How fast is the Universe expanding?

Quasars and Dark Energy

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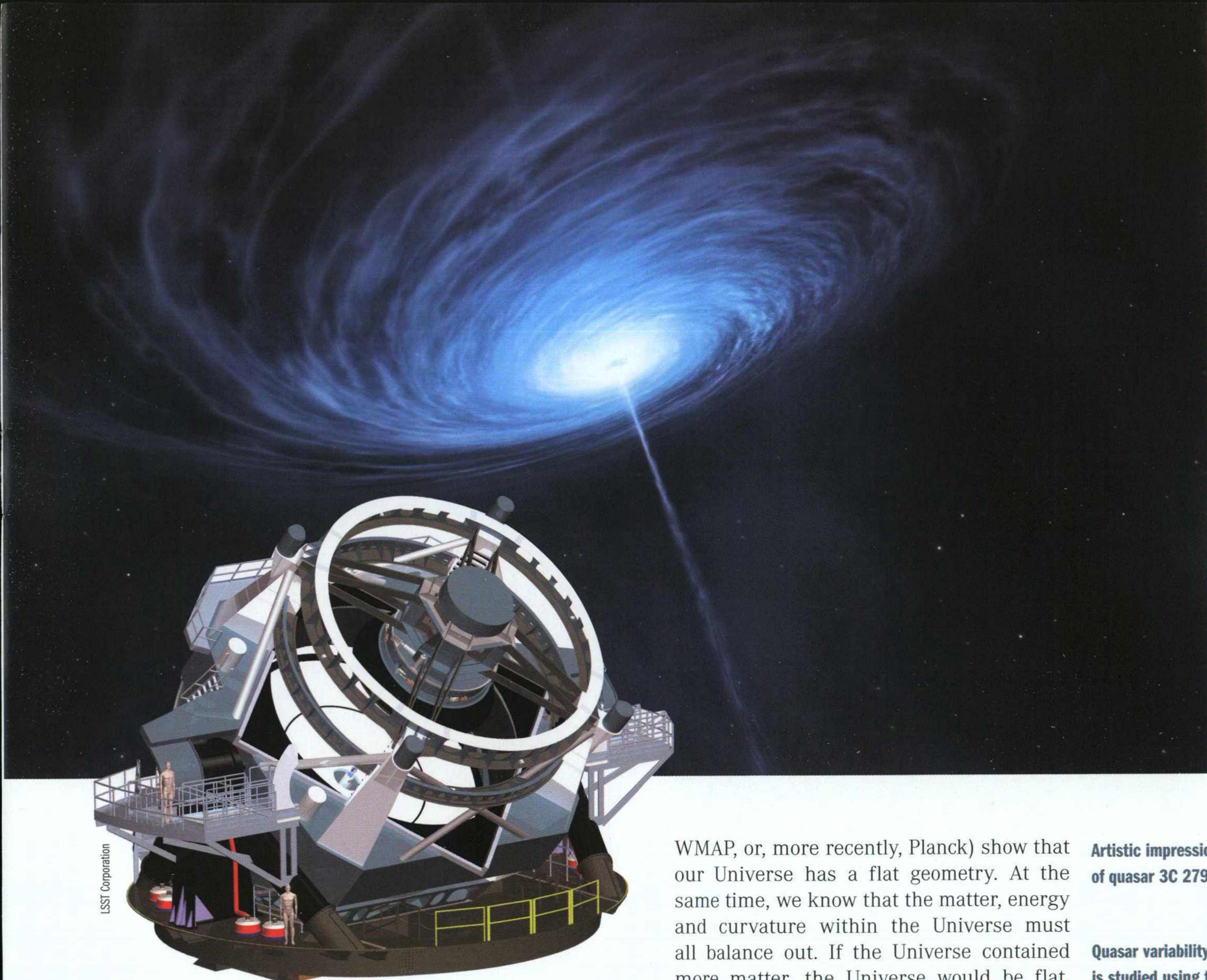
The discovery that the Universe is expanding faster than we previously thought is one of the most fundamental findings in cosmology of recent years, but we are still some way from understanding precisely how this expansion occurs. Our team from the Nicolaus Copernicus Astronomical Centre and the Jagiellonian University is using quasars to try to unravel the mystery

We have been aware that the Universe is expanding since the 1920s, when Edwin Hubble first discovered the phenomenon known as receding galaxies. Astronomers trying to resolve the riddle since then have been working on two main scenarios. According to the first, the Universe would only continue expanding up to a certain point, after which the gravitational force of the matter within it would halt the expansion, and the Universe would start contracting again. The other scenario posits that the Universe would continue to expand until eternity, albeit at an increasingly slower rate.

In 1997, two research teams independently published their findings based on measurements of the brightness of distant supernovae, which suggested that the Universe is not showing any signs of collapsing, but instead its rate of expansion is actually increasing! While such a model had long been entertained theoretically, not many scientists took it very seriously. This discovery of the Universe's accelerated expansion won the Nobel Prize in 2011.

However, we are still faced with a problem: although there is a growing body of indirect evidence that the Universe is indeed expanding at an increasing rate, the only direct proof we have thus far has been provided by studies of supernovae. As such, any alternative method of precisely measuring the rate of the Universe's expansion during different cosmological eras is worth its weight in gold. Our research team has looked for such a method using quasars, which are extremely luminous, usually very distant objects.

First named during the 1960s, quasars (short for "quasi-stellar radio sources") resemble stars, although they are in fact compact regions in the centers of massive galaxies, containing a central supermassive black hole and surrounding luminous matter. The brightness of a quasar is many times greater than the brightness of all the stars in its host galaxy. Quasars emit radiation



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LSST Corporation

The Large Synoptic Survey Telescope (LSST), slated to come online in the coming decade, will study changing astronomical sources across the sky

across the entire electromagnetic spectrum, and they are visible from great distances; our team has been observing them in the optical range.

Universe in a nutshell

The distances to quasars and distant galaxies are usually established by measuring their redshift (denoted as z). Each photon emitted by a quasar has a lower frequency (and therefore a greater wavelength) when it reaches us than at the point when it starts its journey across the Universe. This is due to the expansion of the Universe, or the space containing galaxies. Observations of distant supernovae indicate that instead of slowing down as a result of gravitational force of matter, the expansion is in fact accelerating. This phenomenon is described using the concept of dark energy. Measurements of microwave background radiation emitted when the Universe was a mere few hundred thousand years old (conducted by satellites such as COBE, WMAP, or, more recently, Planck) show that our Universe has a flat geometry. At the same time, we know that the matter, energy and curvature within the Universe must all balance out. If the Universe contained more matter, the Universe would be flat. However, many measurements demonstrate that there is simply not enough matter to account for the observed flatness. What is more, this flat Universe, containing only the ordinary matter, would slow down its expansion instead of accelerating it. So there must be an additional component acting as

Artistic impression of quasar 3C 279

Janus Brink

Quasar variability is studied using the Southern African Large Telescope (SALT) in South Africa; Polish scientists have access to 10% of the telescope's observation time a "negative gravity". This is a cosmological constant generally denoted with the Greek letter lambda (Λ), often referred to as dark energy.

Distance and luminosity

As already mentioned, the distance to quasars and other distant objects is usually established on the basis of their redshift. One of the problems with this method (the most important one from our perspective) is that in order to give this distance in absolute units such as kilometers or parsecs, we first have to decide upon a cosmological model. Depending on the density of matter, the curvature of the Universe and the value of the cosmological constant, a given degree of redshift will correspond to a different number of parsecs.

This is why measuring "absolute" distances is so important in cosmology: by comparing distances calculated based on redshift and measured using an independent method, we can verify whether a proposed model of the Universe is accurate. This was the concept used during the first measurements of dark energy, in which distant supernovae were used as "standard candles." If we assume that we know their absolute brightness (which is reasonable for certain types of supernovae), we can mark their distance regardless of the redshift, and thus verify the cosmological model.

Quasars instead of supernovae

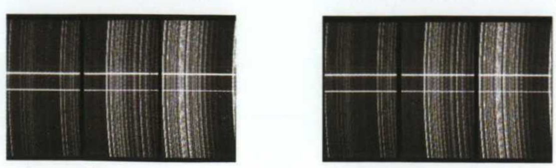
The problem is that it is extremely difficult to find objects that are not supernovae that might be appropriate for such measurements. They must meet several criteria: they must occur with a high frequency, they must be visible from great distances, and we must be able to estimate their absolute luminosity. Can we use quasars? Well, they do meet the first two conditions, although marking their absolute luminosity is fraught with difficulties. However, this latter task should be possible.

The solution comprises two stages. First, we must measure the observed luminosity of a quasar and its redshift; the second, much more complex stage involves identifying the absolute luminosity of the object. Our method is based on the theory of formation of the Broad Line Region near the black hole in the center of an active galaxy. The region forms a ring above a disc containing gas clouds. From the inside, its existence is limited by the temperature of the disk being low. The dusty plasma is subject to radiation pressure; as a result, clouds of matter are ejected into the ring at high velocities from the fast-spinning disc. The cosmological redshift is compounded by the Doppler effect - emission lines of moving gas are shifted slightly differently for each cloud. We cannot measure them separately for each cloud; however, spectral lines of the quasar as a whole, comprising lines of many individual clouds, become extremely wide.

These wide lines, emitted by atoms of fast-moving gas, can be observed using terrestrial telescopes. The radius of the disc at which temperature favors sublimation is linked to the quasar's absolute luminosity. As such, by measuring the distance between the broad line region and the black hole we are able to determine the quasar's absolute luminosity. The problem comes down to establishing this distance. In order to achieve this, in turn, we measure the variation in the quasar's luminosity and its emission lines. The distance can be found by measuring the delay of the line versus the changing luminosity of the quasar.

Our measurements use quasars with redshift values approaching 1; this means that they are approximately 8 billion light years away. Had we been dealing with significantly less distant objects with spectra at a lower redshift, we could conduct measurements using Balmer lines (spectral line emissions of the hydrogen atom; Hβ). However, the spectrum of our quasars is shifted such that this line falls within the infrared, beyond the region that can be observed optically. This is why we have been focusing on the line of ionized magnesium (MgII), which in this instance shifts from the ultraviolet to the optical region of the spectrum.

Comparing the absolute and observed luminosity of a quasar allows us to mark



Spectrum of quasar HE 0413-4031: on the left, image prior to reduction; on the right, image following reduction. The effect of removing traces of cosmic rays is visible on the image prior to reduction as individual bright points

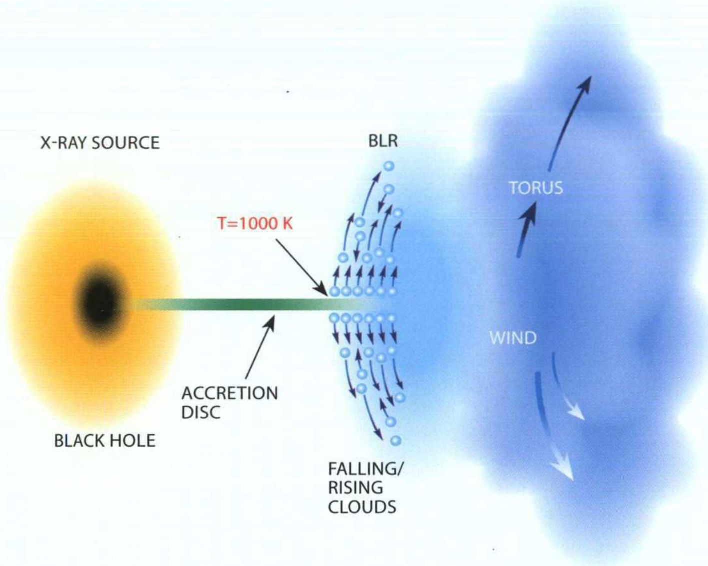
the distance modulus, used to calculate the distance to the quasar irrespective of its redshift. This is an alternative method to using supernova studies to obtain information about the rate of expansion of the Universe and the content of dark matter within it.

Years of observations

In order to measure the delay in luminosity of emission lines with respect to changing luminosity of a quasar we need to conduct observations over several years. We have been working with the 10-meter Southern African Large Telescope (SALT), the largest optical telescope in the southern hemisphere operating independently of other instruments. It consists of 91 hexagonal mirror segments with sides 1.2 meters long. SALT belongs to an international consortium, of which Poland is a member. Our financial contribution is 10%, entitling us to 10% of the telescope's operating time. However, this is not assigned automatically; in order to obtain observation time, we must submit a request indicating the objects we wish to observe, the required dates, and the results we hope to obtain. After the decision is granted, the requested observations are conducted by a team from SALT, so Polish astronomers do not actually operate the telescope at all. The images are sent to us in two formats: original data, and preliminarily reduced data; the data are ready for further analysis. Primary data are distorted due to processing by electronic systems; the preliminary reduction involves eliminating these distortions.

In order to convert the images obtained by the telescope into scientifically useful data, they need to be reduced further. The process involves "cleaning" the images of interference arising from the varying sensitivity of pixels on the CCD matrix used for registering them. It is also necessary to remove traces of cosmic rays - high-energy particles that enter the Earth's atmosphere.

Images processed this way can be used to obtain a quasar's spectrum. Next, by comparing the lengths of emission lines against the lengths of lines of calibration lamps, we can mark the redshift of the lines in the images. If we have also been able to measure the observed luminosity of the quasar, the first stage is completed.



Krzysztof Hryniewicz/Paweł Adamów

Diagram showing the formation of broad emission lines in quasars

What will the future bring?

Having concluded the first round of observations, we are currently waiting to conduct the second round, which should enable us to determine the distance to the quasars we have been studying over the coming years.

However, while we remain committed to the project, we are also thinking ahead. In the future, we intend to use photometric observations obtained from the Large Synoptic Survey Telescope (LSST), which should start collecting data in the coming decade. The LSST is projected to be an 8.4 meter optical telescope, installed in Chile. It will be used to observe up to 100 million quasars whose redshifts will reach $z \sim 2.5$ and above.

For the time being, however, we are focusing on data obtained from observations conducted by SALT. Data continue to arrive, and with it hope of findings which should allow us to reveal some of the secrets surrounding mysterious dark matter. ■

Further reading:

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