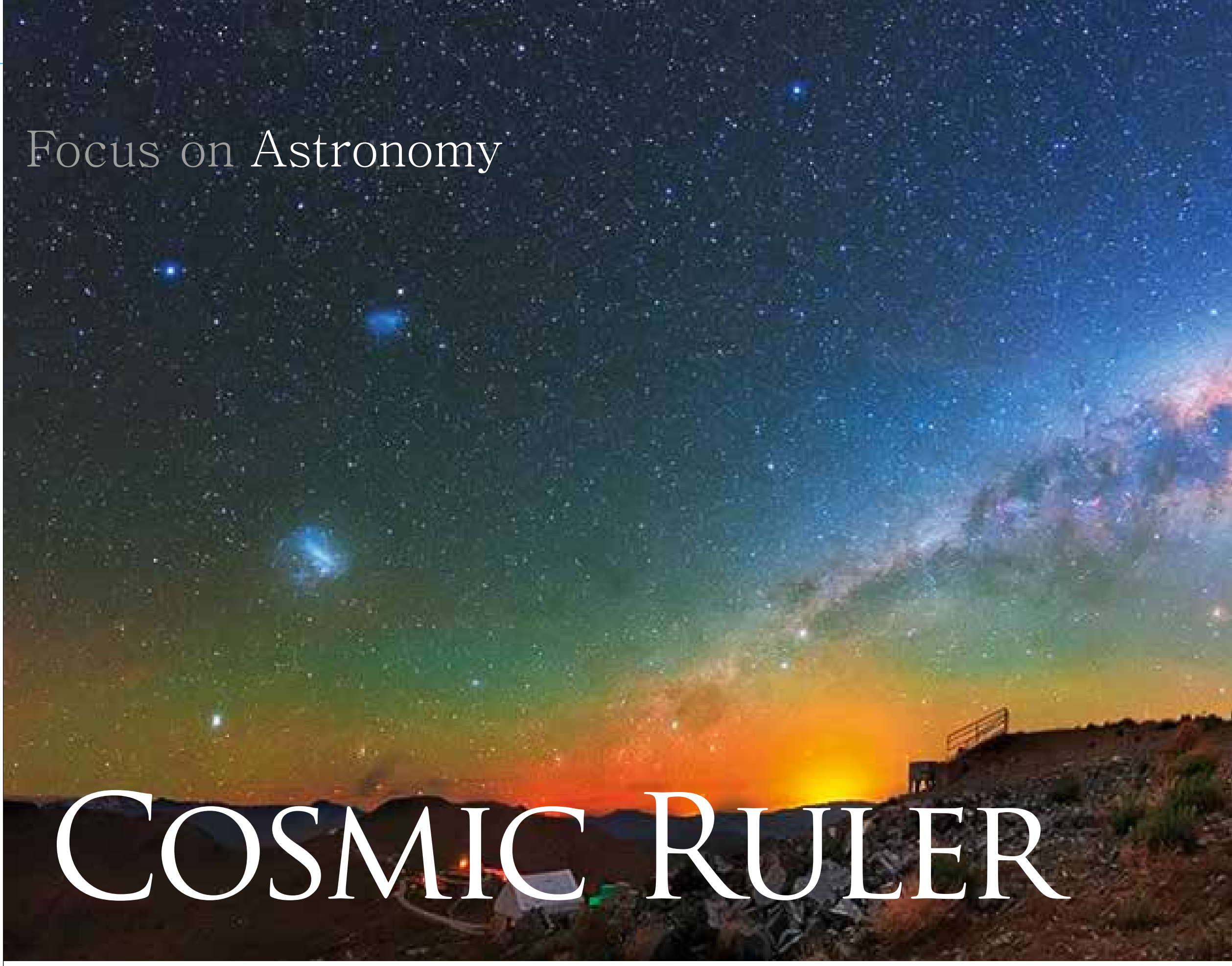

COSMIC RULER

Measuring cosmic distances is one of the most important, fascinating and difficult challenges facing astronomers today. The objective is not just to identify the distances between objects in space – such distances are also key to finding out how our Universe is structured and how it evolves. They also evidence the amount of energy emitted by objects and makes it possible to determine their nature.

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Grzegorz Pietrzyński, PhD, DSc is an astronomer. His main interests are cosmic distances, nearby galaxies, variable stars and star clusters. He has published 340 research papers in leading astronomical journals (including 11 in *Nature* and *Science*) which have had over 15,000 citations. He has won numerous prizes and prestigious research grants, including an Advanced Grant from the European Research Council. He is the director of the international Araucaria project.

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To date, every significant improvement made in the accuracy of measurements of cosmic distances has revolutionized our understanding of the cosmos. Measuring the distances to globular clusters helped us pinpoint the location of Earth within our own galaxy, the Milky Way. Measuring the distance to the M31 object revealed that the Universe actually stretches far beyond the Milky Way and includes myriad other galaxies which – just as our own – comprise hundreds of billions of stars each. Such measurements also revealed that the distances between galaxies are increasing rapidly, and so the observable Universe is constantly expanding. The farther a given object is from Earth, the faster it is moving away. This simple observation is known as Hubble's law and it forms the foundation of our understanding of the Universe. The Hubble constant, or parameter, is the estimated rate of this expansion. Twenty years ago, the most up-to-date distance measurements revealed that the rate of expansion of the Universe was accelerating, a discovery that earned Saul Perlmutter, Brian P. Schmid,t and

YURIJ BELETSKI

The Las Campanas observatory at night. The Milky Way stretches above the enormous telescopes.

Left: two galaxies, the Large and Small Magellanic Clouds – our nearest neighbors

Adam G. Riess a Nobel Prize in 2011. To explain this accelerating rate of expansion, the researchers postulated the existence of a mysterious substance, termed dark energy, which constitutes around 70% of the total energy in the present-day observable Universe.

The improved accuracy of distance measurements made in recent decades has again significantly shifted our view of the Universe. The Hubble parameter is key to contemporary descriptions of the Universe. It defines the size of the Universe and its evolution (it is present in the equation of state), and it is essential in research into the physical nature of dark energy. As such, continuing to improve the parameter's accuracy is one of the key challenges faced by contemporary physics.

Several methods of measuring the Hubble parameter are currently available. A recent breakthrough in observational cosmology means the Hubble parameter can be derived from cosmological methods of microwave radiation analysis and baryon acoustic oscillations. Though these methods are highly attractive, they require scientists to make additional assumptions, which in turn depend on the model assumed. The Hubble parameter can also be determined using the classical method using standard candles. This is the simplest, fully empirical and potentially most precise method, which is why it was chosen for the Araucaria project.

In search of standard candles

In order to measure the Hubble parameter using the classical method, we first need to carefully select standard candles – groups of objects which emit the same amount of energy, found at different locations in the Universe. Observations of such objects assume that the difference in observed (or measured) luminosity is due to the difference between their distance from Earth, but in reality the situation is far more complicated. Space contains gas and dust which absorb and scatter some of the light emitted by our standard candles. Additionally, perfect standard candles, with absolutely invariable luminosity, simply do not exist. Their luminosity generally depends on a range of factors such as their metal content. In order to conduct accurate measurements, astronomers need to select the best candles and investigate how their luminosity depends on various factors and how observations are affected by the presence of cosmic gas and dust. It should be noted that standard candles can only be used to determine relative distances – for example, we can determine that one object is located at a distance four times larger than another. Determining absolute distances in physical units requires different methods to determine distances to groups of standard candles.

The vast range of distances in the Universe means that determining the Hubble parameter requires us to use several different standard candles, to build a distance ladder. The best standard candles for measuring the Hubble parameter are Cepheid variable stars and supernovas. Following over a century of extensive research, it turns out to be possible to measure the Hubble parameter in just three steps. In the first step, we build the lowest rung of the ladder by measuring the distance to Cepheids. Next, using Cepheids, we

The name of the project originates from the name of a tree found in southern Chile. Pictured: an araucaria tree in Chile, with the Llaima volcano in the background

measure the distances to galaxies where supernovas have been observed, to calibrate the luminosity of the supernova. This extends our ladder sufficiently to use these extremely bright objects to reach out into the distant corners of the Universe and determine the value of the Hubble parameter. This method has made it possible to determine the Hubble parameter with an accuracy of around 4%. Up to 70% of the measurement error stems from the uncertainty in the calibration of the brightness of Cepheids. As such, in order to significantly improve the accuracy of the Hubble parameter, we must first improve the measurement methods used to build the first rung of the cosmic distance ladder.

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Distant Cloud

This is the hardest part of the entire arduous task of marking the Hubble parameter, and it is the main aim of the Araucaria project, an international endeavor which has spent the last 15 years making precise measurements of distances to neighboring galaxies using different standard candles. The project has already published over 120 papers, including four in *Nature*. So far we have obtained very accurate measurements of distances to 20 nearby galaxies. Our pioneering observations in the near infrared have determined the impact of intervening gases and cosmic dust on the brightness of our standard candles, including Cepheids.

One of the greatest achievements of the Araucaria team has been to measure the distance to the Large Magellanic Cloud – our nearest neighboring galaxy – with an unprecedented accuracy of approx. 2%. This is the most accurately measured distance to another galaxy obtained to date. It is also akin to the degrees of error we are used to in our daily lives – it's similar to the accuracy with which we measure the height of children, for example – except our team applied it to the truly astronomical distance of 1,693,000,000,000,000,000 km. The Large Magellanic Cloud contains over 3,000 Cepheids, making our measurement key for calibrations of the luminosity of these standard candles. It forms the most substantial basis for measuring the Hubble parameter, with an accuracy better than 3%.

The distance to the Large Magellanic Cloud was measured using eclipsing binaries. These are systems of two stars orbiting one another, which we observe at a large angle. The mutual eclipses mean observers can register the fluctuations in the system's brightness.

In eclipsing binaries, the observed changes in brightness together with the measurements of the speed of the stars in orbit made using simple laws of physics allow us to determine basic stellar parameters (or parameters of stars), including their mass, linear size and temperature, with a great degree of precision (better than 1%). Basically, the only limitation is the precision of observations. Our team has determined such physical parameters including linear sizes for eight eclipsing systems in the Large Magellanic Cloud. Next, using the known relationships between temperature, brightness and angular sizes, we calculated the angular sizes of stars in our eclipsing systems. Using both linear and angular sizes we were able to determine distances to the studied stars with a great degree of precision using simple geometrical methods.

We also used the same method to measure the distance to another nearby galaxy, the Small Magellanic Cloud, with an accuracy of 3%. We discovered thousands of Cepheids in the galaxy, which means we can determine their absolute luminosities with a high degree of precision. Cepheids in the Small Magellanic Cloud have a far lower metal content than those in the Large Magellanic Cloud. This means that by comparing their luminosities in both galaxies we can empirically determine the extent to which Cepheid brightness depends on their metal content. In other words, we can define how stable the Cepheids are as standard candles.

Our team is currently working on improving the cosmic ruler originally developed by Polish researchers. A more precise calibration of the relationship between temperature, brightness and angular sizes for stars will help us measure the distance to the Large Magellanic Cloud with an accuracy better than 1%. Such measurements are essential if we are to determine the Hubble parameter with a similar accuracy. Additionally, by comparing an empirical measurement of the Hubble parameter obtained using classical methods with similar measurements made with cosmological methods we can conduct a unique test of contemporary physics. Comparisons of existing calculations of the Hubble parameter indicate that the measurements differ, although the accuracy isn't sufficient to confirm this.

Weighing Cepheids

An extremely important aspect of distance measurements is having an in-depth understanding of the methods being used. If we want to measure the Hubble parameter using Cepheids, we must first understand their physics. Cepheids are named after one of the first stars of the type, discovered in the Cepheus constellation. These stars are between four and 20 times more massive than our Sun, and at a certain moment of their life their outer layers start to pulsate. Each star's radius and temperature periodically fluctuate by a few percent. The result is that observers register distinctive changes in the star's luminosity. Cepheids are one of the most important and most extensively described types of stars; however, even though they have been studied for over a century, they continue to hold certain secrets.

In 1968, astronomers noted that the values of Cepheid mass, the basic parameter determining their properties and fates, predicted by theories of star evolution and pulsation were out by approx. 20%. The inconsistency kept researchers up at night, since it clearly indicated that there were problems in our understanding of stellar physics. The problem could only be solved by conducting independent, direct measurements of Cepheid mass. Unfortunately all previous attempts carried a very high degree of error (up to 30%), so it wasn't possible to determine which theory was the most accurate at predicting correct values. The Cepheid mass problem remained unsolved for over 40 years. The breakthrough came when the Araucaria team analyzed Cepheids in a few eclipsing binary systems. As I already mentioned above, analyzing such systems makes it possible to determine the physical parameters of stars with a high degree of precision. The project measured the mass of five Cepheids with an unprecedented accuracy of approx. 1%. Comparing this extremely precise and accurate outcome against theoretical results allowed us to finally solve the Cepheid problem. We now know that masses of Cepheids predicted by the theory of star evolution are around 20% too high.

Grzegorz Pietrzyński

A roadsign at the Las Campanas observatory, showing distances to the Large Magellanic Cloud, the Sun and Warsaw.

Further reading:

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