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Perspective

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Orbital Reef and commercial low Earth orbit destinations—upcoming space research opportunities

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As the International Space Station comes to the end of a transformative era of in-space research, NASA's Commercial Low Earth Orbit (LEO) Destinations (CLD) Program aims to catalyze a new generation of platforms with co-investment from the private sector, preventing a potential gap in research performed in LEO, while building a robust LEO economy. In this paper, we provide insight into the CLD Program focusing on Orbital Reef, describing its operational and technical characteristics as well as new opportunities it may enable. Achieving about a third of the pressurized volume of the ISS with the launch of a single pressurized module and growing to support hundreds of Middeck Locker Equivalents (MLE) in passive and active payloads internally and externally, Orbital Reef will enable government, academic, and commercial institutions to continue and expand upon research and development (R&D) efforts currently performed on ISS. Additionally, it will enable nascent markets to establish their operations in space, by initiating new lines of research and technology development and the implementation of new ventures and visions. Using Blue Origin's New Glenn heavy launch system, Sierra Space's cargo and crew Dream Chaser® vehicles, and Boeing's Starliner crew vehicle, and expertise from Amazon/Amazon Supply Chain, Arizona State University, Genesis Engineering, and Redwire, Orbital Reef is being designed to address ISS-era transportation logistics challenges. Finally, this manuscript describes some of the expected challenges from the ISS-to-CLD transition, and provides guidance on how researchers in academia and industry can shape the future of commercial destinations and work performed in LEO.

The International Space Station (ISS) is a multi-nation project, the single largest structure ever put in Earth's orbit. It has hosted over 250 people from over 20 countries and over 3000 completed research investigations since assembly began in 1998[1]. Several of these efforts have translated into scientific and technical breakthroughs and have enabled advancements in a myriad of fields. For example, protein crystal growth investigations performed on ISS have provided novel insights into multiple disease treatments, as have fundamental and applied research on Alzheimer's Disease, Parkinson's Disease, heart disease, and various cancers[2]. The ISS has opened new fields of inquiry and fostered innovative techniques and capabilities, including the use of tissue chips in space, quiescent colloid research, 3D printing in microgravity, the development of new water purification systems, and lessons in how to live and thrive in space for longer durations[2]. As the ISS comes to the end of its design life, NASA now plans to retire the platform in 2030, and has established the Commercial LEO Destinations (CLD) Program to plan for the future[3,4].

NASA's commercial LEO destinations (CLD) program

NASA's commercial LEO programs are designed to support a transition to commercially owned and operated services that support the agency's science, technology maturation, and astronaut training needs in Earth orbit[3,5,6]. In early 2020, NASA awarded a contract for commercial modules to be attached to the ISS to Axiom Space[3,7]. The Commercial Destinations-Free Flyer program was established in 2021 as a two-phase acquisition. In December 2021, NASA announced three awards through 2025: Northrop Grumman, Nanoracks "Starlab", and Orbital Reef[5]. In Phase 1, private industry, in coordination with NASA, designs CLD capabilities to address government and commercial needs. Phase 2 will support certification of one or more platforms for U.S. government astronauts and end-to-end services including ground support, transportation, and on-orbit operations[5,6]. These services will ensure NASA's ability to maintain a permanent presence in LEO with at least two crew members, performing approximately 200 scientific investigations annually[5]. These services are intended to be

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轨道礁和商业低地球轨道目的地——即将到来的太空研究机会

路易斯·齐亚 1，✉伊丽莎白·沃伦 2，✉塔拉·拉特利 2，托德·莫舍，劳拉·凯尔西 & 埃里卡·瓦格纳

随着国际空间站进入太空研究变革时代的尾声，美国国家航空航天局（NASA）的商业低地球轨道（LEO）目的地（CLD）项目旨在通过私营部门的共同投资，催化新一代平台，防止在 LEO 进行的潜在研究差距，同时建立强大的 LEO 经济。在本文中，我们深入探讨了 CLD 项目，重点关注轨道礁，描述其运营和技术特性以及它可能带来的新机遇。通过发射一个压力舱模块实现约三分之一国际空间站的压力体积，并扩展到支持数百个内部和外部被动和主动有效载荷的 Middeck Locker Equivalents（MLE），轨道礁将使政府、学术和商业机构能够继续并在国际空间站上进行的研发（R&D）工作基础上进行扩展。此外，它还将通过启动新的研究和技术开发路线，以及实施新的企业和愿景，使新兴市场能够在太空中建立其运营。 利用蓝色起源的新格伦重型发射系统、西雅图太空的货物和乘员梦幻追捕®车辆、波音的星际穿越乘员车辆，以及亚马逊/亚马逊供应链、亚利桑那州立大学、创世纪工程和红线的专业知识，轨道礁正在设计以解决国际空间站时代的运输物流挑战。最后，这篇论文描述了从国际空间站到 CLD 过渡的一些预期挑战，并为学术界和工业界的研究人员如何塑造商业目的地和低地球轨道上的工作提供了指导。

国际空间站（ISS）是一个多国项目，是迄今为止送入地球轨道的最大单一结构。自 1998 年开始组装以来，它已接待了来自 20 多个国家的 250 多人，并完成了 3000 多项研究调查。其中一些努力已经转化为科学和技术突破，并在众多领域推动了进步。例如，在 ISS 上进行的蛋白质晶体生长调查为多种疾病治疗提供了新的见解，阿尔茨海默病、帕金森病、心脏病和多种癌症的基础和应用研究也是如此。ISS 开辟了新的研究领域，并促进了创新技术和能力的发展，包括在太空中使用组织芯片、静息胶体研究、微重力中的 3D 打印、开发新的水净化系统以及如何在太空中长时间生活和繁荣的教训。随着 ISS 接近其设计寿命的结束，NASA 现在计划于 2030 年退役该平台，并已建立商业低地球轨道目的地（CLD）计划来规划未来。

美国国家航空航天局（NASA）的商业低地球轨道（LEO）目的地（CLD）计划

美国国家航空航天局的商业低地球轨道项目旨在支持向商业拥有和运营的服务过渡，这些服务支持该机构在地球轨道上的科学、技术成熟化和宇航员培训需求。2020 年初，NASA 向 Axiom Space 授予了为国际空间站附加商业模块的合同。2021 年，商业目的地自由飞行器计划作为两阶段采购项目成立。2021 年 12 月，NASA 宣布了 2025 年之前的三个奖项：诺斯罗普·格鲁门公司、Nanoracks“Starlab”和轨道礁。在第一阶段，私营行业与 NASA 协调，设计 CLD 能力以满足政府和商业需求。第二阶段将支持为美国政府宇航员认证一个或多个平台，以及包括地面支持、运输和轨道操作在内的端到端服务。这些服务将确保 NASA 能够以至少两名船员在低地球轨道上保持永久存在，每年进行大约 200 项科学调查。这些服务旨在

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operational in the late 2020s to prevent a gap in LEO presence for the U.S. and its partners, and to ensure a smooth transition of operations from ISS[3,6].

A self-reinforcing ecosystem in space: an Orbital Reef

Orbital Reef will be a mixed-use business and research park; one of the world's first commercial free-flying space stations. It is being jointly developed across the U.S. by Blue Origin, with Sierra Space, Boeing, Redwire Space, Amazon/Amazon Supply Chain, Genesis Engineering, and Arizona State University as teammates. Orbital Reef's name follows the premise under which it is being developed: to serve as a robust infrastructure for a diverse, growing, and self-reinforcing ecosystem in Earth's orbit, much like the ecosystems of coral reefs in the ocean. By providing a turnkey service with accessible infrastructure in LEO, Orbital Reef lowers the barriers to entry, and enables existing and nascent users to establish their operations in space. Customized spaces within Orbital Reef allow for government and private institutions, as well as commercial and academic entities to implement new ventures and visions, ranging from basic and applied R&D to entertainment and hospitality to port-of-call for exploration missions[8]. The station will be occupied by a mix of professional Orbital Reef crew members, national astronauts, and commercial users. Orbital Reef will have the capabilities needed to address scientific research and technology maturation currently being performed on ISS, ensuring the smooth transition envisioned by NASA's CLD Program.

In its initial phase, Orbital Reef will consist of (i) a Node and (ii) a Large Integrated Flexible Environment (LIFE™) developed by Sierra Space, (iii) a Core module and (iv) a power/thermal Mast developed by Blue Origin, and (v) a Research Module developed by Boeing (Fig. 1). The Core, with 250 m^3 of habitable volume, nearly a third of that available on the ISS, will serve as the central hub for the rest of Orbital Reef's modules and visiting vehicles, as well as the center for command and control, data processing, and communications with the ground. It will host internal and external payloads, stowage, an environmental control and life support system (ECLSS) sized to support up to ten crewmembers, a commode, and will include six of the largest windows ever flown to space facing Earth. The Research Module, similar in size to the Core, will include a payload airlock/cupola and will host internal and external payloads, serving as a multi-disciplinary laboratory, customizable to user requirements. The Mast will generate 100 kWe through its deployable solar arrays. It will collect and reject heat, and will serve as the bus for communications and other critical systems, including an external robotic arm and docking and berthing nodes. The LIFE™ habitat is an expandable module that will provide over 300 m^3 of habitable volume to host payloads and research facilities, an ECLSS and sleeping quarters for up to ten crewmembers, two commodes, a health and hygiene compartment, a galley, exercise equipment, and plant growth hardware. Finally, the ~40 m^3 Node will include two International Docking System Standard (IDSS)-compatible visiting vehicle ports, an airlock for extravehicular activity (EVA), and will be able to host external payloads and provide station-keeping functions. More details on each of these modules and their operations are described in Mosher & Kelsey, 2023.

This modular architecture can be scaled through linear addition of additional Core and Mast modules, which can each support additional tenant modules to support growing market demand and new functionality.

Upcoming opportunities

Capabilities

Across its modules, Orbital Reef will have hundreds of MLE worth of volume to host passive and active payloads in addition to state-of-the-science research facilities to enable the continuation and expansion of R&D currently performed on ISS, as well as to initiate new lines of research and technology development. To achieve a smooth transition from ISS, Orbital Reef's payload interfaces will be backwards-compatible with ISS MLE standards, i.e., hardware used on the ISS will be by default compatible. Additionally, Orbital Reef's interfaces will offer optional upgraded interfaces to optimize processes and crew time. Orbital Reef will have the capability to host external payloads, accessible through a science airlock and external robotics, which will transfer them from visiting vehicles. An airlock will provide external access to astronauts via Extravehicular Activity (EVA). Additionally, co-orbiting free-flyers from any customer may be qualified for deployment from Orbital Reef or visiting vehicles to serve as platforms for autonomous exploration experiments, isolated microgravity environments, and unique views of the Orbital Reef, the Earth, and deep space. Similarly, full modules developed by third parties may be attached to Orbital Reef, receiving utilities (power, life support, etc.) and services to enable focus on their particular use cases.

For internal payloads, Orbital Reef will provide power at 28 VDC, 120 VDC, and 120 VAC; data transmission via 10 G Base-T ethernet and Wi-Fi; 36 kW of heat rejection; and nitrogen, carbon dioxide, water, air, and vacuum exhaust distribution hardware. Orbital Reef crew time can be made available for the operation of customer payloads and payload facilities, photography and videography, and other activities. Conversely or in parallel, customers themselves may work and live on Orbital Reef with the opportunity to bring their own payload facilities, as needed. Payload facilities will provide the capabilities needed to address multiple scientific and technical R&D and use cases. These include freezer banks (−80 °C and -20 °C), refrigeration (4 °C), incubators, separate life and physical sciences gloveboxes, microscopes, optics bench platform, 3-D printers, biofabrication banks, production facilities, a pressurized gas tank farm, and areas designated for NASA and commercial payload facilities and devices or for multi-purpose use. Externally, Orbital Reef will provide powered payloads with up to 2 kW of power distributed at 120 VDC and 10 G Base-T ethernet. Mounts will be compatible with small, medium, and large on-orbit replaceable unit (ORU) robotics interface standards (SORI, MORI, and LORI, respectively).

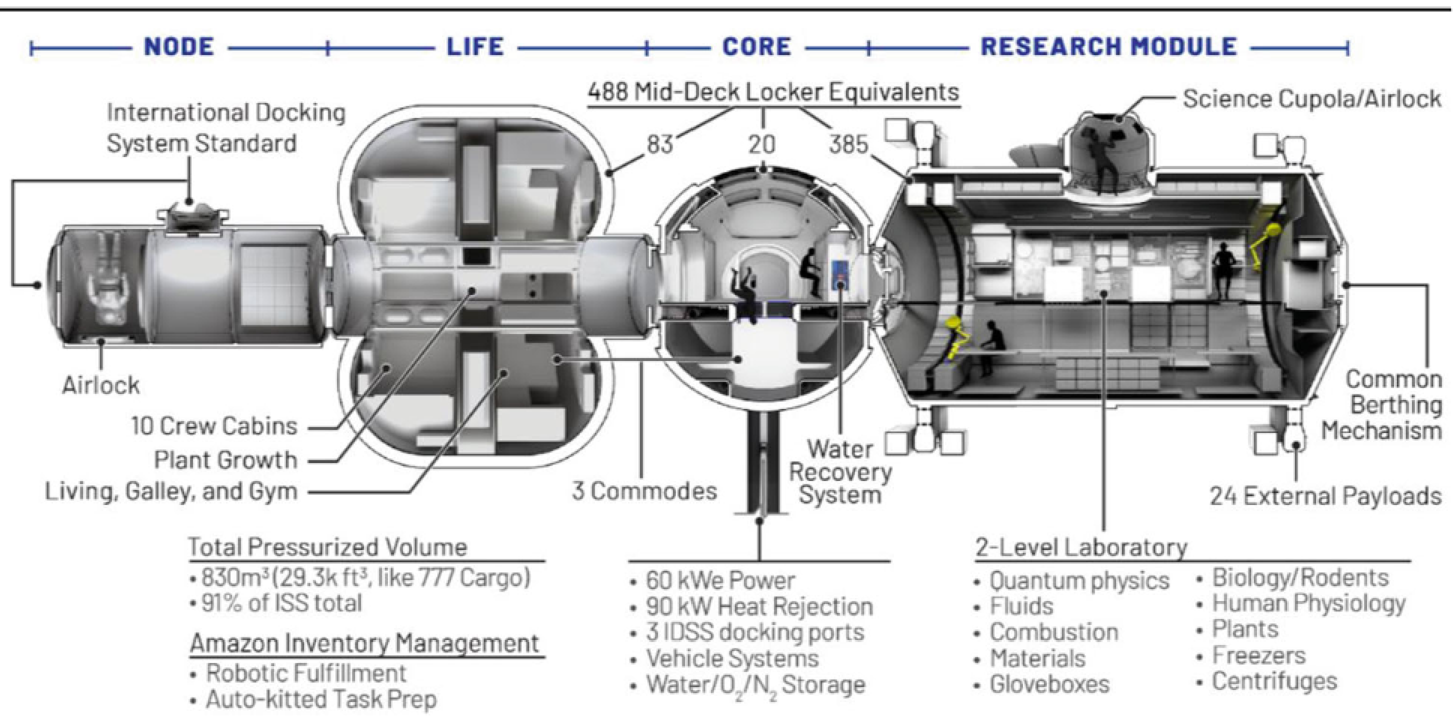

Fig. 1 | Orbital Reef's modular pressurized elements: Node, LIFE™, Core, and Research Module from Mosher & Kelsey, 2023.

2020 年代后期投入使用，以防止美国及其合作伙伴在近地轨道存在上的差距，并确保从国际空间站平稳过渡运营。

太空中的自我强化生态系统：轨道礁

轨道礁将是一个多功能商业和研究园区；世界上第一个商业自由飞行的空间站。它正由蓝源公司与美国 Sierra Space、波音、Redwire Space、亚马逊/亚马逊供应链、Genesis Engineering 和亚利桑那州立大学等合作伙伴共同开发。轨道礁的名称遵循其开发的前提：在地球轨道上为多样化、增长和自我强化的生态系统提供强大的基础设施，就像海洋中珊瑚礁的生态系统一样。通过在近地轨道提供可访问的基础设施的一站式服务，轨道礁降低了进入门槛，并使现有和新兴用户能够在太空中建立他们的运营。轨道礁内的定制空间允许政府、私营机构以及商业和学术实体实施新的项目和愿景，从基础和应用研究开发到娱乐和酒店服务，再到探险任务的停靠港。该站将由专业轨道礁船员、国家宇航员和商业用户混合居住。 轨道礁将具备解决目前在 ISS 上进行的科学研究和技术成熟所需的各项能力，确保 NASA 的 CLD 项目所设想的平稳过渡。

在其初始阶段，轨道礁将包括（i）一个节点和（ii）由 Sierra Space 开发的庞大集成灵活环境（LIFE），（iii）一个核心模块和（iv）由 Blue Origin 开发的动力/热力桅杆，以及（v）由波音公司开发的科研模块（图 1）。核心模块拥有 250 立方米的居住空间，几乎占国际空间站可用空间的近三分之一，将作为轨道礁其余模块和访问车辆的中央枢纽，以及指挥控制、数据处理和地面通信的中心。它将容纳内部和外部有效载荷、储存空间、一个用于支持多达十名船员的环境控制和生命支持系统（ECLSS）、一个厕所，并将包括面向地球的最大六扇窗户。科研模块的尺寸与核心模块相似，将包括一个有效载荷气闸/圆顶，并容纳内部和外部有效载荷，作为一个多学科实验室，可根据用户需求进行定制。桅杆将通过其可展开的太阳能电池板产生 100 kWe 的电力。 它将收集和排除热量，并作为通信和其他关键系统的总线，包括外部机械臂、对接和停靠节点。LIFE™栖息地是一个可扩展模块，将提供超过 300 立方米的居住空间，以容纳有效载荷和研究设施，为最多十名船员提供生命保障系统和生活区，两个洗手间，一个卫生和保健舱室，一个厨房，锻炼设备和植物生长硬件。最后，约 40 米的节点将包括两个与国际对接系统标准（IDSS）兼容的访问车辆端口气闸用于舱外活动（EVA），能够容纳外部有效载荷并提供站务功能。关于这些模块及其操作的更多详细信息，请参阅 Mosher & Kelsey，2023。

这种模块化架构可以通过线性增加额外的核心和桅杆模块进行扩展，每个模块都可以支持额外的租户模块，以满足不断增长的市场需求和新的功能。

即将到来的机会

功能

在其模块中，轨道礁将拥有数百个 MLE 的体积，用于容纳被动和主动有效载荷，以及最先进的研究设施，以实现目前在 ISS 上进行的研发的持续和扩展，以及启动新的研究和技术开发路线。为了实现从 ISS 的平稳过渡，轨道礁的有效载荷接口将与 ISS MLE 标准向后兼容，即 ISS 上使用的硬件默认兼容。此外，轨道礁的接口将提供可选的升级接口，以优化流程和乘员时间。轨道礁将能够容纳外部有效载荷，通过科学气闸和外部机器人，将它们从访问车辆中转移。气闸将为宇航员提供通过舱外活动（EVA）的外部通道。此外，任何客户的共轨道自由飞器可能被认定为从轨道礁或访问车辆部署，作为自主探索实验、隔离微重力环境和轨道礁、地球和深空的独特视角的平台。 同样，第三方开发的完整模块也可能连接到轨道礁，接收公用事业（电力、生命维持等）和服务，以便专注于其特定用例。

对于内部有效载荷，轨道礁将提供 28 VDC、120 VDC 和 120 VAC 的电力；通过 10 G Base-T 以太网和 Wi-Fi 进行数据传输；36 kW 的热量排放；以及氮气、二氧化碳、水、空气和真空排放分布硬件。轨道礁可以为操作客户有效载荷和有效载荷设施、摄影和录像以及其他活动提供船员时间。相反或并行，客户自己可以在轨道礁上工作和生活，有机会根据需要携带自己的有效载荷设施。有效载荷设施将提供解决多个科学和技术研发及使用案例所需的能力。这包括冷冻库（-80° C 和-20° C）、冷藏（4° C）、孵化器、独立的生命科学和物理科学手套箱、显微镜、光学平台、3D 打印机、生物制造库、生产设施、一个加压气体储罐农场，以及为 NASA 和商业有效载荷设施和设备或多功能用途指定的区域。在外部，轨道礁将为有效载荷提供最多 2 kW 的电力，以 120 VDC 和 10 G Base-T 以太网的形式分配。 支架将与小型、中型和大型在轨可更换单元（ORU）机器人接口标准（分别称为 SORI、MORI 和 LORI）兼容。

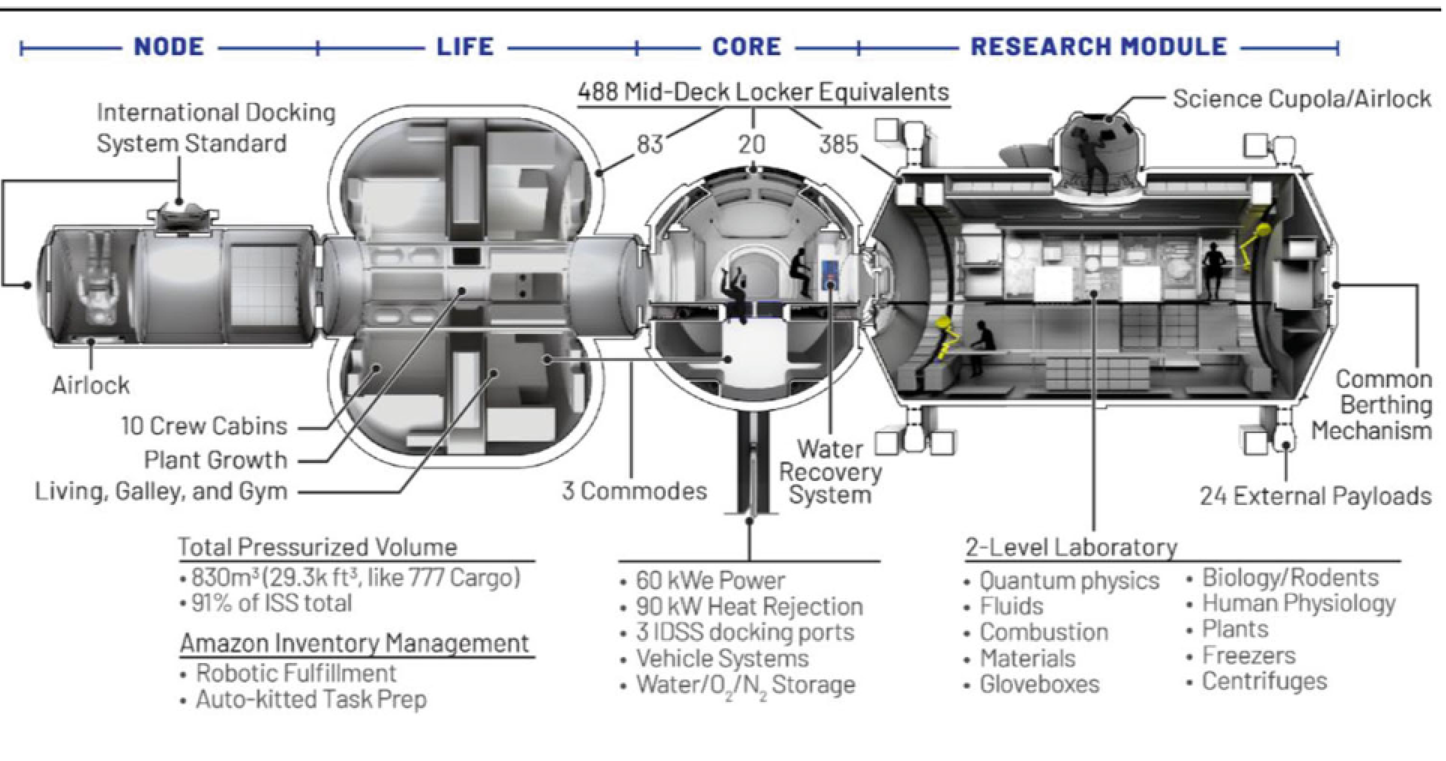

图 1 | 轨道礁的模块化加压组件：节点、生命维持系统、核心和研究舱，来自 Mosher & Kelsey，2023。

Designed to solve ISS-era challenges

As described above, the ISS has been the premier in-space platform where we have learned to develop processes and technologies, made ground-breaking discoveries, and opened the doors to new fields of science. Yet, multiple challenges must be solved to enable the continuation of R&D in space. For example, 42 flights were necessary to achieve the fully assembled 1005 m^3 of pressurized volume on the ISS[1]. Similarly, the ISS was designed in a way that required external spacewalks to be maintained, and this feature has impacted crew time availability to perform research activities. Ironically, the success of R&D on ISS has generated several other challenges, including limitations in stowage (especially temperature-controlled) and competition for on-orbit facilities. These problems have been exacerbated by the relatively low cadence of flights to bring new payloads, the limited up-mass of visiting vehicles, and the lack of down-mass opportunities. While several vehicles have visited the International Space Station, after the space shuttle retired in 2011, only Russia's Progress, ESA's ATV (retired in 2015), JAXA's HTV (retired in 2020), Northrop Grumman's Cygnus and SpaceX's Dragon could carry significant cargo to ISS. But because all but Dragon and Soyuz burn up on re-entry, sample return has been limited to these vehicles. This pace delays investigators access to their science, reduces cadence of research, and results in over-committed ISS stowage and freezer space. Other challenges that need to be solved by the CLD community include the ability to upgrade research facilities as quickly as technology advances, and to provide access to non-ISS partner countries and private industry with fewer restrictions. While the intention was set in the 1980s to develop a space station to galvanize the commercialization of LEO, so far these and other challenges have resulted in slow realization[9].

Orbital Reef's modules will take advantage of two key innovations: the larger 7-meter diameter fairing of Blue Origin's New Glenn rocket, and soft-goods and expandable technologies of Sierra Space's LIFE™ habitat. The LIFE™ module alone offers about a third of ISS's pressurized volume. Additionally, Orbital Reef is being designed so that it can be maintained from the inside of the space station, avoiding complex EVA operations and helping focus crew time on R&D, production, and revenue-generation efforts. The primary assembly of Orbital Reef will rely on Extravehicular Robotics (EVR), limiting conventional EVAs to contingencies and training missions. Substantial improvements in robotic technologies, as well as designing for robotic assembly and maintenance, will support this economical and safety-driven approach[8]. This reduction in operational expenses translates into lower cost to do research on Orbital Reef for the scientific community.

To address ISS-era transportation challenges, Orbital Reef will utilize Blue Origin's New Glenn launch system and Sierra Space's Cargo and Crew Dream Chasers. Additionally, Orbital Reef will be able to receive other vehicles (e.g., Dragon, Boeing Starliner, Cygnus) with both standard berthing and docking interfaces. Furthermore, as a winged vehicle, Dream Chaser will provide a low-g return path to ensure gravity-sensitive samples (e.g., protein crystals) return safely to Earth, and it may land in any runway that can accommodate a Boeing 737 around the world, providing investigators and companies with quick access to their samples or in-space developed products. In addition, our teammates at Amazon/Amazon Supply Chain are reimagining the art of the possible for space logistics. Our robust access to up- and down-mass, together with a philosophy of moving at the speed of business, will allow prompt updates to on-orbit facilities to stay current with the state of art of the science. Robotics and automation will enhance research activities and optimize crew time, and technologies such as augmented reality will connect space-based researchers to their laboratories on Earth, optimizing collaboration and efficiency of research activities. Given its commercial nature, Orbital Reef will provide access to orbit to both ISS and non-ISS partner countries and the private sector. University and Industry R&D Advisory Councils managed by Arizona State University and MIT, respectively, provide focused user inputs to shape the next generation of facilities and processes needed by researchers in academia, government, and industry.

Discussion

The 2023 'Decadal Survey on Biological and Physical Sciences Research in Space' for 2023–2032, produced by the National Academies of Sciences, Engineering, and Medicine provides recommendations for "a comprehensive vision and strategy for a decade of transformative science at the frontiers of biological and physical sciences research in space"[10]. This report provides long-term strategic advice to NASA and clarity to researchers on which fields of biological and physical sciences are more likely to be supported by the U.S. federal government. Similarly, this decadal survey offers a roadmap towards future facility needs, which community advocacy can leverage to advance the state-of-the-art for science hardware on Commercial LEO Destinations. In this way and many others, investigators can inform CLD developers of their needs, and work with implementation partners to mature their technologies, as described below.

There are numerous ways for the research community to take action now towards conducting research, technology development, and manufacturing activities on Orbital Reef, well before the planned retirement of ISS in 2030. The Orbital Reef team provides a continuum of microgravity research services to payload customers that currently includes suborbital New Shepard flights and soon will include Dream Chaser orbital flights. Both platforms can be used to de-risk projects and collect proof of concept validation. NASA, the ISS international partner agencies, and the ISS National Laboratory have nearly continuous open calls for researchers seeking to leverage the ISS for technology development and both fundamental and applied R&D—to further space exploration and for terrestrial benefit. There are also related funding opportunities from the National Science Foundation (NSF), National Institutes of Health (NIH), Department of Defense (DoD), and others.

In March of 2023, the LEO Science and Technology Interagency Working Group of the U.S. National Science and Technology Council (NSTC) published an interagency strategy and action plan to enable U.S. Government-wide collaboration and support of public-private partnerships to ensure continuity of access and sustainable LEO research and development activities[11]. The research community should continue to advocate for robust government funding to implement this strategy, through publishing thought leadership papers and editorials, responding to NASA Requests for Information (RFI's), participating in National Academies' workshops, and shaping the conversation toward the importance of continuous research access to LEO. The research community can also engage directly with the Orbital Reef team to share requirements for next-generation research-enabling facilities in orbit. The research community can position itself to be ready with preliminary data, collaborations, and ground research completed in time to win planned upcoming awards to transition LEO science from ISS to CLDs.

Orbital Reef's unique environment in Low Earth Orbit offers long-term microgravity, extreme environmental conditions, and a vantage point from which to study the Earth and space. For researchers and organizations who are pushing the limits of understanding and capability, space is a rich environment to probe for new insights and develop new paths to innovation. By reimagining the art of the possible, Orbital Reef will help us take a key step toward a bold vision of millions of people living and working in space for the benefit of Earth.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

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旨在解决国际空间站时代挑战

如上所述，国际空间站一直是我们在太空中学习和开发流程和技术、取得突破性发现以及开启新科学领域的大门的首选平台。然而，为了使太空研发得以继续，必须解决多个挑战。例如，需要 42 次飞行才能在空间站上组装出完全组装的 1005 立方米压力舱。同样，国际空间站的设计需要外部太空行走来维护，这一特性影响了机组人员执行研究活动的时间可用性。讽刺的是，国际空间站研发的成功产生了其他几个挑战，包括存储限制（尤其是温控存储）和对轨道设施的竞争。这些问题因新有效载荷运输飞行的相对低频率、访问车辆的有限上行质量以及缺乏下行质量机会而加剧。 尽管有几艘飞船访问过国际空间站，但在 2011 年航天飞机退役后，只有俄罗斯进步号、ESA 的 ATV（2015 年退役）、JAXA 的 HTV（2020 年退役）、诺斯罗普·格鲁曼的赛格尼斯号和 SpaceX 的龙飞船能够携带大量货物前往 ISS。但由于除了龙飞船和联盟号外，其他所有飞船在再入大气层时都会烧毁，样品返回仅限于这些飞船。这种速度延迟了研究人员获取他们的科学数据，减少了研究频率，并导致 ISS 的储存空间和冷冻空间过度占用。CLD 社区需要解决的挑战还包括，随着技术的进步，能够快速升级研究设施，以及以更少的限制向非 ISS 合作伙伴国家和私营企业提供访问权限。虽然早在 20 世纪 80 年代就设定了发展空间站以推动 LEO 商业化的目标，但到目前为止，这些和其他挑战导致了缓慢的实现。

轨道礁的模块将利用两项关键创新：蓝色起源新格伦火箭更大的 7 米直径整流罩，以及 Sierra Space 的 LIFEhab 的软货物和可扩展技术。仅 LIFEmodule 就提供了国际空间站约三分之一的压力体积。此外，轨道礁的设计使其可以从空间站内部进行维护，避免了复杂的出舱活动，并有助于将机组人员的时间集中在研发、生产和创收努力上。轨道礁的主要组装将依赖于舱外机器人（EVR），将传统的出舱活动限制在应急和训练任务中。机器人技术的重大改进以及为机器人组装和维护而进行的工程设计将支持这一经济和安全驱动的方法。这种运营成本的降低将转化为科学界在轨道礁上进行研究成本的降低。

为了解决国际空间站时代的运输挑战，Orbital Reef 将利用 Blue Origin 的 New Glenn 发射系统和 Sierra Space 的货运和乘员 Dream Chaser。此外，Orbital Reef 还将能够接收其他车辆（例如，龙飞船、波音星际客船、天鹅座）并具备标准对接和停靠接口。此外，作为一架有翼飞行器，Dream Chaser 将提供低重力返回路径，以确保重力敏感样品（例如，蛋白质晶体）安全返回地球，并且它可以在全球任何可以容纳波音 737 的跑道上着陆，为研究人员和企业提供快速获取其样品或在轨开发产品的途径。此外，我们亚马逊/亚马逊供应链的队友正在重新构想太空物流的艺术。我们强大的上行和下行物资接入能力，以及以商业速度行动的哲学，将允许对轨道设施进行及时更新，以跟上科学技术的最新水平。 机器人自动化将增强研究活动并优化乘员时间，增强现实等技术将使太空研究人员与地球上的实验室相连，优化研究活动的协作和效率。鉴于其商业性质，轨道礁将为国际空间站和非国际空间站合作伙伴国家以及私营部门提供进入轨道的途径。亚利桑那州立大学和麻省理工学院分别管理的大学和工业研发咨询委员会，为学术界、政府和工业界研究人员所需的下一代设施和流程提供专注的用户输入。

讨论

2023 年《2023-2032 年空间生物和物理科学研究十年调查》由美国国家科学院、工程和医学院编制，为“在空间生物和物理科学研究前沿的十年变革性科学提供一个全面愿景和战略”提供建议。本报告为 NASA 提供长期战略建议，并为研究人员阐明哪些生物和物理科学领域更有可能得到美国联邦政府的支持。同样，这项十年调查为未来设施需求提供路线图，社区倡导可以利用它来推进商业低地球轨道目的地科学硬件的最新技术水平。通过这种方式和其他许多方式，研究人员可以告知 CLD 开发者他们的需求，并与实施伙伴合作，成熟他们的技术，如以下所述。

有许多途径让研究界现在就可以采取行动，在 2030 年国际空间站计划退役之前，在轨道礁进行研究、技术开发和制造活动。轨道礁团队为有效载荷客户提供一系列微重力研究服务，目前包括亚轨道的 New Shepard 飞行，并将很快包括 Dream Chaser 轨道飞行。这两个平台都可以用于降低项目风险并收集概念验证证据。NASA、国际空间站合作伙伴机构和国际空间站国家实验室几乎持续开放对研究人员寻求利用国际空间站进行技术开发和基础与应用研发的申请——以进一步太空探索和为地球利益服务。此外，还有来自国家科学基金会（NSF）、国家卫生研究院（NIH）、国防部（DoD）和其他机构的相关资助机会。

2023 年 3 月，美国国家科学技术委员会（NSTC）的近地轨道科学与技术跨部门工作组发布了一项跨部门战略和行动计划，以促进美国政府各部门之间的合作和支持，确保持续获得近地轨道研究和开发活动的机会。研究界应继续倡导强有力的政府资金，以实施此战略，通过发表思想领导力论文和社论，回应 NASA 的信息请求（RFI），参加国家学院的工作坊，以及引导对话，强调持续研究访问近地轨道的重要性。研究界还可以直接与轨道礁团队合作，分享对下一代轨道研究设施的需求。研究界可以准备好初步数据、合作和地面研究，以便及时赢得计划中的即将到来的奖项，将近地轨道科学从国际空间站过渡到 CLDs。

轨道礁在低地球轨道的独特环境提供了长期微重力、极端环境条件，以及从地球和空间进行研究的有利位置。对于推动理解和能力极限的研究人员和组织来说，太空是一个丰富的环境，可以探索新的见解并开发新的创新路径。通过重新构想可能的艺术，轨道礁将帮助我们迈出关键一步，实现数百万人在太空中生活和工作的宏伟愿景，以造福地球。

报告摘要

更多关于研究设计的信息可在与本文链接的《Nature Research 报道摘要》中找到。

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Author contributions

E.W. conceived of and critically guided the development of the manuscript; L.Z., L.W., T.R., T.M., and L.K. contributed to the manuscript content, and L.Z. supervised production of the manuscript.

Competing interests

L.Z. and L.K. are employed by Sierra Space Corporation. L.W., T.R., T.M., and E.W. are employed by Blue Origin, LLC.

Additional information

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