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Instrumentation for Testing Whether the Icy Moons of the Gas and Ice Giants Are Inhabited

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Abstract

Evidence of life beyond Earth may be closer than we think, given that the forthcoming missions to the Jovian system will be equipped with instruments capable of probing Europa's icy surface for possible biosignatures, including chemical biomarkers, despite the strong radiation environment. Geochemical biomarkers may also exist beyond Europa on icy moons of the gas giants. Sulfur is proposed as a reliable geochemical biomarker for approved and forthcoming missions to the outer solar system. Key Words: JUICE mission—Clipper mission—Geochemical biomarkers—Europa—Moons of the ice giants—Geochemistry—Mass spectrometry. Astrobiology 17, xxx–xxx.

1. Radiation-Resistant Inorganic Biomarkers

To date, organics on Europa have not been detected. Furthermore, the radiation environment at Europa is so strong that any organics in existence, regardless of whether they are biogenic in origin, would have very short lifetimes (Teodoro *et al.*, 2016). Consequently, the potential to distinguish biologically mediated isotopic fractionation of elements among organic species on Europa's icy surface may not be possible (Cooper *et al.*, 2001; Barnett *et al.*, 2012). For these reasons, we have argued (Chela-Flores and Kumar, 2008; Chela-Flores, 2010) that it is unlikely that forthcoming missions slated for Europa or Ganymede flybys will ever carry instruments capable of detecting biosynthetic molecules unique to known cell biology, namely, amino acids, lipids, polysaccharides, and nucleic acids (either DNA or RNA).

A type of geochemical biomarker that would be immune to destruction by the intense radiation at the surface of outer solar system (OSS) moons, should they be present on Europa and other icy worlds, is inorganic S-bearing compounds that were isotopically fractionated by biological compounds. The inherent resistance of such compounds to radioactive destruction is especially important given that the Galileo Mission detected sulfur in patches at the moon's surface at locations such as Castalia Macula (0°N, 225°W), which is of relatively recent origin (Prockter and Schenk, 2005). The JUICE mission (Grasset *et al.*, 2013) and the Europa Clipper (Phillips and Pappalardo, 2014) carry instruments that could potentially investigate S isotopes in sufficient detail to detect an S biomarker.

Evidence of life beyond Earth may be within reach among these solar system moons. Pappalardo *et al.* (2013) reviewed the evidence for the existence of an active ocean on Europa, a hypothesis under consideration for some time (*e.g.*, Reynolds *et al.*, 1983) and supported by Na/K measurements in the extended atmosphere of Europa (Cassidy *et al.*, 2009). While isotopically fractionated, S-bearing compounds may be found that are consistent with biological activity; additional biomarkers would be needed to determine definitively whether the source of such biomarkers on Europa is due to a ''second genesis'' (McKay, 2001).

2. Missions to Ocean Worlds of the OSS

At present, there is interest in developing astrobiology missions to search for evidence of life beyond the gas giants. As we learn more about other planetary bodies in our solar system, it has been recognized that the surfaces of other planets, such as Neptune's moon Triton, also serve as candidates for hosting geochemical biomarkers (Gaeman *et al.*, 2012; Nimmo and Spencer, 2014). Hussmann *et al.* (2006) considered models of the internal structure of Triton and other moons of the ice giants. These models predict an Europa-like rocky core, a subsurface ocean, and—significantly—an outer icy surface for Triton, Ariel, Iapetus, Umbriel, Titania, Oberon, and Pluto's moon Charon (Rhoden *et al.*, 2015). In light of the geochemical considerations that apply in particular to Europa, it is critical to discuss at this juncture what would be required to facilitate the search for geochemical biomarkers by way of the elemental isotopic content of the icy surfaces and exoatmospheres of more

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TABLE 1. A SELECTION OF CURRENT INSTRUMENTATION RELEVANT FOR BIOGEOCHEMICAL MASS SPECTROMETRY MEASUREMENTS FOR THE DETECTION OF BIOMARKERS

Miniaturized instruments (JUICE)	*Miniaturized instruments (Clipper)*	*References*
Particle environment package (PEP)		Barabash *et al.* (2013) Meyer *et al.* (2017)
	The MAss SPectrometer for Planetary EXploration/Europa (MASPEX)	Kempf *et al.* (2012)
	SUrface Dust Mass Analyzer (SUDA)	Kempf *et al.* (2012)

The information concerns the exploration of the Jovian System with JUICE and Clipper, but it may be used eventually elsewhere in the outer solar system.

distant unexplored moons in the solar system (Chela-Flores *et al.*, 2015).

Specific missions to the ice giants have not, to date, been endorsed, although proposals for future missions to the ice giants (NASA study, 2015) are currently under discussion. These proposals include origins, dynamics, and interiors of Neptunian and Uranian systems (ODINUS) (Turrini *et al.*, 2014), OSS (Christophe *et al.*, 2012), an orbital mission to Uranus (Arridge *et al.*, 2014), and a mission to the Uranian system (MUSE) (Bocanegra-Bahamón *et al.*, 2015). If any of these mission concepts is flown, data acquired by mid-century would allow for insights into habitability beyond the gas giants and, quite possibly, could address the question as to whether worlds in the realm of ice giants are inhabited.

3. Sulfur as a Measurable Geochemical Biomarker

Mass spectrometers (MSs) have unique capabilities that can be applied to studies of habitability and, perhaps, more importantly, life detection on icy worlds. In this regard, two forthcoming missions to the Jovian system have been provided with astrobiologically relevant instrumentation (Table 1).

Possible candidates for biota on the icy worlds are extremophilic microorganisms, which account for a major portion of life on Earth. It is worth noting that remarkable variations in microbial sulfate reduction, which were not previously detected as a product of nonliving processes, have been discovered in pure culture experiments (Sim *et al.*, 2011). These experiments revealed a large S mass-dependent fractionation of δ^{34}S of up to –70‰. This biogenic phenomenon is exclusively observed in a handful of natural environments on Earth, which raises the question as to whether an Europan biota would be composed of sulfate reducers and disproportionators that could give rise to measurable geochemical biomarkers. Such a possibility could be tested with the MS approved for the JUICE and Europa Clipper missions.

Geochemical biomarkers on the icy surface of Europa could arise, for example, from mineralogy that is indicative of habitable environments (Tulej *et al.*, 2015). Alternatively, the source of geochemical biomarkers could arise from isotopic fractionation of biological or metabolic processes. At the University of Bern, many instruments capable of addressing these possibilities have an impressive flight hardware development heritage (Riedo *et al.*, 2013a, 2013b), as some are part of the JUICE payload, including the particle environment package (PEP) that includes a neutral and ion gas mass spectrometer (Meyer *et al.*, 2017). The accuracy necessary for testing the presence of biogenicity in S isotope systematics on Europa would be achievable with the PEP instrumentation.

The Europa Clipper, an upcoming NASA mission designed to investigate habitability on Europa, has the capability to measure biogenic stable S-isotope fractionation: The MAss SPectrometer for Planetary EXploration/Europa (MASPEX), which will be included in the Europa Clipper scientific payload, was designed to determine the composition of the surface and subsurface ocean by measuring Europa's tenuous atmosphere and any surface material ejected into space. As a part of the Europa Clipper mission, the SUrface Dust Mass Analyzer (SUDA) will measure the composition of small solid particles ejected from Europa and provide an opportunity to sample directly the surface and potential plumes on low-altitude flybys. Significantly, the latter instrument is capable of identifying biosignatures in the ice matrix of Ejecta. A lander has also been approved with a payload that includes a MS, as was the case for previous spacecraft missions such as Cassini, Phoenix, and Curiosity (Pappalardo *et al.*, 2016).

At present, however, it is not completely clear whether the effects of radiation on the detection efficiency of these instruments can be reduced (Tulej *et al.*, 2016). Europa's exoatmosphere is normally considered to be an extension of its surface (Coustenis *et al.*, 2010). If its chemical elements are endogenic, the ultimate source must be regions that have a young surface, where the upwelling of subsurface material may occur (Tobie *et al.*, 2010). Tests of biogenicity are feasible on exoatmospheric particles that arise from surficial patches. This raises the possibility that the chemical elements of the exoatmosphere may be from the subsurface ocean. Given the available accuracy of the instruments, anomalous S isotope ratios can be measured in the forthcoming missions and may provide the first evidence for life in the OSS.

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References

Arridge, C.S., Achilleos, N., Agarwal, J., Agnor, C.B., Ambrosi, R., André, N., Badman, S.V., Baines, K., Banfield, D., Barthélémy, M., Bisi, M.M., Blum, J., Bocanegra-Bahamon, T., Bonfond, B., Bracken, C., Brandt, P., Briand, C., Briois, C., Brooks, S., Castillo-Rogez, J., Cavalié, T., Christophe, B., Coates, A.J., Collinson, G., Cooper, J.F., Costa-Sitja, M., Courtin, R., Daglis, I.A., de Pater, I., Desai, M., Dirkx, D., Dougherty, M.K., Ebert, R.W., Filacchione, G., Fletcher, L.N., Fortney, J., Gerth, I., Grassi, D., Grodent, D., Grün, E., Gustin, J., Hedman, M., Helled, R., Henri, P., Hess, S., Hillier, J.K., Hofstadter, M.H., Holme, R., Horanyi, M., Hospodarsky, G., Hsu, S., Irwin, P., Jackman, C.M., Karatekin, O., Kempf, S., Khalisi, E., Konstantinidis, K., Krüger, H., Kurth, W.S., Labrianidis, C., Lainey, V., Lamy, L.L., Laneuville, M., Lucchesi, D., Luntzer, A., MacArthur, J., Maier, A., Masters, A., McKenna-Lawlor, S., Melin, H., Milillo, A., Moragas-Klostermeyer, G., Morschhauser, A., Moses, J.I., Mousis, O., Nettelmann, N., Neubauer, F.M., Nordheim, T., Noyelles, B., Orton, G.S., Owens, M., Peron, R., Plainaki, C., Postberg, F., Rambaux, N., Retherford, K., Reynaud, S., Roussos, E., Russell, C.T., Rymer, A.M., Sallantin, R., Sánchez-Lavega, A., Santolik, O., Saur, J., Sayanagi, K.M., Schenk, P., Schubert, J., Sergis, N., Sittler, E.C., Smith, A., Spahn, F., Srama, R., Stallard, T., Sterken, V., Sternovsky, Z., Tiscareno, M., Tobie, G., Tosi, F., Trieloff, M., Turrini, D., Turtle, E.P., Vinatier, S., Wilson, R., and Zarka, T. (2014) The science case for an orbital mission to Uranus: exploring the origins and evolution of ice giant planets. *Planet Space Sci* 104:122–140.

Barabash, S., Wurz, P., Brandt, P., Wieser, M., Holmström, M., Futaana, Y., Stenberg, G., Nilsson, H., Eriksson, A., Tulej, M., Vorburger, A., Thomas, N., Paranicas, C., Mitchell, D.G., Ho, G., Mauk, B.H., Haggerty, D., Westlake, J.H., Fränz, M., Krupp, N., Roussos, E., Kallio, E., Schmidt, W., Szego, K., Szalai, S., Khurana, K., Xianzhe, J., Paty, C., Wimmer-Schweingruber, R.F., Heber, B., Asamura, K., Grande, M., Lammer, H., Zhang, T., McKenna-Lawlor, S., Krimigis, S.M., Sarris, T., and Grodent, D. (2013) Particle Environment Package (PEP). *European Planetary Science Congress 2013,* 8–13 September, London, UK, Vol. 8, EPSC2013.

Barnett, I.L., Lignell, A., and Gudipati, M.S. (2012) Survival depth of organics in ices under low-energy electron radiation (≤2 keV). *Astrophys J* 747:13.

Bocanegra-Bahamón, T., Colm Bracken, Marc Costa Sitjà, Dominic Dirkx, Ingo Gerth, Kostas Konstantinidis, Christos Labrianidis, Matthieu Laneuville, Armin Luntzer, Jane L. MacArthur, Andrea Maier, Achim Morschhauser, Tom A. Nordheim, Renaud Sallantin, and Reinhard Tlustos. (2015) MUSE—mission to the uranian system: unveiling the evolution and formation of ice giants. *Adv Space Res* 55:2190–2216.

Cassidy, T.A., Johnson, R.E., and Tucker, O.J. (2009) Trace constituents of Europa's atmosphere. *Icarus* 201:182–190.

Chela-Flores, J. (2010) Instrumentation for the search of habitable ecosystems in the future exploration of Europa and Ganymede. *Int J Astrobiol* 9:101–108.

Chela-Flores, J., and Kumar, N. (2008) Returning to Europa: can traces of surficial life be detected? *Int J Astrobiol* 7:263–269.

Chela-Flores, J., Cicuttin A., Crespo, M.L., and Tuniz, C. (2015) Biogeochemical fingerprints of life: earlier analogies with polar ecosystems suggest feasible instrumentation for probing the Galilean moons. *Int J Astrobiol* 14:427–434.

Christophe, B., Spilker, L.J., Anderson, J.D., André, N., Asmar, S.W., Aurnou, J., Banfield, D., Barucci, A., Bertolami, O., Bingham, R., Brown, P., Cecconi, B., Courty, J.-M., Dittus, H., Fletcher, L.N., Foulon, B., Francisco, F., Gil, P.J.S., Glassmeier, K.H., Grundy, W., Hansen, C., Helbert, J., Helled, R., Hussmann, H., Lamine, B., Lämmerzahl, C., Lamy, L., Lehoucq, R., Lenoir, B., Levy, A., Orton, G., Páramos, J., Poncy, J., Postberg, F., Progrebenko, S.V., Reh, K.R., Reynaud, S., Robert, C., Samain, E., Saur, J., Sayanagi, K.M., Schmitz, N., Selig, H., Sohl, F., Spilker, T.R., Srama, R., Stephan, K., Touboul, P., and Wolf, P. (2012) OSS (Outer Solar System): a fundamental and planetary physics mission to Neptune, Triton and the Kuiper Belt. *Exp Astron* 34:203–242.

Cooper, J.F., Johnson, R.E., Mauk B.H., Garrett, H.B., and Gehrels, N. (2001) Energetic ion and electron irradiation of the icy Galilean satellites. *Icarus* 149:133–159.

Coustenis, A., Tokano, T., Burger, M.H., Cassidy, T.A., Lopes, R.M., Lorenz, R.D., Retherford, K.D., and Schubert, G. (2010) Atmospheric/exospheric characteristics of icy satellites. *Space Sci Rev* 153:155–184.

Gaeman, J., Hier-Majumdera, S., and Roberts, J.H. (2012) Sustainability of a subsurface ocean within Triton's interior. *Icarus* 220:339–347.

Grasset, O., Dougherty, M.K., Coustenis, A., Bunce, E.J., Erd, C., Titov, D., Blanc, M., Coates, A., Drossart, P., Fletcher, L.N., Hussmann, H., Jaumann, R., Krupp, N., Lebreton, J.P., Prieto-Ballesteros, O., Tortora, P., Tosi, F., and Van Hoolst, T. (2013) JUpiter ICy moons Explorer (JUICE): an ESA mission to orbit Ganymede and to characterise the Jupiter system. *Planet Space Sci* 78:1–21.

Hussmann, H., Sohl, F., and Spohn, T. (2006) Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-Neptunian objects. *Icarus* 185:258–273.

Kempf, S., Srama, R., Grün, E., Mocker, A., Postberg, F., Hillier, J.K., Horanyi, M., Sternovsky, Z., Abel, B., Beinsen, A., Thissen, R., Schmidt, J., Spahn, F., and Altobelli, N. (2012) Linear high-resolution dust mass spectrometer for a mission to the Galilean satellites. *Planet Space Sci* 65:10–20.

McKay, C.P. (2001) The search for a second genesis of life in our solar system. In *The First Steps of Life in the Universe*, edited by J. Chela-Flores, T. Owen, and F. Raulin, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 269–267.

Meyer, S., Tulej, M., and Wurz, P. (2017) Mass spectrometry of planetary exospheres at high relative velocity: direct comparison of open- and closed-source measurements. *Geosci. Instrum. Method. Data Syst* 6:1–8.

NASA Study; Hofstadter, M., Murphy, N., and Reh, K. (2015) Ice Giant Mission Status and Planning CAPS Meeting, Irvine, CA. www.lpi.usra.edu/icegiants/

Nimmo, F., and Spencer, J. (2014) Powering Triton's recent geological activity by obliquity tides: implications for Pluto geology. *Icarus* 246:2–10.

Pappalardo, R.T., Vance, S., Bagenal, F., Bills, B.G., Blaney, D.L., Blankenship, D.D., Brinckerhoff, W.B., Connerney, J.E.P., Hand, K.P., Hoehler, T.M., Leisner, J.S., Kurth, W.S., McGrath, M.A., Mellon, M.T., Moore, J.M., Patterson, G.W., Prockter, L.M., Senske, D.A., Schmidt, B.E., Shock, E.L., Smith, D.E., and Soderlund, K.M. (2013) Science potential from a Europa lander. *Astrobiology* 13:740–773.

Pappalardo, R.T., Senske, D.A., Prockter, L., Hand, K.P., Goldstein, B.; and the Europa Science Team. (2016) Science of the Europa Multiple Flyby Mission. Division of Planetary Scientists and European Planetary Science Congress Conference, Pasadena, CA. *American Astronomical Society,* DPS meeting #48, id.123.26.

Phillips, C.B., and Pappalardo, R.T. (2014) Europa Clipper Mission Concept. *Eos Trans AGU* 95:165–167.

Prockter, L.M., and Schenk, P. (2005) Origin and evolution of Castalia Macula, an anomalous young depression on Europa. *Icarus* 177:305–326.

Reynolds, R.T., Squyres, S.W., Colburn D.S., and McKay, C.P. (1983) On the habitability of Europa. *Icarus* 56:246–254.

Rhoden, A.R., Henning, W., Hurford, T.A., and Hamilton, D.P. (2015) The interior and orbital evolution of Charon as preserved in its geologic record. *Icarus* 246:11–20.

Riedo, A., Bieler, A., Neuland, M., Tulej, M., and Wurz, P. (2013a) Performance evaluation of a miniature laser ablation time-of-flight mass spectrometer designed for in situ investigations in planetary space research. *J Mass Spectrom* 48:1–15.

Riedo, A., Neuland, M., Meyer, S., Tulej, M., and Wurz, P. (2013b) Coupling of LMS with fs-laser ablation ion source: elemental and isotope composition measurements. *J Anal Atom Spectrom* 28:1256–1269.

Sim, M.S., Bosak, T., and Ono, S. (2011) Large sulfur isotope fractionation does not require disproportionation. *Science* 333: 74–77.

Teodoro, L.F.A., Davila, A.F., McKay, C.P., Dartnell, L.R., and Elphic, R.C. (2016) Ionizing radiation on the surface of Europa: implications for the search for evidence of life. In *47th Lunar and Planetary Science Conference*, The Woodlands, TX, USA.

Tobie, G., Giese, B., Hurford, T.A., Lopes, R.M., Nimmo, F., Postberg, F., Retherford, K.D., Schmidt, J., Spencer, J.R., Tokano, T., and Turtle, E.P. (2010) Surface, subsurface and atmosphere exchanges on the satellites of the outer solar system. *Space Sci Rev* 153:375–410.

Tulej, M., Neubeck, A., Ivarsson, M., Riedo, A., Neuland, M.B., Meyer, S., and Wurz, P. (2015) Chemical composition of micrometer-sized filaments in an aragonite host by a miniature laser ablation/ionization mass spectrometer. *Astrobiology* 15:1–14.

Tulej, M., Meyer, S., Lüthi, M., Lasi, D., Galli, A., Piazza, D., Desorgher, L., Reggiani, D., Hajdas, W., Karlsson, S., Kalla, L., and Wurz, P. (2016) Experimental investigation of the radiation shielding efficiency of a MCP detector in the radiation environment near Jupiter's Moon Europa: nuclear instruments and methods. *Phys Res* B383:21–37.

Turrini, D., Politi, R., Peron, R., Grassi, D., Plainaki, C., Barbieri, M., Lucchesi, D.M., Magni, G., Altieri, F., Cottini, V., Gorius, N., Gaulme, P., Schmider, F.-X., Adriani, A., and Piccioni, G. (2014) The comparative exploration of the ice giant planets with twin spacecraft: unveiling the history of our Solar System. *Planet Space Sci* 104:93–107.

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Abbreviations Used

MS = mass spectrometer
PEP = Particle Environment Package