ECONOMIC PLANETARY SCIENCE IN THE 21ST CENTURY. P.T. Metzger[1], [1] University of Central Florida, Florida Space Institute, 12354 Research Pkwy, Suite 214, Orlando FL 32826, philip.metzger@ucf.edu.

Introduction: Economic planetary science is a young discipline set to expand rapidly with potential to become a primary driver of science in this century [1,2]. Similar to economic geology on Earth, economic planetary science is concerned with utilizing resources in space for economic and industrial activity. Science is produced only as a byproduct (either incidentally or to support business decisions), but experience shows it can exceed the science produced intentionally by government investment. Commercial companies are beginning new activities in space and some national governments are setting policy to encourage them. The trends that have made this possible are: maturity of rocket technology leading to lower launch costs; autonomous robotics; and the overall growth of Earth's economy and supply chain enabling an ever widening range of activities. Supporting government-lde space exploration has long been an economic pursuit of commercial companies. The best known of the new activities is asteroid mining to produce rocket propellant for purely commercial uses such as boosting telecommunications satellites into their final orbits. Commercial companies are also pursuing the in-space manufacture of large antennas to keep up with Internet growth [2-4], beaming microwave energy to Earth to replace carbon-based energy more affordably than ground-based renewables [5], space tourism including lunar landings [6-8], and providing services and material to anyone attempting settlement (such as Elon Musk [9]). While some of these may seem fanciful, some already have reasonable business cases while the expanding space and terrestrial economies suggest the others may get there soon.

Relationship of Science with Economic Development: Terrestrial experience shows that science and economic development are mutually supportive, although some conflicts do occur. The U.S. Bureau of Labor Statistics website shows that about 65% of geoscientists are in economic geology such as mining, 18% are in research (many of whom are funded by economic interests), 12% are in government (mostly managing economic activities), and only 5% are in academia (with most of their students going into economic geology). This shows that most terrestrial geoscientists are funded by economic activity rather than pure science. Likewise, most geological data have been funded by economic mining and drilling. We may therefore expect most planetary scientists will work in economic applications or be supported by the tuition of students destined mostly for economic planetary science as our economic sphere advances into space. This will represent a great broadening of our field, both in access to data and in the number of funded scientists. This is good news for our newly graduated colleagues who would otherwise face many years of hand-to-mouth survival in soft money positions, too often leaving science in the end.

Gantman [10] showed through the publication records of scientists in 147 countries that their scientific productivity correlates strongly with two factors: how developed their country is (intensive), and the overall scale of their country's economy (extensive). More intensively developed countries have better supply chains to provide tools and opportunities for scientists. Extensively larger economies have greater freedom to command funding toward science. These mechanisms ought to work when it comes to the region we call space, as well. A greater in-space supply chain will provide better in-space tools and opportunities for working scientists, and the space economy will create economic ability to fund science. If space mining is destined to create the first trillionaires, then it is destined to create the golden age of planetary science, too.

Concerns about economic activity ruining sites of high scientific value (such as lunar polar volatiles) or running contrary to other ethical or environmental values will need to be worked through government regulation. An example is NASA's recent document providing guidelines for visiting the historic sites on the Moon. Commercial companies were contacting the author to learn the best practices to visit these during the Google Lunar X-Prize without ruining the scientific value of the sites. This led to discussions with NASA headquarters, which led to the effort to develop that document. NASA legal counsel has mentioned they may eventually amend it to become mandatory rules rather than voluntary guidelines. It is noteworthy that this process was initiated by the commercial companies seeking government involvement. More such policy will be needed in the future, and commercial mining companies desire the clarity it brings, reducing uncertainty for potential investors.

Business Case for Asteroid Mining: There is already a sufficiently clear business case for asteroid mining. When a rocket company lifts a telecommunications spacecraft, it typically goes into geostationary transfer orbit (GTO) with perigee at the altitude of low Earth orbit (LEO) and the apogee near the altitude of geostationary orbit (GEO). Some years ago, it was standard practice to include an upper stage that would circularize the spacecraft's orbit to GEO within a day. Today, it is standard practice to use an electric thruster on the spacecraft, which produces very low but extremely efficient thrust, circularizing the orbit over a period of 6 to 12 months. During this time, the spacecraft owners lose revenues in the hundreds of millions of US dollars. (This preferance indicates how expensive it is to launch an upper stage.) For asteroid mining to be commercially profitable, it needs to provide fast circularization from GTO to GEO for a price less than these lost revenues. This requires spacecraft to mine the water from asteroids, an in-space depot to store the water and convert it upon need to rocket propellant through electrolysis, and a refuelable space tug. (If the space tug runs on thermal steam propulsion instead of chemical combustion then the depot can be simplified but more water will be expended per customer.) The business expenses will include deployment of this infrastructure, ongoing space operations, and finance costs appropriate to the level of risk. Several persons known to the author (including myself) have run these numbers using reasonable assumptions and have shown there is a potential to profit. Apparenntly Luxembourg's Economic Ministry agrees since it is investing heavily in asteroid mining. NASA may help establish this activity by developing the technologies, establishing an in-space depot, and/or giving contracts to purchase water to make Mars missions or other activities more affordable. The United Launch Alliance has also set a price they are willing to pay for water in space [11].

Business Case for Additional Activities: Once asteroid propellant mining is profitable, the marginal cost of extracting metals or other materials from asteroids will be low enough to make other in-space activities economic. One example is building giant antennas that are too large to launch, enabling the Internet's continued growth beyond the looming fiber optic capacity crunch [12]. These additional activities may benefit from lunar polar deposits, which possess carbon for making plastics and other materials. Another problem we must solve in this century is the energy crunch. The population is expected to grow to 11 billion by 2100, but sociologists believe the birthrate is stabilizing because all nations are becoming developed. This assumes that all nations will in fact become developed, which necessitates more energy from sources that have high energy return on investment (EROI) [13,14]. Proposals have been offered to solve world energy problems by collecting it in space and beaming by microwave to the surface [5]. Such concepts become increasingly economic as space industry expands so that larger fractions of the necessary infrastructure can be made in space. Metaanalysis of 133 computer models suggests by 2100 the world might easily require 4 times more than today's global energy supply [15]. With the EROI dropping and energy demands rising, the future energy sector may be as large as today's entire economy. If only this fraction of our future economy were put into space, it would tremendously benefit the ecosphere. The basic idea is that human civilization has grown so large that it pushes against planet-scale physical limits, and moving industry off-planet becomes increasingly vital to our planet's health.

Space Policy to Encourage Space Development: If spacefaring nations pursue a policy of space development, it will result in greater space science in addition to solving global challenges such as clean energy and global development. A lunar outpost could be focused on developing space mining and manufacturing while the same activities make the outpost more affordable, enabling concomitant lunar science. While astronauts can be replaced by robots for most sortie science missions – probably all of them sometime during this century – one thing robots cannot do is repair and develop other robots, so astronauts are absolutely vital for this effort. Time is of the essence to address global challenges, and human astronauts on the Moon will develop space industry faster than robots alone could do. This is arguably the most highly leveraged investment humanity could ever make. This will enhance the importance of astronautics in the public's view and create even greater support for space. Thus, science can help the globe, perpetually greater science will be the result, and the citizenry will strongly support it. In summary, planetary science is about to enter its golden age precisely because it is becoming crucial to the health of our civilization and of our planet.

References: [1] Metzger, P. T. et al. (2013) *J. Aerosp. Eng.* 26, 18–29. [2] Metzger, P. T. (2016) *Space Policy* 37, 77–91. [3] Skomorohov, R., et al. (2016), IAC-16.E6.1.2 [4] MacEwen, H.A. and Lillie, C.F. (2016) *J. Astronom. Telesc. Instrum. Sys.* 2, 041208–041208. [5] McSpadden J.O. and Mankins J.C. (2002) *IEEE Microw. Mag.* 3, 46–57. [6] Collins P. and Autino A. (2010) *Acta Astronaut.* 66, 1553–1562. [7] Webber D. (2013) *Acta Astronaut.* 92, 138–143. [8] Collins P. (2006) *Adv. Space Res.* 37, 116–122. [9] Jamieson V and Biever C (2012) *New Scient.* 216, 27. [10] Gantman E.R. (2012), *Scientometr.* 93, 967–985. [11] Sowers G. (2016), SRR XVII. [12] Ellis A. D., et al. (2016) *Phil. Trans. R. Soc. A* 374, 20150191. [13] Lambert J. G. et al. (2014) *Energy Policy* 64, 153–167. [14] Ayres R. U. et al. (2013) *Struct. Chang. Econ. Dyn.* 27, 79–88. [15] Fisher B. S. et al. (2007), In: Climate Change 2007, Cambridge Univ. Press, 169–250.