The Universe as a physics laboratory

It is 400 years since humans first explored the Universe using more than the naked eye. What began with the modest magnification of visible light by Galileo Galilei's telescopes, which helped oust the geocentric view, has transformed into a vista spanning 18 orders of magnitude of the electromagnetic spectrum: ranging from the 13.7 billion-year-old microwave radiation produced when the first atoms formed, to the short-wave γ-rays emitted by extreme events in the centres of distant galaxies.

This relentless technological progress has given astronomers a wealth of knowledge about the Sun, the planets and their moons, comets and asteroids, extrasolar planets, stars, galaxies and black holes. It has also allowed investigation of some of civilization's oldest and deepest questions, such as how the Universe began and how it might end. Yet the closer we look, the more puzzles we find.

DARK ORIGINS

Perhaps the most astounding realization of the past two decades is that 96% of the Universe is composed of dark matter, which does not emit or absorb electromagnetic radiation, and dark energy that is causing the expansion of the Universe to accelerate. Neither of these invisible entities fits current understanding of fundamental physics; however, major observational and experimental programmes such as the Fermi satellite, the earthbound Square Kilometre Array (SKA) and EUCLID will help clarify their nature by revealing their effect on ordinary matter[1,2].

The 4% of the Universe that is observable via electromagnetic radiation also offers plenty of mystery[3]. Most of the chemical elements that comprise the planets and life on Earth were forged in the extreme conditions within stars, before being thrown into interstellar space during supernovae explosions; however, how these stars are born and die, and how galaxies evolve, are poorly understood. By combining large-scale numerical simulations with infrared observations of ancient objects — such as those made by the recently launched Herschel Space Observatory and the Institute for Radio Astronomy in the Millimeter Range (IRAM) 30 m telescope and interferometer — scientists hope to understand stellar evolution at different cosmic epochs, as well as from where and what the Earth evolved[4,5].

> » Astronomers are about to open a new window on the Universe through which to observe systems that do not emit electromagnetic radiation.

Observations of our nearest star, the Sun, over the past decade have revealed it to be surprisingly dynamic, with ramifications for our global climate. Missions such as the Solar Dynamic Observatory and Solar Orbiter will use helioseismology to probe the processes in the Sun's interior and the corresponding activity in the solar atmosphere that affect our environment. Astronomers have recently identified more than 400 planets orbiting other stars, with the attendant possibility of extraterrestrial life. Using the next generation of infrared instruments at the European Extremely Large Telescope, radio facilities such as the Atacama Large Millimeter/submillimeter Array (ALMA) and the SKA, and spectroscopy aboard the James Webb Space Telescope (JWST), we expect to detect young exoplanets in their formation stage and thereby shed light on how our planetary system came into being[6].

Space missions in the solar system hint that liquid water, and perhaps microbiological life, might have existed on other planets closer to home. New insight into the origins of life on Earth is expected from the Rosetta and Dawn missions, which will analyse the primordial material in comets and asteroids. Further such questions will be addressed by the Exobiology on Mars (ExoMars) mission (due for launch in 2018), the BepiColombo mission (due to arrive at Mercury in 2019) and, later on, by instruments aboard Marco Polo and the Europa Jupiter System Mission (EJSM).

NEW WINDOW

Observations across the electromagnetic spectrum have revealed the dynamic nature of the sky, and its variety of extreme events and objects[7]. For instance, by studying the orbits of stars over many years we have found that super-massive black holes reside at the centre of most galaxies — including our own — where they influence the evolution of their host[8]. Black holes and other extreme objects, such as supernovae, drive the cosmic matter cycle by accelerating particles to energies that dwarf man-made efforts, including the Large Hadron Collider, and these too are traced through the electromagnetic radiation they emit.

Astronomers are about to open a new window on the Universe through which to observe systems that do not emit electromagnetic radiation. It is hoped that three large interferometers — GEO-600 in Germany, the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the United States and Virgo in Italy — will

The origin, content and structure of the cosmos, as well as its evolution, are key research topics at a number of astronomical institutes in the Max Planck Society. At the Max Planck Institute for Astrophysics, scientists simulated the Universe and followed its evolution in a time-lapse video, comparing the results with actual observations. One important result revealed how the mysterious dark matter is distributed, and how it clumps in the vicinity of galaxies and galaxy clusters (Springel, V. *et al. Nature* **435**, 39, 2005).

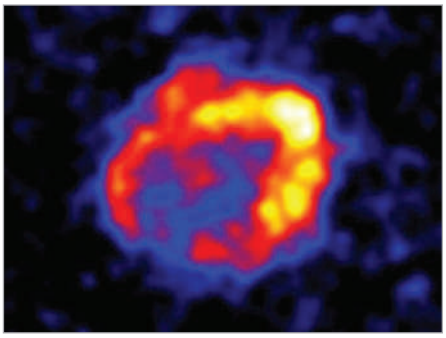
- By observing light emitted over the past 13.7 billion years, astronomers and astrophysicists can study our cosmic origins.
- Incredibly, 96% of the Universe is unobservable: made of mysterious dark entities that apparently defy both observation and fundamental physics.
- A phalanx of powerful new telescopes, combined with our ability to detect gravitational radiation, is set to make the next decade significant in the history of astronomy.

discover gravitational waves, which are ripples in space–time produced during extreme events such as the merger of two small, dense stars[9]. Upgrades to these, in combination with the planned Einstein Telescope, the Laser Interferometer Space Antenna (LISA) and radio observations of pulsars, will ensure that key parts of the gravitational-wave spectrum are covered — perhaps picking up gravitational noise from the Big Bang, hundreds of thousands of years before atoms formed and electromagnetic radiation could travel through space.

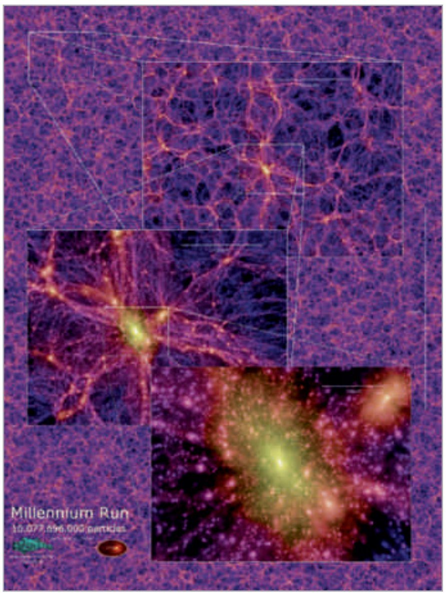
ASTONISHING PROGRESS

The search for gravitational waves is just one example of the enormous international collaboration required to tackle the toughest problems in modern astronomy and astrophysics: others include the Dutch radio-frequency Low Frequency Array, which will look back to when the first stars formed; the Planck mission, which measures the cosmic microwave background (the oldest electromagnetic radiation); and the Very Large Telescope in Chile, which detects infrared radiation to reveal the hearts of distant galaxies. In the optical and infrared region of the spectrum, the Large Binocular Telescope in Arizona, United States will bring cosmic evolution into view and, by picking up higher frequency X-rays and γ-rays, facilities such as the European Space Agency's X-ray Multi-Mirror Mission (XMM)–Newton, the High Energy Stereoscopic System (HESS), the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescope, Fermi and eROSITA will hunt for the most energetic processes in the Universe, potentially bringing dark matter into view.

Equally vital is the continued development of, and access to, computing power, which allows us to handle, model and understand data from new experiments. Soon the whole sky will be monitored with unprecedented regularity and resolution. Certainly, the questions of tomorrow will be even more exciting and fascinating than those of today.

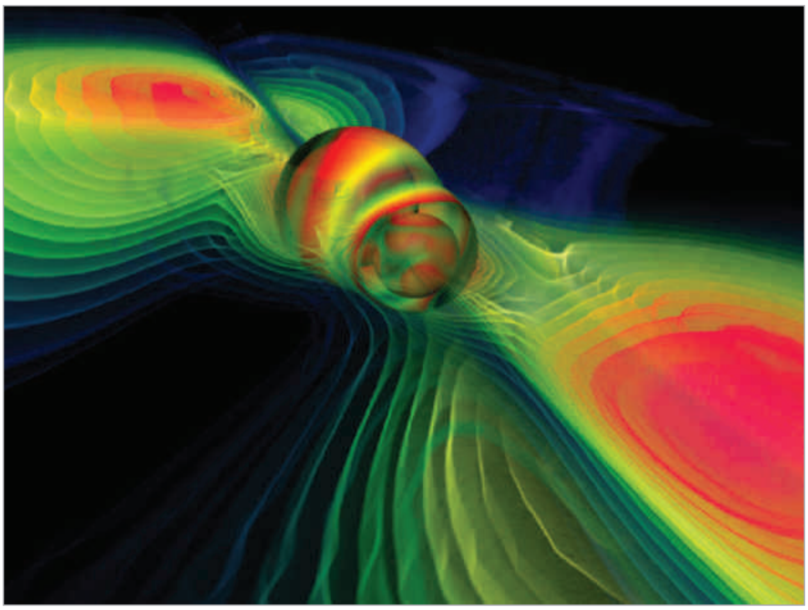


left — Telescopes able to detect high-energy gamma radiation reveal the shock wave of a supernova explosion which extends over tens of light years, and covers roughly twice the angular diameter of the moon.



left — The Millennium simulation reveals how structure formed in the Universe, with dark matter performing a vital role (each overlaid panel zooms in by a factor of 4).

below — A numerical simulation showing the gravitational radiation emitted by the violent merger of two black holes.



Top image: HESS Collaboration, MPI-K Heidelberg. Middle image: V Springel, MPI Astrophysics. Bottom image: AEI/ZIB/Benger.

For references see pages 70 and 71