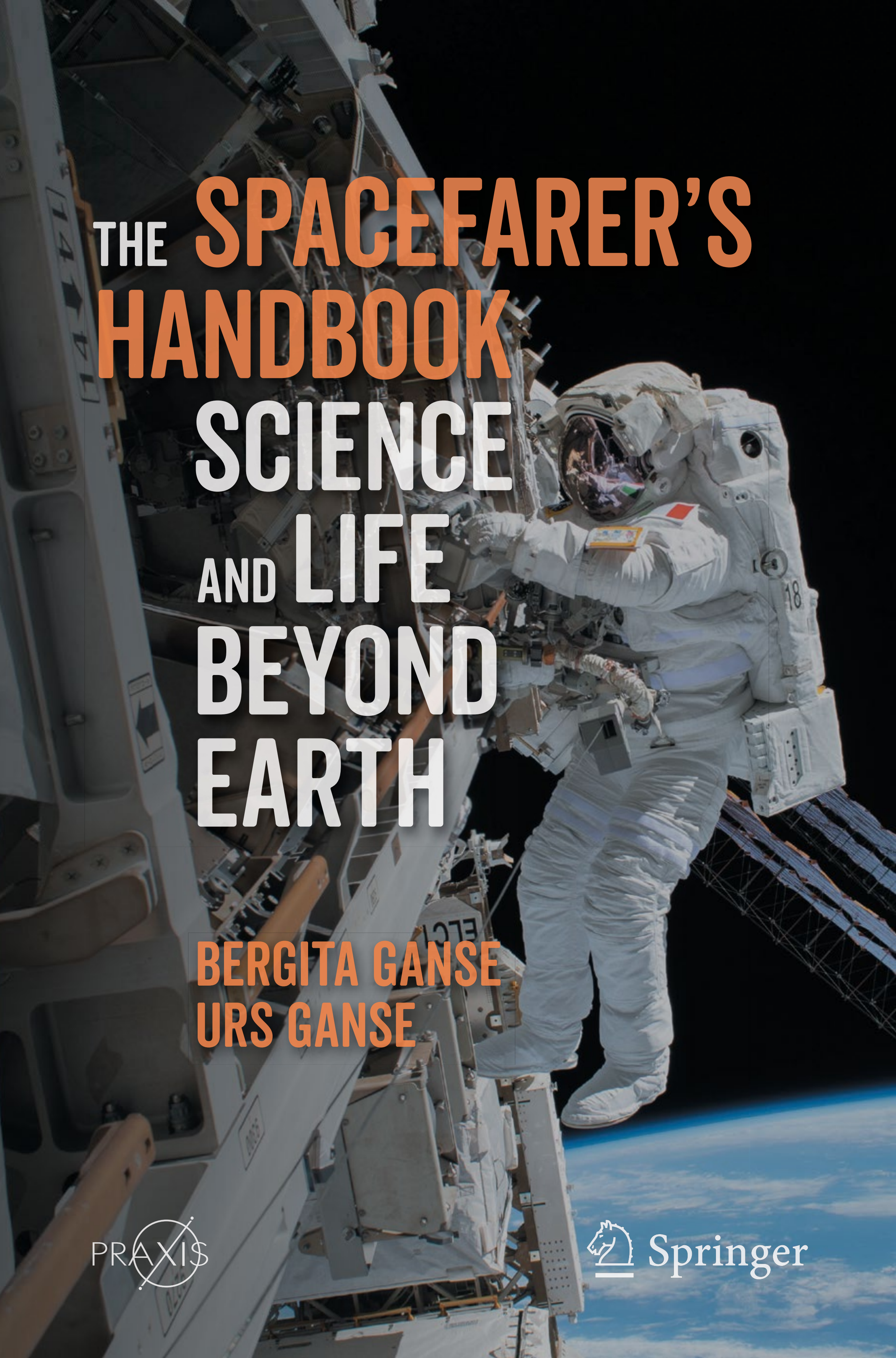

THE SPACEFARER'S HANDBOOK

SCIENCE AND LIFE BEYOND EARTH

BERGITA GANSE
URS GANSE

PRAXIS

Springer

The Spacefarer's Handbook

Bergita Ganse • Urs Ganse

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Science and Life Beyond Earth

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PRAXIS

Bergita Ganse
Manchester Metropolitan University
Manchester, UK

Urs Ganse
University of Helsinki
Helsinki, Finland

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Cover Figure: iss061e143462 (Jan. 25, 2020) — ESA (European Space Agency) astronaut Luca Parmitano is pictured tethered to the International Space Station while finalizing thermal repairs on the Alpha Magnetic Spectrometer, a dark matter and antimatter detector, during a spacewalk that lasted 6 hours and 16 minutes. Credit: NASA. Source: https://www.nasa.gov/image-feature/esa-astronaut-luca-parmitano-is-tethered-to-the-space-station-0.

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Preface

Born as a spacefarer and just not been to space yet? Getting ready for a flight? Currently on orbit and got a question? This book explains the practical reality of space travel and covers the most important fields—from spaceship construction, planning and navigation via life in space and medicine in weightlessness to exploration and the search for extraterrestrial life. It is a guidebook written by scientists!

As an astrophysicist and a space physician, we professionally cover entirely different areas of the field. We are siblings and have spent a significant amount of our childhood enjoying science fiction (in particular Star Trek), stargazing, simulating flying spacecraft and colonising planets on various computer systems and consoles. We are excited to be a part of the space age and look forward to the further exploration of our solar system and beyond. We hope to share and celebrate the atmosphere of fascination that we have experienced and still feel every single day while working as scientists in two separate areas of space research. As such, we feel honoured to be a part of this great adventure!

Despite human spaceflight being a gigantic interdisciplinary and international masterpiece, it all comes down to basic science. In our book, we want to unveil some of the spaceflight magic and correct the belief that only superheroes can fly to space, as well as the misconception that spacecraft only work when an alien artefact from the future grants its power. This book presents interesting facts, phenomena, anecdotes and tips. We frequently laughed our heads off when finding new stories and fun facts. In addition, we are in contact with a number of people who have been to space and who inspired us and answered our questions to make this book a compendium of real-life spaceflight knowledge. We are especially thankful for astronaut Story

Musgrave's permission to print an interview with him. As he so eloquently put it, "I don't collect the data, I am the data!".

Many aspiring spacefarers are eager to find out how they can make their own spaceflight a reality. For others, the matter is already settled or the flight currently takes place. Someone may find the idea ridiculous to ever enter a spacecraft and feel safe and comfortable on the ground. This book is intended for all reader groups! We want to help everyone in successfully planning and undertaking their flight. In addition, we hope to feed those readers who think they know it all with some exciting and enjoyable additional facts.

In 2017, we published the Handbook for Aspiring Spacefarers in German. Since our non-German-speaking friends kept complaining they wanted an English version, we have now translated, updated and extended our book and hope it turned out to be an enjoyable read!

Have a good flight!

Manchester, UK — Bergita Ganse
Helsinki, Finland — Urs Ganse

Additional information, videos, downloads and other links are sometimes included as QR-codes. A QR-code scanner (app) may be used to access the content, or the URL be typed into a web browser.

Acknowledgements

This book would not have been possible without the help, patience and support of our colleagues, friends and family over several months.

We would especially like to thank the proofreaders, Julia Attias, Harriet George, Alex Ireland, Diana Morosan and Marje Niemelä for bearing with our sometimes puzzling use of the English language.

Lisa Edelhäuser and Ramon Khanna of Springer deserve a special mention for supporting us in the authoring and publishing process.

Contents

About the Authors

PD Dr. Bergita Ganse is an Orthopaedic Surgeon and a Physiologist with a research focus on Space Medicine and the musculoskeletal system in spaceflight. She has received her Dr. med. from Lübeck University and her habilitation (postdoctoral thesis) from RWTH Aachen University in Germany. She is currently a Research Fellow at Manchester Metropolitan University in the UK, funded by the German Research Foundation (DFG). She is a co-investigator of an ISS experiment and involved in large international studies working with the German Aerospace Center (DLR), the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA).

Dr. Urs Ganse is a Theoretical Space Physicist, with a research focus on plasma simulations. After studying physics and obtaining his doctorate from the University of Würzburg, Germany, on the subject of solar radio bursts, he has worked as a postdoc in Finland and South Africa, with research funding from DFG, ESA and the Academy of Finland. In his current position as a University Researcher at the University of Helsinki, he uses supercomputers to model the near-Earth plasma environment and its interactions with Earth's magnetic field.

1

How to Become a Spacefarer

Contents

1.1 Nothing Ventured, Nothing Gained

Why are the most capable spacefarers usually selected from thousands of applicants? Because space agencies can choose from big crowds of volunteers desperately wanting to go! The selection processes limit risks associated with the "human factor", which includes health and psychology, and also ensures candidates are skilled in a multitude of fields. So, there is actually no real reason that makes most applicants ineligible. In fact, most humans would be totally able to survive a spaceflight in good order. As most of those who would have loved to go have not made it to space so far, and as job offers for spacefarers are rare, we have collected potential options to grab a flight opportunity:

1. Applying for a job advertisement—for example, when one of the big space agencies searches for new candidate spacefarers. The European Space Agency (ESA) last selected six candidates in the year 2008. In 2016, women

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in Germany could apply to become the first German woman in space. The best odds seem to exist in the USA, where astronaut candidates are annually selected by the National Aeronautics and Space Administration (NASA). Other nations with a human spaceflight programme include China, Russia, Canada and Japan.
2. Buying a ticket. Many companies have sold tickets in the past, but most of them were unable to deliver! All space tourists until now have spent multiple days on the International Space Station (ISS). It has been the only destination for space tourists up until now. However, shorter flights should also be available soon.
3. Spending a big sum of money to build an own spacecraft or to buy one from a commercial company. This option has previously only been successfully applied by the company Scaled Composites—however with funding by Microsoft founder and billionaire Paul Allen. Although one could argue that it does not count as a do-it-yourself project when an established aerospace company funded by an IT-billionaire builds a spacecraft.
4. (The strategy to wait until aliens come to pick one up is probably less promising…)

By now, humans from many countries have been to space. The Soviet Union/Russia, the USA and China have been the only countries to build and launch their own spacecraft carrying humans into space. Many other nations have used their infrastructure to bring their own spacefarers into orbit. Depending on the country that has built the vehicle, these spacefarers are called either *astronauts*, *cosmonauts* or *taikonauts*. One is an astronaut when the rocket was American, a cosmonaut if one went with the Russians or previously with the Soviet Union, and a taikonaut if one had the chance to fly with the Chinese (the ending "naut" meaning sailor). Despite this, India calls their spacefarers *vyomanauts*, Malaysia theirs *angkasawan* and Germany *raumfahrer*. Figure 1.1 shows a world map indicating all launch sites humans have departed from so far.

1.2 Open Challenges and the Story So Far

Figure 1.2 is an illustration of the most important first time events of human spaceflight's pioneering days—as a refresher, inspiration and motivation to add new achievements, such as the self-experienced first landing on an asteroid or a planet.

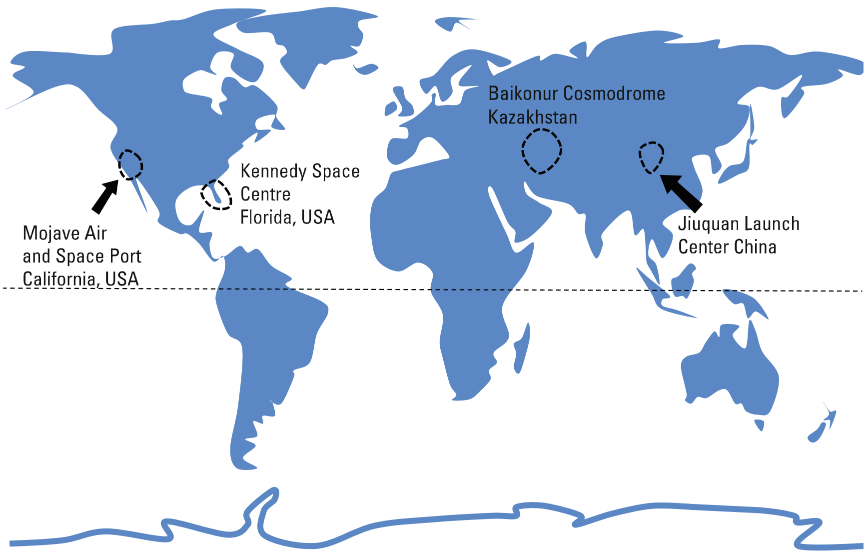

Fig. 1.1 Map of the world showing all launch sites that have been used for crewed spaceflight so far. The biggest spaceport of the world (by area) is Baikonur Cosmodrome in Kazakhstan. All crewed NASA missions including all Space Shuttle flights have departed from the Kennedy Space Center in Florida. The only exception is the SpaceShipOne, that launched from California. The Chinese crewed rockets depart from the Jiuquan Launch Centre

So far, the Soviet Union/Russia, China and the USA have had their own spacestations in Earth's orbit. The Soviet Union's Salyut 1 station was the first spacestation in human history and had numerous successors, including the Almaz military spacestations. These spacestations were designated as Salyut stations to hide their military purpose (all three Almaz spacestations were armed with an anti-air cannon). Overall, seven Salyut stations were delivered to orbit. Salyut 2 was the only one to lose altitude and depressurise, which occurred after only 2 weeks. The other Salyut stations were operational, and Salyut 7 even stayed in orbit for almost 9 years until 1991. The last spacestation of the Soviet Union and later Russia was Mir (1986–2001), an amazing success story with many visits from international spacefarers and American Space Shuttles. The name Mir is a pun, and means *peace* and *world* at the same time. On the US-side, the huge spacestation Skylab was operational from 1973 to 1979. With 360 m^3, this station was bigger than Mir (350 m^3). It

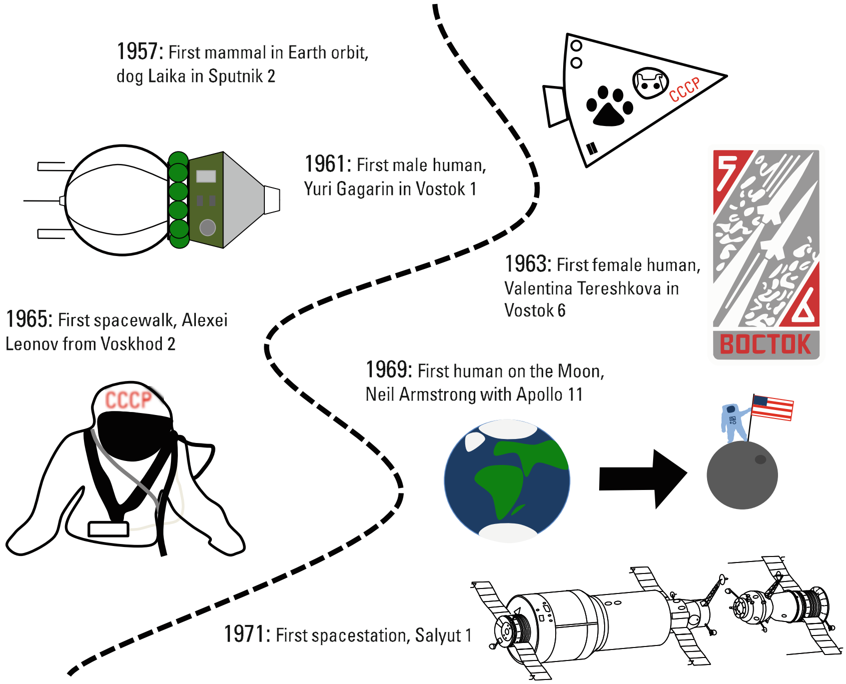

Fig. 1.2 First times in the history of crewed spaceflight

was, however, the only operational and crewed US spacestation in history. The planned spacestation *Freedom* was never built. Instead, parts and concepts of it were later used to create the International Space Station, which is an international endeavour. Russia's contribution to the ISS originated in the same way from a planned and never built spacestation *Mir 2*. China had the crewed spacestations Tiangong-1 (2011–2018) and Tiangong-2 (2016–2019) in orbit until recently.

So far, the Apollo programme was the only time in human history when men visited the Moon. In December 1972, the last human set his foot on the Moon and nobody has been there since. The Soviet Union and China have never sent a cosmonaut or taikonaut beyond the Earth orbit.

Apart from this, no human has ever been on another planet, on an asteroid, on a moon other than our own, outside the Earth-Moon system, or anywhere else in the solar system. Once space tourism accelerates, individuals of many countries will have the chance to be the first in space, and many countries might get their first spacefarer up there.

1.3 Space Tourism

The concept of space tourism and the dream of tourist spaceflight has existed for generations. Already back in the 1960s, Barron Hilton proposed hotels in space, and American airline Pan Am had a list of almost 100,000 individuals interested in booking a trip to the Moon. In 1991, however, Pan Am was bought by Delta Airlines after its financial collapse, and never delivered a single person into space. The movie *2001: A Space Odyssey* (1968) presented what flights could look like.

But how many people have been in space as tourists to date? That depends on the definition! So, who has been to space as a self-paying spaceflight participant at an altitude above 100 km as of 2020? The first space tourist in human history was the 60-year-old American engineer and multibillionaire Dennis Tito, who went on a 7 day and 22 h Soyuz mission to the ISS in 2001, apparently paying US$ 20 million for the trip. He was housed in the Zvezda module of the ISS and was officially only permitted inside the other modules when escorted. The South African Mark Shuttleworth followed Tito in the year 2002 to become the second ever space tourist. The first female self-paying spaceflight participant was American-Iranian multibillionaire Anousheh Ansari in 2006. Between 2001 and 2009, a total of seven paying individuals went to space this way. The others were Gregory Olsen (2005), Charles Simonyi (2007 and 2009), Richard Garriott (2008) and Guy Laliberté (2009). Missions apparently went well and were enjoyable for all of them. All of these trips were organised and sold by the US company Space Adventures, the only business that has successfully brought tourists to space so far. Indeed, many businesses have made millions by selling tickets, but only this one company really managed to keep their promise so far. All seven tourists paid US$ 20 million or more and were launched in Russian Soyuz spacecraft, as Space Adventures does not have their own rockets or spaceships. In 2009, tourist flights to the ISS were discontinued when the permanent crew size on board the ISS was increased. After the Space Shuttle became retired, the Soyuz was the only spaceship capable of and available for bringing humans to the ISS. All capacities were then needed by the national space agencies, which had priority over tourist flights. This policy lasted until 2019, when Emirati spacefarer Hazza Al Mansouri of the United Arab Emirates Astronaut Programme spent 7 days and 21 h on board the ISS. He became the first Emirati in space and the first Arab on board the ISS. However, again, it is a matter of definition, whether or not he can be counted as a tourist, as he did not cover the costs himself, but was sent by the Prime Minister of his country.

Depending on the definition of space tourism, one might as well count numerous *payload specialists* on board the Space Shuttle as tourists. These are crew members without command or pilot functions, who did not get the same training as the NASA astronauts and were sometimes not even employed by NASA. These individuals, however, did not pay for the flights either, but the costs were often covered by their companies or institutions. Similarly, the Soviet Union, within the Intercosmos programme, brought cosmonauts from allied countries to space—again individuals who did not share the same training and experience as the proper crew. This development might be the future of human spaceflight, as remote control, new technologies and artificial intelligence are expected to reduce the required skillset, and automated flights carrying laypersons become the norm. While astronauts in the Apollo-times were trained for all worst case scenarios and ready to navigate their spaceships entirely by hand and eye, today's systems allow for more flexibility in the crew members' qualifications.

Over the past years, several companies have developed their own spaceships for commercial applications. The Ansari X-Prize of ten million US dollar, announced in 1996 for the first private human spaceflight, was won by the American company Scaled Composites with their *SpaceShipOne* and its carrier airplane *White Knight* on 4 October, 2004. To win the prize, a crewed, reusable spaceship had to reach the Kármán line (100 km altitude) twice within a period of 2 weeks. For a short moment, the success of SpaceShipOne led many people to the assumption that space tourism would now finally progress quickly. However, this was not the case. The prototype of the successor *SpaceShipTwo* named *VSS Enterprise* was destroyed in a crash on 31 October, 2014. Only one of the two pilots survived. A new spaceship, the *VSS Unity*, now owned by Virgin Galactic was presented to the public in February 2016.

In parallel, a number of companies are developing commercial spaceflight capabilities for crewed missions, including SpaceX, Blue Origin and Boeing. As of early 2020, however, only SpaceX has succeeded in bringing a human into space. Also SpaceX's Dragon spaceship has reliably delivered cargo to the ISS for several years now. Boeing's Starliner (previously named CST-100) has reached a very promising state, too, but by early 2020, it was still struggling with technical difficulties in its test flights, and crewed launches were delayed multiple times. It only seems to be a question of time when the first space tourists will depart in a commercial vehicle. As books can never be up-to-date with launch schedules, a QR-code leads to the Spacefacts website, for one of the most accurate and updated global crewed launch schedules available (Fig. 1.3).

Fig. 1.3 The *Spacefacts* website shows which missions and individuals are currently in space, and who will launch and land next. http://spacefacts.de/schedule/e_schedule.htm

Many people like to think that astronauts and cosmonauts fly to space all the time. Crewed flights, however, take place less often than the intense media attention might suggest. Over the last years, usually three to four crewed flights were launched per year world-wide. Three crewed Soyuz spacecraft launched in both 2018 and 2019, respectively. In 2014, 2015 and 2017, four crewed flights took place, while five were recorded in 2012, 2013 and 2016. Activity was much more intense in the 1980s and 1990s. In 1985, for example, eleven crewed missions were launched (nine Space Shuttle and two Soyuz launches). Indeed, there is hope for these numbers to rise considerably in the near future.

1.4 Astronaut Selection

Which criteria need to be fulfilled to be selected as an astronaut? Most of the formal criteria concern education, work history, health, experience and personality of the applicant. But the most important factor is luck! With regard to education and qualification, a great number of people are wonderful candidates. Military, aviation and science backgrounds have in the past promised the greatest chances to be selected. In Germany, eight out of the eleven men who have been to space are physicists. NASA's astronaut corps usually selects the most diverse crowd with all kinds of skills, including engineers, doctors and teachers.

Many people ask themselves if their health is good enough to fly to space. This question can, however, not be answered easily, as there is not simply one clear rule. Certainly, as minimum, at least the requirements for a pilot medical license need to be fulfilled. It is often required as part of the initial astronaut application. So far, only very healthy individuals have been to space, and there is almost no experience with diseases and medical conditions in spaceflight.

In aviation, however, plentiful experience has been gained over many years, that is for now a good approximation. In addition to this, spaceflight exposes participants to weightlessness, hyper-G, radiation, extreme excitement, and a lot more stressors. An applicant usually has no opportunity to argue when anomalies are found during the selection process, and is instead automatically deselected. At the same time, astronauts have flown with minor abnormalities, such as Gilbert's syndrome, a mild liver disorder, where people usually do not have symptoms or limitations.

To choose the very best candidates in the frame of an astronaut selection is called a *select-out*. That means, any candidate with only the slightest flaw is discarded from the crowd of applicants. When it comes to letting experienced spacefarers fly again, to benefit from their experience, insignificant aberrations may be overlooked more easily, as long as they are unlikely to be a risk for mission success. This approach is called *select-in*. The authors believe that many tiny health issues would not be a problem and assume that criteria for tourist flights will become less rigid over the years (see Chap. 5). However, when considering in- or exclusion, many spaceflight-relevant aspects must be taken into account. Selection criteria need to be particularly strict with regard to mental health. Other obvious exclusion criteria are serious heart problems or recent surgery.

It is easily understandable why space agencies select the fittest and best-suitable candidates. This is to minimise risks as much as possible for their expensive programmes paid by tax money. Often, politics and PR aspects play a role, too. The first woman in space was Valentina Tereshkova, a factory worker who was sent to space by the Soviet Union. The political message to the population was that she was not only one of them, but also that normal factory workers could achieve everything, and that everyone is valued.

Which selection criteria for astronaut candidates have played a role in the past? Which steps did the applicants have to complete in the selection process? The European Space Agency last selected astronauts in 2008 (as of early 2020):

- Initially, a formal application had to be submitted including proof of a pilot medical. A university degree, research experience, or when applying as a military pilot, proof of flight experience, and, if available, further evidence of additional skills such as a diving certificate, doctoral degree, Russian language skills, etc. had to be provided.

- Two steps of psychological and professional assessment followed, which also included behavioural and cognitive examination.
- The next level was extensive medical testing by medical specialists of different fields, including blood tests, endurance and cardiac tests, eye and ear examinations.
- A formal job interview by an ESA committee followed. After this stage, only 20 out of more than 8000 applicants were left. The last decision of which individuals to choose from those 20 was mainly political and had a lot to do with their nationality, as the European countries contribute differently to ESA.
- The last step was the announcement of the six new ESA astronauts in training.

NASA's astronaut selection programme has been accepting applications almost on an annual basis since the Space Shuttle days. Pilot and non-pilot individuals may apply. The latest non-pilot application criteria were:

- A bachelor's degree in fields of engineering, biology, physics, computer sciences or mathematics (which ones exactly was not specified).
- At least 3 years of work experience after the bachelor's degree. A master degree and/or PhD were particularly appreciated.
- In case of vision disorders, these needed to be correctable, for example, by wearing glasses.
- Anthropometric dimensions had to fulfil the permitted sizes for spacesuits (these were measured during the interview).
- Applicants had to have US citizenship (having two citizenships was acceptable, too).

Relatively young people were usually selected in the past, but a recent trend towards older spaceflight participants can be observed. One of the reasons why it makes sense to choose more senior individuals for long-term flights to points of interest outside the Earth's magnetic field are the high radiation doses expected there. Exposure to space radiation for a longer period of time significantly increases the likelihood for cancer in later life, that usually does not show up immediately but several years after. When exposing older individuals, their natural remaining lifespan is shorter anyway and the cancer may not even appear anymore, while the life expectancy and quality of life of younger candidates may be affected badly.

Hint for Aspiring Spacefarers It is impossible to predict in detail which spaceflight selection criteria will become most crucial in the future. A lot of luck is needed to be selected anyway! To score well in an astronaut selection, it is not at all required to be an elite athlete or a Nobel Prize winner. The ones chosen are usually good in a great variety of things, and are most of all great team players. Showing no deficits in any one of the tests is most important. Drop-out is often caused by supposedly trivial aspects before consideration of the real strengths of an individual has even taken place. Sometimes space agencies want to find someone with a specific background or in a certain age group, but were unable to communicate this beforehand. To prepare for the selection process, a healthy lifestyle with a balanced exercise routine is recommended, that may include activities such as running, cycling, swimming, going to the gym and team sports. Top results are irrelevant, but overall fitness and consistency are what counts. It is essential to stop smoking and limit alcohol consumption (both habits are reflected in the blood results). Additional skills, such as a pilot or diving certificate, previous expedition experience, such as overwintering in Antarctica or fluency in several languages, help. To prepare for the testing, one might want to repeat and practice school level maths and physics. Basic spaceflight knowledge should be beneficial, too. A good answer to the question why one is the ideal candidate might be helpful in a job interview. To get there, we recommend reading this book!

White men are dominating human spaceflight and have been ever since the beginning. When getting the chance to be decision makers in the future, the readers of this book could choose to optimise their crews' potential as much as possible by selecting the most capable candidates independently of their cultural backgrounds or sexes. Studies have shown that teams consisting of both women and men work best in spaceflight. A diverse team seems to limit aggressions and conflict situations among crew members. In the past, fist fights reportedly took place among male cosmonauts. In several relevant fields (for example, teamwork) women even outperform men. In addition, their body mass is lower and they consume less food and oxygen, saving payload (carrying capacity) and resources.

Back in April 1959, the *Mercury 13* were thirteen female pilots with more than 1000 h of airplane flight experience each, who participated in a privately funded astronaut screening campaign, but never became members of the NASA astronaut corps or flew. Sally Ride much later became the first female NASA astronaut in 1983.

1.5 Checklist Before the Flight

Spaceship built and launch date booked? What is next? Here is a list of issues to consider:

- Cameras ready? Data management planned? See Chap. 2.6 for more.
- Calculated fuel and flight route? Consider reading Chap. 3.3.
- Selected and packed diversified food options in large amounts? Taste changes in space! More details in Chap. 4.3.
- Ordered a spacesuit that is a little oversized? Elongation of the spine by about 5 cm is normal in weightlessness! For details see Chap. 4.4.
- In good shape and exercise routines planned? Check out Chap. 5.4.
- Ready to face the Space Adaptation Syndrome including nausea, vomiting and back pain? Details: Chaps. 5.3 and 5.6.
- Got a message for extraterrestrial life ready? Find inspiration in Chap. 6.8.
- Mission patch ready? (read on)

Before the start of the mission, one item is crucial: the mission emblem. Designing a specific and characteristic patch for each mission has become a wonderful tradition in spaceflight NASA (2012). Apart from the mission name, it may contain the names of all participants. Mission patches are attached to the spacesuits and stuck to all kinds of equipment boxes, devices, notebooks, and the scientists involved in the mission love to have them on their lab or office doors. See Fig. 1.4 for some examples from spaceflight history.

Fig. 1.4 Mission emblems: Apollo 11 (1969, first human on the Moon), STS-71 (1995, first docking of a Space Shuttle to spacestation Mir), Spacelab D1 mission (1985 with German contribution), Soyuz T-9 (1983, fourth crewed flight to spacestation Salyut 7), Shenzhou 9 (2012, beginning of operation of the first Chinese spacestation Tiangong-1) and the FORESAIL satellite patch (with involvement of both authors) (Images: NASA & U. Ganse)

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2

Building Spacecraft

Contents

Let's not waste any time and start: To go to space, some gear will be required. First and foremost, one needs a device that can transport humans into space and keep them alive there: a spaceship!

2.1 Spacecraft Classes

Initially, a clarification of terms: The rockets used in human spaceflight are standing on their launchpad like skyscrapers, yet only a small part at the top of them eventually arrives in space. The lower stages, called the launch vehicle, which are entirely built out of fuel tanks and rocket engines, are required for racing up through the atmosphere and are detached after that. The *proper* spaceship, also called spacecraft, in which spacefarers fly and navigate through

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space, is just the topmost section (see Fig. 2.1). In some cases, it can be further subdivided into the return capsule and the service module.

There is, naturally, more than one type of spaceship: A multitude of different utilisations, special cases and environmental conditions exist, in which spaceships are used. Their shapes and construction styles are therefore equally plentiful. Figure 2.2 shows a rough overview of which classes of spaceships have been built and employed by humans so far. This classification is in no way strict: it would totally be possible to build a spaceplane with the intention to land it on another celestial body, thus making it also a lander. Yet, in spacecraft design it is always necessary to keep weight limitations in the back of the mind, since every kilogram of weight carries massive extra costs. Additionally, every electronic or mechanical system can fail, needs to be maintainable and requires lots of testing on the ground beforehand.

Thus, in order to make spaceship construction in any way economically feasible, the fundamental design principle is always that the simplest, most robust, most streamlined and cheapest method will be used. Hence, in all nuances of spaceship construction this very same principle will occur over and over. It is true for the outer hull of a spaceship, for rocket engines, and even for minute details such as furnishings and interior design.

2.2 A Spacecraft's Hull

Space is cold, devoid of air, abundant in radiation and swirling with small and big meteoroids. In order to survive in this environment, it is absolutely essential to have proper implements to keep unpleasantries outside, while keeping necessary things like air and warmth inside the spacecraft. A spacecraft's hull must fulfil all those functions. The challenge in designing a good spaceship hull is to optimise the requirements, while at the same time being as light and cost-effective as possible. Every kilogram of hull that gets transported to space means 1 kg less of payload mass!

The most common construction material for spacecraft is aluminium, similarly as in airplanes. It benefits from a high level of sophisticated manufacturing techniques available from aviation, it is easily brought into any desired shape by bending, casting and machining and it nicely dissipates thermal stress thanks to its good heat-conducting properties. Recently, however, composite materials containing carbon fibres have found their way into spacecraft construction, for example, in the SpaceShipOne and SpaceShipTwo produced by Scaled Composites and in the Falcon rocket series of SpaceX. The very light and

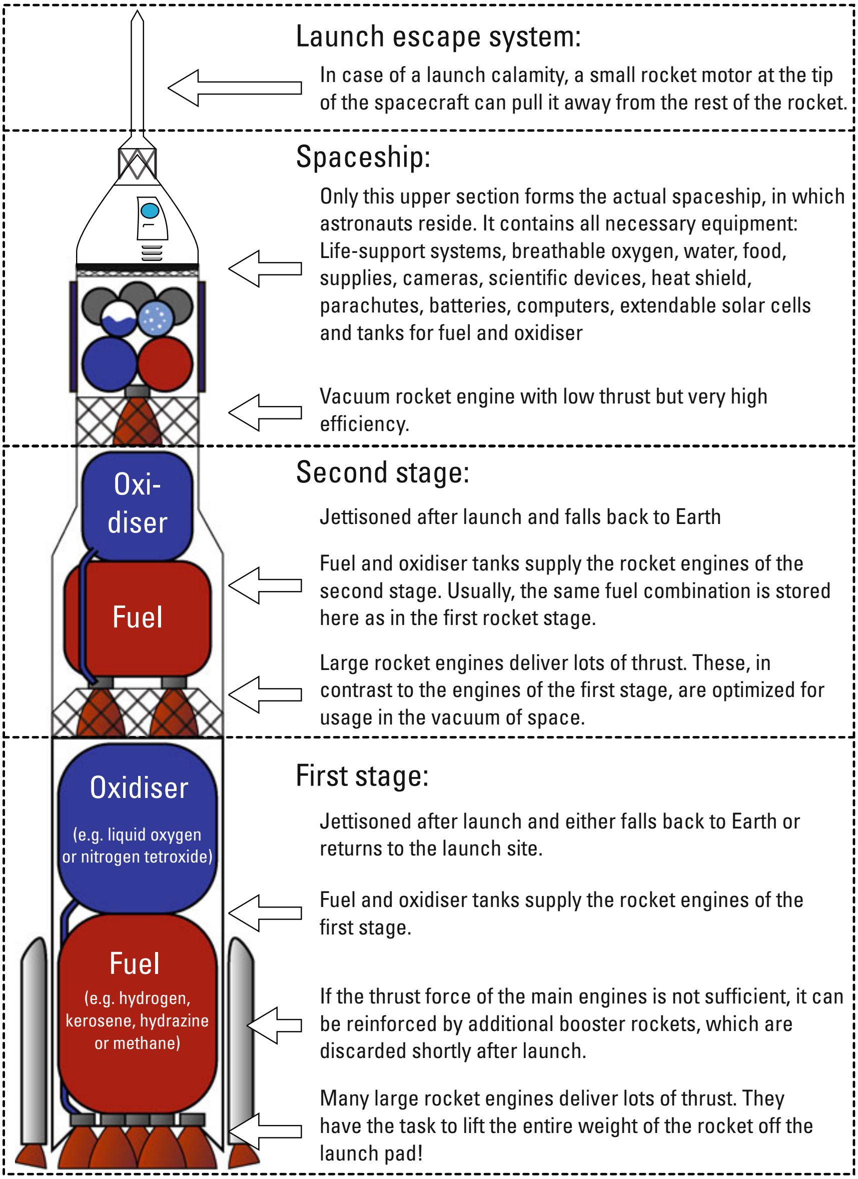

Fig. 2.1 Schematic diagram of a typical liquid fuelled multi-stage rocket, the most common rocket type to propel crewed spacecraft off the ground. The actual spaceship is situated in the topmost stage of the rocket, everything else returns or plummets back to Earth immediately after launch

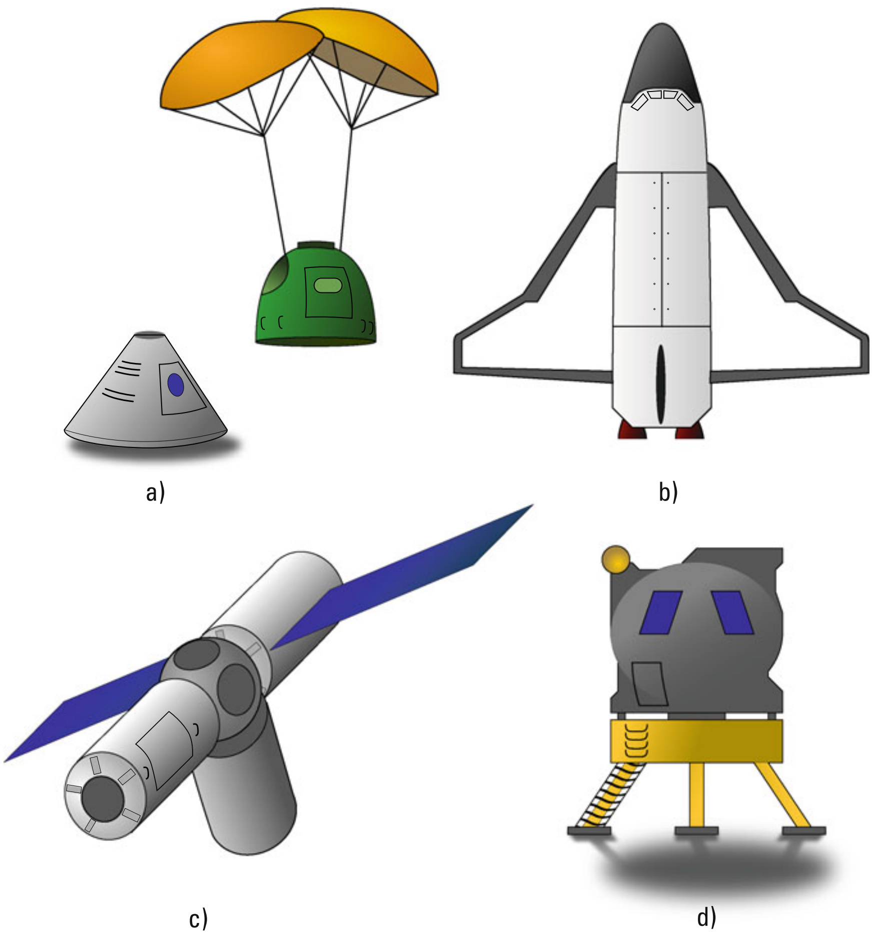

Fig. 2.2 Typical shapes of spacecraft which have been used in human spaceflight: (**a**) Capsules are the most common form of launch and return vessels (they are usually connected to other components until the reentry phase). (**b**) Spaceplanes like the Space Shuttle are used to transport both humans and uncrewed payloads, and can land like an airplane thanks to their aerodynamic profile. (**c**) Bigger spacecraft and structures are constructed from modules in space by docking them together. The modules are launched successively by separate rockets. (**d**) Landers, like the Apollo Lunar Module, are especially designed to touch down on other celestial bodies and launch back to space from them. Their configuration strongly depends on the properties of the target body!

heat-resistant metal beryllium also finds use in spacecraft components, but its toxicity means that it is usually kept away from the crew compartment.

A special case of one-person-spaceship is the spacesuit: Just like a proper spaceship hull, it is designed to protect the human inside from the negative effects of space. It comes with the special requirement that its hull should be built from elastic bendable materials to allow freedom of motion. Oftentimes, layers of Kevlar (as used in bulletproof vests) provide protection against micrometeoroids, Mylar foil (commonly used in emergency blankets) enables a vacuum tight seal and special underwear with sewed-in cooling pipes takes care of thermal regulation (compare Sect. 4.5).

Since spacesuit materials have been optimised and refined over many decades, even spacecraft and spacestation modules are nowadays starting to be assembled from the same flexible materials as opposed to rigid aluminium construction. The inflatable spacestation modules manufactured by the American company Bigelow Aerospace (such as the BEAM module on the International Space Station, see Fig. 6.18) are the most well-known examples of this.

Radiation, Heat and Meteoroids

The Sun is the solar system's biggest source of light, heat and ionising radiation. A total of 1.36 kW/m^2 of overall irradiance reaches Earth at any given moment, the largest part being infrared, visible and ultraviolet light. Earth's atmosphere (especially the ozone layer) protects us from most of the UV radiation and additionally absorbs parts of the visible and infrared light, so that only about 1 kW/m^2 eventually reaches the surface. The number changes rapidly when travelling into different parts of the solar system. Flying closer to the Sun, the irradiance per square metre rises as an inverse square law of the distance: In the same way as the apparent size of the solar disc grows when getting closer to the Sun, the energy flow increases. In journeys to the outer part of the solar system, the irradiance decreases likewise. This is the reason why space probes travelling outwards towards Jupiter require significantly larger solar panels than those orbiting Venus.

As opposed to the glaring Sun, the other areas surrounding the spacecraft are cold and dark. Almost no heat reaches the spacecraft from the blackness of space, as its heat radiation corresponds to the thermal glow of a black body at a temperature of −270 °C, only 2.73 K above absolute zero.[1] While the sun-facing side of a spaceship is continuously heated by the Sun, the backside is radiating heat out into cold space. The large difference in heat flux between the Sun and empty space makes it necessary to take heat transport into account when designing spacecraft and potentially add heating and/or cooling mechanisms. Without these, recurrent thermal expansion and contraction may lead to material fatigue and could eventually cause the hull to break and start leaking air.

A hull constructed out of heat-conducting materials could take care of the thermal problems by itself, but this is not always sufficient, especially if the structure is very thin. To actively manage spacecraft temperature, a fluid-based heat transport system can be used (the International Space Station is cooled in this way, using an ammonia-based coolant loop), or heating and cooling devices can be distributed throughout the hull. Another option is to cool via evaporation of volatile substances. All these methods help to counteract thermal stress and minimise material fatigue (thermal management is discussed in detail in Sect. 2.4). The spacecraft of the Apollo programme solved this problem using an even simpler and pragmatic approach: During the uneventful flight period between low Earth orbit and Moon landing, the ship was spinning slowly along its long axis (called the "Barbecue Roll"). Hence, all surfaces were equally exposed to sunlight, levelling out the heating.

Thermal management is also the reason for satellites' typical golden hull colour. As an outer layer, they tend to be wrapped in Mylar foil that has been coated with a thin layer of gold. Gold reflects most of the incoming light, thus keeping the illuminated side cool, while thermally insulating the satellite's cold side.

The design of spacecraft that are intended to spend longer than a couple of days in space further needs to account for the effects of unfiltered solar UV radiation. Certain kinds of plastic, for example, would become brittle and non-UV-resistant colourings would quickly be bleached out. The American flags left on the Moon by the Apollo missions are nowadays completely white, since their 1960s colours were not able to withstand constant exposure to the blistering sunlight!

[1]This thermal background radiation is actually the echo of the Big Bang and fills the whole universe equally.

Anecdote

The windows of the International Space Station are fitted with UV filters. In some windows of the Russian side of the station, these filters can be manually flipped away to allow unimpeded observations of Earth's atmosphere.

When opened for this purpose, it quickly became apparent that exposure of human skin to unfiltered UV light from the Sun leads to heavy sunburns after only a couple of seconds! Nowadays, the filters are no longer supposed to be flipped away.

Light (be it visible or invisible) is far from the only kind of radiation a spaceship's hull has to shield off. *Cosmic rays* in particular need to be taken care of! Apart from their harmful effects on humans (see Sect. 5.7), radiation can knock electrons loose from atoms, so that random electric charges appear, and microscopic electronic circuits can be disturbed or damaged. Complex molecules, such as the active compounds in medicine, age at an increased rate under radiation exposure (see Sect. 5.8). On the surface of the Earth, cosmic radiation is warded off almost completely by Earth's magnetic field and atmosphere, but in space its average energy density is around 1.8 eV (approximately 3 nJ) per cubic centimetre. While this number lies significantly below the value of visible light from the Sun, fending off this kind of radiation comes with a whole lot of extra problems. As the high-energy charged particles that form cosmic rays easily penetrate deeply into materials (including human tissue), they cannot simply be stopped by thin layers of metal.

When travelling in low Earth orbit, Earth's magnetic field gives reasonably efficient protection against these rays, at least when it comes to less energetic ones. The charged particles follow the magnetic field lines towards the magnetic poles of Earth and plummet into the atmosphere there, causing colourful aurora above the Arctic and Antarctic regions. This deflection effect vanishes when rising into and above the Van Allen radiation belts (between 1000 and 60,000 km above the surface, see Fig. 2.3), as the magnetic field can no longer trap particles at those distances.

Cosmic rays are best protected against, like radioactivity on Earth, by a wall that is as thick, as dense and as massive as possible. Ideal materials to absorb them would be lead or tungsten, but exactly these heavy substances are unpopular for spaceship construction, as mass comes at a premium. For radiation shielding that uses the available mass budget efficiently, it makes sense to employ substances which will anyway be needed in long duration spaceflight. There are, for example, plans to build a spacecraft's fuel and water