Measuring the universe

BY BOB RIDDLE

Because the universe is expanding, measuring distances to celestial objects requires different measurement techniques, all of which are based on the standard ruler or standard candle. A *standard ruler* is a measurement of the diameter of the celestial object; a *standard candle* is a celestial object of a known luminosity. Both methods build on a succession of measurements from one distant object to the next.

As discussed in last month's column (Riddle 2017), it's best to think of celestial distances by picturing a ladder, where the lower rungs represent a more accurate measurement of distance. When you ascend farther up the ladder, the celestial distances become less accurate and uncertain.

Measurements on a celestial ladder range from the very accurate that result from direct observation of nearby objects to less accurate measurements of distances much further away such as galaxies (Figure 1). RADAR, or Radio Detection and Ranging, is a technique using radio signals that are directed toward a not-too-distant object, perhaps one

FIGURE 1: The cosmic distance ladder

Standard candle	Approximate distance limit	Example of celestial object
Radar ranging	Within the Solar System	Venus, Mars, Dwarf Planets
Parallax	Individual stars within the local area of our galaxy within to about 1000 parsecs	61 Cygni
Spectroscopic parallax or main sequencing	Uses the H/R Diagram with individual stars within about 500 parsecs that are part of a star cluster to determine the absolute magnitude and then distance	Betelgeuse, Sirius
Cepheid Variable Stars	Uses the relationship between luminosity and the period of variability of individual stars in other galaxies— distances to about 50 million parsecs (50 Mpc)	Polaris, δ Cepheid, M100 (galaxy)
Supernova (Type 1a)	Supernova events between 1 Mpc–1000 Mpc	SN 1572 (Tycho's Nova)

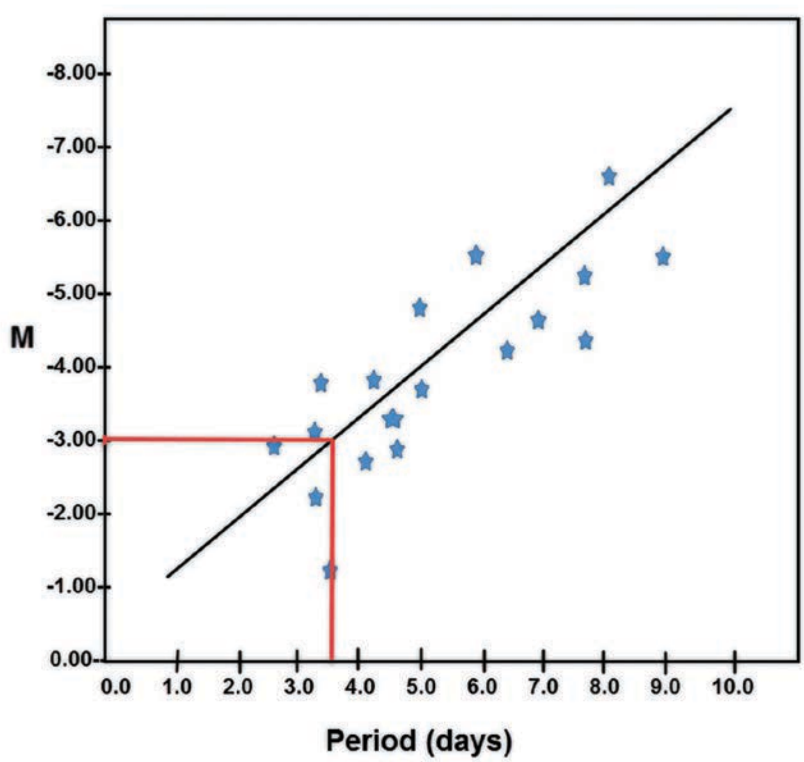
within our Solar System. The technique involves timing how long it takes for the radio signal to return to Earth and then dividing that time by two to get the distance to the object. Spectroscopic Parallax is a method for determining distances to stars by using the apparent and absolute magnitude of the star. The absolute magnitude of the star may be determined by noting the spectral class of the star on the H/R Diagram. Named after astronmers Ejnar Hertzsprung and Henry Norris Russell, the H/R Diagram is a graph used by astronomers to classify stars based on certain physical properties, including spectral type, luminosity, and temperature.

Measuring distances with Leavitt's Law

The *luminosity* is the total energy output of a celestial object, or, in other words, how bright the celestial object would appear at a distance of 10 parsecs (One parsec equals3.26 light-years.) This is also referred to as an object's absolute magnitude. Standard candles may be used to infer the distance to objects that are too far away for parallax methods to be reliably used. Before it can be used to measure celestial distances, a standard candle must be calibrated, meaning that enough observations must be made of the same type of celestial object so that it is considered to be an accurate measurement.

To understand standard candles, you need to first understand variable stars, whose luminosity varies over a specific period of time. The *intrinsic brightness*, also known as absolute magnitude, of a star is the star's luminosity or total output of energy in all directions. Knowing the period of variability—the number of days it will take a star to reach its intrinsic brightness—will reveal the distance to the star as well as the cluster or galaxy in which it resides. In 1908, astronomer Henrietta Leavitt discovered this relationship between time and luminosity. Leavitt was

FIGURE 2: Determining absolute magnitude for a Cepheid variable star



- From direct observations or using photographic data from different times plot the apparent magnitude of a variable star
- Determine the period of variability for the star
- Using the period for the observed changes in apparent magnitude change, determine the absolute magnitude
- Plug the values for apparent and absolute magnitude into the distance modulus formula to get the distance to the star.
- Distance Modulus: m-M or $d = 10^{(m - M + 5)/5}$

part of a team of women scientists at the Harvard Observatory who were hired more for cataloging stars than for their academic qualifications or participation in astronomical research, which was considered to be men's work at the time.

Leavitt primarily catalogued Cepheid variable stars within the small Magellanic Cloud, an irregular galaxy visible from the southern hemisphere. After plotting the change in luminosity and period of variability of these stars, she discovered that Cepheids with longer periods are brighter than Cepheid stars with shorter periods. The discovery led Danish astronomer Ejnar Hertzsprung in 1913 to calculate distances to Cepheid variable stars in the small Magellanic Cloud.

Observations of a star's apparent magnitude over time may be plotted with a light curve, which can determine the star's variability period and average apparent magnitude (Figure 2). The apparent magnitude (m) and *absolute magnitude* (M), the brightness of a star at 10 parsecs, are then plugged into the distance modulus equation ($d = 10^{(m - M + 5)/5}$). The answer reveals the distance to the star in parsecs.

For students

1. Solve the mystery word in the Universal Puzzler (see Resources).
2. How long will it take to travel to stars? Complete the Calculate Stellar Travel Times (see Resources).
3. Learn about some scientists, such as Henrietta Leavitt, whose work has been overlooked (see Resources).
4. A variable star in our galaxy was determined to have an average apparent magnitude of 12.0, with an average period of 3.5 days, and an absolute magnitude of 3.0. Use the distance modulus to determine the distance to the star in Figure 2. Is it less than, equal to, or farther than 10 parsecs? Or, what is the star's calculated distance?

   The variable star is greater than 10 parsecs. Its calculated distance $d= 10^{(12 - 3 + 5)/5} = 28$ *parsecs.*
5. When estimating apparent magnitude, distance is an important factor to consider. What is another important factor that would have an impact on the magnitude estimation?

   In addition to distance, the light from a distant star may be lessened depending on what lies between the star and the observer—interstellar dust and gases.

Measuring distant galaxies

Cepheid variable stars may allow astronomers to measure distances tens of millions of parsecs away, but this does not come close to determining distances to even more distant galaxies. For this, astronomers rely on a supernova, one of the brightest objects in a galaxy.

A supernova comes in two forms, with some variations. A Type 1a supernova occurs within a binary star system when a white dwarf star pulls material from its companion until it triggers a fusion reaction that causes the white dwarf star to explode. Type 1b and 1c supernovae are massive stars with collapsing cores that lost their outer hydrogen layers. The Type 2 supernova occurs when the cores of much larger stars are crushed into a small compact object, possibly a neutron star. As the remaining layers of the star collapse, they encounter the dense core and rebound in a huge wave of star material forced explosively away from the core. The rapidly expanding star material then turns into brightly glowing clouds of gases known as a nebula. The release of energy, or luminosity, in terms of absolute magnitude is approximately the same for all Type 1a supernovae. Because of this, astronomers are able to use the absolute magnitude to determine the distance to the supernova and, in turn, the supernova's galaxy. ●

REFERENCE

Riddle, B. 2017. Scope on the Skies: A candle in space. *Science Scope* 41 (2): 98–101.

RESOURCES

Calculating Stellar Travel Times—*www.quia.com/files/quia/users/cmcdonald/astronomy/13.bike-years.pdf*

Cosmic Distance Ladders—*www.as.utexas.edu/astronomy/education/spring05/komatsu/lecture28.pdf*

Distances: Simple Request Form—*http://ned.ipac.caltech.edu/ui*

Henrietta Leavitt—*www.womanastronomer.com/hleavitt.htm*

Measuring the Age of the Universe—*http://lco.global/measuring-the-age-of-the-universe*

Measuring the Universe (video)—*www.vimeo.com/41434123*

Named Galaxies—*http://ned.ipac.caltech.edu/level5/CATALOGS/naga.html*

NASA/IPAC Distances to Galaxies—*http://ned.ipac.caltech.edu/Library/Distances*

Play Bingo With Charles Messier—*http://lco.global/education/messierbingo*

Solar System Math—*www.nasa.gov/pdf/622130main_SSML1Tchr.pdf*

Supernova—*www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-a-supernova.html*

Supernovae—*http://imagine.gsfc.nasa.gov/science/objects/supernovae2.html*

The Universal Puzzler—*http://starchild.gsfc.nasa.gov/docs/StarChild/universe_level2/javascript/universal_puzzler.html*

Unsung Heroes of Science—*http://cosmictimes.gsfc.nasa.gov/teachers/downloads/lessons/1929/unsung_heroes.doc*

November

2 Venus near Spica

3 Full Moon

5 Moon at perigee 361,400 km (224,563 mi.)

Waning gibbous Moon near Aldebaran

9 Waning gibbous Moon near beehive star cluster

10 Last quarter Moon

Waning crescent Moon at ascending node

11 Waning crescent Moon near Regulus

12 Mercury near Antares

14 Waning crescent Moon near Mars

17 Leonid meteor Shower: ZHR = 15

18 New Moon

20 Waxing crescent Moon near Saturn

21 Waxing crescent Moon at apogee: 252,339 miles: (406,100 km)

23 Mercury at eastern elonga-tion (22° E)

25 Waxing crescent Moon at descending node

26 First quarter Moon

29 Mars near Spica

Visible planets

Mercury will be visible over the western horizon after sunset for most of the month.

Venus will be visible over the eastern horizon a couple of hours before the Sun rises, but each morning, it will be closer to the Sun.

Mars will be visible over the southeastern horizon at sunrise.

Ceres will rise before midnight and will be located between the stars of Cancer the Crab and Leo the Lion.

Jupiter will start becoming more visible later this month as it rises earlier each day.

Saturn will move too close to the Sun to be visible this month.

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