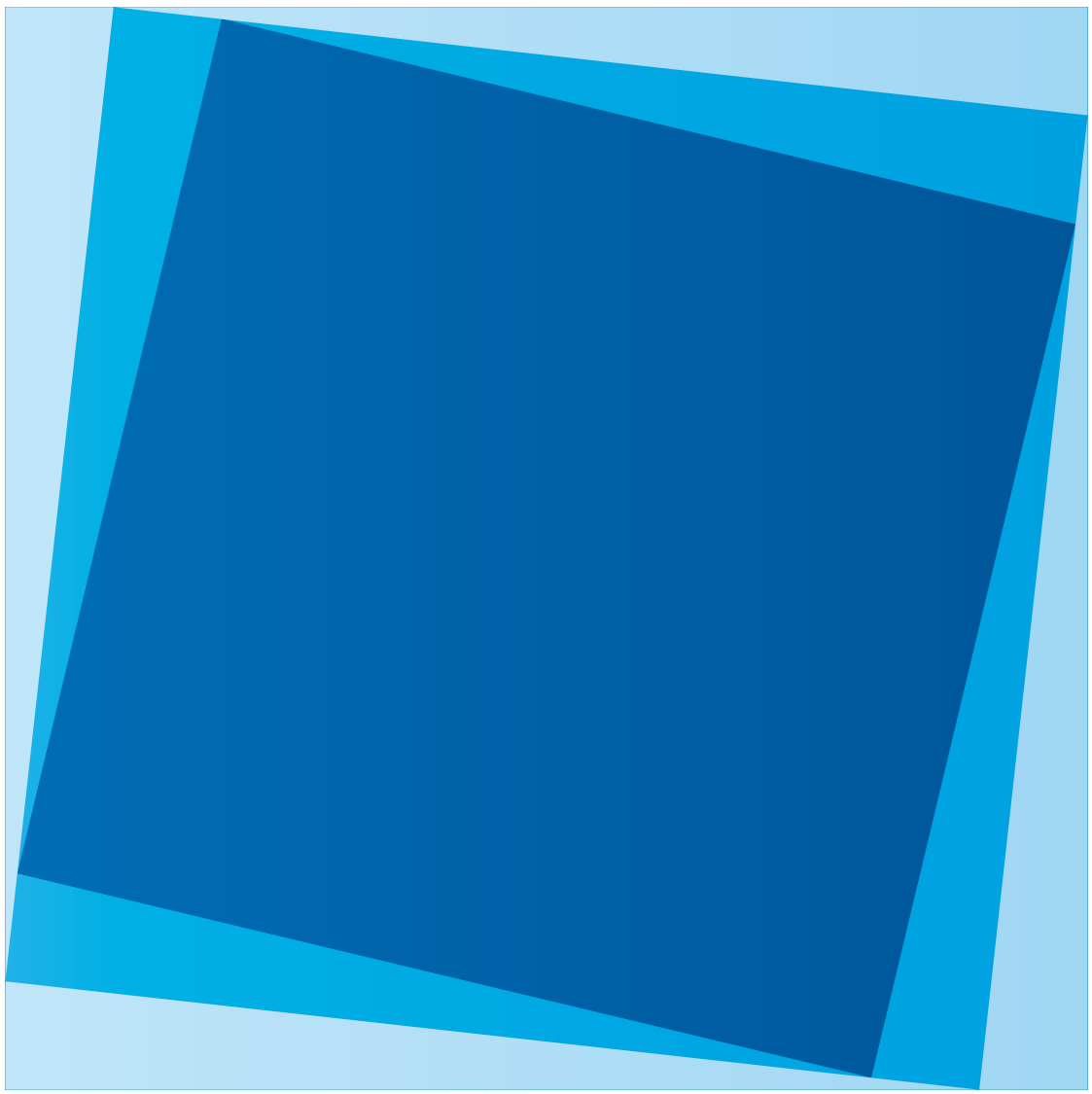
Towards a New Enlightenment? A Transcendent Decade



The Past Decade and the Future of Cosmology and Astrophysics

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Recommended books: *Universe*, Martin Rees, Dorling Kindersley, 2012; *On the Future*, Martin Rees, Princeton University Press, 2018.

In the last decade, there has been dramatic progress in exploring the cosmos. Highlights include close-up studies of the planets and moons of our Solar System; and (even more dramatic) the realization that most stars are orbited by planets, and that there may be millions of Earth-like planets in our Galaxy. On a still larger scale, we have achieved a better understanding of how galaxies have developed, over 13.8 billion years of cosmic history, from primordial fluctuations. These fluctuations might have been generated via quantum effects when our entire cosmos was of microscopic size. Einstein's theory received further confirmation with the detection of gravitational wave—a tremendous technological achievement. Future advances will depend on more powerful instruments, which could reveal evidence of life on exoplanets, and yield a better understanding of the big bang, and the ultimate fact of our cosmos.

Introduction

Astronomy is the grandest of the environmental sciences, and the most universal—indeed, the starry sky is the one feature of our environment that has been shared, and wondered at, by all cultures throughout human history. Today, it is an enterprise that involves a huge range of disciplines: mathematics, physics, and engineering, of course; but others too.

Astronomers aim to map and survey all the various entities—planets, stars, galaxies, black holes, and so forth—that pervade the cosmos. We then want to use our knowledge of physics to understand the exotic objects that our telescopes have revealed. A more ambitious aim is to understand how the entire cosmic panorama, of which we are a part, emerged from our universe's hot, dense beginning.

The pace of advance has crescendoed rather than slackened; instrumentation and computer power have improved hugely and rapidly. The last decade, in particular, has witnessed some astonishing advances. And the promise for the future is even brighter—astronomy offers splendid opportunities for young researchers who want to enter a vibrant field.

In this paper I focus on three topics: firstly, planets and exoplanets, relatively "local" on a cosmic scale; secondly, gravity and black holes, the extragalactic realm; and then thirdly, and more speculatively, some concepts that aim to understand the cosmos as a whole.

Planets, Exoplanets, and Life

Human spaceflight has somewhat languished in the decades since those of us who are now middle-aged were inspired by the Apollo program and the Moon landings. But space technology has burgeoned—for communication, environmental monitoring, satnav, and so forth. We depend on it every day. And for astronomers it has opened new "windows": telescopes in space reveal the far infrared, the UV, X-ray, and gamma ray sky. Even though humans have not ventured further than the Moon, unmanned probes to other planets have beamed back pictures of varied and distinctive worlds.

Among highlights of the last decade, ESA's "Rosetta" mission landed a small probe on a comet—to check, for instance, if isotopic ratios in the cometary ice are the same as in the Earth's water. This is crucial for deciding where that water came from. NASA's "New Horizons" probe has passed Pluto, and is now heading into the Kuiper Belt, replete with minor planets.

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Rosetta took about a decade to reach its destination, preceded by almost that long in planning and construction. Its robotic technology dates from the 1990s—that is plainly frustrating for the team that developed the project, because present-day designs would have far greater capabilities. And the same is true for "New Horizons"—which nonetheless transmitted back to us high-definition pictures of Pluto, ten thousand times further from Earth than the Moon is. And the "Cassini" probe, which spent thirteen years exploring Saturn and its moons, is

even more of an antique: twenty years elapsed between its launch and its final plunge into Saturn in late 2017.

We are aware how mobile phones have changed in the last fifteen to twenty years—so imagine how much more sophisticated today's follow-ups to these missions could be. During this century, the entire Solar System—planets, moons, and asteroids—will be explored and mapped by flotillas of tiny robotic craft, interacting with each other like a flock of birds. Giant robotic fabricators will be able to construct, in space, huge solar-energy collectors and other artifacts. The Hubble Telescope's successors, with huge gossamer-thin mirrors assembled under zero gravity, will further expand our vision of stars, galaxies, and the wider cosmos. The next step would be space mining and fabrication. (And fabrication in space will be a better use of materials mined from asteroids than bringing them back to Earth.)

It is robots, and not humans, that will build giant structures in space. And sophisticated robots will explore the outer planets: they will have to utilize the techniques of deep learning and artificial intelligence (AI) to make autonomous decisions—the travel time for a radio signal to the outer planets is measured in hours or even days, so there is no possibility of direct control from Earth. These robots will not be humanoid in size and shape. Humans are adapted to the Earth's environment. Something more spider-like would be better suited to the weaker gravity of Pluto or the asteroids.

But will these endeavors still leave a role for humans? There is no denying that NASA's "Curiosity," a vehicle the size of a small car that has, since 2011, been trundling across Martian craters, may miss startling discoveries that no human geologist could overlook. But machine learning is advancing fast, as is sensor technology; whereas the cost gap between manned and unmanned missions remains huge.

Robotic advances will surely erode the practical case for human spaceflight. Nonetheless, I hope people will follow the robots, though it will be as risk-seeking adventurers rather than for practical goals. The most promising developments are spearheaded by private companies. For instance, SpaceX, led by Elon Musk, who also makes Tesla electric cars, has launched unmanned payloads and docked with the Space Station. He hopes soon to offer orbital flights to paying customers.

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Indeed, I think the future of manned spaceflight, even to Mars, lies with privately funded adventurers, prepared to participate in a cut-price program far riskier than any government would countenance when civilians were involved—perhaps even one-way trips. (The phrase "space tourism" should definitely be avoided. It lulls people into believing that such ventures are routine and low-risk; and if that is the perception, the inevitable accidents will be as traumatic as those of the US Space Shuttle were. Instead, these cut-price ventures must be "sold" as dangerous sports, or intrepid exploration.)

By 2100, groups of pioneers may have established bases independent from the Earth—on Mars, or maybe on asteroids. But do not ever expect mass emigration from Earth. Nowhere in our Solar System offers an environment even as clement as the Antarctic or the top of Everest.

Space does not offer an escape from Earth's problems. Dealing with climate change on Earth is a doddle compared with terraforming Mars.

What are the long-term hopes for space travel? The most crucial impediment today stems from the intrinsic inefficiency of chemical fuel, and the consequent requirement to carry a weight of fuel far exceeding that of the payload. Launchers will get cheaper when they can be designed to be more fully reusable. But so long as we are dependent on chemical fuels, interplanetary travel will remain a challenge. A space elevator would help. And nuclear power could be transformative. By allowing much higher in-course speeds, it would drastically cut the transit times to Mars or the asteroids (reducing not only astronauts' boredom, but their exposure to damaging radiation).

The question that astronomers are most often asked is: "Is there life out there already? What about the 'aliens' familiar from science fiction?" Prospects look bleak in our Solar System, though the discovery of even the most vestigial life-forms—on Mars, or in oceans under the ice of Europa (one of Jupiter's moons) or Enceladus (a moon of Saturn)—would be of crucial importance, especially if we could show that this life had an independent origin.

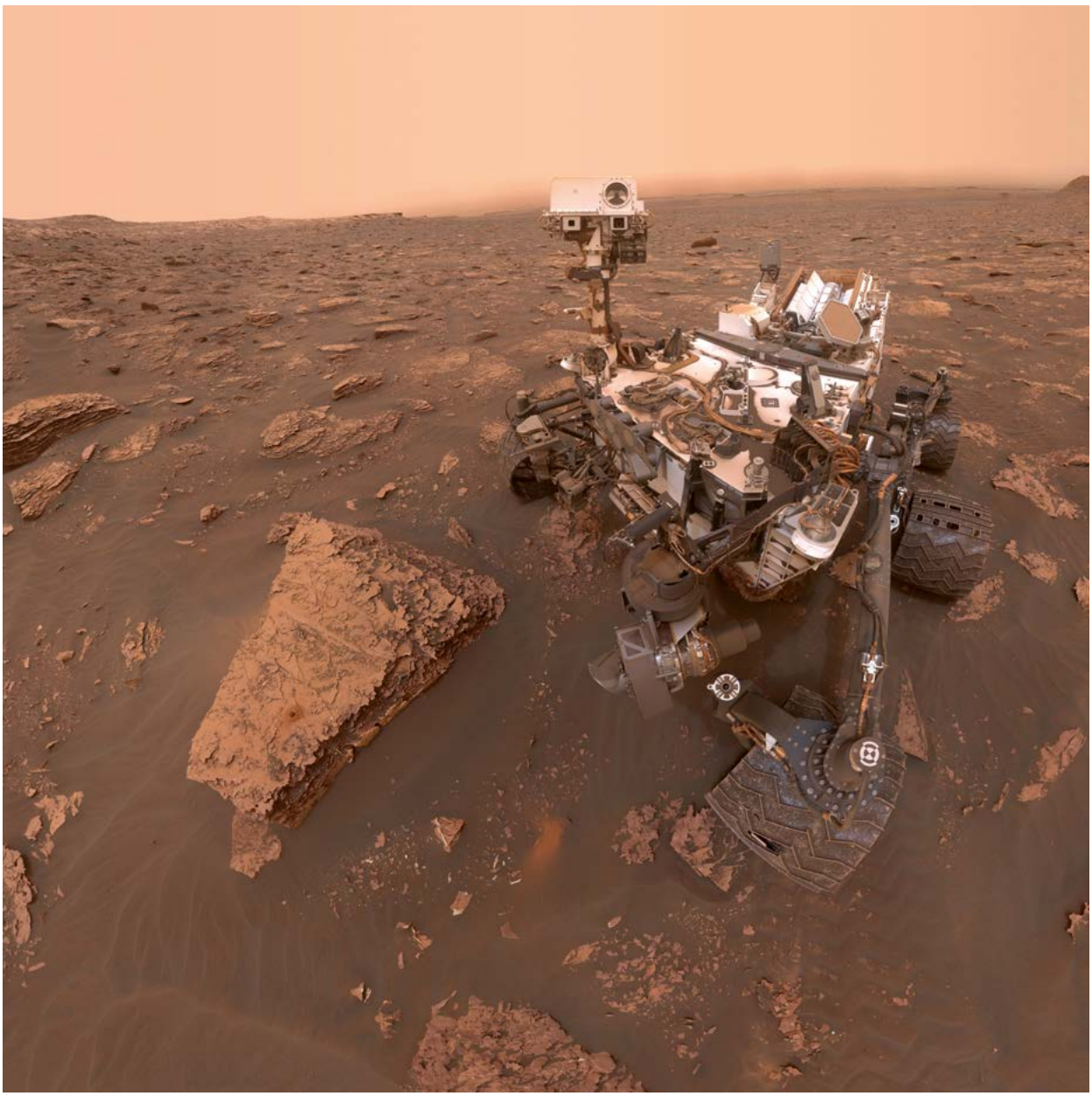
But prospects brighten if we widen our horizons to other stars—far beyond the scale of any probe we can now envisage. The hottest current topic in astronomy is the realization that many other stars—perhaps even most of them—are orbited by retinues of planets, like the Sun is. These planets are not directly seen but inferred by precise measurement of their parent star. There are two methods:

1. If a star is orbited by a planet, then both planet and star move around their center of mass—the barycenter. The star, being more massive, moves slower. But the tiny periodic changes in the star's Doppler effect can be detected by very precise spectroscopy. By now, more than five hundred exo-solar planets have been inferred in this way. We can infer their mass, the length of their "year," and the shape of their orbit. This evidence pertains mainly to "giant" planets—objects the size of Saturn or Jupiter. Detecting Earth-like planets—hundreds of times less massive—is a real challenge. They induce motions of merely centimeters per second in their parent star.

2. But there is a second technique that works better for smaller planets. A star would dim slightly when a planet was "in transit" in front of it. An Earth-like planet transiting a Sun-like star causes a fractional dimming, recurring once per orbit, of about one part in 10,000. The Kepler spacecraft was pointed steadily at a 7-degree-across area of sky for more than three years—monitoring the brightness of over 150,000 stars, at least twice every hour, with precision of one part in 100,000. It found more than two thousand planets, many no bigger than the Earth. And, of course, it only detected transits of those whose orbital plane is nearly aligned with our line of sight. We are specially interested in possible "twins" of our Earth—planets the same size as ours, on orbits with temperatures such that water neither boils nor stays frozen. Some of these have already been identified in the sample, suggesting that there are billions of Earth-like planets in the Galaxy.

The real challenge is to see these planets directly, rather than inferring them from observations of their parent star. But that is hard. To illustrate the challenge, suppose an alien astronomer with a powerful telescope was viewing the Earth from (say) thirty light-years away—the distance of a nearby star. Our planet would seem, in Carl Sagan's phrase, a "pale blue dot,"[1] very close to a star (our Sun) that outshines it by many billions: a firefly next to a searchlight. But if it could be detected, even just as a "dot," several features could be inferred. The shade

A self-portrait by NASA's Curiosity rover taken on Sol 2082 (June 15, 2018). A Martian dust storm has reduced sunlight and visibility at the rover's location in Gale Crater. A drill hole can be seen in the rock to the left of the rover at a target site called "Duluth"



of blue would be slightly different, depending on whether the Pacific Ocean or the Eurasian land mass was facing them. The alien astronomers could infer the length of our "day," the seasons, the gross topography, and the climate. By analyzing the faint light, they could infer that it had a biosphere.

Within ten to fifteen years, the huge E-ELT (Europe's "Extremely Large Telescope"), being built by the European Southern Observatory on a mountain in Chile—with a mosaic mirror thirty-nine meters across—will be drawing inferences like this about planets the size of our Earth, orbiting other Sun-like stars. But what most people want to know is: could there be life on them—even intelligent life? Here we are still in the realm of science fiction.

We know too little about how life began on Earth to lay confident odds. What triggered the transition from complex molecules to entities that can metabolize and reproduce? It might have involved a fluke so rare that it happened only once in the entire Galaxy. On the other hand, this crucial transition might have been almost inevitable given the "right" environment. We just do not know—nor do we know if the DNA/RNA chemistry of terrestrial life is the only possibility, or just one chemical basis among many options that could be realized elsewhere.

Moreover, even if simple life is widespread, we cannot assess the odds that it evolves into a complex biosphere. And, even it did, it might anyway be unrecognizably different. I will not hold my breath, but the SETI program is a worthwhile gamble—because success in the search would carry the momentous message that concepts of logic and physics are not limited to the hardware in human skulls.

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And, by the way, it is too anthropocentric to limit attention to Earth-like planets even though it is a prudent strategy to start with them. Science-fiction writers have other ideas—balloon-like creatures floating in the dense atmospheres of Jupiter-like planets, swarms of intelligent insects, and so on. Perhaps life can flourish even on a planet flung into the frozen darkness of interstellar space, whose main warmth comes from internal radioactivity (the process that heats the Earth's core). We should also be mindful that seemingly artificial signals could come from superintelligent (though not necessarily conscious) computers, created by a race of alien beings that had already died out. Indeed, I think this is the most likely possibility.

We may learn this century whether biological evolution is unique to our Earth, or whether the entire cosmos teems with life—even with intelligence. We cannot give any firm estimates of how likely this is. Even if simple life is common, it is a separate question whether it is likely to evolve into anything we might recognize as intelligent or complex. It could happen often. On the other hand, it could be very rare. That would be depressing for the searchers. But it would allow us to be less cosmically modest: Earth, though tiny, could be the most complex and interesting entity in the entire Galaxy.

The E-ELT will reveal exoplanets, but still only as points of light. But by mid-century there may be huge mirrors in space that could actually resolve an image of an Earth-sized world orbiting another star. Perhaps some of these may have evidence of vegetation or other life. We have had, since 1968, the famous image—iconic ever since among environmentalists—of

our Earth, taken by Apollo astronauts orbiting the Moon. Perhaps by its centenary, in 2068, we will have an even more astonishing image: another Earth, even one with a biosphere.

Strong Gravity and the Large-Scale Cosmos

Back now to the inanimate world of physics and chemistry—far simpler than biology. What has surprised people about the newly discovered planetary systems is their great variety. But the ubiquity of exoplanets was not surprising. We have learned that stars form via the contraction of clouds of dusty gas; and if the cloud has any angular momentum, it will rotate faster as it contracts, and spin off a dusty disk around the protostar. In such a disk, gas condenses in the cooler outer parts; closer in, less volatile dust agglomerates into rocks and planets. This should be a generic process in all protostars.

The crucial force that allows stars to form and holds planets in orbit around them is, of course, that of gravity. And it is Einstein's theory of general relativity that describes precisely how gravity behaves. Einstein did not "overthrow" Newton, but his theory applied more widely than Newton's and offered a deeper understanding of gravity in terms of space and time: in the words of the great physicist John Archibald Wheeler: "Spacetime tells matter how to move; matter tells spacetime how to curve."[2] This great theory was proposed in 1915. But for the first fifty years after its discovery relativity was somewhat isolated from the mainstream of physics and astronomy. The gravitational effects governing ordinary stars and galaxies were weak enough to be adequately described by Newtonian theory—general relativity was no more than a tiny correction.

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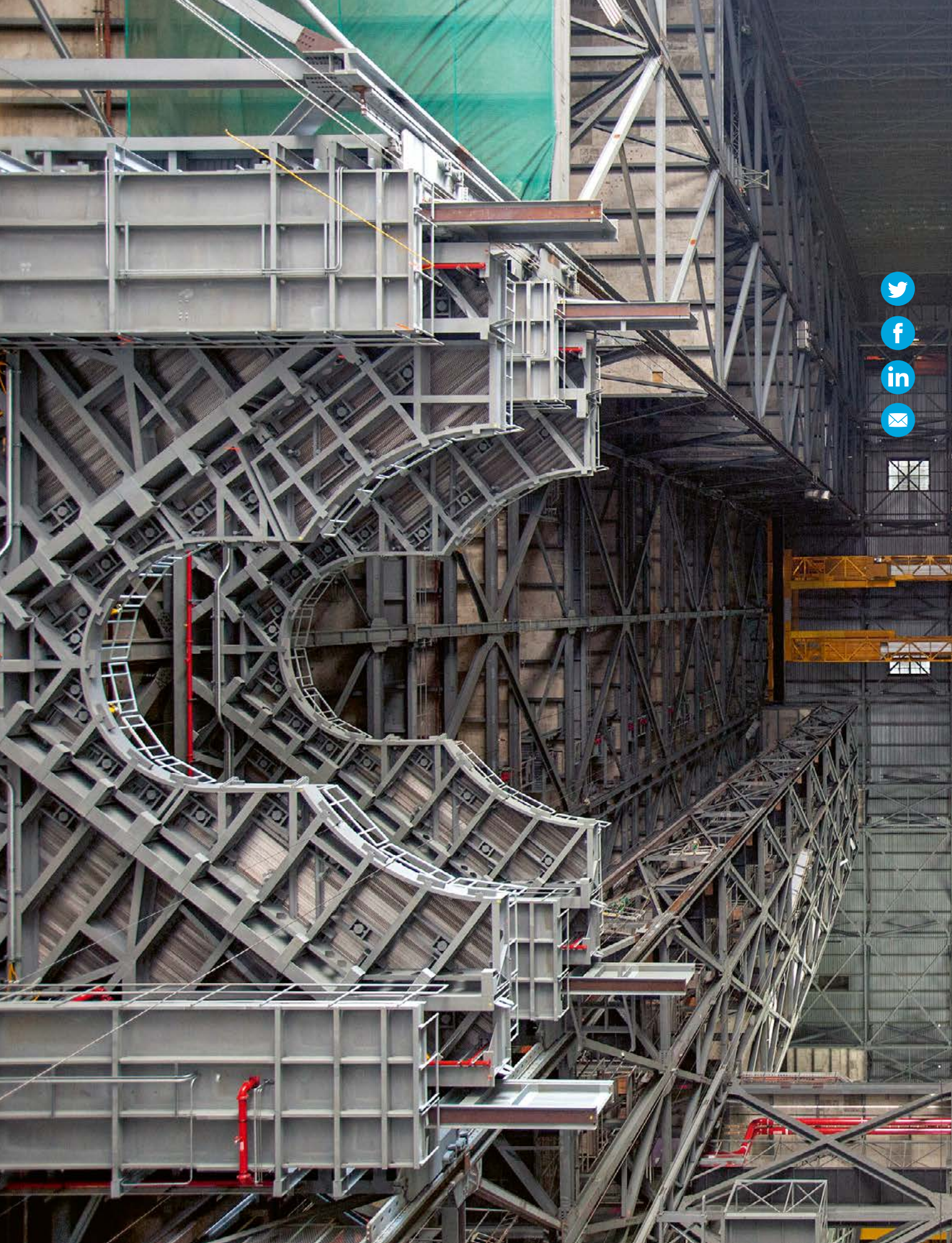
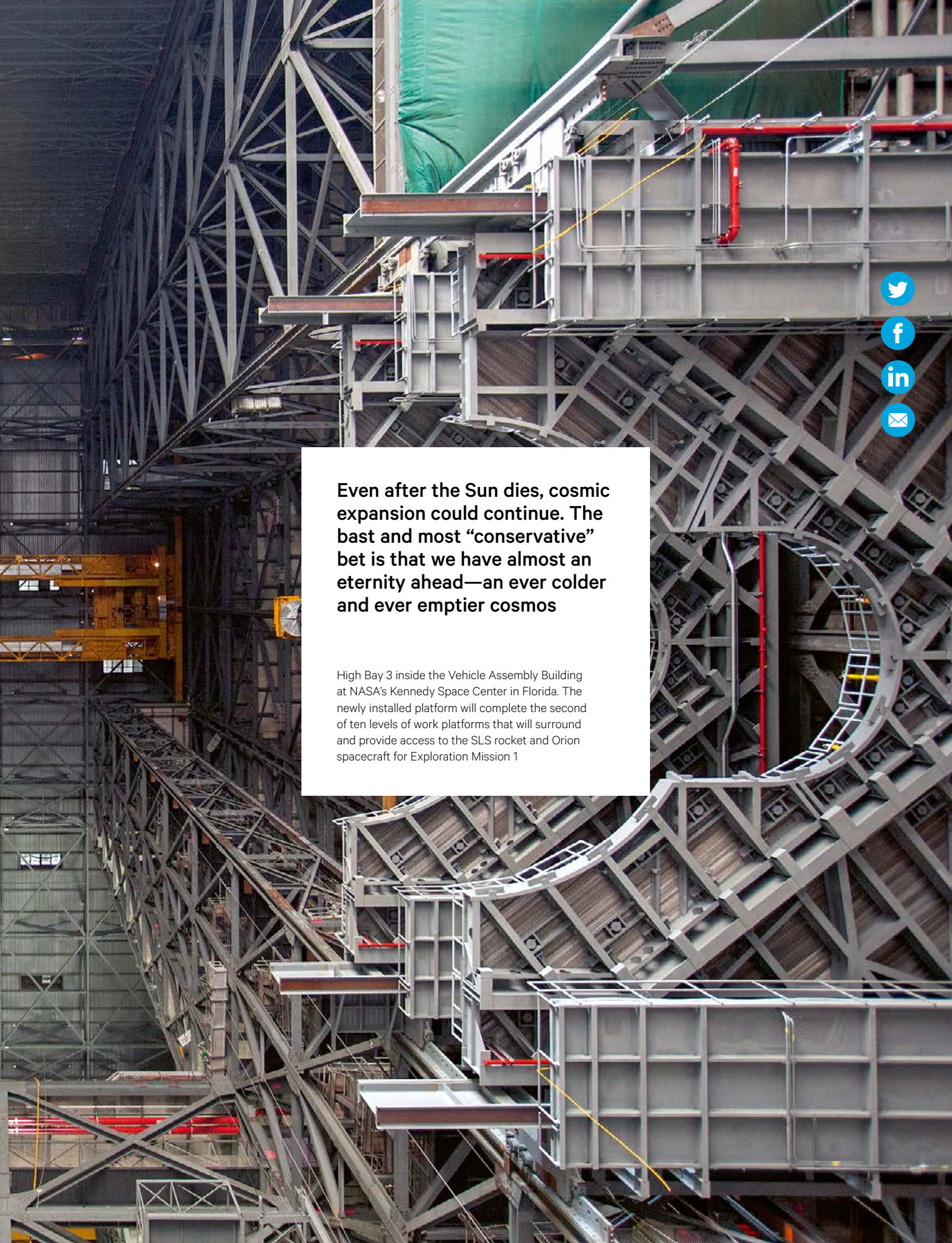
This situation changed in 1963 with the discovery of quasars—hyper-luminous beacons in the centers of some galaxies, compact enough to vary within hours or days, but which vastly outshine their host galaxy. Quasars revealed that galaxies contained something more than stars and gas. That "something" is a huge black hole lurking in their centers. Quasars are specially bright because, as we now recognize, they are energized by emission from magnetized gas swirling into a central black hole.

Quasars were a key stimulus to the emergence of "relativistic astrophysics." But not the only one. In particular, another surprise was the detection of neutron stars. One of the best-known objects in the sky is the Crab Nebula: the expanding debris from a supernova witnessed by Chinese astronomers in AD 1054. What kept it shining, so blue and bright, was a longtime puzzle. The answer came when it was discovered that the innocuous-seeming star in its center was anything but normal. It was actually a neutron star spinning at 30 revs per second and emitting a wind of fast electrons that generated the blue light. In neutron stars relativistic effects are ten to twenty percent—not merely a tiny correction to Newton.

Supernovae are crucial to us: if it was not for them we would not be here. By the end of a massive star's life, nuclear fusion has led to an onion skin structure—with hotter inner shells processed further up the periodic table. This material is then flung out in the supernova





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High Bay 3 inside the Vehicle Assembly Building at NASA's Kennedy Space Center in Florida. The newly installed platform will complete the second of ten levels of work platforms that will surround and provide access to the SLS rocket and Orion spacecraft for Exploration Mission 1

explosion. The debris then mixes into the interstellar medium and recondenses into new stars, orbited by planets.

The concept was developed primarily by Fred Hoyle and his associates. They analyzed the specific nuclear reactions involved, and were able to understand how most atoms of the periodic table came to exist and why oxygen and carbon (for instance) are common, whereas gold and uranium are rare. Some elements are forged in more exotic environments—for instance, gold is made in the cataclysmic collisions of neutron stars—a phenomenon not observed until 2017, when a gravitation wave signal, interpreted as a merger of two neutron stars, was followed up by telescopes that detected the event in many wavebands.

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Our Galaxy is a huge ecological system where gas is being recycled through successive generations of stars. Each of us contains atoms forged in dozens of different stars spread across the Milky Way, which lived and died more than 4.5 billion years ago, polluting the interstellar cloud in which the Solar System condensed.

The 1960s saw the first real advance in understanding black holes since Julius Robert Oppenheimer and his co-workers, in the late 1930s, clarified what happens when something falls into a black hole and cuts itself off from the external world. (And it is interesting to conjecture how much of the 1960s work Oppenheimer might have preempted if World War II had not broken out the very day—September 1, 1939—that his key paper appeared in the *Physical Review*.)

Theorists in the 1960s were surprised when their calculations showed that all black holes that had settled into a steady state were "standardized" objects, specified by just two numbers: their mass, and their spin—no other parameters. This realization hugely impressed the great theorist Subrahmanyan Chandrasekhar, who wrote that "in my entire scientific life, the most shattering experience has been the realization that an exact solution of Einstein's equations … provides the absolutely exact representation of untold numbers of massive black holes that populate the Universe."[3]

A dead quasar—a quiescent massive black hole—lurks at the center of most galaxies. Moreover, there is a correlation between the mass of the hole and that of its host galaxy. The actual correlation is with the bulge (non-disk) component, not the whole galaxy. Our own Galaxy harbors a hole of around four million solar masses—modest compared to the holes in the centers of giant elliptical galaxies, which weigh billions of solar masses.

Einstein was catapulted to worldwide fame in 1919. On May 29 that year there was a solar eclipse. A group led by the Cambridge astronomer Arthur Eddington observed stars appearing close to the Sun during the eclipse. The measurements showed that these stars were displaced from their normal positions, the light from them being bent by the Sun's gravity. This confirmed one of Einstein's key predictions. When these results were reported at the

Royal Society in London, the world press spread the news. "Stars all askew in the heavens; Newton Overthrown" was the rather over-the-top headline in *The New York Times*.[4]

And in February 2016, nearly a hundred years later, there came another equally momentous announcement—this time at the Press Club in Washington—which offered the newest and strongest vindication of Einstein's theory. This was the detection of gravitational waves by LIGO (the acronym stands for Laser Interferometer Gravitational-Wave Observatory). Einstein envisaged the force of gravity as a "warping" of space. When gravitating objects change their shapes, they generate ripples in space itself. When such a ripple passes the Earth, our local space "jitters": it is alternately stretched and compressed as gravitational waves pass through it. But the effect is minuscule. This is basically because gravity is such a weak force. The gravitational pull between everyday objects is tiny. If you wave around two dumbbells you will emit gravitational waves—but with quite infinitesimal power. Even planets orbiting stars, or pairs of stars orbiting each other, do not emit at a detectable level.

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Astronomers are agreed that the sources that LIGO might detect must involve much stronger gravity than in ordinary stars and planets. The best bet is that the events involve black holes or neutron stars. If two black holes form a binary system, they would gradually spiral together. As they get closer, the space around them gets more distorted, until they coalesce into a single, spinning hole. This hole sloshes and "rings," generating further waves until it settles down as a single quiescent black hole. It is this "chirp"—a shaking of space that speeds up and strengthens until the merger, and then dies away—that LIGO can detect. These cataclysms happen less than once in a million years in our Galaxy. But such an event would give a detectable LIGO signal even if it happened a billion light-years away—and there are millions of galaxies closer than that.

To detect even the most propitious events requires amazingly sensitive—and very expensive—instruments. In the LIGO detectors, intense laser beams are projected along four-kilometer-long pipes and reflected from mirrors at each end. By analyzing the light beams, it is possible to detect changes in the distance between the mirrors, which alternately increases and decreases as "space" expands and contracts. The amplitude of this vibration is exceedingly small, about 0.0000000000001 centimeters—millions of times smaller than a single atom. The LIGO project involves two similar detectors about 3,220 kilometers apart—one in Washington State, the other in Louisiana. A single detector would register micro-seismic events, passing vehicles, and so on, and to exclude these false alarms experimenters take note only of events that show up in both.

For years, LIGO detected nothing. But it went through an upgrade, coming fully on line again in September 2015. After literally decades of frustration, the quest succeeded: a "chirp" was detected that signaled the collision of two black holes more than a billion light-years away, and opened up a new field of science—probing the dynamics of space itself.

This detection is, indeed, a big deal: one of the great discoveries of the decade. It allayed any residual skepticism about the validity of Einstein's equations when LIGO detected events

attributable to a merger of two holes. The detected "chirps," complicated patterns of oscillations, are excellently fit by computational models based on Einstein's theory.

The holes detected by LIGO are up to thirty solar masses—the remnants of massive stars. But still more energetic events are expected, involving supermassive holes in the centers of galaxies. When two galaxies merge (as Andromeda and the Milky Way will in about four billion years) the black holes in the center of each will spiral together forming a binary, which will shrink by emitting gravitational radiation and create a strong chirp when the two holes coalesce. Most galaxies have grown via a succession of past mergers and acquisitions. The consequent coalescences of these supermassive black holes would yield gravitational waves of much lower frequencies than ground-based detectors like LIGO can detect. But they are the prime events to which detectors orbiting in space would be sensitive. And ESA has a project called LISA that aims to detect these powerful low-frequency "ripples" in space-time.

Beyond Galaxies—Cosmic Horizons

We know that galaxies—some disc-like, resembling our Milky Way or Andromeda; others amorphous "ellipticals"—are the basic constituents of our expanding universe. But how much can we actually understand about galaxies? Physicists who study particles can probe them, and crash them together in accelerators at CERN. Astronomers cannot crash real galaxies together. And galaxies change so slowly that in a human lifetime we only see a snapshot of each. But we are no longer helpless: we can do experiments in a "virtual universe" via computer simulations, incorporating gravity and gas dynamics.

We can redo such simulations making different assumptions about the mass of stars and gas in each galaxy, and so forth, and see which matches the data best. Importantly, we find, by this method and others, that all galaxies are held together by the gravity not just of what we see. They are embedded in a swarm of particles that are invisible, but which collectively contribute about five times as much mass as the ordinary atom—the dark matter.

And we can test ideas on how galaxies evolve by observing eras when they were young. Giant telescopes, in space and on the ground, have been used to study "deep fields," each encompassing a tiny patch of sky. A patch just a few arc minutes across, hugely magnified by these telescopes, reveals hundreds of faint smudges: these are galaxies, some fully the equal of our own, but they are so far away that their light set out more than ten billion years ago. They are being viewed when they have recently formed.

But what happened still further back, before there were galaxies? The key evidence here dates back to 1965, when Penzias and Wilson discovered that intergalactic space is not completely cold. It is warmed to three degrees above absolute zero by weak microwaves, now known to have an almost exact black body spectrum This is the "afterglow of creation"—the adiabatically cooled and diluted relic of an era when everything was squeezed hot and dense. It is one of several lines of evidence that have allowed us to firm up the "hot big bang" model.

But let us address an issue that might seem puzzling. Our present complex cosmos manifests a huge range of temperature and density—from blazingly hot stars, to the dark night sky. People sometimes worry about how this intricate complexity emerged from an amorphous fireball. It might seem to violate the second law of thermodynamics—which describes an inexorable tendency for patterns and structure to decay or disperse.

The answer to this seeming paradox lies in the force of gravity. Gravity enhances density contrasts rather than wiping them out. Any patch that starts off slightly denser than average

This celestial object looks like a delicate butterfly, but nothing could be farther from reality. What appear to be its wings are roiling cauldrons of gas heated to more than 36,000 degrees Fahrenheit. The gas is tearing across space at more than 600,000 miles an hour—fast enough to travel from Earth to the Moon in twenty-four minutes. The Wide Field Camera 3 (WFC3), a new camera aboard NASA's Hubble Space Telescope, snapped this image in May 2009

would decelerate more, because it feels extra gravity; its expansion lags further and further behind, until it eventually stops expanding and separates out. Many simulations have been made of parts of a "virtual universe"—modeling a domain large enough to make thousands of galaxies. The calculations, when displayed as a movie, clearly display how incipient structures unfold and evolve. Within each galaxy-scale clump, gravity enhances the contrasts still further; gas is pulled in, and compressed into stars.

And there is one very important point. The initial fluctuations fed into the computer models are not arbitrary—they are derived from the variations across the sky in the temperature of the microwave background, which have been beautifully and precisely delineated by ESA's Planck spacecraft. These calculations, taking account of gravity and gas dynamics, reveal, after the 1000-fold expansion since the photons were last scattered, a cosmos that yields a good statistical fit to the conspicuous present structures and allow the universe's mean density, age, and expansion rate to be pinned down with a precision of a few percent.

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The fit between the fluctuation spectrum measured by the Planck spacecraft (on angular scales down to a few arc minutes) and a six-parameter model—and the realization that these fluctuations develop, under the action of gravity and gas dynamics, into galaxies and clusters with properties matching our actual cosmos—is an immense triumph. When the history of science in these decades is written, this will be one of the highlights—and I mean one of the highlights of all of science: up there with plate tectonics, the genome, and only very few others.

The Very Early Universe—More Speculative Thoughts

What about the far future? Any creatures witnessing the Sun's demise six billion years hence will not be human—they will be as different from us as we are from a bug. Post-human evolution—here on Earth and far beyond—could be as prolonged as the Darwinian evolution that has led to us—and even more wonderful. And, of course, this evolution is even faster now—it happens on a technological timescale, operating far faster than natural selection and driven by advances in genetics and in artificial intelligence (AI). We do not know whether the long-term future lies with organic or silicon-based life.

But what happens even further into the future? In 1998 cosmologists had a big surprise. It was by then well known that the gravity of dark matter dominated that of ordinary stuff—but also that dark matter plus ordinary matter contributed only about thirty percent of the so-called critical density. This was thought to imply that we were in a universe whose expansion was slowing down, but not enough to eventually be halted. But, rather than slowly decelerat-

ing, the redshift versus distance relationship for a particular population of exploding star—Type 1a supernovae—famously revealed that the expansion was speeding up. Gravitational attraction was seemingly overwhelmed by a mysterious new force latent in empty space which pushes galaxies away from each other.

Even after the Sun dies, cosmic expansion could continue. Long-range forecasts are seldom reliable, but the best and most "conservative" bet is that we have almost an eternity ahead—an ever colder and ever emptier cosmos. Galaxies accelerate away and disappear over an "event horizon"—rather like an inside-out version of what happens when things fall into a black hole. All that is left will be the remnants of our Galaxy, Andromeda, and their smaller neighbors. Protons may decay, dark-matter particles annihilate, occasional flashes when black holes evaporate—and then silence.

The nature of dark matter may well be pinned down in a decade, but this dark energy—latent in empty space itself—poses a deeper mystery. It will not be understood until we have a model for the microstructure of space. I am not holding my breath for this: all theorists suspect this will involve phenomena on what is called the "Planck length"—the scale where quantum effects and gravity overlap. This scale is a trillion trillion times smaller than an atom. Dark energy may be the biggest fundamental challenge presented by the present-day universe.

But now, back to the past. The background radiation is a direct messenger of an era when the universe was a few hundred thousand years old—the photons have mainly traveled uninterruptedly, without scattering, since then. But we have firm grounds for extrapolating further back—to hotter and denser eras. We are definitely vindicated in extrapolating back to one second, because the calculated proportions of helium and deuterium produced (for a nuclear density fitting other data) match beautifully with what is observed. Indeed, we can probably be confident in extrapolation back to a nanosecond: that is when each particle had about 50 GeV of energy—an energy that can be achieved in the LHC (Large Hadron Collider) at CERN in Geneva—and the entire visible universe was squeezed to the size of our Solar System.

But questions like "Where did the fluctuations come from?" and "Why did the early universe contain the actual mix we observe of protons, photons, and dark matter?" take us back to the even briefer instants when our universe was hugely more compressed still—into an ultra-high-energy domain where experiments offer no direct guide to the relevant physics.

For close to forty years we have had the so-called "inflationary paradigm"—seriously invoking an era when the Hubble radius was a billion times smaller than an atomic nucleus. It is an amazingly bold backward extrapolation, to an era when the physics was extreme, and cannot be tested by experiments. This paradigm is supported already by some evidence. Be that as it may, it might be useful to summarize the essential requirements that must be explained, if we are to understand the emergence of our complex and structured cosmos from simple amorphous beginnings.

1. The first prerequisite is, of course, the existence of the force of gravity—which (as explained earlier) enhances density contrasts as the universe expands, allowing bound structures to condense out from initially small-amplitude irregularities. It is a very weak force. On the atomic scale, it is about forty powers of ten weaker than the electric force between electron and proton. But in any large object, positive and negative charges almost exactly cancel. In contrast, everything has the same "sign" of gravitational charge so when

sufficiently many atoms are packed together, gravity wins. But stars and planets are so big because gravity is weak. Were gravity stronger, objects as large as asteroids (or even sugar-lumps) would be crushed by gravity. So, though gravity is crucial, it is also crucial that it should be very weak.

2. There must be an excess of matter over antimatter.

3. Another requirement for stars, planets, and biospheres is that chemistry should be non-trivial. If hydrogen were the only element, chemistry would be dull. A periodic table of stable elements requires a balance between the two most important forces in the microworld: the nuclear binding force (the "strong interactions") and the electric repulsive force that drives protons apart.

4. There must be stars—enough ordinary atoms relative to dark matter. (Indeed, there must be at least two generations of stars: one to generate the chemical elements, and a second able to be surrounded by planets.)

5. The universe must expand at the "right" rate—not collapse too soon, nor expand so fast that gravity cannot pull together the structures.

6. There must be some fluctuations for gravity to feed on—sufficient in amplitude to permit the emergence of structures. Otherwise the universe would now be cold ultra-diffuse hydrogen—no stars, no heavy elements, no planets, and no people. In our actual universe, the initial fluctuations in the cosmic curvature have an amplitude 0.00001. According to inflationary models, this amplitude is determined by quantum fluctuations. Its actual value depends on the details of the model.

Another fundamental question is this: how large is physical reality? We can only observe a finite volume. The domain in causal contact with us is bounded by a horizon—a shell around us, delineating the distance light (if never scattered) could have traveled since the big bang. But that shell has no more physical significance than the circle that delineates your horizon if you are in the middle of the ocean. We would expect far more galaxies beyond the horizon. There is no perceptible gradient across the visible universe—suggesting that similar conditions prevail over a domain that stretches thousands of times further. But that is just a minimum. If space stretched far enough, then all combinatorial possibilities would be repeated. Far beyond the horizon, we could all have avatars—and perhaps it would be some comfort that some of them might have made the right decision when we made a wrong one!

But even that immense volume may not be all that exists. "Our" big bang may not be the only one. The physics of the inflation era is still not firm. But some of the options would lead to so-called "eternal inflation" scenario, in which the aftermath of "our" big bang could be just one island of space-time in an unbounded cosmic archipelago.

In scenarios like this, a challenge for twenty-first-century physics is to answer two questions. First, are there many "big bangs" rather than just one? Second—and this is even more interesting—if there are many, are they all governed by the same physics or not? Or is there a huge number of different vacuum states—with different microphysics?

If the answer to this latter question is "yes," there will still be underlying laws governing the multiverse—maybe a version of string theory. But what we have traditionally called the laws of nature will be just local bylaws in our cosmic patch. Many domains could be stillborn

or sterile: the laws prevailing in them might not allow any kind of complexity. We therefore would not expect to find ourselves in a typical universe—rather, we would be in a typical member of the subset where an observer could evolve. It would then be important to explore the parameter space for all universes, and calculate what domains within it allow complexity to emerge. This cannot be done unless (probably after a long wait) a theory such as string theory becomes believable and "battle-tested."

Some claim that unobservable entities are not part of science. But few really think that. For instance, we know that galaxies disappear over the horizon as they accelerate away. But (unless we are in some special central position and the universe has an "edge" just beyond the present horizon) there will be some galaxies lying beyond our horizon—and if the cosmic acceleration continues they will remain beyond for ever. Not even the most conservative astronomer would deny that these never-observable galaxies are part of physical reality. These galaxies are part of the aftermath of our big bang. But why should they be accorded higher epistemological status than unobservable objects that are the aftermath of other big bangs?

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To offer an analogy: we cannot observe the interior of black holes, but we believe what Einstein says about what happens there because his theory has gained credibility by agreeing with data in many contexts that we can observe. Likewise, if we had a model that described physics at the energies where inflation is postulated to have occurred, and if that model had been corroborated in other ways, then if it predicts multiple big bangs we should take that prediction seriously.

If there is just one big bang, then we would aspire to pin down why the numbers describing our universe have the values we measure (the numbers in the "standard model" of particle physics, plus those characterizing the geometry of the universe). But if there are many big bangs—eternal inflation, the landscape, and so forth—then physical reality is hugely grander than we would have traditionally envisioned.

It could be that in fifty years we will still be as flummoxed as we are today about the ultra-early universe. But maybe a theory of physics near the "Planck energy" will by then have gained credibility. Maybe it will "predict" a multiverse and in principle determine some of its properties—the probability measures of key parameters, the correlations between them, and so on.

Some do not like the multiverse; it means that we will never have neat explanations for the fundamental numbers, which may in this grander perspective be just environmental accidents. This naturally disappoints ambitious theorists. But our preferences are irrelevant to the way physical reality actually is—so we should surely be open-minded.

Indeed, there is an intellectual and aesthetic upside. If we are in a multiverse, it would imply a fourth and grandest Copernican revolution; we have had the Copernican revolution itself, then the realization that there are billions of planetary systems in our Galaxy; then that there are billions of galaxies in our observable universe.

But we would then realize that not merely is our observable domain a tiny fraction of the aftermath of our big bang, but our big bang is part of an infinite and unimaginably diverse ensemble.

This is speculative physics—but it is physics, not metaphysics. There is hope of firming it up. Further study of the fluctuations in the background radiation will reveal clues. But, more important, if physicists developed a unified theory of strong and electromagnetic forces—and that theory is tested or corroborated in our low-energy world—we would then take seriously what it predicts about an inflationary phase and what the answers to the two questions above actually are.

I started this talk by describing newly discovered planets orbiting other stars. I would like to give a flashback to planetary science four hundred years ago—even before Newton. At that time, Kepler thought that the Solar System was unique, and Earth's orbit was related to the other planets by beautiful mathematical ratios involving the Platonic regular solids. We now realize that there are billions of stars, each with planetary systems. Earth's orbit is special only insofar as it is in the range of radii and eccentricities compatible with life (for example, not too cold and not too hot to allow liquid water to exist).

Maybe we are due for an analogous conceptual shift, on a far grander scale. Our big bang may not be unique, any more than planetary systems are. Its parameters may be "environmental accidents," like the details of the Earth's orbit. The hope for neat explanations in cosmology may be as vain as Kepler's numerological quest.

If there is a multiverse, it will take our Copernican demotion one stage further—our Solar System is one of billions of planetary systems in our Galaxy, which is one of billions of galaxies accessible to our telescopes—but this entire panorama may be a tiny part of the aftermath of "our" big bang—which itself may be one among billions. It may disappoint some physicists if some of the key numbers they are trying to explain turn out to be mere environmental contingencies—no more "fundamental" than the parameters of the Earth's orbit round the Sun. But, in compensation, we would realize that space and time were richly textured—but on scales so vast that astronomers are not directly aware of it, any more than a plankton whose "universe" was a spoonful of water would be aware of the world's topography and biosphere.

We have made astonishing progress. Fifty years ago, cosmologists did not know if there was a big bang. Now, we can draw quite precise inferences back to a nanosecond. So, in fifty years, debates that now seem flaky speculation may have been firmed up. But it is important to emphasize that progress will continue to depend, as it has up till now, ninety-five percent on advancing instruments and technology—less than five percent on armchair theory, but that theory will be augmented by artificial intelligence and the ability to make simulations.

Concluding Perspective

Finally, I want to draw back from the cosmos—even from what may be a vast array of cosmoses, governed by quite different laws—and focus back closer to the here and now. I am often asked: is there a special perspective that astronomers can offer to science and philosophy? We view our home planet in a vast cosmic context. And in coming decades we will know whether there is life out there. But, more significantly, astronomers can offer an awareness of an immense future.

Darwinism tells us how our present biosphere is the outcome of more than four billion years of evolution. But most people, while accepting our emergence via natural selection, still

somehow think we humans are necessarily the culmination of the evolutionary tree. That hardly seems credible to an astronomer—indeed, we are probably still nearer the beginning than the end. Our Sun formed 4.5 billion years ago, but it has got six billion more before the fuel runs out. It then flares up, engulfing the inner planets. And the expanding universe will continue—perhaps for ever—destined to become ever colder, ever emptier.

But my final thought is this. Even in this "concertinaed" timeline—extending billions of years into the future, as well as into the past—this century may be a defining moment. Over most of history, threats to humanity have come from nature—disease, earthquakes, floods, and so forth. But this century is special. It is the first where one species—ours—has Earth's future in its hands, and could jeopardize life's immense potential. We have entered a geological era called the anthropocene.

Our Earth, this "pale blue dot" in the cosmos, is a special place. It may be a unique place. And we are its stewards at a specially crucial era. That is an important message for us all, whether we are interested in astronomy or not.

Notes

1. Carl Sagan, *Pale Blue Dot: A Vision of a Human Future in Space*, New York: Random House, 1994.
2. See, for instance, Charles W. Misner, Kip S. Thorne, and John Archibald Wheeler, *Gravitation*, New Jersey: Princeton University Press, 2017 (1st ed. 1973).
3. Subrahmanyan Chandrasekhar, *The Mathematical Theory of Black Holes*, Oxford: Oxford University Press, 1998 (1st ed. 1983).
4. *The New York Times*, November 10, 1919.

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