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THE COSMOS AS WE'VE NEVER SEEN IT BEFORE

The James Webb Space Telescope has the power to unravel some of the biggest mysteries of the universe. Here are some of the cosmic wonders it will look at first, says astronomer **María Arias**

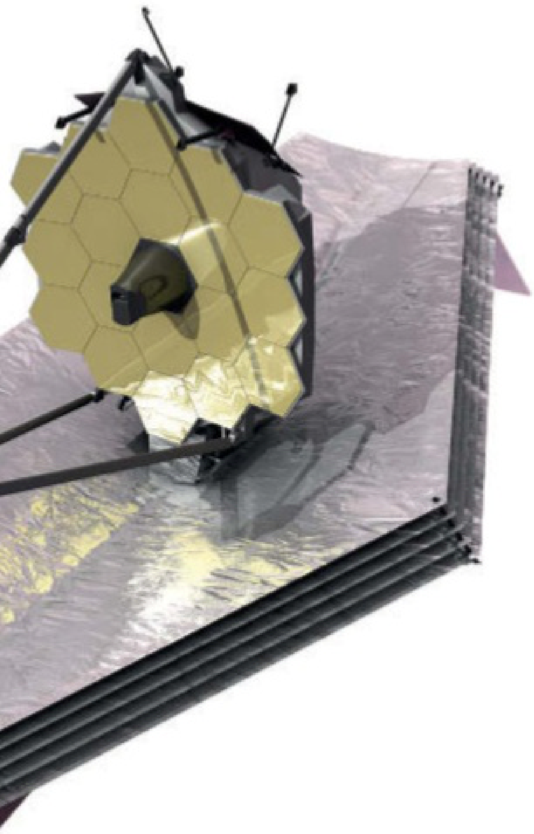
NASA/ESA/CSA/STSCIESA

ON 12 JULY, the James Webb Space Telescope (JWST) will release its first scientific images, raising the curtain on a new era in astronomy. After years of delays, a suspenseful launch and months of testing, the most powerful telescope ever made is finally ready to gather fresh clues relating to questions we could only dream of answering with its predecessors.

The JWST will allow us to peer further into the universe's distant past than ever before thanks to its special combination of capabilities. As an infrared observatory with a massive mirror floating beyond the orbit of the moon, it can collect light from the faintest, most distant stars and galaxies – light that has been stretched into infrared wavelengths after travelling through expanding space for billions of years. It will see these objects in exquisite detail due to its unrivalled angular resolution. Its infrared spectrograph should also allow us to characterise molecules lurking in the atmospheres of potentially habitable exoplanets.

The data we receive from the JWST will help us to unravel some of the largest mysteries of the cosmos, from how the first stars and galaxies formed and how fast the universe is expanding to the prospects for extraterrestrial life.

Here we examine seven of the biggest questions the JWST is expected to shed new light on, focusing on specific projects that have been granted time in its first observation cycle, to reveal precisely how this $10 billion telescope will transform our understanding of the cosmos.



The James Webb Space Telescope's mid-infrared image of nearby galaxy the Large Magellanic Cloud

ESA (C. CARREAU)

WHERE AND WHEN DID THE FIRST STARS FORM?

After the big bang came the cosmic dark ages. Matter at this stage was either dark matter, which neither emits nor reflects light, or neutral hydrogen and helium gas. Then, over the course of a few hundred million years, the gas started to coalesce, forming stars – and the lights switched on.

The radiation from these first stars ionised the neutral gas around them. By the time this so-called epoch of reionisation was complete, the universe had gone from a homogeneous, primordial soup to a highly structured arrangement, with galaxies, stars and probably even planets. We know this happened, but we have few observations to show us how.

Jeyhan Kartaltepe at the Rochester Institute of Technology in New York has 256 hours of observation time on the JWST – among the longest stints in the instrument's first observation cycle – to answer a broad set of questions about this cosmic dawn. What types of stars were the first stars? In what kinds of galaxies did they form? How early did reionisation happen, and how long did it take? "A detection [of a primordial galaxy] with the Hubble Space Telescope is just a smudge in an image and you can say how bright it is, and that's it," says Kartaltepe. "Now, we'll be able to measure their stellar masses and resolve out structure, so we'll learn a lot more about the physics."

Kartaltepe's project will give us a comprehensive view of reionisation. "It didn't happen everywhere, all at once," she says. "It started in little pockets and then expanded out to these reionisation bubbles."

Meanwhile, Rohan Naidu at Harvard University reckons he has identified one of these little pockets as the place where the cosmic dawn first broke – and now he can finally take a look. "We think that these are amongst some of the first galaxies that may have formed," he says.

We measure the distance of objects in deep space by looking at "red shift": the extent to which their light has been stretched, and made redder, as it travelled through our expanding universe for billions of years before reaching us. A number describes how redshifted that light is; the bigger it is, the older the object.

The cosmic dawn is thought to have started at around red shift 10, when the universe was roughly 500 million years old. But Naidu thinks we might find evidence that the first stars formed in an ionised bubble that we now observe at red shift 9. "This is a very special place," he says, because this tiny patch of sky contains a quarter of all known high red-shift galaxy candidates – and what we know about the formation of structure in the universe suggests the first stars would have developed in just such a location. "I'm very excited about seeing these high red-shift galaxies. We might be able to see the first stars," he says. ›

WHAT ARE THE ORIGINS OF SUPERMASSIVE BLACK HOLES?

Black holes are regions of space-time so dense and warped, with such intense gravitational pull, that not even light can escape them. There are stellar-mass black holes, created when massive stars collapse, which range from a few to a few hundred times the mass of the sun. And there are supermassive black holes, ranging from 100,000 to tens of billions of times the mass of the sun, found at the centres of most galaxies. These monsters shape the evolution of galaxies as they accrete, or accumulate, mass and launch powerful jets that disrupt everything around them.

One of the most bewildering observations in astrophysics is that we see supermassive black holes that were already billions of solar masses when the universe itself was well under a billion years old. Even if these black holes were growing exponentially by gobbling stars and gas, they must have started out as massive as thousands of suns – and we have no idea how that would work given our existing models of how black holes form and grow.

Theorists have proposed two routes to these early supermassive black holes. The first is the collapse of a massive gas cloud, either directly to a supermassive black hole or first to a massive star that then itself collapses into a black hole. The second hypothesis is that they formed from dense clusters of stars, which merged into each other, growing ever larger and eventually resulting in a black hole.

To learn more about supermassive black holes, Xiaohui Fan at the University of Arizona is going to observe distant quasars, extremely bright objects generated when gas spirals at high speeds into these black holes, launching gigantic jets of particles and radiation. Looking closely at three of the most distant quasars we know of, Fan and his colleagues will measure the velocity of the disc of gas and dust spiralling into the black holes, which directly probes their mass. Combine this with a measure of luminosity and you also get the rate at which the black hole is accreting material. This will give them the tightest constraints yet on the initial mass of the black hole, and how early in the young universe the seeding happened.

Fan's observations won't be able to rule out ideas for how supermassive black holes were seeded. They should shed light on how they grow, however, and how their growth influences the evolution of galaxies. We know that the most massive black holes reside in the most massive galaxies. But which came first, and whether one is responsible for the other, is a cosmological chicken-and-egg conundrum. With the JWST's sensitivity, we will see the stellar light from the host galaxies of these black holes for the first time. Its infrared observations mean we can characterise their ages and therefore learn when the star and galaxy formation happened relative to the black hole growth.

"It is a cosmological chicken-and-egg conundrum"

Expect the unexpected

Even if the astronomers granted time on the James Webb Space Telescope's first observation cycle know exactly what they are going to look at, they are still energised by the prospect of seeing something unexpected. "My hope is that we're going to discover something that we didn't see coming," says Wendy Freedman at the University of Chicago.

"I'm most excited about the questions we don't know enough to ask," says Kristen McQuinn at Rutgers University in New Jersey. She cites the Hubble Ultra Deep Field, an image captured in 2004 by the Hubble Space Telescope after it was pointed at an unpromising little patch of sky. Many expected it to come out dark, but the long exposure revealed thousands of twinkling stars and galaxies that were older than anyone had ever imagined. This captivating image transformed the field of cosmology, just as the accidental discovery of the relic photons from the big bang, the cosmic microwave background, had in the 1960s.

Whenever a new instrument opens a fresh observational window, it creates a universe of possibilities, says Freedman. The JWST is no exception. "Almost every field of astronomy is going to learn new things," she says. "Then there are going to be the discoveries that nobody anticipates at all, and those are sometimes the most fun."

Decades in the making, NASA's new space telescope should produce some surprises

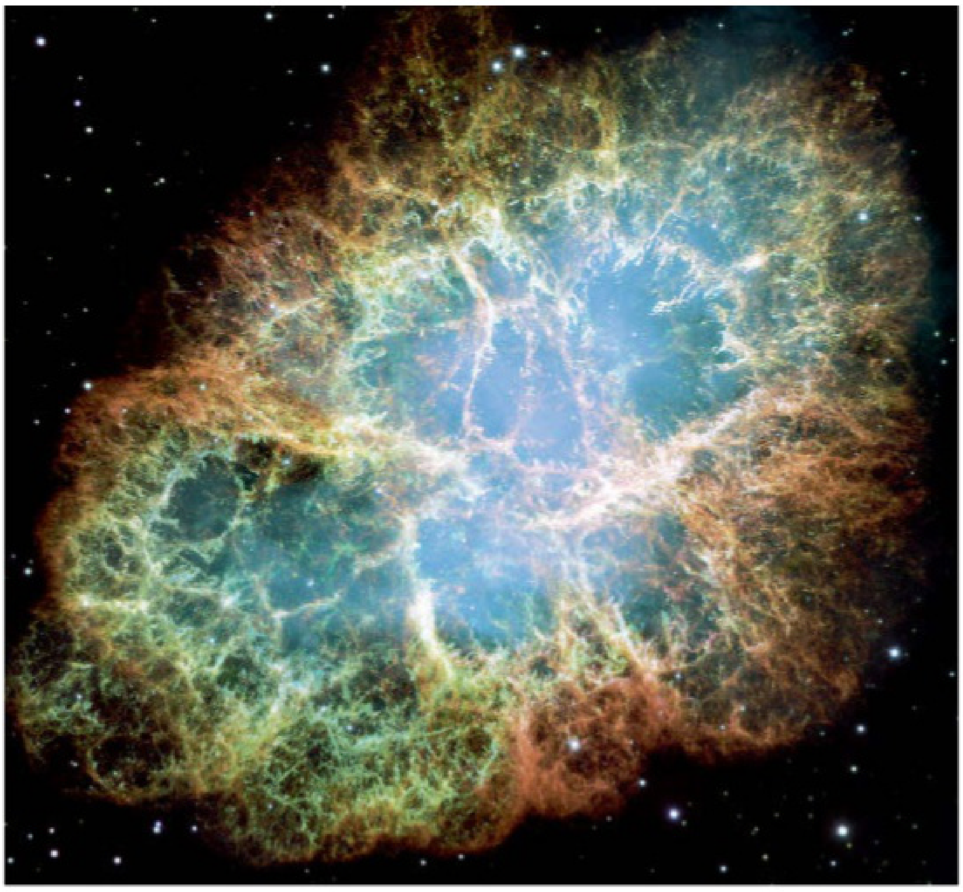
BOTTOM: NASA/DESIREE STOVER; TOP: NASA/CHRIS GUNN

IS DARK MATTER COLD?

Dark matter is a mysterious form of matter whose existence we can only infer from its gravitational effects. We believe that it accounts for roughly 85 per cent of all matter in the universe, but we don't know what kinds of particles it is made of, if indeed it is made of particles. For the time being, we think dark matter is "cold", meaning it moves slowly, which allows small clumps to assemble due to their own gravity and grow into more massive structures known as "haloes". In our current best picture of how the universe evolved, dark matter helped to sculpt the universe, as these haloes attracted gas that clumped and collapsed to form stars and galaxies.

Dark matter haloes come in various sizes, from a quadrillion solar masses to as little as the mass of Earth. When the dark matter haloes are lighter than 10 million solar masses, they can't attract enough gas to form galaxies. According to our understanding of cosmic evolution, they exist as little, invisible pockets of dark matter, in which case we are presumably surrounded by many of these smaller dark matter haloes.

Anna Nierenberg at the University of California in Merced and her colleagues will seek to test this assumption, and by extension the idea that dark matter is cold and sluggish, by looking at quasars. In this case, the light released by the quasars will be lensed, or bent, by the gravity of the small, galaxy-less dark matter halo. The light would be deflected in such a way that it creates repeated images in the telescope, which is what Nierenberg and her colleagues will be looking for. Detecting these tiny haloes would be a huge success for this model, she says. Alternatively, "their absence would imply that dark matter cannot be cold, but must be of a more exotic nature".



NASA/ESA/JPL/ARIZONA STATE UNIV.

The Crab nebula, the remnant of a supernova explosion

HOW DO MASSIVE STARS GO SUPERNOVA?

When they die, stars like our sun go relatively quietly. More massive stars go out in a blaze of glory in spectacularly violent explosions called core-collapse supernovae. These cosmic fireworks inject huge amounts of energy into their surroundings and as the shock waves from the explosion heat and ionise interstellar material, they drive the formation of new generations of stars. Supernovae also release all manner of chemical elements, enriching the gas clouds that create planets like ours with the ingredients that form us.

We see supernovae all the time. We know that stars with masses of at least eight times that of the sun will end their lives in these explosions. At some point, the core of the star is unable to withstand the weight of its outer layers, causing the star to collapse and blow up. What we don't know is what the explosion mechanisms are, meaning exactly how massive stars blow up the way they do.

Two models are on the table for massive stars in the lower end of the mass range that can go supernova. In the electron-capture model, a star has a core composed of oxygen, neon and magnesium and that core is held up by the pressure of these atoms' electrons, a result of a quantum mechanical law that says they can't all occupy the same energy state. If the core becomes too dense, however, the nucleus of the neon and magnesium atoms can absorb their electrons in what we call an electron-capture reaction. This reduces the pressure and results in the gravitational collapse of the outer layers of the star, causing the explosion. The alternative is the iron-core collapse model. Here, an iron core forms and because iron is a very stable element, it can't fuse into other elements and release energy, so nuclear reactions can no longer counterbalance gravity, resulting in collapse and ignition.

It is impossible to observe what is going on inside a star at the moment of explosion because the outer layers shield the core from view. But Tea Temim at Princeton University will use the JWST to bring some clarity by looking more closely at the Crab nebula, the remnant of a supernova explosion of a star in the eight to 10 solar mass range. It was recorded by astronomers in 1054, and is one of the most thoroughly studied astronomical objects of all time. If we get a closer look at it, however, we might be able to figure out how it exploded, because each of our two possible explosion mechanisms would leave signatures: a different ratio of iron to stable nickel, in each case, and different distributions of iron in the material ejected by the star.

"The Crab has a very complicated ionisation structure," says Temim, so they need to make sure that the measurements of the different elements come from the exact same place in the remnant. Only the JWST boasts sufficient resolution to tell the two possible signatures of star explosion in the nebula apart in this way.

NASA/STSCI

NASA EARTH OBSERVATORY/JOSHUA STEVENS/NOAA

Earth's water may have been delivered from the outer solar system

WHERE DO PLANETS LIKE EARTH GET THEIR WATER?

We are fortunate that our planet is a lush world of oceans, lakes, rivers and waterfalls. According to our current understanding of our solar system's history, however, our pale blue dot wasn't blue at all when it formed.

When Earth came together out of a maelstrom of gas and dust some 4.5 billion years ago, it was inside the sun's "snowline", the radius outside which the temperature is low enough that all water is ice. What's more, at that time, the sun was throwing out more energy than it is today and the radiation pressure would have pushed any water vapour close to Earth out behind the snowline. All of which means that, as far as we know, the material that formed Earth didn't contain any water. "So Earth's water must have come from somewhere," says Isabel Rebollido at the Space Telescope Science Institute in Baltimore, Maryland.

Planetary scientists have proposed that it might have been delivered later by asteroids or comets in a period known as the Late Heavy Bombardment. The idea is that the knock-on effects of the movements of the gas giant planets in the outer solar system could have pushed ice-containing debris further in, dispatching water to Earth and creating many of the moon's craters in the process.

Rebollido will use the JWST to look at five exoplanetary systems in a similar stage of evolution – when the gas giants have already formed and their movements are shuffling material around. "One possible explanation for the gas we detect in the inner regions of planetary systems is that solid, icy bodies sent in from the outer regions are evaporating," says Rebollido. The idea is simple: look for water in the middle region. If it is there, the implication is that icy bodies can indeed be delivered from the outer regions of a solar system to rocky planets inside the snowline, allowing otherwise barren worlds to become pale blue dots.

COULD THE MOST PROMISING EXOPLANETS HARBOUR LIFE?

The prospect of life on planets beyond Earth has intrigued us for centuries. These days, we search for it by looking for "biosignatures" in exoplanet atmospheres. If certain combinations of molecules are present – methane and carbon dioxide, say – it is a sign that life could exist there. But there has to be an atmosphere to begin with.

We characterise the composition of exoplanetary atmospheres with the transit technique: when a planet passes in front of its host star, the various molecules in its atmosphere interact with light from the star and emit or absorb infrared radiation at specific wavelengths that form fingerprints of the molecules involved. The spectrograph aboard the JWST is sensitive to these fingerprints, which means it can identify which molecules are present. "JWST is going to be completely revolutionary because the Hubble and Spitzer space telescopes had relatively restricted wavelength ranges, so you couldn't measure a lot of stuff in the atmospheres," says Megan Mansfield at the University of Arizona.

For the transit method to work, the signal from the planet's atmosphere has to be detectable against the much brighter signal from the star. Even with the JWST's unprecedented capabilities, finding biosignatures will probably only be possible for planets orbiting cool, low-mass stars called M dwarfs. Fortunately, that puts a particularly appealing group of exoplanets in our sights. The Trappist 1 system, a collection of seven rocky planets discovered in 2016, hosts more planets capable of sustaining liquid water than any other system we know of.

The catch is that we don't know if the Trappist planets, or any other worlds orbiting M dwarfs, can retain their atmospheres for long enough for life to develop, says Mansfield. That's because M dwarfs start out much more active than stars like the sun, and the copious amount of high-energy radiation they throw out could strip the atmospheres from their planets.

One of the most useful things the JWST can do for the search for extraterrestrial life is to establish whether exoplanets around M dwarfs have atmospheres at all. Kevin Stevenson at Johns Hopkins University in Maryland will observe five terrestrial exoplanets orbiting the nearest M dwarfs as they transit, including one in the Trappist system.

> "We want to establish whether exoplanets around M-dwarf stars have any atmospheres at all"

The atmospheres of the remaining Trappist planets will be observed as part of other JWST projects. "If none of the five planets have atmospheres, that tells us that atmospheres in M-dwarf planets are rare," says Stevenson, "and that we should start looking at planets around other types of stars."

If we detect atmospheres, on the other hand, we have good candidates for thorough follow-ups. Even if that is the case, whether we will be able to detect faint signs of alien life with the JWST remains to be seen. Much will depend on how well its instruments perform. "I don't know if we'll get there in the next 10 years with Webb, but we'll try," says Stevenson.

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Cepheid stars are key to measuring up the cosmos

DOES THE RATE OF EXPANSION OF THE UNIVERSE BUST OUR BEST COSMOLOGICAL MODEL?

We live in an expanding universe, where galaxies recede away from each other at a rate known as the Hubble constant. This can be measured directly, by determining the distances to faraway astronomical objects, or indirectly by combining observations of the early universe with our best theory of how the cosmos evolved. The problem is that the two measurements are inconsistent.

Our current cosmological model posits that the universe is composed of radiation, matter (including cold dark matter) and dark energy – a puzzling form of energy thought to be responsible for the expansion we observe. Taking data from relic radiation from the big bang, known as the cosmic microwave background, and feeding it into that model, cosmologists estimate that the universe is expanding at a rate of 67 kilometres per second per megaparsec – a megaparsec being a distance equal to 3.26 million light years. Yet when astronomers measure the Hubble constant from observations of distant objects, they find a value of 73 kilometres per second per megaparsec.

The discrepancy, known as the Hubble tension, could indicate that something is seriously wrong with our understanding of cosmic evolution. But the standard cosmological model is hugely successful, accounting for all manner of observations, so we will need a very good reason to chuck it out.

The JWST could finally settle the argument. To get their value for the Hubble constant, astronomers use the "cosmic distance ladder". This makes use of stars called cepheids that fluctuate in brightness at a rate related to their absolute luminosity, which allows us to measure their distance from us. We then move to the next rung of the ladder by using other "standard candles", such as supernovae, to calculate the distance to nearby galaxies and, ultimately, to the edge of the observable universe.

To be sure that those measurements are accurate, you need to reduce uncertainties at every step. To understand those uncertainties, Wendy Freedman at the University of Chicago plans to measure the distance to the same galaxies using a variety of standard candles. Cepheids, for instance, are often surrounded by other young stars. The sharper images provided by the JWST will help to distinguish the contribution in the measured light from cepheids relative to their neighbours. Moreover, higher sensitivity will allow us to see cepheids in more distant galaxies. Freedman will combine the cepheid measurements with other methods for measuring distances to other galaxies to better understand how accurate we can consider our calculations for the Hubble constant.

To address the same issue, Sherry Suyu at the Technical University of Munich, Germany, is instead looking at the flickering of quasars. When there is a massive object between us and the quasar, such as another galaxy, its gravity can act like a lens, resulting in multiple images of the quasar in our telescopes. There is a lag in the arrival of the quasar's flicker in the various images because each has a different light path due to this lensing effect and those lags are related not only to the distance of the quasar, but also to the gravitational potential of the lensing galaxy. With the JWST, Suyu will measure the velocities of stars in the lensing galaxy, allowing her to understand its mass distribution – and therefore to better correct for its gravitational potential when estimating a Hubble constant from the quasar flicker time delays, another method that has been used by astronomers.

If these independent methods of determining distance reach the same value for the Hubble constant, we will know the astronomical measurement is robust. Should they agree with the Hubble value from the cosmological model, then the tension disappears. "If we actually show that the standard model works, that's a really important result," says Freedman.

And if the astronomical measures still differ from the cosmological model? "It would be really interesting if this turns out to be new physics," says Suyu. "But if it does, I want to make sure we're right." ▮

THIBAULT RENARD/GETTY IMAGES

María Arias is an astronomer at Leiden University in the Netherlands