International Academy of Astronautics
Cosmic Study 3.17

Space Mineral Resources
A Global Assessment
Challenges and Opportunities

Art Dula, Editor

Briefing for the ISECG
Cologne, Germany
October 8, 2015

ISECG
International Space Exploration Coordination Group

1. Background
2. Study description
3. Principal finding
4. Major conclusion
5. Specific findings
6. Recommendations
7. Back up slides

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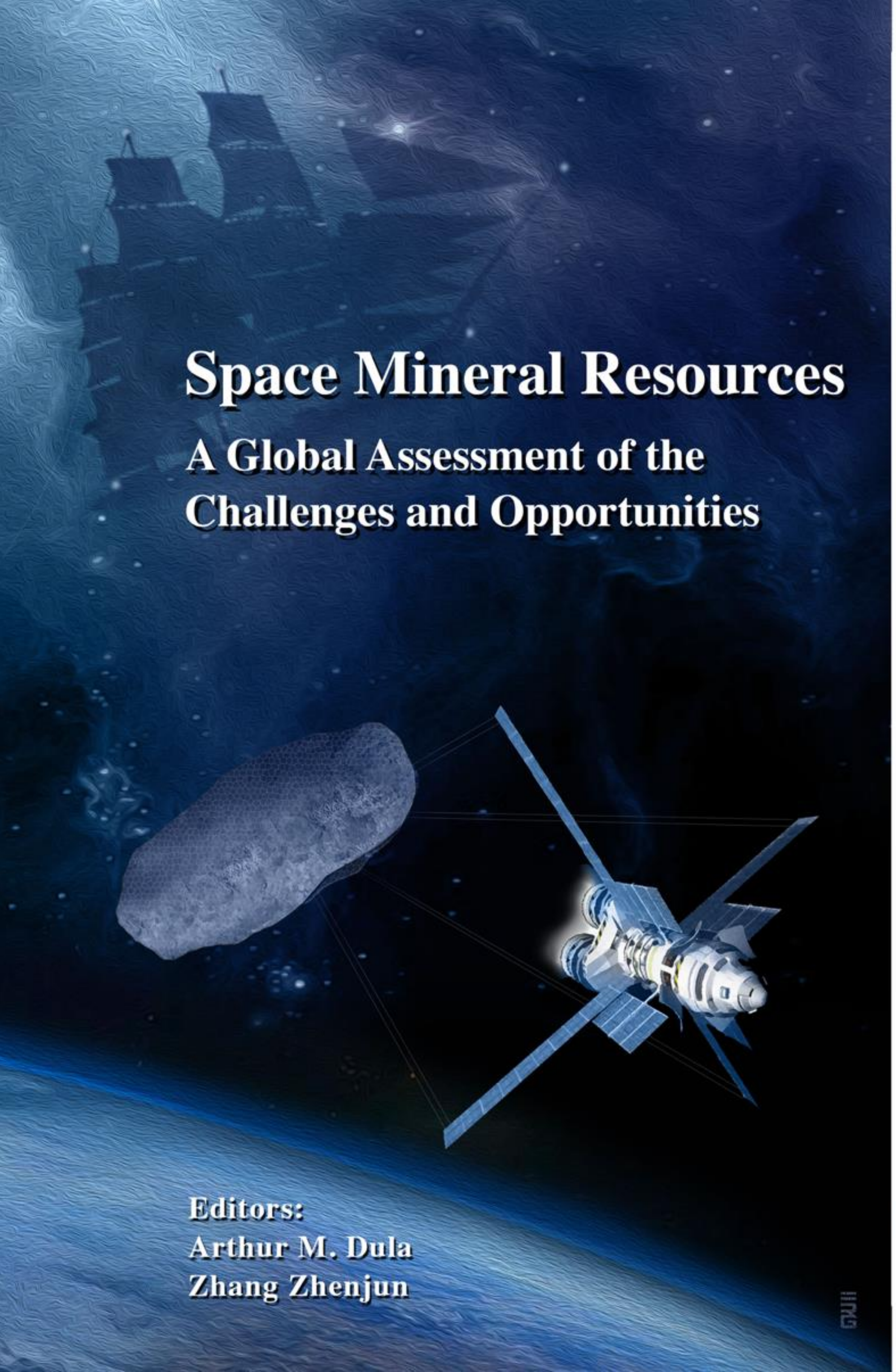

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Purpose of the study as approved by the Scientific Commission of the International Academy

To provide, in one document, the current state of the art of the technology, economics, law & policy related to Space Mineral Resource opportunities and to make recommendations for moving forward.

To provide a logical, systematic and practical road map to promote and encourage near term evaluation, development and use of space mineral resources.

No comprehensive summary of the current literature on this subject is now publicly available. This IAA study is the first comprehensive study of the subject; and, thus it should be of significant value to its development for the benefit of humanity.

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11 organizations provided study content

Heinlein Prize Trust
U.S. National Space Society
International Space Development Conference
Texas A&M University – Aerospace Engineering Department
European Space Conference – Turino
Newspace Conference
International Space University
International Space Elevator Consortium
Chinese Society of Astronautics
Canadian Space Society
Australian Space Society

5 firms provided business road maps

Moon Express
Excalibur Exploration Limited
Deep Space Industries
Ad Astra Rocket Company
Shackleton Energy Corporation

Organization:

This study is organized to provide technical information, policy and legal analyses, economic context and opportunity analyses, and recommended steps for moving forward. Finally, an international roadmap showing pathways forward is offered. Following this roadmap will maximize the rate and likelihood of SMR development, as well as have the corollary benefit of saving humanity from one or more potential civilization or species-ending disasters. The layout of the study report is structured across a logical sequence:

First – Set the stage; general background and then “how to mine.”
Second – Describe the market and potential roadmaps to profit
Third – Look at the technologies necessary to achieve success
Forth – Conduct analysis between choices
Fifth – Assess the legal, policy and governance issues
Sixth – Summarize conclusions and recommendations

Chapter 1 Introduction: This chapter shows the ideas expanded upon throughout the document, as well as, a description of space mineral resource approaches and a listing of the types of resources being sought. In addition, some quick insights are shown to set the stage for the rest of the report.

Chapter 2 Mining of Space Resources: This chapter sets out the mineral content of likely locations for mining and processing materials as well as discussions of the processes and the technological equipment needed. Asteroids have tremendous potential; but, each is different and needs to be understood prior to approaching. Planetary surfaces provide a spectrum of mineral resources; but, where and how to develop them is the question.

Chapter 3 Market Approach: This chapter examines financial approaches to ensure commercial success. Economic models will look at not only the value of the minerals to be mined, but the investment required to get there, provide mining facilities, store the resources, and then transport them to the customer.

Chapter 4 Roadmaps for SMR Development: This chapter provides an understanding of “how to” achieve commercial viability on space mineral resource development, four company SMR roadmaps will be shown to lay out the approaches that each of these companies has taken.

- Deep Space Industries
- Shackleton Energy Company
- Excalibur Exploration

Chapter 5 Quick Look at SMR Systems: This chapter analyzes the systems aspects of these solar system level ventures. It will help identify the various risks that much be understood and mitigated. Technologies will be assessed as to their level of readiness for space with the traditional NASA Technology Readiness Level [TRL] approach and rating. In the end, this will assess the technological feasibility of the effort to provide a profit for SMR commercial ventures.

Chapter 6 Modeling and Analysis: This chapter looks at the needs of commercial venders in understanding the issues. In addition, the modeling and analyses will help ventures understand where to invest near term funding to create a successful venture.

Chapter 7 SMR Policy, Legal and Other Considerations: This chapter analyzes international treaties and policies around the world for operations in space.

Chapter 8 Findings, Conclusions & Recommendations: This chapter consolidates the findings and lead to the report's conclusions and recommendations.

Chapter 9 Concept for the Future – Water is the Currency for Space: This is a brief extrapolation towards the future recognizing the importance of mining water.

Principle Finding:

SMR ventures cannot wait for government programs to lower technological and programmatic risks. Commercial ventures must determine the optimum path for commercial success and aggressively lead the way beyond low Earth orbit (LEO). During the first half of the 21st century, space leadership will come from commercial enterprises and not depend upon government space programs. One concept that would leverage this series of initiatives is to convince government agencies that commercial enterprises will be there first and will be able to support government explorations by selling products to them at designated locations.

Major Conclusion:

Members of the study group found that mining space mineral resources will enable economic travel between the Earth’s surface and near-by locations within our solar system. The process of mining water from asteroids, the Moon or Mars will ensure that key elements are available at the spaceports of the future. Water will ensure that human exploration will expand beyond low Earth orbit with the profit motive driving the exploitation of resources.

With this conclusion, the following is supported.

Finding 1: Technical

Technological risk reduction and engineering design: The mining of asteroids and lunar regolith is within the current state of the technical art. The extrapolation of Earth-based mining seems to be a one-for-one trade with some significant alterations due to vacuum, low gravity and temperature extremes. Many proposed solutions have been suggested and tested [on Earth] leading to positive conclusions on this topic.

Finding 2: Economic:

Financial aspects of any activity focuses upon the initial lift to orbit costs. Low cost access to space will enable space mineral resource utilization. Reducing cost of delivery to an EML-1 Lagrangian spaceport by two orders of magnitude will ensure that commercial entrepreneurs will spring up and pursue the vast opportunities then available.

Finding 3: Legal

Although space is inherently multi-national and international in its scope, experience indicates that national laws are the only framework that individual actors, both private and governmental, will accept as a means for specifically developing and acting in space. Mining and ownership of space mineral resources is parallel to national laws and, as such, is consistent within current international law. International space law has established that national laws govern national activities in outer space within the current framework. History has repeatedly demonstrated that areas controlled primarily by national, as opposed to international, law prosper most readily.

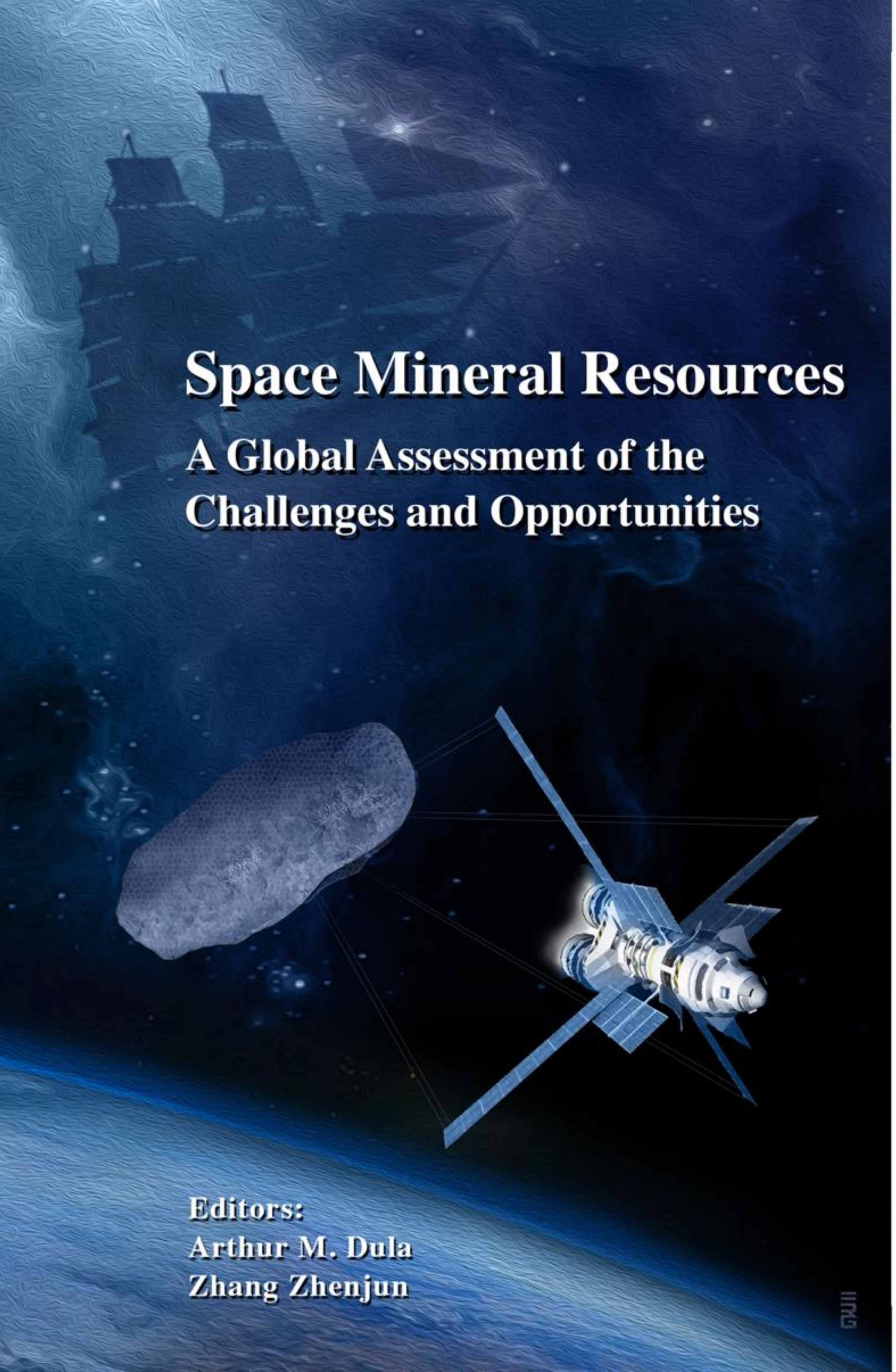
Finding 4 – Publication of this study during 2015 is timely because interest in space mineral resources is growing. Recent events include:

A – “The Economics of NEOs:” A workshop held at NASA's Ames Research center in September 2014 with the aim: “… to serve as a catalyst for discussions and to foster collaborations between industry, academia and government.” Its summary is included in the study as an appendix.

B – “Space Mineral Resources Governance:” A meeting held in the Hague on December 1, 2014, resulting in the formation of “The Hague Space Resource Governance Working Group."

C – “Towards the Use of Space Resources:” A follow-on meeting to the NASA Ames workshop held by the Minister of Economics of the Luxembourg in March 2015 to discuss the relationship and needs of commercial ventures and parallel government activities. Much of the discussion focused on risk identification and investment vs. technological readiness level.

A key feature of Finding #4 is that commercial space ventures are currently aggressively investing in risk reduction and reaching out to form commercial and governmental partnerships. These types of actions, in the past, led to development of major new industries. It is reasonable to expect that this will happen in space industry.



International Academy of Astronautics

Recommendation

Develop technologies, corporations and government relationships to support the following action plan.

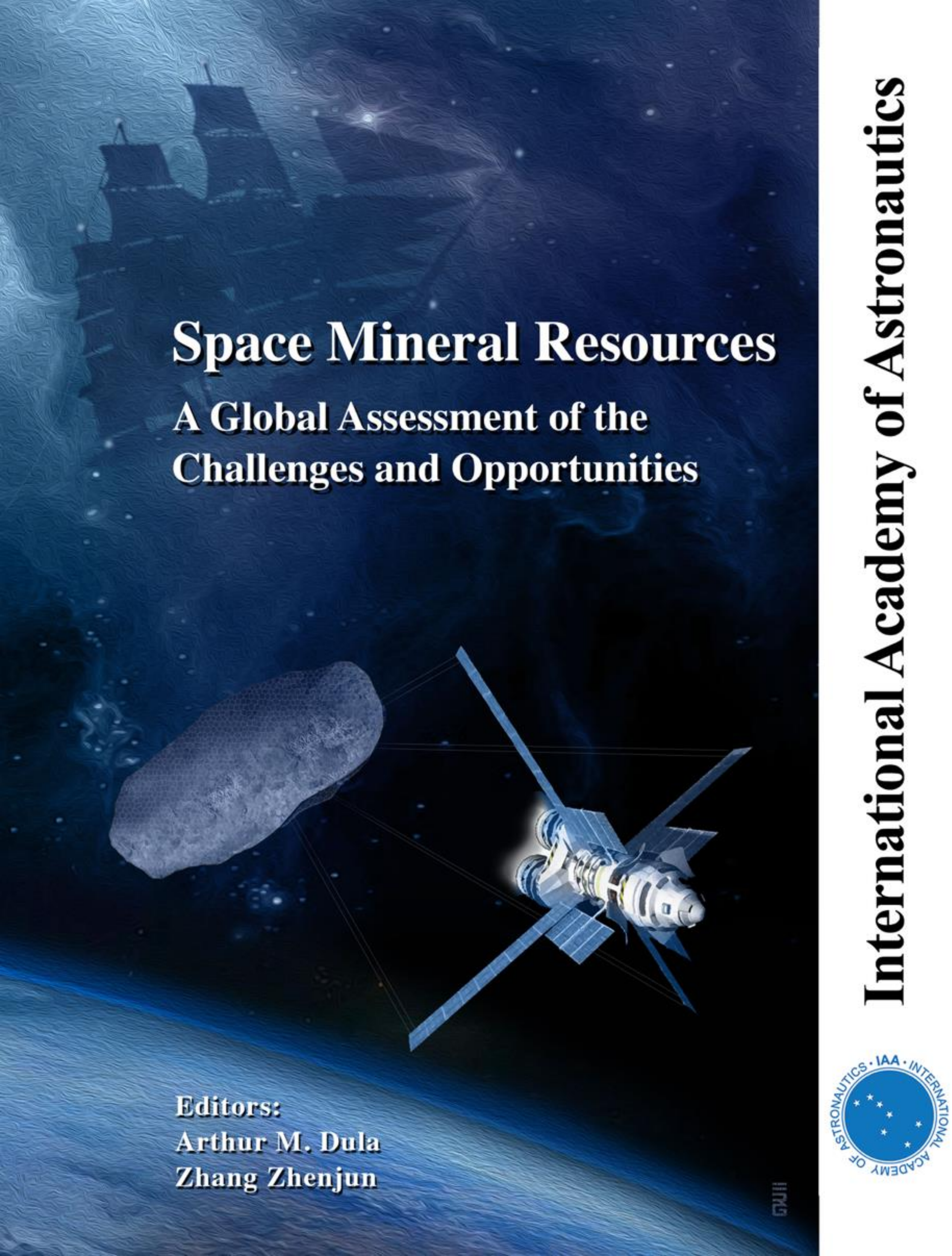
Phase One: Initiate the business infrastructure on Earth 2014-2020

Phase Two: Execute prototype flights to potential asteroids as well as testing hardware in LEO 2015-2022

Phase Three: Initiate mining operations with sale of product 2018-2029

Expected Results: Selling water at the Earth-Moon Lagrangian Point #1.

Examples of technology development are given in the back up slides.



The participants acknowledge that this study is only a beginning.

A second IAA study on this subject has already begun.

The participants hope that their work will be of value to those who follow.

Thank you for your attention.

For more information please contact

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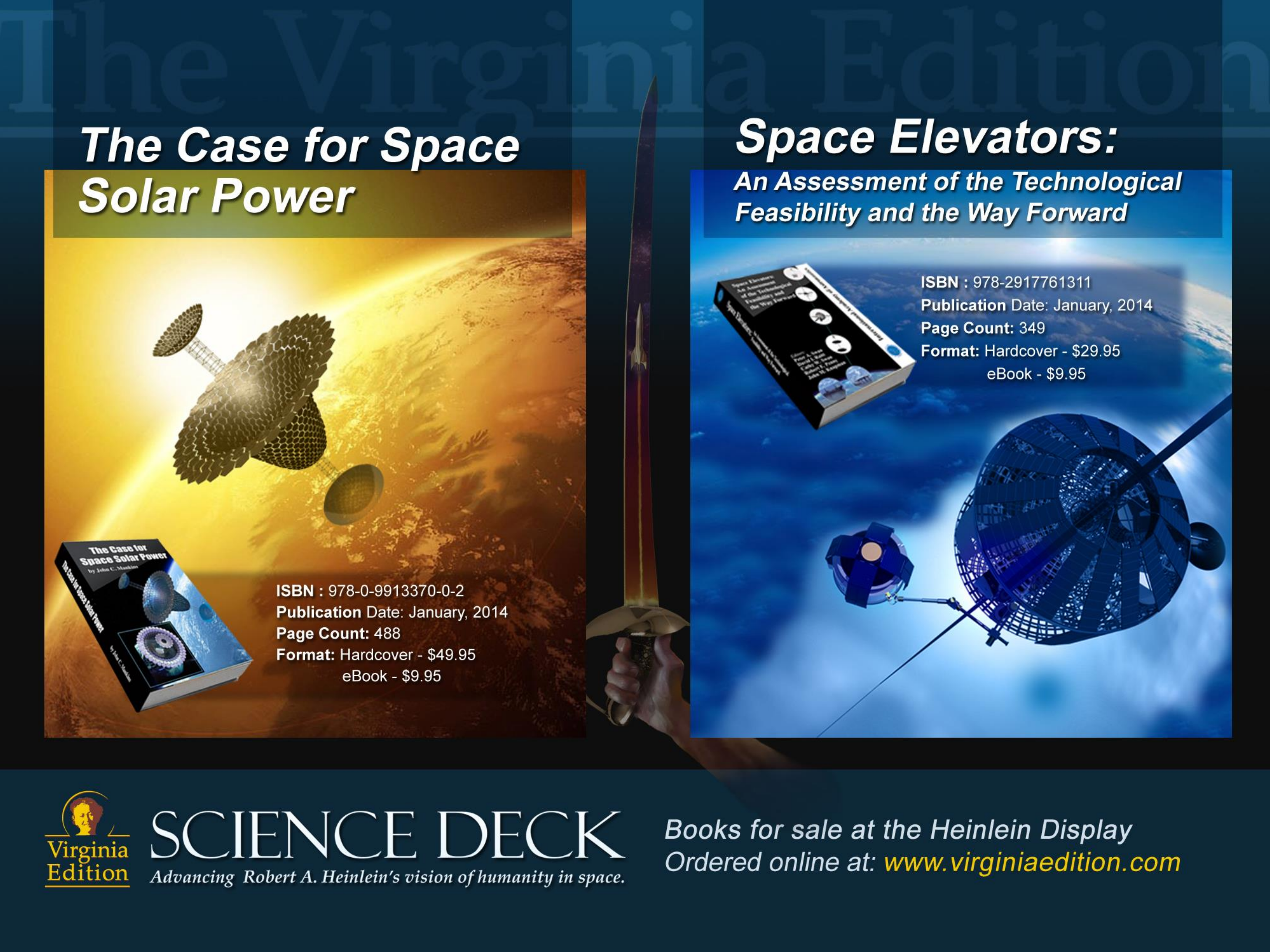
Copies of the hardbound or electronic editions of this study may be purchased at www.heinleinbooks.com


The Virginia Edition
The Case for Space Solar Power
ISBN : 978-0-9913370-0-2
Publication Date: January, 2014
Page Count: 488
Format: Hardcover - $49.95
eBook - $9.95
Space Elevators:
An Assessment of the Technological Feasibility and the Way Forward
ISBN : 978-2917761311
Publication Date: January, 2014
Page Count: 349
Format: Hardcover - $29.95
eBook - $9.95
Virginia Edition
SCIENCE DECK
Advancing Robert A. Heinlein's vision of humanity in space.
Books for sale at the Heinlein Display
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Back Up Slides

1. Technology development example: U.S. commercial innovation assisted by NASA: Trans Astro Corporation's research work on optically mining asteroids and solar thermal propulsion.

2. Technology development example: European private innovation: Excalibur Exploration Limited's private ground and space research work for risk reduction for in situ processing of metal asteroid regolith for nickel.

3. Development Example: UK-Indian cooperative commercial research. Astrome Technology Pvt. Ltd. results on a patent pending reentry technology for safely landing large payloads on the Earth’s surface.

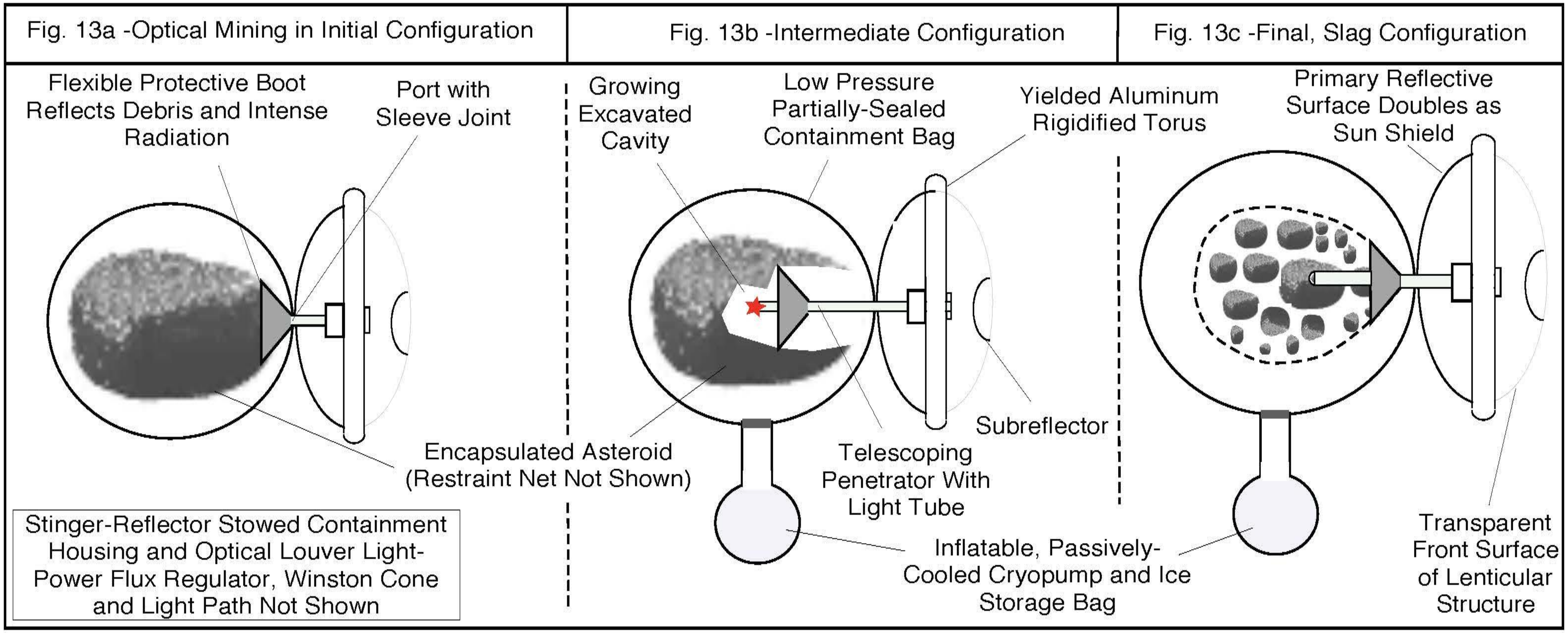
4. The Heinlein Prize Trust's large scale economic context for the development of space resources.

Any sufficiently advanced technology is indistinguishable from magic.

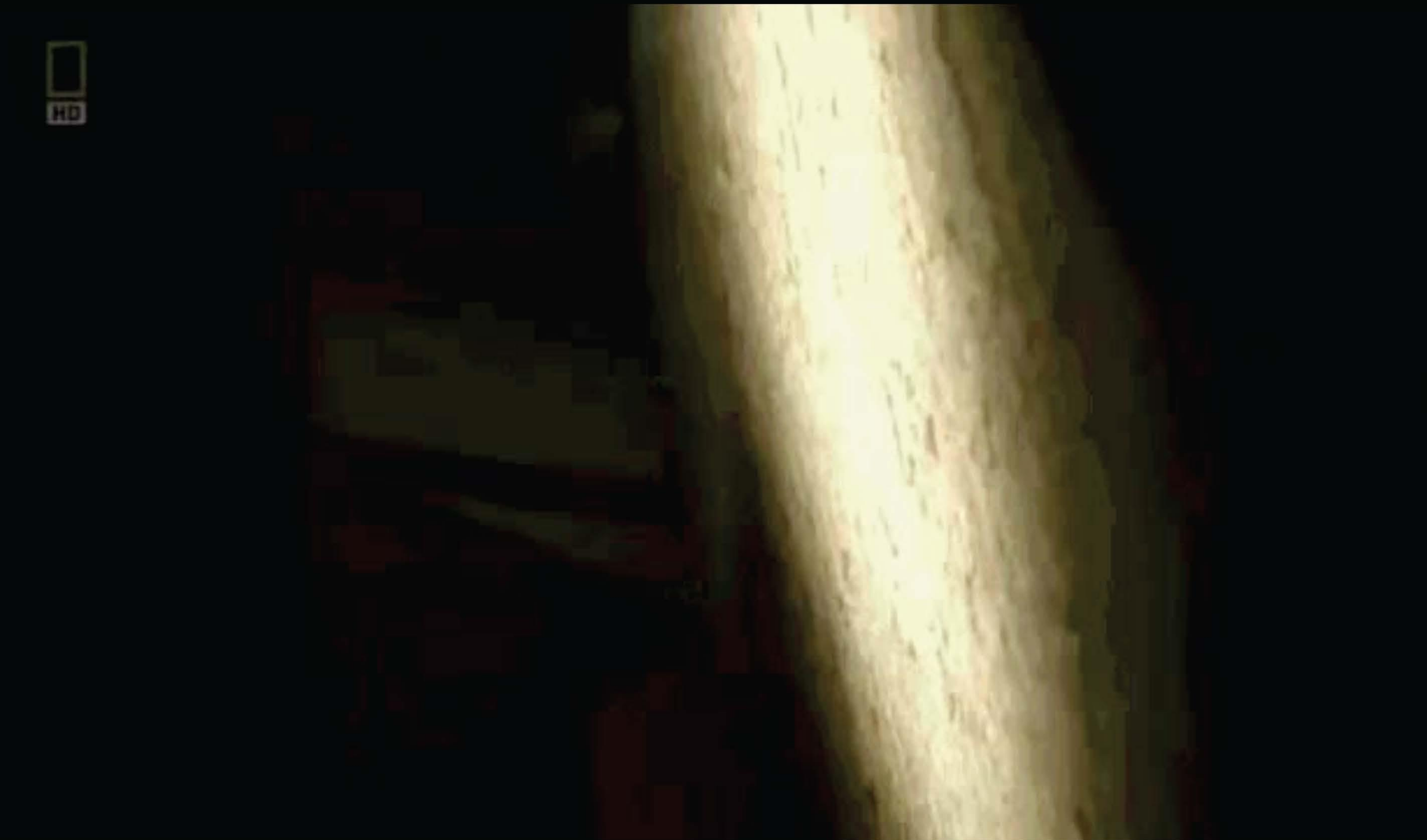
Arthur C. Clarke

One man's 'magic' is another man's engineering. 'Supernatural' is a null word.

Robert A. Heinlein



The Trans Astra Corporation has developed a new patent pending invention called “optical mining” – a way to excavate and process asteroids using sunlight. Space News called this invention "a possible game changer for space exploration." *The ability to tap mega-amounts of water from asteroids could be used directly as propellant in solar thermal rockets to provide inexpensive space transportation."* **The ground research into this new concept is funded by private capital and government contracts from NASA and others.**



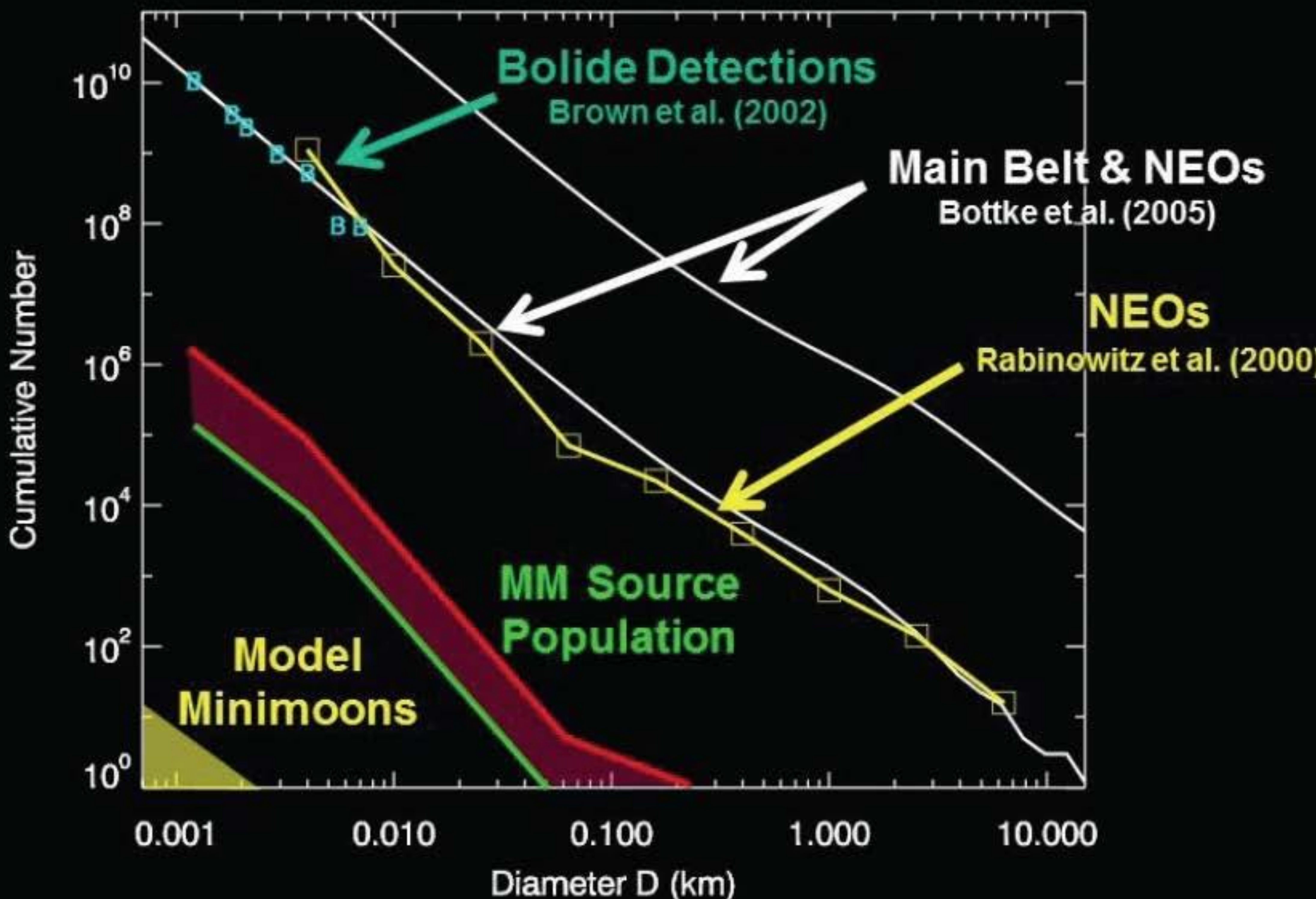
What Happens When Highly Concentrated Sunlight Hits An Asteroid-Like Rock?

Heating a CI Chondrite

37 Optical Mining Tests Have Been Completed

Test #	Sample Type	Form	Result	Test #	Type	Form	Result
1	Serpentine	Block	preparatory	20	Tray	None	Control
2	Serpentine	Block	preparatory	21	Lizardite	Thin slice	Floatation
3	Serpentine	Block	preparatory	22	UCF Simulant 2	Thin slice	Off gassing
4	Lizardite	Block	Particle spalling	23	UCF Simulant 2	Block	Preparation test
5	Lizardite	Block	Explosive fracturing	24	UCF Simulant 2	Block	Preparation test
6	Lizardite	Thin slice	Floatation	25	Lizardite	Block	Floatation
7	Murchison	Thin slice	Floatation	26	Lizardite	Block	Preparation test
8	Serpentine	Thin slice	Control	27	UCF Simulant 2	Powder	Cancelled
9	Anorthosite	Thin slice	Control	28	Lizardite	Block	Floatation
10	Harzburgite	Thin slice	Control	29	Lizardite	Block	Irradiance Testing
11	Serpentine	Thin slice	Control	30	Lizardite	Block	Irradiance Testing
12	Serpentine	Thin slice	Control	31	Lizardite	Block	Particle spalling, Floatation
13	Murchison	Thin slice	Floatation	32	UCF Simulant 2	Block	Spalling
14	UCF Simulant	Thin pieces	Melting	33	UCF Simulant 2	Block	Spalling
15	UCF Simulant	Block	Off gassing	34	UCF Simulant 2	Block	Cryotrapping
16	Jbilet	Block	Off gassing	35	UCF Simulant 2	Block	Cryotrapping
17	Lizardite	Thin slice	Floatation	36	Murchison	Block	Cryotrapping, Particle spalling
19	Ceramic Base	none	Control	37	Lizardite	Asteroid Regolith	Spalling/Floatation plume

Asteroid Source Populations



Volatile Materials in Asteroids

- 10 to 50% of known large asteroids are likely hydrated CI-CM-like, possibly parent bodies of CI-CM chondrite meteorites

- CI-CM chondrites are typically 10-20% water by weight in the form of hydrated minerals with significant other volatile (e.g. CO2) content that can be thermally extracted

- CI-CM materials are friable and may be in rubble piles with regolith or in blocks on asteroids.

Typical CI and CM Chondrite Meteorite Properties*

Meteorite	Class	Water (wt%, ref.)	Porosity (vol %, ref.)	Bulk Density (g/m^3, ref.)
Alais	CI	19.62, 1, 2, 3		
Ivuna	CI	43.47, 1		
Orgueil	CI	16.9, 2	11.3, 3	2.11±0.12,3
ALH 81302	CM	12.94, 2		
ALH 83100	CM	13.38, 2		
Benten	CM	10.7, 2		
Cold Bokkeveld	CM	15.3, 1	12.9, 3	2.31, 3
Erakot	CM	19.26, 1		
Essebi	CM	9.9, 1		
Haripura	CM	36, 1		
Mighei	CM	2.16, 1	28.2, 3	1.94±0.03, 3
Murchison	CM	10.09, 2	17.1, 3	2.37±0.02, 3
Murray	CM	12.51, 1		
Nawapali	CM	16.56, 1		
Santa Cruz	CM	10.44, 1	30.3, 3	1.79, 3
S. Boriskino	CM	0.99, 1		
Yamato 791824	CM	12.5, 2		
Yamato 793321	CM	9.23, 2		

References:

1 Wiik (1969)

2 Jarosewich (1990)

3 Britt and Consolmagno (2005)

*Data tabulated by Derek Sears
Space Science and Astrobiology Division, NASA Ames Research Center
Personal Communication

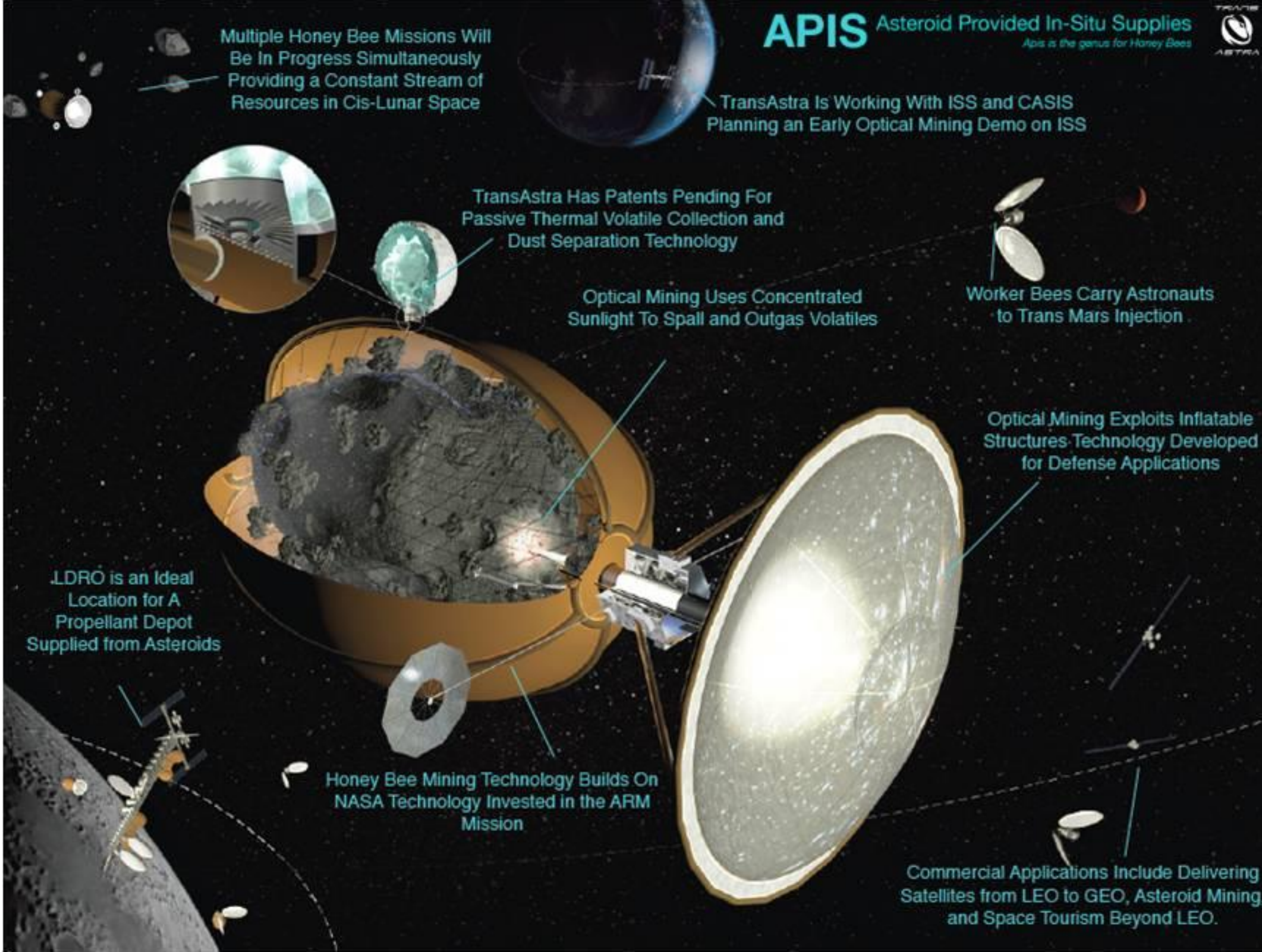

APIS Asteroid Provided In-Situ Supplies
Apis is the genus for Honey Bees
Multiple Honey Bee Missions Will Be In Progress Simultaneously Providing a Constant Stream of Resources in Cis-Lunar Space
TransAstra Is Working With ISS and CASIS Planning an Early Optical Mining Demo on ISS
TransAstra Has Patents Pending For Passive Thermal Volatile Collection and Dust Separation Technology
Optical Mining Uses Concentrated Sunlight To Spall and Outgas Volatiles
Worker Bees Carry Astronauts to Trans Mars Injection
Optical Mining Exploits Inflatable Structures Technology Developed for Defense Applications
LDRO is an Ideal Location for A Propellant Depot Supplied from Asteroids
Honey Bee Mining Technology Builds On NASA Technology Invested in the ARM Mission
Commercial Applications Include Delivering Satellites from LEO to GEO, Asteroid Mining and Space Tourism Beyond LEO.

Fig. 3 – ΔV's Between Nodes in a Transportation Network Supporting NASA and Industry. Impulsive ΔV's Overwritten on Black Lines, ΔV's With Aerobraking or Aerocapture On Red Lines

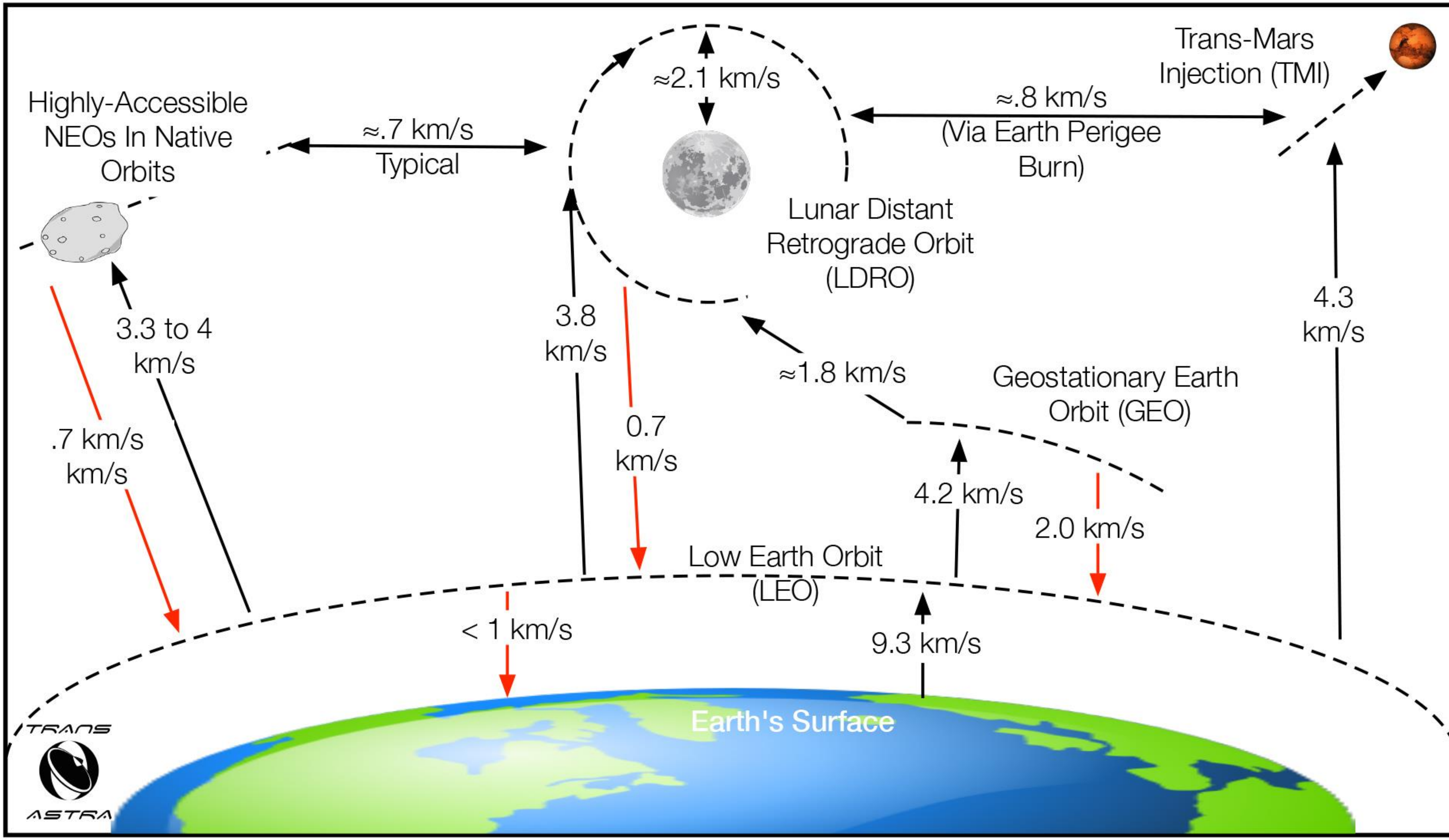


Fig. 2 – Figure from a Paper in *Nature* Showing A Large Population of NEOs Far More Accessible Than the Moon (Binzel 2014)

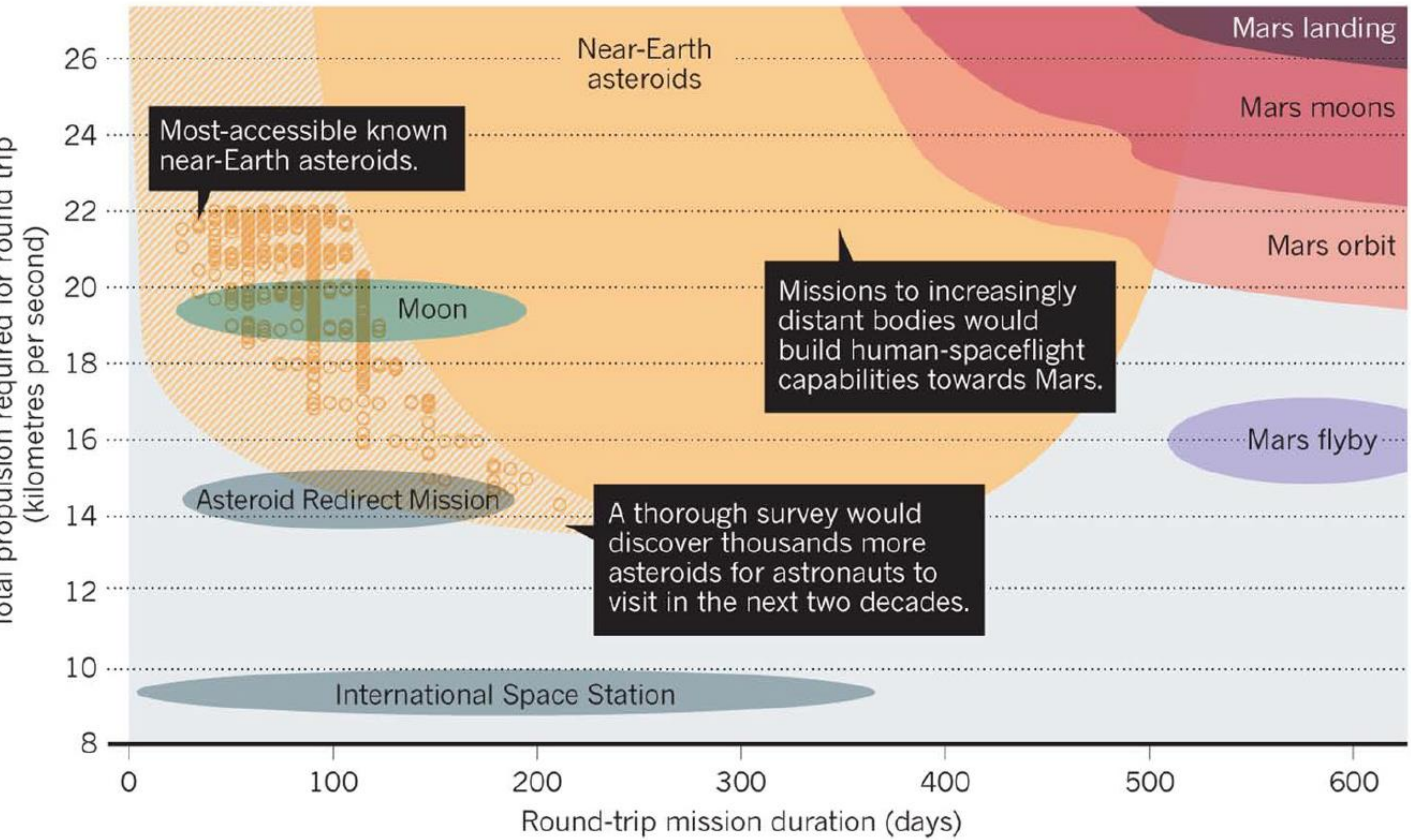


Fig. 1 – The Tyranny of Space Launch and Transportation Costs

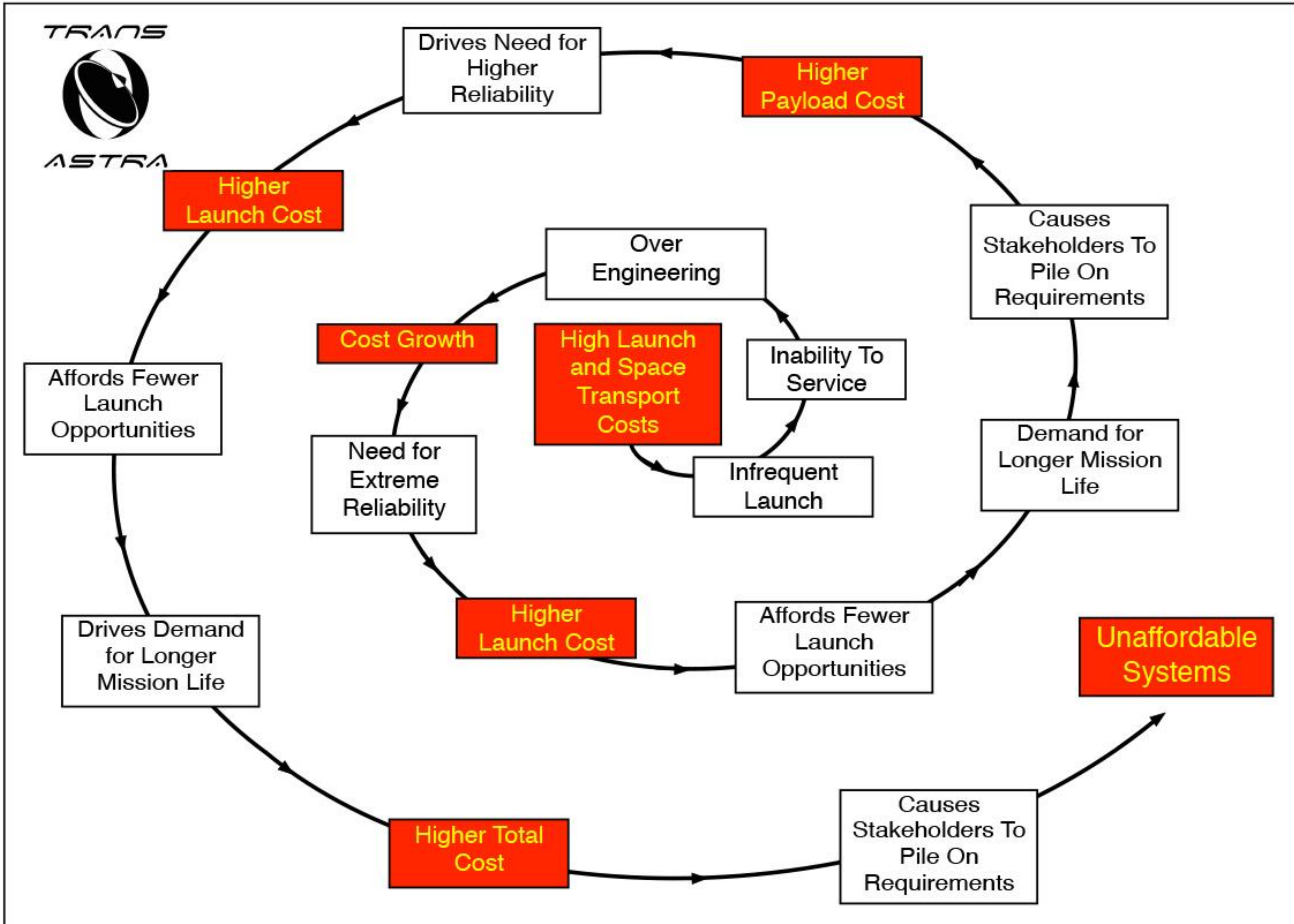


Fig. 4 – NASA Cost Analysis Comparing NASA's Predicted Cost vs. SpaceX Falcon 9 Actual Costs: >10X Cost Reduction (NASA 2011)

		NASA Model Based Prediction				SpaceX Actual Performance		
		NASA Approach				Firm Fixed Price Acquisition		
Elements	Weight (lbs)	DDT&E (FY2010 $M)	Flight Unit (FY2010 $M)	Total (FY2010 $M)	Weight (lbs)	DDT&E (FY2010 $M)	2 Test Flt Units (FY2010 $M)	Total (FY2010 $M)
Stage One (Including Engines)	39,080	$1,535	$206	$1,741	39,080	$188.7	$109.3	$298.0
Stage Two (Including Engine)	6,520	$608	$44	$651	6,506	$89.0	$23.6	$112.6
Fee (12.5%)		$268	$30	$298		$0.0	$0.0	$0.0
Program Support (10%)		$241	$21	$263		$0.0	$0.0	$0.0
Contingency (30% Vehicle, 10% Engine))		$674	$68	$741		$0.0	$0.0	$0.0
Vehicle Level Integration (8%)		$258	$24	$282		$22.2	$10.6	$32.8
Total	**45,600**	**$3,584**	**$393**	**$3,977**	**45,586**	**$299.9**	**$143.6**	**$443.4**

>10X Cost Reduction

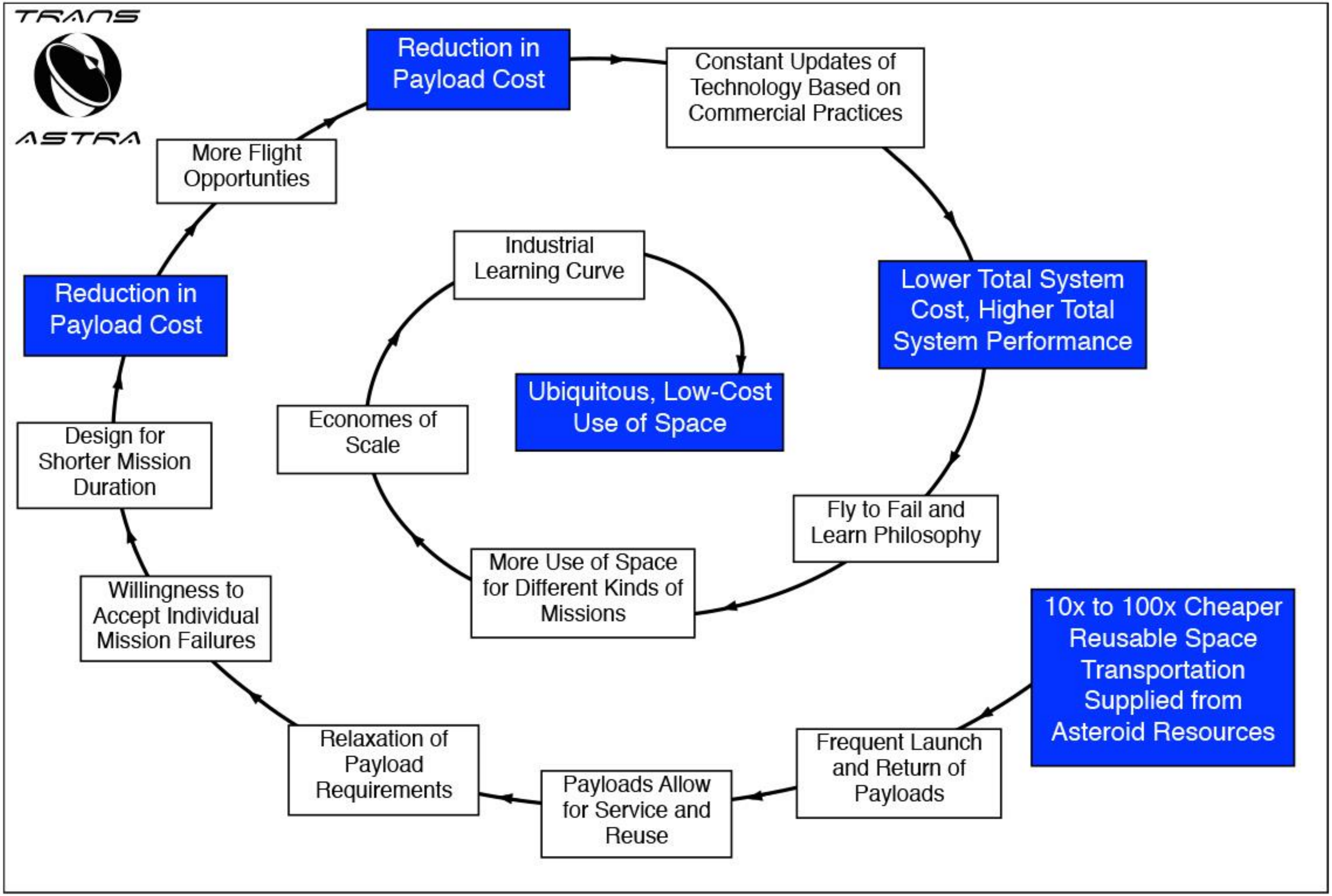
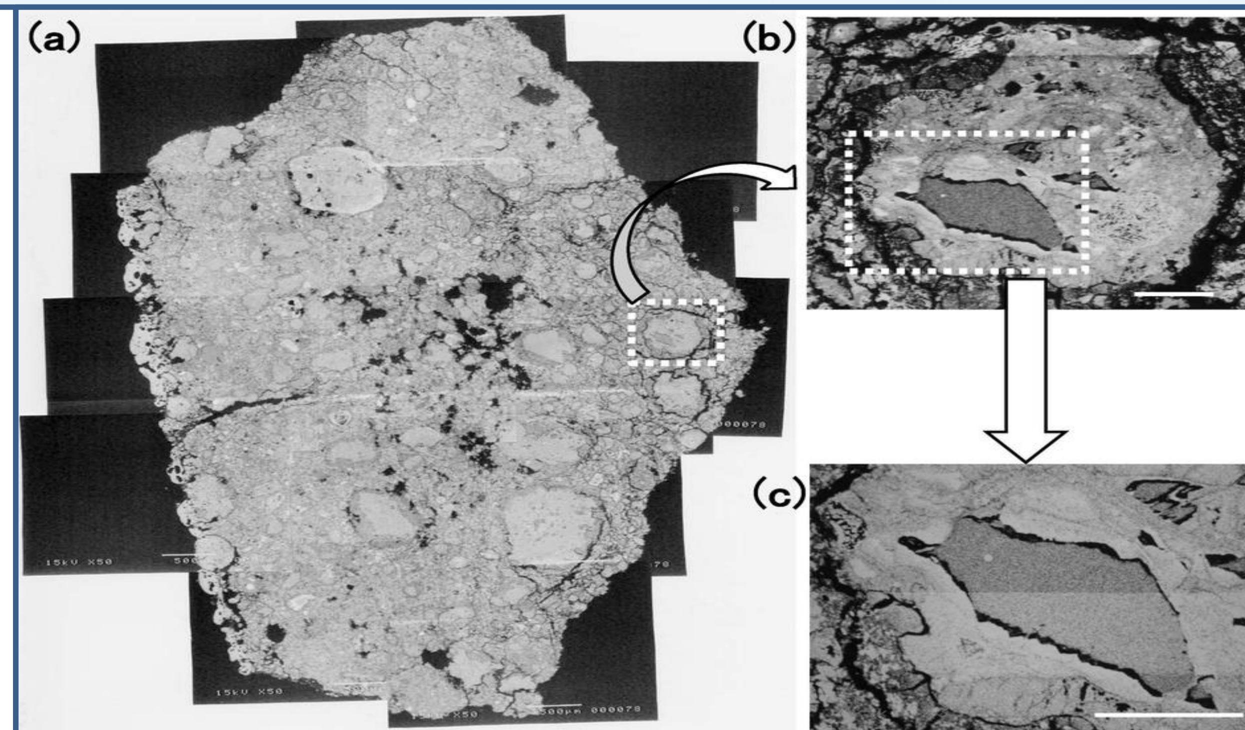


Fig. 7 – Reversing the Cycle of Cost Grow To Make Affordable Exciting Missions of Exploration and Whole New Industries in Space

Examples of Asteroid SMR Technology identified for ground testing with ISU/university partners that could be flight tested on the Almaz ROSS laboratory

Ground Demo: Meteorite Chemistry

The terrestrial meteorite inventory could help us to experimentally understand the influence of asteroid chemistry mineralogy and diversity on basic processing choices



Research Highlights

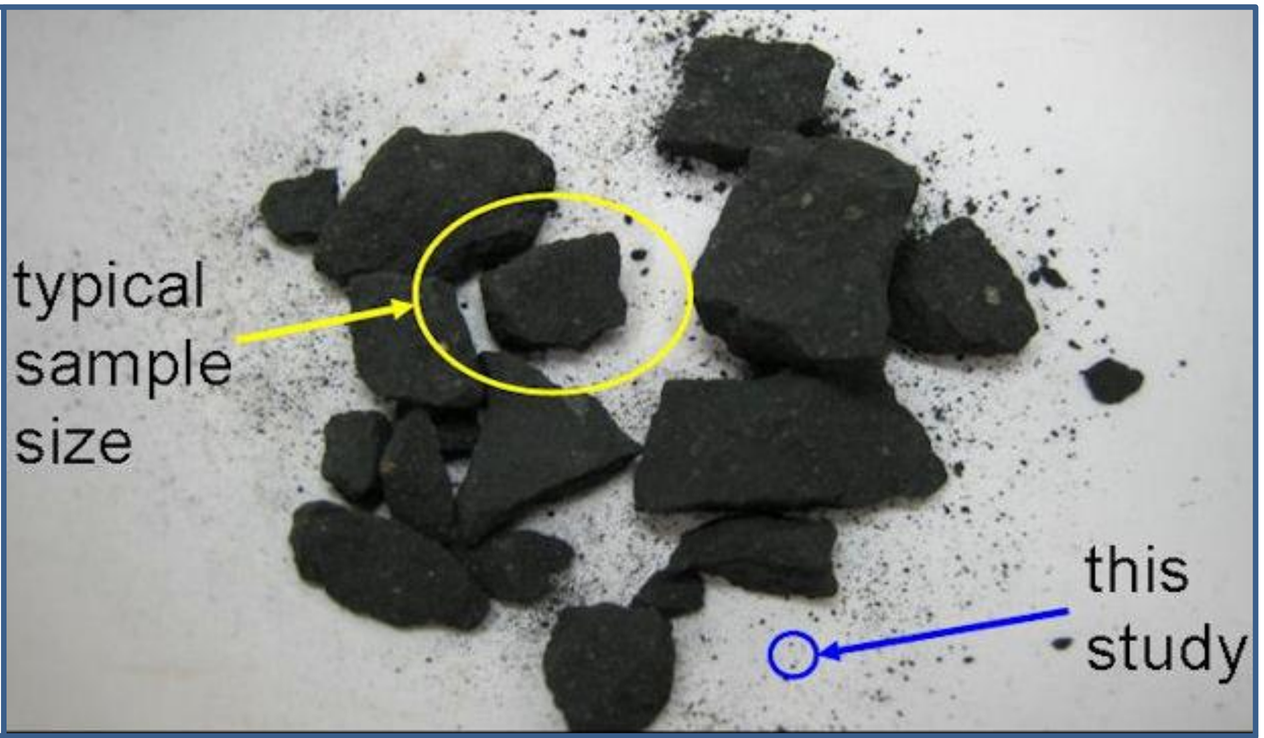
- Meteorite samples represent a random sampling of asteroid chemistry and mineralogy
- Design and development of chemical processes can leverage meteorite diversity to discern robustness and generality

Benefits and results

- Develops a heuristic for process applicability vs. asteroid class
- Demonstrates **how** generalized a specific process can be
- Could prove that a process will work for any class of asteroid

Ground Demo: Fragmentation

Process efficiency is a function of surface area for mineral/gas interactions. The fragmentation state of asteroid regolith is a key variable in predicting process reaction kinetics and warrants significant research focus.



Research Highlights

- Inputs and process
  - meteorite samples
  - crushing and grinding
- Measure and modeling
  - fragmentation state
  - reaction rates and kinetics

Benefits & Results

- Can measure the influence of surface area on reaction kinetics
- Highlights the advantage of rubble piles vs boulders
- Creates exploration targets for remote sensing spacecraft

Ground Demo: Meteorite Digestion

Carbon monoxide could be used to dissolve nickel, iron and cobalt from a wide variety of meteorites to discern process dynamics – but this needs to be verified in the lab

Research Highlights

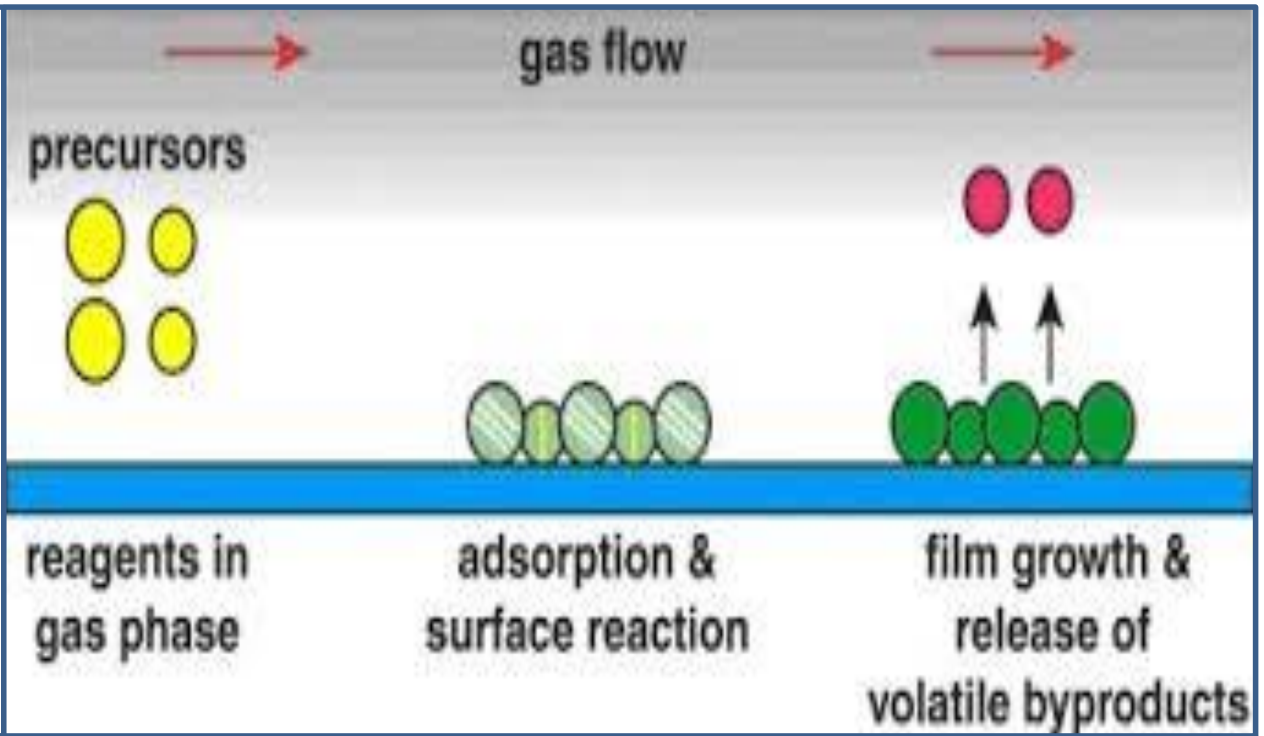
- Digestion of asteroid nickel can be demonstrated on the ground using existing meteorite samples
- Carbonyl process efficiency and reaction kinetics can be directly measured to show process robustness and generality

Benefits and results

- Develops a heuristic for process applicability vs. asteroid class
- Demonstrates **how** generalized the carbonyl process can be
- Could prove that the process will work for any class of asteroid

Ground Demo: Nickel Deposition

Solid materials (particles, thin films, shells or wires) can be deposited on a substrate by a gas phase reactive species – this is a process known as chemical vapor deposition



Research Highlights

- demonstrate nickel metal deposition as precursor gases travel over a heated substrate

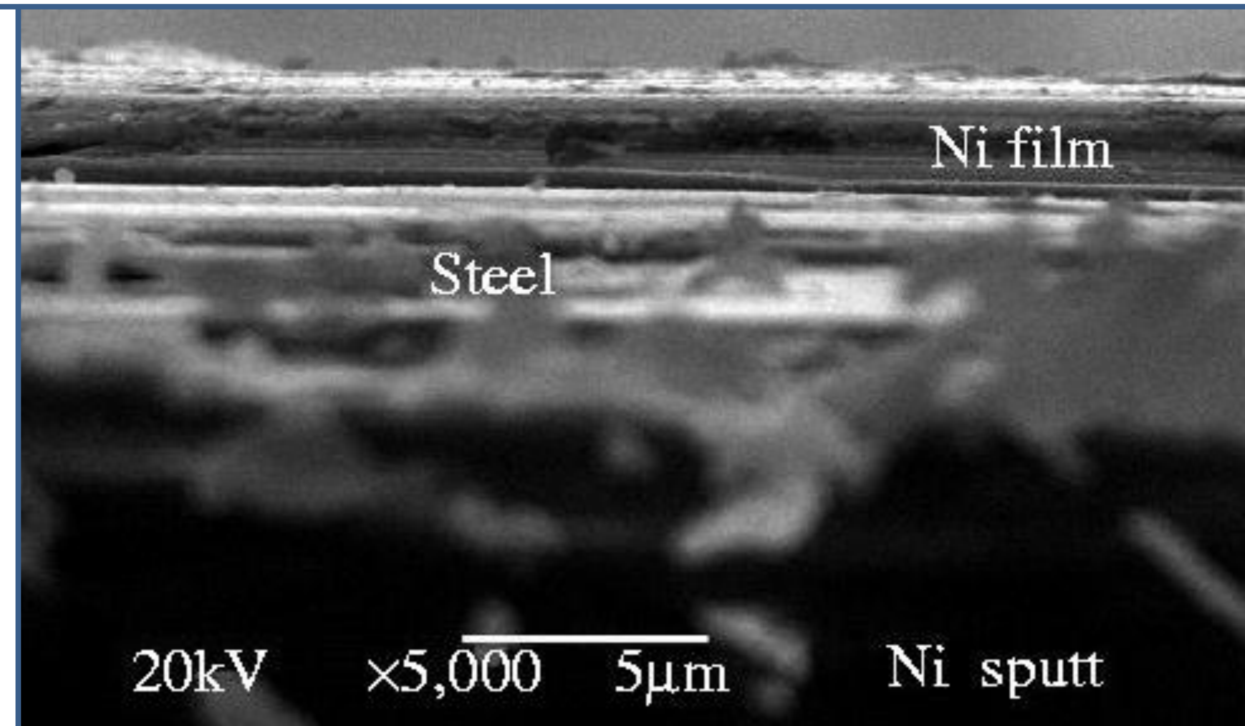
Key process variables

- temperature, partial pressure of precursor and byproduct gases

- Demonstration of the Mond process for nickel deposition would raise the TRL of candidate asteroid processing technology
- This demo would be particularly useful if the precursor gas were derived from meteorite samples

Ground Demo: Forms & Substrates

The chemical vapor deposition (CVD) process converts a gas to solid phase across an interface called a substrate. This substrate can be any arbitrary shape.



Research Highlights

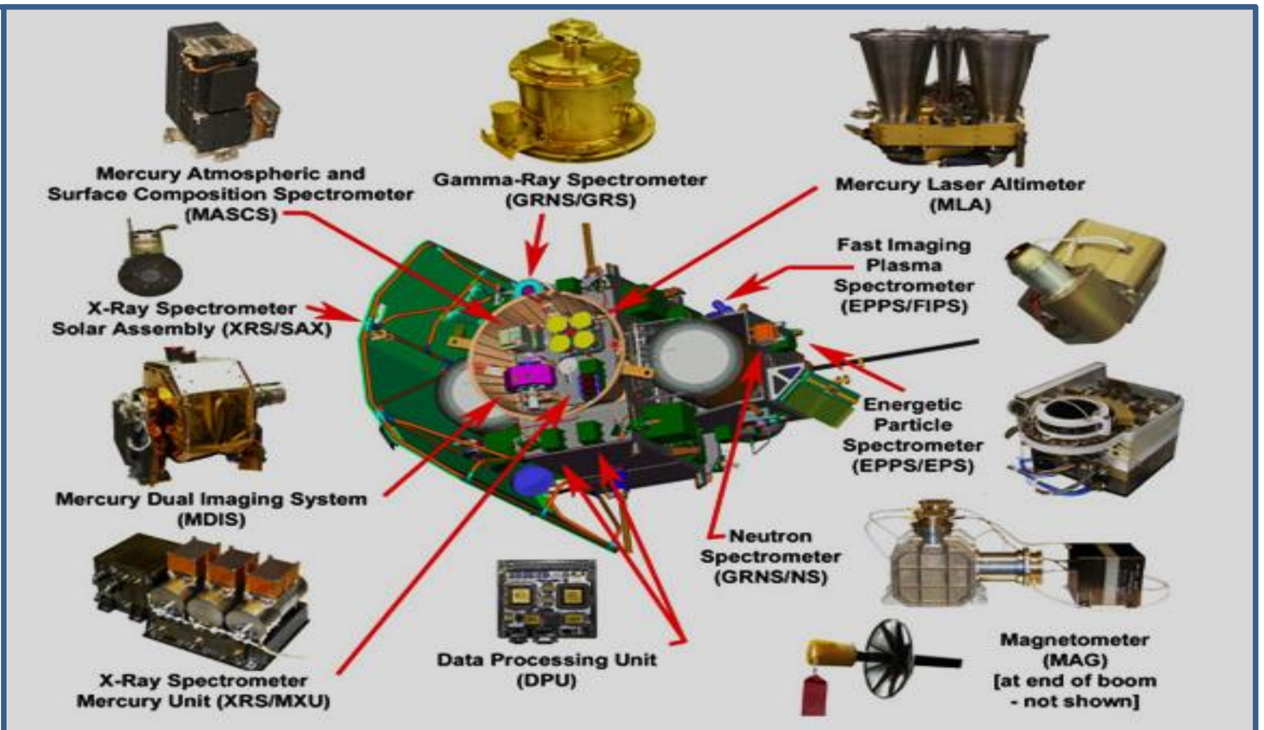
- develop and demonstrate CVD of nickel onto a substrate designed for and suitable for use in space
- extend demonstration of CVD to a form or shape that would have utility for a space application

Benefits and Results

- CVD of thin or thick films of nickel could demo breakthroughs for in-space additive manufacturing
- Sourcing the nickel carbonyl gas from a meteorite would add to the value of the press release

Ground Demo: Sensing & Control

The path from laboratory to spacecraft instrument can be long and tortuous – a proper sensing and control strategy can maximize asteroid in-situ process effectiveness



Research Highlights

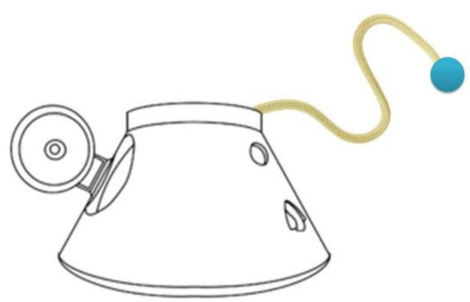
- determination and measurement of process control parameters

Key process variables

- temperature, partial pressure vs. chemical species, dynamic state of gas and solid phases

Benefits and Results

- Autonomous control is critical given 10min+ teleop delays
- Effective process control strategy starts with ground demos
- Dynamic process optimization could result from this research



Reentry using Skipper Tether System

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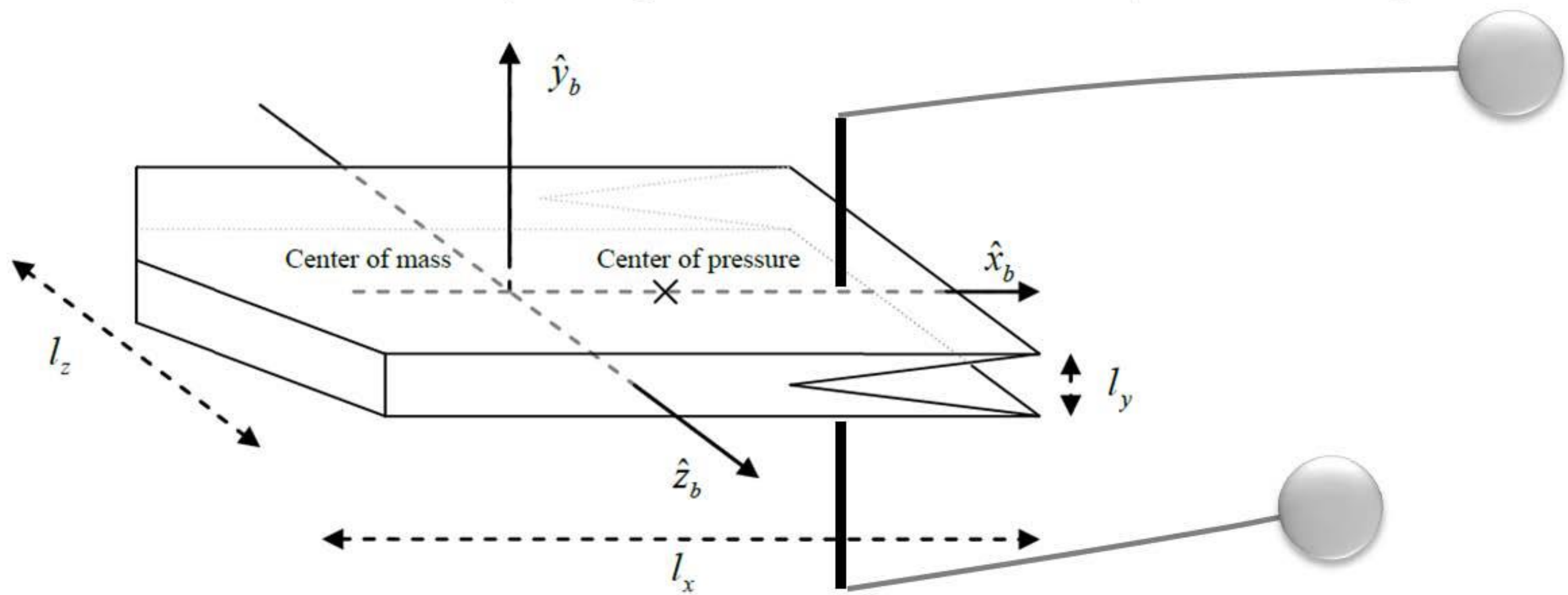
Differentially acting tether with individually variable length

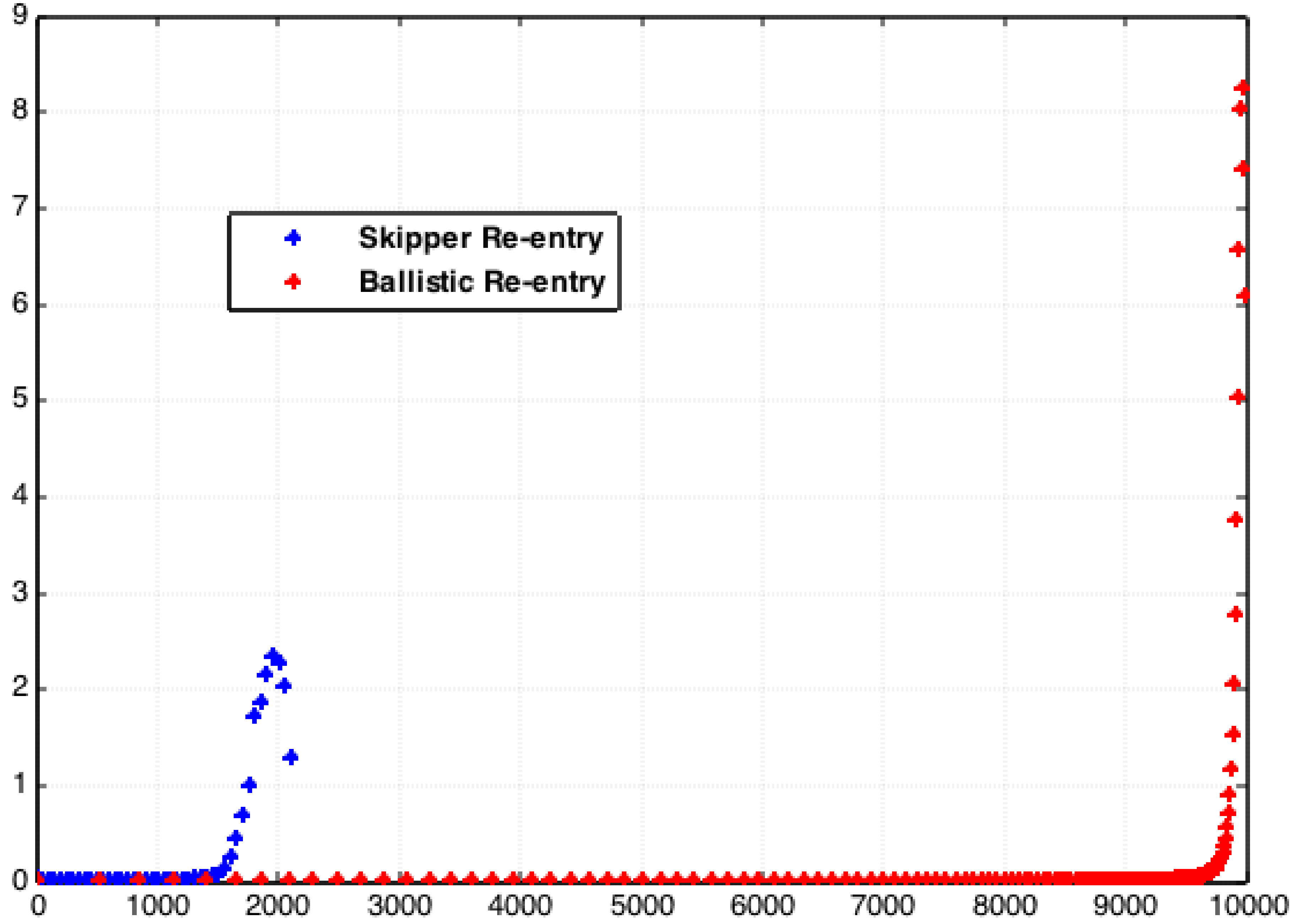


Design Conclusions I

1. Metal blocks of 10 tonne, 25 tonne or 40 tonne scaled appropriately to maintain the same aerodynamic shape, attain qualitatively the same re-entry trajectory. The orbital case of $\Omega = \Omega_0$ experience around 2.5 to 3gs when controller performance is good. Therefore, one can bring in any amount of mass.

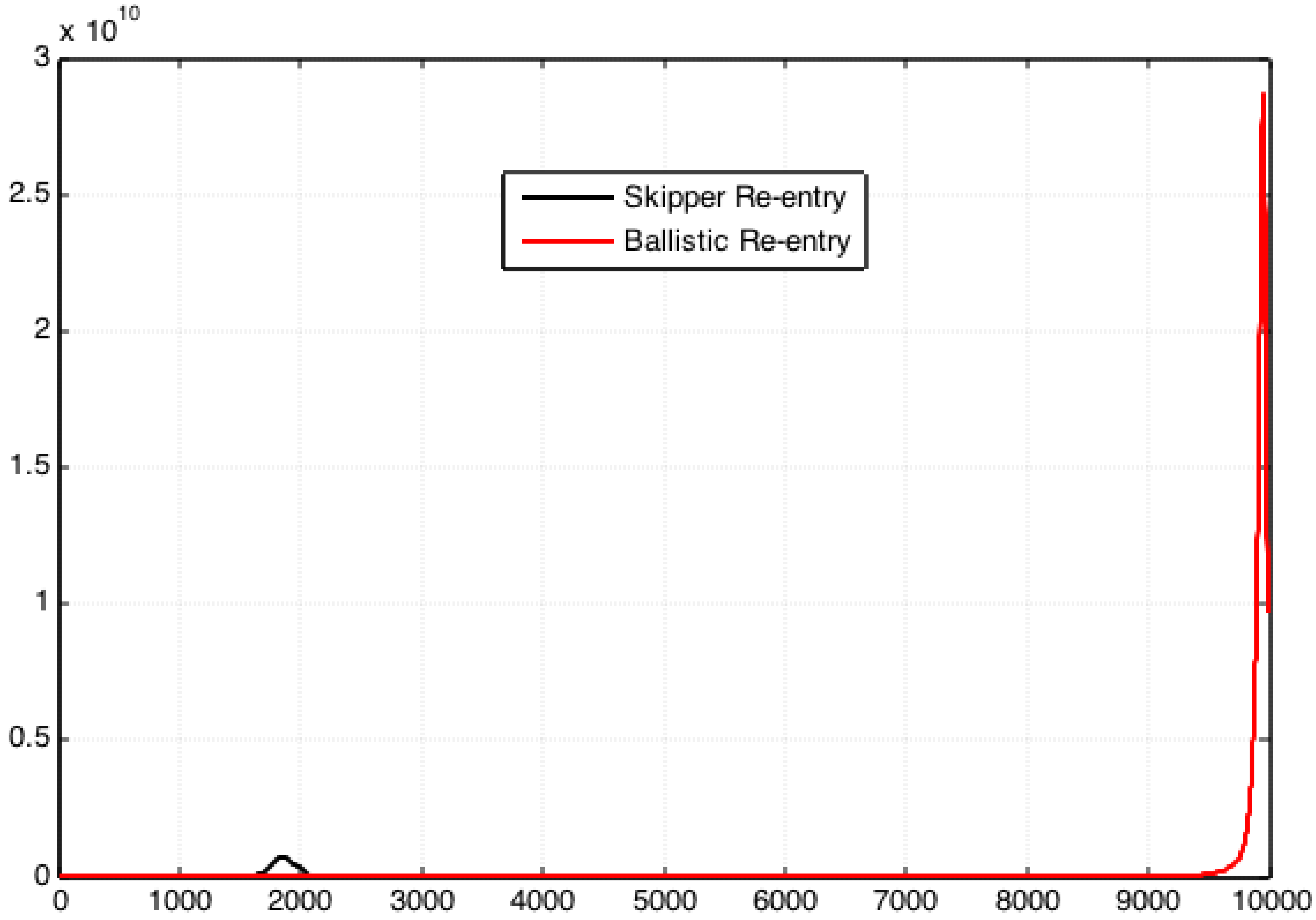
2. If the aerodynamic shape of the forebody is improved such that it has more lift then the body experiences less heating rate and g-loads owing to better de-acceleration profile.

Chevron Body



Maximum g-load for skipper re-entry is 2.5gs. The g-loads have been reduced by 71%

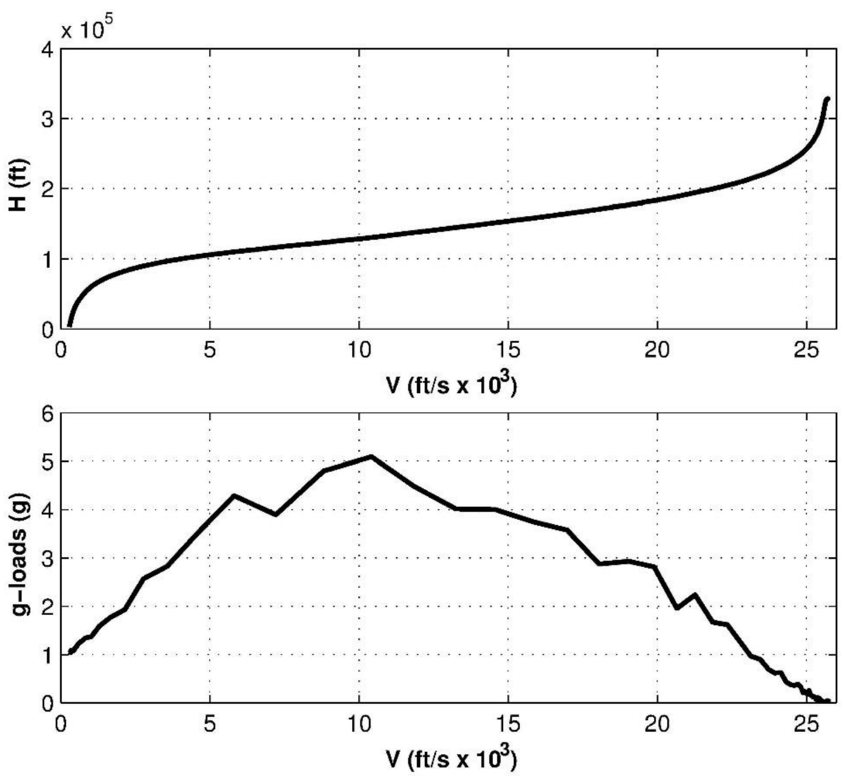
Chevron Body



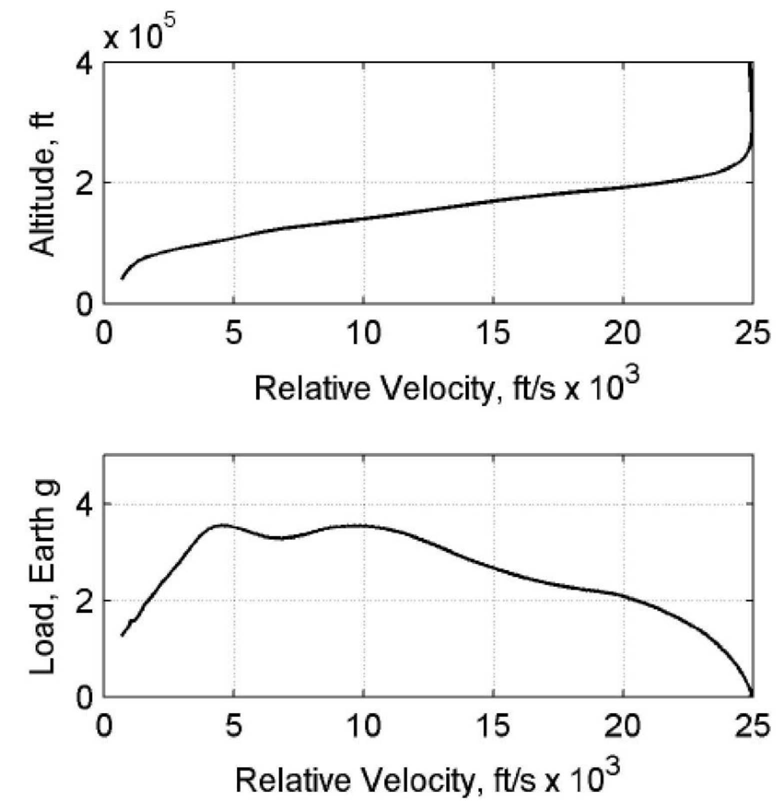
97.5 % reduction in thermal loads

Comparison with Orion CM

RRV - 5 tonne, $H_0 = 100$Km



*Orion - 8.5 tonne, $H_0 = 121$Km



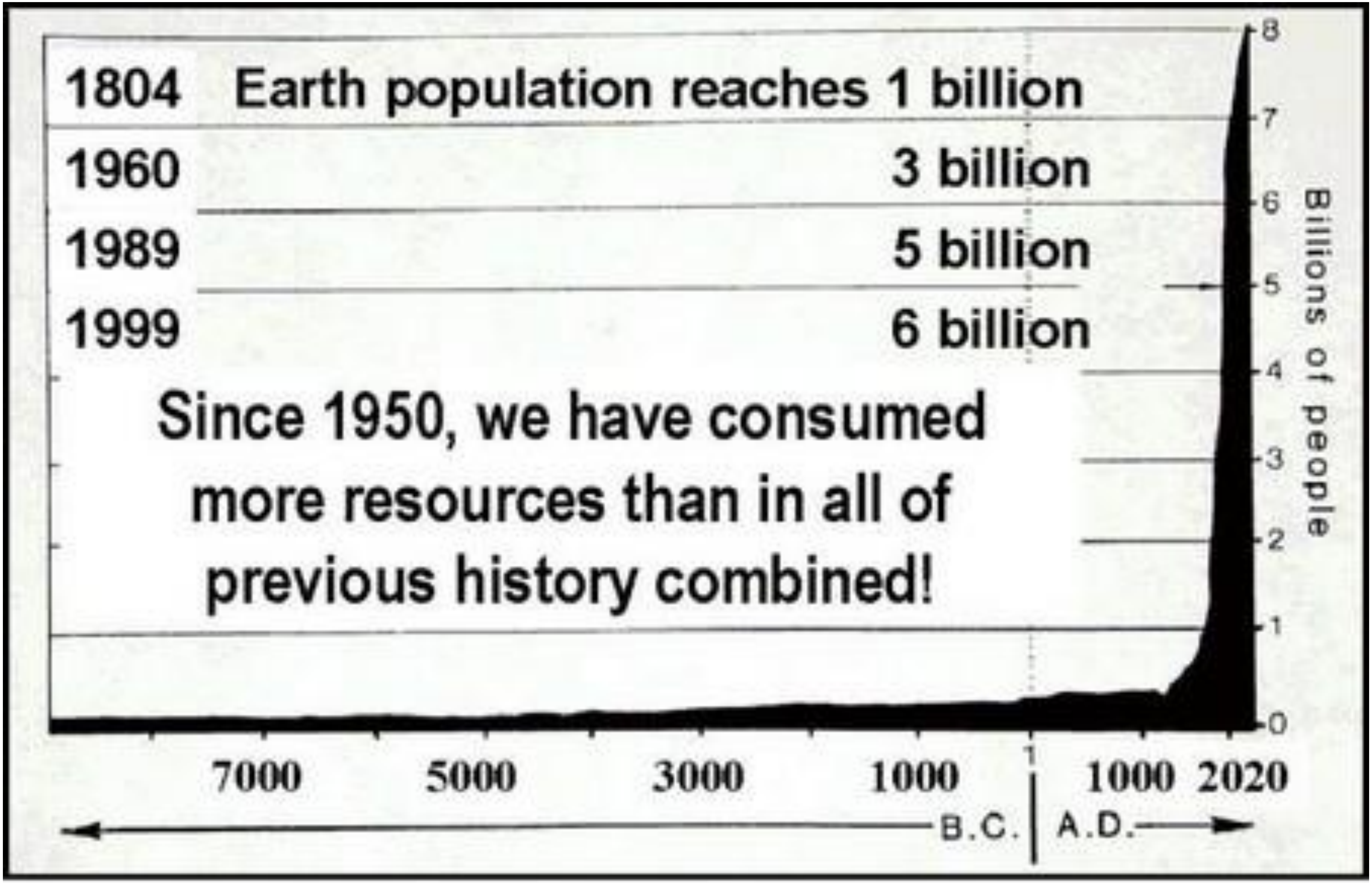
Orion spacecraft uses RCS system to control and RRV uses the skipper system for control. The results are very similar. An optimized skipper system is expected to be competitive to the current reentry technology.

* Reference: Putnam, Zachary R., Matthew D. Neave, and Gregg H. Barton. "PredGuid entry guidance for Orion return from low Earth orbit." Aerospace Conference, 2010 IEEE. IEEE, 2010.

HEINLEIN PRIZE TRUST

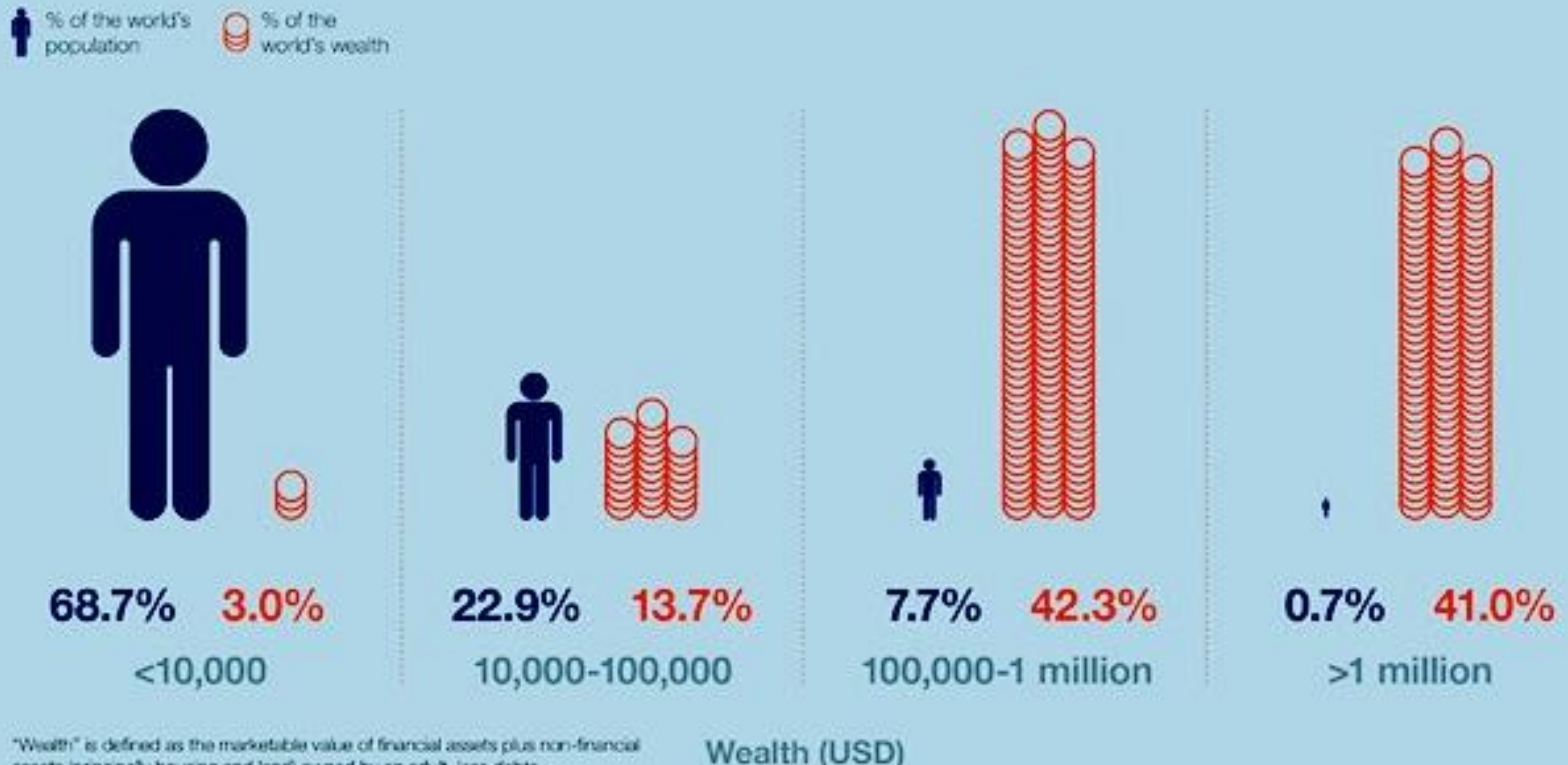
What are the facts? Again and again and again — what are the facts? Shun wishful thinking, ignore divine revelation, forget what “the stars foretell,” avoid opinion, care not what the neighbors think, never mind the unguessable “verdict of history” — what are the facts, and to how many decimal places? You pilot always into an unknown future; facts are your single clue. Get the facts!

R. A. Heinlein
Class of 1929



Human Population Explosion

How is the **world's wealth** shared amongst its population?



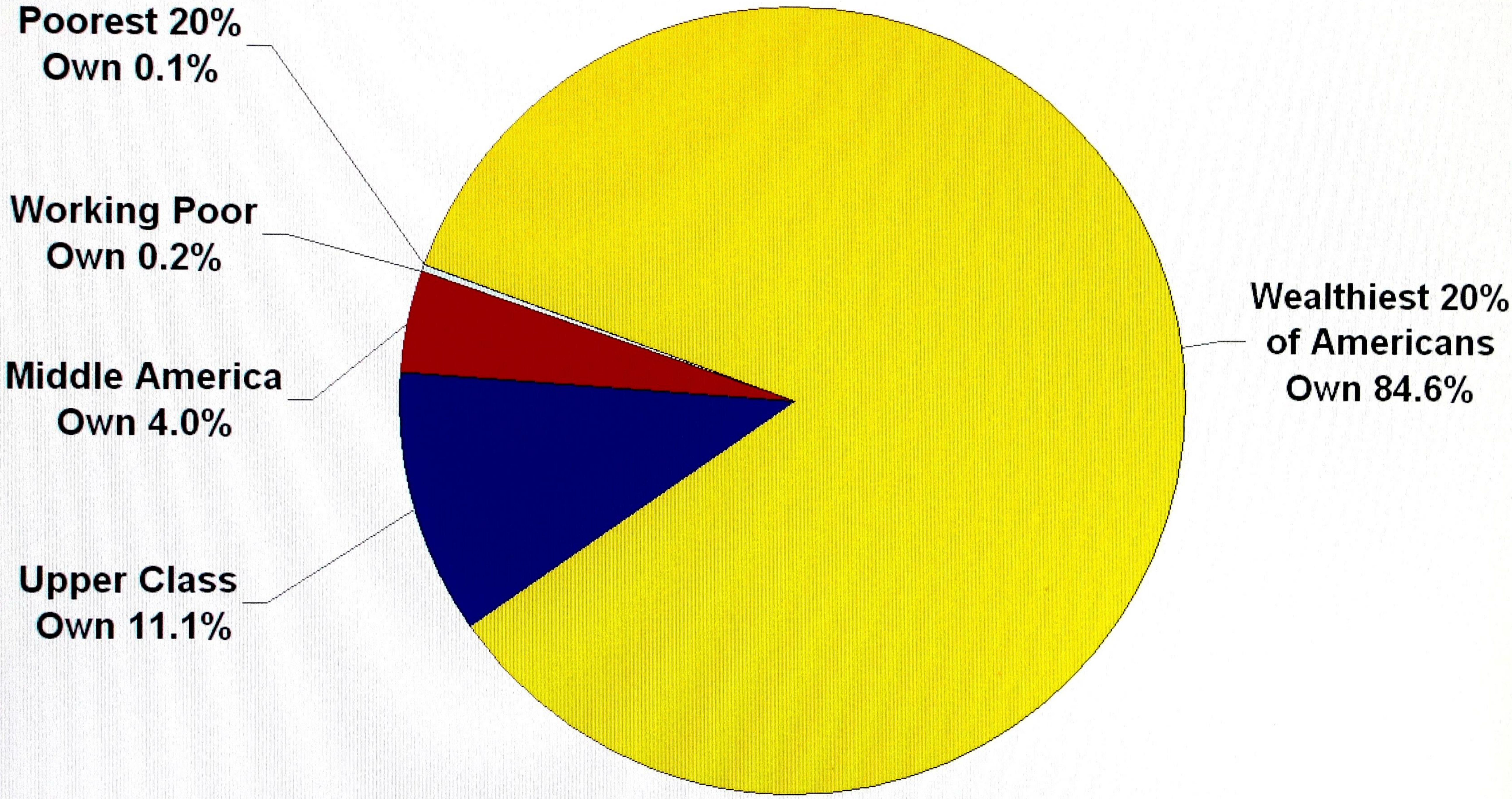
"Wealth" is defined as the marketable value of financial assets plus non-financial assets (principally housing and land) owned by an adult, less debts
Source: Global Wealth Report 2013. Zurich: Crédit Suisse

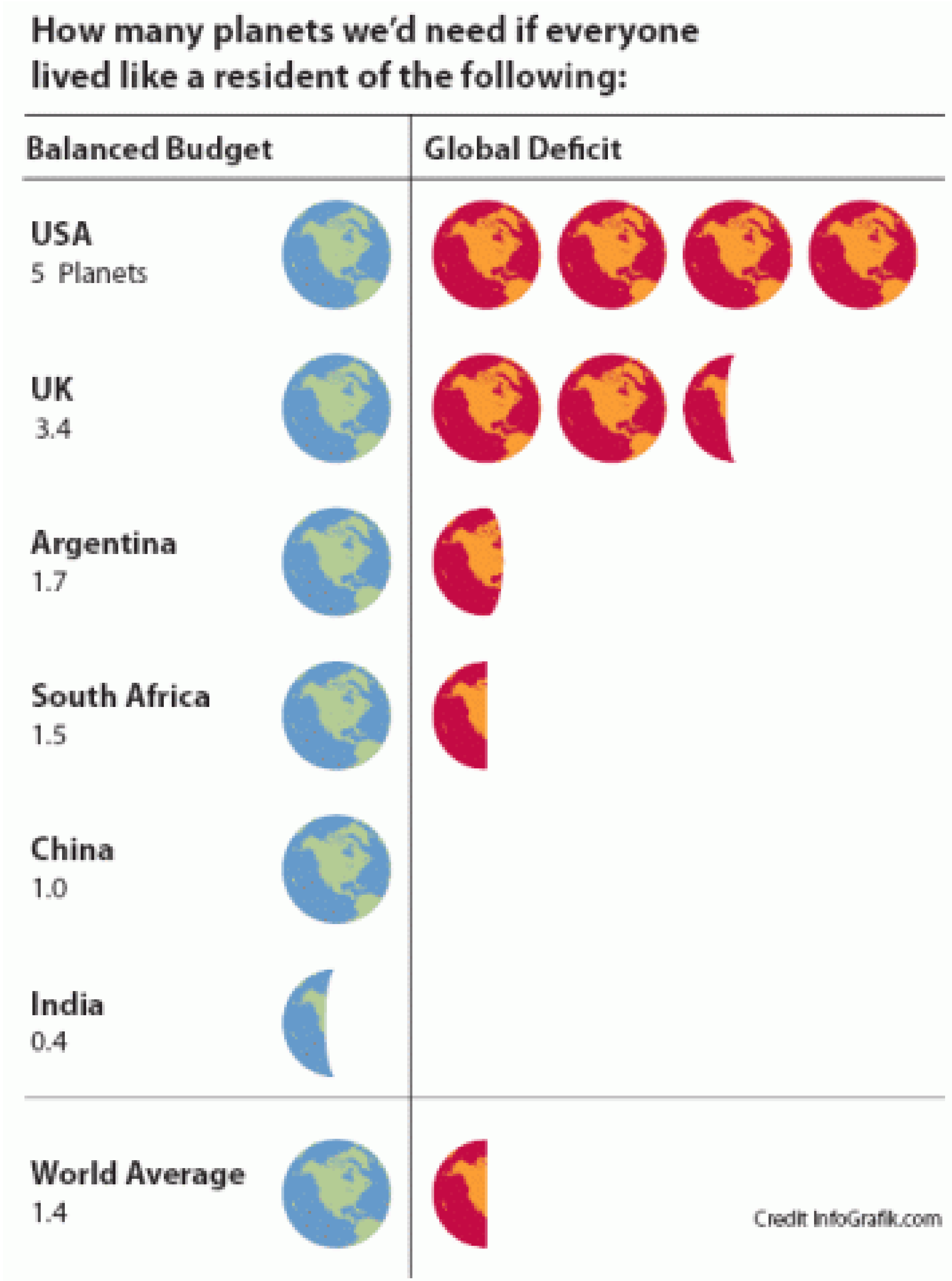
Read the report **#Outlook2015**

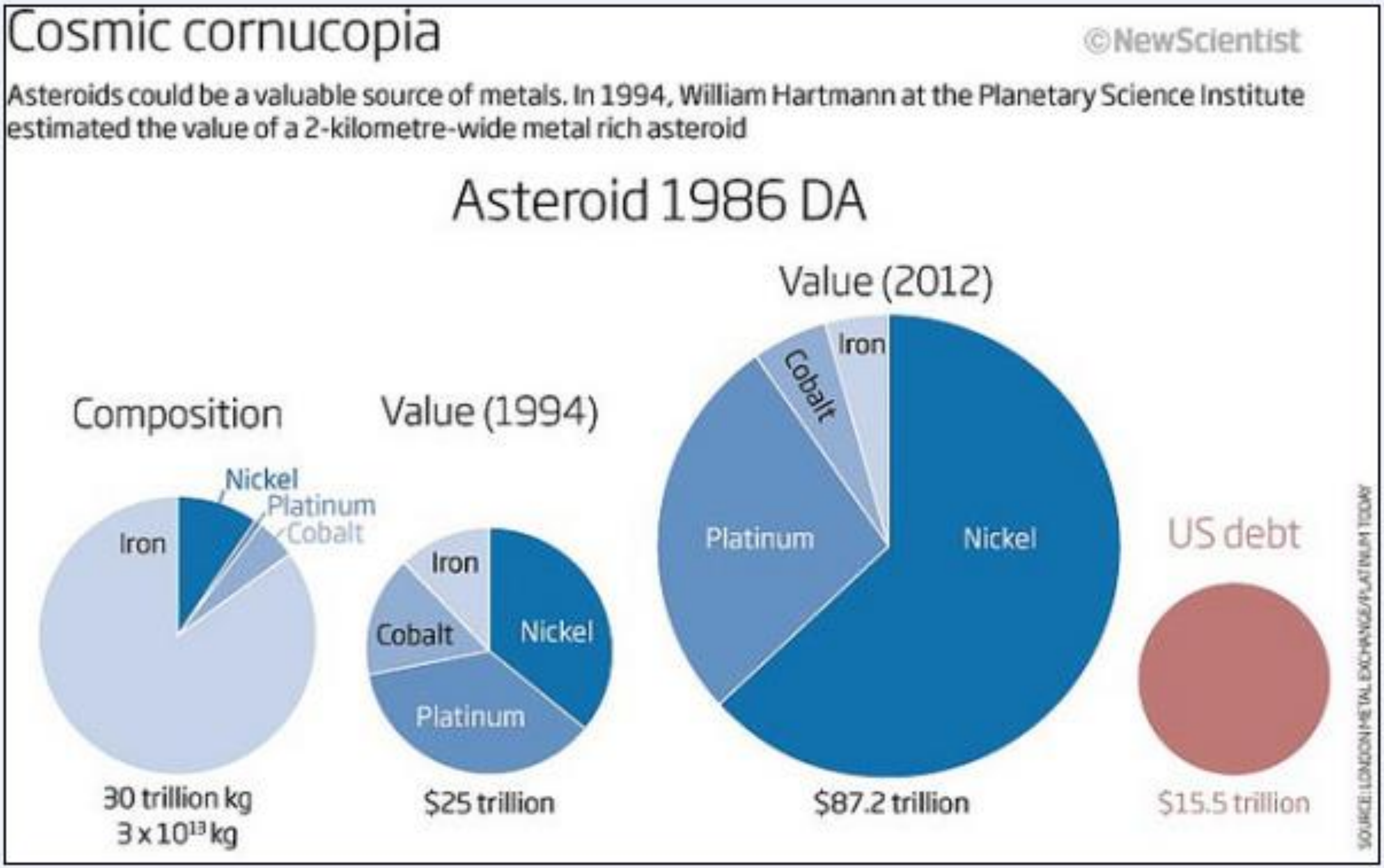
WORLD ECONOMIC FORUM

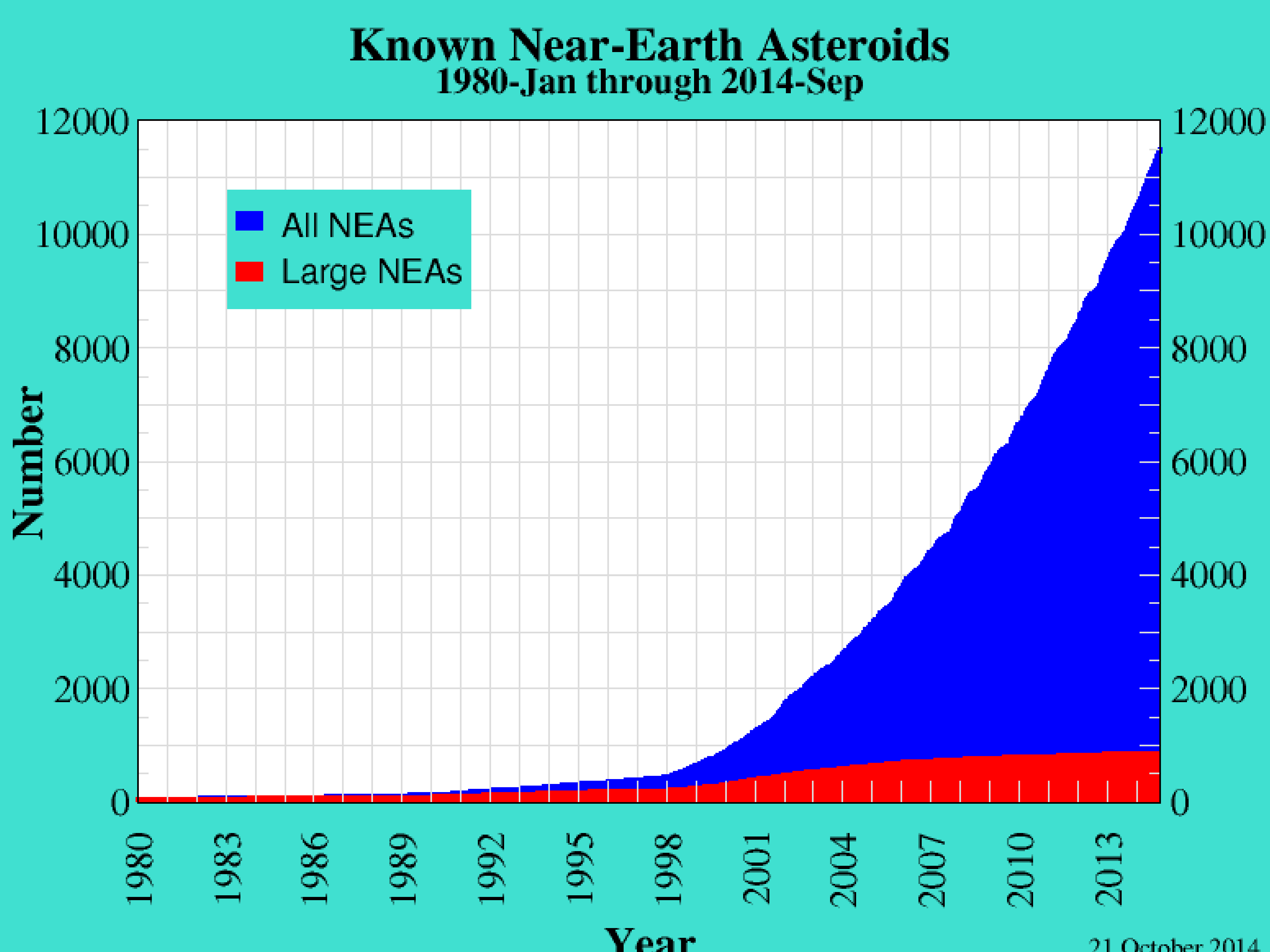
U.S. Wealth Distribution

(each slice = 62 million people)

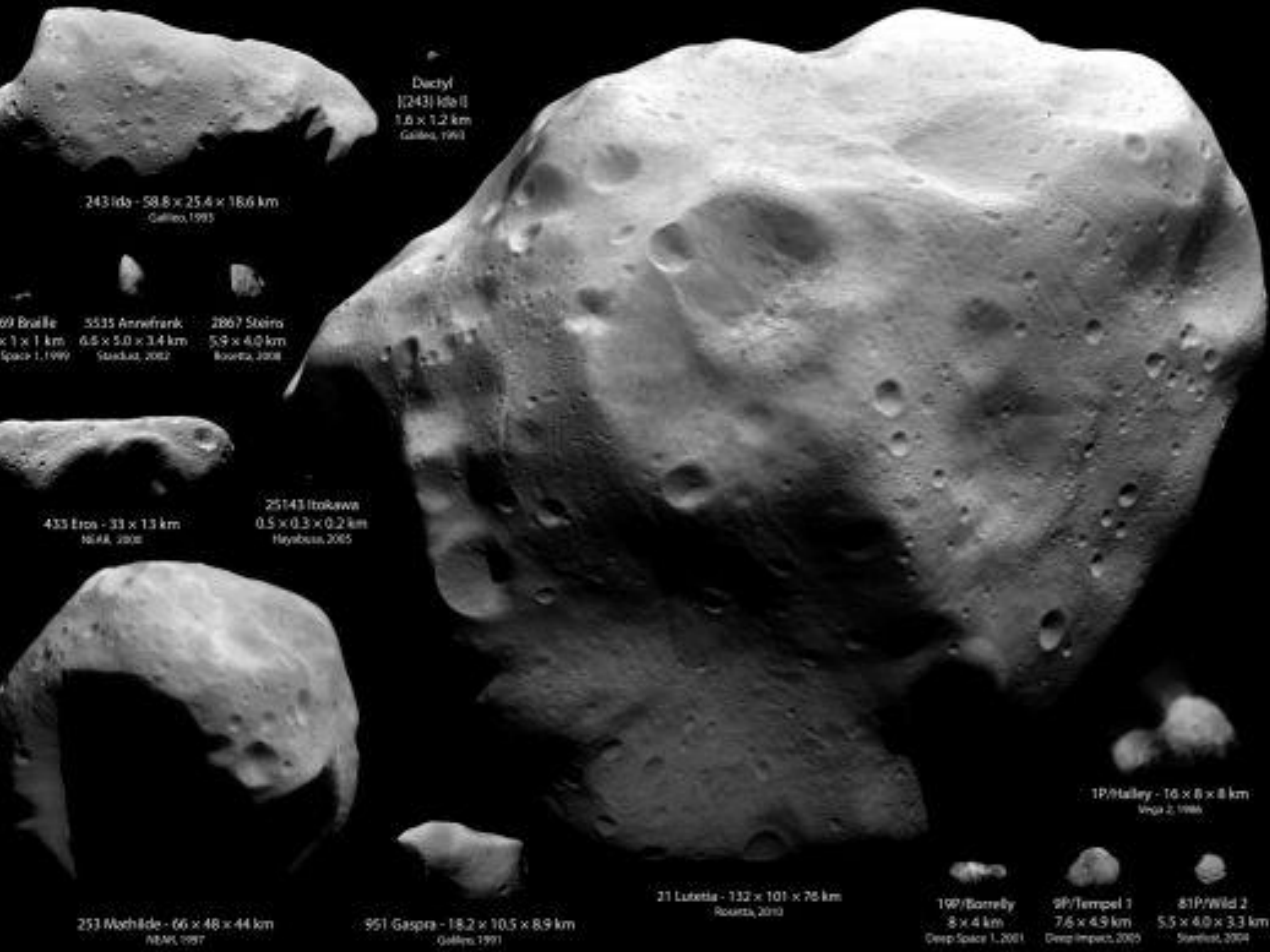


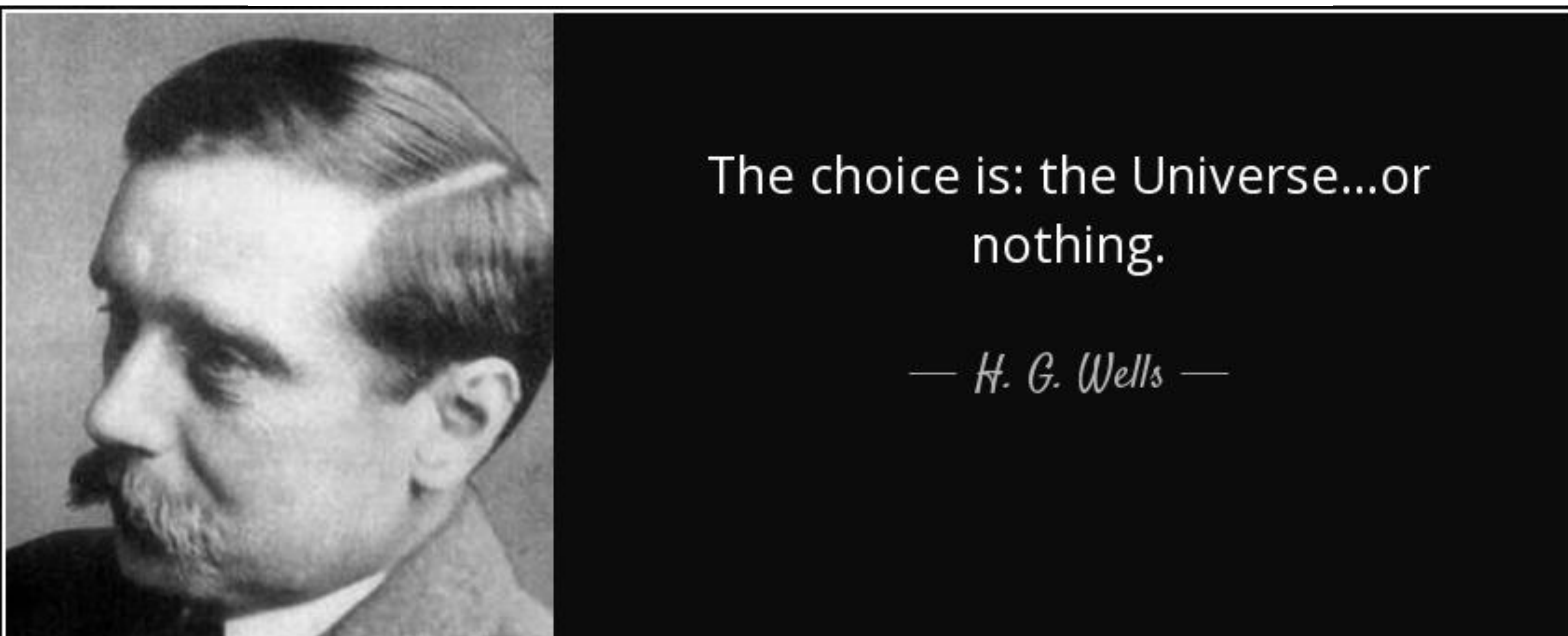

How many planets we'd need if everyone lived like a resident of the following:
Balanced Budget
Global Deficit
USA
5 Planets
UK
3.4
Argentina
1.7
South Africa
1.5
China
1.0
India
0.4
World Average
1.4
Credit InfoGrafik.com


Cosmic cornucopia
©NewScientist
Asteroids could be a valuable source of metals. In 1994, William Hartmann at the Planetary Science Institute estimated the value of a 2-kilometre-wide metal rich asteroid
Asteroid 1986 DA
Composition
Nickel
Platinum
Cobalt
Iron
30 trillion kg
3 x 10^13 kg
Value (1994)
Iron
Cobalt
Nickel
Platinum
$25 trillion
Value (2012)
Iron
Cobalt
Platinum
Nickel
$87.2 trillion
US debt
$15.5 trillion
SOURCE: LONDON METAL EXCHANGE/PLATINUM TODAY



Known Near-Earth Asteroids
1980-Jan through 2014-Sep
12000
10000
8000
6000
4000
2000
0
Number
All NEAs
Large NEAs
1980
1983
1986
1989
1992
1995
1998
2001
2004
2007
2010
2013
Year
21 October 2014


Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993
69 Braille
× 1 × 1 km
Space 1, 1999
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
433 Eros - 33 × 13 km
NEAR, 2000
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
951 Gaspra - 18.2 × 10.5 × 8.9 km
Galileo, 1991
21 Lutetia - 132 × 101 × 76 km
Rosetta, 2010
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004


The choice is: the Universe...or nothing.
— H. G. Wells —