TAKSHASHILA INSTITUTION

Human Spaceflight

Indian Goals & Global Ambitions

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This document examines how national space agencies and private companies are pursuing human spaceflight. It analyses emerging trends and uses them as context to provide recommendations on how India can pursue its own goals for sending humans into outer space.

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Executive Summary

- There is renewed interest in human spaceflight around the world. This is being driven by both higher government spending and greater private sector dynamism. This is evident in plans to commercialise low Earth orbit habitation and the US-led Artemis lunar exploration programme.
- Space exploration remains a high-risk venture for both technical and commercial reasons. While private sector actors are still working out their business models, they are already changing the way states approach lunar exploration.
- India has laid out its ambition to operate a space station by 2035 and send an Indian to the Moon by 2040. To achieve these goals, India will need to move away from its traditional approaches and seek out international cooperation and commercial opportunities more actively.
- India must embed ISRO programmes such as the Gaganyaan human spaceflight project into the effort to build a commercially sustainable low-Earth orbit economy. It must also join the Artemis lunar exploration programme to accelerate its journey to putting a person on the Moon.

This document has been formatted to be read conveniently on screens with landscape aspect ratios. Please print only if absolutely necessary.

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I. Introduction

On 17 October 2023, Indian Prime Minister Narendra Modi set deadlines for two ambitious goals for India's human spaceflight endeavours. Addressing officials from the Department of Space (DoS), PM Modi said India should have a "Bharatiya Antariksha Station" or Indian Space Station in orbit by 2035 and send the first Indian to the Moon by 2040. [1]

India's space programme has traditionally been focused on space applications and is known for its frugality. However, starting in 2018, the Indian Space Research Organisation (ISRO) began working on the Gaganyaan human spaceflight programme and later revealed that it had plans for a space station.[2]

These developments come as major spacefaring states and some private space companies invest in new projects for sending humans into Earth orbit or beyond. This document looks at India's new ambitions in the global context. The first section is a wide-ranging survey of ongoing human spaceflight undertakings around the world. The second section looks at India's endeavours and outlines how India can pursue international cooperation to manage the costs and risks associated with human spaceflight programmes.

II. Types of Human Spaceflight

Only Russia, the United States and China have achieved the ability to independently send humans to space and return them to Earth. Crewed missions to space can be classified into four categories: (1) suborbital flight (2) orbital flight, (3) earth orbit habitation, and (4) missions to celestial bodies. We consider each of these below:

Suborbital Flight

In suborbital flights, spacecraft enter space but are not traveling fast enough to enter full orbit and thus fall back towards Earth. The US' first astronaut, Alan B. Shepard, entered space in a Mercury capsule in 1961, in what was a suborbital flight.[3] More recently, private spacecraft such as Blue Origin's New Shepard series and Virgin Galactic's Unity have successfully completed several suborbital flights.[4] On 10 August 2023, the Unity took tourists to the fringes of space.[5]

Human-rated suborbital craft have important limitations. The New Shepard vehicles only promise to take passengers on a 11-minute ride just past the Karman Line, the generally accepted boundary for space, at an altitude of 100 kilometres above sea level.[6] Virgin Galactic's rocket-powered space planes reach an apogee of about 88 kilometres, which is technically below the Karman Line.[7] However, there are arguments for the line to be revised downwards from the arbitrary 100-kilometre mark, since satellites on some elliptical orbits can briefly reach perigrees as low as 80 kilometres.[8]

There are few practical use cases for suborbital flight. For instance, crews on the Virgin Galactic Unity craft only experience about four minutes of weightlessness.[9] This is far too little time for most microgravity experiments or for providing crews exposure to conditions they would experience in orbit or beyond.[10] Furthermore, suborbital craft cannot reliably dock with spacecraft in orbit, which means they cannot be used for space transport. These shortcomings could limit demand and thus reduce the willingness of private enterprises to invest in suborbital systems. For instance, Blue Origin's New Shepard launch vehicle and spacecraft are reported to be "hemorrhaging" cash.[11] In the coming years, it could make sense for some companies to cut down on their suborbital programmes and focus on more profitable space transport systems.

Despite these limitations, suborbital flights have potential advantages that could help keep some vehicles in business. For one, they can allow users to access space more frequently and cheaply, making them useful for some kinds of microgravity experiments, and space tourism.[12] In the future, suborbital Earth-transportation may become feasible, allowing people and cargo to be transported across continents in less than an hour.[13] However, even if such capabilities become feasible, high costs are likely to restrict them to government and military customers.

Orbital Flight

Spacecraft in Earth orbit make regular revolutions around the planet on the same path. To achieve this, the craft must achieve orbital velocity, which varies with altitude.

The Soviet Union pioneered orbital human flight with cosmonaut Yuri Gagarin's mission in 1961. The United States put astronaut John Glenn into orbit in 1962, and China sent taikonaut Yang Liwei on an elliptical orbit in 2003. India's LVM3 vehicle is also intended to be an orbital craft.

At present, the primary purpose of orbital capsules is to transport personnel and freight between the two operational space stations (the International Space Station and Tiangong) and Earth.

The United States: After the US scrapped its Space Shuttle programme, Russian capsules became the sole mode of crew transport to and from the International Space Station (ISS) between 2011 and 2020. From 2012 onwards, privately built and launched cargo spacecraft started supplying the ISS under NASA's programme for commercial resupply services.[14] These were the SpaceX Dragon-series, which was followed in 2014 by Northrop

Grumman's Cygnus-series of expendable craft.[15] While not crew-rated vehicles, these orbital craft are designed for the sole purpose of supporting human spaceflight missions. Indeed, this support is not restricted to freight deliveries. When docked to the ISS, the Cygnus can also fire its engines to boost the space station's altitude, thus correcting gradual orbital degradation.[16]

Another contender under NASA's cargo transport programme is the Dream Chaser spaceplane from Sierra Space. The Dream Chaser, which is scheduled to undergo a series of tests in 2023, is designed to launch from a United Launch Alliance (ULA) rocket, deliver cargo in an expendable capsule, and then re-enter the Earth's atmosphere and land like a plane.[17]

NASA has also developed a Commercial Crew Program (CCP) for human spaceflight, concluding contracts with SpaceX and Boeing.[18] In 2020, SpaceX began operating the crew-rated version of the Dragon spacecraft to the ISS. Dragons can carry a crew of seven including a pilot. At present, they are the only American-made means of human transport to low Earth orbit. SpaceX's Crew Dragons have also been employed on two private missions to the ISS organised by Axiom Space in 2022 and 2023.[19] Boeing's candidate, the CST-100 Starliner, has suffered several delays and its first Crew Flight Test (CFT) is not expected before April 2024.[20]

Barring the Cygnus cargo capsule, all the orbital craft discussed above are reusable. For private companies, this is an essential part of managing costs as they fulfil their obligations under fixed-price, indefinite-delivery/indefinite-quantity (IDIQ) contracts for NASA.[21] However, reusable orbital craft are still a nascent technology, and maintaining profitability with fixed-price contracts may be a challenge for Boeing, at least in the short-term.[22] In June 2022, NASA's official blog recognised SpaceX's market dominance by noting that Crew Dragons remained the only viable option for transport to the ISS.[23]

This lack of diversity in supply is matched by limited demand. The small market for orbital vehicles is primarily determined by the needs of space station transport. Having built a small fleet of four Crew Dragons that can fulfil its contracts with NASA, SpaceX has halted production of the spacecraft.[24] Any resumption of production will depend on future demand, whether from the ISS or future commercial space stations.

<u>China:</u> The China National Space Administration (CNSA) uses the Shenzhou series of spacecraft to transport taikonauts and cargo to and from the Tiangong space station.[25] The spacecraft carries crews of three on the Long March LM-2F human-rated rockets.[26] Neither the spacecraft (which superficially resembles the Soyuz capsule), nor the rocket are reusable.

China appears to be making conscious efforts to close the technology gap with the United States. The state-owned China Aerospace Science and Technology Corporation is working on a new reusable capsule designed to ferry up to seven crew members. It has carried out at least two uncrewed tests.[27] Besides Earth-orbit flight, the capsule is also being designed to be capable of deep space exploration.[28]

For freight transport, CNSA operates the Tianzhou cargo craft to service the Tiangong space station.[29] Like its American counterpart, the Cygnus, the Tianzhou burns up on re-entry.[30] The Tianzhou can also refuel the Tiangong, and like the Cygnus, can provide an orbital boost to space stations by firing its own engines when docked.[31]

Russia: While SpaceX Crew Dragons now dominate passenger transport to the ISS, Soyuz capsules continue to ferry Russian cosmonauts and some of their international colleagues.

In September 2023, the Soyuz MS-23 mission brought back two Russian cosmonauts and an American astronaut from the ISS. The three crew members had to extend their stay on board after their original capsule, the Soyuz MS-22, developed a coolant leak, most likely after it was struck by a micrometeoroid.[32] MS-23 was the 68th successful crewed Soyuz mission to the ISS.

Soyuz capsules have a proven track record over decades and the newest versions incorporate major upgrades such as greater payloads and fully digital systems.[33] Russia is also developing a next-generation, fully reusable spacecraft called the Oryol. However, the first uncrewed Oryol test won't take place before 2028.[34]

Furthermore, Russia's Progress-series of automated and expendable cargo spacecraft have been in operation since 1978.[35] Based on elements of the Soyuz, Progress capsules have carried pressurised cargo along with fuel and atmosphere to the Soviet Salyut space stations, the Mir space station and the ISS .[36]

Japan: Mitsubishi Heavy Industries built the H-II Transfer Vehicle (HTV) as an uncrewed, expendable cargo capsule to service the ISS. HTVs were designed to be operated by Japan's space agency, JAXA, to supply cargo to the ISS. The first capsule was launched in 2009[37] and the last one in 2020.[38] Japan is slated to replace the HTV with a new HTV-X expendable craft.[39]

	United States	**China**	**Russia**
Crewed	Crew Dragon	Shenzhou	Soyuz
Cargo	Dragon, Cygnus	Tianzhou	Progress

Figure 1: Human Spaceflight Supporting Orbital Craft (In Operation)

Earth Orbit Habitation

Orbital spacecraft that can support sustained human presence are commonly called space stations. Besides pressurised habitation, they typically have more elaborate systems for supplying power and recycling water. Newer space stations also include more comfortable amenities for living as well as separate designated areas for carrying out space-based activities such as scientific experiments.

The only two space stations presently in Earth orbit are the International Space Station (ISS) and China's Tiangong. Both operate in low Earth orbit (LEO) at altitudes of about 400 kilometres and 425 kilometres respectively.[40] Both are modular space stations, which are assembled in orbit from separately launched modules. The ISS can sustain a crew of seven, while the Tiangong can host up to five.[41]

International Space Station: Built over a span of 14 years between 1998 and 2011, the ISS has been crewed continuously since 2 November 2000.[42] It has 16 pressurised modules, a mass of 450 tons, and a total habitable volume of 388 cubic metres.[43] As of this publication, the ISS has hosted 273 visitors from 21 countries. These include 163 Americans and 59 Russians.[44] Crews have carried out more than 3,000 scientific experiments[45] and engaged in 269 spacewalks.[46] The station's eight solar arrays cover more than an acre of area and provide up to 90 kilowatts of power. In 2021, NASA estimated it alone spent $3 billion a year on the ISS.[47] By even conservative estimates, the station cost a total of about $150 billion by 2015, making the ISS a prime candidate for the most expensive human-made object in history.[48] The ISS is also, by a wide margin, the largest artificial object in space, and can be frequently spotted from Earth, moving across the night sky.

Notwithstanding its impressive accomplishments, the ISS is currently an ageing platform. Initial plans called for it to be decommissioned in 2024.[49] With no immediate replacements in sight, Western participants have pushed that date to beyond 2030.[50] Roscosmos has agreed to stay on until 2028[51] but plans to pivot to its own future Russian Orbital Station (ROS).[52]

The ISS is also the product of an ageing multilateral deal. In January 1998, NASA, the ESA, Roscosmos, Japan's JAXA, and the Canadian Space Agency (CSA) signed an 'Intergovernmental Agreement' (IGA) that laid the foundation for collaboration on a multilateral space station.[53] The IGA covered the rights and responsibilities of partners. It also outlined a system of utilisation rights. Under this system, participating space agencies could swap the goods and services they contributed to the station. This allowed the space agencies to barter resources based on their level of contribution to the station's operations rather than pay cash.[54] It also allowed relatively small agencies like CSA (which built the Canadarm-series of robotic arms for the ISS), to gain reliable access to human spaceflight.

However, the political conditions that enabled this remarkable instance of space cooperation are now fraying. In 1998, the US had managed to draw a severely weakened post-Soviet Russia into the ISS project. For Russia this was a way of retaining its institutional experience with running a space station. For the US, it was a way of keeping the Russians friendly and encouraging them to adopt technology export controls in line with US policy. Mutual dependency strengthened further after the US scrapped its Space Shuttle programme in 2011, making Russia's Soyuz capsules the sole means of moving people between the ISS and Earth.

Two developments since 2011 changed these circumstances. One, NASA's Commercial Crew Program succeeded in eliminating American dependency on Soyuz capsules following the success of SpaceX Crew Dragons. Two, US-Russia ties have turned adversarial. Key factors include the Syrian civil war[55], Russia's two wars with Ukraine in 2014 and 2022-23, and Russia's alleged interference in the US presidential election of 2016.[56] Besides undertaking coercive economic measures against Russia, the US has also put in place technology denial regimes that have significantly hurt Roscosmos.[57] While the US will continue to operate the ISS with its Western partners, the model of cooperation that enabled the creation of the largest space station in orbit, is unlikely to be replicated anytime soon.

The Tiangong Space Station: China's human spaceflight programme has evolved over three phases. The first phase involved the development of the

Shenzhou capsule for orbital flight. The second phase was dedicated to developing the various capabilities that underpin space station operations. These included rendezvous and docking in orbit, extravehicular activity, and maintaining a small-sized orbital lab. The third phase was the construction and habitation of a modular space station, the Tiangong.[58]

After first accomplishing its first human spaceflight mission in 2003, China commenced the second phase of the programme in 2011 with the launch of the small Tiangong-1 space lab. A total of three Shenzhou capsules docked with the lab. In the last mission, Shenzhou-10, a crew of three taikonauts docked with the lab in 2013 and spent 15 days onboard. The Tiangong-1 de-orbited seven years later.[59]

In 2016, China launched the more elaborate Tiangong-2. This time, a Shenzhou capsule took two taikonauts who spent 30 days working in the space lab. In 2017, China also tested the Tianzhou cargo capsule, which docked with the Tiangong-2 multiple times.[60] The lab was deo-orbited in 2019.[61]

The first part of the Tiangong space station, the Tianhe habitation module, entered orbit in April 2021. In June of that year, a crew of three docked with the module and spent 90 days in it. The following year, the remaining two modules, the Wentian and Mengtian lab modules docked with the Tianhe.[62]

China now maintains continuous human presence on the Tiangong space station.

The Tiangong was thought to be complete with the assembly of three modules. However, in October 2023, the China Academy of Space Technology (CAST) indicated that there were plans to add three more modules to the Tiangong and invite crews from other countries.[63] CAST also indicated that the station was expected to have a life of 15 years.[64]

China has clearly identifiable motives to build and expand its own space station. Its key partner, Russia, has limited capacity as a result of financial and technological constraints. China also cannot collaborate meaningfully with the US on space, since that country has domestic legislation called the Wolf Amendment that makes such cooperation almost impossible. This leaves China with little choice but to build its own space station. Furthermore, expanding the Tiangong gives China a powerful tool for space diplomacy with other governments as well as commercial opportunities from corporate clients or tourists.

Commercial Space Stations: All substantial plans for commercial Earth-orbit habitation are being developed by US-based companies. This is not only because these companies enjoy significant technological advantages but also because NASA has institutionalised a programme to support the development of what it calls commercial low Earth orbit destinations (CLDs) from which customers (including NASA itself) can purchase services. NASA's stated goal is to "implement an orderly transition from current International Space Station (ISS) operations to these new CLDs." [65] By nurturing a commercialised LEO ecosystem, NASA expects to save $1.3 billion a year by 2031 and $1.8 billion by 2033.[66]

NASA supports three CLD projects. One is Axiom Space. The first segment of this planned station is scheduled to launch in 2026, and will dock with the ISS, serving as an additional module. Subsequent launches will add more modules following which the Axiom station is to separate from the ISS and become a fully functional independent orbital habitat.[67] Axiom's approach allows it to use the ISS as a testing and validation platform. Its marketing literature also vaunts Axiom's ability to seamlessly "adopt and service the multinational user base of the ISS"[68], suggesting the company will be focused on supporting the kind of scientific experiments carried out on the ISS rather than other applications such as tourism.

Another CLD partner is Blue Origin, which has received $130 million in initial funding from NASA for its Orbital Reef station, which it plans to operate in collaboration with Sierra Space.[69] In contrast to Axiom, Blue Origin describes Orbital Reef as a "mixed-use business park" that can accommodate up to 10 people[70] who may be engaged in a variety of undertakings, whether those be a research lab or a hotel.[71] As part of its business development efforts, Blue Origin has reached out to organisations around the world, including India.[72]

The third CLD partner is Nanoracks, which has received $160 million in initial funding from NASA for its Starlab station.[73] Nanoracks is partnering with Voyager Space, Northrop Grumman, and Airbus for building and operating this small, single module station that will house up to four people.[74] Like Axiom, the station will focus on ISS customers and related opportunities for states engaged in science diplomacy. It's stated purpose is to "conduct investigations, advance scientific discovery, and foster industrial activity in microgravity."[75]

All three CLD projects feature some level of vertical integration, bringing together companies that operate launch systems and capsules with the planned space stations. Axiom has an existing relationship with SpaceX for its Crew Dragon spacecraft.[76] Blue Origin is partnering with Boeing to provide crew transport on Starliners and with Sierra Space to move freight on Dream Chasers. Blue Origin's New Glenns launch systems will put these spacecrafts into orbit.[77] Starlab has also concluded a memorandum of understanding (MoU) with the European Space Agency (ESA) that opens up the possibility of future European cargo and crew capsules providing transport to the station.[78] One of the Starlab companies, Voyager Space, has also signed an MoU with ISRO "to explore opportunities for the utilization of ISRO's Gaganyaan crewed spacecraft".[79]

It is evident that the development of CLDs entails considerable technical risk. Many of the platforms and systems mentioned above are still in testing or development stage. For example, Boeing's Starliner has experienced multiple delays, and its first crewed test is planned only in early 2024. Similarly, Blue Origin's New Glenn launch system is yet to complete testing and receive regulatory approval.[80] This is over and above the risks and uncertainties involved in building new space stations, not least of which will be the likely cost overruns.

Business risks will be at least as significant. The market for low Earth orbit services is likely to be limited to a handful of paying customers. The main clients are likely to be national space agencies, government labs, and private sector research and development initiatives. Tourism and media companies such as film crews can provide additional business. Even if all three planned CLDs are successful, they may be joined in orbit by an expanded six-module Tiangong and other private space stations not part of the CLD. If ISRO meets its schedule for an Indian outpost and even Russia manages to build one of its own, the space station market may suffer a supply glut. It is entirely possible that some future space station may have to be abandoned and de-orbited simply because it is losing too much money.

Missions to Celestial Bodies

While uncrewed probes have explored the outer solar system, all major plans for human spaceflight to celestial bodies are restricted to the Moon. The Moon remains the only celestial body visited by humans and has not seen any human visitors since the Apollo 17 mission in December 1972.

There are presently only two substantial projects being undertaken to return humans to the lunar surface. The biggest of these is the NASA-led Artemis programme. The other is the International Lunar Research Station (ILRS) project led by China National Space Administration (CNSA) and Roscosmos.

The motives for human spaceflight to the Moon are primarily political, economic, and scientific. Placing humans on the Moon is a major demonstration of a state’s technological prowess and economic wherewithal. It also has the potential to inspire students to take up careers in space science or the space industry. Furthermore, undertaking such a complex project can serve as a stimulant to high-technology industries, encouraging innovation, providing support to startups, and retaining talent. Finally, the Moon is of significant scientific interest for two reasons. One, it can provide insights about the Earth and the early solar system. Two, it can serve as a springboard for more deep space exploration.

<u>The Artemis Programme:</u> Renewed US interest in the Moon can be traced back to White House Space Policy Directive 1, signed by then President Donald Trump in 2017.[81] The directive called on NASA to lead an "innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system".[82] This led to the formal Artemis Plan, first made public in September 2020.[83] Under the plan, NASA and its international and private partners would pursue two phases of Artemis simultaneously. The goal of Phase 1 was to put humans on the Moon "as efficiently as possible with acceptable technical risk". In Phase 2, the goal would be to put in place systems needed to support "a robust lunar presence". [84]

Artemis requires an entirely new fleet of launchers and spacecrafts. For the first two Artemis missions, NASA is employing its own Space Launch System (SLS) and Orion spacecraft. The uncrewed Artemis-I mission in November 2022 validated the SLS and Orion. During the mission, Orion went into orbit around the Moon and eventually reached a maximum distance of 429,700 kilometres from Earth, the farthest any human-rated vehicle has even been.[85] The spacecraft safely splashed down into the Pacific Ocean on December 11, 2022, 25 days after its launch.[86]

Artemis-II is a 10-day long crewed mission slated for 2024. It will take four astronauts beyond the far side of the Moon and back.[87] During this journey, the crew will test various critical systems on the Orion and perform manoeuvres intended to validate the spacecraft's system for docking with other space objects.[88]

In the meantime, NASA will first have to launch and assemble the Lunar Gateway, a small "human-tended" space station going around the Moon in a near-rectilinear halo orbit (NRHO). Over the course of this unique one-week-long orbit, the Gateway will swing away from the Moon before returning closer to its surface. This will allow spacecraft such as the Orion to dock with the Gateway when it is still far from the Moon. When the Gateway draws closer to the Moon, astronauts will transfer to a Human Landing System (HLS) that will detach from the Gateway and land at the Moon's south pole.[89]

NASA's stated plan for Artemis-III follows this template. It has selected SpaceX's Starship spacecraft to serve as the HLS. According to the plan, an uncrewed Starship HLS will launch and dock with the Gateway. Later, an Orion spacecraft carrying the crew of four astronauts will dock with the Gateway. As the Gateway approaches the surface of the Moon's south pole, two astronauts will transfer to the Starship HLS and land on the lunar surface, while the remaining two stay in the Gateway. The crew will spend 6.5 Earth days on the Moon before returning the Gateway on the HLS. Once onboard the Gateway, the four astronauts will transfer back to the Orion and head back to Earth.[90]

The current plan for Artemis-III relies on multiple untested systems including Starship and the Gateway. The Phase 1 plan had set a deadline of 2024 for Artemis-III[91]. This date has now been pushed to 2025 or later.[92] However, even this revised deadline appears unduly optimistic. NASA concedes that the two modules of the Gateway that need to be in place for Artemis-III will not be launched before 2025.[93] Furthermore, SpaceX's first test launch with Starship in April 2023 ended in an explosion.[94] Under the current Artemis-III plan, the Starship HLS will also need to be refuelled in Earth orbit by a SpaceX storage tanker before heading for its rendezvous with the Gateway. Until the entire Starship system is validated, none of these stepping stones for Artemis-III will be in place. NASA has made it clear that it is open to changing the flight plan for Artemis-III if key elements are delayed, however, it is unclear what a modified Artemis-III might look like.[95]

Notwithstanding these uncertainties, NASA's goal is to set up sustained human habitation on the lunar surface with an Artemis Base Camp.[96] As part of this, Artemis focuses heavily on logistics, with uncrewed missions greatly outnumbering crewed ones. For instance, NASA is working with several companies to send scientific and technical payloads to the Moon under its Commercial Lunar Payload Services (CLPS) programme.[97] NASA also plans to launch its VIPER probe to the lunar south pole in late 2024 to locate and investigate water ice.[98] In a similar vein, the ESA plans to despatch its European Large Logistics Lander to the south pole to collect samples and return them to Earth via the Gateway. Finally, NASA and its collaborators also plan a constellation of satellites and ground stations called LunaNet, that is meant to provide communications, navigation, space weather services.[99]

Surveying the Artemis programme, it is possible to discern two sets of strengths and three sets of risks. One strength is that the programme is based on decades of experience with human spaceflight, space station operations, and the docking of spacecraft, as well as a decade of crewed lunar exploration. Two, the US has been able to leverage the strengths of its private sector international partners. Lockheed Martin is the prime contractor for the Orion.[100] SpaceX is responsible for the HLS. Boeing and Northrop Grumman are responsible for different segments of the SLS.[101] Japan's JAXA is building on its experience with the ISS to provide life support systems and environment controls for the Gateway.[102]

Similarly, the ESA has built the European Service Module (ESM) that provides life support to the Orion spacecraft.[103] In exchange for these contributions, the ESA and JAXA will get seats on the Artemis flights. In 2022, Japan's science and technology minister said they would seek to make a Japanese astronaut the first non-American on the Moon.[104]

The risks with Artemis are conceptual, technical, and budgetary. The Artemis programme in its current form has been subject to criticism for both the SLS (which is deemed too expensive) and for the Gateway (which some see as a distraction from a terrestrial base on the Moon). In the future, companies such as SpaceX and Blue Origin may develop more cost-efficient solutions for landing on the Moon directly, thus undercutting support for Artemis.[105] Two, Artemis is ultimately predicated on in-situ resource utilisation (ISRU). In particular, access to lunar water ice will be needed to sustain human presence on the Moon. However, it is unclear if uncrewed or crewed missions to the lunar south pole will find sufficient quantities of extractable water, or if methods will be developed to safely extract the water from lunar impurities. Three, international political and economic changes could cause disruptions or even an end to budgetary support.

The International Lunar Research Station (ILRS): Details about the ILRS are much scarcer than those for the Artemis programme. In March 2021, Roscosmos and CNSA signed an agreement to build a research facility either on the Moon or in lunar orbit.[106] Since then, states that have joined the ILRS besides China and Russia include Pakistan, Azerbaijan, South Africa, Venezuela[107], and Belarus.[108]

Three months after the announcement of the project agreement, Wu Yanhua, the deputy head of CNSA laid out the three-stage plan for ILRS:

1. Phase 1 (2021 – 2025): Collect and validate data using uncrewed missions such as Russia's Lunas and China's Chang'e probes.

2. Phase 2: (2026 – 2035): The first part of this phase would include return of samples for analysis and delivery of cargo. The next part would involve laying down the infrastructure for communications, power supply, and resource utilisation.

3. Phase 3: Human crews would finally land.[109]

The English-language version of CNSA's 2021 roadmap for ILRS describes five types of facilities:

1. Cislunar transport between Earth and Moon.

2. A long-term support facility on the Moon.

3. Lunar transportation and operation facilities for cargo transportation, movement on the lunar surface, and exploring lava tubes on the Moon.

4. A scientific facility to support experiments on both the surface and in orbit.

5. A ground support facility on Earth.[110]

There are two key takeaways on the ILRS. One, Russia's contribution to ILRS is likely to dip given Roscosmos' financial troubles. Two, both ILRS and Artemis appear to be pursuing exploration in the same area in the lunar south pole. This is the region that has both permanently shadowed regions[111] that are believed to contain water ice, as well as highlands with continuous sunlight that can power solar arrays.[112]

III. India's New Goals for Human Spaceflight

Orbital Flight

During his annual speech on 15 August 2018, Prime Minister Narendra Modi said that his government had 'resolved' that Indians would 'unfurl the Tricolour in space' by 2022, to mark 75 years of Indian independence.[113] Subsequently, in December, the Union Cabinet approved what was by then called the Gaganyaan human space flight programme.[114] A release announcing the approval provided some details of the mission objective, its timelines, expected budget, and potential benefits.[115]

The parameters were as follows:

1. Sending two uncrewed missions and one crewed mission into Low Earth Orbit (LEO).

2. The period of the crewed mission would be for a minimum of one orbit and a maximum of seven Earth days.

3. The mission would use a human-rated version of the GSLV Mk-III launch vehicle that can sustain a three-member crew.

These objectives were to be accomplished in 40 months (April 2022) and the expected expenditure was ₹9023 crores.[116]

Current Status: The government has cited the COVID-19 pandemic as the primary reason for the delays in the Gaganyaan project.[117] On 17 October, ISRO successfully tested the emergency escape system for the Gaganyaan crew module.[118] Officially called the "In-flight Abort Demonstration of Crew Escape System," it involved a crew module, which was mated to a single stage rocket. Upon launch of the rocket, the crew module separated and parachuted down into the Bay of Bengal.[119] This demonstrated a key safety feature: the ability of the crew module to jettison the launch vehicle if something goes wrong. The next steps for ISRO include another test of the escape system and an integrated air drop test, in which the crew module will be dropped from a helicopter.[120] Finally, ISRO will launch an uncrewed flight test that will carry one of ISRO's Vyommitra humanoid robots.[121] The first crewed mission is unlikely to occur before 2025.

Four IAF personnel selected for the Gaganyaan project underwent training in Russia in 2020-21.[122] They are to go through further training and preparation at ISRO's new astronaut training facility.[123] All four personnel were selected by and received their initial training from the Indian Air Force's (IAF) Institute of Aerospace Medicine.[124]

Other Goals: Besides achieving orbital flight, the Gaganyaan project envisages a "national effort" that involves industry, academia, and other government labs. Some of the benefits expected include increased research and development, technology spinoffs, and the potential for international collaboration on human spaceflight.[125]

The ISS Mission: In June 2023, US President Joe Biden announced that India and the US were working together to send an Indian astronaut to the ISS.[126] Biden's statement came during a visit to the US by Prime Minister Narendra Modi. Previous negotiations may have set the stage for this decision. Earlier in the year, India and the US had concluded an initiative on critical and emerging technologies (iCET), which included training for an Indian astronaut (presumably one of the four IAF personnel selected for Gaganyaan) at the NASA Johnson Space Center.[127]

The goals of the ISS mission, which will occur before the first Gaganyaan flight, are unclear. Sending an Indian to the ISS may have symbolic significance because it will be the 40th anniversary of the flight of Indian cosmonaut Rakesh Sharma on a Soviet Soyuz capsule in 1984. More substantially, the mission could act as a spur for further human spaceflight cooperation between India and the United States.

Bharatiya Antariksha Station & the Moon Mission

Little is understood about the goals for an Indian space station or Moon mission. ISRO officials have revealed little in public statements and it is possible the plans have been gradually evolving.

The Space Station: In 2019, then ISRO chief, K Sivan announced that India would have its own space station and that it would "join the international community" in crewed missions to the Moon. Sivan's made three points about space stations as part of his announcement:

1. The Indian space station was necessary to "sustain the Gaganyaan programme".
2. The space station would be a small module for microgravity experiments and not linked to the ISS. The station would have a mass of about 20 tonnes.
3. ISRO was not considering space tourism.[128]

Sivan's successor, S. Somanath provided a few more details in an interview in early October 2023. Somanath said space station development would take 20-25 years and that building the station would commence with robotic operations.[129]

Sivan and Somanath's assumptions will require revision. With a new deadline of 2035, ISRO has only 12 years to commence operations on a new space station.

The Moon Mission: A human mission to the Moon would require ISRO and its partners to develop at least three key capabilities. One, they will need a heavier launch vehicle that can put a sizeable crew capsule into lunar orbit. Two, they will need to design a crew capsule and a lunar landing system. Three, the crew capsule must be capable of taking off from the lunar surface, returning to the Earth and making re-entry. While there can be variations (for instance, a deep space vehicle could dock with an Earth-orbit station and transfer its crew), any human mission to the Moon will pose unprecedented challenges for ISRO. To meet the 2040 deadline, it may have no choice but to actively seek greater international cooperation.

Charting a Way Forward

While ISRO officials have referred to international cooperation in the past, the accelerated timelines for a space station and a human mission to the Moon will necessitate foreign collaboration at a deeper level.

Based on the limited information available in the public domain, India appears to be following a human spaceflight path similar to China's. The steps include perfecting orbital human spaceflight, building one or more small space stations before graduating to a larger modular outpost, and pursuing uncrewed lunar sample return missions to gain some of the experience needed to send people to the Moon.

However, China's circumstances are very different from India's. For one, China's space budget is much higher, being estimated at about $12 billion in 2022[130] compared to ISRO's budget estimate of $1.64 billion in the financial year 2022-23.[131] While these figures may not be exactly comparable, they indicate the differences in budgetary support available for ambitious space missions.

Two, China has a single spacefaring partner: Russia. While Russia's Roscosmos has formidable capabilities and experience, it remains financially constrained and lacks easy access to foreign technology.

For China, independent development of its space programme is more necessity than choice. On the other hand, India not only has a history of partnering with Roscosmos, but is also witnessing growing cooperation with NASA, JAXA, and the ESA. If divisions between China and other states heighten in the coming decade, the incentive for cooperation will only increase.

Three, the growing prominence of commercial actors in the space sector provides India the opportunity to grow its own space industry. While ISRO has historically engaged in vendor-level agreements with several private sector companies, it will need to encourage both established players and startups to move up the value chain.

In summary, India must seek international cooperation to (1) gain experience and access technology, and (2) seek commercial opportunities that can help reduce the budgetary burden of human spaceflight. To achieve this India must do the following:

1. Firmly embed the Gaganyaan and Bharatiya Antariksha Station projects into plans for developing a commercial low Earth orbit economy. As discussed earlier, at least two commercial players, Blue Origin and Voyager Space have shown interest in using the Gaganyaan capsule for crew transport to their planned stations. ISRO can leverage these collaborations to gain access to commercial space stations and thus provide experience to Indian crews.

2. Encourage joint ventures between Indian and foreign companies pursuing projects related to both low Earth orbit and lunar exploration. Indian engineering talent combined with cost advantages and ISRO's space facilities can help build Indian expertise and intellectual property.

3. To meet its goal of putting a human on the Moon by 2040, India must join the Artemis programme. In June, India made the decision to sign the Artemis Accords, a series of principles on lunar conduct that are a pre-requisite for joining the Artemis programme. Signing the accords does not obligate India to join the US-led drive to return the Moon. However, joining Artemis programme can provide both ISRO and Indian commercial actors new opportunities and learnings.

While the steps outlined above are unprecedented for India's historically state-led space programme, Indian leaders and officials will have to adapt to the new realities of human spaceflight if they wish to accomplish the ambitious goals laid out in October 2023.

IV. References

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[1] Press Information Bureau. "Prime Minister reviews readiness of Gaganyaan Mission." October 17, 2023. Accessed on November 9, 2023.
https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1968368

[2] Pramanik, Ayan & Raghu Krishnan. "After Gaganyaan, ISRO chairman K Sivan to set sights on space station". Economic Times. January 14, 2020. Accessed on November 9, 2023.
https://economictimes.indiatimes.com/news/science/after-gaganyaan-isro-chairman-k-sivan-to-set-sights-on-space-station/articleshow/73237162.cms

[3] NASA. 60 Years Ago: Alan Shepard Becomes the First American in Space. May 5, 2021. Accessed on November 9, 2023.
https://www.nasa.gov/image-feature/60-years-ago-alan-shepard-becomes-the-first-american-in-space

[4] Wall, Mike. "Blue Origin still investigating New Shepard failure 6 months later". Space.com. March 4, 2023. Accessed on November 9, 2023.
https://www.space.com/blue-origin-investigating-new-shepard-failure-6-months

[5] Foust, Jeff. "Virgin Galactic conducts first space tourist suborbital flight". Space News. August 10, 2023. Accessed on November 9, 2023.
https://spacenews.com/virgin-galactic-conducts-first-space-tourist-suborbital-flight/

[6] Blue Origin. "New Shepard". Accessed on November 9, 2023.
https://www.blueorigin.com/new-shepard

[7] Rose, Greg. "Virgin Galactic completes first private astronaut spaceflight". Virgin. August 10, 2023. Accessed on November 9, 2023.
https://www.virgin.com/about-virgin/latest/virgin-galactic-completes-first-private-astronaut-spaceflight

[8] Bartels, Meghan. “Where DOES Space Begin? Virgin Galactic's SpaceShipTwo Flies Right into the Debate”. November 14, 2022. Accessed on November 9, 2023. https://www.space.com/42733-virgin-galactic-space-claim-relies-on-karman-line.html

[9] Harwood, William. “Virgin Galactic launches its first space tourist flight, stepping up commercial operations”. CBS News. August 10, 2023. Accessed on November 9, 2023. https://www.cbsnews.com/news/virgin-galactic-launching-space-tourist-flight/

[10] https://www.nasa.gov/mission_pages/station/research/news/iss-20-years-20-breakthroughs

[11] https://arstechnica.com/space/2023/11/as-virgin-galactic-soars-blue-origins-new-shepard-remains-grounded/

[12] An example of this is the 2021 Inspiration mission that featured no professional astronauts. https://www.space.com/inspiration4-spacex.html

[13] https://www.wired.co.uk/article/sub-orbital-flight-virgin-galactic-blue-origin

[14] https://www.spacex.com/human-spaceflight/iss/

[15] https://www.northropgrumman.com/space/cygnus-spacecraft

[16] https://www.space.com/41172-cygnus-leaves-space-station-orbital-boost.html

[17] https://arstechnica.com/space/2023/11/after-decades-of-dreams-a-commercial-spaceplane-is-almost-ready-to-fly/?utm_source=pocket-newtab-en-intl

[18] https://www.nasa.gov/humans-in-space/commercial-space/commercial-crew-program/commercial-crew-program-overview/

[19]
https://www.axiomspace.com/ax1

https://www.axiomspace.com/missions/ax2

[20] https://blogs.nasa.gov/commercialcrew/2023/10/12/nasa-updates-commercial-crew-planning-manifest/

[21] https://blogs.nasa.gov/commercialcrew/2022/06/01/nasa-to-purchase-additional-commercial-crew-missions/

[22] https://arstechnica.com/space/2023/10/boeing-says-it-cant-make-money-with-fixed-price-contracts/

[23] https://blogs.nasa.gov/commercialcrew/2022/06/01/nasa-to-purchase-additional-commercial-crew-missions/

[24] https://www.reuters.com/lifestyle/science/exclusive-spacex-ending-production-flagship-crew-capsule-executive-2022-03-28/

[25] https://spaceflight101.com/spacecraft/shenzhou-spacecraft-overview/

[26] http://www.cgwic.com/launchservices/launchvehicle/lm2f.html

[27] https://www.space.com/china-next-gen-space-capsule-landing-success.html

[28] https://www.space.com/china-next-gen-space-capsule-landing-success.html

[29] https://www.space.com/china-launches-tianzhou-6-cargo-mission-tiangong

[30] https://spaceflightnow.com/2023/05/10/long-march-7-tianzhou-6-launch/

[31] https://www.space.com/china-preparing-tianzhou-6-cargo-mission-tiangong

[32] https://www.spaceflightinsider.com/missions/iss/a-record-ride-soyuz-ms-23-trio-return-to-earth-after-a-year-in-orbit/

[33] https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/MagISStra/Facts_about_the_Soyuz

[34] https://interfax.com/newsroom/top-stories/93573/

[35] https://space.skyrocket.de/doc_sdat/progress.htm

[36] https://spaceflight101.com/spacecraft/progress-ms/

[37] https://spaceflightnow.com/2016/12/09/flight-history-of-japans-htv-resupply-spacecraft/

[38] http://www.spacefacts.de/iss/english/exp_63.htm

[39] https://humans-in-space.jaxa.jp/en/htv-x/

[40] https://www.space.com/16748-international-space-station.html

https://www.space.com/tiangong-space-station

[41] https://www.space.com/16748-international-space-station.html

https://www.space.com/tiangong-space-station

[42] https://www.space.com/16748-international-space-station.html

[43] https://www.nasa.gov/international-space-station/space-station-facts-and-figures/

https://www.space.com/tiangong-space-station

[44] https://www.nasa.gov/international-space-station/space-station-visitors-by-country/

[45] https://www.nasa.gov/missions/station/five-space-station-research-results-contributing-to-deep-space-exploration/

[46] https://www.nasa.gov/international-space-station/space-station-overview/

[47] https://oig.nasa.gov/docs/IG-22-005.pdf

[48] https://www.thespacereview.com/article/1579/1

[49] https://www.space.com/16748-international-space-station.html

[50] https://spacenews.com/nasa-open-to-extending-iss-beyond-2030/

[51] https://www.space.com/russia-stay-international-space-station-partner-2028

[52] https://tass.com/science/1566383?utm_source=en.wikipedia.org&utm_medium=referral&utm_campaign=en.wikipedia.org&utm_referrer=en.wikipedia.org

[53] https://www.state.gov/wp-content/uploads/2019/02/12927-Multilateral-Space-Space-Station-1.29.1998.pdf

[54] https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/International_Space_Station/International_Space_Station_legal_framework

[55] https://carnegieendowment.org/politika/90784

[56] https://www.whitehouse.gov/briefing-room/statements-releases/2023/02/24/fact-sheet-on-one-year-anniversary-of-russias-invasion-of-ukraine-biden-administration-announces-actions-to-support-ukraine-and-hold-russia-accountable/

[57] https://warontherocks.com/2022/06/sanctions-and-satellites-the-space-industry-after-the-russo-ukrainian-war/

[58] S. Chandrashekar. China's Space Programme: From the Era of Mao Zedong to Xi Jinping. P 183.

[59] https://chinaspacereport.wordpress.com/spaceflight/shenzhou10/

[60] S. Chandrashekar. China's Space Programme: From the Era of Mao Zedong to Xi Jinping. P 184.

[61] https://www.theverge.com/2019/7/20/20701831/china-tiangong-2-deorbited-experimental-space-station

[62] https://www.space.com/tiangong-space-station

[63] https://www.reuters.com/technology/space/china-double-size-space-station-touts-alternative-nasa-led-iss-2023-10-05/

[64] https://www.reuters.com/technology/space/china-double-size-space-station-touts-alternative-nasa-led-iss-2023-10-05/

[65] https://www.nasa.gov/humans-in-space/commercial-space/low-earth-orbit-economy/commercial-destinations-in-low-earth-orbit/

[66] https://www.nasa.gov/wp-content/uploads/2015/01/2022_iss_transition_report-final_tagged.pdf

[67] https://www.space.com/axiom-space-private-station-iss-2026

[68] https://www.axiomspace.com/axiom-station

[69] https://www.nasa.gov/news-release/nasa-selects-companies-to-develop-commercial-destinations-in-space/

[70] https://www.theverge.com/2021/10/25/22744526/blue-origin-space-station-orbital-reef-announcement

[71] https://www.orbitalreef.com/

[72] For instance, a Blue Origin team visited India in September, 2022.

[73] https://www.nasa.gov/news-release/nasa-selects-companies-to-develop-commercial-destinations-in-space/

[74] https://spaceflightnow.com/2023/10/05/northrop-grumman-leaves-behind-solo-commercial-space-station-venture-partners-with-nanoracks-on-starlab/

[75] https://starlab-space.com/

[76] https://www.axiomspace.com/news/category/Ax-2+Mission

[77] https://www.orbitalreef.com/

[78] https://techcrunch.com/2023/11/09/european-space-agency-signs-agreement-with-starlab-developers-to-secure-ongoing-access-to-low-earth-orbit/

[79] https://voyagerspace.com/2023/07/10/voyager-space-signs-mou-with-isro-and-in-space-to-explore-utilization-of-gaganyaan-spacecraft-for-the-starlab-space-station/

[80] https://www.wsj.com/articles/jeff-bezos-blue-origin-new-glenn-rocket-a328067

[81] https://www.nasa.gov/news-release/new-space-policy-directive-calls-for-human-expansion-across-solar-system/

[82] https://www.nasa.gov/news-release/new-space-policy-directive-calls-for-human-expansion-across-solar-system/

[83] https://www.nasa.gov/wp-content/uploads/2020/12/artemis_plan-20200921.pdf

[84] https://www.nasa.gov/wp-content/uploads/2020/12/artemis_plan-20200921.pdf

[85] https://www.nasa.gov/humans-in-space/view-the-best-images-from-nasas-artemis-i-mission/

[86] https://www.nasa.gov/humans-in-space/view-the-best-images-from-nasas-artemis-i-mission/

[87] https://www.nasa.gov/missions/artemis/nasas-first-flight-with-crew-important-step-on-long-term-return-to-the-moon-missions-to-mars/

[88] https://www.nasa.gov/missions/artemis/nasas-first-flight-with-crew-important-step-on-long-term-return-to-the-moon-missions-to-mars/

[89] https://www.nasa.gov/missions/artemis/lunar-near-rectilinear-halo-orbit-gateway/

[90] https://www.nasa.gov/centers-and-facilities/marshall/artemis-iii-nasas-first-human-mission-to-the-lunar-south-pole/

[91] https://www.nasa.gov/wp-content/uploads/2020/12/artemis_plan-20200921.pdf

[92] https://www.nasa.gov/centers-and-facilities/marshall/artemis-iii-nasas-first-human-mission-to-the-lunar-south-pole/

[93] https://www.nasa.gov/reference/nasas-gateway-program/#:~:text=Gateway%20Assembly,-Initial%20Gateway%20launch&text=The%20first%20two%20Gateway%20elements,an%20expected%20arrival%20in%202026

[94] https://www.space.com/spacex-starship-launch-date-november-2023

[95] https://spacenews.com/nasa-weighs-changes-to-artemis-3-if-key-elements-are-delayed/

[96] https://www.nasa.gov/wp-content/uploads/2020/08/a_sustained_lunar_presence_nspc_report4220final.pdf

[97] https://www.nasa.gov/commercial-lunar-payload-services/

[98] https://science.nasa.gov/mission/viper/science-and-exploration/

[99] https://www.nasa.gov/humans-in-space/lunanet-empowering-artemis-with-communications-and-navigation-interoperability/

[100] https://www.lockheedmartin.com/en-us/products/orion.html

[101] https://www.wsj.com/livecoverage/nasa-artemis-launch-moon-updates/card/the-companies-behind-nasa-s-artemis-program-Wq7vxCS57iPVDWcQb7w0

[102] https://sdgs.jaxa.jp/en/article/detail/12.html

[103] https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Orion/European_Service_Module

[104] https://spacenews.com/japan-agrees-to-space-station-extension-and-gateway-contributions/

[105] https://web.archive.org/web/20210428040537/https://www.thenewatlantis.com/publications/moon-direct

106 https://www.bbc.com/news/world-asia-china-56342311

107 https://spacenews.com/pakistan-becomes-latest-country-to-join-chinas-ilrs-moon-project/

108 https://spacenews.com/china-adds-belarus-as-partner-for-ilrs-moon-base/

109 https://spacenews.com/china-russia-reveal-roadmap-for-international-moon-base/

110 https://www.cnsa.gov.cn/english/n6465652/n6465653/c6812150/content.html

111 https://spacenews.com/nasa-and-china-are-eyeing-the-same-landing-sites-near-the-lunar-south-pole/

112 https://solarsystem.nasa.gov/news/907/moons-south-pole-in-nasas-landing-sites/#:~:text=Other%20extremes%20at%20the%20Moon's,Earth%20days%20of%20constant%20illumination.

113 https://www.pmindia.gov.in/en/news_updates/pms-address-to-the-nation-from-the-ramparts-of-the-red-fort-on-the-72nd-independence-day/?tag_term=independence-day&comment=disable

114 https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1557587

115 Ibid

116 ibid

117 https://pib.gov.in/PressReleasePage.aspx?PRID=1779647

118 https://www.ndtv.com/india-news/isros-unmanned-test-flight-for-its-first-human-spaceflight-mission-gaganyaan-lifts-off-in-second-attempt-4501802

https://economictimes.indiatimes.com/news/science/india-to-launch-gaganyaan-mission-by-end-of-2023-or-2024-jitendra-singh/articleshow/100337040.cms?from=mdr

119 https://www.isro.gov.in/media_isro/pdf/TVD1/TVD1-Brochure.pdf

[120] https://timesofindia.indiatimes.com/city/bengaluru/gaganyaan-isro-to-attempt-air-drop-test-using-chopper/articleshow/104684899.cms

[121] https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1966325

[122] https://www.thehindu.com/news/national/four-indian-cosmonauts-complete-training-in-russia-for-gaganyaan-mission/article34140964.ece

[123] https://pib.gov.in/PressReleasePage.aspx?PRID=1779647

[124] Insight gained from talk CII's International Conference on Space, 15 September 2023.

[125] https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1557587

[126] https://www.thehindu.com/sci-tech/technology/india-us-plan-to-send-indian-astronaut-to-international-space-station-in-2024-biden/article66999117.ece

[127] https://www.whitehouse.gov/briefing-room/statements-releases/2023/01/31/fact-sheet-united-states-and-india-elevate-strategic-partnership-with-the-initiative-on-critical-and-emerging-technology-icet/

[128] https://www.indiatoday.in/india/story/india-will-have-its-own-space-station-isro-k-sivan-1548112-2019-06-13

[129] https://www.livemint.com/science/news/india-to-build-its-own-space-station-in-next-25-years-isro-chief-gaganyaan-chandrayaan-3-s-somanath-11696598196806.html

[130] https://payloadspace.com/china-to-invest-heavily-in-its-race-to-the-moon/#:~:text=China's%20budget%3A%20Research%20firm%20Euroconsult,its%20space%20program%20in%202022.

[131] https://www.moneycontrol.com/news/business/economy/weekly-numerics-isros-shoestring-budget-soaring-price-of-onions-rise-of-the-cashless-and-more-11256371.html