UNIVERSITÀ DEGLI STUDI DI TORINO

Masali M., Schlacht I. L., Argenta M., Gamba M., Ligabue Stricker F., Micheletti Cremasco M., 2013. Human Adaptation in Extreme Conditions: Anthropology and Ergonomics Applied to Outer Space. *International Journal of Anthropology,* Vol. 28 n. 2-3: 171-185. Angelo Pontecorboli Editore. Firenze.

ISSN: 0393-9383 (Print)   1824-3096 (Online)

Human Adaptation in Extreme Conditions: Anthropology and Ergonomics Applied to Outer Space

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"A planet created for humans" is the mental image that Man has of Earth, but what would be the mental image if in a distant future Man were to inhabit the Moon? A good riddle for Alice, and a challenge for anthropologists, biologists, physicians, and space engineers. Besides, why should we not populate the Moon? The Moon is probably a piece of Earth, or at least is of a similar nature , it stays in the same place in the Solar System since both globes have a common center of gravity within the Earth's surface. Nevertheless, it seems to be wholly unwelcoming and hostile. Probably because *we are not adapted to live there*! Travelling beyond the Earth's atmosphere is a relatively new feat for mankind; however, the relationship between humans and other planets has a much longer history. While a student, Johannes Kepler devoted one of his dissertations to the question: "*How would phenomena occurring in heaven appear to an observer on the Moon*?" The thesis submitted by Kepler at the Tübingen University, in 1593, contained some of the major questions regarding Man's exploitation of Moon and Space. Questions we shall attempt to answer in the optics of Anthropology and Ergonomics.

Key words: *human adaptation to outer space, earth, gravity, ergonomics, spandrels traits*.

L'homme sait enfin qu'il est seul dans l'immensité indifférente
de l'univers d'où il a émergé par hasard.
Non plus que son destin, son devoir n'est écrit nulle part.
Le Hasard et la Nécessité (1970)— Jacques Monod

A Planet for Humans

Nevertheless, we have no reason for such optimism since H_2O eutectic band planets (the so called 'life band' where water is manifest contemporarily in its three fundamental states: ice, liquid, vapor) may be extremely few and far between amidst the countless exoplanets in the Galaxies. Only recently has evidence become available to enable us to consider and evaluate opinions ranging from Epicurus: "*There are infinite worlds both like and unlike this world of ours*" to Aristotle: "*There cannot be more worlds than one*" (Perryman, 2011).

The subject matter may appear to be too theoretical or to belong to the realm of Science Fiction, yet nevertheless, our studies began at the time of the EuroMIR "Real Man" Space habitability projects (Ferrino & Gaia, 2003), parabolic 0g flights (Schlacht et al. 2007), and the Moon-Mars habitation simulator (Schlacht, 2012), and appear to match the latest studies on human adaptation to Outer Space: how future generations will make the voyage from our earthly home to the planets and beyond—and what it will mean for our species as envisaged by Cameron M. Smith in the magazine Scientific American (Smith, 2013).

Adaptation means evolution; but in this domain the question of adaptation to new, unexpected environments (or at least making allowances for the possibility of survival) appears to be quite unresolved. Adaptation requires extremely long periods and involves the architecture of the whole organism, even where only a specific trait is involved. In the theory of evolution, Darwin posed the question of how organisms could survive in new environmental conditions (Harrison Matthews, 2008). This occurs when a species or population has characteristics that are suited for conditions that have not yet arisen.

Gould and Lewontin (1979) argue (in a humorous way) that the traits of animals (their body and behavior) may have developed in the same way as '*spandrels*'. Spandrels, like the *pendentifs* of Renaissance domes, are the blank areas between arches which are utilized by artists for decorative purposes. However, this was not their primary function; they originated for architectural reasons to support a dome, and not for the adapted function of adornment.

Just as spandrels arose because of architectural constraints, these 'spandrel traits' are the consequences of true adaptations that actually evolved under the pressures of natural selection. In extreme environmental adaptations there is no time to evolve, so the spandrel pathway may provide a possible approach. Therefore, how can adaptation develop in line with current evolutionary doctrine in the domain of the Outer Space, where the time available for adaptation is minimal? Outer Space Human Adaptation, the levels of habitability and performance in Space and in Extreme Environments are closely related to the human capacity to adapt to a specifically premeditated technical interface design, which is also called human-system integration. A well-designed habitat and a mission with, "a good habitability can decrease the probability that the environment will contribute to crew error or other performance issues"… "In the case where the environment cannot be adapted to

Fig. 1. A Spandrel in San Marco Cathedral, Venice.

the human, research indicates the human does have the ability to adapt to the environment," (Blume Novak, 2000). Human adaptation is aimed at supporting human-system integration. Human adaptation can be achieved in the following ways: by way of selection and training; artificial adaptation; and, as can be suggested today, by *natural exaptation;* posed primarily by Charles Darwin, to comprehend how organisms can survive in new environmental conditions when a species or population has characteristics that are suited to conditions which have not yet arisen. To elaborate:

1. Selection and training: astronauts are integrated into the system through selection and training on the basis of the human-system integration protocols.
2. Artificial adaptation: the system is designed and adapted to support human needs in an extreme environment.
3. Natural exaptation: the astronaut's body naturally reacts to the new psycho-physiological constraints following the *exaptation* process, exploiting in a new mode the natural traits that are positive for the human-environment integration.

These three processes support the operational tasks but necessitate time in order to evolve the specific traits, yet where there is no time, should the counting start from the "gravitational adaptation", similar to the evolutionary history of Lemurs? To live in Outer Space, humans again need to adapt and evolve in completely different environmental conditions. (Masali et al., 2010).

Astronaut Selection and Training

Astronauts are selected on the basis of the characteristics which determine their ability to best react under the psycho-physiological constraints in space, and are trained to improve their potential to be productive under such constraints. In the NASA SSP 50005C report, selection and training are part of the human-system integration study so as “to form an effective Human-Machine System” (AA.VV., 1999).

Selection and training are particularly important for astronauts and apply to both the physical and psychological levels. For example, as elucidated by Sonya Ongaro (2005), the main focus of the psychological training should be on self-management, leadership and teamwork, and group living. Those aspects affect habitability, particularly at the social level.

In the past 50 years of the Space Age, selection has been based on aptitude. The Fédération Aéronautique Internationale (FAI) defines spaceflight as any flight beyond 100 km from the Earth’s surface. Following this definition, up to the report date, we have only had a total of 520 astronauts, of whom only 24 have traveled beyond low Earth orbit, and only 12 have walked on the Moon. Six of the 520 were space tourists, and two were commercial private spacecraft astronauts (Anikeev, 2011). Moreover, many professionals and students, among them one of the coauthors of this article (I.L. Schlacht), have experienced suborbital 0g flights with simpler medical fitness checks. This means that only two of the 520 astronauts were outside of the agencies’ aptitude-based selection. In the future, with improvements in the conditions of space habitability and greater involvement by private spacecraft, more and more humans will go to space without aptitude-based selection.

In training for long duration space missions, like Earth orbit and Moon or Mars missions, the creative process is a fundamental contribution to mission success. As mentioned by Martius, creativity stimulates the learning process and self-awareness in relation to the environment (Martius et al., 2008). Creative expression may extensively contribute to psychological stability and to astronaut safety. Music, poetry, and painting are art mediums that can be used in space for self-expression or for expressing ideas, adding also a new dimension to knowledge. As the psychologist Csikszentmihalyi (1996) explains, “Creativity … leaves an outcome that adds to the richness and complexity of the future” (Schlacht & Ono, 2009).

Artificial Adaptation

How can these humans adapt other than from aptitude selection to the extreme Space environment? One option could be the physical integration of technology with the human body to approach extreme environmental conditions, in order to create a new “cyborg” identity that transcends the boundary of “the relationship between *inner space* to *outer space*” (Halacy, 1965). This concept is based on the cybernetic idea of a powered exoskin to survive in extreme environments, and is nothing other than the space suit. Indeed, a *cyborg*, or a human being with an integrated machine, was intended by Clynes and Kline (1960) to support extra-terrestrial exploration: “Altering man’s bodily functions to meet the requirements of extra-terrestrial environments would be more logical than providing an earthly environment for him in Space". One less acceptable hypothesis discussed within the space industry was the use of smaller humans to fit better in space stations (source: personal communications to Irene Schlacht from Space staff in November 2005). However, ethical constraints must *absolutely* be observed since astronauts need to represent humanity in its integrity, as underlined by Prof. Ernst Messerschmid (personal communication to Irene Schlacht, Stuttgart 2009).

If the human being is "taking an active part in his own biological evolution" (Clynes & Kline, 1960), allowing himself to be artificially modified or manipulated by genetic engineering to fit into the extraterrestrial environment, then he may obviously end up as a new species…! Ultimately, *cyborgs* appear to be a "useless" human manipulation to fit with something that has already adapted, so we are likely to encounter a few difficulties before inhabiting the Moon or Planets.

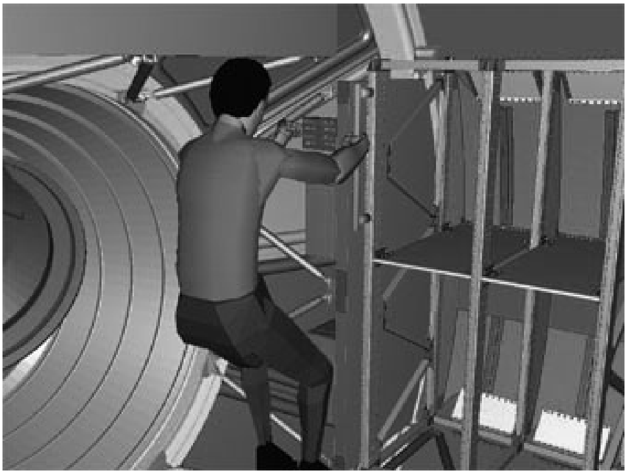

Fig. 2. Astronaut at work in 0g: computer graphics mannequin (courtesy of Thales Alenia Space, Torino, Italy)

Natural Exaptation

Fundamentally, in order to live in the Space environment, a different process of adaptation is needed. As we have said, one such process is the aptitude-based selection and training program applied by agencies, another is the adaptation of the environment to support human life, in an attempt to create a sustainable and Earth-autonomous habitat. However, where the environment can not be adapted, there is a third possibility: exaptation. Exaptation, first proposed by Gould and Vrba means that the 'archetypal' structures developed by an organism for specific needs are co-opted by the new environment to evolve into new functions (Gould & Vrba, 1982; Gould, 1991). It is similar to the case of certain types of dinosaurs of small dimensions who, via natural selection, developed

Fig. 3. Ballistic leap of an Indri Lemur (Original photo by Viviana Sorrentino).

feathers, since features were useful for protecting them from the increasingly cold environment. Subsequently, this same feature, being already present, allowed them then to fly as they evolved into birds. With the exaptation mechanism, "different adaptive patterns may derive from unusual environmental conditions. This approach may be the challenge for extraterrestrial adaptation of Earthly organisms". One example is the capacity of humans to move and coordinate themselves in the absence of gravity. It may be thanks to the same exaptation, that introduced the 'archetypal' structures which developed in Lemurs to enable them to perform ballistic (micro gravitational) leaps from tree to tree - then 0g considering Lemurs low *Reynolds number* aerodynamic lifting efficiency, owing to mostly turbulent airflow and the absence of airfoil shaped body surfaces (cf. Torres & Mueller, 2001) - that will ultimately enable astronauts to move in the absence of gravity (Masali et al., 2010).

Some Evolutionary Questions: Exaptations or Co-opted Traits?

Hence, we may find a better explanation for the adaptation process to Space by extending the concept of exaptation. Put simply, this means that 'archetypal' structures developed by an organism for a specific need are co-opted by the new environment to evolve into new functions, but the question is complicated by environments quite different from the Earthly ones.

From this perspective, Darwinian evolution may be seen as historical courses of action, and not simply a sequence of stochastic events, irrespective of time and place. In actual fact, adaptive events in a species occur according to particular circumstances. In living species, the stochastic nature of evolutionary events as an ensemble of unpredictable changes arises as the evolutionary causes are not identified with the ensuing effects. Yet, in historical contexts, an ensemble of causes appears to have led to the origination of events. These events are only possible where there is positive fitness within the limited dominion of a factual environmental context (Masali, 1994). Such a *modus operandi* (*teleonomic* as intended by Monod, 1970) establishes a sort of 'project' in the living organism generated by all the events of its past channeled through the environmental constraints. Such a view would allow the following historical perspective of events to be applied also to the present, and possibly to the future. In accordance with which different adaptive patterns may derive from unusual environmental conditions. And this may be the key for extraterrestrial adaptation by Earthly organisms.

Physical Adaptation and Cultural Needs

The genetic code, which is continually replicated and extremely constant (despite all the mutations), provides, perhaps, the most important biological answer to the historical question of actual natural history. While in a general context, biology without a historical perspective can not be fully understood. Yet in the dawn of a new world, this may be the only way to understand evolution. Whether or not natural selection is the only known causal process capable of producing complex functional organic mechanisms**,** it may be important to establish its possible effects on cultural aspects. Adaptation and natural selection are also central concepts in emerging sciences aimed at understanding human behavior.

A short time ago, S. J. Gould (1991) proposed that exaptation and spandrel traits may be more important than evolutionary adaptations in the cultural domain (Buss et al., 1998). Gould suggested that many primary cultural characteristics, despite having evolved, are complementary spandrels of the human brain. Anthropological and psychological sciences may draw from the conceptual and evidentiary in order to consider the relative utility of these concepts in a completely new environment. The newness of the environment relating mostly to gravitation, since the other environmental parameters (air pressure, dampness, light, water, waste, isolation, crowding, etc.) can be satisfactorily resolved by technology and good ergonomic user-centered design – but there is no shielding from the forces of gravity (except centrifugal hyper gravity).

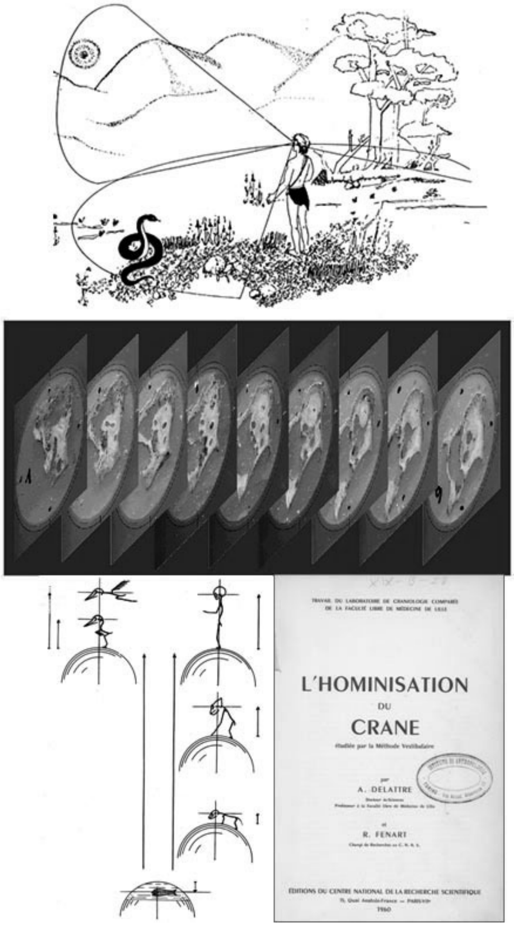

Fig. 4. The "vestibular" perception of the world and gravity (Author's original and Delattre& Fenart 1960).

Gravitation, Evolution and Space Adaptation

Gravitation is the most stable environmental factor on Earth; the evolutionary history of all living beings involves a natural adaptation to it. Hominids walking upright are a by-product of gravitational adaptation by antagonism (Humans and the other Primates react to Gravity developing complex postural and locomotion structures and behaviors). However, zero gravity, Moon gravity, and the hypo- and hyper-gravities of the Solar System's planets and moons are conditions for which terrestrial organisms have not as yet been naturally evolved.

Gravity-force or earthly gravity, otherwise referred as the "little-g" or (g), is the free fall of mass in the gravitational field on the surface of the Earth. It is certainly a component of the environment which may be perceived at a first approximation as a physical constant; something like, and frequently confused with, Newton's universal gravitational constant, the 'big G'. At the Earth's surface the gravitational field shows only variations detected by sophisticated precision instruments, with virtually no effect on the living. Gravity is a weak force (a small magnet attracts a nail as opposed to the mass of a planet), yet nevertheless, it has absolute influence in determining the survival of living animals or plants and no species can survive if it is not adapted to the gravitational environment.

This brings us to the work of the French scholar, Professor A. Delattre (and his senior anatomist R. Fenart from the Libre Université de Lille) who, in the 60s, proposed gravitation and in particular its effect on the organs of equilibrium located in the inner ear in the vestibule of the membranous labyrinth, as the fundamental cause behind the evolution of the human form (Delattre & Fenart, 1960). Their 'Methode vestibulaire' formed the basic principles that enabled us to design a path in Hominids evolution from equatorial forest to the grassland ecosystem, and to better begin to understand human postures in extreme conditions such as on the surface of the Moon, travelling in interplanetary space, or even climbing the Nix Olimpica on Mars.

Unfortunately, the oeuvre of Delattre is overlooked by most scholars who deal with human postural evolution: we could not find a single reference to the function of the labyrinth and vestibule in investigations reported in an exhaustive review on "Fifty Years of Debate on the Origins of Human Bipedalism" (Senut, 2012) at the XIX Congress of Italian Anthropologist held at Turin in 2011. This fault may have resulted in a serious bias in the interpretation of the hominization process.

A vestibular (gravitational) interpretation of human morphology shows that the equilibrium organ, represented by the semicircular canals, kept a constant stable spatial orientation throughout the entire postural evolution process, while the body tilted vertically through a complicated path from primitive terrestrial to arboreal vertical ancestors, in about 60 My. The consequences of the effects of the spandrel from the tilting of the *basicranium* (skull base) may have been the additional anatomical space, spandrel-trait breathing space, for future brain development. It now seems to be generally accepted that the hominid brain increased in dimensions after the adaptation to man-like structures even at the level of the ear-bones (Quam et al., 2013).

Ergonomics, Shape Anthropology and Space

Living in Outer Space has recently inspired a vast amount of literature in the fields of space technology, medicine and psychology.

As humankind faces peculiar environmental conditions affecting locomotion, working capabilities and general living, new forms of biological and socio-cultural adaptations

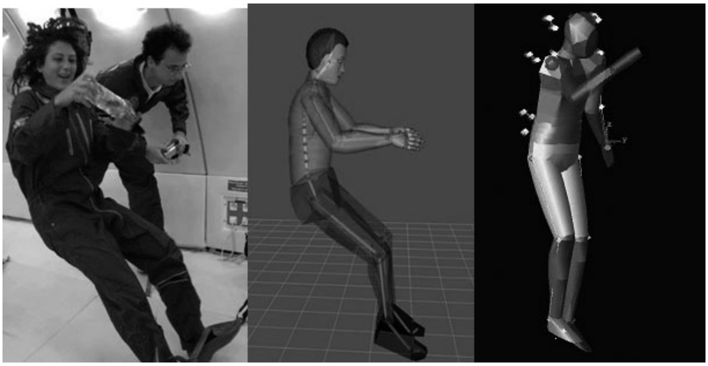

Fig. 5. 0g neutral posture: a) co-autor in parabolic flight, b) computer grapfics , c) optoelectronic mannequin (a: original by Irene L. Schlacht; b,c: courtesy of Thales Alenia Space, Italy).

are likely to occur. This represents an enormous challenge for human research. Since good interior design and interface usability will depend on human characteristics that are modified by variations in the environment, it will be necessary to urge a re-thinking of the whole concept of human 'well-being' (Ferrino & Gaia, 2003).

In a spacecraft, body shapes are modified, reflecting human variability, and also the physiological adaptation to zero gravity. In space station experiences: from the Salyut orbital stations, to Cosmos, Skylab, Mir and the now orbiting ISS Alpha, everyday objects, such as toothbrushes, may be lost due to the visual chaos and the lack of 'up-and-down' references. During long space missions in micro-gravity, social interactions are constrained, and astronauts have to deal with psychological stress and difficulties in communication. Concepts such as power and gender, which are strictly linked to human bodies and their symbolic and physical functions, are going to change in a place where gravity is absent. Within the space domain, physical and cultural anthropology seem to belong to a less exploited field. One exception is anthropometry, limited to its strict meaning, the measurements of man: the astronaut.

From studies on shape in space, the neutral posture was defined as, *inter alias*, by the experiment "Human Posture in Microgravity". Results confirm the excellent metamorphosis capability of motor arrangement by the central nervous system in order to best exploit environmental constraints. Moreover, the project allowed the construction of anthropometric mannequins using 'Jack' computer graphics (REAL MAN IST-2000-29357**).** Our cooperation, albeit limited, in the anthropometric method to measure the astronaut and the provision of an Anthropometer, has enabled our team to get to the root of the problem by stimulating the search for behavioral archetypes present in humans.

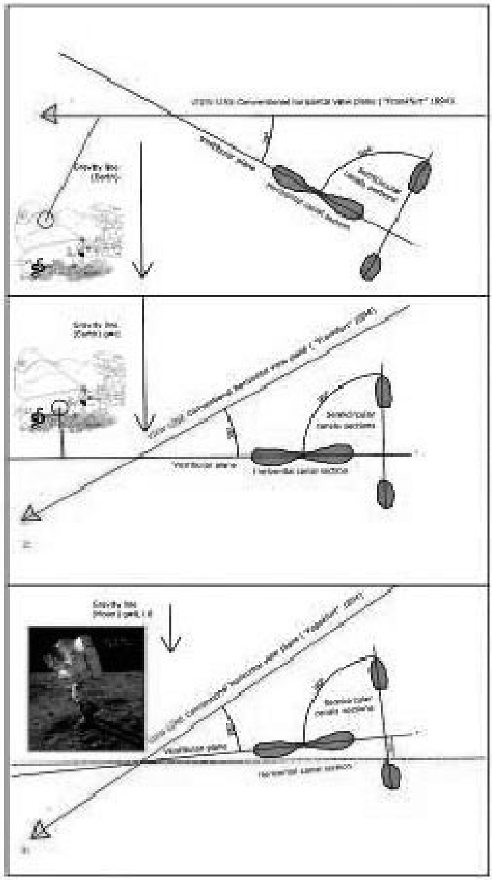

Fig. 6. View line when head is oriented a) in the "Frankfort Plane (O.A.E.)" b,c) in the "Vestibular Plane" c) as expected on the Moon".

Adaptation: a Human Factors Question?

One of the focal points of our inquiries (as a part of the Extreme-Design.eu research team) is the study of body movement, orientation and posture which are influenced by gravity. Our hypothesis is that if gravity decreases, the body loses its 'upright posture' being less enforced by vestibular reflexes, which converge to the 'neutral posture'. As a consequence, in microgravity the ground point at which the view is aimed should be closer.

Although, as astronaut Armstrong stated, there is no 'difficulty walking', the difference in gravity on the Moon affects the upright posture, and he suggested that astronaut

Aldrin test methods for moving around, including two-footed kangaroo hops. Which, incidentally, reminds us how some Lemurs walk, keeping the same upright posture on the ground acquired in the forest by arboreal vertical clinging (Napier & Walker, 1967): another exaptation? However, on the Moon, the angle of vision generated by vestibular reflexes can be tilted more toward the ground. An image of the posture of astronaut Mitchell (Apollo 14) identical to that of astronaut Aldrin (Apollo11) provides evidence and perhaps we can prudently begin to measure the effects.

Microgravity alters the movements and the capacity for orientation, as witnessed by the French choreographer Kitsou Dubois**:** gymnastics and dance can be performed in little or no gravity, offering a new opportunity to develop the study of human movement when highly formalized with optoelectronic techniques (Buraud, 2009). In our opinion, the complexity of such extreme types of physical activity strongly related to gravity could provide ample opportunities for study when devoid of the major parameter: weight (Masali et al., 2009).

An improbable task: Building a "new Man"*?*

The main question that arises is whether the solution lies in adapting humans– in the near future, say in the next 10,000 years, based on some very recent positive selection observations regarding the adaptation of modern humans to local conditions (Voight et al., 2006) –or the environment to humans. Earth's mimicry of the vital parameters and life environment, should be mostly obtained from a careful design of outer space crafts, both vehicles and planetary living structures, according to human factors and ergonomics principles (Schlacht et al., 2008). The task is to design structures to maximize human well-being. Such a task may be complicated but is possible with: air, warmth, water, elimination of waste, and food. Gravity is the real difficulty; unless space designers build something like the Spacelab squirrel-cage footpath or other types of devices to simulate weight. However, living in a centrifuge on a spacecraft requires a continuous engine thrust to generate weight by acceleration. Otherwise gravity, the mould of the human form, remains an irresolvable factor.

Finally, when attempting to understand the effects of aptitude selection on genetics, morphology and culture in future space humans, the risk is to create a new isolated human population, rather like the ongoing Caribbean working/climbing group, observed operating at high altitudes, particularly in the Italian Dolomites in a landscape similar to the surface of the Moon. Another bottleneck event? (Argenta, 2008).

The "Bottleneck" theory attempts to describe the impacts of small founder groups on present wider populations: there is a strong consensus that modern humans originated in Africa, and moved outwards to colonize the world, approximately 50,000 years ago (Amos & Hoffmann, 2009). During the process of expansion, a significant degree of genetic variability was lost, creating a linear gradient of decreasing diversity with the increasing distance from Africa. However, some essential traits concerning adaptation to the different environmental and climatic conditions were radically modified. The exact way in which these events occurred remains somewhat unclear: did it involve one, several, or a continuous series of population bottlenecks? Could the events be associated with exaptations? Will we be facing similar events in Space, with reduced biodiversity and increased co-optation of specific traits? It seems to be a contradiction; nevertheless a few key genes with high fitness in the new environment may lead the exaptation process so that the new population may eventually appear to be considerably different from the original. Cameron Smith (2013) proposes something like a new species (*Homo extraterrestrialis*). Whereas we are rather more inclined to believe that instead of a *H. novus* (Masali, 2010) there will be humans, with a different appearance, and only a fragment of terrestrial heritage. Hence, the Moon and Planets will have a highly selective population with very limited genetic heritage starting with a highly select group of astronauts.

ACKNOWLEDGEMENTS — Our thanks and acknowledgements go to Prof. E. Fubini, Arch. Alessandra Fenoglio (Life Sciences and System Biology Dept. University of Torino, Italy); Ing. E. Gaia, Dr. M. Ferrino, Arch. G. Musso (Thales Alenia Space, Torino, Italy); Prof. Mila Tommaseo Ponzetta (Universities of Bari and Padua).

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