AstroTalk: Behind the news headlines of August–October 2020

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Four-hundred-year-old stellar explosions reveal their secrets

Astronomers have used NASA's Chandra X-ray Observatory (CXO) to record material blasting away from the site of an exploded star at speeds faster than 20 million kilometres per hour—about 25,000 times faster than the speed of sound in air on Earth.

Kepler's supernova remnant is the debris from a detonated star located in the constellation of Ophiuchus, about 16,000 light-years away from Earth in our Milky Way galaxy. In 1604 early astronomers, including Johannes Kepler, saw the supernova explosion that destroyed the star.

We now know that Kepler's supernova remnant is the aftermath of a so-called Type Ia supernova, where a small dense star, known as a white dwarf, gains enough mass to exceed a critical limit—the 'Chandrasekhar' mass limit, equivalent to 1.44 times the mass of our Sun—after interacting with a companion star and undergoes a thermonuclear explosion that shatters the white dwarf and launches its remains outwards.

The latest study, published in August 2020, tracked the speed of 15 small 'knots' of debris in Kepler's supernova remnant, all glowing brightly in X-rays. The fastest knot was measured to have a speed of 37 million kilometres per hour, the highest speed ever detected of supernova remnant debris in X-rays. The average speed of the knots is about 16 million kilometres per hour, and the blast wave is expanding at about 24 million kilometres per hour. These results independently confirm the 2017 discovery of knots travelling at these high speeds in Kepler's supernova remnant.

Researchers estimated the speeds of the knots by analysing X-ray spectra from the CXO, which give the intensity of X-rays at different wavelengths. The observations were already obtained in 2016. By comparing the wavelengths of features in the X-ray spectrum with laboratory values and using the Doppler effect, they measured the speed of each knot along the line of sight from Earth to the remnant. They also used CXO images obtained earlier, in 2000, 2004, 2006 and 2014, to detect changes in position of the knots and measure their speeds perpendicular to our sightline. These two measurements combined to give an estimate of each knot's true speed in three-dimensional space.

The earlier, 2017 work applied the same general technique as the new, 2020 study, but used X-ray spectra from a different CXO instrument. The new study resulted in more precise determinations of the knot's speeds along the line of sight and, therefore, the total speeds in all directions.

The high speeds in Kepler are similar to those scientists have seen in optical (visual-light) observations of supernova explosions in other galaxies only days or weeks after the explosion, well before a supernova remnant forms decades later. This comparison implies that some knots in Kepler have hardly been slowed down by collisions with material surrounding the remnant in the approximately 400 years since the explosion.

Based on the CXO spectra, eight of the 15 knots are definitely moving away from Earth, but only two are confirmed to be moving towards it. (The other five do not show a clear direction of motion along our line of sight.) This asymmetry in the motion of the knots implies that the debris may not be symmetric along our line of sight, but more knots need to be studied to confirm this result.

The four knots with the highest total speeds are all located along a horizontal band of bright X-ray emission. These four knots are all moving in a similar direction and have similar amounts of elements such as silicon, suggesting that the matter in all of these knots originated from the same layer of the exploded white dwarf.

The explanation for the high-speed material is unclear. Some scientists have suggested that Kepler's supernova remnant is from an unusually powerful Type Ia explosion, which might explain the fast-moving material. It is also possible that the immediate environment around the remnant is itself clumpy, which could allow some of the debris to tunnel through regions of low density and avoid being slowed down very much.

The 2017 team also used their data to refine previous estimates of the location of the supernova explosion. This allowed them to search for a companion to the white dwarf that may have been left behind after the supernova, and learn more about what triggered the explosion. They found a lack of bright stars near the centre of the remnant. This implied that a star like the Sun did not donate material to the white dwarf until it reached critical mass. A merger between two white dwarfs is favoured instead.

In these systems, when at least one of the stars (with the highest mass) reaches the end of its life and becomes a white dwarf, the other can begin to transfer matter up to the Chandrasekhar limit. This process leads to the central ignition of carbon in the white dwarf, producing an explosion that can multiply its original brightness 100,000 times.

Kepler's supernova is known to have arisen from the explosion of a white dwarf in a binary system. Therefore, a different team of researchers searched for the possible surviving companion of the white dwarf, which allegedly transferred mass up to the level of the explosion. The impact of this explosion would have increased the brightness and speed of the missing companion; it could even have modified its chemical composition. The team, therefore, searched for stars with some anomaly that would allow them to identify one of them as the companion of the white dwarf that exploded in 1604.

Pilar Ruiz Lapuente, researcher at University of Barcelona, Spain, says,

> "*We were looking for a peculiar star as a possible companion of the progenitor of the Kepler supernova, and we characterised all stars around the centre of the remnant, but we have not found any with the expected characteristics. So everything points to the explosion being caused by the merging mechanism of the white dwarf with another or with the core of the already evolved companion*."

To carry out this investigation, the researchers studied images taken with the *Hubble Space Telescope*.

> "*The goal was to determine the proper motions (the apparent motions in the sky as seen from Earth) of a group of 32 stars around the center of the supernova remnant that still exists today*," says Luigi Bedin, researcher at Padova Observatory in Italy.

They also used data obtained with the 8.2m (diameter) Very Large Telescope (VLT), at the European Southern Observatory in Chile to characterise stars, and determine their distance and their radial velocity with respect to the Sun.

> "*The stars of the Kepler supernova field are very weak stars, only accessible from the Southern Hemisphere with a large diameter telescope such as VLT telescopes*," says John Pritchard, a researcher at the European Southern Observatory.
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> "*There is an alternative mechanism to produce the explosion. It consists of the merging of two white dwarfs, or the white dwarf with the carbon and oxygen core of the companion star, in a late stage of its evolution, in both cases giving rise to a supernova*," explains Jonay González Hernández of the Astrophysical Institute of the Canary Islands (Spain). "*In the Kepler field, we do not see any star that shows anomalies. However, we found evidence that the explosion was caused by the merging of two white dwarfs or a white dwarf with the core of the companion star, possibly exceeding the Chandrasekhar limit*."

The Kepler supernova is one of five 'historical' thermonuclear supernovas. Among the other four, the most famous is Tycho Brahe's supernova. When the star that created this supernova remnant exploded in 1572, it was so bright that it was visible during the day. And although he wasn't the first or only person to observe this stellar spectacle, the Danish astronomer Tycho Brahe wrote a book about his extensive observations of the event, gaining the honour of it being named after him.

In modern times, astronomers have observed the debris field from this explosion—what is now known as Tycho's supernova remnant—using data from the CXO, the Karl G. Jansky Very Large Array (VLA), a radio telescope based in the USA, and many other telescopes. Today, they know that the Tycho remnant was created by the explosion of a white dwarf star, therefore also making it part of the Type Ia class of supernovas used to track the expansion of the universe.

Since much of the material being flung out from the shattered star has been heated by shock waves—similar to sonic booms from supersonic planes—passing through it, the remnant glows strongly in X-ray light. Astronomers have now used CXO observations from 2000 through 2015 to create the longest movie of the Tycho remnant's X-ray evolution over time, using five different images. This shows the expansion from the explosion is still continuing about 450 years later, as seen from Earth's vantage point roughly 10,000 light-years away.

By combining the X-ray data with some 30 years of observations in radio waves with the VLA, astronomers have also produced a movie, using three different images. Astronomers have used these X-ray and radio data to learn new things about this supernova and its remnant.

The researchers measured the speed of the blast wave at many different locations around the remnant. The large size of the remnant enables this motion to be measured with relatively high precision. Although the remnant is approximately circular, there are clear differences in the speed of the blast wave in different regions. This difference was also seen in earlier observations.

This range in speed of the blast wave's outward motion is caused by differences in the density of gas surrounding the supernova remnant. This causes an offset in position of the explosion site from the geometric centre, determined by locating the centre of the circular remnant. The astronomers found that the size of the offset is about 10% of the remnant's current radius. The team also found that the maximum speed of the blast wave is about 19 million kilometres per hour.

Offsets such as this between the explosion centre and the geometric centre could exist in other supernova remnants. Understanding the location of the explosion centre for Type Ia supernovas is important because it narrows the search region for a surviving companion star. Any surviving companion star would help identify the trigger mechanism for the supernova, showing that the white dwarf pulled material from the companion star until it reached the Chandrasekhar mass limit and exploded. The lack of a companion star would favour the other main trigger mechanism, where two white dwarfs merge causing the critical mass to be exceeded, leaving no star behind.

The significant offset from the centre of the explosion to the remnant's geometric centre is a relatively recent phenomenon. For the first few hundred years of the remnant, the explosion's shock was so powerful that the density of gas it was running into did not affect its motion. The density discrepancy has increased as the shock moved outwards, causing the offset in position between the explosion centre and the geometric centre to grow with time. So, if future X-ray astronomers, say 1,000 years from now, do the same observation, they should find a much larger offset.

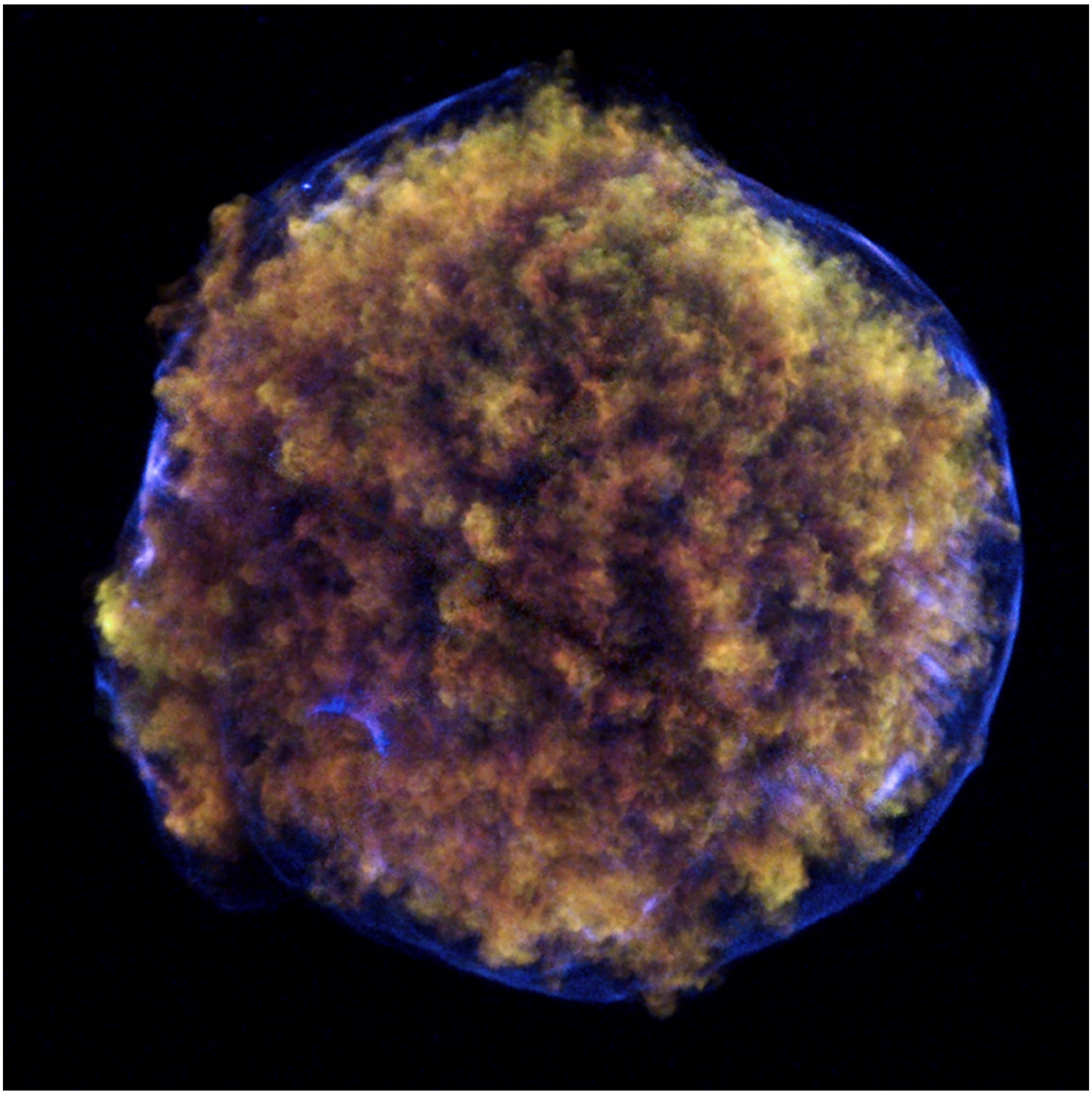

Figure 1: CXO image of the Tycho supernova remnant. In the lower left region of Tycho is a blue arc of X-ray emission. Several lines of evidence support the conclusion that this arc is due to a shock wave created when a white dwarf exploded and blew material off the surface of a nearby companion star. (*Credit: NASA/CXC/Chinese Academy of Sciences/F. Lu et al.*)

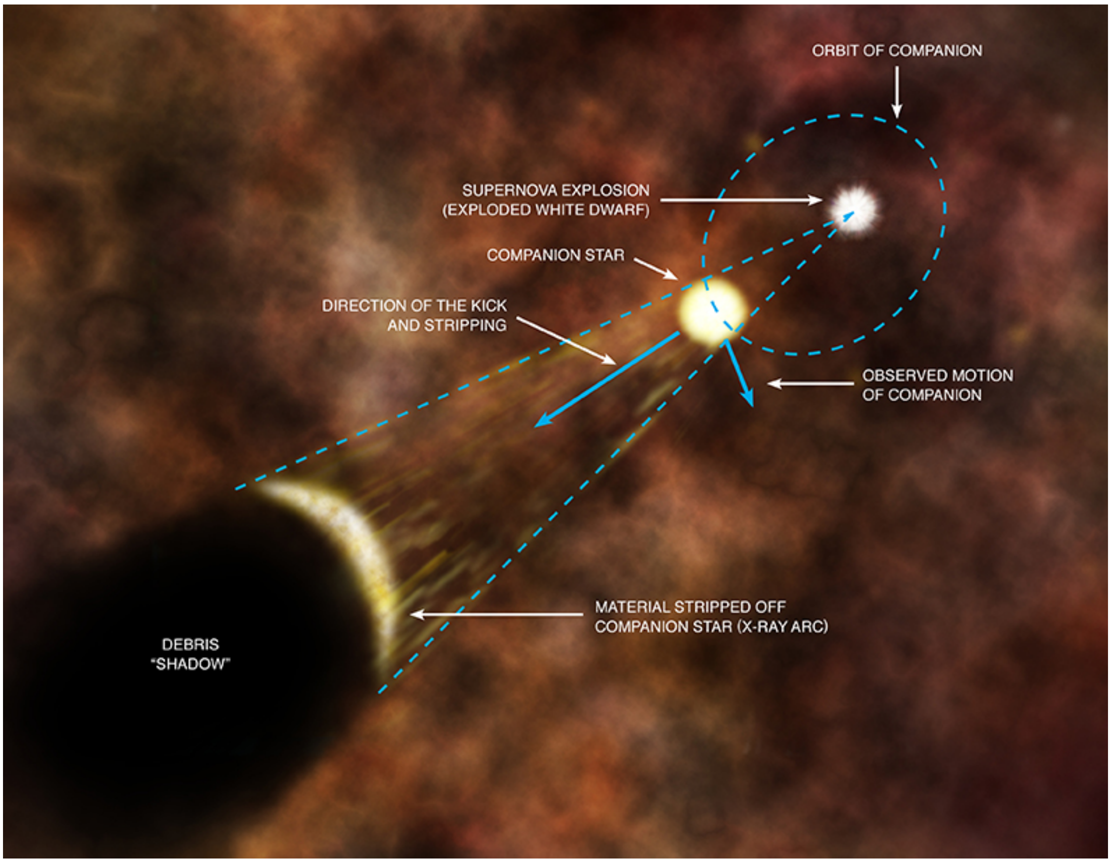

Figure 2: Artist's impression showing an explanation for the origin of the blue X-ray arc in Tycho's supernova remnant. It is believed that material was stripped off the companion star by the explosion of the white dwarf in the Type Ia supernova explosion, forming the shock wave seen in the arc. The arc has blocked debris from the explosion, creating a 'shadow' behind the arc. The force of the explosion imparted a kick to the companion star, and this combined with the orbital velocity of the companion before the explosion to give the 'observed' motion of the companion. Previously, studies with optical telescopes have revealed a star within the remnant that is moving much more quickly than its neighbours, showing that it could be the companion to the supernova. The size of the companion's orbit is not shown to scale here: the separation between it and the white dwarf before the explosion is estimated to have only been about a millionth of a light-year, while the full scale of the illustration is over 10 light-years. (*Credit: NASA/CXC/M. Weiss*)

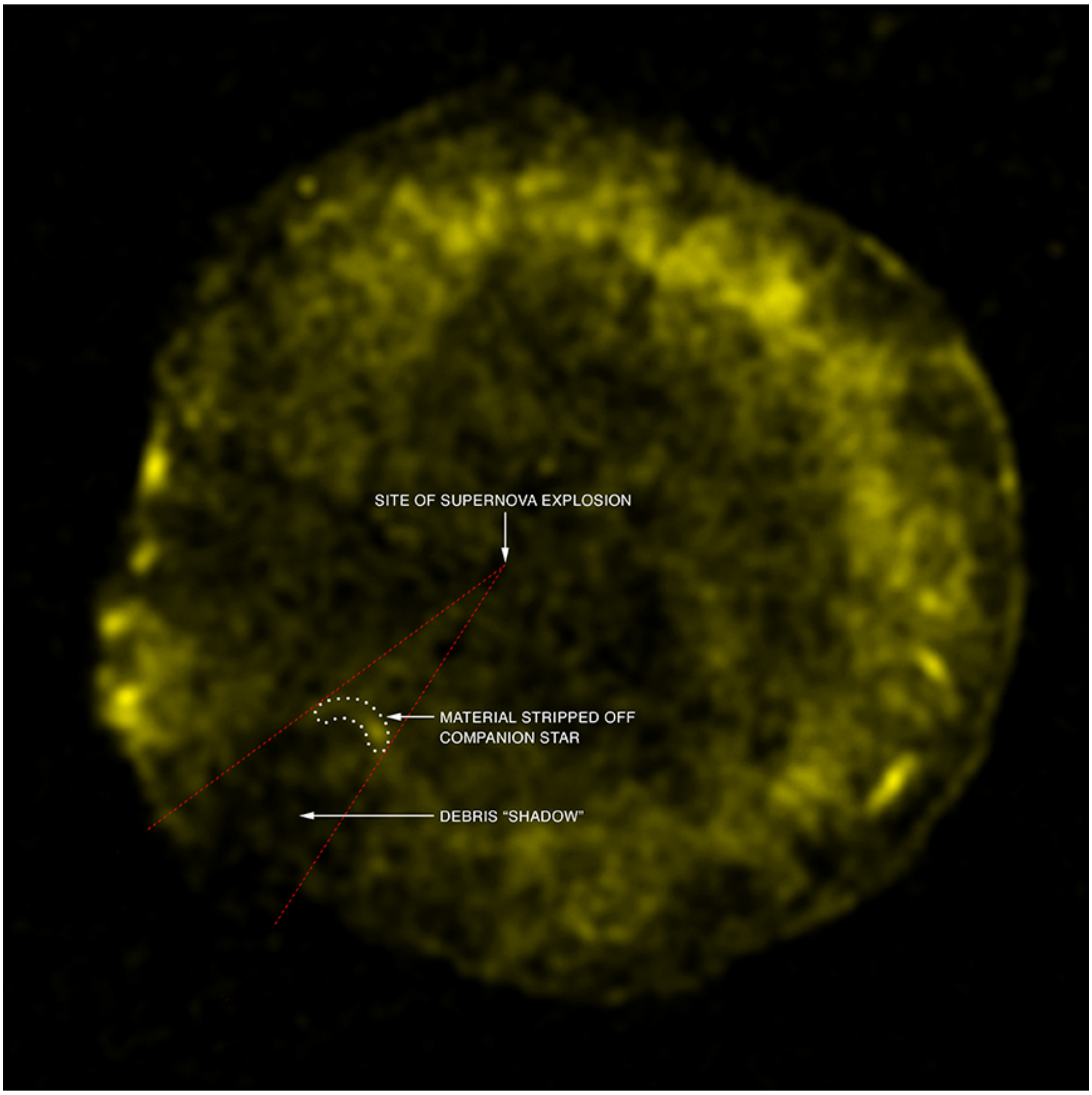

Figure 3: This image shows iron debris in Tycho's supernova remnant. The site of the supernova explosion is shown, as inferred from the motion of the possible companion to the exploded white dwarf. The position of material stripped off the companion star by the explosion, and forming an X-ray arc, is shown by the white dotted line. This structure is most easily seen in an image showing X-rays from the arc's shock wave. Finally, the arc has blocked debris from the explosion creating a 'shadow' in the debris between the red dotted lines, extending from the arc to the edge of the remnant. (*Credit: Credit: NASA/CXC/Chinese Academy of Sciences/F. Lu et al.*)

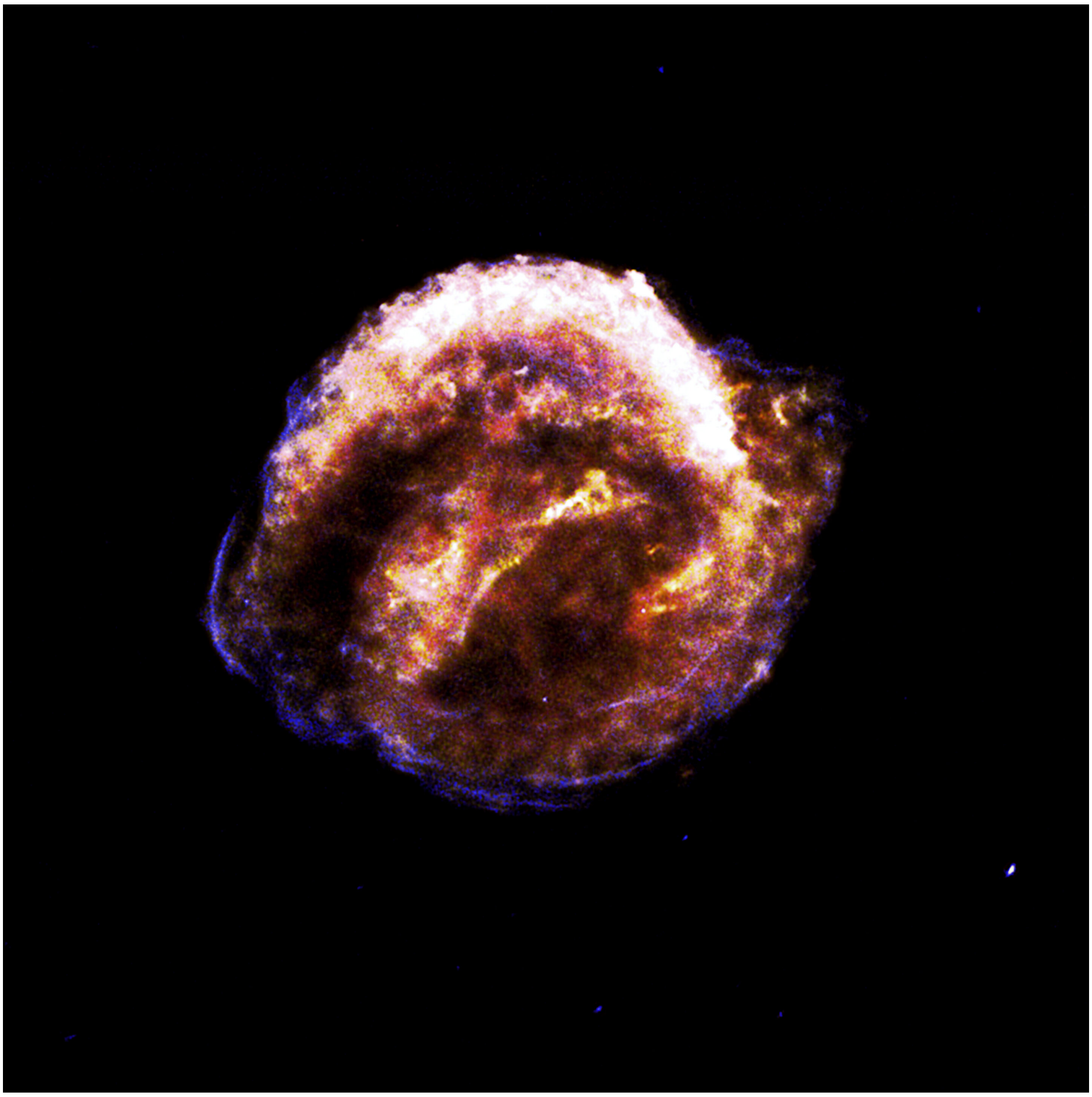

Figure 4: Kepler's supernova remnant. (*Credit: NASA/CXC/Univ of Texas at Arlington/M. Millard et al.*)

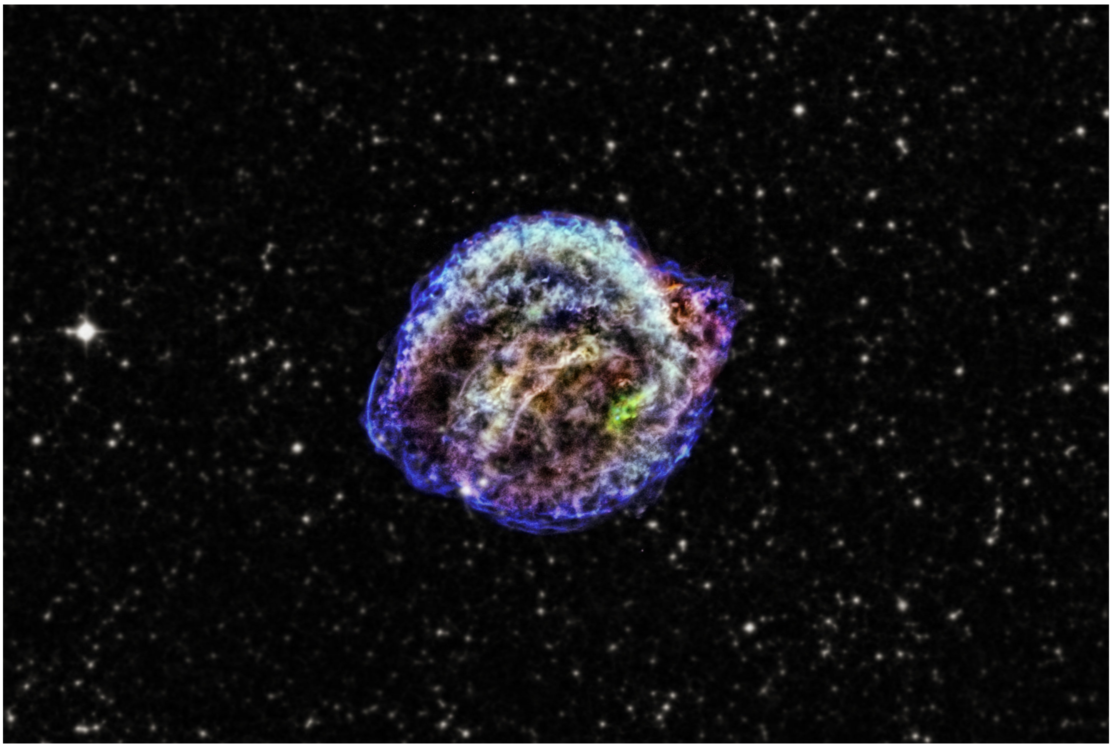

Figure 5: Kepler's supernova remnant. The red, green and blue colours show low, intermediate and high-energy X-rays observed with the CXO; the star field is from the Digitized Sky Survey. (*Credit: X-rays: NASA/CXC/NCSU/M. Burkey et al.; infrared: NASA/JPL-Caltech*)

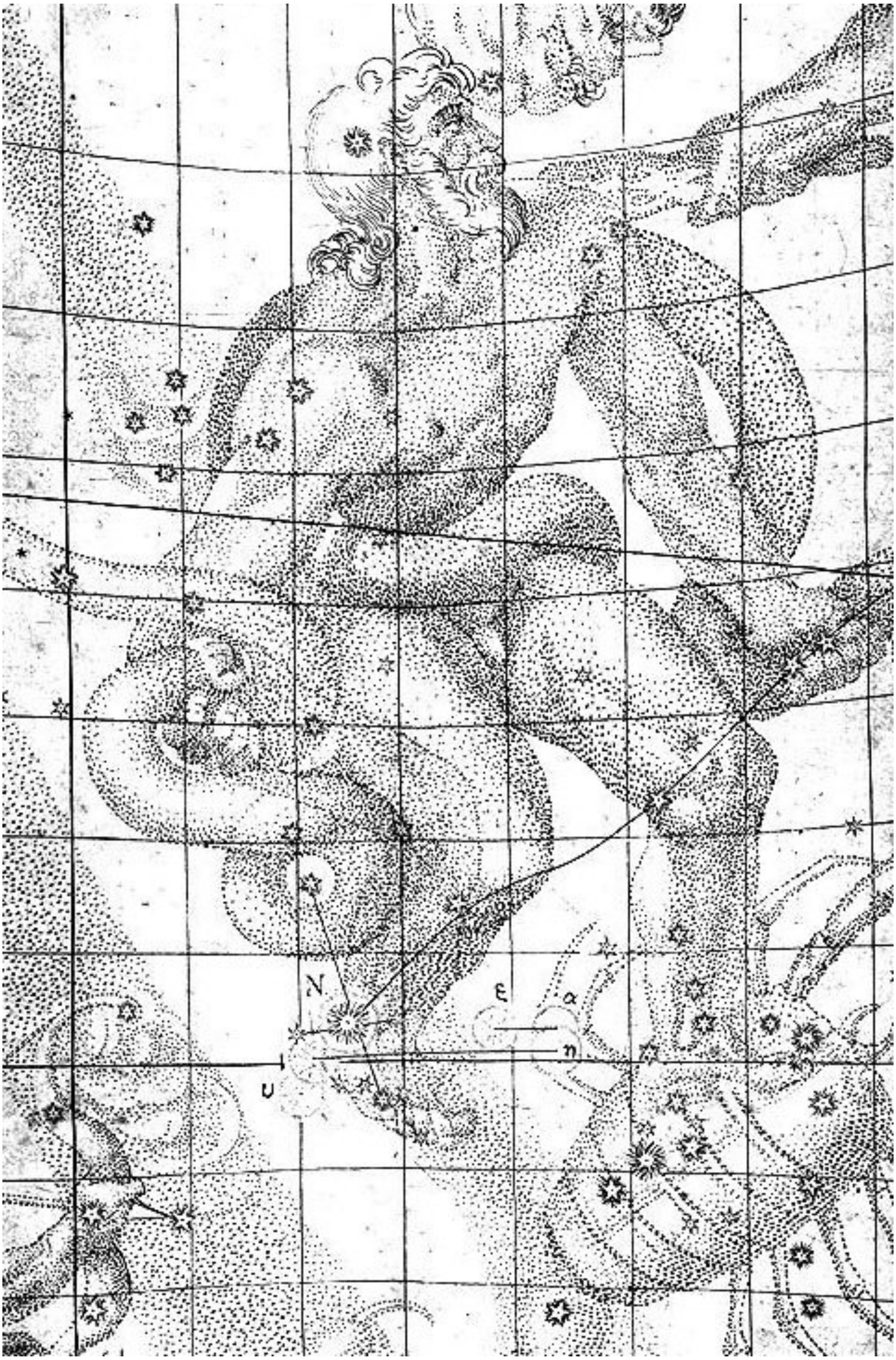

Figure 6: Johannes Kepler's original drawing from *De Stella Nova* (1606) depicting the location of the supernova, marked with an N.

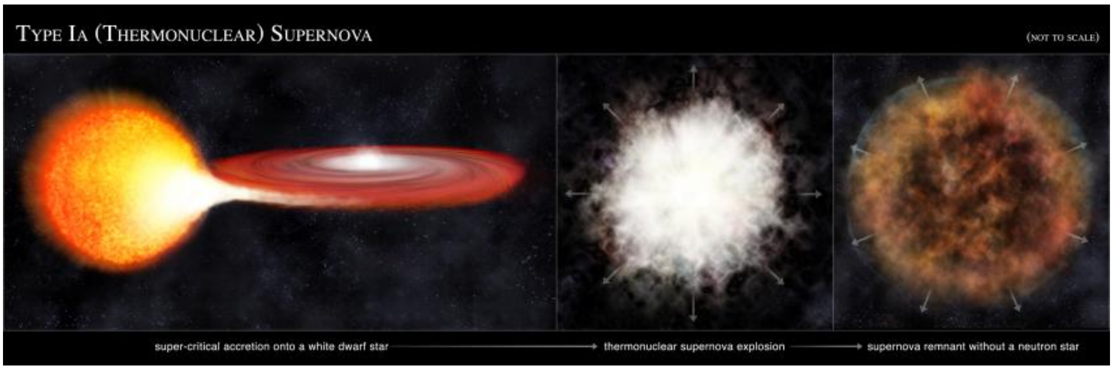

Figure 7: Type Ia supernovae. (*Credit: NASA/CXC/M. Weiss*)

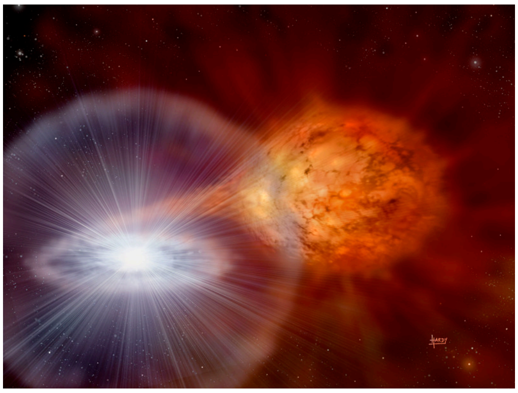

Figure 8: Artist's conception of a white dwarf slowly accreting matter from a companion star. (*Credit: David A. Hardy & STFC*)