory Exercises in Astronomy--Proper Motion, Owen Gingerich, **49:** 96.

Laboratory Exercises in Astronomy--Pulsars, Kurtiss J. Gordon, **53:** 178.

Laboratory Exercises in Astronomy--Quasars, Darrel B. Hoff, **63:** 20.

Sky & Telescope Labs



Laboratory Exercises in Astronomy--The Rotation of Mercury, Darrel B. Hoff and Gary Schmidt, **58:** 219.

Laboratory Exercises in Astronomy--The Rotation of Saturn and Its Rings, Owen Gingerich, **28:** 278.

Laboratory Exercises in Astronomy--The Rotation of the Sun, Owen Gingerich and Richard Tresch-Fienberg, **64:** 433 (correction, **64:** 533).

Laboratory Exercises in Astronomy--Spectral Classification, Owen Gingerich, **28:** 80.

Laboratory Exercises in Astronomy--Spectral Classification, Owen Gingerich, **40:** 75.

Laboratory Exercises in Astronomy--Variable Stars in M15, Owen Gingerich, **34:** 239.

Laboratory Exercises in Astronomy--The Wilson-Bappu Effect, Donald J. Bord and V. Marye Ogle, **68:** 20.

Lab Exercises in Astronomy

These exercises are suitable for introductory classes in astronomy and for amateurs interested in learning professional methods. Each exercise was prepared or approved by Professor Owen Gingerich, Harvard-Smithsonian Center for Astrophysics. The Notes for Teachers *with most of the exercises contain each author's results.*

LE001 The Moon's Orbit / Whitin Observatory photos

As the Moon revolves around the Earth in its noncircular orbit, its apparent size undergoes a change of about 10 percent. In this exercise, devised by John C. Duncan at Wellesley College, the student measures the Moon's diameter as accurately as possible on 12 photographs taken during a month. Each measure is multiplied by a factor to permit plotting the distance it represents against the Moon's geocentric longitude for the date. On the resulting polar plot, the 12 points can be joined by a smooth curve (nearly an ellipse) that shows the shape of the Moon's orbit. The student finds perigee and apogee, draws the line of apsides, works out the law of areas, finds the orbital eccentricity, and draws the line of nodes from latitudes tabulated in the experiment.

LE002 Spectral Classification / Warner & Swasey photos

Just reading about how astronomers use the spectra of stars to learn their physical and chemical secrets can't compare with taking samples of such spectra and classifying the various types for yourself. This exercise is based on a large objective-prism photograph of a region of the Milky Way near Gamma Cygni, taken with a 24-inch Schmidt telescope. The student compares 30 numbered spectra and a dozen detailed reproductions of standard spectra, covering the entire spectral sequence from hot WN and O stars through classes B, A, F, G, K, and M. The text elaborates on the clues by which the classes are recognized and a star's position within a class refined. The exercise contains considerable information concerning chemical elements in stars and the role of temperature in the apparent abundances. A separate answer sheet is provided.

LE003 Rotation of Saturn and Its Rings / Lick photos

When the slit of a spectrograph is placed across Saturn and its rings, extending east-west, the resulting spectrum shows the Doppler effect of the rotation of Saturn itself. Its spectral lines slope to the red on the planet's western limb, which is moving away from us, and to the violet on the eastern limb (approaching). The rings exhibit a similar effect, but the ring particles nearest the planet revolve faster than those farther out, in accordance with Kepler's laws, so the spectral lines' slope for the rings is opposite to that for the planet. These effects show up clearly on the high-dispersion spectrogram. By measuring spectral line tilts for both planet and rings, the student determines the rotation periods and deduces the nature of the rings and the planet's mass.

LE004 Variable Stars in M15 / Whitin Observatory

This advanced exercise requires considerable judgment by the student. On eight Duncan 100-inch telescope plates of the globular cluster M15 in Pegasus, magnitudes of six short-period (RR Lyrae) stars are measured against nonvariable comparison stars. For several variables good sections of their light curves can be obtained. Assuming a median absolute magnitude of +0.5 for RR Lyrae stars, the cluster's distance and linear extent are computed from the magnitude estimates and angular measurements.

LE005 The Earth's Orbital Velocity / Hale Observatories

On two high-dispersion spectrograms of Arcturus taken six months apart, the positions of selected absorption lines are measured accurately. In one case the lines are shifted to the violet (shorter wavelengths) as the Earth approaches the star; in the other case they are shifted to the red. These Doppler shifts are measured to 0.1 millimeter and calculations made to obtain the star's motion relative to the Sun, the Earth's orbital velocity, and the Earth's distance from the Sun. As many as seven lines can be measured, increasing the accuracy of the results. Prepared by Darrel B. Hoff.

LE006 Proper Motion / Palomar-National Geographic

On a Bonner Durchmusterung chart (for Epoch 1855.0), the position of the famous binary 61 Cygni is measured with reference to fainter, presumably more distant neighbors; the process is repeated for a field picture taken in 1951 with the 48-inch Schmidt telescope of Palomar Observatory. The difference in position of 61 Cygni over 96 years yields its proper motion across the sky.

LE007 Pulsars / National Radio Astronomy Observatory

This exercise is based on observations of three pulsars made at the National Radio Astronomy Observatory. Recordings are provided of radio power received from PSR 0809+74, 0950+08, and 329+54 on as many as four frequencies (234, 256, 405, and 1420 megahertz). The student makes precise measurements to determine the period at which pulses recur, studies a currently favored model of a pulsar, and determines the pulse dispersion or difference in pulse arrival times at the various frequencies. This leads to estimating each pulsar's distance. Prepared by Kurtiss J. Gordon of Hampshire College.

LE008 The Crab Nebula / Hale, Kitt Peak, and Lick

Owen Gingerich begins this five-page, fully illustrated exercise with a historical overview of observations of the Crab Nebula. Then, on large-scale photographs taken 34 years apart, proper motions of knots and filaments in the Crab supernova remnant are measured to find its rate of expansion across the sky. Radial velocities (line-of-sight motions) of the filaments are obtained from a high-dispersion spectrogram showing red- and blueshifted lines. The combined measurements yield the nebula's size and distance, as well as the year the expansion began.

LE009 Hubble's Law / Hale Observatories

Hubble's constant, which gives the rate of expansion of the universe, is of basic significance in modern cosmology. This exercise clearly presents one way of deriving this quantity from observational data. The redshifts of five elliptical galaxies are measured from their spectra, and the distances of the same galaxies are found from their angular sizes on photographs. By plotting the galaxies' redshifts against their distance, Hubble's constant is determined, leading to a discussion of the universe's age and size. Prepared by Aneurin Evans, University of Keele.

LE010 Cosmic Distance Scale / ESO

The determination of extragalactic distances and the proof that galaxies other than the Milky Way exist were major 20th-century discoveries. They stemmed from the realization that the light cycles of Cepheid variable stars were correlated with their intrinsic luminosities. This exercise by J. M. Pasachoff and R. W. Goebel applies this relation to the Small Magellanic Cloud to determine its distance. The exercise also stresses calibration of the period-luminosity relation.

LE011 The Rotation of Mercury / Arecibo

Early visual determinations of Mercury's rotation have proved to be entirely spurious. This exercise uses radar observations made with the 1,000-foot radio telescope at Arecibo, Puerto Rico. Five pulse spectra are provided, and from them the student can derive a fairly accurate rotation period for the planet. An explanation of why the visual work was wrong is given, along with a composite map based on the true 59-day period. Prepared by Darrel B. Hoff and Gary Schmidt.

LE012 The Orbit of a Visual Binary / McCormick-Sproul

Binary stars are of great astrophysical importance, because they are the only stars for which masses can be determined directly. From seven photographic observations of the star system Krüger 60, the student determines some of the orbital characteristics of the pair and sees how Kepler's three laws of planetary motion apply to stellar systems as well. By Aneurin Evans, University of Keele.

LE013 Quasars / Hale-Harvard

The discovery of quasars was one of the most important and unexpected events in the history of astronomy. Darrel B. Hoff, University of Northern Iowa, shows how to determine some fundamental properties of these objects, which are the most luminous bodies in the universe. Using Palomar Observatory spectra, the student measures the redshift of 3C 273 and calculates its velocity of recession. Next, the distance is computed by means of an extension of Hubble's "law," which relates distance to the observed redshift. The absolute magnitude of this object is then determined from the calculated distance and an apparent magnitude obtained from a photograph showing labeled comparison stars. A light curve extending from 1887 to 1963 is used to set a maximum size to the light-emitting region. The exercise closes with some considerations of the nature of these enigmatic objects.

LE014 The Rotation of the Sun / Naval Observatory-Yerkes

A sequence of 12 solar photographs enables the student to derive a fairly accurate rotational period for the Sun by measuring the positions of sunspots, and to gain some knowledge about the stability of sunspot groups. The exercise explains how to convert apparent sunspot motion to a circular arc on the surface of the Sun. Once the synodic rotation period (that seen from the moving Earth) is determined, instructions are given for converting it to the sidereal period, the rate with respect to the "fixed" stars. Solar rotation can also be measured from the Doppler shifts of spectral lines, and this exercise includes high-dispersion spectra of the Sun's east and west equatorial limbs for this purpose. The rotational velocity is then calculated from the Doppler-shift relations and known line wavelengths. Also discussed are differential rotation and the rotation of other stars.

LE015 The Orbit of Mars / Uraniborg

The relatively large eccentricity of Mars's orbit makes its elliptical shape very accessible to study. Following the method invented by Johannes Kepler, this exercise employs some of the same planetary position measurements by Tycho Brahe that Kepler used. The observations, equipment, and mathematics needed to determine the true shape of the orbit are remarkably simple.

LE016 Wilson-Bappu Effect / Mt. Wilson, Palomar

In the 1950s Olin C. Wilson and Manali K. Vainu Bappu provided a new method for determining the distances of certain stars. They showed that for spectral types G through M there exists a relationship between the absolute visual magnitude of a star and the width of the emission component of its Ca II line. In this exercise by Donald J. Bord and Mary Ogle, spectra are measured to determine absolute magnitudes.

LE017 How Far Is the Galactic Center? / SMU

This exercise follows in the footsteps of Harlow Shapley, who first used the distribution of globular clusters to find the distance to the Milky Way's nucleus and the overall size of our star system. Alan Hirshfeld of Southeastern Massachusetts University has gathered data on 20 globular clusters, together with their color-magnitude diagrams, to allow students to repeat Shapley's pioneering work. Included is a brief discussion of galactic coordinates and also R. P. Waldron's computer program for displaying the cluster-galaxy relationship.

LE018 Star-Cluster Distances and the Dustiness of Space / Sky Publishing Corp.

Owen Gingerich and Richard Tresch Fienberg retrace R. J. Trumpler's 1930 discovery of dust between the stars. Students measure angular sizes of six star clusters on photographs and apply the rule "smallness means farness." Then H-R diagrams are used to gauge distance with the rule "faintness means farness." The discrepancy between the methods shows the fogginess of space.

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The Small Magellanic Cloud is the second-nearest galaxy to our Milky Way, close enough for its stars to be studied as individuals. This photograph is a 60-minute exposure in blue light, taken with the 1-meter Schmidt telescope of the European Southern Observatory in Chile. North is up and the height of this picture is about 2°. Copyright ESO.

Laboratory Exercises in Astronomy — Cepheid Variables and the Cosmic Distance Scale

JAY M. PASACHOFF and RONALD W. GOEBEL, *Williams College*

THE MOST ACCURATE means of determining the distances to the nearest stars is known as the method of *trigonometric parallax*. This involves measuring the angular shift of a star with regard to much more remote objects, as seen from different positions in the earth's orbit. The distance of a star in parsecs (1 parsec = 3.26 light-years) is equal to the reciprocal of its parallax in seconds of arc.

Every parallax determination has a probable error of about 0.005 second, as a rule. Hence, as astronomers try to determine the distances of increasingly remote stars, the trigonometric parallax method gives less and less accurate results. At a distance of 200 parsecs, the probable error is about as large as the parallax itself. Despite the success of modern astronomers in decreasing the errors of parallax determinations, this method of determining star distances is reliable only for objects in the sun's own "backyard."

Other methods are needed for objects more distant than a few hundred parsecs. In this exercise we will use *Cepheid variable stars*, those that change in brightness with periods from 1 to 100 days in the manner of the 5.4-day variation of δ Cephei. Some of these supergiant stars are more than 10,000 times as luminous as our sun and thus can be seen at great distances, being recognizable in the nearer galaxies. The Cepheids played a key role, in the early years of this century, in providing proof that there are other galaxies than our own. Although today we readily acknowledge that other galaxies exist besides the Milky Way, it wasn't until the 1920's that this idea became commonly accepted.

CEPHEID VARIABLES

The first known Cepheid was δ Cephei, discovered in 1784 by an English amateur astronomer, John Goodricke. About 1879, A. Ritter theorized that the light variations of these stars are due to pulsations, the star alternately expanding and contracting. Later astronomers verified this idea by spectroscopic observations. In this exercise, we are not concerned with why the stars pulsate but rather how they are used as distance indicators.

At the beginning of this century the distance of the Small Magellanic Cloud (today recognized as a neighbor galaxy) was unknown. On Harvard Observatory photographs of it, Henrietta S. Leavitt had discovered many faint Cepheids. In 1912 she showed, in a detailed study of about two dozen of these Cepheids, that there was a clear-cut correlation between the apparent magnitudes and the periods of these stars, in the sense that the longer-period stars are the brighter.

Since all the stars in the Small Magellanic Cloud are basically at the same distance from the sun, it follows that the apparently brighter Cepheids in it are in fact intrinsically more luminous. In other words, the period of a Cepheid is an indicator of its intrinsic luminosity, and in the following problem we shall use this property to determine the distance of the Small Magellanic Cloud.

STEP I

Shown on the page that follows are light curves of four Cepheid variables in the Small Magellanic Cloud, based on photographic observations by H. C. Arp in yellow light. For each star, read off the apparent magnitudes at maximum and at

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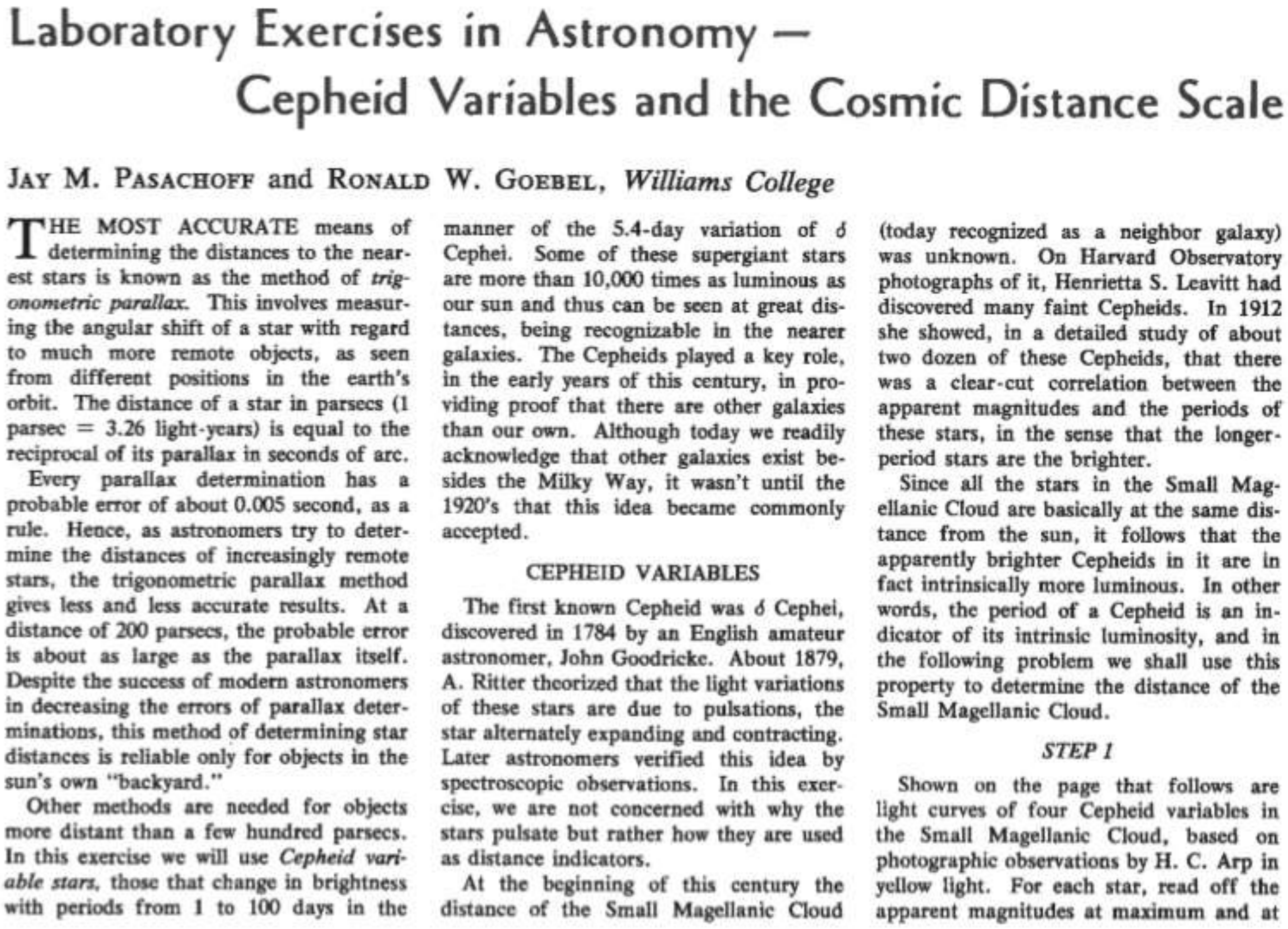

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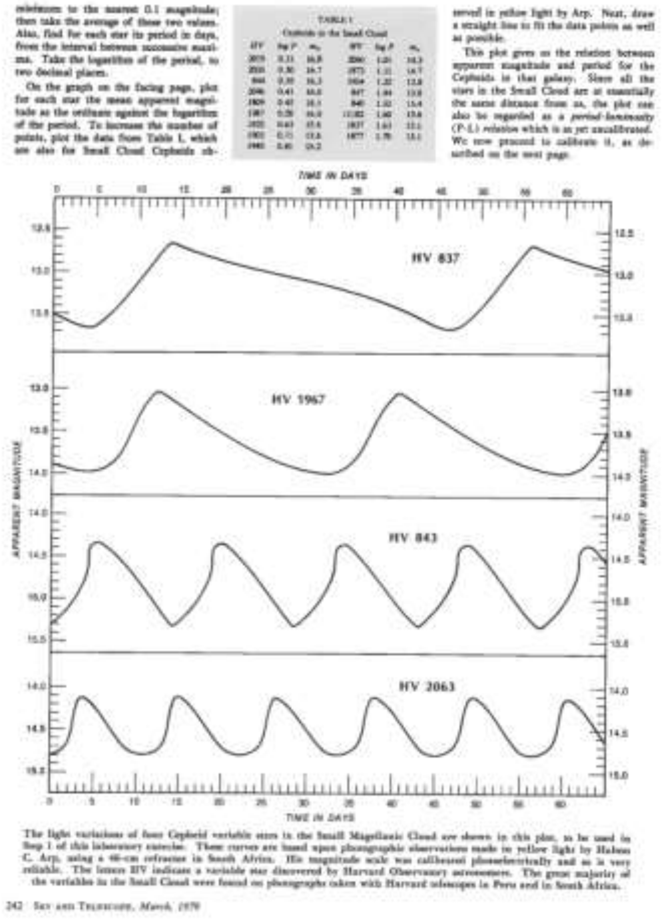

estimates to the nearest 0.1 magnitude; then take the average of these two values. Also, find for each star its period in days, from the interval between successive maxima. Take the logarithm of the period, to two decimal places.

On the graph on the facing page, plot for each star the mean apparent magnitude as the ordinate against the logarithm of the period. To increase the number of points, plot the data from Table I, which are also for Small Cloud Cepheids observed in yellow light by Arp. Next, draw a straight line to fit the data points as well as possible.

This plot gives us the relation between apparent magnitude and period for the Cepheids in that galaxy. Since all the stars in the Small Cloud are at essentially the same distance from us, the plot can also be regarded as a *period-luminosity* (P-L) *relation* which is as yet uncalibrated. We now proceed to calibrate it, as described on the next page.

TABLE I

Cepheids in the Small Cloud

The light variations of four Cepheid variable stars in the Small Magellanic Cloud are shown in this plot, to be used in Step 1 of this laboratory exercise. These curves are based upon photographic observations made in yellow light by Halton C. Arp, using a 66-cm refractor in South Africa. His magnitude scale was calibrated photoelectrically and so is very reliable. The letters HV indicate a variable star discovered by Harvard Observatory astronomers. The great majority of the variables in the Small Cloud were found on photographs taken with Harvard telescopes in Peru and in South Africa.

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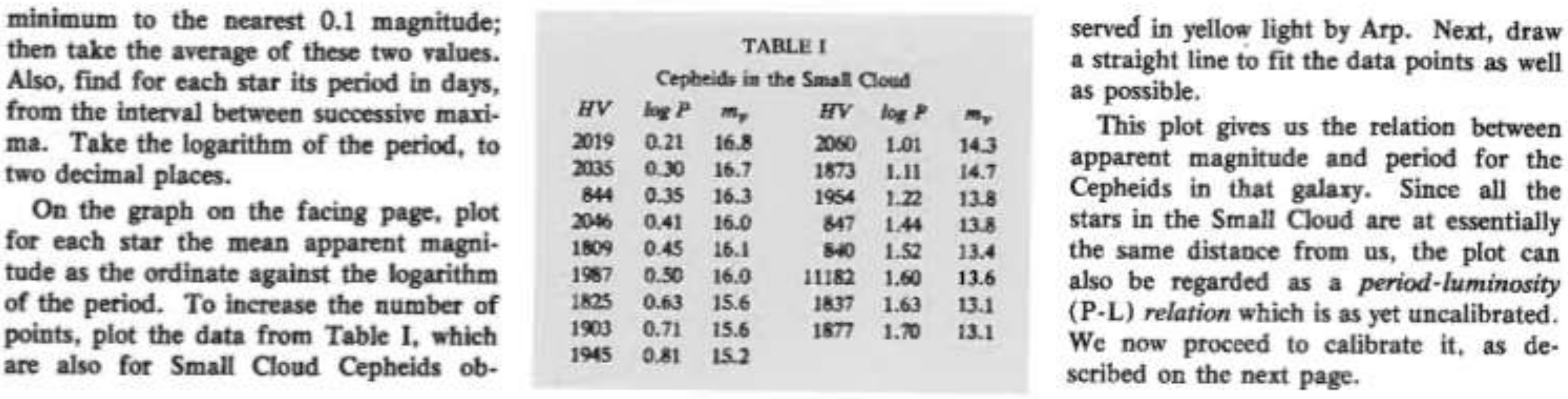

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TABLE I

Cepheids in the Small Cloud

HV	*log P*	m_v	*HV*	*log P*	m_v
2019	0.21	16.8	2060	1.01	14.3
2035	0.30	16.7	1873	1.11	14.7
844	0.35	16.3	1954	1.22	13.8
2046	0.41	16.0	847	1.44	13.8
1809	0.45	16.1	840	1.52	13.4
1987	0.50	16.0	11182	1.60	13.6
1825	0.63	15.6	1837	1.63	13.1
1903	0.71	15.6	1877	1.70	13.1
1945	0.81	15.2			

This plot gives us the relation between apparent magnitude and period for the Cepheids in that galaxy. Since all the stars in the Small Cloud are at essentially the same distance from us, the plot can also be regarded as a *period-luminosity* (P-L) *relation* which is as yet uncalibrated. We now proceed to calibrate it, as described on the next page.

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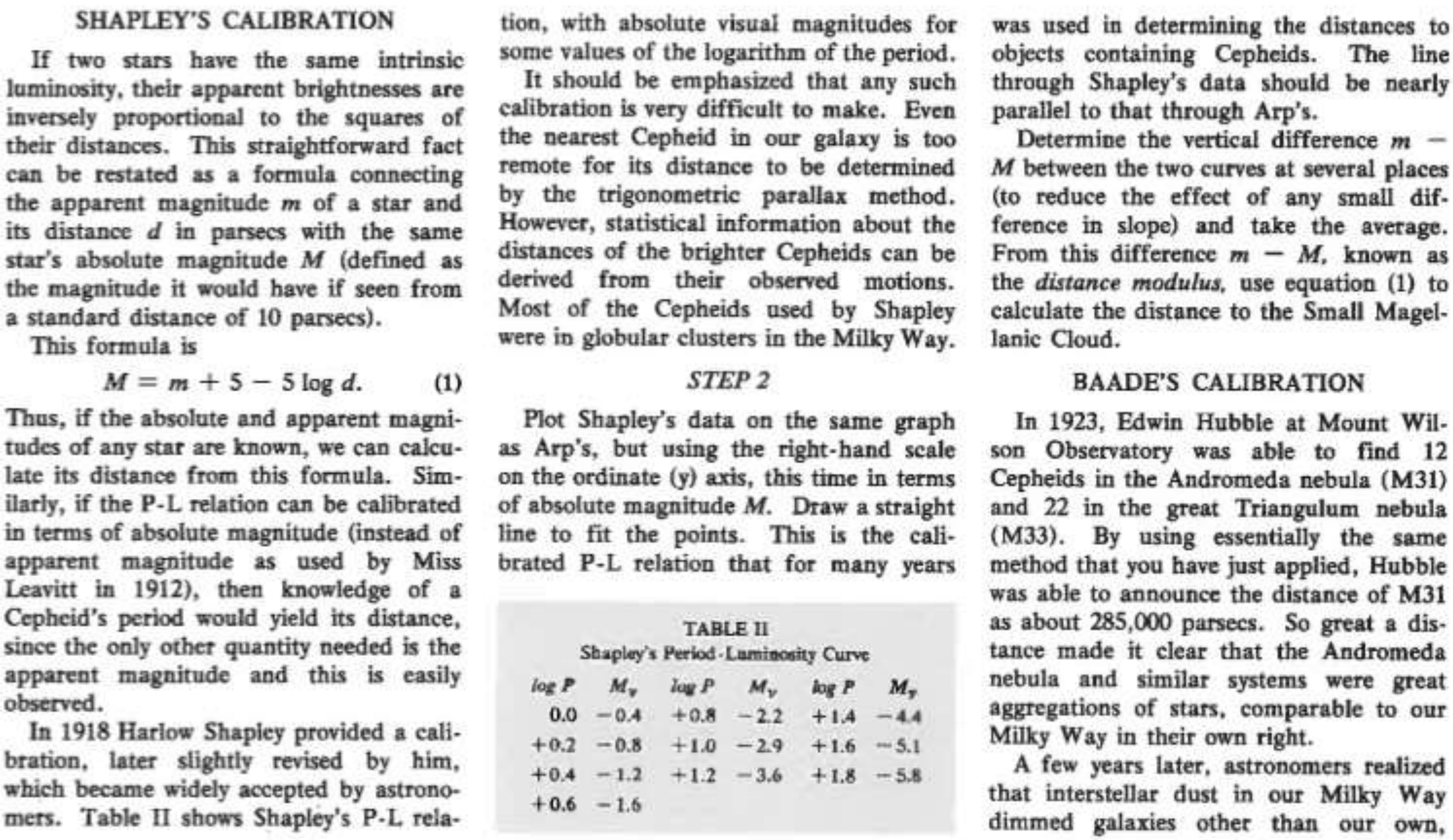

SHAPLEY'S CALIBRATION

If two stars have the same intrinsic luminosity, their apparent brightnesses are inversely proportional to the squares of their distances. This straightforward fact can be restated as a formula connecting the apparent magnitude *m* of a star and its distance *d* in parsecs with the same star's absolute magnitude *M* (defined as the magnitude it would have if seen from a standard distance of 10 parsecs).

This formula is

$$M = m + 5 - 5 \log d. \qquad (1)$$

Thus, if the absolute and apparent magnitudes of any star are known, we can calculate its distance from this formula. Similarly, if the P-L relation can be calibrated in terms of absolute magnitude (instead of apparent magnitude as used by Miss Leavitt in 1912), then knowledge of a Cepheid's period would yield its distance, since the only other quantity needed is the apparent magnitude and this is easily observed.

In 1918 Harlow Shapley provided a calibration, later slightly revised by him, which became widely accepted by astronomers. Table II shows Shapley's P-L relation, with absolute visual magnitudes for some values of the logarithm of the period.

It should be emphasized that any such calibration is very difficult to make. Even the nearest Cepheid in our galaxy is too remote for its distance to be determined by the trigonometric parallax method. However, statistical information about the distances of the brighter Cepheids can be derived from their observed motions. Most of the Cepheids used by Shapley were in globular clusters in the Milky Way.

STEP 2

Plot Shapley's data on the same graph as Arp's, but using the right-hand scale on the ordinate (y) axis, this time in terms of absolute magnitude *M*. Draw a straight line to fit the points. This is the calibrated P-L relation that for many years was used in determining the distances to objects containing Cepheids. The line through Shapley's data should be nearly parallel to that through Arp's.

TABLE II

Shapley's Period-Luminosity Curve

log P	M_v	*log P*	M_v	*log P*	M_v
0.0	−0.4	+0.8	−2.2	+1.4	−4.4
+0.2	−0.8	+1.0	−2.9	+1.6	−5.1
+0.4	−1.2	+1.2	−3.6	+1.8	−5.8
+0.6	−1.6				

Determine the vertical difference $m - M$ between the two curves at several places (to reduce the effect of any small difference in slope) and take the average. From this difference $m - M$, known as the *distance modulus*, use equation (1) to calculate the distance to the Small Magellanic Cloud.

BAADE'S CALIBRATION

In 1923, Edwin Hubble at Mount Wilson Observatory was able to find 12 Cepheids in the Andromeda nebula (M31) and 22 in the great Triangulum nebula (M33). By using essentially the same method that you have just applied, Hubble was able to announce the distance of M31 as about 285,000 parsecs. So great a distance made it clear that the Andromeda nebula and similar systems were great aggregations of stars, comparable to our Milky Way in their own right.

A few years later, astronomers realized that interstellar dust in our Milky Way dimmed galaxies other than our own,

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The Andromeda galaxy M31 flanked by its satellites, M32 (lower right) and NGC 205 (above). Photograph from Space Division, Chrysler Corporation.

making them appear too far away. Because of this the distance of M31 was revised downward, and a figure of 230,000 parsecs was generally accepted. In addition, distances to other galaxies were determined by Shapley's calibrated P-L relation. Thus, the distance scale of the universe was based on Shapley's work.

But as we shall now see, these distances were seriously underestimated. A major revision was made in 1952 by Walter Baade, from the first photographs of the Andromeda galaxy taken with the new 200-inch Palomar telescope. Baade had previously discovered that stars basically can be divided into two age categories. *Population I* stars are relatively young, hot ones, typically found in the spiral arms of galaxies, while *Population II* stars are old objects, characteristically found in globular clusters and in the halos of galaxies. In his 1952 photographs of M31 with the 200-inch telescope, Baade found that only the brightest of the Population II stars could be actually photographed, although fainter ones were expected to show up. This implied that the Andromeda galaxy must be even more distant than previously believed.

Since he could find no Cepheids in the globular clusters of M31 but many in the spiral arms, he deduced that the Cepheids in the globulars must be Population II and that the spiral-arm Cepheids are Population I. Along with this came the realization that the globular-cluster Cepheids, used by Shapley in his P-L relation calibration, must be about 1.5 magnitudes fainter than the Cepheids observed by Miss Leavitt in the Magellanic Clouds, which are of Population I. This discovery led to a revision of the extragalactic distance scale by a factor of slightly more than two. Although it was popularly written that the universe had become "twice as big," of course it was only the numerical values of the distances that changed.

STEP 3

Calculate the revised distance to the Small Magellanic Cloud which results if the distance modulus is changed by −1.5 magnitudes.

AN ALTERNATIVE CALIBRATION

Even after Baade's contribution, additional revision may be needed to the P-L relation. The fundamental problem remains, as in Shapley's day, determining the zero point of the P-L relation. There is still uncertainty about the accuracy of the statistical methods Shapley used to infer Cepheids' distances from their motions. Therefore, modern astronomers have sought other observational means of establishing the zero point.

In 1961, Robert Kraft at Lick Observatory deduced the absolute magnitudes of six Population I Cepheids that were members of open clusters, which are also of Population I and whose distances can be found in other ways. By themselves, these six stars are insufficient to define completely the zero point and the slope of the curve. But, by determining the intrinsic colors of these six stars, Kraft was able to extend his list to include 26 other Cepheids not associated with any cluster. A selection of the 32 Cepheids is given in Table III with an asterisk affixed to the six in open clusters.

TABLE III

Kraft's Period Luminosity Curve

Star	*log P*	M_v	*Star*	*log P*	M_v
SU Cas	0.29	−1.7	*U Sgr	0.83	−3.5
*EV Sct	0.49	−2.4	Eta Aql	0.86	−3.5
SS Sct	0.56	−2.4	RX Cam	0.90	−3.7
SU Cyg	0.58	−2.8	*DL Cas	0.90	−3.7
Y Lac	0.64	−2.8	*S Nor	0.99	−3.7
FF Aql	0.65	−3.1	Z Lac	1.04	−4.1
*CF Cas	0.69	−3.4	RW Cas	1.17	−4.5
V350 Sgr	0.71	−3.0	Y Oph	1.23	−5.3
*CV Mon	0.73	−3.0	T Mon	1.34	−5.6
RR Lac	0.81	−3.4	SV Vul	1.65	−6.4

STEP 4

On the same graph that contains Arp's and Shapley's work, also plot the values of *M* and log *P* from Table III. Then draw the straight line that gives the best fit to those points. In the same way as before, determine the distance modulus $m - M$ for the Small Magellanic Cloud, and calculate the distance from (1).

FUTURE DEVELOPMENTS

Although the Cepheid variables continue to be powerful indicators of the cosmic distance scale, astronomers now tend to believe that the Cepheids in one galaxy may not be physically identical with those of the same period in another galaxy. The slope of the P-L relation may be different from one galaxy to the next, depending upon the relative abundances of the elements in each. Moreover, within any one galaxy, the slopes of the P-L relations for the two populations of stars may not be the same.

Therefore, even though the distance scale is more accurately known today than it was during Shapley's time, we must await additional observations and theoretical models of Cepheid variables before astronomers can estimate just how accurate it really is.

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Reviews of the P-L relationship for Cepheids can be found in an article by Walter Baade (*Publications of the Astronomical Society of the Pacific*, *68*, 5, 1956); O. Struve and V. Zebergs, *Astronomy of the 20th Century* (Macmillan, 1962); R. Berendzen, R. Hart, and D. Seeley, *Man Discovers the Galaxies* (Neale Watson, 1976); and J. Pasachoff, *Contemporary Astronomy* (Saunders, 1977).

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To include more historical flavor in the exercise, you might consider having the students plot H. Shapley's original data (*Astrophysical Journal*, *48*, 107, 1918).

The best current estimates for the distance to the Small Magellanic Cloud are between 53,000 and 60,000 parsecs. G. de Vaucouleurs (*Astrophysical Journal*, *223*, 730, 1978) got 53,000 parsecs, using five different kinds of distance indicators — novae, Cepheids, RR Lyrae variables and horizontal branch stars, supergiants, and eclipsing binaries. Recent work by S. van den Bergh agrees with his result. A. Sandage and G. Tammann (*Astrophysical Journal*, *167*, 293, 1971) deduced a distance which after adjustment by de Vaucouleurs is still 15 percent larger. The values differ chiefly because of different treatment of interstellar reddening.

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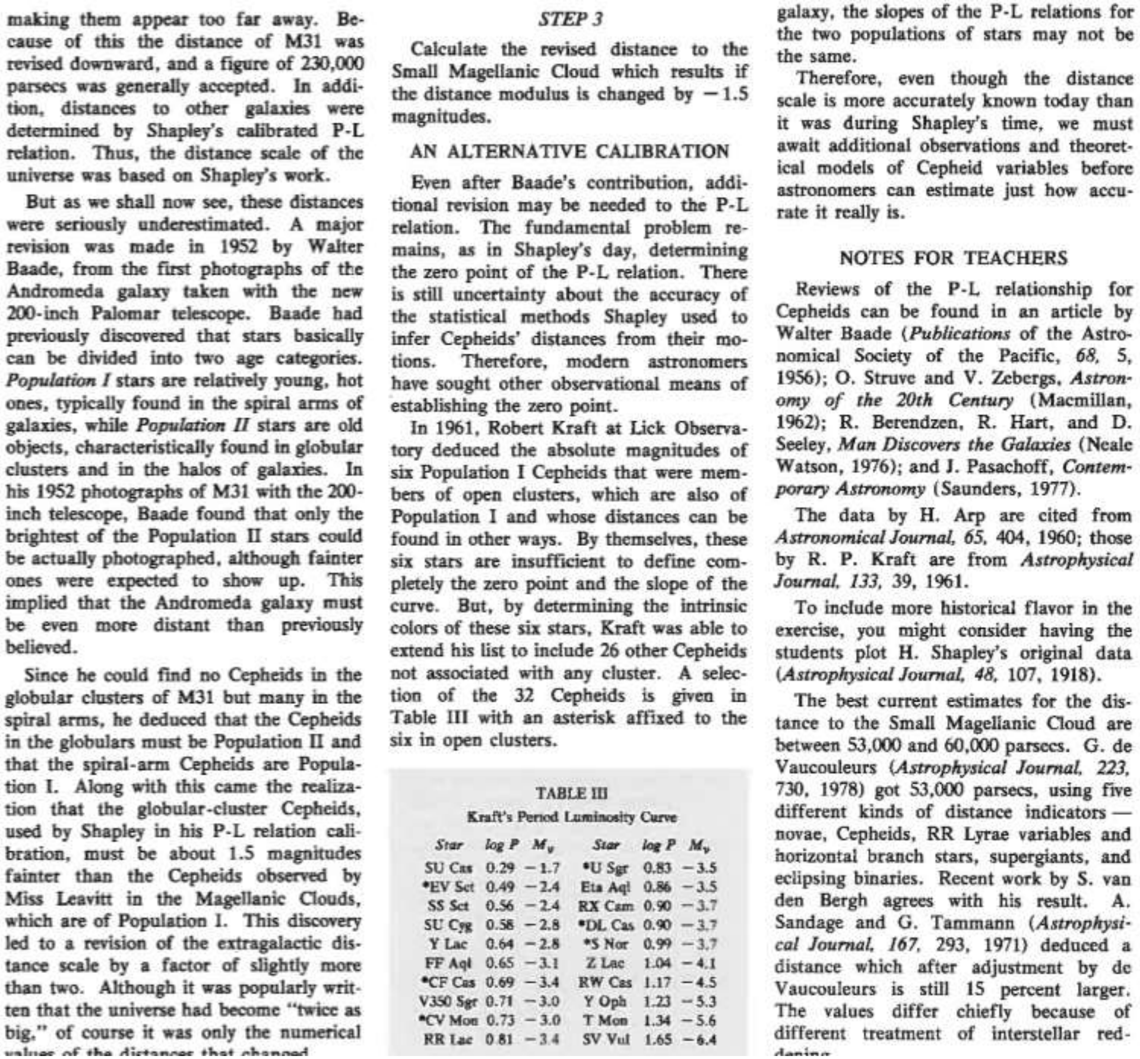

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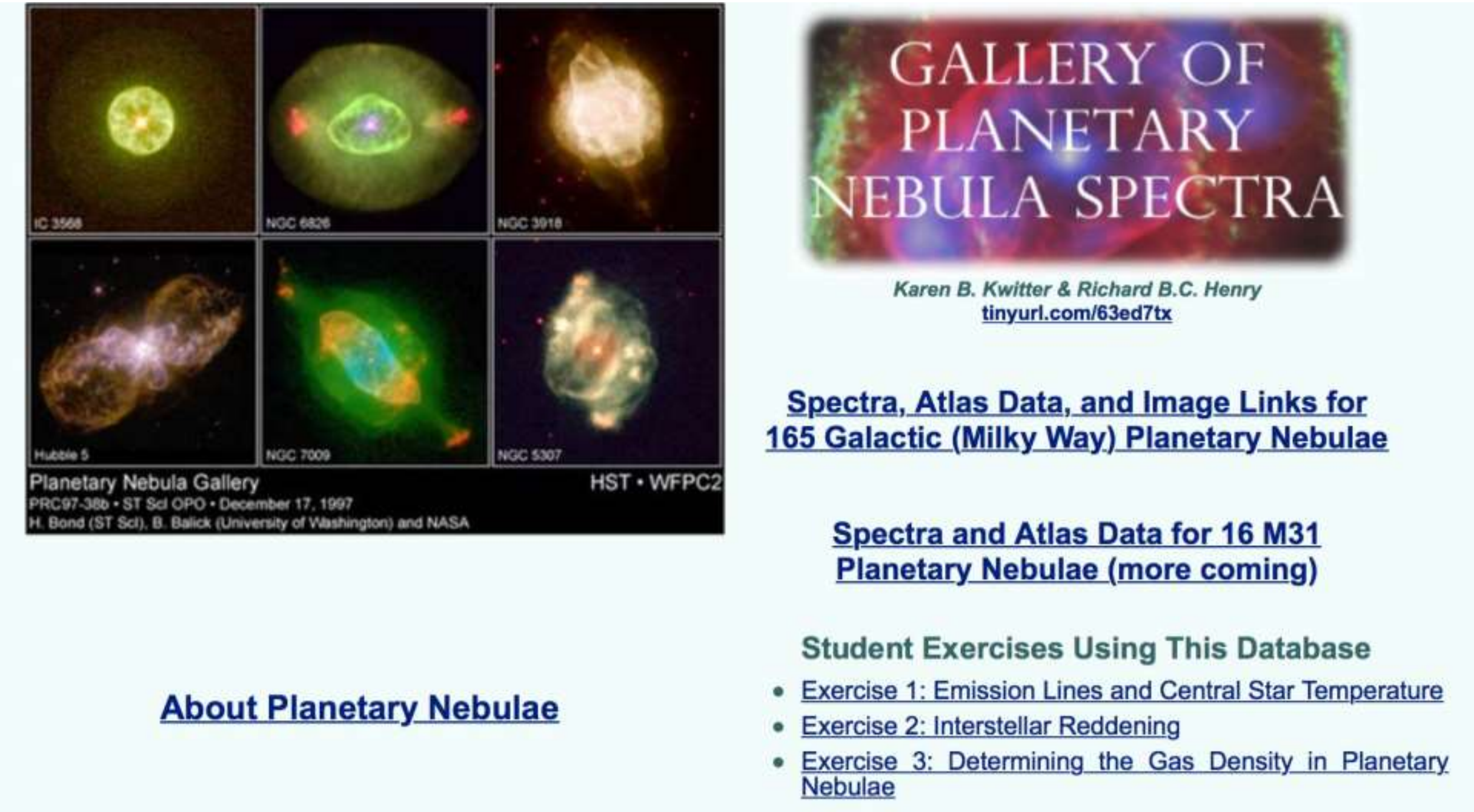

Planetary Nebula Gallery
PRC97-38b • ST Sci OPO • December 17, 1997
H. Bond (ST Sci), B. Balick (University of Washington) and NASA

GALLERY OF PLANETARY NEBULA SPECTRA

Karen B. Kwitter & Richard B.C. Henry
tinyurl.com/63ed7tx

Spectra, Atlas Data, and Image Links for 165 Galactic (Milky Way) Planetary Nebulae

Spectra and Atlas Data for 16 M31 Planetary Nebulae (more coming)

Student Exercises Using This Database

- Exercise 1: Emission Lines and Central Star Temperature
- Exercise 2: Interstellar Reddening
- Exercise 3: Determining the Gas Density in Planetary Nebulae

About Planetary Nebulae

http://web.williams.edu/Astronomy/research/PN/nebulae/

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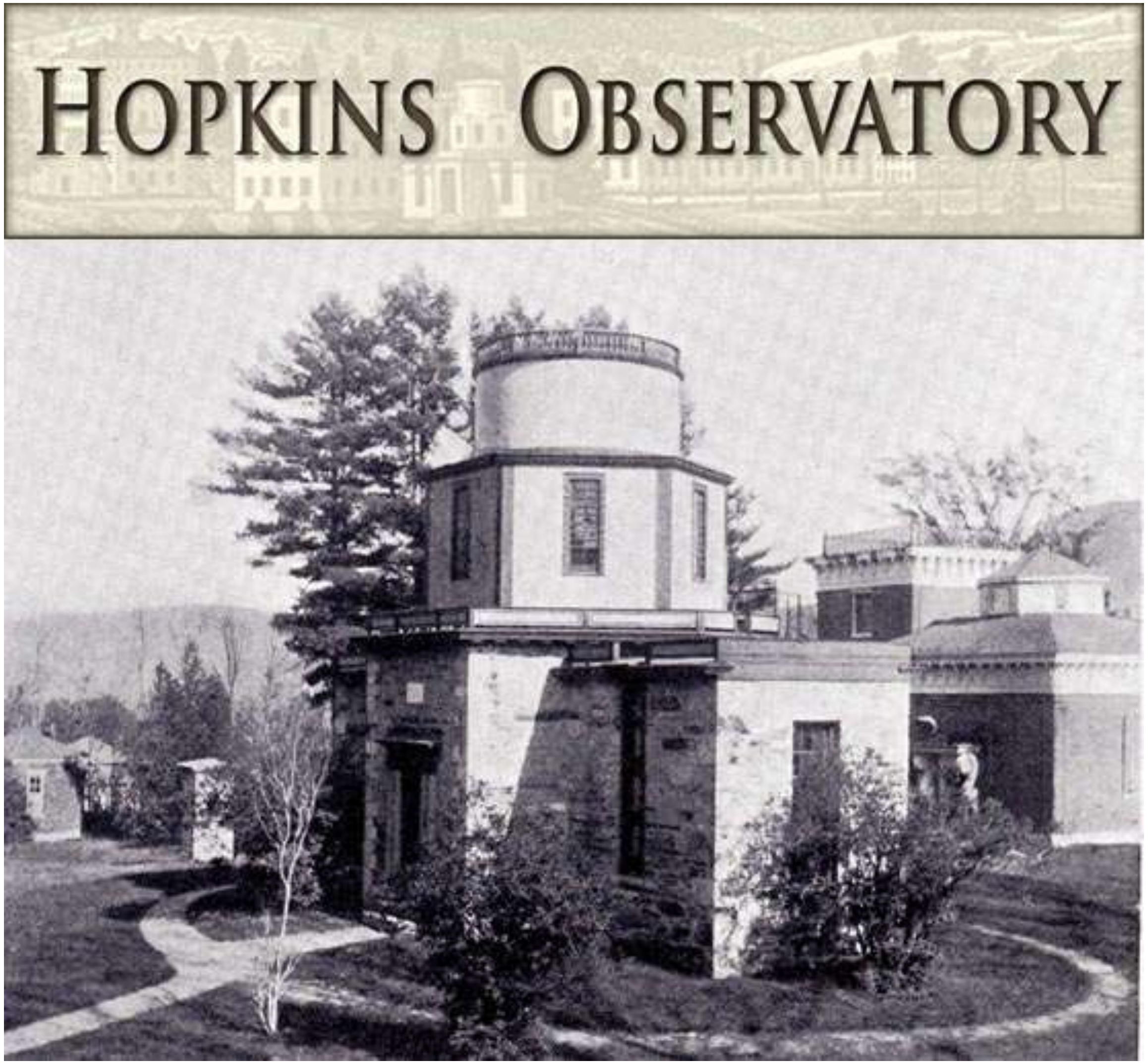
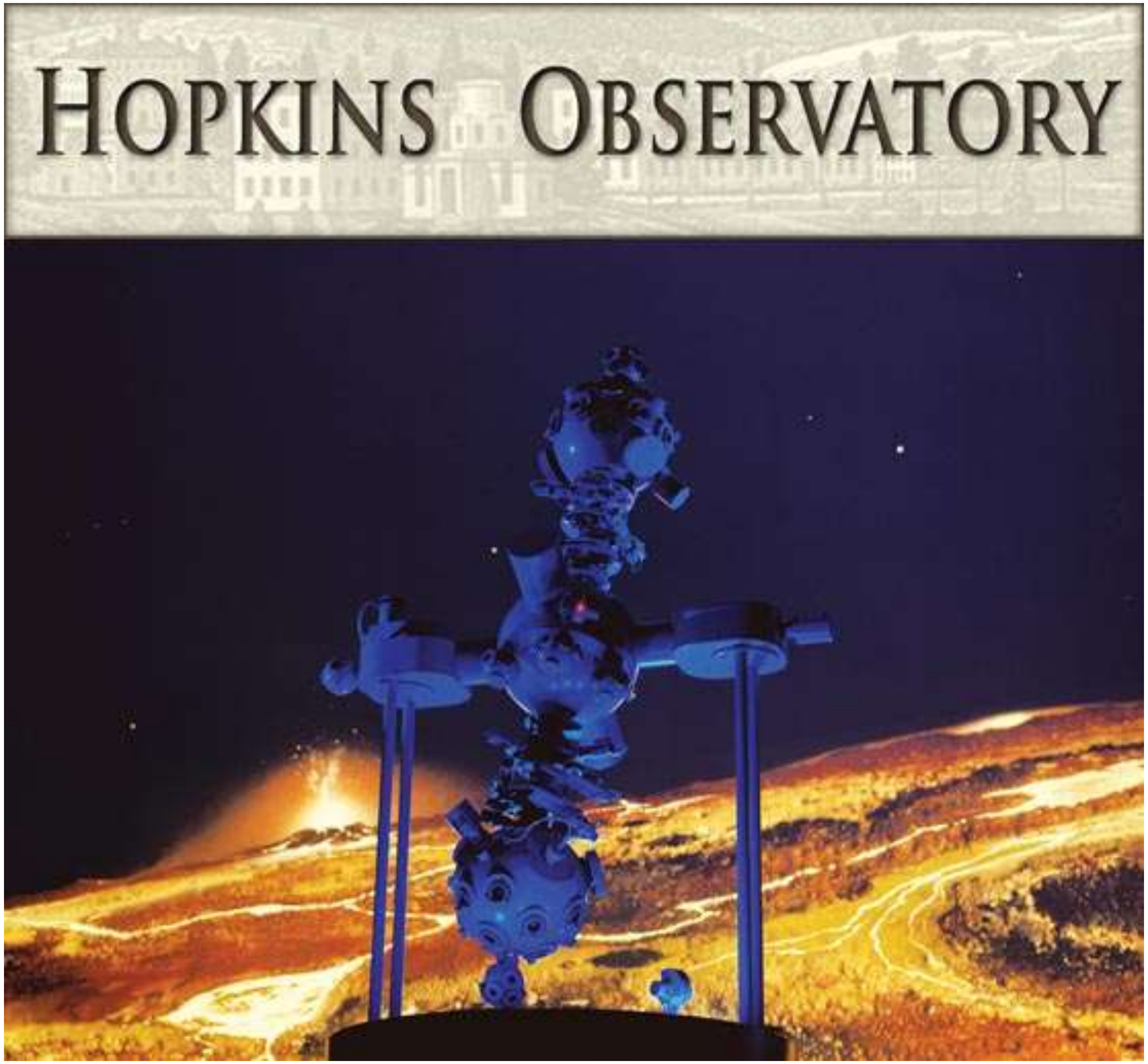


HOPKINS OBSERVATORY

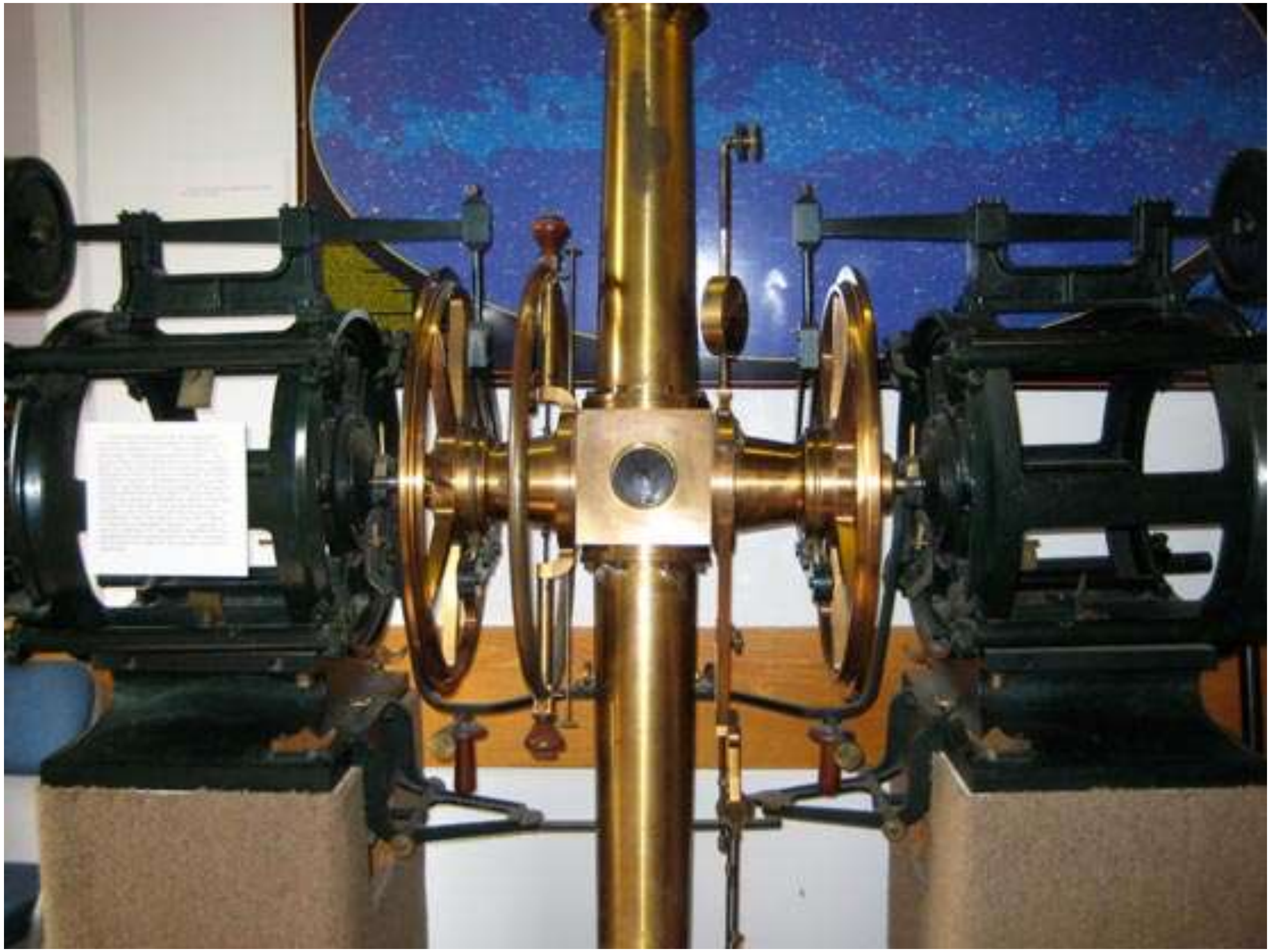
Zeiss ZKP3/B Planetarium, installed 2006



shows are given by undergraduate teaching assistants: weekly + school and other groups

Alvan Clark's first telescope (1851)
7" refractor

Repsold Meridian Transit
brought from London by Prof. Hopkins in 1834



Junior/Senior Independent/Thesis Work

- Often done in the field
- Prof Kwitter: planetary nebula spectra

interstellar medium course: [O III], Hα, other filters

https://sites.williams.edu/scientephic/research/the-space-between-the-stars-astronomy-students-study-interstellar-medium/ - more-595

- Prof Pasachoff: solar eclipses, transits of Venus and Mercury, occultations by Pluto

http://totalsolareclipse.org, transitofvenus.info, stellaroccultations.info

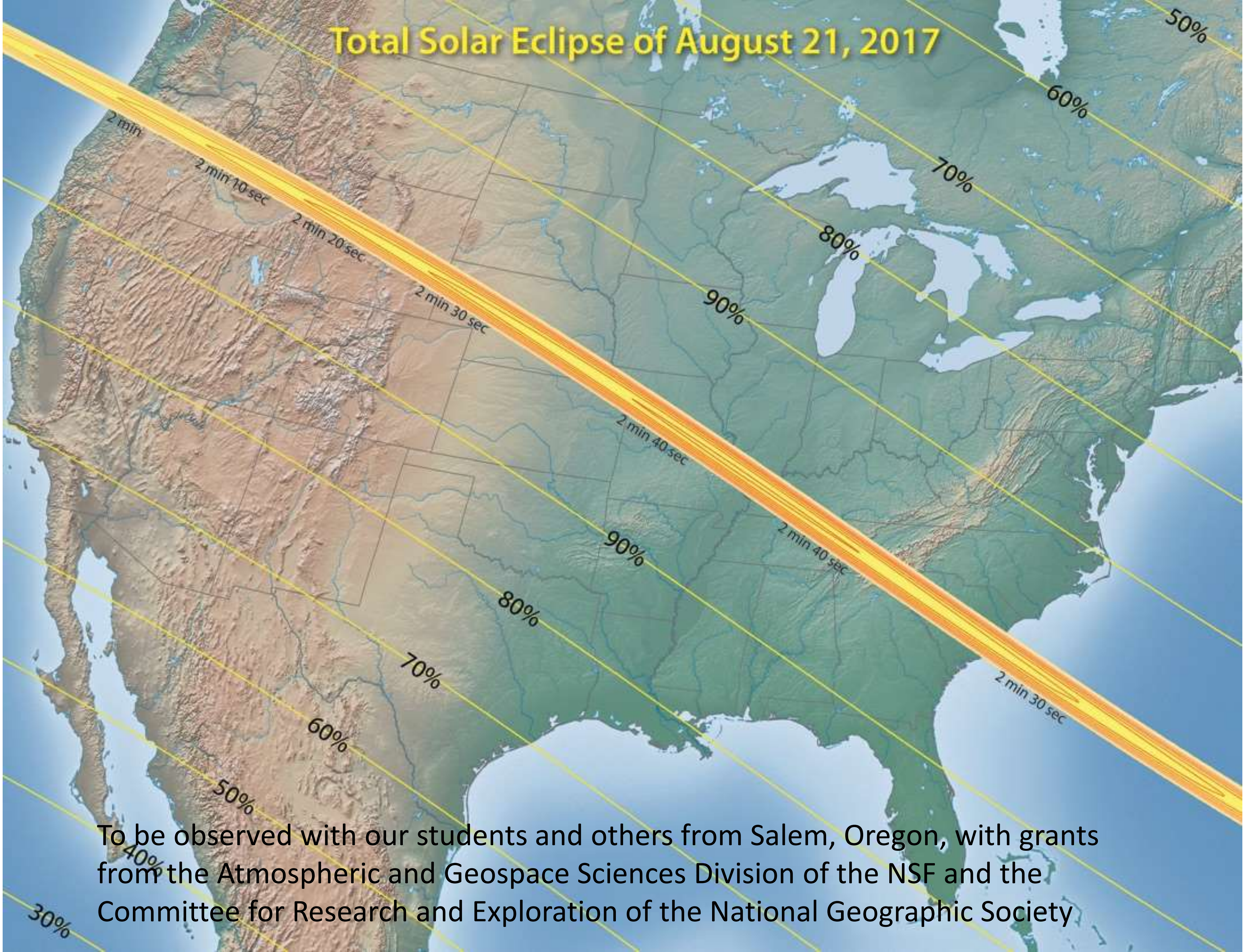
- Dr Souza: variable stars and clusters
- Visiting Prof Demianski: cosmology
- Geosciences colleague Prof Ronadh Cox: Mars, Io

2013 total solar eclipse, observed from Gabon

© Jay Pasachoff, Allen Davis, Vojtech Rusin © 2014 Miloslav Druckmüller

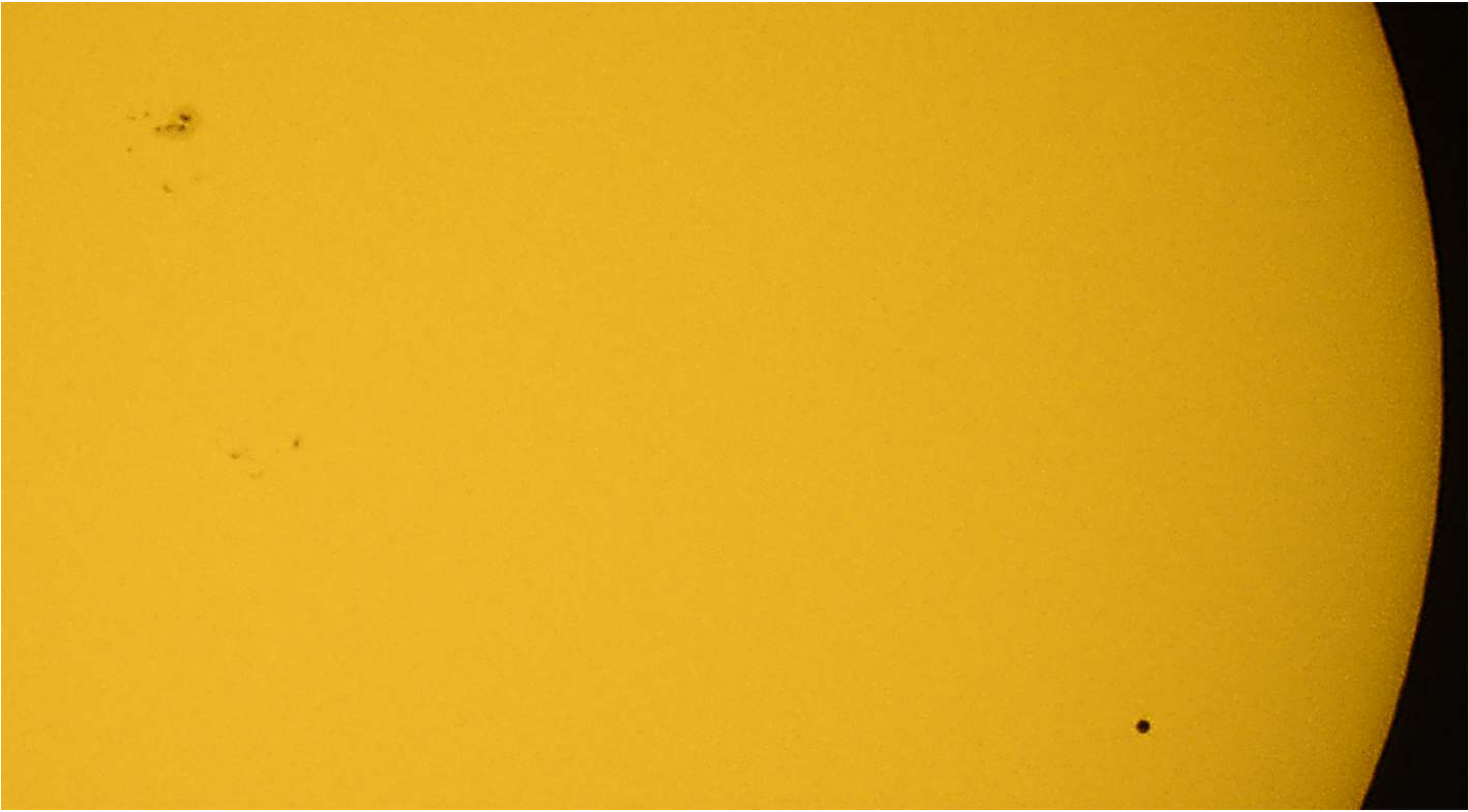
2012 annular solar eclipse from the VLA

Including all the students from my Solar Physics course



To be observed with our students and others from Salem, Oregon, with grants from the Atmospheric and Geospace Sciences Division of the NSF and the Committee for Research and Exploration of the National Geographic Society

transit of Mercury, May 9, 2016

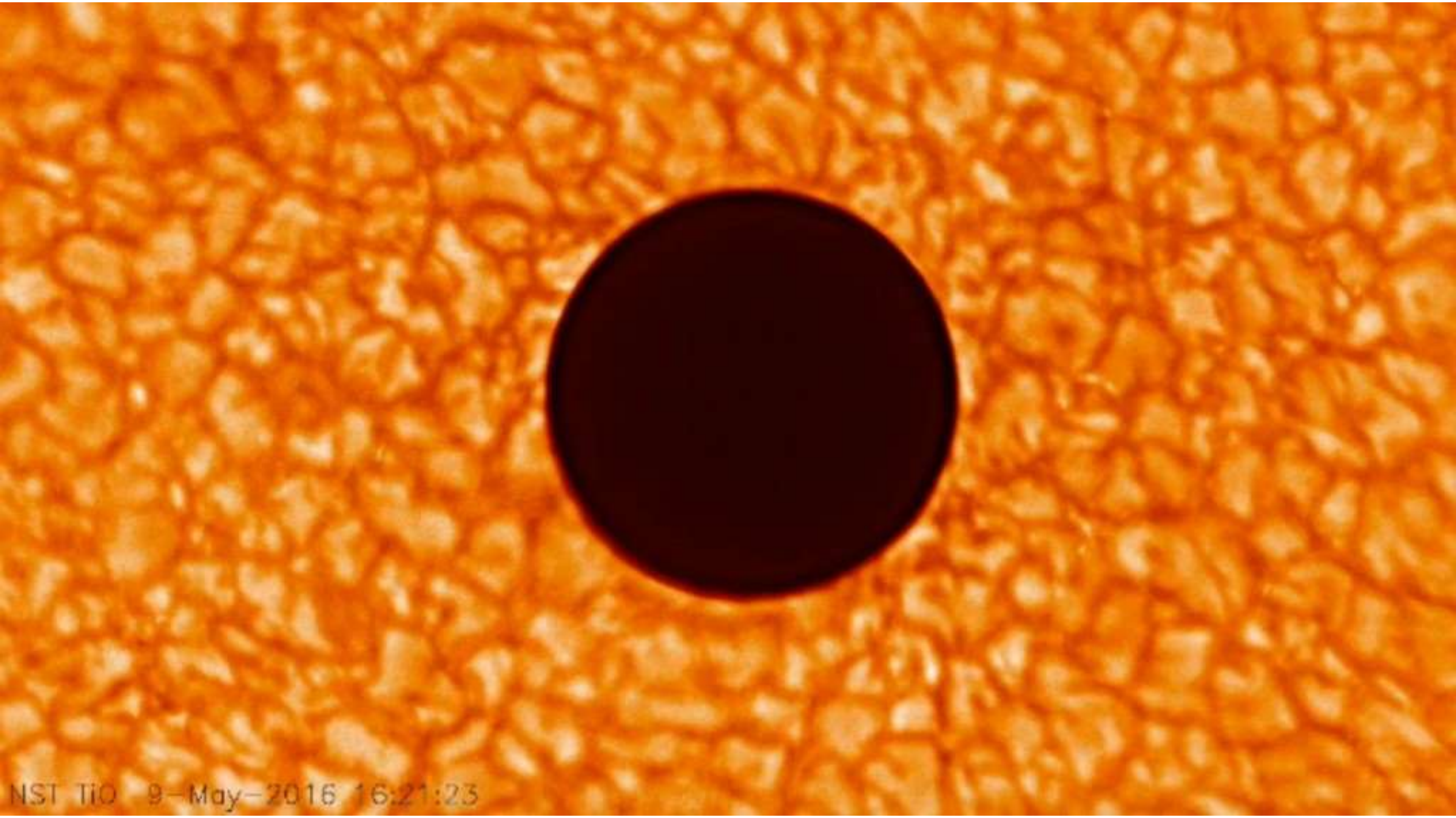


Questar images by Jay Pasachoff and Glenn Schneider; reprocessed by GS

Big Bear Solar Observatory

1.6-m New Solar Telescope

transit of Mercury, May 9, 2016

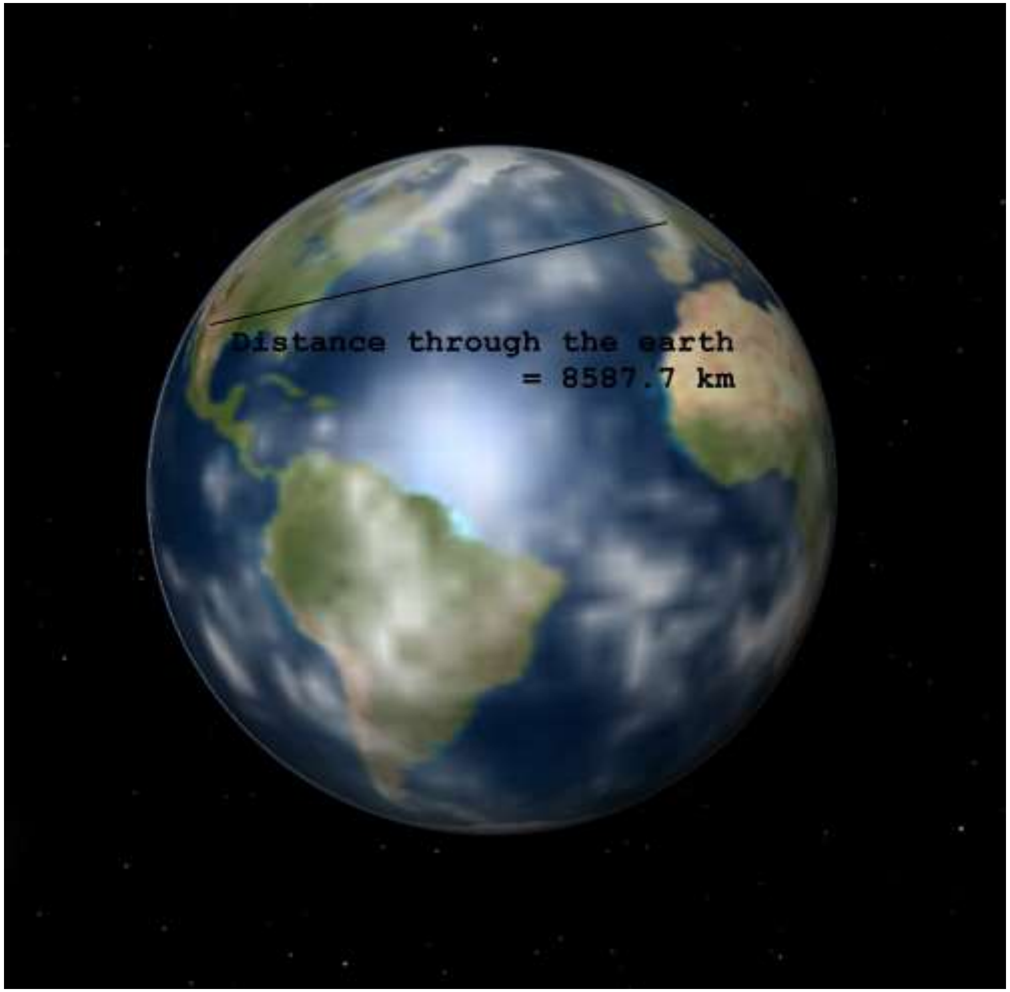


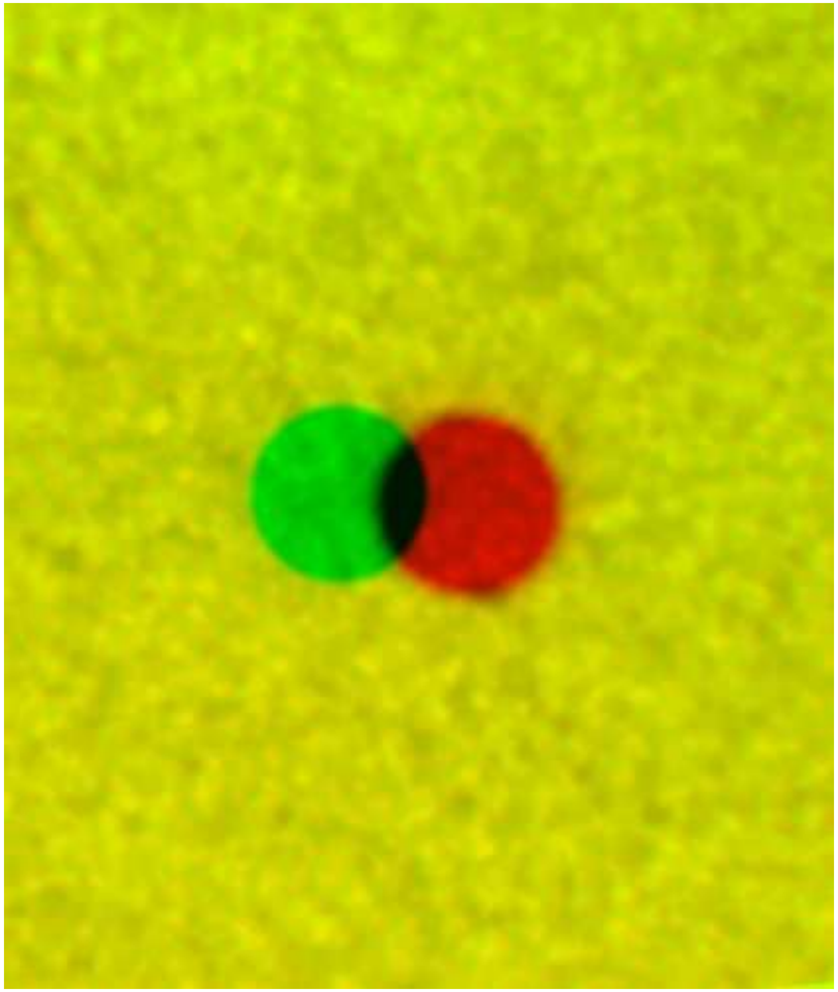
BBSO/NJIT, Jay Pasachoff, Glenn Schneider, Dale Gary, Bin Chen

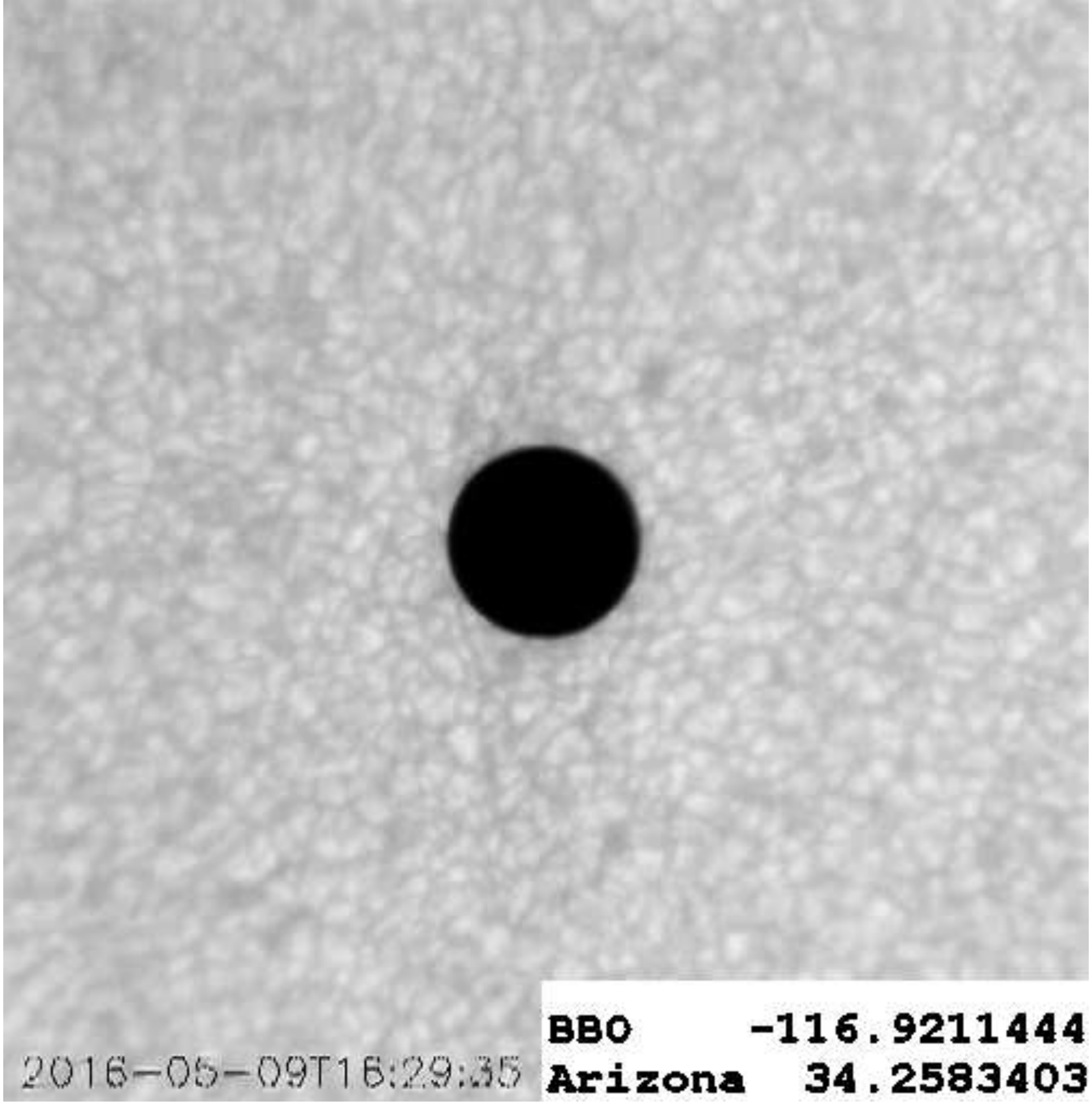
For *The Physics Teacher*

Using the 2016 transit of Mercury to find the distance to the Sun

Jay M. Pasachoff, Williams College and Caltech, Pasadena, CA
Bernd Gährken, Bavarian Public Observatory, Munich, Germany
Glenn Schneider, Steward Observatory, The University of Arizona, Tucson, AZ







2016-05-09T16:29:35
BBO -116.9211444
Arizona 34.2583403

We are happy to collaborate with ZTF’s educational program through Bryan Penprase.
Here is the group at Big Bear Solar Observatory in June.

Astronomy Labs at Williams College

Jay Pasachoff

eclipse@williams.edu

jmp@caltech.edu

GROWTH

Global Relay of Observatories Watching Transients Happen

eclipse@williams.edu
jmp@caltech.edu

Total Solar Eclipse 2013

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