JWST detects radiation from the veiled neutron star in the iconic supernova SN 1987A

Supernovae are the spectacular end result of the collapse of stars more massive than 8-10 times the mass of the sun. Besides being the main sources of chemical elements such as the carbon, oxygen, silicon, and iron that make life possible, they are also responsible for creating the most exotic objects in the universe, neutron stars and black holes.

Supernova 1987A (or SN 1987A for short) was the first naked eye supernova in four centuries and provided astronomers with an unprecedented close-up view of a supernova explosion with modern observatories. Despite being one of the most studied objects in the sky, SN 1987A is not without its mysteries, with the most enduring questions being 'what did the explosion leave behind?' The detection of neutrinos, unimaginably small sub-atomic particles produced in the supernova, indicated that a neutron star must have formed. However, whether or not the neutron star persisted or collapsed into a black hole has been one of the biggest unknowns regarding SN 1987A. Even after three and a half decades of intense monitoring with cutting-edge, world-class observatories, no conclusive evidence for the presence of a neutron star at the centre of SN 1987A has been found, until now.

In a study published on February 22nd 2024 in the journal Science, an international team of astronomers announced their discovery with the James Webb Space Telescope (JWST) of narrow emission lines from ionized argon and sulphur atoms located at the centre of a nebula around SN 1987A (Figs. 1-3). The authors of the study show that the emission line strengths observed by JWST must be triggered by radiation from the hot neutron star or from a pulsar wind nebula around the neutron star.

"Thanks to the superb spatial resolution and excellent instruments on JWST we have for the first time been able to probe the center of the supernova and what was created there." said Claes Fransson (Stockholm University, Sweden), the lead author of the study, "We now know that there is a compact source of ionizing radiation, most likely by a neutron star. We have been looking for this from the time of the explosion, but had to wait for JWST to be able to verify the predictions"

"It was so exciting looking at the JWST observations of SN 1987A for the first time," said Patrick Kavanagh (Maynooth University, Ireland), another author of the study, "as we checked the MIRI and NIRSpec data, the very bright emission from argon at the centre of SN 1987A jumped out. We knew immediately that this was something special that could finally answer the question on the nature of the compact object."

About Supernova (SN) 1987A:

SN 1987A is the most studied and best observed supernova of all and therefore of special importance for understanding these objects. Exploding on February 23 1987 in the Large Magellanic Cloud in the southern sky at a distance of 160,000 light years, it was the closest supernova since the last naked eye supernova observed by Johannes Kepler in 1604. For several months before it faded SN 1987A could be seen with the naked eye even at this distance. Even more importantly, it is the only supernova to have been detected via its neutrinos. This is highly significant since 99.9 % of the enormous energy emitted in this event was predicted to be lost as these extremely weakly interacting particles. The remaining 0.1 % appears in the expansion energy of the remnant and as light. Of the huge number (about 10^{58}) of neutrinos emitted, about 20 were detected by three different detectors around the Earth, from the collapse in the core of the star on February 23 at 7:35:35 UT. SN 1987A was also the first supernova where the star which exploded could be identified from images that had been taken before the explosion (Fig. 4).

Besides the neutrinos, the most interesting result of the collapse and explosion is the prediction that a black hole or neutron star was created. This constitutes only the central core of the collapsed star, with a mass of 1.5 times that of the Sun. The rest is expelled with a velocity up to 10% of the speed of light, forming the expanding remnant we observe directly today.

The 'long' 10 second duration of the neutrino burst indicated the formation of a neutron star, but despite several interesting indications from radio and X-ray observations, no conclusive evidence for a compact object had been found until now, and was the main remaining unsolved problem for SN 1987A. An important reason for this may be the large mass of dust particles that we know was formed during the years after explosion. This dust could block most of the visible light from the center and therefore hide the compact object at visible wavelengths.

This has now changed with the observation of SN 1987A at infrared wavelengths by a team using the James Webb Space Telescope. Their observations with two of its instruments, MIRI and NIRSpec, have revealed a point source in the very center of the extended SN remnant, emitting light from argon and sulphur ions (see Figs. 1 and 2). Thanks to the spatial resolution of the JWST and the ability of its instruments to accurately determine the velocity of the emitting source, we know it is very close to the center where the explosion originated in 1987. While most of the mass of the exploding star is now expanding at up to 10,000 km/second, and is distributed over a large volume, this source is still close to the explosion site, consistent with what is expected from the compact central remnant. The observed argon and sulphur emission comes from ionized atoms, requiring energetic photons from the compact object. This requires UV and X-ray radiation from a source in the center, as predicted already in 1992 as a unique signature of a newly created neutron star.

We do not see directly the compact object, but only the effects of its energetic radiation on the surroundings. In their study the authors discuss two main possibilities: either radiation from the hot, million degree newly born neutron star powers the observed emission lines or, alternatively, radiation from energetic particles accelerated in the strong magnetic field from the rapidly rotating neutron star (pulsar). This is the same mechanism as operates in the famous Crab nebula with its pulsar in the center, which is the remnant of the supernova observed by Chinese astronomers in 1054.

Models of these two scenarios result in similar predictions for the spectrum, which agree well with the observations, but are difficult to distinguish. Further observations with JWST and groundbased telescopes in visible light, as well as the Hubble Space Telescope, may be able to distinguish these models. However, in either case these new observations with JWST provide compelling evidence for a compact object, most likely a neutron star, at the center of SN 1987A.

In summary, these new observations by JWST, together with the previous observations of the progenitor and neutrinos, provide a complete picture of this unique object.

The team behind these results was comprised of 34 authors from 12 different countries in Europe and the USA:

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NIRSpec was built for the European Space Agency by Airbus Industries; the micro-shutter assembly and detector subsystems were provided by NASA.

MIRI development was an equal collaboration between European and US partners. The MIRI optical system was built by a consortium of European partners from Belgium, Denmark, France, Germany, Ireland, the Netherlands, Spain, Sweden, Switzerland, and the United Kingdom. EADS-Astrium (now Airbus Defence and Space) provided the project office and management. The full instrument test was conducted at Rutherford Appleton Laboratory. The Jet Propulsion Laboratory (JPL) provided the core instrument flight software, the detector system, including infrared detector arrays obtained from Raytheon Vision Systems, collaborated with Northrop Grumman Aerospace Systems on the cooler development and test, and managed the US effort.

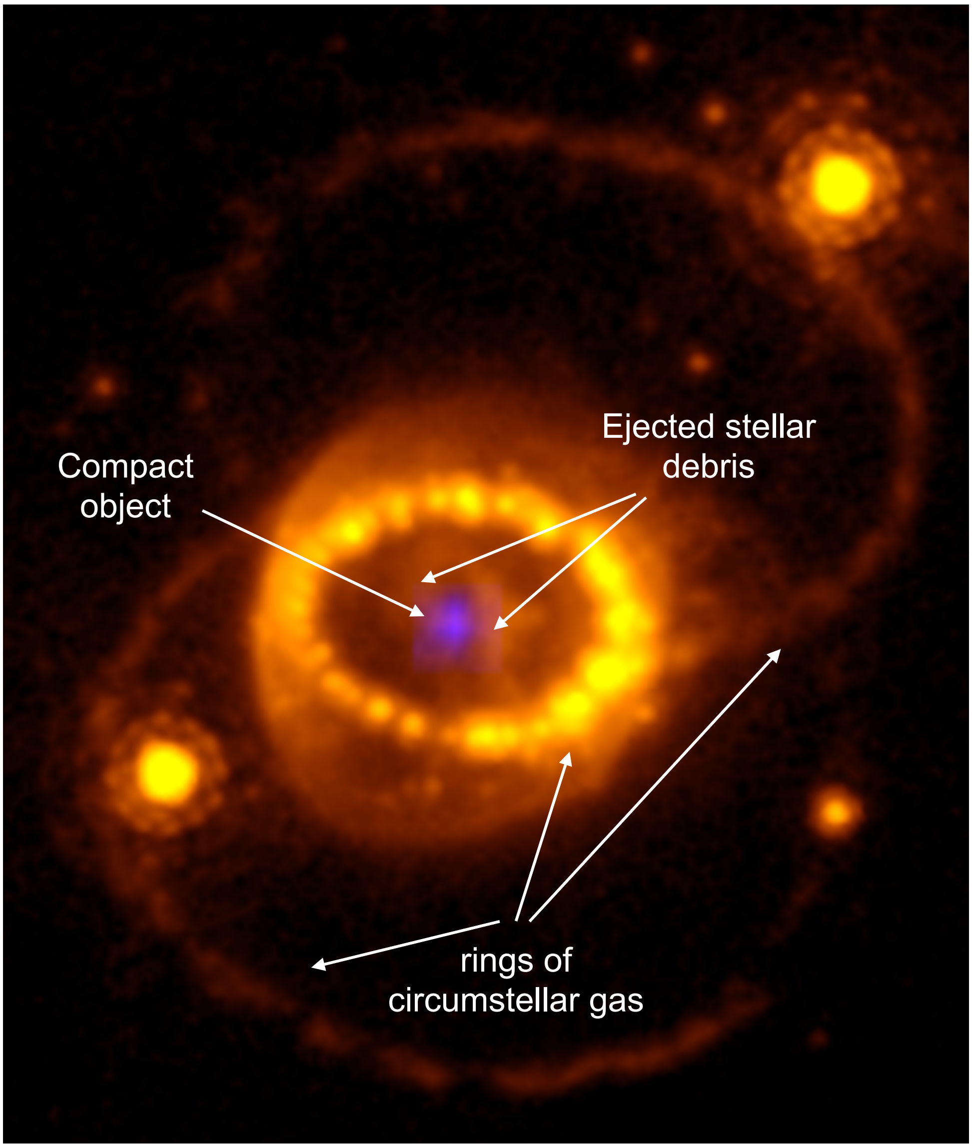


Fig. 1. Combination of a Hubble Space Telescope image of SN 1987A and the compact argon source in Fig. 2. The faint blue source in the center is the emission from the compact source detected with the JWST/NIRSpec instrument. Outside this is the stellar debris, containing most of the mass, expanding at thousands of km/second. The inner bright "string of pearls" is the gas from the outer layers of the star that was expelled about 20,000 years before the final explosion. The is the fast debris are now colliding with the ring, explaining the bright spots. Outside of the inner ring are two outer rings, presumably produced by the same process as formed the inner ring. The bright stars to the left and right of the inner ring are unrelated to the supernova.

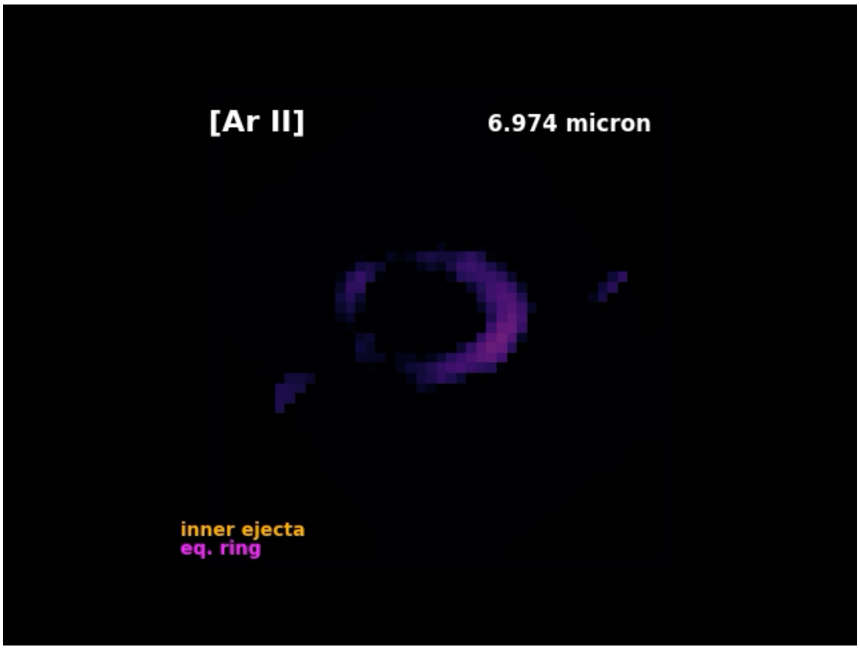


Fig. 2. Movie showing the appearance of the compact ionized argon source (at a wavelength of 7 micrometers) with the MIRI instrument. The inner ring in Fig. 1 also emits light at this wavelength. However, the shift in velocity (wavelength) between the ring and the compact source in the center, seen in the appearance of the central source before the brightening of the ring, shows that these are unrelated. (mpeg4 file enclosed separately)

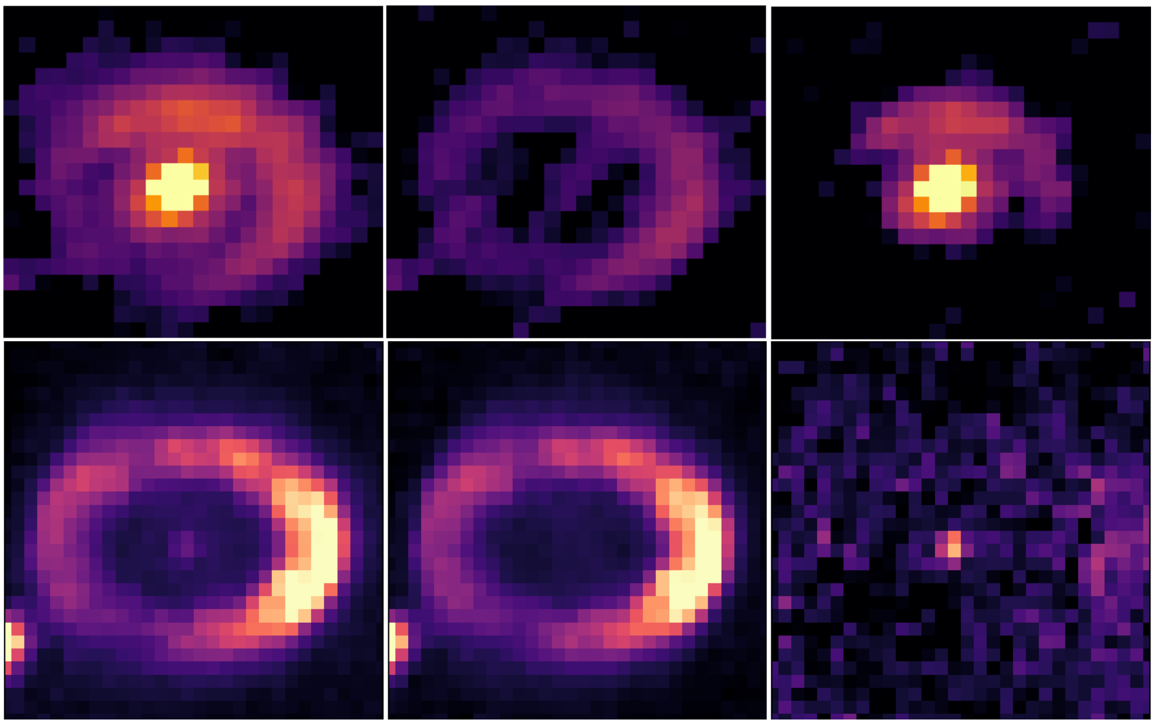
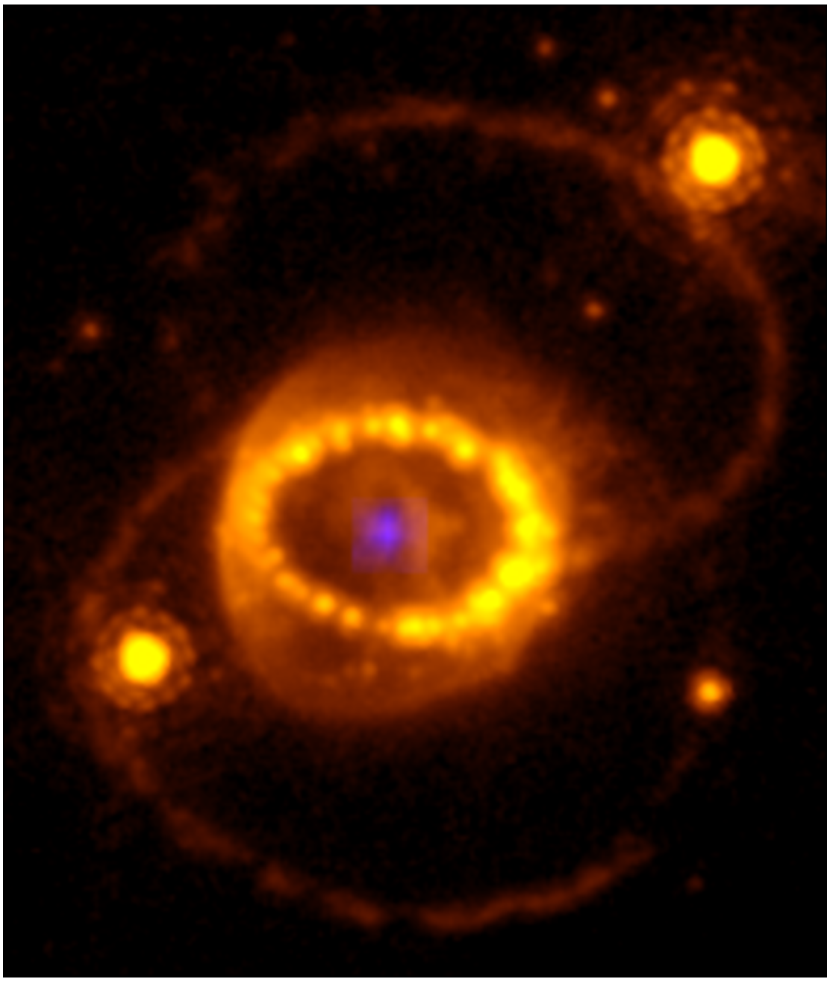


Fig. 3. Upper row. Left. The Ar II image at the velocity of the compact object. Middle: Same at the velocity of the ring. Right: The subtracted image, only showing the Ar II source from the compact object in the center. Lower row: Same for the Ar VI line

Fig. 4. The star that exploded before the explosion on Feb. 23 1987 (right) and after the explosion (left). This illustrates the enormous increase in the brightness of the supernova. Credit: David Malin AAT.



High resolution image of Fig. 1 without annotations