The Political Economy of the Space Age

How Science and Technology Shape the Evolution of Human Society

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Vernon Series in Economic Development

Vernon Press

www.vernonpress.com

In the Americas:
Vernon Press
1000 N West Street,
Suite 1200, Wilmington,
Delaware 19801
United States

In the rest of the world:
Vernon Press
C/Sancti Espiritu 17,
Malaga, 29006
Spain

Vernon Series in Economic Development

Library of Congress Control Number: 2018933283

ISBN: 978-1-62273-264-7

Cover design by Vernon Press, using elements by Nasa

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Acronyms

AMAZE	Additive Manufacturing Aiming Towards Zero Waste & Efficient Production of High-Tech Metal Products
APRSAF	Asia-Pacific Regional Space Agency Forum
APSCO	Asia-Pacific Space Cooperation Organization
ARM	Asteroid Redirect Mission
AU	Astronautical unit
CASC	China Aerospace Corporation
CERN	European Organization for Nuclear Research
CNSA	China National Space administration Comsat Communications Satellite Corporation
COSPAR	United Nation Committee on Space Research
DBS	Direct Broadcast Satellite
DoS	Indian Department of Space
DRM	Design Reference Mission
DSP	Defense Support Program
EADS	European Aeronautic Defense and Space Company
ELT	Extremely Large Telescope
EOS	Earth Observing System
ESA	European Space Agency
EU	European Union
FAA	Federal Aviation Administration
GAO	Government Accountability Office
GEO	Geosynchronous Orbit
GDL	Leningrad Gas Dynamics Laboratory
GDP	Gross Domestic Product
GIRD	Moscow Group for Investigation of Reactive Motion
GNP	Gross National Product
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System

HIAD	Hyper-sonic Inflatable Atmospheric Decelerators
HOPE	Human Outer Planets Exploration
HSF	Human Space Flight
IC	Integrated Circuits
ICBM	Intercontinental Ballistic Missile
ICF	Inertial Confinement Fusion
ICSU	International Council of Scientific Unions
IGY	International Geophysical Year
IISL	International Institute of Space Law
IRBM	Intermediate Range Ballistic Missile
ISAS	Japanese Institute of Science Astronautics
ISRO	Indian Space Research Organization
ISS	International Space Station
ISU	International Space University
ITS	Intelligent Technology Systems
ITU	International Telecommunication Union
JAXA	Japanese Space Agency
JIOA	Joint Intelligence Objectives Agency
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
LEM	Lunar Excursion Module
LEO	Low Earth Orbit
LIP	Large Igneous Provinces
LOR	Lunar Orbit Rendezvous
MAD	Mutual Assured Destruction
MiDAS	Missile Defense Alarm System
MOM	Mars Orbiter Mission
MPD	Magneto-plasma Dynamic
MSL	Mars Science Laboratory
MTF	Magnetized target fusion
NACA	National Advisory Committee for Aeronautics
NAL	Japanese Aerospace Laboratory

NASA	National Aeronautics and Space Administration
NASDA	Japanese National Space Development Agency
NDRC	National Defense Research Committee
NEA	Near Earth Asteroids
NERVA	Nuclear Engine for Rocket Vehicle Application
NIAC	NASA Institute for Advanced Concepts
NISAR	NASA-ISRO SAR Mission
NPV	Net Present Value
OECD	Organization for Economic Cooperation and Development
OSRD	Office of Scientific Research and Development
OTP	The White House Office of Telecommunications Policy
PGM	Platinum Group Metals
PICA	Phenolic Impregnated Carbon Ablator
PLA	People Liberation Army
ppm	Parts per million
PS300	High Temperature Solid Lubricant Coating
RCA	Radio Corporation off America
REE	Rare Earth Elements
REM	Roentgen Equivalent Man
REO	Rare Earth Oxide
RFSA	Russian Federal Space Agency
RNII	Reaction Propulsion Scientific Research Institute
RPM	Resource Prospector Mission
SBPS	Space-based Solar Power
SLS	Space Launch System
SKA	Square Kilometer Array
SOI	Sphere of Influence
TESS	Transiting Exoplanet Survey Satellite
TRL	Technology Readiness Level
ULA	United Launch Alliance
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space

USAF	United States Air Force
USSR	Union of Soviet Socialist Republics
VfR	Verein für Raumschiffahrt
VISTA	Vehicle for Interplanetary Transport Applications

Forward

This book is dedicated to my friend Giovanni F. Bignami who has recently passed away. Nanni was an astrophysicist, fascinated by many other disciplines. He was a member of the Accademia dei Lincei and of the French Academy. He had key roles in the European Space Agency, and directed the largest institute for space research in France. He was elected Presidency of the COSPAR (Committee on Space Research World), was president of the Italian Space Agency and of the Italian National Institute of Astrophysics. This book was made possible by our long collaboration and discussions, not only on the technical aspects of space flight and astronautics, but also on the role of space exploration in the developments of our civilization. This book also benefited from discussions with several people at the International Academy of Astronautics, in particular, Prof. Giancarlo Genta and Art Dula. It is evident that all remaining errors are mine.

Introduction

Space and human space exploration have always fascinated mankind. The question of what is space has intrigued philosophers such as Lucretius, Kepler, and Kant; and scientists such as Newton, Mach, and Einstein. The concept of space is considered to be of fundamental importance to an understanding of the physical universe. Physical space was often conceived by scientists in three linear dimensions, although modern physicists usually consider it, with time, to be part of a boundless four-dimensional continuum known as spacetime. But disagreement continues between philosophers over whether it is itself an entity, a relationship between entities, or part of a conceptual framework.

Space exploration inspired modern non fiction and fiction works. Non fiction works include Tsiolkovsky's famous book *"The Exploration of Cosmic Space by Means of Reaction Engines"*[1]. Fiction works span from Verne to Asimov, A. C. Clark, Fred Hoyle, and Italo Calvino. They are not only pleasant entertainment but also ways to expand the reader's imagination, allowing him to explore responses to future scientific developments and to speculate on how they might develop. In the second half of the 20th century, space exploration moved away from the realm of pure imagination. The launch of the Sputnik 1 in October 1957 and the first landing on the moon by the American Apollo program in July 1969 opened the way to the exploration of the solar system.

During this period, a space economy emerged. According to the OECD[2] *"the space economy is the full range of activities and use of resources that create value and benefits to human beings in the course of exploring, researching, managing, and utilizing space"*. It is a mixed economy. Governments participate through space agencies and military programs, while the private sector activities are centered on low earth orbit (Earth's observation) and geosynchronous orbit (telecommunications). The space economy has been analysed using different approaches from the effects of public expenditures on economic growth to its medium term effects on productivity and growth. This book analyzes the space economy from a broader perspective. This prospective is heavily influenced by the pioneering work of Nelson and Winter[3] on the evolutionary theory of economic change. This approach is both holistic and evolutionary. It is holistic in that the parts of any whole cannot exist and be

[1] See Tsiolkovsky K. English edition (1995).
[2] OECD (2014)
[3] See R. R. Nelson et al (1982).

understood except in their relation to each other and the whole. It is evolutionary in the sense that it studies processes that transform the economy through the interactions among diverse economic agents, governments, and the extra systemic environment in which governments operate.

At the core of the discussion is the role of technical change in economic development. Such dynamic adjustments involve advancement in science and modifications in technology, changes in organization, and the introduction of new rules of behavior. As a result, new waves of consumption, technology, and socio-economic organization emerge overwhelming pre-existing practices. In the economics and management textbooks there exist a wide range of reference the Schumpeter's Trilogy of 'Invention-Innovation-Diffusion'. Schumpeter divides the technological change process into three stages. The first stage is the invention process, encompassing the generation of new ideas. The second stage is the innovation process encompassing the development of new ideas into marketable products and processes. The third stage is the diffusion stage, in which the new products and processes spread across the potential market.

The social process which produces inventions and the social process which produces innovations do not stand in any invariant relation to each other and such relation as they display is much more complex than appears. In many cases, invention and innovation are the result of conscious efforts to cope with a problem independently presented by an economic situation or certain features of it. Sometimes innovation is so conditioned, whereas the corresponding invention occurred independently of any practical need. Historical analysis indicates that new technologies often require a prolonged period of incubation before offering a wide range of opportunities for profitable new investments, new markets, and changes in socio-economic organization, in essence the evolution of human culture. But the same historical analysis indicates that these transitions periods are shortening. For example, it took several thousand years for agriculture to spread around the world, but only two centuries for industrialization to do so, and only a decade for the internet to spread globally. This acceleration indicates that technical change is becoming something contemporary and of immediate interest.

One important debate on technical change has centered on the relative roles of governments and/or other non profit institutions, and markets. An important conclusion of this broader approach is that the idea of government as a static bureaucratic organization only needed to fix market failures, leaving dynamic entrepreneurship and innovation to the private sector, is wrong, and that governments have important roles in fostering these changes. Governments, and in some cases other non profit institutions, have motives other than profit to invest in new technologies, determined by the internal and external socio-economic environment (the extra systemic environment) in which they operate. Once the opportunities for profitable new technologies are established, allocation of resources becomes the main mechanism for investments, and the market is the most efficient institution to allocate resources. But there is a growing perception in social sciences that, in a complex and non stationary environment, one cannot deduce behavior solely from knowledge of market-delivered information and self-seeking goals of individual agents. Public institutions shaping the vision of the world, behavioral conventions, and interactions between economic agents are important in explaining what economic agents do, what kind of technical progress they expect in the future, how much they invest in innovations, what appropriability mechanisms they build, and how much they cooperate and compete with each other. In summary, laws, policies, and institutions are an important part of the environment that shapes the evolution of private sector activities. As the above factors and the extra systemic environment undergo continuing changes, over the long run the cumulative result of private and public actions and reactions gradually modify the basic structure of society.

The development of the space economy is a good case study to verify if this broader approach fits the historical evidence. It may also provide insights for public policies directed to foster future evolution. This book examines: (i) the history of space exploration and of the space economy from its beginning up to now, and the respective roles of governments and the private sector in the evolution of the space economy; (ii) short-medium-term prospects of human deep space exploration and the expansion of the space economy beyond Earth's orbit, and their interrelations; and (iii) possible longer-term developments.

History helps to better understand motivations and constraints - technical, political, and economical - that shaped the growth of the space economy. Short-medium term prospects enable to identify the driving forces that will shape the next phase in the evolution of the space economy beyond Earth's orbit. Central to this discussion are the global issues such as population changes, critical or limited natural resources, and environmental damages, which are transnational in nature, and threaten to affect all. The book explores how space technology could mitigate some of these problems and/or solve some of them, and the role of public institutions and the private sector in fostering those changes. The book analyzes whether present institutions and policies are adequate to foster short-medium term developments and to suggest possible alternatives.

Long term expansion of the space economy in the solar system beyond the Moon requires technologies that are not yet mature, while longer term interstellar exploration and colonization, although within present scientific and technological capabilities, call for advances in technologies that we do not yet have. The book examines the political and institutional framework required in the longer term. Longer term expansion of the space economy call for a civilization in which human beings see themselves as inhabitants of a single planet and global governance is conducted on a cooperative international basis. The establishment of a new international framework is a gradual process driven not only by changes in objective conditions but also by a shift of values or understanding. Changing global issues are part of the objective conditions, and space technology is part of their solutions. Enhanced role education will play a crucial role when broader questions of values, trade offs, and strategies are explored.

A little practical advice before leaving the reader to progress through the book. To ease reading the text, all technical details have been placed in the footnotes or in end-of-chapter appendices. Bibliographic references are collected at the end of each chapter. They are unnecessary to understand the text. However, they are necessary to the curious reader wanting to know more.

Bibliography

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Chapter 1

The invention stage

"Earth is the cradle of humanity, but one cannot live in a cradle forever."

Konstantin E. Tsiolkovsky

Astronautics is the theory and practice of navigation beyond Earth's atmosphere. Newton established astronautics' mathematical basis in his treatise *"The Mathematical Principles of Natural Philosophy".* They are embedded in his laws of motion and gravitation. Reactions in the spaceship's engine produce enormous pressures, which cause the expulsion of gas and/or radiation at high speed in the direction opposite to travel. It is this reaction force that pushes forward the engine and the spaceship attached to the engine.

Although Newton laid the mathematical foundations of astronautic long ago, astronautics became a science in its own right in the early twentieth century. During the first half of the twentieth century, there were also some advances in space technologies and engineering. This chapter tries to answer the following questions: (i) who developed the science and the technologies of space flight, and under what circumstances; (ii) what kind of institutions were established, who financed them, and how did they produce, structure, and organize knowledge; (iii) what were the main obstacles of the earlier experiments in space flight; and (iv) what geopolitical changes occurred at the end of the 1940s that created the conditions for the birth of the space economy.

1.1 K. E. Tsiolkovsky

Konstantin Eduardovich Tsiolkovsky was born Sept. 17, 1857, in Izhevskoye, Russia. At a young age, he caught scarlet fever and became hard of hearing. He was not admitted to elementary schools because of his hearing problem. As a reclusive home-schooled child, he passed much of his time by reading books and became interested in mathematics and physics. As a teenager, he began to contemplate the possibility of space travel, inspired by the fiction of Jules Verne. After falling behind in his studies, Tsiolkovsky spent three years attending college in Moscow where Russian cosmism proponent Nikolai Fyodorov worked, one of the main proponents of Russian cosmism. It was in this intellectual environment that Tsiolkovsky further developed his interests in space travel. At the end of his studies, he was accomplished in both science and mathematics. He became a teacher at Kaluga, Russia, where he spent the rest of his life.

Starting from 1883, Tsiolkovsky theorized many aspects of space flight. He published his most famous work, *"The Exploration of Cosmic Space by Means of Reaction Engines"*, in 1903. In this book, Tsiolkovsky derived the basic formula for rocket propulsion (see Appendix to this chapter). The equation had been derived earlier by the British mathematician William Moore in 1813[1]. But Tsiolkovsky is honored as being the first to apply it to the question of whether rockets could achieve speeds necessary for space travel. This formula calculates the final velocity of a rocket from the escape speed of the gases, and the initial (including propellant) and final (without propellant) masses of the spaceship. This equation also plays an important role in evaluating the economic feasibility of a space project, as will become clear in subsequent chapters. In other theoretical works, he studied gyroscopes and liquid fuel rockets; calculated the escape velocity from a gravitational field; and analysed the problem of the control of a rocket that moves between gravitational fields. Among his works are the designs for rockets with steering thrusters, multistage boosters, space stations, airlocks for exiting a spaceship into the vacuum of space, and closed-cycle biological systems to provide food and oxygen for space colonies. He never complemented his theoretical writings with practical experiments in rocketry. But his work greatly influenced space and rocket researches and experiments carried out in the Soviet Union and Europe.

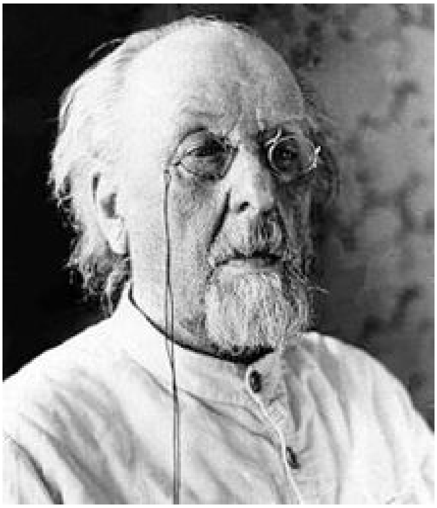

Figure 1.1 – K. E. Tsiolkovsky
Source: http://petersrussia.blogspot.it

Tsiolkovsky elaborated the theory

[1]See W. Moore (1813)

of space flight as a supplement to his philosophical inquiries on the cosmos. He is remembered for believing in the dominance of humanity throughout space, also known as anthropocosmism. Russian cosmism appeared as sort of antithesis to the classical physical paradigm based on strict differentiation of man and nature. Cosmism made an attempt to revive the ontology of an integral vision to unites man and the cosmos. These problems were discussed both in the scientific and the religious[2] form of cosmism. But while religious cosmism was more notable for the fantastic and speculative character of its discourses, the natural scientific trend, solving the problem of interconnection between man and cosmos, paid special attention to the comprehension of scientific achievements that confirmed that interconnection. Kholodny attempted to reconsider the question of man's place in nature and of his interrelations with the cosmos on the basis of natural scientific knowledge. In his opinion, the anthropocentric worldview started to collapse under the influence of the achievements of science and philosophy.

Tsiolkovsky was influenced by the works of N. G. Kholodny. In Kholodny's book *The Unknown Intelligence,* he propounded a philosophy of panpsychism. Panpsychism is the view that consciousness, mind or soul (psyche) is a universal and primordial feature of all things[3]. He believed humans would eventually colonize the Milky Way galaxy, because of the advance in science and industry. Although Tsiolkovsky's philosophical theories are now generally discarded, he was the first to inquire into motivations of man traveling into deep space, and to advance ideas on space stations, industrialization of space, and exploitation of space resources, which constitute actual programs of today space agencies and private space industries.

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[2]N. Fedorov was the most significant author. He was a Russian Orthodox Christian philosopher, who was part of the Russian cosmism movement. Fedorov argued that evolutionary process was directed towards increased intelligence and its role in the development of life. Humanity is the culmination of evolution, as well as its creator and director. Humans must therefore direct evolution where their reason and morality dictate. Fedorov also argued that mortality is the most obvious indicator of the still imperfect, contradictory nature of humanity and the underlying reason for most evil and nihilism of humankind. Fedorov stated that the struggle against death can become the most natural cause uniting all people of Earth, regardless of their nationality, race, citizenship or wealth (he called this the Common Cause).

[3]Panpsychism is one of the oldest philosophical theories, and has been ascribed to philosophers like Thales, Parmenides, Plato, Averroes, Spinoza, Leibniz and William James. Panpsychism can also be seen in ancient philosophies such as Stoicism, Taoism, Vedanta and Mahayana Buddhism. During the 19th century, panpsychism was the default theory in philosophy of mind, but it saw a decline during the middle years of the 20th century with the rise of logical positivism

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