22. Jolliff et al. 2011, Nature Geosci., doi:10.1038/ngeo1212.
23. Jolliff et al. 2012, 43rd LPSC, Abs. 2097.
24. Lipman, P.W. 1997, Bull. Volcanol., 59, 198-218.
25. Lipman, P.W. 2000b, Academic Press, San Francisco, 643-662.
26. Malin, M. 1974, EPSL,21, 331–341.
27. Martí, J. et al. 2009, Volcanology, Geol. Soc. Lond., 2, 249-266.
28. Petro, N. E. et al. 2013, LPSC, Abs. 2688.
29. Prockter, et al. 2010, Science, 329, 668–671.
30. Rutherford, M.J. and Hess P.C. 1975, Proc.6th LPSC, 696-698.
31. Rutherford, M.J. and Hess P.C. 1978, Proc. 9th LPSC, 987-989.
32. Sanchez, L. and R. Shcherbakov 2012, Nonlin. Proc. Geophys., 19, 585-593, doi:10.5194.
33. Shaw, H. 1968, Ann. Mtg. Geol. Soc. Amer., 274-275.
34. Stolper, E. 1982, Geochim. Cosmochim.Acta, 46, 2609-2620.
35. Wilson, L. and Head, J. W. 2003, JGR,108, 5012.
36. Wilson, L. 2009, Nature Geosci., 2, 388-396, doi:10.1038/ngeo529.
37. Wood, C.A. and Head, J. W. 1975, Lunar Sci. Inst., Houston, Tex, 234, 189-193.

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Cave Biosignatures on Earth: Implications for Extraterrestrial life

The key to understand past microbial life would be possible, if microbes left behind evidences of their activity, directly or indirectly. Microbes are known to often leave various evidences of their presence/activity and terrestrial cave ecosystems are reported to preserve biosignatures. Martian caves have renewed scientific excitement in the field of speleology as they are considered potential sites for future human habitation and astrobiology research. Basaltic volcanism is generally considered analogous between the Earth and Mars (e.g., Glaze et al., 2005) and volcanic caves are common on Mars. Occurring frequently in terrestrial basaltic volcanism, lava tubes are expected to be common in Mars's volcanic regions as well (e.g., Horz, 1985; Keszthelyi, 1995; Sakimoto et al., 1997). Cave entrances into Martian near-surface lava tubes, volcano-tectonic fracture systems, and pit craters are similar to terrestrial features such as tube-fed lava flows, volcano-tectonic fractures, and pit craters, that can produce caves (Cushing, 2012).

Because of the harsh Martian environment like dust storms, extreme temperature variations, high UV and cosmic rays (e.g., Mazur et al., 1978; De Angeles et al., 2002; Boston et al., 2004; Cushing et al., 2007), the organic materials cannot withstand such extreme environmental conditions. It is therefore assumed that Martian caves may be among the few human-accessible locations that preserve evidence of whether microbial life ever existed. To understand Martian sub-surface ecosystem, it is necessary to understand the Earth's subsurface ecosystem. The terrestrial caves due to unique biogeochemical conditions provide one of the best possible sites to look for the existence of life and their characteristic biosignatures. The term "Biosignatures" can include any one or combination of the following: microfossils, fossilized filaments, microfabrics, microbial mats/ biofilms, genetic data, biomineral formation, stable isotopic values consistent with microbial metabolism and unusual concentrations of certain elements.

Interestingly, carbonate minerals have now been identified in a wide range of localities on Mars as well as in several martian meteorites. The martian meteorites contain carbonates in low abundances (<1 vol %) and with a wide range of chemistries (Niles et al., 2012). The carbonate caves in earth are the dominant category. Speleothems are mineral deposits formed in caves, typically in karstified host rocks (Gunn, 2004). Caves are subsurface, nutrient-deficient ecosystems and usually dark due to lack of penetration of sunlight in deeper parts. Caves are reported to host diverse microbial communities. During the early Earth conditions, microbial life survived in an environment with limited nitrogen availability. Majority of the early earth microbes used minerals as their source of energy as the process of photosynthesis had not started. When compared to the surface environments, caves ecosystems are protected subsurface environments that are less vulnerable to weathering, UV radiation, temperature fluctuations and grazing by higher organisms. Thus, cave environments are ideal candidates to explore ancient evolutionary relationships, subterranean systems, microbial metabolic pathways and to understand biosignatures (Groth et al., 1999, 2001; Laiz et al., 1999, 2003; Schabereiter-Gurtner et al., 2002; Barton et al., 2004; Chelius and Moore, 2004). Caves being windows to the subsurface, allows direct access to the subsurface environment for study and experimentation. In caves it is easy to make observations, select specific areas to perform on-site experiments, repeat experiments without cumbersome, time consuming and costly processes like drilling.

Past three decades of research in cave geomicrobiology has led us to understand that microbial metabolic activities in caves often lead to *in vivo* lithification and *in situ* preservation. The elements present in the cave deposits get transformed during the various metabolic process of diverse microbial communities. Microbes do this for their own survival and benefit as they gain energy through various redox reactions (e.g., Ehrlich, 1996; Banfield and Nealson, 1997; Boston, 1999a). The application of a biosignature for astrobiological purposes depends on the degree of preservation and post-fossilization alteration processes. In cave geomicrobiological studies, researchers have reported and identified various structures and mineral types that appear to be biological in origin or as an indirect result of biological activity (Northup et al., 1997, 2000; Boston et al., 1995, 1999b, 2000, 2001; Melim et al., 2001; Spilde et al., 2001; Baskar et al., 2014). One of the important biosignatures identified in the Indian caves is moonmilk (Baskar et al., 2011; 2014).

Moonmilk

Moonmilk reported from some cave environments, has attracted the scientific attention of geomicrobiologists. Moonmilk is a type of speleotherm, typically reported from the ceilings, floors, and walls of carbonate caves (Fischer, 1988; Hill and Forti, 1997). Carbonate dominates the known moonmilk composition (about 95%), while 5% of the moonmilk deposits are represented by sulphates, phosphates, and silicates precipitated in unspecific cave environments (Chirienco, 2004). Moonmilk mineralogically consists of micrometer to nanometer-sized crystal aggregates of calcite, hydromagnesite, aragonite, gypsum, and also minerals such as silicate, phosphate, and sulfate.

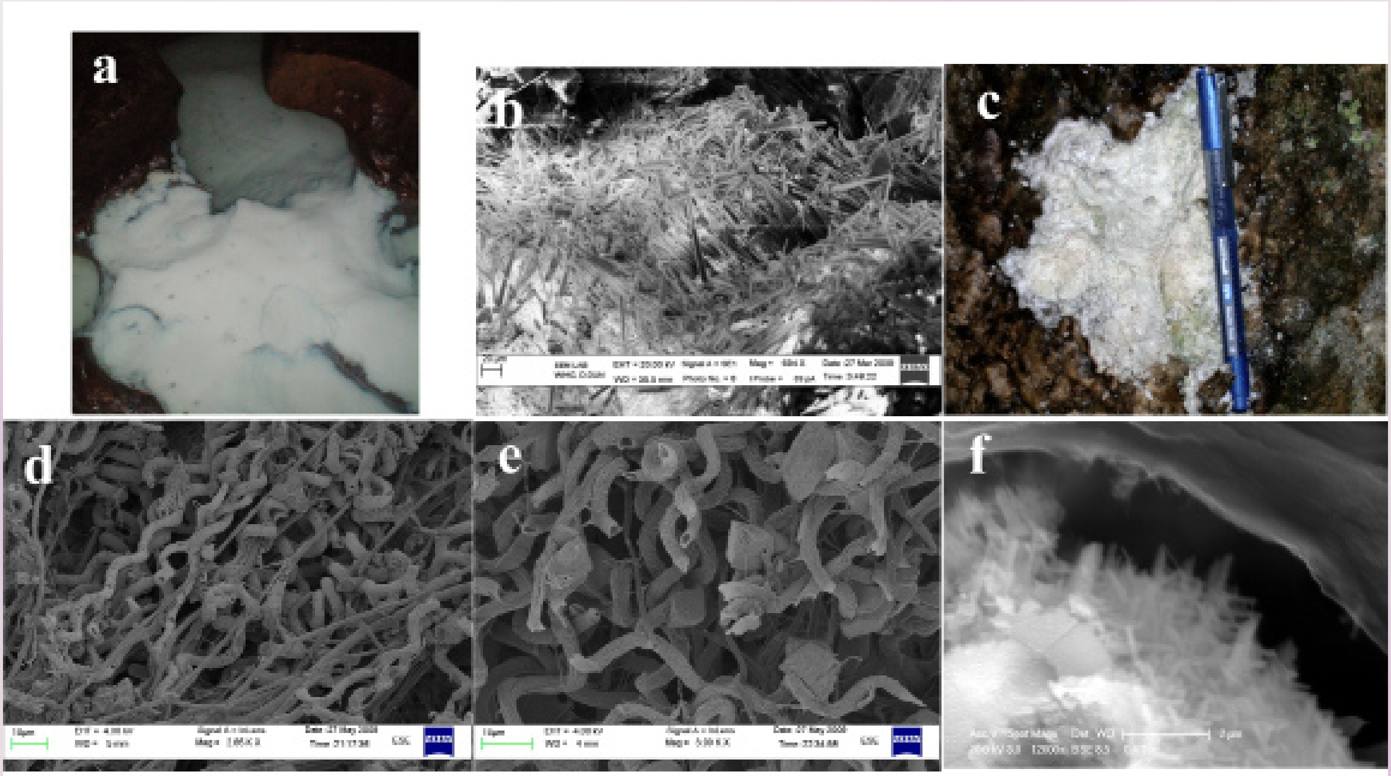

Figure 1: Moonmilk from Krem Mawmluh, Meghalaya and Sahastradhara cave, Dehradun
(a) Moonmilk seen as floor deposit in Krem Mawmluh, Meghalaya
(b) SEM of Krem Mawmluh moonmilk showing abundant needle-fibre calcites and microfibers
(c) Moonmilk sampled from cave wall at Sahastradhara cave, Dehradun
(d, e) SEM of Sahastradhara moonmilk showing enormous number of microbial structures similar to Spirulina, Cyanobacteria and bacterial filaments
(f) ESEM without coating (wet mode) of Sahastradhara moonmilk showing fibre calcites.

Physically, hydrated moonmilk is pasty, cottage cheese like with 40-96% water content, some traces of organic matter and other insoluble clay minerals. It is dominantly white in colour and sometimes appears black or in other hues. The morphological appearance of moonmilk is diverse as some deposits appear like a cauliflower with serrate flower like edges; some are botryoidal, round and smooth, while some others are reported to be knobby (Fig. 1a, c). Microscopically, moonmilk has needle-shaped or fibrous crystal morphology (e.g., Gradzíñski et al., 1997; Cañaveras et al., 2006; Bindschedler et al., 2010). Association of carbonate minerals with microbial filaments is also reported from Krem Mawmluh moonmilk deposits in Meghalaya, India (Baskar et al., 2011). In this deposit, scanning electron microscopy photomicrographs showed abundant fibre crystals (Fig. 1b) and the total viable culturable microbes showed high population densities. Scanning electron microscopy of the deposits at Sahastradhara showed that they were colonized by a microbial community similar to Cyanobacteria and Spirulina (Fig. 1d, e; Baskar et al., 2014). The furry moonmilk has also been observed in Sahastradhara caves, Dehradun, India. Environmental scanning electron microscopy showed that the crystals were found developing in a closed microbial network (Fig. 1f; Baskar et al., 2014). Further, these authors conducted culture experiments, which demonstrated that many of the bacterial strains isolated from moonmilk were able to induce calcite precipitation *in vitro.*

In addition to moonmilk, Boston et al., (2001) has identified/ recommended three more potential biosignature in caves suitable for astrobiological applications. These include: snottites, pool fingers and filamentous manganese snow.

1. ***Snottites:*** Snottites are similar to small stalactites that hang from the walls and ceilings of caves and have the consistency of mucus. In Cueva de Villa Luz, Tabasco, Mexico, selenite and gypsum crystals in snottites are precipitated *in situ* by novel Thiobacillus relatives (Boston et al., 2001). The chemically active cave system produces hydrogen sulfide and the cave enlargement occurs due to sulfuric acid driven speleogenesis (Hose and Pisarowitz, 1997; Hose et al., 2000).

2. ***Pool Fingers:*** These are finger shaped deposits found in caves (e.g., the Hidden Cave, New Mexico). They are lithified, stratified, elongate pool structures with micritic fabrics, entombed microfossils, and biogenic isotopic signatures (Melim et al., 2001).

3. ***Filamentous Manganese "Snow":*** This deposit consists of manganese, iron oxides, oxyhydroxides and associated microbial communities. Filamentous and fabric-like manganese "snow" deposits were reported from the ceiling of Lechuguilla Cave, New Mexico (Spilde et al., 2001). These deposits are a type of low-density mineral assemblage known as "corrosion residue" and may be related to microbial activity or abiotic processes (Spirakis and Cunningham, 1991).

Significance:

While selecting biosignatures, it is important to rule out materials that appear biogenic in nature whose genesis is purely physical/ or chemical (Little et al., 1991; Kirkland et al., 1999; Cisar et al., 2000). Further, sample preparation techniques are important as it can result in loss of microbial biomass, dehydration and/ or removal of extracellular polymeric substances and mineral alteration e.g. techniques involved in transmission electron microscopy, scanning electron microscopy and other imaging techniques (Little et al., 1991). Biosignatures for astrobiological studies should be detectable at both macroscopic and microscopic scales (Boston et al., 2001). If we encounter life in Mars, it is predicted that it would be microbial life hidden below the surface. Understanding and cataloging of cave biosignatures has great astrobiological applications as the subsurface of other planets and rocky bodies will be a geobiological target of future research and missions in the search for life beyond Earth (Boston et al., 1992; Boston et al., 2000a, b).

Further reading/References:

1. Banfield JF, Nealson KH. 1997. Reviews in Mineralogy, Geomicrobiology: Interactions Between Microbes and Minerals, Mineralogical Society of America, Vol. 35, 448 p.
2. Barton HA, Taylor MR, Pace NR. 2004. Molecular phylogenetic analysis of a bacterial community in an oligotrophic cave environment. Geomicrobiol. J., 21, 11–20.
3. Baskar S, Baskar R, Routh J. 2011. Biogenic Evidences of Moonmilk deposits in the Krem Mawmluh Cave, Meghalaya, India. Geomicrobiol. J., 28, 3, 252-265.
4. Baskar S, Baskar R, Routh J. 2014. Speleothems from Sahastradhara caves in Siwalik Himalaya, India: Possible biogenic inputs. Geomicrobiol. J., 31, 8, 664-81.
5. Bindschedler et al., 2010. Calcitic nanofibres in soils and caves: a putative fungal contribution to carbonatogenesis. Geological Society, London, Special Publications, 336, 225-238.
6. Boston PJ, Ivanov MV, McKay CP. 1992. On the possibility of chemosynthetic ecosystems in subsurface habitats on Mars. Icarus, 95, 300-308.
7. Boston PJ. 1995. Report: Preliminary Findings of the Mars Underground Consortium of Scientists, National Park Service, Carlsbad Caverns National Park,

Carlsbad, NM.
8. Boston et al., 1999a. Cave microbes: microbial mats lining hydrogen sulfide springs. Int. Symp. Subsurf. Microbiol. Abstr. 4, 36.
9. Boston PJ, Spilde MN Northup DE. 1999b. It's alive! Models of Martian biomarkers derived from terrestrial cave microbiota. Geol. Soc. Am. Abstr. 31, A303.
10. Boston et al., 2000. A garden inside out: microbial mats in springs, wall muds, and ceiling formations of a sulfur-dominated cave, Cueva de Villa Luz, Tabasco, Mexico. J. Cave Karst Stud., 62, 3, 198–199.
11. Boston PJ. 2000a. Life below and life "out there." Geotimes 45, 8, 14–17.
12. Boston PJ. 2000b. Bubbles in the rocks: natural and artificial caves and cavities as life support structures. In NASA Technical Memorandum: Mars Greenhouses: Concepts and Challenges: Proceedings from a 1999 Workshop, RM. Wheeler and C. Martin-Brennan editors, NASA, Kennedy Space Center, FL, 9–17.
13. Boston et al., 2001. Microbes, minerals, and mars. Astrobiology, 1, 1, 25-55.
14. Boston PJ, et al., 2004. Extraterrestrial subsurface technology test bed: Human use and scientific value of Martian caves: American Institute of Physics. Conference Proceedings, 699, 1007–1018
15. Cañaveras JC, et al., 2006. On the origin of fiber calcite crystals in moonmilk deposits. Naturwissenschaften, 93, 27–32.
16. Chelius MK Moore JC. 2004. Molecular Phylogenetic Analysis of Archaea and Bacteria in Wind Cave, South Dakota: Geomicrobiol. J., 21, 123–134.
17. Chirienco M. 2004. The crystalline phase of the carbonate moonmilk: a terminology approach. Acta Carsologica, 33, 1, 17, 257-264.
18. Cisar JO, Xu DQ, Thompson J, Swaim W, Hu L Kopecko DJ. 2000. An alternative interpretation of nanobacteria-induced biomineralization. Proc. Nat. Acad. Sci. USA 97, 11511–11515.
19. Cushing et al., 2007. THEMIS observes possible cave skylights on Mars: Geophy. Res. Lett., v. 34, L17201.
20. Cushing G.E. 2012. Candidate cave entrances on Mars. Candidate cave entrances on Mars. J. Cave Karst Stud., 74, 1, 33–47.
21. De Angeles et al., 2002. Lunar Lava Tube Radiation Safety Analysis: Journal of Radiation Research, v. 43 S41– S45.
22. Ehrlich HL. 1996. Geomicrobiology, 3rd edition., Marcel Dekker, New York.
23. Fischer H. 1988. Etymology, terminology, and an attempt of definition of mondmilch. NSS Bulletin, 50, 54-58.
24. Glaze LS, Anderson SW, Stofan ER, Baloga S, Smrekar SE. 2005. Statistical distribution of tumuli on pahoehoe flow surfaces:Analysis of examples in Hawaii and Iceland and potential applications to lava flows on Mars. J. Geophy. Res., v. 110, B08202.
25. Gradzíñski M, Szulc J Smyk B. 1997. Microbial Agents of Moonmilk Calcification. In: Proceedings of the 12th International Congress of Speleology, La Chaux-de-Fonds, 1, 275-278.
26. Groth et al., 2001. Geomicrobiological study of the Grotta dei Cervi, Porto Badisco, Italy: Geomicrobiol. J., 18, 241–258.
27. Groth et al., 1999. Actinomycetes in karstic caves of northern Spain (Altamira and Tito Bustillo): J. Microbiol. Meth., 36, 115–122.
28. Gunn J. 2004. Encyclopedia of Caves and Karst Science. Fitzroy Dearborn, New York.
29. Hill CA Forti P. 1997. Cave Minerals of the World. Huntsville, Nat. Speleol. Soc., 463.
30. Horz F. 1985. Lava tubes: Potential shelters for habitats. In: Mendell WW, editors. Lunar Bases and Space Activities of the 21st Century: Houston, Lunar and Planetary Institute, 405–412.
31. Hose L Pisarowicz JA. 1997. Geologic setting of Cueva de Villa Luz—a reconnaissance study of an active sulfur spring cave. In National Speleological Society Abstracts, National Speleological Society, Sullivan, MO, 71 p.
32. Hose et al., 2000. Microbiology and geochemistry in a hydrogen sulphide-rich karst environment. Chem. Geol., 169, 399–423.
33. Keszthelyi L. 1995. A preliminary thermal budget for lava tubes on the Earth and planets: J. Geophy. Res., v. 100, B10, 20411–20420.
34. Kirkland et al., 1999. Alternative origins for nanobacteria-like objects in calcite. Geology, 27, 347–350.
35. Laiz L, Groth I, Gonzalez I, Saiz-Jimenez C. 1999. Microbiological study of the dripping water in Altamira Cave (Santillana del Mar, Spain): J. Microbiol. Meth., 36, 129–138.
36. Laiz et al., 2003. Monitoring the colonization of monuments by bacteria: Cultivation versus molecular methods: Env. Microbiol., 5, 72–74.
37. Little et al.,1991. Biofilms: an ESEM evaluation of artifacts intro- duced during SEM preparation. J. Indust. Microbiol. 8, 213–221.
38. Mazur et al., 1978. Biological implications of the Viking mission to Mars: Space Science Reviews, 22, 3–34.
39. Melim et al., 2001. Evidence for microbial involvement in pool finger precipitations, Hidden cave, New Mexico. Geomicrobiol. J., 18, 311–329.
40. Niles et al., 2012. Geochemistry of Carbonates on

Mars: Implications for Climate History and Nature of Aqueous Environments. Space Sci Rev., (25th October, 2012), 1-28, DOI 10.1007/s11214-012-9940-y.

41. Northup et al., 2000. Evidence for geomicrobiological interactions in Guadalupe caves. J. Cave Karst Stud., 62, 2, 30–40.
42. Northup DE, Reysenbach AL, Pace NR. 1997. Microorganisms and speleothems. In: Cave Minerals of the World (Hill C. and Forti P. Eds). Nat. Speleol. Soc., Huntsville AL. 2nd edn, 261–266.
43. Sakimoto SEH, Crisp J, Baloga, S.M. 1997. Eruption constraints on tube-fed planetary lava flows. J. Geophy. Res., v. 102, E3, 6597–6613.
44. Schabereiter-Gurtner et al., 2002. Cave paleolithic paintings harbour complex and partly unknown microbial communities: FEMS Microbiol. Lestt., 211, 7–11.
45. Spilde MN, Brearley AJ, Papike JJ. 2001. Mn-oxide minerals from a terrestrial cave environment: biomarkers for the search for life on Mars? In: Program of the 32nd LPSC, 1454 p.
46. Spirakis C, Cunningham KI. 1991. Genesis of sulfur deposits in Lechuguilla Cave, Carlsbad Caverns National Park, New Mexico. In: Native Sulfur: Developments in Geology and Exploration, G. Wessel and B. Wimberley editors, American Institute of Mineralogy, Metallurgical and Petroleum Engineering, 139–145.

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Dust in Solar System

Introduction

Over the last couple of decades, there have been remarkable changes in the field of dust science due to in-situ space experiments on Galileo and Ulysses, remote sensing and observations of a spectacular dusty comet, Hale-Bopp. Ulysses[1] aimed to characterize the heliosphere as a function of solar latitude. The heliosphere is the vast region of interplanetary space occupied by the Sun's atmosphere and dominated by the outflow of the solar wind. The first satellite to orbit the Jupiter was Galileo[2], which made two passages in the gossamer rings, which are shown in Fig. 1. There was an impact-ionization detector to detect the dust impacts, which recorded events for both the passages and it was the first to show in-situ dust measurements from the dusty ring[2]. The Comet Hale-Bopp has been the brightest and most observed comet for the past century and it could even be seen with unaided eyes for many months.

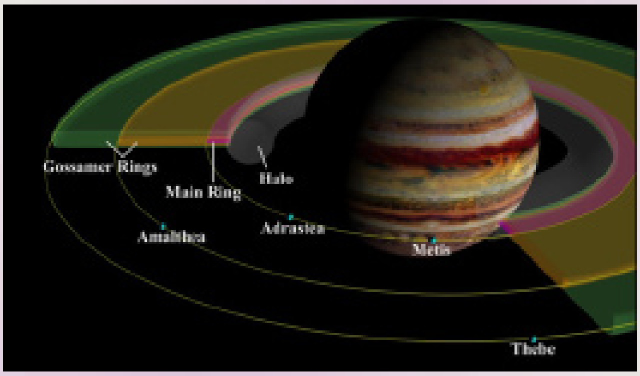

Figure 1: Jupiter's ring system[3].

The Cassini and Stardust missions have provided information regarding the dust from Saturn and the comet, respectively. Cassini-Huygens was sent to the Saturn as unmanned mission, which had a Cosmic Dust Analyzer (CDA)[4] to directly measure the speed, direction as well as the size of small dust particles near the Saturn. It is known that some of the dust particles near the Saturn rotate around the planet while the others may come from different star systems. The CDA has been designed to obtain more information about the unexplained dust particles which are actually the materials in celestial bodies. It is also likely that the study of dust particles by CDA may provide information about origins of the universe[4]. Stardust[5] was launched by NASA in 1999 as a robotic mission with major scientific objective to collect the dust samples from the coma of comet Wild 2 along with cosmic dust and return the samples to Earth for further laboratory analysis. Stardust[5] studied the asteroid 5535 Annefrank en route the comet during a flyby and it was the first mission of its kind that successfully completed the operation in 2006. Comets are space bodies made up of dust as well as frozen ice and they could be formed at distances very far from the orbits of planets in our solar system. The comets may include the matter from which the solar system was formed and such materials might have been preserved in ice for billions of years[6]. More-