AstroTalk: Behind the news headlines of November 2015

Richard de Grijs (何锐思)
(Kavli Institute for Astronomy and Astrophysics, Peking University)

New developments offer a boost to extragalactic distance determination

While I browsed through my compilation of recent developments in astronomy this past month, two stories piqued my interest in particular. Those of you who know me personally will also know that I have a keen interest in measures that allow us to determine the size and shape of the Universe, as well as the physical processes underlying them. I wrote a high-level textbook on distance determination in astronomy a few years ago, so when I came across some exciting new insights in this context, I decided to share these with you in this month's article.

Less than 20 years ago, we learned that the expansion rate of the Universe is accelerating, propelled by a mysterious pressure called "dark energy." That discovery was made possible by careful observations of Type Ia supernovae; extraordinarily bright and remarkably similar in brightness, they serve as "standard candles"—astronomical objects whose intrinsic luminosity can be calculated from another of their observable properties—essential for probing the Universe's history.

In fact, Type Ia supernovae are far from standard. Intervening dust can make them appear redder (by absorbing and scattering mostly light emitted at blue wavelengths) and dim them, and the physics of their thermonuclear explosions differs—a single white dwarf (an Earth-sized star as massive as our Sun) may explode after borrowing mass from a companion star, or two orbiting white dwarfs may collide and explode. These "normal" Type Ia supernovae can vary in brightness by as much as 40%. This range in brightnesses can be reduced by well-proven methods, but cosmology continues to be done with catalogues of supernovae that may differ in brightness by as much as 15%.

Now members of the international Nearby Supernova Factory, based at the U.S. Department of Energy's Lawrence Berkeley National Laboratory in California, have dramatically reduced the scatter in supernova brightnesses. Using almost 50 nearby supernovae, they identified supernova twins—pairs whose spectra are closely matched—which reduced their brightness dispersion to a mere 8%. The distance to these supernovae can be measured about twice as accurately as before.

> "*Instead of concentrating on what's causing the differences among supernovae, the supernova-twins approach is to look at the spectra and seek the best matches, so as to compare like with like*," says Greg Aldering, the Berkeley Lab cosmologist who led the team. "*The assumption we tested is that if two supernovae look the same, they probably are the same*."

Hannah Fakhouri initiated the supernova-twin study for her doctoral thesis. She says that the theoretical advantages of a twins match-up had long been discussed at Berkeley Lab; for the researchers, one of the main goals was gathering a data set of sufficient quality to test their hypothesis. Fakhouri's timing was good; she was able to take advantage of precise spectrophotometry—simultaneous measures of spectra and brightness—of numerous nearby Type Ia's, collected using the team's SuperNova Integral Field Spectrograph (SNIFS) on the University of Hawaii's 2.2-meter (diameter) telescope on Mauna Kea, Hawaii.

"Nearby" is a relative term in this context, however; some of her supernovae are more than a billion light-years away. But all yield more comprehensive and detailed measurements than the really distant supernovae that are also needed for cosmology. Despite the surprising results, Fakhouri describes the initial research as "a long slog," requiring hard work and attention to detail. One challenge was making fair comparisons of time series, in which spectra are taken at frequent intervals as a supernova reaches maximum luminosity, then slowly fades; different colours (wavelengths) brighten and fade at different rates. Cleaning up the spectra and ranking the supernovae for "twinness" was done completely "blind"—the researchers had no information about the supernovae except their spectra.

> "*The unblinding process was suspenseful*," Fakhouri says. "*We might have found that twinning was completely useless*." The result was a relief: the closer the twins' spectra, the closer their brightnesses.

The result strongly suggests that the long-accepted 15% uncertainty in Type Ia brightness is not merely statistical; it masks real, but unknown differences in the nature of the supernovae themselves. The twin method's dramatic reduction of brightness dispersion suggests that hidden unknowns about the physical explosion processes of twins have been severely reduced as well, a strong step toward using such supernovae as true standard candles.

The conventional approach has so far been to fit a curve through a series of data points of brightness versus time: a light curve. Dimmer Type Ia's have narrower light curves and are redder; this fact is used to "standardize" supernovae, that is, to adjust their brightnesses to a common system. The twin method beats the light-curve method without even trying. Plus, the team found that this can be done with just one spectrum—an entire light curve is not needed.

> Fakhouri says, "*Supernovae offer unique advantages for cosmology, but we need multiple techniques*," including statistical methods charting how dark energy has shaped the structure of the Universe. "*The great thing about Nature is that it provides different kinds of probes that can be decoupled from one another.*"
>
> Supernovae are a singular asset, notes Aldering: "*Supernovae found dark energy, and they still provide the strongest constraints on dark energy properties.*"

When based on a reference sample of well-measured supernovae large enough for every new supernova to find its perfect twin, twin-supernova technology could lead to precise measures of dark energy's effect on the Universe over the past 10 billion years. Each point in space and time so labeled will be an accurate milestone on the journey that led to the universe we live in today.

At the time when I came across these new insights into the use of Type Ia supernovae as potential "standardizeable" candles, I was just about to lecture about them in my graduate course on the distance scale at Peking University. This thus allowed me to show my students the immediate impact of what they were learning – and this also shows the value of research-led teaching! Around the same time, I came across another interesting new development with a direct bearing on firming up the extragalactic distance scale, and indeed one that will soon be the topic of one of my lectures.

This latter approach relates to a newly developed technique to use quasars—powerful sources driven by supermassive black holes at the centre of galaxies—to study the Universe's history and composition. To demonstrate the new method, based on a relation between a quasar's luminosity at X-ray and ultraviolet wavelengths, a team of Italian scientists made extensive use of data from the European Space Agency's *XMM–Newton* X-ray observatory. The *X-ray Multi-Mirror Mission* was launched in December 1999. The largest scientific satellite to have been built in Europe, it is also one of the most sensitive X-ray observatories ever flown. More than 170 wafer-thin, cylindrical mirrors direct incoming radiation into three high-throughput X-ray telescopes.

At the core of most massive galaxies in the Universe is a supermassive black hole—a concentration of matter so dense that it attracts anything nearby. Such black holes have masses from millions to billions of times that of the Sun and are generally idle, only capturing the occasional star or gas cloud that ventures too close to the galaxy's centre. A small fraction of them are, however, extremely active, devouring matter at a very high rate, causing the surrounding material to shine brightly across the electromagnetic spectrum, from radio waves to X-rays and gamma rays. In some cases, emission from matter in the vicinity of the black hole is so intense that the core of the galaxy outshines the stars. These objects appear as point sources in the sky, like stars, and are known as quasars, "quasi-stellar objects."

Quasars allow scientists to study gravity in the very strong field of the supermassive black holes. In addition, comparing the properties of quasars with those of other galaxies that host black holes can reveal interesting aspects about the evolution of galaxies over cosmic history. But one other aspect piqued the interest of two scientists from the Arcetri Astrophysical Observatory in Firenze, Italy: they realized that quasars can be used as probes of the expansion history of the Universe.

> "*The history of cosmic expansion holds a wealth of information about the Universe, including its age and the relative abundance of its components, and to pin it down we need to observe astronomical sources at a wide range of distances from us*," explains Guido Risaliti, one of the scientists who led the study. "*But determining distances in the Universe is not at all trivial and*

> *can be best performed only with a few classes of sources. In this study, we show how it can be done with quasars*."

The main obstacle to measuring distances to astronomical objects lies in our ignorance of their true brightness, which makes it virtually impossible to assess whether a source is intrinsically bright or whether it just appears so because it is very close to us. For relatively nearby stars in our own Milky Way galaxy, astronomers can get a very precise handle on distances using parallaxes, the tiny apparent shift of a star's position in the sky when viewed from different locations in the Earth's orbit. However, the greater the distance the smaller the parallax, which restricts the reach of this method to our local cosmic neighbourhood. Farther away, astronomers have to rely on standard or standardizeable candles, like the Type Ia supernovae used by the Berkeley lab team we discussed at the beginning of this article.

> "*Type Ia supernovae are a powerful tool for cosmology, but they cannot be observed at very large distances from us, so they are mostly used to probe the relatively recent Universe*," says Elisabeta Lusso.

Few Type Ia supernovae have been observed in earlier cosmic phases, when our almost 14 billion-year-old Universe was younger than 5 billion years.

> "*This is why we suggest to complement Type Ia supernovae with quasars, which can be observed in large quantities out to much greater distances, probing cosmic history up to the epoch when the Universe was only one billion years of age*," she adds.

To determine how far quasars are from us, Risaliti and Lusso used an interesting property of these sources: a link between the amount of light they emit at ultraviolet and X-ray wavelengths, which has been known since the late 1970s. Both types of emission derive from the black hole's activity, although they are caused by different processes. As the accreted material flows towards the black hole through an "accretion disk," it is heated by friction and shines brightly at visible and ultraviolet wavelengths. Then, part of the light emitted by the disk interacts with nearby electrons, receiving an extra energy boost and turning into X-rays.

The key point underlying the application of this relation to cosmology is that the link between the luminosities at the two different wavelengths is not linear. This means that the ratio between a quasar's measured X-ray and ultraviolet emission is not fixed, but varies depending on the ultraviolet luminosity itself. So by measuring a quasar's X-ray and ultraviolet emission the scientists can estimate the luminosity at ultraviolet wavelengths; in turn, this can be used to gauge the quasar's distance.

While the physical mechanism underlying this relation is unclear, Risaliti and Lusso could still use it to treat quasars as standard candles and employ them as distance indicators for cosmological studies. To do so, they compiled a sample of 1138 quasars with both ultraviolet and X-ray measurements.

"*First, we verified that the relation between ultraviolet and X-ray luminosity holds for quasars observed at any cosmic epoch: this is an essential condition if we want to treat them as cosmological probes,*" explains Risaliti.

Then, the scientists determined distances to the quasars in their sample and used these to study how the expansion of the Universe changed in the span of cosmic history covered by these sources.

"*Quasars are a less precise tool to measure distances than Type Ia supernovae, but they yield complementary information about the distant Universe that is inaccessible to supernova observations*," says Lusso.

The power of this new approach is best unleashed through the combination of quasars and Type Ia supernovae, spanning over 13 billion years of cosmic evolution to investigate how the Universe changed across most of its history. In fact, combining data from current surveys of both types of sources yields constraints on the relative abundance of dark matter and dark energy that are tighter and more precise than those obtained from supernovae alone. The method developed by Risaliti and Lusso appears especially promising in light of future surveys, since a larger quasar sample means smaller errors on the cosmological parameters.

It appears, therefore, that we are now finally getting close to being able to measure high-accuracy distances to objects that existed when the Universe was less than its current age! Very exciting developments indeed…

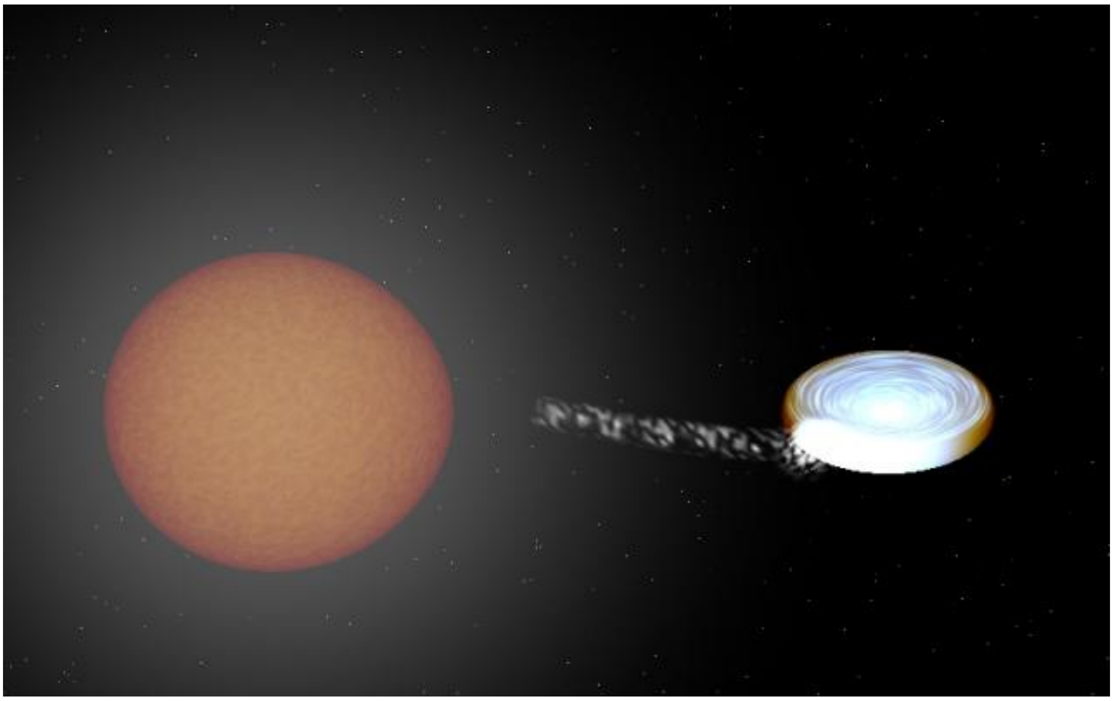

Figure 1: Configuration of progenitor binary system in the case of a red-giant star (left) and a white dwarf (right, but too small to be seen). Gas is flowing from the red giant. The white dwarf accretes a part of the gas through the accretion disk (blue white disk

around the white dwarf). Once the white dwarf has attained a certain minimum mass (approximately 1.4 times the mass of our Sun), it will explode as a Type Ia supernova.

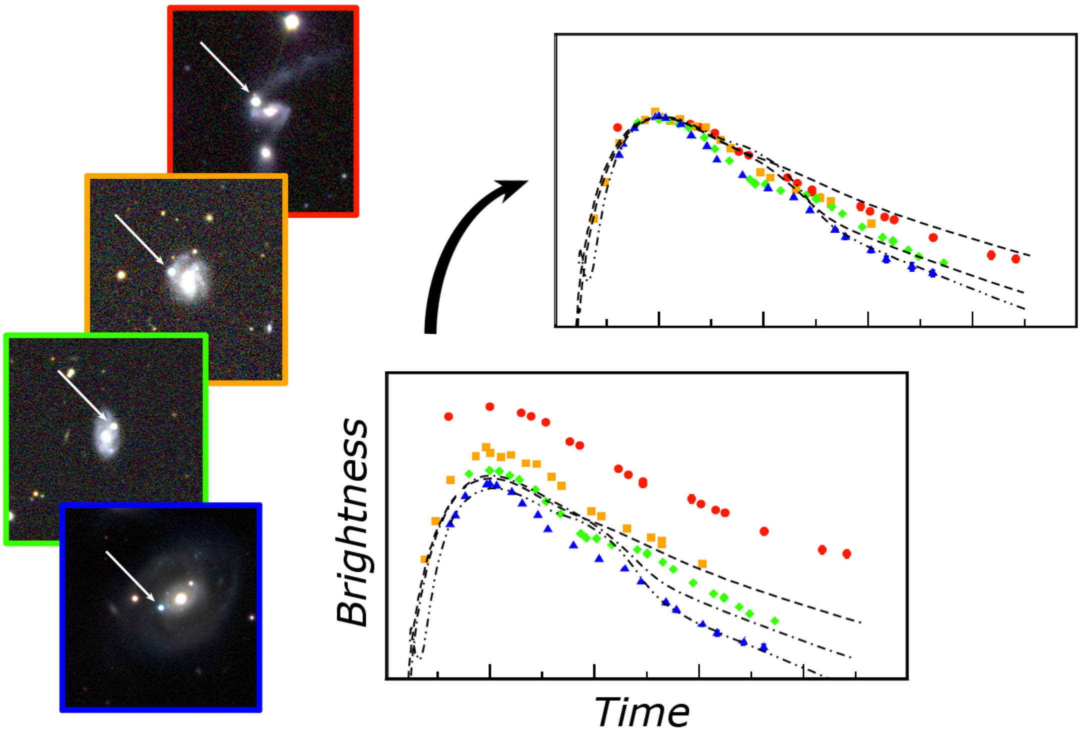

Figure 2: Type Ia supernovae result from the explosions of white dwarf stars. These supernovae vary widely in peak brightness, how long they stay bright, and how they fade away, as the bottom graph shows. Theoretical models (dashed black lines) seek to account for the differences, for example why faint supernovae fade quickly and bright supernovae fade slowly. A new analysis by the Nearby Supernova Factory indicates that when peak brightnesses are accounted for, as shown in the top graph, the late-time behaviour of faint and bright supernovae provides solid evidence that the white dwarfs that caused the explosions had different masses, even though the resulting blasts are all "standard candles."

Figure 3: Supernova 2011fe was discovered by the Palomar Transient Observatory just hours after it exploded in the Big Dipper. Studies by the Nearby Supernova Factory of its colours and spectrum as they evolved over time have produced a benchmark atlas of data by which to measure all future Type Ia supernovae. *(Credit: B. J. Fulton, Las Cumbres Observatory Global Telescope Network)*

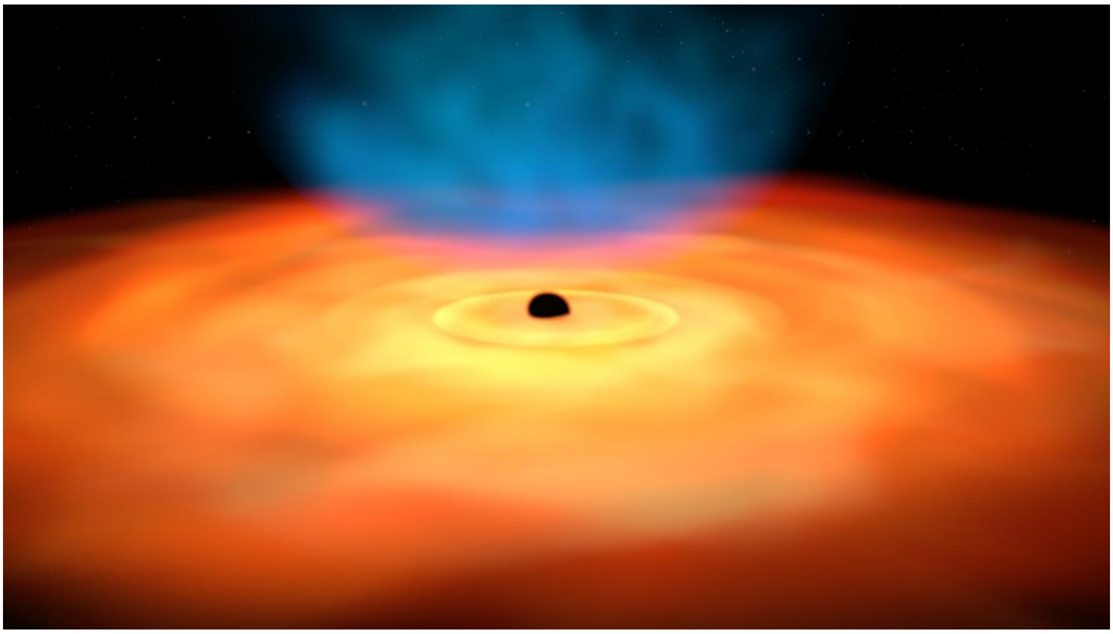

Figure 4: This artistic view shows an accreting supermassive black hole at the core of a galaxy. Actively accreting supermassive black holes devour matter at very high rate, causing the surrounding material to shine brightly across the electromagnetic spectrum, from radio waves to X-rays and gamma rays. In some cases, emission from matter in the vicinity of the black hole is so intense that the core of the galaxy outshines the total

luminosity of its stars: as a result, these objects appear as point sources in the sky, like stars, and are known as quasars. As the accreted material flows towards the black hole through an “accretion disk,” it is heated by friction and shines brightly at visible and ultraviolet wavelengths, shown here in red and yellow, respectively. Part of the light emitted by the disk interacts with highly energetic electrons in a corona near the disk (shown in blue), receiving an extra energy boost and turning into X-rays. *(Credit: ESA, C. Carreau)*

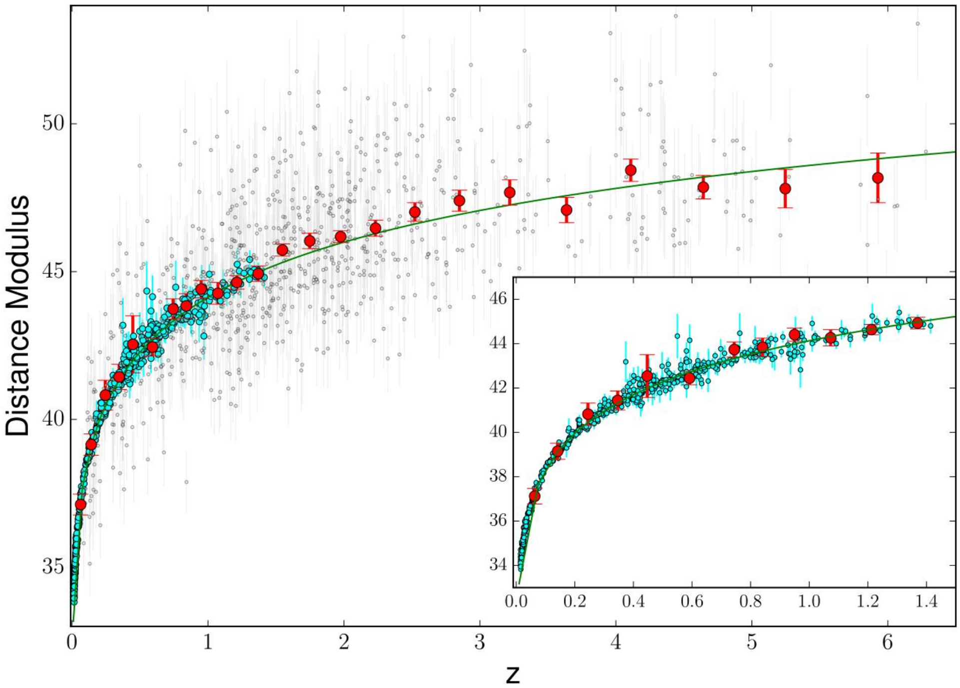

Figure 5: This graph shows how measurements of distant astronomical objects can be used to study the expansion history of the universe. *(Credit: Risaliti & Lusso, Astrophysical Journal, Volume 815, 2015)*