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Jupiter exploration: high risk and high rewards

Edwin S. Kite, Department of Earth Sciences, Cambridge University, CB2 3EQ, United Kingdom. (ek265@cam.ac.uk)

Jupiter exploration is big science, and only the United States can afford self-contained missions to the gas giant and its four planet-sized moons. The Galileo spacecraft, which was recently flown into Jupiter to prevent it from contaminating Europa's ocean, cost $1.6 bn. Despite the failure of its High Gain Antenna (HGA), Galileo discovered briny, subsurface oceans on Europa, Ganymede and Callisto; globally mapped all four Galilean moons; monitored Io's volcanic activity; carried out a seven-year study of the Jovian magnetosphere; and dropped an atmospheric probe into Jupiter's upper cloud layer.

Of these achievements, the most significant is the indirect detection of a deep subsurface liquid-water layer on Europa [*Pappalardo* et al. 1999; *Kivelson* et al., 2000]. The case for a Europan ecosystem can be made [e.g., *Marion* et al, 2004], although it is important to remember the energetic and biogeochemical limits on putative Europan life [e.g., *Soare and Green*, 2002]. Europa's low moment of inertia (0.346 ± 0.005 MR2) suggests a silicate mantle below the ocean, permitting chemical exchanges between ocean and silicates as occurs on Earth. Europa's surface is geologically young, likely emplaced 20-180 Mya [*Zahnle* et al., 2003]. Any recycling of surficial icy crust into the ocean could add O, S and organic compounds, either impact-delivered or generated in-situ by UV irradiation and the implantation of ionized particles from Jupiter's radiation belts. Because of its astrobiological potential, the Space Studies Board has accorded a science priority to Europan exploration equal to that of Mars [*COMPLEX*, 1999; *Space Studies Board*, 2003]. The icy crust (probably ~ 25 km thick, but possibly much thinner [*Nimmo* et al., 2003; *Greenberg* et al, 2000]), bars direct access to the ocean in the near term, but fresh ocean material may be exposed at localities on the surface. Beneath a thin, heavily-irradiated layer, biosignatures may be detectable with today's instruments.

Models of the Europan ocean remain poorly constrained. Its redox state and temperature are unknown. Its salt component may be dominated by H_2SO_4, $MgSO_4$, $(Na\text{-}K)_2SO_4$, or Na_2CO_3.. Its thickness could be 6 km, or 100 km [*Kargel et al*., 2000].

NASA's current plan for the next phase of Jupiter exploration is an orbiter using nuclear-electric propulsion: preliminary studies envisage a mass of 30 tonnes and a length of 30 metres. The Jupiter Icy Moons Orbiter (JIMO) will successively orbit Callisto (for ~ 2 months), Ganymede (~ 4 months) and Europa (1-2 months), after which time Jovian radiation is expected to degrade its onboard electronics [*JIMO SDT*, 2004].

JIMO will serve as a testbed for Project Prometheus, an ambitious Department of Energy (DoE)/NASA programme to develop advanced radioisotope power sources and nuclear fission reactors [*Johnson*, 2003]. Compact, high-output power is a prerequisite for piloted deep-space missions, and might enable lengthy unmanned voyages to exotic destinations beyond Saturn. Radiosotope Thermoelectric Generators (RTGs), or even solar panels [*Noca* et al., 2002], are likely better suited to a Jupiter orbital tour.

JIMO fits well with NASA Administrator Sean O'Keefe's declared goal of field-testing the technologies needed for a revolutionary jump in spaceflight capabilities. Catastrophic failure of a U^{235} fission reactor would cause less environmental damage than that of a Pu^{238} RTG. Fission power would allow JIMO to operate all its instruments in parallel, and to return data to Earth at unprecedented rates.

However, there are serious concerns with an exploration strategy relying on JIMO. 1) JIMO is not expected to arrive at Europa before 2025, and the troubles of Galileo and Cassini legitimate doubt about this schedule. 2) Because it must be placed in a safe orbit before reactor startup, JIMO requires a heavy-lift launch vehicle that does not yet exist. 3) Innovative science approaches are yoked to the politically sensitive Project Prometheus, which could be abruptly cancelled. 4) Concerns have been raised [*Eluszkiewicz*, 2004] that JIMO's radar will be scattered at shallow depths by metre-scale cavities in Europa's regolith. 5) Most importantly, JIMO appears to accord less urgency to an investigation of Europa's biological potential than do NASA's scientific advisors [e.g., COMPLEX, 1999] or the taxpaying public [Appendix D in *Space Studies Board*, 2003]. Because radiolytic processing and impact gardening are likely to erase most biosignatures in the layer of Europa susceptible to remote sensing, a more direct approach is needed if we are to constrain our models of the Europan ocean habitat. Although some Europa specialists have expressed guarded support for JIMO [*EFG*, 2003], it is widely agreed that a JIMO mission with only an orbiter would generate limited interest and support from astrobiology researchers [*Flynn*, 2003]. JIMO is baselined to deploy a "modest" landed package, but weight constraints may preclude sampling beneath the gardened layer, which is roughly 0.7-2 m deep [*Phillips and Chyba*, 2004].

Is there an alternative strategy? A 2001 workshop produced few practical suggestions. One conservative solution would be a Europa-focussed orbiter using chemical propulsion. Experiences elsewhere are instructive. Although the "faster, better, cheaper" approach to space exploration has been criticized, it has achieved some great successes. The Jupiter Millenium Mission in 2000-2001 showed the potential of synergistic studies using multiple spacecraft [*Cassini Science Team*, 2002]. The ambitious goal of sample return has unified astrobiologists, geologists and atmospheric scientists. Proposals to study Jupiter's gravitational and magnetic fields (Juno) and return samples from Europa (Ice Clipper) suggest that low-cost ($300 - $650 mn) missions can now be flown to Jupiter [*Drake et al.*, 2001].

Any Europa landed element should address two disparate goals. The first goal is planetology, and requires only near-surface placement, allowing magnetic field and seismic measurements, surface imaging and radio science. The second goal, astrobiology, requires access to subsurface material and strict sterility of the spacecraft.

As one radical solution, consider the launch of three low-mass, solar-powered spacecraft on direct, ballistic orbits timed for simultaneous arrival around Jupiter in May 2015 [*Kite*, 2004]. One "bus" would enter Europan orbit, dispensing 3 lightweight rough-landers [*Tamppari et al.*, 2001]. Each rough-lander would carry microscopic and far-field imagers, a magnetometer [*Khurana et al.*, 2002], a seismometer [*Makris et al.*, 2004], an enzymatic microarray for chemical assay [*Prieto-Ballesteros et al.*, 2003], and a laser ablation Time-Of-Flight Mass Spectrometer (TOF-MS) [*Wurz et al.*, 2004], relaying data to Earth through the bus. A sacrificial impactor is flown into the leading edge of Europa, taking nested descent imagery, to guarantee at least one signal and calibrate the seismometer net. This was done decades ago for the Moon by crashing discarded Apollo-Saturn third stages. The impact crater and plume is observed by the third spacecraft (carrying a smaller, backup impactor) which flies through the plume at $< 10\ kms^{-1}$ and captures samples on aerogel, tungsten filaments and sapphire wafers for return to Earth [*McKay*, 2002]. Removing any one flight element from the synergy would damage the missions' science capacity, but if desired, the flight elements could be stretched over successive launch opportunities, creating a sustained "Jupiter System Exploration Program". In a similar way, the stability of the Mars Exploration Program (MEP) has replaced the previous drought-glut pattern, and specialising in areology is now a viable choice for young planetary scientists [*Garvin*, 2003].

The predicted cost is $2 bn, about a fifth as much as more detailed JIMO estimates, and multiple-spacecraft missions are well-suited to international cost-sharing. Notably, the 1996 claim of ambiguous evidence for fossil life in a Martian meteorite [*Thomas-Keprta et al.*, 2002; *Treiman*, 2003] led to the creation of NASA's National Astrobiology Institute and the $600 mn/year MEP. Further evidence of a viable, present day habitat on Europa with a volume as much as double that of Earth's oceans would enormously increase the resources available to Jovian science. JIMO faces tremendous challenges, and may be only a long-term solution for next-generation exploration. The case for science at Europa is very strong, arguing that a more direct approach to Europa exploration is a gamble worth taking.

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