

## REVIEW ARTICLE OPEN

## The economics of microgravity research

Jeanne M DiFrancesco<sup>1</sup> and John M Olson<sup>2</sup>

In this introduction to the economics of microgravity research, DiFrancesco and Olson explore the existing landscape and begin to define the requirements for a robust, well-funded microgravity research environment. This work chronicles the history, the opportunities, and how the decisions made today will shape the future. The past 60 years have seen tremendous growth in the capabilities and resources available to conduct microgravity science. However, we are now at an inflection point for the future of humanity in space. A confluence of factors including the rise of commercialization, a shifting funding landscape, and a growing international presence in space exploration, and terrestrial research platforms are shaping the conditions for full-scale microgravity research programs. In this first discussion, the authors focus on the concepts of markets, tangible and intangible value, research pathways and their implications for investments in research projects, and the collateral platforms needed. The opportunities and implications for adopting new approaches to funding and market-making illuminate how decisions made today will affect the speed of advances the community will be able to achieve in the future.

*npj Microgravity* (2015) **1**, 15001; doi:10.1038/npjmgrav.2015.1; published online 27 May 2015

## INTRODUCTION

This work is an exploration of the economics of microgravity research, the history, the opportunities, and how decisions made today will shape the future. The launch of this journal marks an important milestone in the development of this emerging scientific arena, fostering a community of scientists that will pioneer new chapters of development across many disciplines on the dynamics of cells, molecules, and atoms in the microgravity environment. The discoveries published here will advance our understanding of things that are familiar by theorizing and observing their behavior in a completely new environment.

Microgravity research both enables and is enabled by space. Spaceflight over the past 60 years has been a source of great inspiration, significant advancements, vigorous debate, and tragic disappointments. Space is a challenging and relatively expensive operating environment. It has historically been the purview of governmental entities of countries, many which now face shrinking budgets and serious questions about the value of their investments in space.

We are now at an inflection point for the future of humanity in space. Transportation to and from space is being successfully pioneered by many private companies and the potential uses of space continue to expand beyond communications, imagery, and weather observation to research, development, servicing, and exploration on space-based platforms where humans can live and work. Today, human spaceflight and robotic science missions can be undertaken ever more regularly and at lower cost, improving the conditions for full-scale microgravity research programs.

So what could impede or accelerate progress toward achieving this potential? In short, funding. Not just the total amount of funding for research, but funding to ensure the availability of all the factors for success, from the frequency and reliability of access to microgravity research platforms to the consistency of funding required to develop the robust university programming that will attract the best scientific talent. The willingness of governments,

universities, and private entities to make investments will be dependent on a variety of criteria, but the most important is and will remain, value. Value propositions, both real and perceived, are a function of the type, scope, and timeline of the outcomes being pursued and their value relative to the investment required. However, to truly generate value, stimulate broader expansion, and sustain the momentum that has been generated, new approaches must be embraced that have heretofore not been widely used. In many ways, what is required is virtually the opposite of what the conventional wisdom has prescribed. The decisions made now on the approach to funding the exploration, exploitation, and development of the resources required for microgravity research will determine the speed at which we will progress.

Yet, space has always challenged us. Success came not with the conventional but with the exceptional. Advances have been achieved on bold paths pursued with the three factors that are essential for any new endeavor—vision, courage, and capability. In this context, we will explore the existing landscape and begin to define the requirements for a robust, well-funded microgravity research environment.

## WHAT IS MICROGRAVITY RESEARCH?

As defined by the National Research Council, a gravity-related phenomenon is either directly affected by reduced gravity or becomes significant as the gravity level is reduced. In general, the focus of microgravity research and applications is the study and assessment of these biological, physical, and chemical phenomenology and related issues.<sup>1</sup>

Conducting experiments in a microgravity environment has the potential for discoveries that can both improve life on Earth and advance our understanding of space. From integrated circuits, to silicon solar cells and memory foam, the benefits of previous ventures into space have transformed the way we live and operate

<sup>1</sup>ProOrbis, LLC, Malvern, PA, USA and <sup>2</sup>Lakeville, MN, USA.  
Correspondence: JM DiFrancesco (JDiFrancesco@proorbis.com)  
Received 24 February 2015; accepted 2 March 2015

as humans. The promises of this new generation of space exploration are equally vast, offering us the potential for an array of possibilities from the design of more efficient therapies and better vaccines, to creating stronger and more conductive materials, to developing new plant varieties that are better adapted to extreme conditions. The opportunity for advances offers an infinite horizon of possibilities that does not just lead to new products, but to entirely new categories that can fundamentally change the way we live.

## THE HISTORY OF MICROGRAVITY RESEARCH

During the Cold War space race, scientists became quite interested in the effects of microgravity. Before that time, we principally sent assembled equipment to space in the form of satellites starting in 1957 with Sputnik. Prior to the dawn of the Space Age, we did not extensively consider the effects of the zero- or low-gravity environment.

Once the human spaceflight era began, important considerations such as the effects of microgravity on primary systems (atoms, molecules, fluids, cells, tissues, plants and so on) and support systems (environmental control and life support, fire suppression systems, consumables, science glove box and so on) had to be taken into account to enable a sustained human presence in space and to contemplate and then sustain long-duration habitation of space. The access to space afforded by Apollo, Soyuz, the Space Shuttle, and the International Space Station (ISS) provided mechanisms to begin exploring phenomena in the unique microgravity environment. The burgeoning commercial crew programs that will follow promise safe, reliable, more affordable, and regular access that is intended to expand opportunities that will lead to space-enabled terrestrial advancements, greater exploitation of the potential of low Earth orbit, and longer-duration and sustained exploration of the solar system, including the Moon, asteroids, and Mars.

And thus, with this catalytic beginning sparked by an international space race not quite 60 years ago, the field of microgravity research was thrust into the global incubator as space-faring nations hastily pursued basic and applied research and development (R&D), measured and probed their astronauts, rapidly refined their related systems, expanded focused technology development activities, and pushed the boundaries of understanding and applied benefits even further.<sup>1</sup>

Advancements in terrestrial microgravity research capabilities also flourished in the 1990s both domestically and internationally. Countries including Japan, Germany, Russia, and China, as well as academic institutions such as Purdue University, Massachusetts Institute of Technology, and Arizona State University, expanded their capabilities and research programs. These endeavors provided researchers access to a myriad of microgravity research platforms including drop towers, parabolic flights, and suborbital rockets. These alternatives are far less expensive, but also less capable than space-based resources. Collectively, these made up a broad, integrated architecture of experimental flight opportunities that when combined with ground-based R&D capabilities afforded researchers a variety of cost-to-performance options.

Government funding for microgravity research reached its peak during the early effort to assemble the ISS. Regular and recurrent Space Shuttle flights provided a significant traffic flow to and from space, and there was a strong demand for knowledge-informed systems solutions for the ISS. National Aeronautics and Space Agency (NASA)'s budgets related to microgravity R&D exceeded 100 million dollars per year between 1994 and 1998.<sup>2</sup> However, since then, funding for a robust microgravity program has been tenuous and inconsistent due to limited NASA funds available for the ISS program overall. Compounding factors including the US market and housing collapse of 2001 followed by a global recession in 2008, the 2003 Space Shuttle Columbia disaster, and

associated delays in the construction of the ISS, drastically reduced Russian space spending, the lack of a Chinese human spaceflight program in space until 2005, and the 2010 cancellation of the Constellation program with its associated redirection from a lunar and Mars focus all contributed to funding issues in the US Space program. When faced with the choice between finishing the construction of the ISS or funding the science, construction was deemed imperative.

The constrained budgets of the early 2000s precipitated a fundamental shift in the US government's approach to the exploration, development, exploitation, and utilization of space. In 2005, the NASA administrator set forth a new strategic direction that the Congress endorsed in the 2005 NASA Authorization Act and was subsequently reflected in the 2010 National Space Policy, which was an important shift toward the stimulation, growth, and utilization of a robust US commercial space industrial base. This would afford the government purchase of services in low earth orbit with the expectation that the next generation of space would be more heavily funded by the private sector so that limited government funding could be focused on inherently governmental space missions, including deep space exploration.<sup>3</sup>

NASA and its international partners have so far invested tens of billions—some argue as much as \$100 billion—in developing and operating the unique orbiting facility that is the ISS.<sup>4</sup> In the 2005 NASA Authorization Act, the US Congress also embraced a policy that broadened the potential for value creation from its investments in ISS, by designating the US portion of the ISS as a National Laboratory requiring that no less than 15% of all ISS research be nonexploration related. Then, in 2010, Congress passed another Authorization Act directing the establishment of an independent nonprofit entity to manage 50% of the ISS resources for non-NASA mission activities.<sup>5</sup> NASA commissioned a design concept for a national laboratory entity to manage the non-NASA uses of the ISS with an enterprise design that would maximize the value of the American investments in the ISS. This reference model for the ISS National Laboratory (ISS NL report) examined ways to optimize the utilization and derive value from the ISS, given both its capabilities and challenges.<sup>6</sup> The concepts developed in this model outlined and identified the elements needed to create robust and stable market conditions to take maximum advantage of the planned ready-access to space and completion of a world-class facility.

## THE GLOBAL SPACE LANDSCAPE

Since 2005, NASA's Commercial Crew and Cargo Program has invested over \$1.5 billion in private industry to develop a cost-effective commercial cargo and crew transportation service for the ISS.<sup>7</sup> In May 2012, the SpaceX Dragon became the first commercial spacecraft to deliver cargo to the ISS, opening a new era of cargo resupply services.<sup>8</sup> Since then, NASA has awarded additional contracts valued up to \$6.8 billion to Boeing and SpaceX to provide crew transportation services.<sup>7</sup> The ISS has been continuously crewed for 13 years, currently with a crew of 6. It was designed to accommodate a crew of seven, which would increase the time available per week for research activities. Since a US platform for delivering crew to the ISS has not yet become operational, NASA continues to purchase seats for crewed missions from Russia at \$71 million per seat.<sup>4</sup> Cargo upmass and downmass, crew science time, and reliable and responsive domestic crew transportation are all requirements for ISS utilization and productivity. In 2011, the Center for the Advancement of Science in Space was established to manage the US National Laboratory on the ISS. According to its publications, the Center for the Advancement of Science in Space seeks to enable and increase the use of the ISS NL as a unique and dynamic platform for scientific discovery, technology development, and education for the benefit of life on Earth.<sup>9</sup>

The ISS NL report articulated the design of an independent organization that would use a relatively small amount of

government funds to raise a substantial amount of non-NASA investment for research. Since the objective was to maximize return on investment (ROI) for the American taxpayer, the design only called for \$15 million of NASA funding per year for 5 years, after which point the organization would become self-funding. The assumption in the model was that NASA would provide transportation and facilities on the ISS at no charge, but users would need to pay for their own payloads. By year 5 of operations, the model projected that the organization would raise \$20 million to support its own operations and \$90 million for research projects. By 2020, the organization's completely independent funding model estimated raising \$125 million annually for space-based research. As the end date for the ISS at the time of the report was 2020 (it has since been extended), the concept was for the organization to have built the community and resources to explore other options for conducting science in space, seeding markets for the next generation of platforms.

The ISS NL report exhaustively articulated the myriad of conditions required to achieve these results, many of which are completely novel in the management of governmental assets—especially combined in one organization. Although the utilization of, and ROI in, the ISS remains one of NASA's top priorities, one of the key findings in the ISS NL report was that the way to maximize its value was not in focusing solely on its utilization, but rather by leveraging the ISS platform and its remaining useful life to build an entire ecosystem to advance science in space. The highest ROIs in the ISS was to use it as a 'center of gravity' to build a robust, sustained community that could both maximize the valuable uses of the ISS and leverage the experience in space-based research for the next generation of research platforms (space based and terrestrial). As the useful life of the ISS is finite and relatively short, the value maximizing use of the ISS was not to use it up. Rather it was to use the precious time and resources between the beginning and the end of the ISS program to help build a community that included the scientists, universities, companies, space transportation service providers, payload development support and all the other capabilities that are needed for space-based research. An organization with its own wherewithal to design and privately fund the next generation of space-based assets would extend the impact of ISS well beyond its useful life. The ISS remains a shining example of an extraordinary international partnership and technical accomplishment, but it is the vision, courage, and capability brought now to the management of its utilization that will directly affect the strength and sustainability of the environment for microgravity research funding in the future.<sup>6</sup>

Although the United States continues to dominate global spending on space programs, other emerging global powers such as India and China are recognizing the potential value of space to their economy and are developing ways to participate. Today, most countries that are trying to stake a place in space have dedicated the bulk of their space budgets toward launch capabilities, satellite communication, positioning, or sensing technologies.<sup>10</sup> This is likely to remain the focus of global spending in the short term, as security concerns encourage major states to develop national capabilities and countries can readily see and articulate the benefits of these investments. The 5 partner and 16 member nations of the ISS, plus China and India, have also pursued civil space largely due to four primary reasons: (1) to advance technological development, (2) to create a demand pull for technology and operations, (3) to increase international collaboration to enhance geopolitical stability and peaceful cooperation, and (4) to pursue and sustain global prestige, influence, and soft power.

However, nations engaged in space are actively assessing, both qualitatively and quantitatively, the productivity, effectiveness, and ROI of these endeavors, given the intense competition for resources and funding for alternate pursuits. With the high costs

associated with a space program and the limited resources available, a growing number of states are recognizing the need to identify and provide value back to their societies in order to justify spending on space. India, for example, has found a number of ways to articulate the benefit to their people of improved space capabilities including affordable launch and expanding satellite networks that yield terrestrial benefit through increasing crop yields by providing farmers with greater environmental data, or by mitigating the losses from severe weather from better warning systems.<sup>11</sup> India's recent success in its robotic Mars exploration highlights the breakthrough potential of relatively new players in space. Some emerging and aspiring space-faring nations have developed assessment schemes to measure the value of their investments in space and have generally identified positive returns. By considering the broader economic implications of space activities, it is generally easier to make the case for space program spending that generates and delivers sustainable value.<sup>10</sup>

### MICROGRAVITY RESEARCH FUNDING

R&D in the United States has always been both privately and government funded. After the end of World War II and the onset of the cold war, the federal government began pouring money into the historically private-sector-dominated R&D. This federal funding peaked at 67% of all R&D funding in 1964 as the nation raced toward the moon. Since then, the private sector has significantly increased its share of overall R&D funding to around 63%.<sup>12</sup>

Since 1965, total R&D spending has remained consistent, averaging around 2.6% of Gross Domestic Product per year. Funding for basic research has increased slightly from 0.40% of Gross Domestic Product in 1990 to 0.55% in 2009 back to 0.50% in 2011. The Federal government still provides the most basic research dollars spending \$36 billion in 2011 out of a total of \$66.1 billion.<sup>13</sup> Private industry provided only 20% of basic research funding in 2011, so basic science funding is still heavily dependent on government decision processes and priorities.<sup>12</sup>

However, NASA's funding has decreased from 10 to 11% of the federal R&D budget in the 1990s, to just 6% in 2011. Total R&D spending in constant dollars by NASA has increased, from \$5.9 billion in 2009 to \$6.5 billion in 2011, and between 1993 and 2000 NASA's budget for basic research increased steadily from \$1.8 to \$2.3 billion before declining sharply to \$1.7 billion in 2001. It then briefly began increasing again to \$2.2 billion in 2005, before entering into another period of decline reaching a low of \$809 million in 2010. Although NASA's basic research funding has once again been increasing, surpassing \$3.2 billion in 2014,<sup>12</sup> it is difficult to see how much of this is dedicated to microgravity research as NASA no longer specifies this categorically.

Globally, the United States remains the number one source of R&D expenditures, spending \$429 billion in 2011, followed by the European Union with \$320 billion in current Purchasing Power Parity (PPP) dollars. Japan's spending doubled between 1991 and 2011 from \$73 billion to \$146 billion PPP. Other nations are also investing heavily in space and research in general. China has seen the greatest increase, with R&D spending increasing 27-fold between 1991 and 2011 to \$208 billion PPP. South Korea has also seen an impressive increase with expenditures increasing eight-fold in the same period to \$60 billion PPP.<sup>12</sup>

### THE INFLECTION POINT

"There are  $10^{11}$  stars in the galaxy. That used to be a huge number. But it's only a hundred billion. It's less than the national deficit! We used to call them astronomical numbers. Now we should call them economical numbers". Richard Feynman<sup>14</sup>

Given the policy shift of NASA to private funding models and the trends in funding for basic R&D, robust and stable investments will not come from sources of the past. Generally, when government funding is tenuous and inconsistent it is usually driven by the lack of a compelling reason for funding or apparent consequence for failure to fund. Perceived threats (such as in the Cold War) may therefore be more compelling than perceived opportunities (no matter how promising). Attracting private investment requires deep insight and a firm grasp of what makes private markets viable. Without a sophisticated understanding of what it takes to 'make a market', policy and decision making tend to be naive, misguided, and generally inadequate to the task.

The reality is that it takes many factors all working simultaneously to create the conditions in which a market can flourish. If the government is prepared to spend substantial sums of money in exchange for activity performed, there will always be suppliers and hence there will be a 'market', but this is a government-funded monopsony, not an independent multifunder market. The conventional wisdom for space research has been focused on finding and funding the 'one-off' success that will convince the industry that there is promise in space-based research. This is marketing, not market-making. Not only is this insufficient; it is actually distracting from what is required.

Perhaps this is because the successes of the past have planted the seeds of failure (or at least for significant sub-optimization). Space endeavors have been the source of extraordinary human accomplishment and national pride. They have been the genesis of countless patents, the inspiration for the development of entire categories of products, and the stimulus for their own follow-on missions. If something useful for terrestrial applications came out of this mission-driven activity, it was the 'gravity' not the 'goal'. The primary goal was not maximizing the value of the investments made in space; instead, it was executing the mission. The DNA of space agencies is to 'achieve the mission objective' and to 'take the next giant leap', not to make the absolute most of what they are doing for the broad interests they could be affecting. However, to truly achieve the full economic and R&D potential of space, a new mindset is required. The problem with the current perspective is that the real value of space is far more than what most countries can 'see' and therefore far more than most space agencies can 'sell'. As a result, there is often an incoherent 'on again, off again' policy and funding posture that impairs both the performance toward mission and the return on the country's investment.

Microgravity research is significantly enabled by space and in this case, it is not the 'gravity', but rather, the 'goal'. It has its own value. This value, the investment, the risk in either of those factors, and the resultant rate of return can all be defined and known. If sustained funding is to be achieved, all of these factors will need to be well understood, articulated, quantified, and accompanied by the other necessary capabilities to 'make the market'. Given the current trends and policy posture of governments, the absence of any of these factors may substantially impair the potential of this field.

## THE CONCEPT OF VALUE

"The difficulty lies, not in the new ideas, but in escaping from the old ones, which ramify, for those brought up as most of us have been, into every corner of our minds". John Maynard Keynes<sup>15</sup>

Economics is a behavioral science. Instead of examining the behavior of cells, atoms, materials, or molecules, it seeks to describe, explain, and predict the behavior of people.

The underlying assumption is generally, rationality. Making a market requires a set of conditions that create an environment in which sellers and buyers are willing to make an exchange. Many markets just emerge organically especially when the foundations are in place (awareness, standards for conduct, transparent information, enforcement of rules and so on). What makes a market function is an understanding of value. The value of a thing is what someone is willing to pay for it—not what it costs. Markets rely on parties understanding what things are worth.

Government spending is plagued by a lack of understanding of value. In general, governments know what things cost, but not what they are worth. Untold amounts of energy and capital are spent to develop budgets, put contracts out to bid, select the 'lowest or best-value bidder', evaluate research proposals, and shave nickels and dimes off projects in an effort to be fiscally responsible and good stewards of the taxpayer funds. However, the real value of an activity (if it is ever considered) is often used to justify a decision after it has been made. What the government decides to do is not generally informed by an understanding of the value, thereby leaving the investment without a value context.

The question of value then comes down to three principle factors: (1) what is it that is valuable (2) to whom is it valuable, and therefore (3) how would the value be quantified. Although this may seem obvious, the lack of clarity in these factors is a significant contributor to the confusion, miscalculation, and mischaracterization in the discussion of value. Risking oversimplification, we will consider tangible value to be the value that comes to or through an enterprise (i.e., revenue). Intangible value in this case is generally value to 'others' that the activity of the enterprise produces. The tangible value to a government would be measured in terms of items such as tax revenues or avoidance of costs. Intangible value would be the effect of its spending (which we will now refer to as investment) on the value to others (such as the public). Intangible is not synonymous with incalculable. Most intangible value is not only possible to calculate, but also we would argue that it must be calculated to know whether government spending is worth it.

For example, microgravity researchers have discovered new insight into how major human pathogens such as *Salmonella* cause illness, showing that spaceflight culture increased the virulence of this bacterium, yet genes known to be important for its virulence were not turned on and off as expected when it is grown on Earth. By better understanding these events, we may be able to develop more effective therapeutic strategies to combat infectious diseases on Earth.<sup>16</sup> In a similar case, microgravity has been shown to drastically affect the gene expression of poorly differentiated thyroid cancer cells. Such cells were much less likely to proliferate with genetic expression being regulated against metastasis. This may have wide ranging impacts on more effective cancer therapies while offering a valuable new avenue for research.<sup>17</sup>

Advances such as these enable pharmaceutical companies to create novel products, which result in revenue for the company (tangible value to companies). To achieve this revenue, companies must invest in a myriad of assets (plant and equipment, employees, patents), which increase economic activity that, in turn, generates tax revenue for governments (tangible value to governments). However, reduced disease states also decrease morbidity and mortality creating a healthier, more productive workforce, which improves human capital stocks and reduces health-care costs (intangible value to countries). All these factors contribute to the value of this basic research.

The cost of doing research in space can be substantial (as we have discussed). However, the opportunities to conduct experiments on both terrestrial- and space-based microgravity platforms provide researchers with a wide range of capabilities, which, when leveraged can reduce the overall cost of research to create the best possible results for the funds that will be spent.



**Figure 1.** Research pathways.

Making a market requires value to be in the context of investment. ROI is always evaluated from the perspective of the investor. Understanding the tangible and intangible value of research is necessary to identify where the value is coming from and therefore who would be interested in funding it. Sophisticated valuation identifies all the potential value, the investment it will take to achieve that value, and thereby illuminates the highest value version of the project. Using valuation to inform decisions is a different mindset than using it to justify a decision that has already been made. “Seeing” the value is not only helpful to getting a project funded, it allows for the construction of a more valuable project and is absolutely required for evaluating the best and highest use of portfolio of resources.

## THE VALUE OF R&D

“Economists will have to revise their theories of value”. Albert Einstein<sup>18</sup>

To set the stage for this discussion, we will clarify some concepts. Basic scientific research is sometimes thought of as being separate and distinct from applied or industrial research. Although it is always dangerous to overgeneralize, in the extreme, the applied researcher only cares that something happens, not necessarily why. The basic scientist is interested in why something happens, but less in what it would be useful for when applied.

In actuality of course, basic research is on a continuum with applied research. This concept we will term as the research pathway. Pathways begin with the formation of a theory and conclude with the creation of value (see Figure 1). An industry sometimes adopts paradigms to help standardize the definition of where an idea is in its development. Two exemplary frames are the Technology Readiness Level used by government agencies such as NASA and the Department of Defense, and the Food and Drug Administration’s Critical Path Initiative for the development of medical treatments.<sup>19,20</sup>

Generally, risk is reduced the further a project is along the continuum. Investors with varying objectives and risk tolerance are attracted to projects at different phases of development. Investments in R&D are generally guided by an investor’s line of sight to a discovery or development’s value. Later-stage enhancements can generate discoveries that may indicate the need for more basic research. Each stage is associated with a typical funding profile and an intellectual property strategy, which are essential to understanding how and who funds projects throughout the pathway.

Basic research discoveries and understanding may open up multiple opportunities for market applications. Projects may enter the process in any phase of the pathway. Later-stage projects may produce findings that lack theoretical underpinnings. By going back and conducting more basic and theoretical research, additional opportunities for market applications may be created.

Research pathways are essential to valuation. Tangible valuations of product applications are relatively straightforward. However, early-stage research derives its value from the value of the downstream applications. Research pathways put R&D projects in their value context and help to establish what we know, what we

do not know, and what it might be worth to know it. In this way, they provide the frame for selecting projects of the highest overall value and identifying additional activities needed to reduce uncertainty. This information creates the opportunity for more targeted investments that can shorten the cycle time between discovery and practical application, reducing the overall investment, accelerating the revenue, and significantly improving ROI.

Research pathways can be fairly easily established for an individual organization. The value of microgravity research, the investment in that research, the risk in either of those factors, and the resultant rate of return are generally fairly easy to quantify. However, if the investment is in a shared platform (such as the ISS), the research pathway may be comprised of projects from a variety of organizations, and the risks can be everything from the reliability of space transportation to the fundamental behavior of the research target in microgravity; the calculus becomes far more complex.<sup>6</sup> Valuation of multifaceted, system of system entities requires more sophistication to assess, predict, or quantify.

Governments have an interest in the economic benefits (tangible and intangible) of microgravity research and there are investments they can make to reduce the risks, which creates more favorable conditions for private investment. This is a symbiotic relationship. Formulation of research pathways provides the foundation for understanding the possibilities, and if properly constructed can provide guidance for government funding that will yield the highest overall returns. Establishing certain basic findings on the behavior of cells in microgravity might not seem like a ‘quick win’ but may provide researchers and companies the baseline data phenomenology to open completely new categories of product applications.

Finally, understanding the intangible value of a project actually allows for the construct of a better (more valuable) project. Achieving the intangible value may require additional activities that are structured into the project that may increase the cost, but because the value is proportionally higher, so too can the overall ROI. Constructing the highest ROI project is fundamentally a different mindset than efforts to ‘save money’ by cutting corners to meet budgetary restriction. Typical budgeting has inherent in it the assumption that there is no value to the investing, just a need to keep spending within some defined boundary.

## THE FUTURE OF MICROGRAVITY RESEARCH FUNDING

A robust and stable funding environment requires a myriad of conditions, but first and foremost is the vision, courage, and capability to value. Clarifying the concept of value and its application to microgravity research is essential not only to identifying who would invest but why. The extent to which each participant in the market understands and can articulate the tangible and intangible value of the project improves the conditions for making a market. Value, as we have covered at some length, is a complex notion. Investors each have their own objectives and value is not the only basis for decision making, especially for governments who have been historically dominant in funding basic research. However, in the long run, a broad understanding of the value of funding something, or the consequences of failing to fund it, can only add stability to the market.

Most of the time researchers are focused on finding funding for their projects, and the further along the research pathway the

project is, the simpler the value proposition. But failure to fund, especially more early-stage research can have devastating effects on downstream value that is often not readily apparent. The effort and energy required to construct a project designed to extract all the tangible and intangible value can generally yield far better returns than to use that time to shave the cost of the project.

The danger in this discussion is that it sounds easy, but it is hard. Using valuation to justify a project is not the same as using valuation to select the project that will yield the highest return or structuring a project so that it produces the highest value. Creating a robust and stable funding environment will require the shattering of many legacy approaches and a willingness to abandon conventional wisdoms. The vision, courage, and capability of the community to adopt new perspectives as the nascent field of microgravity research forms will not only determine the resources available but can clarify the value this work contributes to our society globally.

The past 60 years of progress have laid the foundation, but a confluence of factors has placed us at a pivotal time in the history of microgravity science. The ability of the community to be more discerning observers, insightful advisors, persuasive advocates, and informed decision makers, will allow space-based research to move beyond the sound bites and the hype to the realization that marketing is not the same as market-making. Building a command of the dynamics of this market as you explore the dynamics of the microgravity environment will enable the construct of better projects and the making of more thoughtful policies. Godspeed and remember that the sky is no longer the limit, it is the stars.

## ACKNOWLEDGMENTS

The authors thank the staff of ProOrbis, LLC for assisting in the production of this paper and Miles O'Brien, Jeff Bingham, Charles Beames, and Lawrence Zanetti for their thoughtful insights and remarks.

## CONTRIBUTIONS

The authors collaborated on the concepts. J.M.D. developed the outline and she and J.M.O. developed sections based on their research. The authors edited the entire manuscript.

## COMPETING INTERESTS

The authors declare no conflict of interest.

## REFERENCES

- 1 Committee on Microgravity Research. *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies*. National Research Council, 2000.

- 2 National Aeronautics and Space Administration Microgravity Research Division. *NASA's microgravity research program 1998 annual report*. National Aeronautics and Space Administration, Report no. NASA/TM-1999-209757, 1998.
- 3 President Obama National Space Policy of the United States of America. The White House, 2010.
- 4 Office of the Inspector General. *NASA's efforts to maximize research on the international space station*. National Aeronautics and Space Administration, Report no.: IG-13-019 (8 July 2013). <http://oig.nasa.gov/audits/reports/FY13/IG-13-019.pdf>. Accessed 23 December 2014.
- 5 US Senate Committee on Commerce, Science & Transportation. The NASA Authorization Act of 2010. [http://www.commerce.senate.gov/public/index.cfm?p=Legislation&ContentRecord\\_id=8d7c1465-f852-4835-ba84-25faf56bbb36&ContentType\\_id=03ab50f5-55cd-4934-a074-d6928b9dd24c&Group\\_id=6eaa2a03-6e69-4e43-8597-bb12f4f5aede](http://www.commerce.senate.gov/public/index.cfm?p=Legislation&ContentRecord_id=8d7c1465-f852-4835-ba84-25faf56bbb36&ContentType_id=03ab50f5-55cd-4934-a074-d6928b9dd24c&Group_id=6eaa2a03-6e69-4e43-8597-bb12f4f5aede) Accessed 1 January 2015.
- 6 ProOrbis. *Reference Model for the International Space Station U.S. National Laboratory*. National Aeronautics and Space Administration, 2010.
- 7 National Aeronautics and Space Administration. Commercial crew program—the essentials, 2014. [http://www.nasa.gov/content/commercial-crew-program-the-essentials/#\\_U\\_ung\\_IdUn3](http://www.nasa.gov/content/commercial-crew-program-the-essentials/#_U_ung_IdUn3). Accessed 29 December 2014.
- 8 Hackler R, Wright R. *Commercial orbital transportation services: a new era in spaceflight*. National Aeronautics and Space Administration, Report no. NASA/SP-2014-617, 2014.
- 9 Center for the Advancement of Science in Space. *CASIS 2013 Annual Report*. CASIS, 2013.
- 10 Organization for Economic Co-operation and Development. *The Space Economy at a Glance 2014*. OECD Publishing: Paris; doi:10.1787/9789264217294-en, 2014.
- 11 Indian Space Research Organization Applications: Earth observation <http://isro.org/applications/earth-observation>, 2014. Accessed 29 December 2014.
- 12 National Science Foundation Science and Engineering Indicators 2014: Chapter 4 <http://www.nsf.gov/statistics/seind14/> Accessed 30 December 2014.
- 13 Kennedy JV. *The Sources and Uses of U.S. Science Funding*. The New Atlantis, 2012.
- 14 Goodstein DL. Richard P Feynman, teacher. *Phys Today* 1989; **42**: 70–75, at p. 73.
- 15 Keynes JM. *The General Theory of Employment, Interest, and Money*. Macmillan Cambridge University Press: Cambridge, UK Cambridge, UK, 1936.
- 16 Wilson JW, Ott CM, Höner zu Bentrup K, Ramamurthy R, Quick L, Porwollik S *et al*. Space flight alters bacterial gene expression and virulence and reveals a role for global regulator Hfq. *Proc Natl Acad Sci USA* 2007; **104**: 16299–16304.
- 17 Ma X, Pietsch J, Wehland M, Schulz H, Saar K, Hübner N *et al*. Differential gene expression profile and altered cytokine secretion of thyroid cancer cells in space. *FASEB J* 2014; **28**: 813–835, 2014.
- 18 Isaacson W. *Einstein His Life and Universe*. Simon & Schuster: London, UK London, UK, 2007.
- 19 Dunbar B Technology Readiness Level <http://www.nasa.gov/content/technology-readiness-level/> Accessed 30 December 2014.
- 20 Food and Drug Administration Critical path initiative <http://www.fda.gov/ScienceResearch/SpecialTopics/CriticalPathInitiative/ucm076689.htm> Accessed 30 December 2014.



This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder to reproduce the material. To view a copy of this license, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>