GEOTHERMAL ENERGY IN PLANETARY ICY LARGE OBJECTS VIA COSMIC RAYS MUON–CATALYZED FUSION. A. de Morais, Brazilian Center of Physics Research (Rua Dr. Xavier Sigaud, 150, 3º andar, Urca, Rio de Janeiro, RJ, 22290-180, Brasil, Email: antonioamore@yahoo.com).

Introduction: In this brief paper, we propose the possibility that p^+-d^+ and d^+-d^+ fusions intermediated and catalyzed by the elementary particles muons (μ^-), produced by cosmic rays, might hypothetically add energy to geothermal reservoirs in the interior of planetary icy large objects of the Solar System, and of other extra-solar planetary systems, interesting for astrobiological considerations. Well, it is known, since the discoveries in the planetary Solar System by the NASA's Voyagers 1 and 2 spacecrafts in the l980's decade, that the four gaseous giant Jovian planets – Jupiter, Saturn, Uranus and Neptune, possess natural satellites displaying on their surfaces (mostly icy ones) recent geologic activity [17]. These moons include Jupiter's Io, Europa and Ganymede, respectively with its active volcanoes, its internal saline seas, and its rugged surface indicating a possible internal ocean of liquid water. Other moons are Saturn's Titan and Enceladus, respectively with its liquid CH_4 and C_2H_5 seas and with its water vapor geysers and global internal ocean of liquid water. Uranus' Miranda, which displays on its icy surface a complex geology, and Neptune's Triton which shows present-state geological activity as geysers expelling dark material from its subsurface. A major heat source for icy satellites of the giant planets is tidal dissipation via orbital resonances [14] [17]. And heat within these objects is also generated by the radioactive decay of internal elements left over from the time of their initial formation. In July 14, 2015, the John Hopkins University's Applied Physics Laboratory – Southwestern Research Institute – NASA's New Horizons spacecraft made the first close flyby over Pluto and its system of 5 moons, being Charon the largest one. Initial data from New Horizons flyby were analyzed by the mission team, and first results were completely intriguing. We are learning that Pluto (and to a lesser extent, Charon) show complex, dynamical, present geologic activity [17]. Models involving tidal dissipation, which would indicate geologically "quiet" worlds, do not account for such present geological activity at Pluto, for the existence of tidal dissipation is necessary orbital eccentricity, which is practically zero in the Pluto–Charon system. Besides such forms of geothermal energy sources as tidal and radiogenic heating, there is another one, fusion of protons in planetary interiors which was mentioned in the literature [9] [10] [13] [27]. It is usually assumed that such nuclear reactions occur only in the star interiors, but there is an elementary particle, muon (μ^-), that can intermediate such reactions in the low-temperature planetary conditions (as compared as to temperatures inside stars) [16]. This natural phenomenon is known as muon–catalyzed fusion (MCF). MCF was first theoretically proposed in the 1940-50's decades [6] [28], and experimentally observed since the 1950's decade [2] [3] [12] [22]. When a muon (μ^-), which lifetime is ~ 2 x 10^{-6} s, interacts with a proton (p^+) and/or a deuteron (d^+) (forming a p^+-μ^--p^+, a p^+-μ^--d^+ or a d^+-μ^--d^+ molecule, during ~ 10^{-11} s), it approximates them to a distance about 207 times smaller than in H_2 molecule with electrons, a catalysis sufficient for their fusion. The reaction $dd\mu \rightarrow {}^3He + n + \mu$ yields a Q = 3.3 MeV, with a reaction rate λ_r ($dd\mu$) ≈ 3.5 x 10^{10} s^{-1}. The reaction $pd\mu \rightarrow {}^3He + \gamma + \mu$ yields a Q = 5.5 MeV, with a reaction rate λ_r ($pd\mu$) ≈ 1.8 x 10^5 s^{-1} [8]. The number of reactions one muon can catalyze was experimentally observed to be about 150, due to the alpha-particle sticking problem [8], but this can be overcome by multiple collisions, which occur normally in icy worlds temperatures. Thus, for just one muon it can yields a minimum of Q = 500 MeV during its multiple reactions until it disintegrates. But where can we find so many muons for their reactions to give some thermal energy inside icy worlds? The most abundant source for muons is cosmic rays, which origins are solar, galactic and extra-galactic. Daily on planet Earth, an enormous quantity of high (~ 10^2 MeV) to extremely high (> 100 TeV), and higher energy (~ 10^{19} eV) protons and nuclei strike nuclei of atoms in the atmosphere, producing cascades of pions (other elementary particle) which decay into muons. Such muons arrive at the Earth surface with energies ranging typically from 10 GeV to 100 TeV and, depending on their energies and on the material, they can penetrate most deeply into liquid and ices than into rocks. For instance, for E_μ = 10 GeV it can penetrate 0.05 Km, and for E_μ = 10 TeV it can penetrate 6.09 Km into rocks [19]. Inside the ices of Antarctica it was measured many muons as deep as 7 km [5], and inside the Baikal lake it was measured muons at 6 Km deep [4], and at the Mediterranean sea it was measured muons at > 10 Km deep [20]. Muons also lose energy by ionization and by radiative processes which adds energy throughout their trajectories. Thus, at a depth of 1 km of rocks their flux is ~ 10^{-6} than at the Earth's surface. About data on cosmic rays in the Solar System, we are fortunate because the two Voyagers are in operational status. The Voyagers' cosmic ray subsystem measured a somewhat spatial steady flux of cosmic rays throughout their trajectories in the Solar System, but variating in time and anti-correlated to sunspots activity [18]. The measured fluxes began to rise in the outer regions of the heliosphere, where the Sun's magnetosphere is weaker due to the distance [11] [18] [21]. For objects in the outer Solar System, an enormous quantity of muons are dayly produced by an enormous quantity of cosmic rays striking the icy surfaces of the Jovian moons, and of the Trans–Neptunian Objects (TNOs) as the dwarf planet Pluto. During the flybys of the Jupiter and Saturnian systems by the Voyagers, they collected data on the energy and flux of high-energy cosmic rays protons trapped into the Jovian magnetospheres, feeded constantly [23] [25]. The trapped protons energies of ~ 10^2 Mev to 1 GeV in the leading and trailing sides of both planets [24] [26] bombards constantly their moons, creating continuous showers of muons to their interiors. As for planet Mars, cosmic rays measurements by spacecraft [17] indicate the production of muons at a similar to or higher rate than on Earth's surface [15] due to the lack of a Martian global shielding magnetic field, thus many muons go into the interior of Mars. For more MCF to occur it is necessary the existence of large quantity of deuterons. Due to equilibrium and kinetic dynamical factors, it is modeled that icy objects that formed farther out in the Solar System (and other extra-solar planetary systems [17]) should generally have higher deuterium content in their ice than objects that formed closer to the Sun, and objects that formed in the same source regions and at similar times should have accreted ice with similar hydrogen isotopic compositions [1]. The observed D/H ratio in the inner Solar System is ~ 10^{-4} [7], which are believed to be higher in the outer Solar System [1], perhaps with D/H ~ 10^{-3}. These ratios are small, but due to the fact the icy bodies are so abundant in the Solar System, the quantity of deuterons might be sufficient for regular MCF to occur via cosmic rays muons. So, integrating time over 4 Gyrs, there were enough time for many muons to have intermediate catalyzed fusion via pdμ and ddμ reactions, yielding regular energy for the interiors of large icy objects in the Solar System. Even being so small in geological energy terms (1 GeV = 1.6 x 10^{-10} J) such MCF energy might have being significant for the energy balance inside the primitive Earth, Mars, the Jovian icy moons, the icy TNOs, and icy worlds of extra-solar planetary systems. Such deposited fusion energy might hypothetically be significant for geological activities observed on the surfaces of the Jovian moons and Pluto, with $\langle T_s \rangle$ ~ 110 K and $\langle T_s \rangle$ ~ 44 K, respectively [17], and other icy TNOs. In such low temperatures, a small quantity of fusion energy might appear on the surface as geological activity. And we also propose that MCF might also be significant for the energy balance in the formation of geothermal reservoirs (with liquid water) inside those icy large objects (hydrated minerals, ponds, small lakes and seas), long enough in time for the maintenance of internal chemistries interesting to astrobiology.

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