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The Astropreneurial Co-creation of the New Space Economy

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ABSTRACT

We are witnessing the emergence of a new "techno-economic paradigm" in the New Space economy. The entrepreneur research during the current "Innovation and Communication" paradigm captured the co-creation of the digital ecosystem through the affordances and platforms of the digital technology. Similarly, New Space is creating opportunities for a new generation of space entrepreneurs, known as astropreneurs, to co-create the ecosystem through the affordances and platforms enabled by space technology. For astropreneurs, the affordances vary depending on whether the application of the space technology is intended for use in space, on earth or "spin-off" to another market. Additionally, the co-creation across the groups of astropreneurs and the fluidity of the technology across markets differs depending on their associated affordances. By exploring how the different context of space and its associated technology affordances introduces new models of co-creation and fluidity across the astropreneurial community, this article aims to broaden the fluidity and co-creation research of entrepreneurs.

1. Introduction

> *"I am following with much interest the emergence of a new breed of "astropreneurs" who are trying out new technologies, business models and indeed, building a whole new industry – without relying on government funding." Sir Arthur C. Clarke* [1]

In Marion Blakey's[1] 2005 testimony, at the hearing on the Commercial Space Transportation: Beyond the X Prize [2], she shared, "*There is a bold new group of people, astropreneurs, and their aim is to bring space flight into everyone's grasp.*" Her quote along with Sir Arthur C. Clarke's quote raises the question, who are these new breeds of astropreneurs? Are astropreneurs limited to the Rocket Billionaires [3] of Elon Musk (SpaceX), Jeff Bezos (Blue Origin), and Richard Branson (Virgin Galactic) and those who provide space flight? Or do we find astropreneurs only in the 310 new angel and venture backed space companies being founded between 2000 and 2019 [4] that do not rely on government funding?

To address these questions, we must first place the astropreneurial ecosystem that is creating New Space in the context of other ecosystems. When it comes to New Space, we are at the cusp of what Freeman and Perez dubbed a new "techno-economic paradigm" [5,6]. In their seminal work, Freeman and Perez captured five "long waves" of techno-economic paradigms. The fifth and last "successive long wave" captured by Freeman and Perez extends from the "1980s and 1990s to ?" and is described as the "Information and communication Kondratieff". A large and growing body of research has captured how digital technologies and digital platforms, from this current long wave, create new opportunities, and enable the co-creation of the ecosystem by the entrepreneurs [6–10]. In a similar fashion, astropreneurs can leverage space technologies and space platforms to co-create the New Space ecosystem.

Astropreneurs share the same challenges as other entrepreneurs in capturing resources (funding, technology, skilled team), creating effective networks, and creating value that will address a customer's need. They differ from other entrepreneurs in the intertwined relationship of the space context, sector fluidity, and co-creation of value [9,11–14]. The astropreneur navigates between the regional context, institutional challenges, and the regulated environments [15] that are found in their region and the evolving context of the space ecosystem. Like startups in other industry sectors, the success of these New Space companies is context specific [13]. Lamine et al. [14] capture the institutional challenges faced by astropreneurs in a European context. They acknowledge that the institutional barriers created by the incumbent space

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companies in Europe may not be seen in other countries and they identify opportunities for future research regarding astropreneurs in the United States. Lamine et al. [14] also share their findings that within the European context "entrepreneurship does not thrive within the space context" and "that while there is little space for entrepreneurship upstream, the sector enables downstream entrepreneurial space." A review of 271 early-stage New Space startups across the whole ecosystem illustrates a growing number of astropreneurs in the United States across the larger New Space Ecosystem.

Astropreneurs, as a group, encompass a larger industry sector than space. Massis et al. define sector-based entrepreneurial capabilities as "the capacities (i.e., processes and routines) of an entrepreneurial actor (entrepreneurs, entrepreneurial teams, and enterprises) to prospect, develop, and exploit opportunities by reconfiguring human, social, and financial resources within and across industry sectors [12]." Astropreneurs exploit opportunities both within the space sector and across other industry sectors. They are found in other industry sectors including medical, energy, clean tech, maritime, agriculture, and others. There is a fluidity across sectors where astropreneurs create new companies for other industry sectors with technologies originally developed for a space application. Massis et al. [12] define sector fluidity "as the extent to which information, knowledge, and resources can flow freely across industry boundaries."

The fluidity across sectors is facilitated by the dual purpose of space technology solutions [8] offered by many of the New Space startups. In this article, dual purpose refers to the application of technology solutions for space as well as terrestrial markets. The term "dual purpose" is exercised instead of "dual use" in this article for two reasons. First, the term dual use is associated with military applications. The European Commission defines dual use as "goods, software, and technology that can be used for both civilian and military applications" [14]. Second, dual purpose is not associated with any policy implications. We see the policy implications of dual use in Lamine et al. [14]. The authors argue that one of the European policies that is negatively impacting the space sector is "the rule of dual use items." Technologies leveraged or commercialized by astropreneurs are not always rooted in military applications and can potentially have a dual use for earth-based markets. Some astropreneurs commercialize space technologies for application in other industry sectors. These commercialized technologies may then be either improved upon or bundled with other technologies and find their way back into a space application.

There is a synergy and co-creation of value amongst astropreneurs that enables their effectiveness [11] and success. I will explore the co-creation of value [9,16] later in the Analysis and Findings section, but a recent example to illustrate this unique synergy and co-creation is found in the seeding of a new lunar ecosystem by National Aeronautics and Space Administration's (NASA). Commercial Lunar Payload Services (CLPSs) program. In 2018, NASA initiated the CLPS program to seek commercial companies for the delivery of payloads to the moon's surface. Under this program, only a portion of the overall costs of the lunar mission would be paid by NASA for delivery of NASA payloads. The commercial companies providing this service would need to identify additional lunar customers to cover the cost of the mission. The ecosystem that is being created by the availability of commercial lunar delivery capabilities is characterized by the simultaneous emergence of lunar startups that are providing essential services required by the lunar ecosystem. This co-creation of value across the New Space startups is essential to astropreneur's success and they are forming value constellations [9,11,16,17] within a strategic network [18] of astropreneurs. It should also be noted that this growing community of astropreneurship in space is enabled by the institutional programs of NASA and highlights a difference between the European context and that found in the United States [14].

For clarity, and to serve as a guide to this paper, I am providing the following empirically derived definition of the astropreneur. This definition is based on a decade of my collaboration with, and observation of astropreneurs and the data collected from reviewing 255 investor pitches and websites from New Space early-stage startups, during my tenure as a Venture Partner at Seldor Capital. Also contributing to the definition are the sixteen startups from the Expanding Frontiers acceleration program for space startups. I define an astropreneur as anyone involved in a startup company that is either providing

(1) space technology or capabilities in space or at a destination beyond the earth or
(2) capabilities on the earth that leverage resources or space technologies from space or beyond the earth or
(3) capabilities on the earth that leverage space technologies originally developed for space applications.

It is the space technology and the affordances that it offers the astropreneurs that differentiates them from other entrepreneurs. By looking at entrepreneurship through the lens of space technology and the co-creation amongst astropreneurs, this article contributes to the larger discourse on the co-creative process of entrepreneurs [19,20]. I propose that the rapidly evolving context [14,21] of space and space technologies is the "sixth long wave", after the "Information and Communication" wave captured by Freemen and Perez [5]. Building on the entrepreneurial research focusing on digital technologies [6,8,16,22], this article introduces the affordances provided to various groups of astropreneurs through the space technologies and platforms that they leverage. Specifically, this article will contribute to the entrepreneurial research in the following three areas: context, fluidity, and co-creation [5]. The sector fluidity enabled by the transfer of space technologies spans across many markets and provides an additional perspective to the sector fluidity captured in the digital technology research [6–8,12]. Finally, as is captured in the co-creation and co-production digital entrepreneurship research [16,19,20,22–24], the astropreneurs are co-creating the new space ecosystem. We are seeing across the astropreneur community what Karami and Read [19] observed in the digital technology ecosystem. It is the "collaborative process undertaken by a constellation of stakeholders that come together to co-create novelty in the environment" [19]. It is through the different affordances available from the space technologies pursued by the different groups of astropreneurs that contribute to the value constellation [9,16,22] of the new space ecosystem.

2. Literature review

Astropreneurship is a relatively unknown term in the research community. An initial search conducted in 2022 (October) for the term "astropreneur*" in SCOPUS resulted in only one reference and a search in Web of Science identified no references. Yet, the phrase is gaining traction in the practitioner community where a search in Google Scholar identified 54 references including "Astropreneurs—The Galactic Guide to Space Entrepreneurship [25] and Astropreneurship" [26]. Additionally, more space organizations are using the term to define the entrepreneurs that they are supporting, including GEN Space (the Space program of the Global Entrepreneurship Network) [27]. When it comes to the companies that astropreneurs create, a common set of markets and the context within which they are defined is not available. A literature review

on space startups, identified four market segment groupings and the context for their grouping (Table 1).

2.1. New space startup markets and context

In Table 1, the markets from Lamine et al. [14] are based on publications of the space consultancy firm, Bryce Tech [4,28], while Moranta and Donati [29] base their market segments on Seraphim Capital [30], an investor supporting and growing space startups from inception to exit. Seraphim Capital employs the familiar context of upstream and downstream used in the energy industry. Seraphim defines upstream to include space companies that build space hardware, launch space vehicles, and satellites. The downstream includes companies focusing on downlink communications; analyze information from space, drones, and UAV (unmanned aerial vehicle) assets; products from space. Seraphim also has a Beyond Earth context capturing companies that focus on space exploration, infrastructure, and space research. Bryce splits space startups between manufacturing companies and those providing services that rely on space systems. Bryce Tech's focuses primarily on a space context but also acknowledges integration of terrestrial systems with space-based systems for analytic services. They also included the criterion for the space startup to receive seed funding or venture capital in order to be included in their data analysis.

In their recent Harvard Business Review article [32], Weinzierl and Sarang distinguish the space startups according to the economy that they impact. They split them between a "space-for-space economy" context and a "space to earth economy" context. Weinzierl and Sarang see the growing space to space economy fueled by the recent orbital and suborbital achievements of SpaceX, Boeing, Blue Origin, and Virgin Galactic. Peeters includes the leveraging of space technologies in his context for space startups [33] and his space markets overlap Weinzierl and Sarang's "space-for-space economy. Like the quote from Sir Arthur C. Clarke, Peeters identifies space companies as independent of governmental space policies and funding.

The companies in Table 1 can be grouped generically into those that provide technologies in space and those that leverage space data to impact markets on the earth. Missing from the above table are companies commercializing space technologies for earth bound markets. It will be discussed later in the Analysis and Findings section how the astropreneurial ecosystem is incomplete if it does not include companies created from space technologies. These space technology spin-off companies play a role in looping back their innovations into the future space ecosystem.

2.2. Value and co-creation ecosystems review

When it comes to value, Porter defines it as what buyers are willing to pay [35]. Corsaro et al. identified value as "always uniquely and phenomenologically determined by the beneficiary" [11]. Corsaro et al. also shared that value was an emergent phenomenon "within networks and spanning and connecting several industries" [11]. In the astropreneur ecosystem, value emerges within the network of astropreneurs, and it crosses industries and sectors [12]. Value in the astropreneurial network is the access to the connections, capabilities, and the resources in the ecosystem that enables the space startup to grow and deliver a capability to a paying customer. It is an emergent phenomenon that is cocreated across the ecosystem as new capabilities, resources, and connections are developed within the New Space ecosystem. Karami and Read's [19] provides insights into the co-creation between startups in their review of "87 published academic works at the intersection of entrepreneurship and co-creation". They propose that

Table 1
Literature overview of new space startup context and markets.

Source	Context for Space startup	Market Grouping & Segments
Lamine, Anderson, Jack Fayolle [14] (Based upon Bryce Tech) [4,28]	• A new business entity that provides space technologies, products, or services • Has received and reported seed funding or venture capital	• Manufactures: o Satellites o Launch vehicles o Other space-based systems o Satellite ground equipment • Provides services that rely on space systems • Provides analytic services based on data collected extensively from space-based systems either alone or in combination with terrestrial systems
Moranta and Donati [29] (Based on Seraphim Capital) [31]	• Company younger than 10 years • Business tends to feature innovative concepts and models • Not yet reached business maturity • Context differentiates between upstream, downstream, and beyond Earth o Upstream: Build, launch, data. o **Downstream**: Downlink, analyze, store, product. o Beyond **Earth**	**Upstream:** • Build: Space Hardware (Satellite manufacturers, propulsion, and modules), other componentry, and engineering • Launch: Launchers, launch services, flight and delivery; space tugs • Data: Satellites, Drones, and UAV **Downstream:** • Downlink: Communications, ground terminals, security, an storage • Analyze: Satellites, drones, and UAV • Product: Data platforms, location, and mapping **Beyond Earth:** • Space exploration and resources, space infrastructure, space research
Matt Weinzierl and Mehak Sarang [32]	• Context differentiates between a space-based or earth-based economy o Space-**for-earth Economy**—Goods or services produced in space for use on earth o **Space-for-Space Economy**—Goods and services produced in space for use in space	**Space-for-earth economy:** o Telecommunications and Internet infrastructure on Earth observation o National security satellites **Space-for-space economy:** o Mining the moon or asteroids on in-space habitats o Refueling depots
Walter Peeters [33,34]	• Private companies, which act independent of governmental space policies and funding, • Target equity funding and promote affordable access to space and novel space applications. • Potentially leverages the transfer of space technologies	• Tourism • Solar power stations • Tele-operated satellite repair robots • Satellite & space transfer services • Space business parks • Industrial platforms • Asteroid mining • Lunar & Mars research stations

"economic value is created by people who voluntarily come together and cooperate to improve everyone's circumstance." Karami and Read offer that "entrepreneurial co-creative collaborations interactively construct both supply and demand."

Additionally, value creation between organizations has been referenced as a chain, network, constellation, loop, or architecture [9,10,16,17,23,35–40]. Among the key differentiators between the theories is the relationship of the organizations in the ecosystem and how value is created between or jointly with other organizations. Table 2 captures five value creation theories that are most relevant to the emerging astropreneurial ecosystems. Michael Porter's seminal work [37,38] on clusters and value chain is the benchmark with respect to which the others compare their theories. For Porter, value is shared linearly from buyers to suppliers and others integrated into the value chain. In 1993, Normann and Ramirez offered the value constellation theory [9] as an alternative to Porter's value chain. They based their insights on the growing digital capabilities and felt that a linear model did not adequately capture the co-creation of value being created in the emerging ecosystem. Normann and Ramirez offered a framework [16] capturing a constellation of nodes that enable the co-production of value with the customers.

Corsaro et al. further expands on the business relationships between organizations by classifying their value outcomes in terms of effectiveness and efficiency.

- "Effectiveness: what is accomplished in the relationship
- Efficiency: how well the processes work within the relationship" [11].

In Corsaro et al.'s framework for value constellations, they identify the below value outcomes across the network that are associated with effectiveness.

- "Scouting of new information in the network
- Establishment of new relationships with third parties
- Creation of synergies in the relationship portfolio
- Improvements of the strategic positioning
- Access to new network resources" [11].

Yoo introduces the concept of the value loop in an ecosystem [10,23]. Similar to Normann and Ramirez, Yoo builds his theory based on the digitization of physical products and services. He captures a feedback loop that occurs between the organizations in an ecosystem. As a product or market matures, there is feedback into the digital ecosystem that enables the evolution of capabilities and introduction of new products. This looping in the ecosystem is seen in the astropreneur ecosystem with space technologies that are spun out into other markets and are later reintroduced as improved capabilities for markets in space.

Adler looks at the value creation through ecosystem disruption [39,40]. He focuses on companies in established industries that are disrupted by new entrants that understand the total value of the ecosystem and how to introduce value that disrupts the industry by leveraging the larger ecosystem. Adner offers that partnership, across the ecosystem, is a strategic component that enables an organization to disrupt an ecosystem. Adner defines the ecosystem "by the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialize" [39]. He further defines multilateral as "not only a multiplicity of partners but also a set of relationships that are not decomposable to an aggregation of bilateral interactions" [39]. This lens into the interaction of the multilateral set of partners is apropos to understanding the astropreneur ecosystem. As will be seen in the analysis, the emerging startups in the new space ecosystem are creating unique value through the formation of multilateral relationships across different types of astropreneurs.

3. Method

My empirical knowledge of the astropreneurial ecosystem is derived from the triangulation [41] of three data sets. The first data set includes the investment presentations and websites of 255 startups for potential investment by Seldor Capital. The second data set includes the ethnographic observations [42] of an entrepreneur acceleration program in the emerging New Space Community in Brownsville, Texas [43]. The final data set is derived from semi-structured interviews with entrepreneurs in the acceleration program and with other entrepreneurs. Collectively, 271 early-stage startups are included in the data set across the ethnographic observations and the pitches and presentations from the Seldor Capital portfolio of potential investments.

3.1. Background

Seldor Capital is a venture fund that invests in early-stage space technology companies with markets in space and/or leveraging space technology to address the United Nation SDGs (Sustainable Development Goals). The General Partner of Seldor Capital is also the founder and CEO (Chief Executive Officer) of the New York Space Alliance, which has a successful partnership with NASA to facilitate the technology transfer from NASA to startups in the New York startup ecosystem [44]. The goal of the collaboration was to connect ten NASA technologies with ten startups in the New York ecosystem.

The Expanding Frontiers organization is a non-profit with a focus of creating space startups in the south Texas region through the commercialization of government technologies from NASA, Department of Energy, and other federal laboratories. They accelerate space startups through their Entrepreneur in Residence Apprenticeship (EIRA) program [43]. The leadership of Expanding Frontiers built the EIRA program upon the success of their Rockets and Rigs collaboration with the NASA Johnson Space Center (JSC) [45]. The EIRA program is an example of the increasing number of programs focused on the commercialization of space technologies. Recognizing that "all individuals are not equally likely to recognize

Table 2
Value creation across ecosystems and clusters.

Researchers	Michael Porter [35,37,38]	Masoud Karami, Kumar Rakesh Ranjan, Stuart Read [19,24]	Richard Normann, Rafael Ramirez [9,16,17] Corsaro et al. [11]	Youngjin Yoo [10,23]	Ron Adner [39,40]
Theory	→Value chain	→Co-creation	→Value constellation	→Value loop	→Value architecture
Value co-creation	No	Yes	Yes	Yes	Yes
Loop	No	No	No	Yes	No

a given entrepreneurial opportunity" [46], Expanding Frontiers provides aspiring astropreneurs with connections to license NASA technology. They also provide the astropreneurs with information about "what its components are, how it operates, what materials it uses, who used it initially, and for what purposes it was used [47]. The EIRA program provides training exercises and hackathons that are similar to the exercises offered by Gregoire and Shepherd [47] in their case studies of the technology transfer of two NASA technologies. Gregoire and Shepherd recommend "training exercises to foster the abilities of individuals to identify multiple opportunities—notably by focusing on abilities to perceive, understand, and communicate the core structural reasons underlying the key capabilities of new technologies and on abilities to imagine the transfer of such capabilities to cognitively distant markets that may not have superficial elements in common with the technologies." [47].

3.2. Data collection

As a Venture Partner at Seldor Capital, I have reviewed the company investment presentations and websites of 255 startups for potential investment by Seldor Capital. Each company was evaluated based on their technology, markets to be addressed, market potential, opportunity for dual purpose application of their technology, strength of the team, and any spinoff technologies from an initial space application. This evaluation was part of the screening process that I used, at Seldor Capital, to recommend an initial set of eight startups for investment in 2021. The review of these early-stage companies identified astropreneur startups that are currently embedded in the New Space ecosystem and those that are either aspiring to enter the market or have a potential of impacting the New Space ecosystem in the future.

The Expanding Frontiers acceleration program has seeded sixteen astropreneur startups with NASA technology and two have recently received funding through various pitch competitions. Their inaugural program has provided a unique opportunity to conduct ethnographic observations of the entrepreneur teams and to interview the entrepreneurs at the launch of a new space technology acceleration program. These entrepreneurs also participated in interviews that were recorded by the program and shared with consent from the astropreneurs.

4. Analysis and findings

The literature review and data from the 271 early-stage startups point towards a new techno-economic paradigm enabled by space technology. This new "long wave" [5] is being accelerated by the declining cost of access to space and by the growing number of launch providers. Additionally, we are seeing the growing number of early-stage New Space startups and the co-creation of the ecosystem by these astropreneurs.

4.1. Space Technology Kondratieff

Freeman and Perez [5] state that the "key factors for the emergence of a techno-economic paradigm are the following conditions.

i. clearly perceived low and rapidly falling relative cost
ii. apparently almost unlimited availability of supply over long periods
iii. clear potential for the use or incorporation of the new key factor or factors in many products and processes throughout the economic system; either directly or through a set of related innovations."

The growth of New Space is meeting the above conditions and I propose that we are entering the sixth long wave, which could be called the "Space Technology Kondratieff" (Table 3). Even though space technology has been around since the mid-twentieth century, this new wave is bounded at one end [48] circa 2004 and was fueled by the Ansari X Prize and NASA's COTS program [48]. These two programs initiated the "rapidly falling relative cost" of access to space. Even though there is still a supply challenge with access to space, we are seeing the rapid growth of commercial vehicles to provide low-cost access to payloads of all sizes. A recurring theme in the literature was the selection of the astropreneurial dimensions based on the investments required to develop the space infrastructure [49–51]. Emphasis is placed in linking launch costs to the creation of new markets and new astropreneurial opportunities. This is captured in the "Key factor Industries Offering Abundant Supply at Descending Price" column in Table 3. The market grouping and segments from Table 1, including the Upstream/Downstream/Beyond Earth and Space-for-Space/Space-for-Earth, are synthesized in the "Main Carrier Branches and Induced Growth Sectors" of Table 3. Finally, we are seeing through the innovations and technologies introduced by the various astropreneurs, the use of space technology throughout the new space ecosystem, and other markets.

With the proliferation of information technology during the information and communication Kondratieff [5], there emerged new theories of co-creation [16,17,19,20,22–24] and digital entrepreneurship and fluidity [6–8]. Normann and Ramirez [16] stated that "Micro-processing and related technologies, and the social transformations have catalyzed and created new options to produce value which cannot be mapped with the linear (one-dimensional), unidirectional and sequential limitations characterizing the value chain." Nambisan [8] shared that "digital technologies herald a new era in entrepreneurship, one in which the traditional ways and forms of pursuing entrepreneurial opportunities are increasingly questioned and refashioned." In a similar fashion, we are witnessing, with the growth and proliferation of space technologies, a shift in the co-creation value and co-production of the ecosystem by the network of astropreneurs. Additionally, in the same manner that "entrepreneurial ecosystems are also distinguished by their exploitation of digital affordances" [6], the astropreneurial ecosystem can be distinguished by the exploitation of space technology affordances.

Paraphrasing Autio et al. perspective on digitization, "To understand modern *astropreneurial* ecosystems, therefore, one should first understand how *space technology* shapes value creation, delivery, and capture in the economy and society" [6]. Additionally, as Freeman and Perez eloquently captured, "the qualitative aspects and the systems interrelatedness of innovations must be taken into account" [5]. To understand this emerging new wave, it is essential to consider the different affordances due to various categories of space technology and the interplay between different groups of astropreneurs. Astropreneurs can be grouped according to their "different dimensions of entrepreneurial innovation and how they vary with context" [13]. Specifically, from an astropreneur viewpoint [33], they face a very different context when their goal is to launch or deploy assets in space versus leveraging space assets on earth [53]. The regulation, testing, resources, funding, and the institutional hurdles required to create a startup for in-space applications is much higher to overcome than the context for an on-earth company that is leveraging existing assets in space. The column capturing the "Other Sectors Growing Rapidly from Small Base" in Table 3 includes markets impacted by space companies that were created through the commercialization of space technologies for terrestrial use. These companies are not included in the current markets in Table 1 and their exclusion results in a hole in

Table 3
Space Technology Kondratieff.

1	2	3	4	5	6	7	8
Number	Approximate periodization	Description	Main carrier branches and induced growth sectors Infrastructure	Key factor industries offering abundant supply at descending price	Other sectors growing rapidly from small base	Limitations of previous techno-economic paradigm and ways in which new paradigm offers some solutions	Organization of firms and forms of cooperation and competition
Sixth	2004 to ?	Space Technology Kondratieff	Launch VEHICLES; Satellites; Tourism; Solar power stations; Tele-operated satellite repair robots; Space tugs; Satellite and space transfer services; Industrial platforms; Asteroid mining; Lunar and Mars research stations Launch services; Space and ground-based communications network	Access to space Growing bandwidth of space comm network Access to Space Data Platforms	Biotech AI Automation Robotics Medical Energy/Clean Tech Manufacturing Agribusiness Maritime Construction	Limitations of Earth-bound data sources Limitation of IT infrastructure impacted by climate change Limited to earth bound resources	COTS CLPS "Commercial Network Model" [52] Public Private Partnerships Co-creation Value Constellation

the understanding of the growth of the astropreneurial ecosystem [47–49].

In order to differentiate between the different groups of astropreneurs and their associated affordances, I offer the following empirically derived definitions for three types of astropreneurs.

- In-Space—astropreneurs that create companies to launch or provide capabilities in space or on at a destination beyond the earth,
- On-Earth—astropreneurs that create companies that leverage space technology or data or resources from space or beyond the earth to benefit earth base industries.
- Space Spinoff—astropreneurs that create companies for non-space earth applications based on commercializing space technologies originally developed for a space application.

Each group of astropreneurs have different affordances available to them depending on the technology that they are pursuing to commercialize, or the assets required to grow their company [7]. Additionally, their interrelatedness and co-creation is different depending on the target markets of their space technology.

4.2. The trio of astropreneurs

The three types of astropreneurs that come together to co-create the astropreneurial ecosystem are captured in Table 4. Astropreneurial ecosystems are similar to other entrepreneurial ecosystems in what Autio et al. characterized as the "horizontal, voluntary knowledge spillovers" [6] across the "distributed innovation" [7] community of astropreneurs. The astropreneurs knowledge sharing contributes to "how value-creating activity is organized" [6] in the astropreneurial ecosystems. Table 4 captures the technology focus as a set of affordances for the trio of astropreneurs and captures the different innovation outcomes in different contexts [7].

The markets captured in Table 4 are representative of the markets that emerged from the review of the 271 startups. There is synergy between the below markets and the markets captured in Table 1. Most notable are the terrestrial markets (e.g., medical, agribusiness, etc.) that are not captured in Table 1 but included in the "Other Sectors Growing Rapidly from Small Base" column in Table 2. These markets are reached through the commercialization of space technologies and indicate the greater fluidity [8,12] of the new space sector. The recombination of space technology with resources in other sectors is accomplished by the space spinoff astropreneur and contributes to the expanded definition of the astropreneur space sector captured in the introduction [12].

4.2.1. In-space astropreneur

Schumpeter's representation of entrepreneurs as those "who introduce change to the economic landscape by constantly undermining and challenging established industry incumbents" [54] captures the spirit of the In-Space astropreneur. Elon Musk and SpaceX are not alone in challenging the existing launch market and providing the assets and capabilities that enable the growth of the space economy. These New Space companies reduce the cost of access to space, which create opportunities for new startups to provide services in space and are lowering the barrier for the emerging space ecosystem to grow and attract future astropreneurs. The In-Space astropreneur also faces greater infrastructure, investment, and policy hurdles [25] than the other astropreneurs. Even though they face these hurdles, national context plays a role in the success of these astropreneurs. Lamine et al. [14] captured the policy and institutional challenges that inhibit the success for European entrepreneurs supporting the upstream space markets. While in the United States, the In-Space astropreneur is enabled by national policies and programs (e.g., NASA COTS (Commercial Orbital Transportation Services) and CLPS program) and the success of new launch providers (e.g., SpaceX). Without the investments of the In-Space astropreneur and their pushing the political and legal boundaries of commercial activities in space and on the moon, the other two types of astropreneurs would not have a platform for their startups.

Another key distinction between the In-Space and other astropreneurs is their requirement to access a launch vehicle. Access to a launch infrastructure is essential for the in-space markets and access to these capabilities belong either to the government space agencies, the rocket billionaires, or by the plethora of smaller launch vehicles being developed for satellite operations. Public private partnerships [14,55,56] are essential to gain access to this infrastructure and yet can prove to be a barrier for new astropreneurs, in different national contexts, attempting to challenge the existing industry base [14]. Space in many ways is the final frontier [57]. The policies related to launch, ownership in space and on the moon as well as the acceptable risks in reaching this new frontier are continually evolving. This will impact the financing of in-space astropreneurs [58]. Yet, this does not dissuade the visionaries that are leveraging the NASA CLPS program to build infrastructure in space. For example, Lunar Station aspires to build an edge

Table 4
Trio of astropreneurs.

	In-Space Astropreneur	On-Earth Astropreneur	Space Spinoff Astropreneur
Technology focus	Space technology targeted for application in space or destination beyond the earth	On earth application that leverages resources or space technologies from space	Space technology commercialized for a different terrestrial market.
Context	Large upfront cost Access to unique infrastructure for - Testing for space environment - Testing for launch conditions - Launch platforms Access to launch vehicle Potential policy and legal hurdles to overcome or to co-create	Less upfront cost as compared to In-Space Astropreneur Access to data from space assets Connection to ground station communications or ground data storage	Upfront cost dependent on market focus and not on space technology Access to space technology Access to space expertise to commercialize the technology
Value creation within astropreneurial ecosystem	Co-creation of value within In-Space Astropreneur community Co-creation of value between On-Earth and In-Space Astropreneur	Co-creation of value between On-Earth and In-Space Astropreneur	Value loop between Space Spinoff Astropreneur and In-Space Astropreneur and On-Earth Astropreneur Receive technology from astropreneurs Provide new commercial solutions to ecosystem
Markets	In-space inspection In-space robotic repair Earth Observation Satellites Human space exploration Tourism Lunar rovers Lunar communications Lunar power systems Launch Re-entry Data Storage/Disaster recovery Edge computing	Data Analytics Energy exploration Mining Communications Processing of earth imaging Command & Control Engineering services GPS and mapping Scheduling/connecting to space assets Agribusiness	Medical Energy/Clean Tech Manufacturing Agribusiness Maritime Construction
Seldor capital companies	125	126	4
Expanding frontier companies			16

computing infrastructure to support the commercial customers carried by the CLPS vehicles. Additionally, Lunar Outpost is creating a suite of robotic vehicles to support the experiments and operations on the moon.

4.2.2. On-earth astropreneur

As the In-Space astropreneurs open the new frontier, it creates opportunities for the On-Earth astropreneur to leverage the space assets to benefit industry on Earth. A common strategy employed by developing nations is to access the satellite infrastructure to aid in agribusiness, urban planning, energy exploration, and other major industries in their region [50,51]. These astropreneurs benefit from the infrastructure created by the In-Space astropreneur but do not have to make the investment to build this infrastructure. They leverage the growing number of space digital platforms [8], including the growing number of satellites collecting data from space, space communication networks, and even Amazon Web Services for aerospace and satellites. Comparable to the observations that Autio et al. [6] made about digital platforms, we are seeing these space platforms "contributing to the dynamic emergence and evolution of entrepreneurial opportunities and outcomes" for the On-Earth astropreneur.

Although, policy is not a major driver for the On-Earth astropreneur, they do have security considerations as they provide insights into communities from the vantage point of satellites in space [25]. On-Earth astropreneurs will have access to international data from satellite companies, like Lunasonde, that provides 3D visualization of the mineral and resources below the earth's surface. The data from Lunasonde will create new market opportunities for On-Earth astropreneurs to bring these data to the industries that would benefit from this information. These astropreneurs also benefit from the lower initial cost to launch their ventures than the In-Space astropreneur.

Another key difference between the In-Space and On-Earth astropreneur is the number of companies that have a dual purpose for their innovations. They range from companies that created a terrestrial market and later discovered an opportunity to expand into new space, to companies initially created to address markets both on earth and in space. The founder of Fusematic has created numerous companies that delivered innovations to the energy industry. Fusematic's portable friction welder has a strong market in the same industry. He created Fusematic with the vision to expand his market from sea to space. The CEO already has penetrated the maritime industry, with the Navy as a customer, and is looking to provide his tool for on-orbit repairs in the International Space Station (ISS) or on the lunar surface.

4.2.3. Space spinoff astropreneur

Historically, spinoffs from space technology have not been included in the grouping of space markets in the New Space ecosystem. Spinoffs were identified as a tangential benefit from space and their contribution focused on the monetary impact to the global economy because of the investment in space. By not including the over 2000 technology spinoffs from NASA and more than 120 spinoffs from the shuttle program alone [59,60], a valuable contributor to the new space ecosystem is missing. Leveraging space spinoffs to create companies that benefit terrestrial markets [44,61,62] creates another path for the astropreneur. Nambisan et al. [7] observations from digital innovations provide insights into how the space spinoff astropreneur is different from the other two groups of astropreneurs. "By looking at technology use as sets of affordances and constraints for particular innovating actors, IS *(information systems)* researchers can explain how and why the same technology can be repurposed by different actors or has different innovation outcomes in different contexts" [7]. By transferring the space technology to different markets, the space spinoff

astropreneur is faced with different affordances and constraints [58,60] compared to the other astropreneurs.

Facilitating the commercialization are a growing number of intermediaries that are connecting startups to space technologies and providing incubation and acceleration programs. These programs are distributed across the country and internationally, through programs like the European Space Agency (ESA)—Technology Transfer Network [63]. Other examples include the Challenge to Innovate program, conducted by Puerto Rico's Acceleration program, Parallel18, connecting budding astropreneurs to NASA's technology [64] and the NFL (National Football League) Players association partnership with NASA to create the Commercialization Training camp to seed new technology startups with the NFL players as the CEOs [65].

Expanding Frontiers connected the astropreneurs from Permittivity to mentors in the energy industry and to the NASA technology at Langley Research Center. They recognized that for these aspiring entrepreneurs "knowledge of customer problems will influence their discovery of products and services to exploit a new technology" [46]. By connecting the astropreneurs with mentors in the industry, they helped to accelerate the knowledge the astropreneur required to commercialize the space technology. With the access to the technology and the NASA inventor, Permittivity created a leak-detection system for industrial-containment solutions. The ability of these astropreneurs to connect with the inventors and understand the space technologies sufficiently to identify new markets is a hall mark of these innovators. Permittivity and the other Space Spinoff astropreneurs proudly share the heritage of their innovation and the licensing from a government laboratory or from the existing space industry base [61,66]. Many of these astropreneurs will highlight their space technology foundation with the expected benefits will have for branding, marketing, selling, and revenue generation.

The other aspect of the space spinoff astropreneur is the potential looping back into the new space ecosystem ("spin-in"). Some spinoffs will first create a terrestrial market and then expand into New Space. Others like Bigelow Aerospace will take the technology and create a new space company. Mazzucato and Robinson [56] capture the success of Bigelow aerospace's commercialization of NASA technology from the Johnson Space Center (JSC). In the 1990's, JSC's TransHab project was creating an inflatable habitat design for space exploration. The inflatable design would provide a reduction of weight for the habitat and would allow it to fit within existing launch vehicles. The challenge was to create a habitat that would not overinflate and explode and could also withstand impacts from the micrometeoroids in space. After the termination of the program, Bigelow Aerospace licensed the technology and eventually entered into an agreement with NASA to attach the inflatable BEAM (Bigelow Expandable Activity Module) to the ISS. NASA benefited from the investment made by Bigelow Aerospace to commercialize the technology and BEAM provided additional storage space on the ISS.

It is this feedback and continuous evolution of space technologies and capabilities that makes the space spinoff astropreneurs contribution to the new space ecosystem unique. Space Spinoff astropreneur's, like Bob Bigelow, embody the perspective shared by Nambisan "Specifically, if entrepreneurial outcomes are amenable to continuous change and evolution, then entrepreneurial success may no longer be reflected by the enactment of a predefined opportunity or the execution of a predefined value proposition. Instead, entrepreneurial actions would need to be oriented toward facilitating a continuously evolving value proposition [8]." The spinning out and spinning back in of space technologies enable the continuous evolving value proposition of the new space ecosystem.

4.3. The space value constellation

In the early years of space activity, when NASA employed a more traditional model for its development approach [52], it would be appropriate to think of the ecosystem in the context of a value chain [37]. In the traditional model, NASA would manage large scale system integration across a supply chain of rocket manufacturers (with all the sub-component manufacturers), launch providers (typically government facilities), satellite or space hardware manufacturers, communication infrastructure and command and control. Any impact or lack of capability in the supply chain would preclude the success of the overall space project. It was a linear relationship between supplier and buyers.

NASA's investments in the COTS and CLPS programs have seeded capabilities in the space ecosystem, thus enabling NASA to pursue, what Heracleous et al. call the "commercial network model" [52], to access capabilities to support its space exploration missions. These programs contributed to the growth of the New Space ecosystem by creating opportunities for the co-creation amongst astropreneurs. We are seeing the simultaneous delivery of capabilities in the ecosystem by space startups that enable the entry of new astropreneurial innovations. The effectiveness [11] of the startups is linked to their ability to network into a constellation of astropreneurs where they can co-create new markets [19]. To paraphrase Autio et al.'s [6] observation of the digital entrepreneur ecosystem, "the *astropreneurial* ecosystems are distributed structures, the constituent elements of which cocreate ecosystem outputs." This is best illustrated in the emerging lunar space economy, where the uncertainty of this new market is being "resolved gradually through the accumulative co-creative entrepreneurial process" [19] of astropreneurs. In particular, the value captured in the investor presentations and follow-up conversations with the astropreneurs in this new lunar ecosystem, highlight their co-creation of value across a community of astropreneurs.

Lonestar is a new space startup focused on providing a premium backup disaster recovery capability on the lunar surface for organizations and communities on Earth that want a secure backup for their digital footprint. The need for this backup capability has grown due to the impacts to many secure backup facilities from climate change. Facilities that were secure have been impacted by the growing number of wildfires and the rising flood waters in various communities. Lonestar found an opportunity to create a capability on the moon by leveraging NASA's CLPS program. By partnering with Intuitive Machines (a CLPS provider), Lonestar can test early concepts on the lunar surface and gain market traction as it builds its lunar storage facility.

One of the many challenges of hardware on the moon is access to power, especially during the lunar night, which lasts about 14 days. Ground solar stations would not be able to provide power to the equipment and without power, the negative 280° Fahrenheit temperatures could potentially damage the equipment. This creates an opportunity for Eternal Light to provide power beaming from the lunar orbit to ground assets. Additionally, communication on the lunar surface will be a challenge, which creates an opportunity for lunar outpost to use its robotic systems (carried by Intuitive Machines to the lunar surface) to partner with Nokia Bell Labs to test the range of communication terminals on the moon.

Lonestar, Eternal Light, Intuitive Machines, Nokia, and Lunar Outpost are "not only co-creating with existing institutions" [19] (e.g., NASA), they are co-creating a new space ecosystem on the moon that will create the future value [24] for each company. They did not wait for the capabilities of the other companies before the creation of their company [20]. Instead, we are witnessing what Karami and Read proposed as a "constellation of co-creative

stakeholders employing a combination of existing institutions, co-created new institutions, and new institutional arrangements to enable the co-creative entrepreneurship process." [19]. There is not a linear value chain relationship between them. As Normann and Ramirez describe the companies in a value constellation, "they need to make new business arrangements and, sometimes, new social and political alliances to make these offerings feasible and efficient" [9].

The co-creation of astropreneur startups is best represented through the value constellation and not the linear value chain model. Normann and Ramirez expand on this idea by explaining that "Instead of 'adding' value one after the other, the partners in the production of an offering create value together through varied types of 'co-productive relationships" [16]. Fig. 1 captures the interplay between all the astropreneurs in the space value constellation. Each astropreneur's affordances and actions in the ecosystem plays a role in the growth and co-creation of the ecosystem [19,20]. There is a two-way value creation relationship between the In-Space and On- Earth astropreneurs. Creation of In-Space capabilities will create, in parallel, market opportunities for the On-Earth astropreneur. As demand for more imagery and data from space grows from the success of the On-Earth astropreneur, more satellite constellations will be required from the In-Space astropreneur.

The Space Value Constellation also includes a value loop [23] aspect that is captured in Fig. 1. The technology from the In-Space and On-Earth astropreneurs are commercialized and introduced to other markets by the Space Spinoff astropreneur. As the commercial technology matures and gains new capabilities, it has the potential of spinning back into the markets of the In-Space and On-Earth astropreneurs. One example of this loop is found with Interstellar Lab. This terrestrial startup is creating bio-pods that increase the production of plants for agribusiness, cosmetics, and the pharmaceutical industry in an efficient enclosed environment. The light technology in their pods, that contributes to their increased production, is a NASA spinoff from the plant growth experiments conducted on the ISS. The immediate market for the bio-pods are those regions with a scarce supply of water or require near access to unique floral and vegetation. The founder is already looking ahead at applications for the bio-pods in low earth orbit and on the moon in an inflatable structure. In this example, technology that began in space will impact a market on earth, which will improve the technology before it is deployed for applications in space. It is also foreseeable that the technology experience in space will identify improvements for the terrestrial pods. This value loop between In-Space and On-Earth astropreneurship, through Space Spinoff astropreneurship, is an integral component of the space value constellation.

5. Implications and avenues for future research

Even though the commercial space market is currently a $477 billion market, [67,68], it is still an emerging and growing market. Investments by the Venture Capital community [10] has seen a 95% increase from 2018 ($2 bn) to 2019 ($4 bn). Additionally, Seed/Prize/Grant funding has seen an increase of 77% from 2017 ($563 m) to 2018 ($998 m) and a 31% increase to 2019 ($1.3 bn) [4]. The growth of this industry is comparable to the growth of the information technology industry that led Normann, Ramirez, and Yoo [9,10,17,23] to propose their value constellation and value loop theories. I believe we are witnessing the creation of a new value creation model with the emergence of this new space sector. The emergence of this new "techno-economic paradigm" will bring, as Freeman and Perez describe, "such widespread consequences for all sectors of the economy that their diffusion is accompanied by a major structural crisis of adjustment, in which social and institutional changes are necessary to bring about a better 'match' between the new technology and the system of social management of the economy" [5]. Freeman and Perez further state that "in the early stages of radical technical innovation uncertainty prevails" [5].

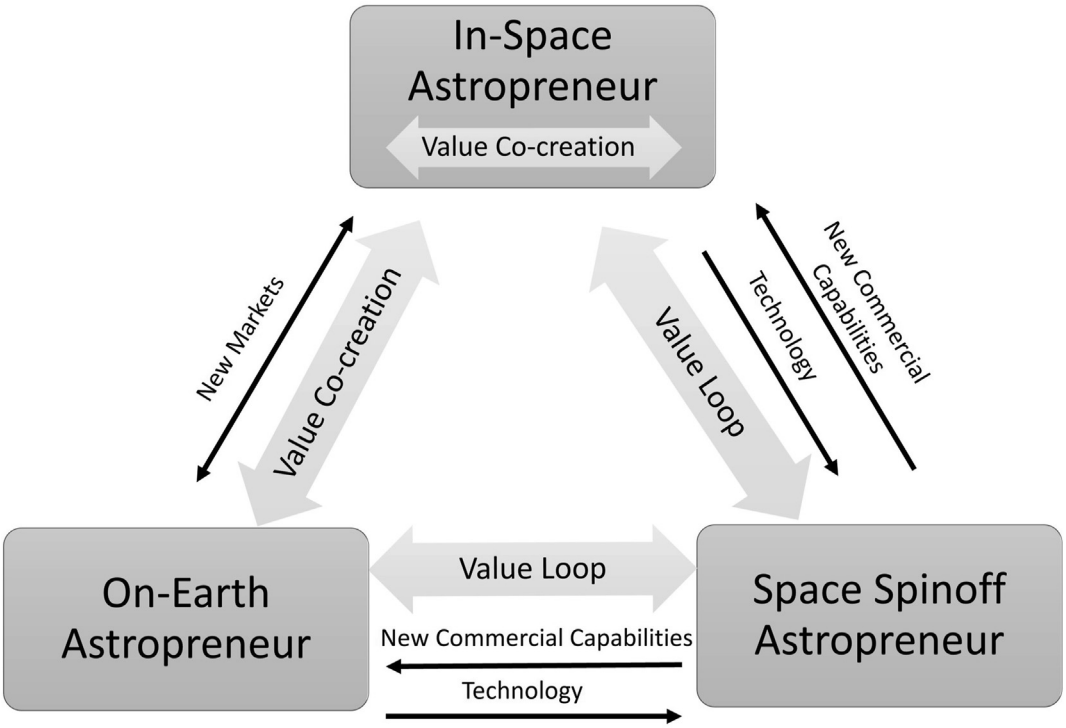

Fig. 1. Astropreneur space value constellation

Where there is uncertainty, there is opportunity for more research to shed light on the phenomena. In this article, my aim was to shed some light on this new technology wave, the Space Technology Kondratieff. I have captured the first seven main characteristics of this wave and more research is warranted to expand on the additional eight characteristics that Freeman and Perez captured for the first five waves [5].

The space and national context, as well as the context associated with the different type of astropreneurs, also offers opportunities for future research. In this article, I have attempted to expand on the dialog on national context initiated by Lamine et al.'s [14] through examples of New Space startups emerging in the space ecosystem in the United States. There is a desire by other communities to create an astropreneur network. Communities including those in India, Africa [50,51], and the predominantly Hispanic community of Brownsville, Texas [69] are aspiring to participate in this trillion-dollar economy. There is an opportunity for research to understand if the context in these communities enables or hinders the growth of the emerging networks and resources [70–74] required to build an effective [11] New Space ecosystem. For these communities, is there a sequencing of the networks and resources that is important to the emergence of *astropreneurial* ecosystems [6]? Additionally, as Autio et al. identified an opportunity for future research in digital infrastructures [6], there is an opportunity to research "how do the qualities of the *space technology* infrastructure in a given region regulate the quality of an *astropreneurial* ecosystem's start-up and scale-up activities in that region?"

As the astropreneurial community continues to grow, the difference between the affordances and context of the three astropreneurs will become more differentiated. More research is needed to understand what contributes to the success of astropreneurs in the context of in-space, on-earth, or spinoff? When it comes to the space spinoff astropreneurs further research should focus on understanding what aspects of programs offered by intermediaries, like Expanding Frontiers, enhance astropreneurial access to space technology? For example, how effective is the prior knowledge of mentors in facilitating the commercialization of space technologies to other sectors [46,47]? Additionally, the sector fluidity of the space ecosystem has been explored through the commercialization of technology into other sectors [60,75–77] but further research is needed to capture the transition back into space applications of these commercialized technologies. I expect we will see an increased pull, by the growing lunar ecosystem, of the improved technologies that were spun out into commercial terrestrial markets.

Finally, just as we saw with the emergence of new value creation methodologies with the growth of the information technology industry, there is an opportunity to research the development of a new value creation model for a rapidly growing ecosystem. Moving from the value constellations theories emerging from the digital ecosystem to that found in emerging space ecosystem is consistent with Busse et al.'s [53] "inside-out exploration approach". Yet, more research is warranted to explore the similarities and uniqueness of the Space Value Constellation compared to digital ecosystems. In this article, I have shared examples of astropreneurs that co-create value in the Space Value Constellation, but more research is required to understand how the value is created between the astropreneurs? What networks [39,78–80] are essential in the co-creation of value? Corsaro et al. [11] described the value outcomes that are facilitated by the effectiveness of the network. More research is needed to understand what specifically contributes to the effectiveness of the networks across the astropreneurial ecosystem? Additionally, we are seeing the rapid co-creation of the lunar ecosystem through the emergence of startups contributing key resources and capabilities to the ecosystem. What enables or facilitates the co-creation across a lunar-earth platform and how does it compare to the earth-bound digital platforms?

Finally, this article focused only on the astropreneurs in an ecosystem and did not include the co-creation contribution of other stakeholders in the ecosystem or customers [53]. Future research should explore the role of customers and other stakeholders in the co-creation of the new space ecosystem [17,19,22,24,81].

6. Conclusions

The Apollo program and the resulting technology fueled the push for the digital economy. New Space will have an even greater impact as we expand to markets beyond the Earth and onto the lunar surface. New Space differs from "old space" [82] or commercial space in more than the market, policy, and legal hurdles that it must overcome. This new techno-economic paradigm [5] introduces a new model of value creation across the ecosystem. This model is the best reflected by an integration of the value constellation and value loop models of Normann, Ramirez, and Yoo [9,16,23]. A model of co-creation is found across the various astropreneurs in the constellation. The lunar example shared previously between Lonestar, Lunar Outpost, Intuitive Machines and Nokia is just one example of the many collaborations and partnerships that are co-creating value. The discussions I have had with astropreneurs lead me to believe that these collaborations are developing in an ever-accelerating pace.

We have crossed the threshold where space was the sole domain of government and the billionaire club. It is accessible to visionary astropreneurs that aspire to "go where no one has gone before" or to transform life on earth. As I have tried to capture in this article, these aspirations to transform life on earth are not tangential but are increasingly colliding with New Space as the market grows. While collisions in space are to be avoided, the collisions of visions by these astropreneurs will have exponential impact to life on earth and humanity's increased presence in space.

Author statement

Steven A. González: Conceptualization, Investigation, Methodology, Validation, Writing - original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The insights captured in this manuscript stem from my thirty-two years at NASA, the research that I am conducting towards my Doctorate in Business Administration, at the Warwick Business School (WBS) and my role as a venture partner at Seldor Capital. My research at WBS is supported by a full scholarship by the Warwick Business School for my Doctorate in Business Administration. Additionally, I am no longer employed by NASA and am not funded by Seldor Capital. I do have future equity shares from Seldor Capital.

Data availability

The data that has been used is confidential.

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