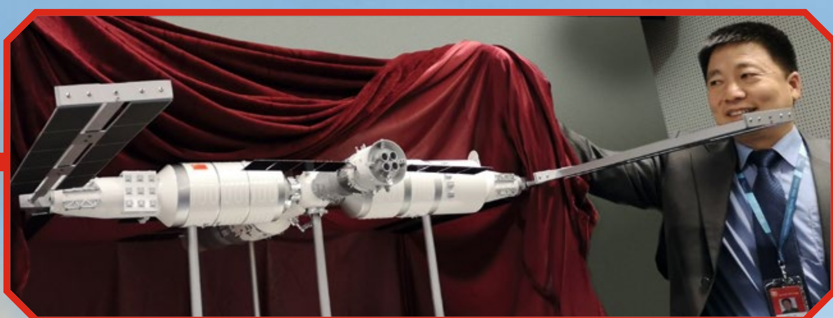
China in Space

The Great Leap Forward



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Brian Harvey

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To
Judith, Valerie, Alistair and Charlie

About the Author

Brian Harvey is a writer and broadcaster on space flight who lives in Dublin, Ireland. He has a degree in history and political science from Dublin University (Trinity College) and a MA from University College Dublin. His first book was *Race into space – the Soviet space programme* (Ellis Horwood, 1988), followed by further books on the Russian, Chinese, European, Indian and Japanese space programs. His books and chapters have been translated into Russian, Chinese and Korean.

Author's Introduction

If the space race between the Soviet Union and the United States was the space story of the 20th century, then the emergence of China as a spacefaring nation was the story of the early 21st century. Indeed, the new century was just three years old when China became only the third country to launch its own astronauts or cosmonauts – called *hangtianyuan* in China – with Yang Liwei spending a day circling the Earth. He was followed by longer spaceflights, spacewalks, a space laboratory called Tiangong and China's first space woman, Liu Yang. The Moon program began in 2007, with an orbiter followed by a lander and a rover. China's space station, now in construction, is likely to be in orbit long after the International Space Station has concluded its work.

Over the long course of history, the emergence of China as a spacefaring nation should be no surprise. Observations made by the ancient Chinese astronomers are renowned for their accuracy and way back in what were sometimes called the dark ages in Europe, the rocket was invented in China. In the 20th century, many of the engineering calculations necessary for rocket flight were done by one of the world's great space designers, Tsien Hsue Shen, while the Chinese space program was founded on 8 October 1956, a year before the first Sputnik was even launched. On that day, China's political leadership decreed the foundation of the Fifth Academy to spearhead the nation's space effort and requisitioned two abandoned sanatoria to be its first laboratories. Had it not been for subsequent political upheaval – the great leap forward and the cultural revolution – China might have achieved much more, much sooner.

As it was, China's first satellite in orbit was the *biggest* first satellite. China was the third space power to recover its own satellites, put animals in orbit and develop hydrogen-fueled upper stages. China developed a broad program for Earth observations, navigation, communications, weather forecasting and materials processing. China overtook Europe in launchings per year, surpassed the United States and even overtook Russia. China replaced its old launchers with a new fleet, opened a new launch base on the island of Hainan and subsequently declared its aim of becoming the world's leading scientific nation by 2050. A simulated Moonbase was built on Earth, a sure indicator of things to follow.

The Chinese space program has sometimes been called the last of the secret space programs and details of its early history still remain obscure. Writing about the early Chinese space program is like trying to assemble a jigsaw for which some of the pieces are not colored in and others are missing altogether. Even today, its facilities are not easy to access, although in recent times, China has become more forthcoming in detailing information on its current programs and future intentions. Launches and missions are now broadcast live, a sign of both confidence and growing openness.

Western misunderstanding of the Chinese space program presents a challenge of similar magnitude. With some honorable exceptions, many in the western media who ought to know better responded to Chinese space developments with a mixture of puzzlement, patronizing put-downs and dismissal. Chinese capabilities were often played down on the basis that their equipment was alternately primitive or imitative. If it worked, the presumption was that it must have been stolen or developed for sinister military purposes. There remains an extraordinary reluctance to concede to the Chinese the credit of having created, designed and built their own equipment. This is a problem not peculiar to the space program, for the west often forgets how China pioneered so many things, from medicine to mathematics and public administration, as well such inventions as the suspension bridge, paper-making, the compass, chemistry, printing, paper money, the stirrup, the plough, the lock gate, the wheelbarrow and clockwork.

This book is the fourth in a series. The first of that series was *The Chinese Space Program – From Conception to Future Capabilities* published by Praxis/Wiley in 1998 and told the story of the program from its pre-history, through its first launch (1970) and its subsequent development in the 1980s and 1990s. The story was brought fully up to date as *China's Space Program – From Conception to Manned Spaceflight* (Praxis/Springer, 2004) after Yang Liwei circled the Earth. The third volume, *China in Space – The Great Leap Forward* (Praxis/Springer, 2013) marked China's first space laboratory, Tiangong 1 and the flight there of China's first space woman, Liu Yang. In this fourth book, *China in Space: The Great Leap Forward - Second Edition*, it is time to focus on China's biggest space construction project, a large permanent space station, along with China's new rocket fleet, the launch center in Hainan, new scientific projects and ever-expanding ambitions across the solar system.

This book opens with the landing of Chang e 4 on the far side of the Moon – a true world first in space exploration – and China's plans for a space station. Chapter 2 (*Medieval rockets to first satellites*) provides a historical context. This is followed by an account of launch sites, tracking ships and organization in chapter 3 (*New rockets, launch sites and ships*); space science (chapter 4); communications satellites (chapter 5); and applications and military satellites (chapter 6). Chapter 7 describes the manned spaceflight program, while chapter 8 examines Chinese exploration of the Moon and Mars. Finally, chapter 9 sets the Chinese space program in perspective. The book brings to the reader the substantial expansion of the Chinese space program since 2013. In doing so, some of the detailed descriptions and related references of earlier missions have been reduced in length, but readers may still find them in the previous books.

Finally, a note on terminology. A complicating feature – one familiar to students of the Soviet space program – is the use of different designators for the same satellites. In the west, Chinese satellites were named China 1, 2, 3 and so on, as well as PRC-1, PRC-2 (People's Republic of China) and even Mao 1, 2 and 3. At the time, the Chinese simply referred to these missions by their date of launch or by their connection to political events. Eventually, the Chinese introduced a set of designators and applied them retrospectively. That should have been an end to the matter, but the Chinese then revised some of these designators several times over – and then changed them again! Even to this day, different designators are applied to the same program and across other programs. As if this were not complicated enough, inconsistent translations mean that many institutes, bodies and organizations acquire slightly different names over time. Sometimes, similar sounding names turn out to be the same thing – but sometimes not. The Chinese also applied a series of numerical codes to their various space projects. Some were based on dates, others not. All this must be carefully disentangled. Here, the most consistent and most universally understandable systems have been used, but readers should be aware that others are also in use. We must also note that the Chinese have sometimes, though not always, followed the Soviet practice of not giving a number to the first satellite of a series. In subsequent numbering of a series, several practices are apparent: the use of A, B, C designators and different ways of recording numbers, with sub-series numbers written both with and without a '0', thus 1-1 and 1-01.

With regard to personal names, this book generally follows the Chinese practice of identifying people by their surname first. Chinese astronauts are called *hangtianyuan*. Three names are in use to describe Chinese space travelers – *yuhangyuan*, which means 'universe travel person' applied mainly to Americans and Russians; *taikonauts*, a popular but invented name (rather like 'Lunik' for early Soviet Moon probes); and *hangtianyuan* ('heavenly travel person'), which applies to Chinese space fliers and is the term which will be used here. Finally, depending on the circumstances, three currencies are used in this book: Chinese yuan (¥); the European euro (€) and before its introduction its precursor, the European Currency Unit (ECU); and the US dollar ($).

Brian Harvey
Dublin, Ireland, 2019

1

The far side of the Moon

This story of China's space program begins in two places: on the far side of the Moon, where in January 2019 China conducted its most ambitious lunar mission to date; and at Jiuquan, in the desert of northwest China, where China began all the necessary tests for the later construction of its first large space station.

Chang e 4

The Chang e 4 mission arose almost by accident. In 2013, China made its first lunar landing, Chang e 3, which deployed a small rover called Yutu, or 'jade rabbit'. With this success (except for the rover wheels becoming stuck early on), China saw little purpose in repeating the mission, but there was a flight-ready backup spacecraft on the ground. For a year, the likelihood was that it would not fly at all and it even disappeared from the manifest, with Chang e 5 scheduled next.

The announcement of a mission for Chang e 4 was made in May 2015, stating that it would make the first ever landing on the lunar far side. This raised many eyebrows, as no country had attempted such an out-of-field, ambitious and challenging mission, although such a mission was outlined by the Soviet Union in the 1970s. This would be a genuine first, an advance for the world.

A far side landing is doubly challenging. Not only is it out of sight of Earth, but the far side of the Moon comprises mainly rocky terrain, with limited flat landing areas – the floors of crater Tsiolkovsky and the Mare Moskve being the only obviously flat parts. Chang e 4 was aimed at a third point, Mare Ingenii, later redefined as the South Pole Aitken (SPA) Basin, the largest impact structure on the Moon at 45°–55°S, 162°–144°W, near the lunar south pole and an

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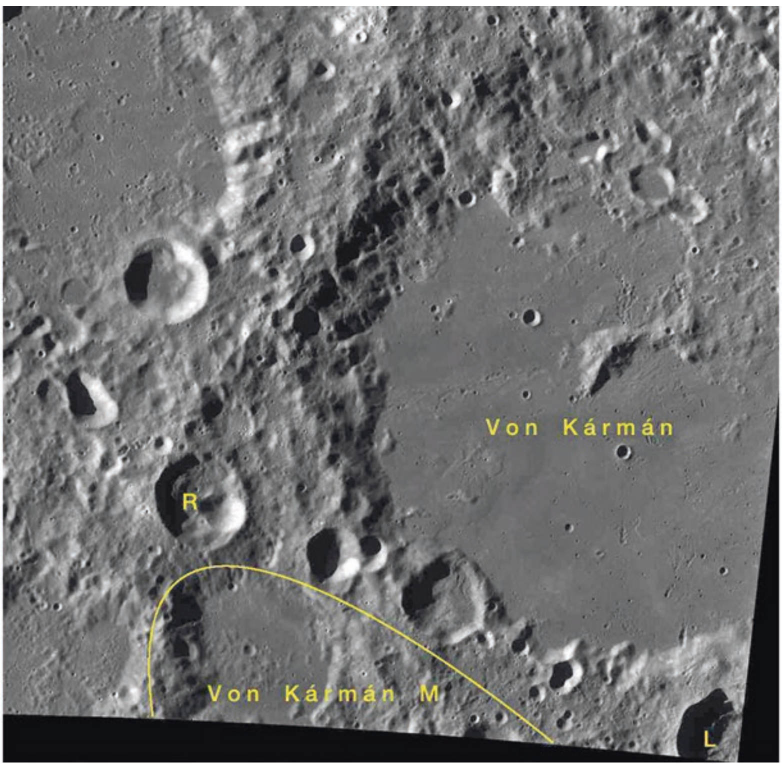
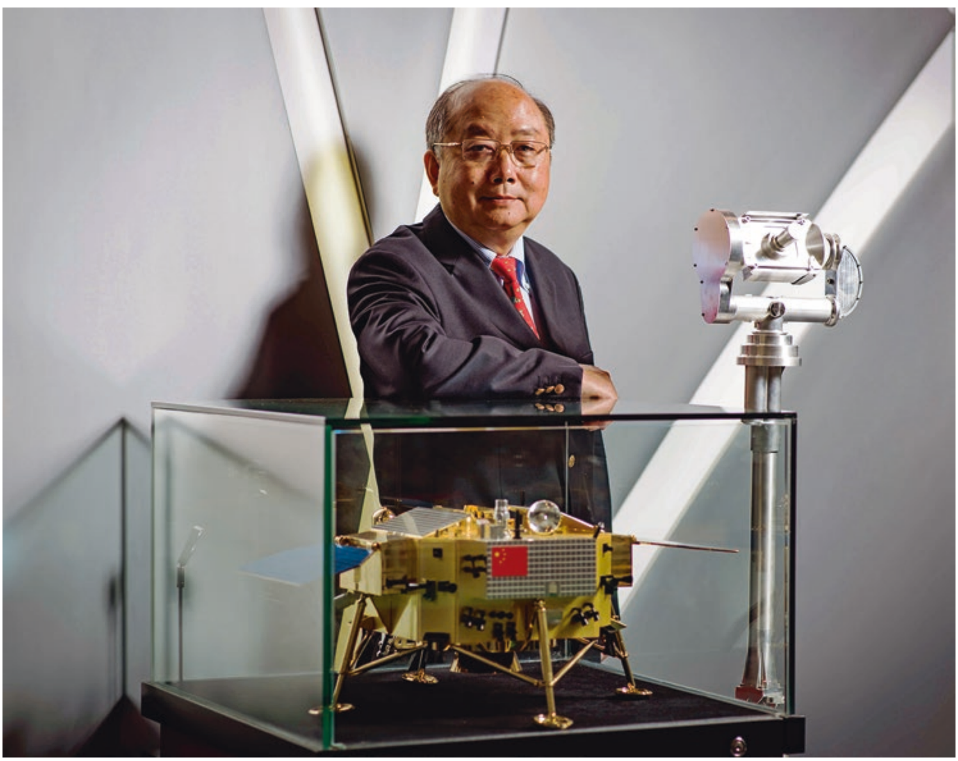
area flooded with several generations of basalts. A first far side landing there would begin to put together a picture of what was thought to be the oldest part of the Moon, up to 3.6 billion years old. The impact of the basin was so deep, almost 6km below the lunar mean, that it might descend well into the crust of the Moon, making investigation there invaluable. The actual landing site was narrowed down to the 186km-diameter crater Von Kármán (45°S, 176°E), believed to be one of the main sources of ejecta and secondary craters there. Its crater floor is relatively flat, at no more than 60m between its high and low points, interrupted by extensive sinuous ridges, with a regolith estimated to be 2.5m to 7.5m deep [**1**].



Crater von Kármán. Credit Andrei Shcherbakov.

Because the far side is, by definition, not visible from Earth, such a landing required a relay satellite, launched into what is called a halo orbit at least three months in advance. This would be a small spacecraft launched on a Long March CZ-4C rocket and stationed 60,000km behind the Moon. It would carry a large dish, the largest ever used for deep space exploration according to the Chinese.

The landing used a technique developed for Chang e 3, whereby detailed, digitized maps were made of the landing site from earlier orbiting spacecraft and then fed into the guidance system. As the spacecraft came into land, these maps were matched against the actual radar imaging so that the guidance could then steer the spacecraft into a landing on the smoothest, flattest site. Chang e 4 carried what was called the Camera Pointing System, developed by Hong Kong Polytechnic University. The instrument weighed 2.8kg and measured 85cm by 27cm by 16cm. Located on the upper part of the lander, it could move vertically 120 degrees and sideways 350 degrees. The university used topographic mapping and geomorphological analysis of terrain slopes, Sun illumination, crater distribution, rock abundances and geological history of the region to characterize the best possible landing site. Finding the right, flat spot was essential and there was always a danger of the spacecraft toppling over on landing. Photographs from lunar orbit subsequently found the Soviet Union's Luna 23 toppled over on its side.



Professor Kai-leung Yung, Hong Kong Polytechnic University (HKPU), who developed the Camera Pointing System. Credit: HKPU.

Chang e 4 science

The formal scientific objectives of the flight were: the first landing on the far side of the Moon; the study of lunar dust; the measurement of lunar surface residual magnetism and its interaction with the solar wind; the study of the lunar surface temperature and particle radiation environment; lunar surface topology and material composition analysis, surveying the shallow layer structure; the exploration of lunar surface interiors; and Very Long Frequency (VLF) observations.

A program of international participation with Europe was then developed, for which a joint seminar was held in July 2015. The University of Kiel, Germany, provided the Lunar Lander Neutron Dosimetry instrument to measure radiation and water content. The Swedish Institute for Space Physics in Kiruna contributed the Advanced Small Analyzer for Neutrals (ASAN) to study the interaction of the solar wind with the lunar surface, placed on top of the rover so that measurements could be made at different locations on the surface. It was housed in a thermally insulated container that could be opened during daytime but closed at night for protection against the cold.

Saudi Arabia and Russia joined later, the latter contributing a lunar dust surveyor [2]. There would be two radio astronomy experiments: a Chinese-built one on the lander to make a low-frequency sky map over the range 0.1 to 40 MHz using three 5m booms; and a Dutch-built radio spectrometer on the relay satellite to make a low-frequency map of the radio sky, detect bright pulsars and pick up auroral transmissions from the large planets of the solar system. Dutch scientists in Radboud University, Nijmegen, hoped to use the data to model the early stages of the universe. Heino Falke, Professor of Astroparticle Physics and Radio Astronomy at Radboud, explained that the radio telescope would search radio waves below 30MHz, which are blocked by the atmosphere. The idea of a low-frequency mission in lunar orbit, taking advantage of shelter from Earth's radio noise, was far from new. Explorer 49, launched into lunar orbit by the United States in 1973, made low frequency observations in the 0.2 to 20 MHz range.

A surprise addition to the lander was a mini-ecosystem of silkworm eggs, Arabidopsis seeds and potato seeds in air in a nutrient solution, in a 3kg, 18cm tall, 0.8-l, aluminum box, the first ever biological laboratory to land on the Moon. It had been developed by Chongqing university with 28 other universities and was selected from 200 proposals. The intention was that the silkworms would hatch and produce carbon dioxide which the potatoes and Arabidopsis seeds would absorb, emitting oxygen that would then help the silkworms. This would be live-streamed by camera. While this was an exotic and spectacular idea, the exact purpose of conducting the experiment on the Moon was unclear – as were the implications for biological contamination. It was explained that this prototypical mini self-sustaining biosphere would be activated when the first rays of the Sun flooded into the top of the box through a tube. The potato flowers were expected to be the first flourishment on the Moon.

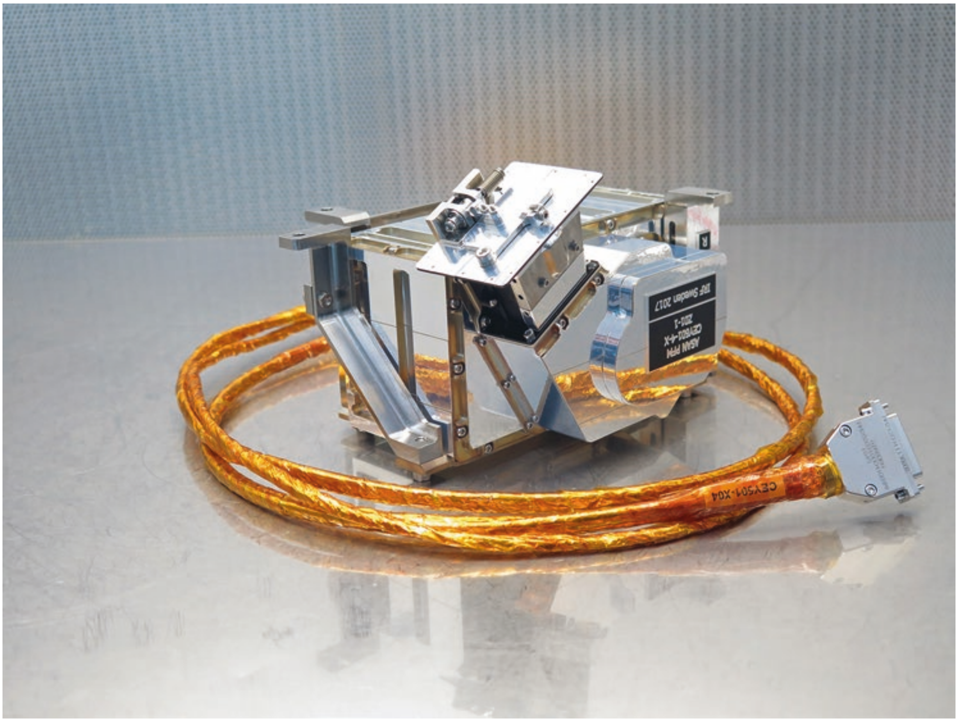
Early in 2018, the relay mission acquired two passengers, a pair of microsatellites called the DSLWP (Discovering the Sky at Longest Wavelengths Pathfinder) A1 and A2, weighing 45kg, measuring 50cm by 50cm by 40cm and designed to fly in formation some 1km to 10km apart. They were developed by students and amateur radio enthusiasts at Harbin Institute for Technology (HIT), the same team that developed the small Lilac satellites (see chapter 6). Each microsatellite carried a set of receivers to support the radio astronomy experiment. DSLWP A2 also carried a Saudi Arabian micro-camera developed by the King Abdulaziz City for Science and Technology.

Again, the idea of microsatellites in lunar orbit was not new, as Japan had deployed microsatellites *Okina* and *Ouna* from their mother craft Kaguya several years earlier. They would be dropped into lunar orbit and fly separately from the main spacecraft. They would be among the smallest satellites to orbit the Moon and the precursors of small satellites to be launched with lunar and interplanetary probes in the future.

Queqiao included a laser reflector developed by Sun Yat-sen University, but like the radio experiment, the actual testing of this experiment was delayed to 2019 and after the intended landing.

China made a formal media presentation of the rover in August 2018, giving its dimensions as 1.5m long, 1.1m high and weighing 135kg, suggesting that it was newly built rather than the flight-ready backup. They described it as ‘lighter, smarter, stronger and more reliable’, able to travel at 200m/hr with the help of two 3D, 360-degree panoramic cameras on top. It retained the same features as its predecessor, such as two solar panels and six wheels. It was programmed to shut down when light levels fell at lunar dusk and re-awaken at lunar dawn. The big design challenge, apparently, was to make the wheels more reliable this time, with improved wiring to prevent short circuits. A competition to choose a name was instigated, with a closing date of 5 September, a prize of ¥3,000 (€330) and an invitation to the launch. There were 40,000 entries, by citizens ranging from seven to 94. Ten were selected for ballot and in the subsequent poll, three names came out on top: ‘Guangming’ (‘brightness’, 39 percent); Wang Shu (from folklore, 25 percent); and Xingzhe (‘hiker’, after a walker who journeyed to the west, 16 percent). In the end, a different decision was made. The lander would be kept warm during the lunar night by a radio-isotope thermoelectric generator. High quality pictures were expected from the terrain camera on top of the lander.

The instruments on Chang e 4 are listed in Table 1.1. They essentially followed the same canon of instruments as flown on Chang e 3, but with the surprising absence of an alpha particle spectrometer to make a chemical analysis of the lunar surface.



Advanced Small Analyzer for Neutrals (ASAN). Credit: Martin Wieser, Swedish Institute of Space Physics, Kiruna, Sweden.

Table 1.1: Chang e 4 instruments

Spacecraft	Instrumentation
Lander	– Lunar Dust Analyzer (LDA) – Electric Field Analyzer (EFA) – Plasma and Magnetic Field Observation Package (PMFOP) – Lunar Seismometer (LS) – VLF Radio Interferometer (VRI; Netherlands) – Lunar Neutron Dosimeter (LND; University of Kiel, Germany) – Low Frequency Spectrometer (LFS), three 5m booms – Landing camera (LCAM), Terrain camera (TCAM)
Rover	– Panoramic camera (PCAM) – Lunar Penetrating Radar (LPR) – Visible and Near Infrared Imaging Spectrometer (VNIS) – Active Source Hammer (for seismic experiments) – VLF Radio Receiver (VRR), like the lander instrument – Advanced Small Analyzer for Neutrals (ASAN; Sweden) – Biosphere experiment
Queqiao relay	– Netherlands China Low-frequency Explorer (NCLE) – Laser reflector
Longjiang microsatellites	– Camera (Saudi Arabia) – Low frequency receivers

Relay satellite Queqiao

The relay satellite was a 448kg spacecraft using an existing design, called the CAST 100 bus, with a 4.2m parabolic antenna and a 130N hydrazine propulsion system. A competition was also held for its naming, the outcome being announced soon after National Space Day – the third – on 24 April 2018. The name selected was Queqiao, or 'bridge of magpies'. This came from a folklore story of lovers crossing the Milky Way (or Silver River to the Chinese) with the help of magpies making a bridge for them, enabling Zhi Nu, the seventh daughter of the goddess of heaven, to be reunited with her husband on the seventh night of the seventh month of the lunar calendar. The microsatellites were named Longjiang, meaning Dragon River. People were also invited to contribute messages to be sent to the Moon, with 120,000 received and 8,000 selected. Those who came up with the three most highly regarded were given tickets to see the launch.

As the launch date neared, the Yuanwang 6 tracking ship left port on May 5, its sides decked in red motivational slogans. Mothers held their children aloft to wave goodbye from the quayside. Another Yuanwang had sailed earlier, assisting first in the launch of the Apstar 6C satellite before moving to a new location in the Pacific.

Queqiao was duly launched on an eight-day journey to its destination orbit aboard the CZ-4C rocket from Xi Chang rocket base in Sichuan, at night on 21 May 2018, the first CZ-4C from that site. The third stage flew past the Moon at 9,900km and ended up in a high Earth orbit of 16,910 by 444,000km, 14.5 degrees.

On May 25, Queqiao passed 100km over the Moon, firing its braking rocket for lunar capture to prevent it rounding the Moon and returning to Earth. At this point, the two sub-satellites were detached. Although Longjiang 2 successfully entered an orbit of 395 by 14,587km, 27.5 degrees – more elliptical than that planned – contact with Longjiang 1 was lost. Amateur radio enthusiasts at HIT continued to make attempts to contact the satellite, but to no avail. It is still probably in an extreme, distant orbit of the Earth.

Queqiao entered the planned halo orbit on 14 June, 65,000km away from the Moon, with a period of 14 days. It had taken 20 days to reach this point and it began describing an irregular 3D curve. This was an unusual orbit that required weekly maintenance, where even a slight gravitational disturbance could cause the loss of the satellite. It was a new type of orbit, which had been carefully calculated, but engineers accepted that they had no previous experience of this type of maneuver. Three burns were required to settle the orbit. Technically, Queqiao was at an Earth-Moon L2 (EML2) point, not to be confused with Sun-Earth L1 and L2 (SEL2). This halo orbit was not quite the same as the L2 orbit of the earlier Chang e 2. 'L' orbits, named after the French scientist Joseph Louis Lagrange, are points of gravitational equilibrium in the Sun-Earth-Moon system.

At the end of June, the small Saudi camera on Longjiang 2 sent back its first images, downloaded by the students and radio enthusiasts at HIT. They showed a half-Earth rising over the eastern limb of the Moon – Arabia appropriately in the middle – with crater Petropavlovsky, Bayley rille in Mare Imbrium and another group of craters (Wegener, Wood, Perrine and Stefan). More pictures followed in the autumn, for example of the Mare Nubium (Sea of Clouds). The students even managed to capture photographs of Mars and the constellation of Capricorn. On 20 July, Longjiang 2 used its engine to raise its orbit by 200km, otherwise it would have crashed into the Moon by the end of December. Because of its amateur role, Longjiang acquired an AMSAT amateur call sign, Amsat Lunar Oscar 94. As Chang e 4 prepared to land the following month, Longjiang 2 was turned off to avoid any signal interference.

Chang e 4's mission

On 27 November, the newest ship in China's tracking fleet, the 220m-long Yuanwang 7, set sail from Jiangyin in Jiangsu on the river Yangtze to track the upcoming launch. The actual launch of Chang e 4 at nighttime on 7 December was very low-key, with no live television. China simply reported on the launch and the successful subsequent translunar injection. Photographs of the CZ-3B rocket climbing on a pillar of yellow-orange flame were released later. Chang e 4 entered what was technically a highly elliptical Earth orbit of 200 by 420,000km, 29.4 degrees. The third stage accompanied it to the Moon, passed by at a distance of 4,840km and ended up in an even more elliptical orbit of 181,000 by 735,800km, 23.6 degrees.

Up to three course corrections were envisaged on the way to the Moon. The first, set for 11:42am GMT on 8 December, was cancelled because the trajectory was sufficiently accurate. The second took place at 8:42am GMT on 9 December. About 110 hours after leaving Earth, Chang e 4 braked into lunar orbit at 8:39am GMT on 12 December, leading six minutes later to a polar orbit of 100 by 400km. Amateur radio observers were able to give more precise figures of 138 by 445km, 85 degrees. Chang e 4 made contact with Queqiao on 18 December and established a good communications link. The descent orbit burn was commanded on the last day of the old year, bringing Chang e 4 down to 15km over its planned landing site and with an apogee of 100km.

The powered descent to the surface began during the afternoon of 3 January 2019, Beijing time, in darkness during the night and early in the morning of that Thursday. The landing time was 2:26am GMT. In mission control, banks of young controllers sat tensely behind their screens, telephones at the ready, with a big screen at the front displaying the landing path (a dotted line) and a dot to mark the intended landing point, with another dot denoting the lander moving toward it.

Dr. Bo Wu, Hong Kong Polytechnic University (HKPU), at the Xi Chang launch site with the CZ-3B used to launch Chang e 4. Credit: HKPU.

'Descent command given' reported one of the controllers, which was then relayed on loudspeaker to his colleagues. There was little they could do, apart from watch and hope, as the signals were relayed in via the Queqiao satellite. NASA scientists called their Mars landings the 'seven minutes of terror', but China's controllers had to face a longer 12 minutes of powered descent.

This landing was unlike its predecessor, Chang e 3, which had come down on one of the flattest parts of the Moon and was able to describe a gentle parabola as it curved down toward the lunar surface. By contrast, Chang e 4 had a small landing ellipse and had to come in over 10km-high mountains. Animation on the big screen showed Chang e 4, horizontal to the surface, firing against its direction of travel, as craters and mountains passed by underneath. The landing camera came on five minutes into the powered descent, with the spacecraft still horizontal to the Moon. The firing brought the lander from a speed of 1.7km/sec down to a halt 6km above the terrain, at which point it pitched over 90 degrees to be vertical to the surface, now over crater Von Kármán. The optical and radar imaging systems were now on, as the guidance computer tried to guide the lander in to the right spot. With the hexagonal of the lander visible on the side, the landing camera gave viewers a picture of its gradual descent into fields of large, medium-size and small craters. At 100m altitude, the descent halted and the lander hovered. Now, 3D laser imaging came into operation to measure small obstacles and the gradient of the surface. After a satisfactory scan, the engine was throttled down for the descent to 30m and then an even slower descent. Once the surface was detected at 2m below, the command went in to switch the engine off and Chang e 4 fell unaided the rest of the way – gently enough because of the Moon's lower gravity. The landing legs flexed to absorb the shock and dust blew away as the pads made their imprint into the surface.

The signal could now come from the computer and be sent to Earth that Chang e 4 had landed on the surface and was intact. On the big screen, the dots united to become one and the dotted line of the flight path was gone. Controllers allowed themselves a brief moment of applause and smiles, in the full knowledge that there was much to do to make sure everything was alright and in working order. The first test was of course a photograph, which came through quickly. And what a picture it was! In the immediate foreground was a good-size crater deep enough to topple or wreck a landing spacecraft, its bottom too far down even to see. In the far background, stretching into the distance, were the encircling high hills of the crater wall and the flat lunar plain in between extending to the right horizon. Small craters, one small rock sitting on the surface and the black shadow of an unidentifiable part of the spacecraft completed the panorama. Above the browns and whites of the surface was the absolute blackness of the sky over the distant hills and mountains. The first ever picture from on the far side of the Moon. For the really grizzled veterans of the space age, it was like the moment in 1959 when the USSR got the first pictures of the far side – but that was from far above the surface, not actually on it.

The reaction of the mission controllers may have been one of discipline and restraint – none of the exuberance of NASA controllers marking a landing on Mars – but that was not the attitude of young Chinese people. In minutes, China's social media came alive with the excitement of achieving the first ever far-side landing. 'China had really arrived in space exploration' was the overwhelming sentiment expressed. State media coverage of the mission had been relatively low key, probably because they knew the difficulty and risks of the enterprise and that failure was never more than a small mistake or error away. In a gesture that was strikingly ecumenical – because the United States Congress prohibits cooperation with China – the new administrator of NASA, Jim Bridenstine, headed the list of congratulatory messages from abroad.

Later that evening, at 10:22pm Beijing time, came the next most difficult step: deploying the rover. At the flat top of the lander, two landing ramps extended. The rover atop the lander drove onto them and the ramps lowered the rover to just above the surface. The ramps then divided, into a first part with a slight slope and a second part with a steeper slope, as the rover inched its way forward and then drove away its own length, heading straight toward the big crater seen in the first photograph. The little wheels dug just into the surface, like car wheels might depress a little into a slightly muddy field. The rover's two solar panels were open at the side and the high panoramic camera was visible on top of its dish antenna. The sunlight was now coming from behind on its left side, causing the dish antenna and its other silvery parts to reflect bright sunlight back toward the lander. In the 12 hours that had followed the landing, the Sun had already risen over crater Von Kármán, with both the lander and rover now casting their own shadows over the lunar surface. By this stage the rover had acquired a name, Yutu 2 ('jade rabbit'), the first having been the Yutu rover of Chang e 3 five years earlier. Although the national competition had suggested other names, it had been decided to stick to the former designator.

For China, the Chang e 4 landing was the greatest triumph of its space program so far and the landing was the top story on the news worldwide. The photographs from the far side were a vivid illustration of just how far the country had come, a visible confirmation, if one were needed, that China was now at the top table of worldwide space exploration. Not far behind would be a space station that would match the International Space Station of the other spacefaring nations.

Yutu 2 rolls over the lunar far side. Credit: Reuters.

Building a space station

The idea of a space station goes back to before the space age. Indeed, images of space stations appeared in Wernher von Braun's popular articles in the 1950s. The early manned space programs in the 1960s and 1970s were built on the twin axes of missions of exploration (e.g. Apollo to the Moon) and learning to live in space (space stations in Earth orbit). A space station made an excellent base for experiencing microgravity, or weightlessness, carrying out experiments and observing the Earth and heavens. The first space station was the Soviet Union's Salyut (1971), followed by the American Skylab (1973). The USSR became the master of space station development with the Salyut series (the last was Salyut 7) and then the first permanently occupied station, Mir (1986–2001). In 1998, construction began on the International Space Station, built by Russia, the United States, Canada, Japan and Europe, which passed its 20th year of operation in 2018. It was no surprise that following its first manned space flights, China should announce its intention of building a large space station.

Before doing so, China launched a space laboratory, Tiangong 1 (2011), which was boarded by the crews of Shenzhou 9 (2012) and Shenzhou 10 (2013, see chapter 7). It was small, not much larger than the manned Shenzhou spacecraft that ferried up these crews; had only one docking port, so could only receive one spacecraft at a time; and could host a crew for only a few weeks. A true space station would have multiple docking ports, host shifts of rotating crews for months at a time and carry a significant scientific payload. Before launching the space station, China launched a second space laboratory, Tiangong 2, a rehearsal of the key elements necessary for its larger and more ambitious project.

Rehearsal for the space station: Tiangong 2 laboratory

The Tiangong 2 mission started at the factory where the eight-tonne laboratory was built in Beijing. It was actually the flight-ready back-up spacecraft for the earlier Tiangong 1 and had been kept carefully sealed in storage ever since. On 7 July 2016, it was laid to the horizontal, placed in a sealed railway car and made a two-day train journey to the northwest of China. Tiangong 2 reached the desert launch center of Jiuquan on 9 July, where it was carefully unloaded, brought into its assembly building and waited for the Long March CZ-2F rocket to launch it. That arrived on 6 August, after a similar journey.

Jiuquan was China's original launch base, constructed in the early 1960s far away from inhabited areas to avoid attracting the attention of American spy planes. The base, which comprised living quarters and distant pads, was well away from Jiuquan city, an old oasis at the far end of the Great Wall. The launch center is on a high plateau ringed by mountains to the northwest, with dry, pure desert air, hot in summer and cold in winter and with clear nights, perfect for following ascending rockets downrange.

Tiangong 2 ready to launch. Credit Reuters.

Tiangong 2, on its rocket, was moved to the launch pad on 9 September 2016 and was quickly connected for a pad rehearsal two days later. Tiangong 2 lit up the night sky on 15 September and headed into the darkness, briefly passing by a fully lit Moon during its ascent, with all this broadcast live on Chinese television. Tiangong 2 reached an orbit of 393km, an altitude slightly below the 400km of the International Space Station but higher than its predecessor, Tiangong 1. The rocket was similar to the CZ-2F piloted version, except that the pencil-shaped launch tower that would carry the astronauts (or hangtianyuan) to safety was not carried and the top of the rocket had a large fairing 12.7m long and 4.2m diameter to encapsulate the Tiangong. The rocket's overall height was 52m, against 58m for the piloted version. Tiangong 2 itself was 10.4m long, 4m in diameter and weighed 8,600kg, some 100kg heavier than its predecessor. Each solar panel extended

8.4m. It was only partially fueled, to make room for fuel to be pumped on board later by a refueling freighter, Tianzhou 1.

After entering its orbit, Tiangong twice adjusted its pathway on 15 and 16 September to set up a perfect target orbit for rendezvous, a repeater pattern passing over the same point of the Earth every 46 passes. Tiangong 2 quickly began to communicate with Earth through the Tianlian network of communications relay satellites, circling the world in 24-hour orbit at 36,000km, with three sufficient to provide round-the-clock uninterrupted communications. Just before launch, Tianlian 1-02 moved ten degrees easterly to take up a new position at 176.2°E, while Tianlian 1-03 moved during the first week of July to 10.1°E. Out at sea, the mission was being followed by the fleet of large Yuanwang ships, bristling with communications aerials, dishes and arrays and joined that autumn by the brand-new 25,000-tonne tracking ship, Yuanwang 7.

While it awaited the arrival of a human crew, Tiangong 2 carried a large experimental package. This comprised experiments that operated automatically and those which would be operated by the hangtianyuan themselves (see Table 1.2) [**3**].

Table 1.2: Experiments on Tiangong 2

- POLAR, an instrument to make a survey of gamma ray bursts in the 30–250keV range (with ESA)
- 3D Interferometry Radar Imaging Radar with an Ocean Topography Microwave Sensor
- Push-broom Wide Band Imaging Spectrometer (PWBIS)
- 3D Multi-Band Ultraviolet Edge Imaging Spectrometer (MBUEIS)
- Instruments for monitoring the space environment (e.g. electrons, protons)
- Cold atomic clock built by the Shanghai Institute of Optics and Fine Mechanics
- Plant Growth Chamber for higher plants and seed germination experiment
- Materials furnace
- Multi-band Ultra Violet Limb Imager comprising Limb Imaging Spectrometer and Annular Ultraviolet Imager (AUI)
- Multi-angle polarization wide-band spectral imager for air pollution, aerosols, forests, crops and climate change
- Liquid bridge thermo-capillary convection experiment
- Radiation monitoring instrument
- Oxygenator and water recycling system
- Quantum Key Distribution Experiment

The most prominent experiment was POLAR, a ¥23 million (€3 million) gamma burst polarization experiment to survey the sky, built in partnership with Switzerland, France and Poland. The instrument was a stack of plastic scintillators weighing 30kg and intended to make a statistically precise sample of gamma ray bursts and jets to prompt an understanding of what drives them. Box-shaped, it was located mid-way along Tiangong's exterior. The Principal Investigator (PI) was China's best-known astrophysicist, Shuang Nan-Zhang of Tsinghua University, Beijing. By 2018, POLAR had detected 55 Gamma Ray Bursts (GRBs), signals from the Crab pulsar and solar flares.

The atomic clock was the size of the trunk of a car and involved trapping, cooling and probing rubidium atoms with sufficient regularity to make precise timekeeping possible. The cold atomic clock, built by the Shanghai Institute of Optics and Fine Mechanics, was declared a success in 2018. The Quantum Key Distribution Experiment involved the transmission of data from the station by laser to the Nanshan ground station in Urumqi at 1.6GBps. By 2018, 460 convection experiments had been made with the thermocapillary liquid bridge. Arabidopsis and rice seeds were germinated, the former completing a full life cycle. Samples were brought back earlier by Shenzhou crews, but both were quite affected by the absence of gravity, leading to ‘differently expressed genes’. The Push-broom Wide Band Imaging Spectrometer (PWBIS) was used for seawater remote sensing in 14 channels with a resolution of 100m, accurately identifying chlorophyll concentrations and suspended substances and estimating sea temperature to an accuracy of 1°C. The radar altimeter presented sea height maps to an accuracy of 8.2cm, observed different kinds of waves (e.g. swell waves) and spotted oil spills. The Multi-band Ultra Violet Limb Imager was able to detect ozone and other trace gases while measuring atmospheric density from 10km to 80km. The materials processing furnace, which could heat to 880°C, was used to test new types of metal matrix composites, ferroelectric film, crystals, alloys, semi-conductors and nanocomposites.

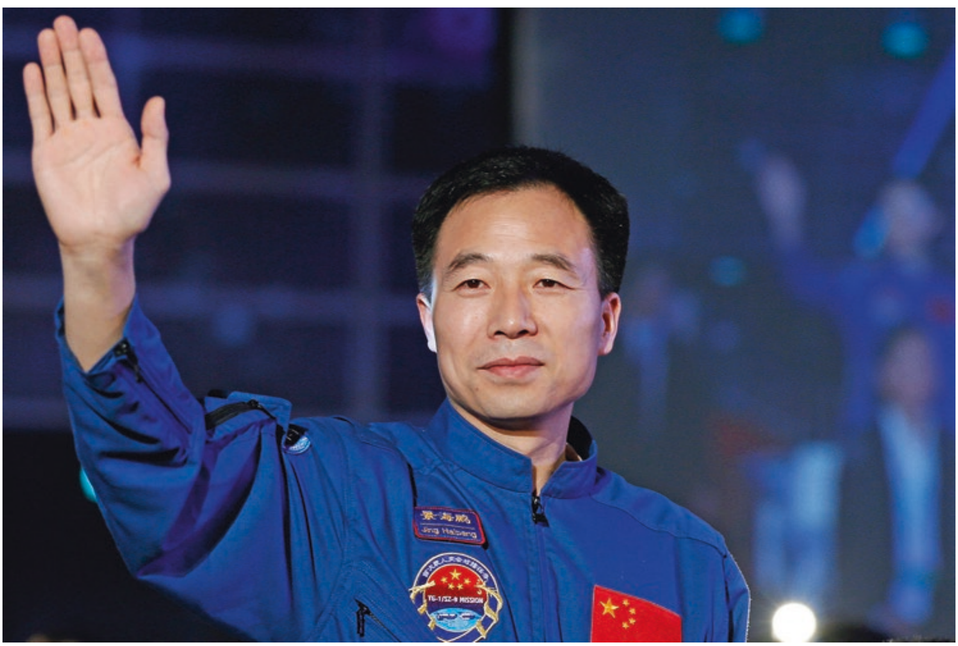
Tiangong 2. Credit Reuters.

Tiangong 2 included the second sub-satellite in the Banxing series, the first having been detached from the manned Shenzhou 7 spacecraft in 2008. It weighed 40kg, had three solar cells, a lithium ion battery and an ammonia-based propulsion system developed by the Shanghai Institute of Space Propulsion. Its camera had a 25m pixel resolution. From the start, China made it clear that there would be only one manned occupancy of Tiangong 2, although it would be twice the length of the two weeks of the earlier Shenzhou 9 and 10 missions.

Rehearsal for the space station: Shenzhou 11 manned mission

As Tiangong 2 orbited, the hangtianyuan who were due to live on board made their final checks in the Jiuquan space center. In the weeks before launch, they lived in what are called the astronauts quarters there, a building that doubles up as a hotel. At the bottom is a suiting-up area and a carpeted room where – in their spacesuits and behind a biomedically protective glass screen – they meet dignitaries before the mission, sometimes even the President of China.

The crew of Shenzhou 11 was announced several days beforehand: Jing Haipeng, 50, veteran of Shenzhou 7 and 9, the first to make a third flight; and newcomer Chen Dong, 38. No information was given on the backup crew. Chen Dong was the first man from his squad to fly (its two women members flew first).



Jing Haipeng. Credit Reuters.

He had been inspired to be an astronaut by the flight of Yang Liwei (no Chinese person had yet flown when Jing Haipeng joined) and had met China's first astronaut during his selection interview. He had cut himself off from the world once he joined, except for weekly visits home to his family and two twin boys and found the initial study tough, but was rewarded with his first selection. Launch time was set for early on 17 October 2016 local time (late 16 October Universal Time). Their CZ-2F launcher was brought to the pad on 10 October.

All suited up and carrying their air-conditioning boxes, the crew left their living quarters, were greeted by noisy crowds of well-wishers and took the bus for the short drive to the launch pad. The launch was carried live on Chinese television in a three-hour broadcast from the moment the bus arrived at the pad with the crew. The two hangtianyuan could be seen boarding the lift up to the top of the gantry and then entering the cabin itself. They settled in and began to go through their checklist. The clasping frame around the rocket was then rolled back. As dawn began to come up the eastern horizon for a clear day, the countdown entered its final stages. As it reached zero, an orange-and-red flame ignited at the base of the rocket. It lifted off almost immediately but then rose slowly into the calm dawn sky. The CZ-2F could be seen arcing in its climb. Cameras then followed the ascent in infrared, monitoring the escape tower peeling off and then staging. Television images direct from the cabin showed the two hangtianyuan monitoring their instruments, while external videocams showed the third stage firing from above. At the nine-minute point, Shenzhou entered orbit and small objects floated free in the cabin. The moment was observed from below by the Yuanwang 7 ship in the Pacific, which tracked the cabin for the crucial 400 seconds around orbital insertion. A minute later, cameras showed the solar panels springing open.

Shenzhou 11 raised the low point of its orbit, its perigee, 14 hours into the mission, then both perigee and its high point, apogee, after 29 hours, before matching Tiangong's orbit after 36 hours. Shenzhou 11 closed in slowly and docked with Tiangong 2, the two spaceships clunking together in an orbit of 393km early on 18 October, some 43 hours 55 minutes after launch. On the way in, stops were made at 5km, 400m, 120m and 30m. The docking altitude was some 50km higher than Tiangong 1, designed to test the higher altitude planned for the later, bigger space station.

The crew entered the station – a two-stage process that involved exiting Shenzhou, entering a tunnel into the station and then opening a second hatch into the station itself – to the applause of mission control. Jing Haipeng entered first, followed by Chen Dong. They took off their spacesuits and put on the blue overalls that they would wear for their month on the station. They made a short report and saluted. External cameras showed the combined station and Shenzhou gliding over the Earth in the background.

Chen Dong. Credit: Gerhard Rosenfeld.

The month-long stay on the station proceeded smoothly. In keeping with the social media age, Jing Haipeng began a daily blog from the station. He and Chen Dong tested a robotic arm on the outside of the station and grew lettuce, rice and Arabidopsis, a plant somewhere between cabbage and mustard. They exercised on a treadmill and bicycle and tested a wide band communications system for relays to the ground. On their second day, they began the cultivation of lettuce, the growing conditions – moisture and temperature – monitored by a sensor built in Cambridge, England. For food, the two had a hundred menu items from which to choose.

Chen Dong was responsible for no less than 38 experiments. One of them was cardiospace, a doppler laser and ultrasound scanner to measure the circulation of the cardiovascular system, developed by the French space agency CNES with the Space Institute of South China in Shenzhen. The experiment in which he was most involved concerned silkworms, an experiment devised by Hong Kong Christian and Missionary Alliance middle school in cooperation with the College of Plant Protection at China Agricultural University. Its purpose was to test their spinning, cocooning and transformation. They lived in a container and fed on mulberry leaves daily, with cloth on the walls for them to climb and holes for air circulation. The duration of the mission made it possible to follow a whole life