EUCLID'S FIRST YEAR IN SPACE

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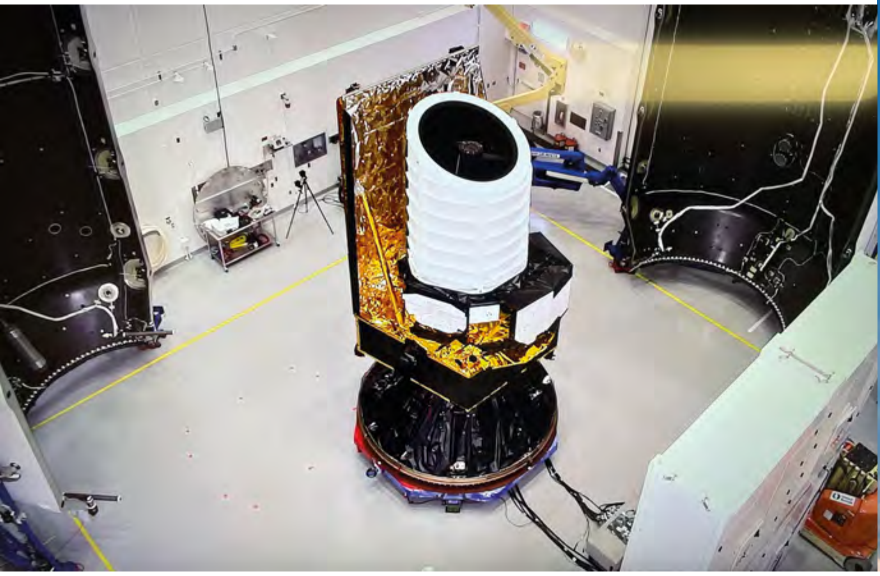

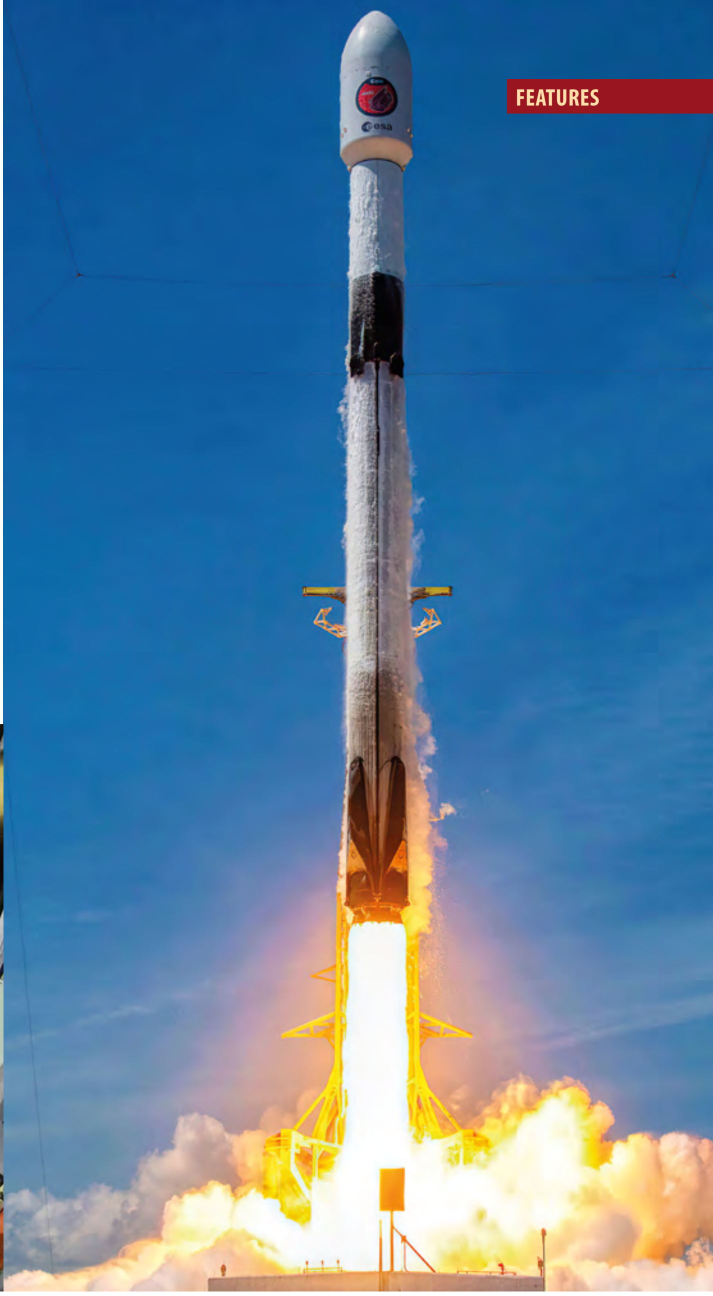

▲**FIG. 1:** The Euclid telescope just before being placed in the fairing (© ASO/SpaceX/ESA/TAS-I), and the launch (© SpaceX)

July 1st, 2023. Cape Canaveral. 11:11 am.

10..9..8..7..6..5..4..3..2..1.. LIFT-OFF!

Against a beautiful blue sky, the Falcon-9 rocket carrying our 'baby' streaks into the sky, 8 miles away from our vantage point. Almost one minute later the crackling sound of the rocket engines arrives. I manage to follow the disappearing rocket with my binoculars for two minutes, until the main engine cuts off. Half an hour later, on the big screen set up next to our bleachers full of colleagues and family at the Banana Creek viewing site, we see the upper stage rocket switch off and deliver its precious cargo into space. Soon after, ultra-relieved mission managers at ESA receive the first radio signals. We have a spacecraft, we have a mission!

Euclid: Europe's new space telescope

It had already been a 12-year journey for thousands of scientists and engineers, but that day the Euclid spacecraft, Europe's newest space telescope, began its real journey: to its orbit around the second Earth-Sun Lagrange point, to carry out a six-year mission of mapping the sky.

Why a space telescope? The advantages of observing the universe from above Earth's atmosphere are great. Most importantly, it avoids the blurring effects due

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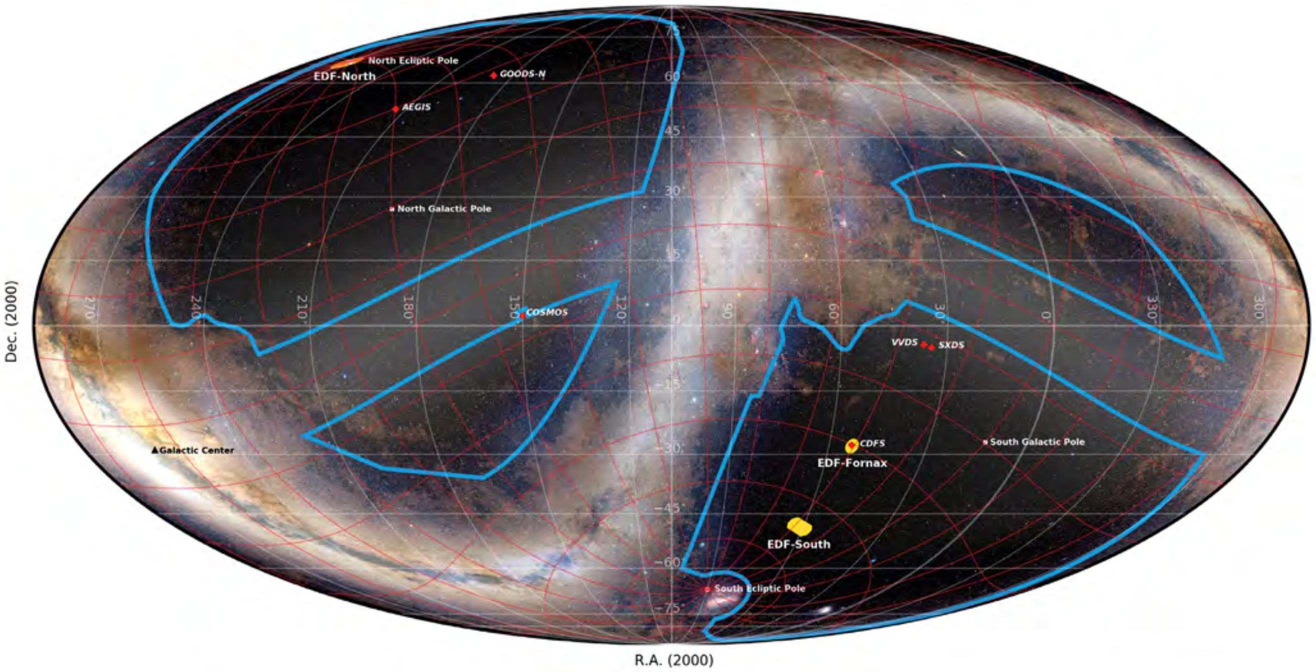


The Euclid Wide Survey (EWS) with the Euclid Deep Survey (EDF) and the deep Euclid Calibration Fields [Mollweide Celestial]

▲ **FIG. 2:** Euclid will observe ~40% of the sky not obscured by the Milky Way or by the zodiacal dust in the solar system (© Euclid Consortium / J.-C. Cuillandre).

to atmospheric turbulence, resulting in much sharper images than can routinely be obtained from even the best ground-based observatories. The famous images taken with the venerable Hubble Space Telescope (launched in 1990 and still working) have been revolutionary. A vantage point in space also greatly reduces the level of background radiation, particularly at infrared wavelengths where the atmosphere glows brightly. And finally, the weightless environment on board a spacecraft allows for much greater stability of the optics, benefiting the image quality.

Why another space telescope? The James Webb Telescope, launched in 2021, is often billed as the successor to Hubble. It excels at making even sharper and more sensitive images than Hubble, thanks to its much larger mirror and new-generation instrumentation. But just like Hubble, there is one important task that it was not designed to do: image large areas of the sky. This is the strength of Euclid, the first large, wide-field telescope in space, which makes it just as much a successor to Hubble as Webb is.

At its heart, Euclid has two very large cameras with multi-detector arrays: the VIS camera that works in visible light (500-900nm) and the NISP camera and spectrograph for near-IR observations (900-1800nm). They simultaneously cover a square patch of sky that is 0.7 degrees across, about 100x larger than the field of view of Hubble and Webb instruments. This huge grasp makes it possible to cover the deep extragalactic sky (the part that is not obscured by the Milky Way or the ecliptic dust band in the solar system) during its six-year mission, at space resolution, with pixels that are only 0.1 (0.3) arc seconds wide in VIS (NISP).

The dark side of the Universe

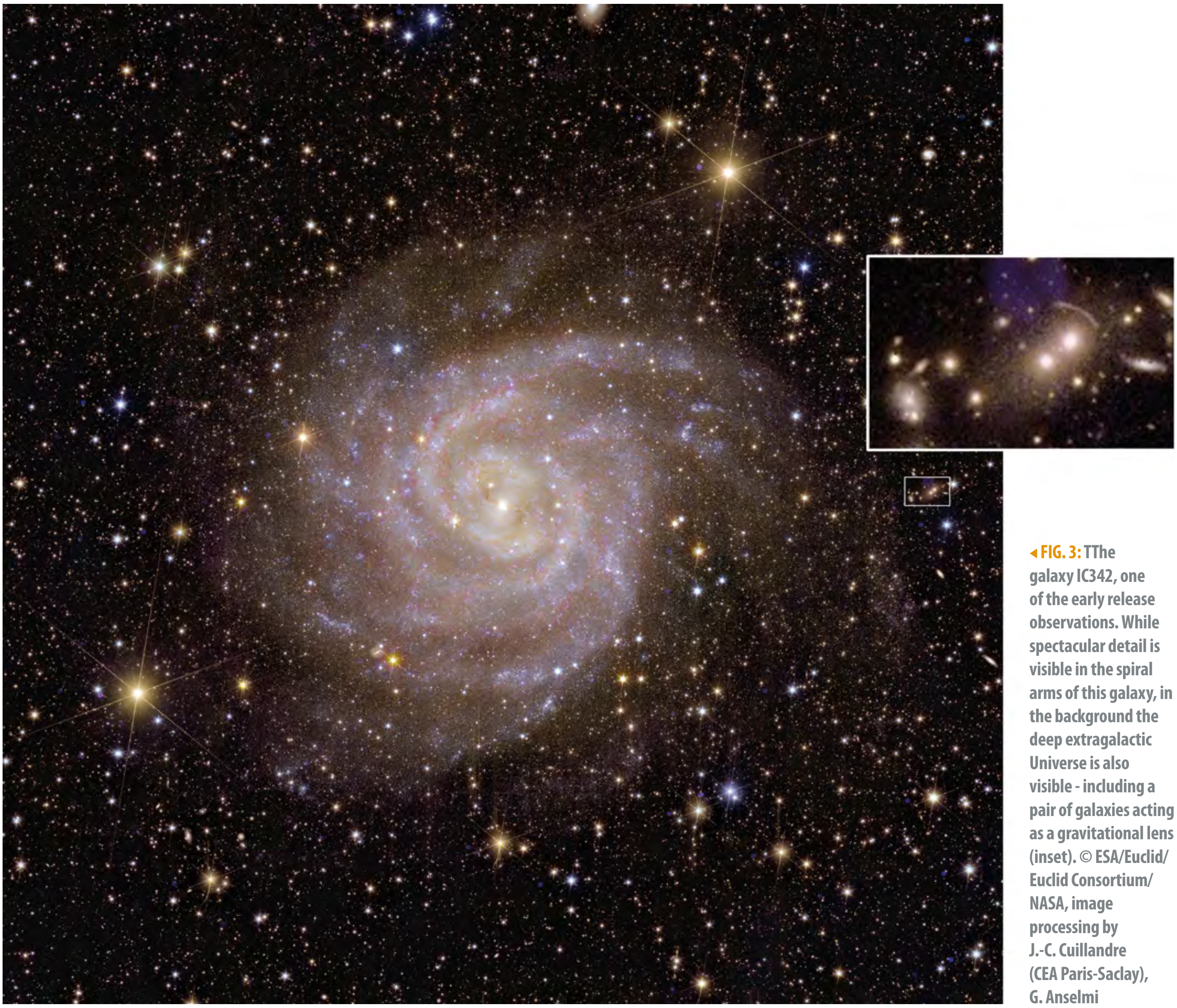
The aim of the Euclid mission is to study the dark ingredients of the Universe, the so-called 'Dark matter' and 'Dark Energy'. In the current standard model of cosmology, which has been spectacularly verified with the ESA Planck mission that mapped the anisotropies in the cosmic microwave background, these two components make up about 95% of the energy density of the Universe, with only 5% consisting of particles familiar from the standard model of particle physics. Even though the evidence for their presence appears strong, very little is known about their physical nature. Euclid's aim is to investigate these aspects in more detail, by mapping out the distribution of dark matter in and between the galaxies, and by studying the history of the expansion of the Universe and the growth of large-scale structure within it, over the most recent 2/3 of its age (since about 4 billion years after the Big Bang).

The evolution of the expansion of the Universe depends on its density and composition: for example, the higher the matter density, the stronger the pull of gravity and the resulting deceleration of the expansion. Therefore, the more dark matter the Universe contains, the more the expansion decelerates. Dark energy, on the other hand, causes the expansion of the Universe to accelerate. Such an accelerating effect would also occur if Einstein's equations of General Relativity contained a positive 'cosmological constant', a term Einstein first added (in an effort to generate a static, non-expanding Universe) and later removed from his equations (when the observation showed that the Universe in fact did expand). Euclid will be mapping the expansion history by looking how large a characteristic scale in the large-scale structure - the Baryon Acoustic Scale - appears on the sky as a function of distance to the galaxies. The underlying 3D map of galaxies is obtained with the near-infrared spectrograph, that is tuned to the epoch when the dark energy began to be dynamically important, about 8 billion years ago.

Mapping the dark matter uses the technique of 'weak gravitational lensing'. Light rays are bent by gravitational fields, an effects that distorts the sky as if it were being viewed through slightly corrugated glass. The stronger the corrugations, the more distorted the sky appears, providing a direct way to measure the degree of inhomogeneity of the matter - dark and visible - along the line of sight to distant galaxies. The distortions can only be detected statistically, as correlated alignments of otherwise randomly-oriented galaxies, and are very weak: they perturb the elongations of galaxy images by of the order of 1% or less, on top of random differences between galaxies that are 30x larger. The more, and the more precisely, the shapes of galaxies can be measured, therefore, the better these coherent distortions can be teased out from the data. Euclid's power lies in the combination of the large area of sky that it will image, with the very fine resolution that allows even small and distant galaxies' shapes to be measured accurately. In fact, to be able to accomplish its goals the Euclid Consortium also gathers a huge amount of data from the best ground-based observatories: while these images cannot be used to measure galaxy shapes nearly as accurately as Euclid's, they are used to determine the colours of the galaxies and hence to estimate their distance - a technique known as 'photometric redshift' and an essential ingredient in the analysis.

Commissioning and Science Verification

Commissioning and science verification of the telescope took eight months, concluding on February 14th. During



◂ **FIG. 3:** TThe galaxy IC342, one of the early release observations. While spectacular detail is visible in the spiral arms of this galaxy, in the background the deep extragalactic Universe is also visible - including a pair of galaxies acting as a gravitational lens (inset). © ESA/Euclid/Euclid Consortium/NASA, image processing by J.-C. Cuillandre (CEA Paris-Saclay), G. Anselmi this time the telescope travelled to its operating orbit, cooled down to stable operating temperatures, and was focused. All systems were activated and tested, and essential calibration data were obtained. The procedures designed for the routine observations were also exercised, and a number of mini-surveys and observations of special targets obtained, including the so-called 'Early Release Observations' (more on these below). This period is also intended to identify and address any unexpected features and problems on board that may otherwise affect the scientific performance of the mission.

In fact, we found several issues that had not been expected: fortunately it was possible to find solutions for all of them that have minimal impact on the mission performance. As the saying goes, "*Space is hard*"!

Stray light - Soon after the VIS instrument started taking sky images, it was apparent that the background was not as dark as expected: extra light was somehow making its way onto the detectors. Scattered light is always a critical aspect of astronomical telescopes, as the Poisson noise of the background is often an important, if not dominant, source of noise. Extra background is therefore not simply something that can be subtracted without penalty.

After some experimentation and analysis it became clear that the scattered light disappeared if the telescope was oriented at particular angles with respect to the Sun, and that this coincided with a particular thruster being shadowed by the rest of the spacecraft. Evidently reflected sunlight off this thruster manages to find its way into the instrument cavity despite the many layers of insulation wrapping it. Fortunately it is possible to operate Euclid with a restricted, scattered-light safe, range of orientations with respect to the Sun, without major impact on the ability to schedule the observations.

▾FIG. 4: The Perseus cluster, one of the largest relatively nearby galaxy clusters. The cluster is dominated by a number of massive galaxies, but the Euclid data allow the cluster galaxy population to be studied down to the thousands of very faint dwarf galaxies. Also here the background 'empty regions' are full of galaxies - these form the main target of the Euclid wide survey. ©ESA/Euclid/Euclid Consortium/NASA, image processing by J.-C. Cuillandre (CEA Paris-Saclay), G. Anselmi

Fine guiding - A key requirement for Euclid is to make the sharpest possible images, essentially limited by diffractive effects. This requires the satellite's attitude to be controlled very precisely, ensuring that over the duration of an exposure (typically up to 10 minutes) the image is steady. Euclid does this by locking on to stars around the field of view, and sending correction commands to the spacecraft to adjust the pointing with tiny squirts of cold gas and with its gyroscopes. Initially this system was not working as expected, leading to 'loopy' tracks on the images, but a software update brought this under control and Euclid has been producing sharp images ever since.

Solar X-rays - Euclid was launched just before Solar maximum, which is the time in the sun's 11-year activity cycle when its surface magnetic field is most eruptive. Consequently, Earth and Euclid regularly receive showers of charged particles, and X-ray flashes. CCDs are actually good X-ray detectors, which they register without damage. Most solar X-rays are stopped by Euclid's sun shield, which is covered with solar cells, but there are a few gaps, which during the most intense flares throw a shadow on part of the VIS detectors. About 1% of the time (during this period of high solar activity), 25% of the focal plane is rendered unusable because of such X rays. These data will simply be filtered out and not used for analysis.

Ice - The final effect that showed up was a slow buildup of ice on the coldest parts of the optics. This was not unexpected: the insulating materials used in Euclid are known to absorb some atmospheric water on Earth, and it takes some time in space for these to be outgassed. This process can be speeded up by heating the material by judiciously tilting the spacecraft towards the sun, and this was done soon after launch, but in the operational phase this plays havoc with the thermal stability of the optics and is therefore very much a measure of last resort. Once the ice buildup was noticed (as a slow decrease in the sensitivity of the VIS instrument) a procedure was run that heated only the most likely optical elements to have been ice-contaminated, in a very targeted fashion. It worked as expected, with the throughput quickly jumping up by 14%. Mysteriously some of the ice quickly returned though, so a second intervention was done a few months later - and since then the throughput has been steady and there has been no indication of any new contamination.

First images

By nature, Euclid is a statistical experiment, so the first cosmology results can only be obtained once a substantial portion of sky has been observed. For this reason a set of data releases are planned containing fully analysed data from the first 1, 3 and 6 years of the mission (the first of these is expected to be made publicly available in 2026). But happily, the nature of Euclid's data makes it useful for many other topics of astronomy research: in essence, Euclid will be providing the best (in terms of sharpness and sensitivity) images available in the extragalactic sky for all but a few well-studied regions. Thus, many of the astronomers in the Euclid Consortium are focused on so-called 'legacy science' - other uses of the data that are not connected to the primary cosmology goals, but profit from the wonderful data quality. As a first taste of such data, in November 2023 and May 2024 ESA and the consortium released a total of ten 'Early Release Observations', that showcase the power of the mission. They range from a nearby star forming region in our Galaxy, star clusters in our Milky Way Galaxy, and one of its dwarf galaxy neighbours, to large galaxies and galaxy clusters at distances up to a billion light years away. Already the first discoveries based on these data have been announced, including for example the deepest-ever study of the population of dwarf galaxies in a large galaxy cluster, very low-surface brightness intra-cluster light between the galaxies, and faint globular cluster systems. A number of supernovae have already been discovered as well, and the first of an expected 100,000 strongly-lensing galaxies, where a distant galaxy happens to line up almost perfectly with a massive foreground object whose gravity distorts its image almost into a ring. What is striking is that the outer parts of the ERO images, far from the prime target - which would normally be outside the field of view of instruments that are not wide-field telescopes - is full of tens of thousands of galaxies in the deep Universe, whose shapes and structures are visible to a detail that would not be possible from the ground. When Euclid's main survey is done, it will have captured about 2 billion such galaxies!

What's coming

Currently we are preparing the 'Quick release' (due in the spring of 2025) that will cover about 50 square degrees, or 0.3% of the planned full survey. It is proving to be an excellent vehicle to test all analysis procedures and software pipelines, and learn in detail about the features of the Euclid data that will become important once we combine many thousands of square degrees and make the first cosmology measurements. Meanwhile the data keep streaming in, 10 square degrees every 24hr.

The first year of Euclid in space has been exciting and tantalising. Its mission to map the extragalactic sky with high fidelity images, and use these to study the dark side of the Universe, is off to a promising start. ■

About the Author

Koen Kuijken is professor of astronomy at Leiden Observatory, the astronomy department of Leiden University. He was a member of the Concept Advisory Team that led to the formulation of the Euclid mission, and his research focuses on using gravitational lensing to map the large-scale structure of the Universe.