Colonizing Jupiter's Moons: An Assessment of Our Options and Alternatives

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Abstract

At the Lifeboat Foundation, we discuss the sustainability of Earth's resources and ecosystems, existential risks to life on Earth, and the safeguards to human existence that could be achieved by eventually branching out and colonizing space. Overviewing current possibilities in manned space exploration and eventual colonization within our Solar System, instinct draws us to consider a permanent base on either the Moon or Mars. Here, I consider what could be a rewarding alternative — outward to the first of the gas giants — and the Galilean moons of Jupiter.

The Galilean Giants

ALTHOUGH THE MOON AND MARS provide possible permanent bases for humans, there are alternatives to them. The polar regions of Mercury, for example, have been suggested because of the suspected presence of water-ice [1] and an abundance of natural resources. Transforming Venus could also be a long term prospect if its runaway greenhouse effect could be permanently reversed. There is a further choice: the Galilean moons.

The Galilean moons are the four large moons of Jupiter which were discovered by Galileo in 1610, their names derived from the lovers of Zeus – Io, Europa, Ganymede, and Callisto. Although Jupiter has 67 confirmed moons [2], the four Galilean moons, with radii larger than any of the dwarf planets in our Solar System, contain the vast majority of the mass in orbit around Jupiter. Indeed the next largest of the Jovian satellites, Himalia and Amalthea, are both less than a mere 200 km in diameter. The Galilean moons, with diameters 3,600 km (Io), 3,120 km (Europa), 5,260 km (Ganymede) and 4,820 km (Callisto) are among the most massive objects in the Solar System after the Sun and the eight planets.

We already know a great deal about the Galilean moons which have been visited by several unmanned spacecraft from the arrival of Pioneer 10 in 1973 to the most recent visit of the New Horizons probe in 2007 en route to Pluto. The Galileo orbiter is the only spacecraft that orbited Jupiter – which it did for over seven years until it was eventually destroyed during a controlled impact with Jupiter in 2003 [3]. Other spacecraft to visit the Jovian system include: Pioneer 11 (1974), Voyager 1 and Voyager 2 (1979), Ulysses (1992), and Cassini (2000). It is from the success of these unmanned spacecraft that we owe most of our knowledge of the Galilean moons and the Jovian system. This includes not just dramatic images of these moons, but an insight into the mass, topography, volcanism and tectonic processes. The images and insights provide evidence of liquid salt water sub-surfaces and atmospheres, and information on the orbital precision of these moons and the magnetic field and radiation belts through which they orbit in the Jovian system.

Reasons to be Enthusiastic

From a scientific point of view and for the advancement of space exploration, we may appreciate reasons to be enthusiastic about setting up a base in the Jovian system. It provides the nearest possible location to Earth where a base could be established to explore the dynamics and weather systems of large gaseous/liquid planets in detail, and study how such planets impact and interact with their satellites. With large gas planets believed to be quite common in our Universe (almost all known exo-planets are of this form [4]) the invitation seems obvious – to explore how such planets affect their moons in order to understand the suitability of such locations for an off-Earth industrial/scientific base toward long-term aspirations for space exploration/colonization. It is worth noting that only two other moons in our outer Solar System are of requisite size to have a gravitational field similar to or greater than that of our Moon — namely Saturn's Titan and Neptune's Triton. Since a significant gravitational field is one of the fundamental essentials for the physical well-being of would-be explorers, the Galilean moons naturally demand our attention for review.

With four such large moons to study in the one region of our Solar System, along with their parent gas giant, we have a uniquely diverse region from Io, the most geologically active body in our Solar System to the water-rich icy moon Europa, often credited as the most likely place in our Solar System where we might find traces of alien life. If we were to consider where a scientific base would maximize its return, the Galilean moons are inviting.

The Great Deterrent: Jovian Radiation

The first difficulty to consider in setting up a base in this region is the intense radiation from Jupiter, which is far stronger than that from the Earth's Van Allen radiation belts. This radiation is formed from charged particles trapped in Jupiter's magnetosphere, a zone one million times the volume of Earth's magnetosphere. The inner magnetosphere, rotating very rapidly with the planet, is a constant presence and a constant deterrent. At greater distances, more than 20 times the radius of Jupiter, the magnetic field becomes blunted by the solar wind on the sunward side, and extended on the leeward side. So the size of the outer magnetosphere varies depending on the intensity of the solar wind. However, in considering setting up a base in this region we would have to consider the worst case scenario of intolerable radiation levels, and not just typical reach and intensities. Proper shielding normally protects living organisms and electronic instrumentation in space voyages. However, as the radiation from Jupiter is whipped up from magnetic fields far stronger than those on Earth (the strongest fields in the Solar System except for sun spots), shielding becomes a much greater challenge. It has been suggested that such radiation would be the greatest threat to any craft closing within 300,000 km of the planet [5], although radiation levels would still be of great concern to us at distances far greater than this.

As illustrated in Figure 1, the magnetic field of Jupiter stretches far beyond the orbit of even the outermost of the Galilean moons, elongated by the solar wind in the anti-solar direction. The field is a complex structure comprising many components including bow shock, magnetosheath, magnetopause, magnetotail, magnetodisk and – most significantly for the purposes considered here – the currents induced as the ionosphere moves relative to Jupiter's dipole magnetic field under the rotation of the planet. A resulting Lorenz force to these currents drives negatively charged electrons to the poles and positively charged ions towards the equator. Due to the presence of highly conductive plasma in Jupiter's magnetosphere, the electrical circuit is considered closed through that force. Estimated at around 60-140 million amperes [6], this current flows along the magnetic field lines from the ionosphere (the direct current) to the equatorial plasma sheet before flowing radially away from the planet within the radial current sheet (the radial current), before finally returning to the ionosphere from the outer reaches of the magnetosphere along the field lines to the poles (the return current).

The Galilean moons orbit through this equatorial plain of Jupiter and receive high levels of radiation – with Io estimated at receiving approximately 3,600 rem/day, Europa 540 rem/day, and Ganymede 8 rem/day. Furthest out, Callisto receives a less problematic 0.01 rem/day.

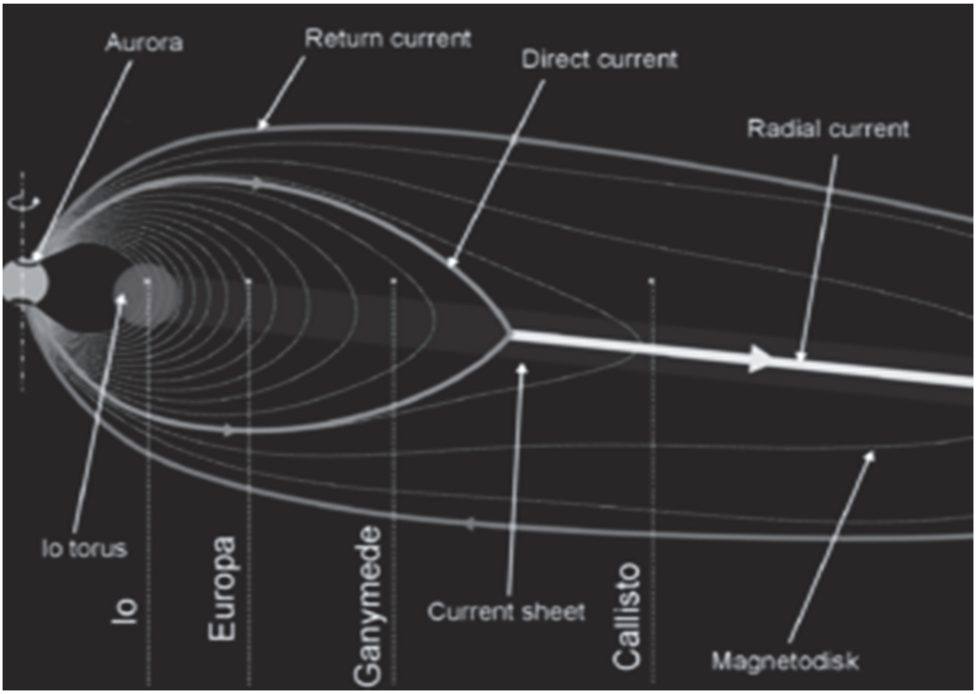

Figure 1: The magnetic field of Jupiter and co-rotation enforcing currents.

The large magnetosphere also has an important function in the region in that it protects the four largest moons of Jupiter – which all orbit within the magnetosphere – from the solar wind. Outside the Jovian radiation belts, the magnetosphere is an important blanket over the region. This is in stark contrast to a hypothetical base on either the Moon or Mars where there is no such blanket. So we can consider the magnetosphere here to provide opportunity and not just deter.

However, with radiation levels of 500 rem or greater considered a fatal dose, and as little as 75 rem over a period of a few days enough to cause radiation poisoning [13], there is little room to argue that Jovian radiation is a significant obstacle to astronauts visiting the region.

More Deterrents: Distance and Low Temperatures

At closest approach Jupiter and Earth are 630 million km apart, or 4.2 AU. This is an order of magnitude further than the closest approach of Mars to Earth, at 56 million km. Such distance makes a manned voyage impractical without significant advancement on spacecraft design, as we frequently find estimates of round trips to Mars proposed in the order of two years.

To meet the challenge of such great distances, one propulsion of choice at NASA in recent years has become ion propulsion, where the High Power Electric Propulsion (HiPEP) project has demonstrated exhaust velocities in excess of 90,000 meters/second (over 200,000 mph) [7]. Although the mission HiPEP was originally designed for the Jupiter Icy Moons Orbiter, that mission was cancelled in 2005. Nevertheless, the technology can be considered ground-tested and feasible.

An advanced ion propulsion drive could reduce a voyage to Jupiter significantly – although we should note that HiPEP research looked at lighter unmanned spacecraft, and achieving such figures with heavier manned space craft could be considered fanciful. However, with continued investment in space aviation research, we will sooner or later be considering round trips to the Jovian moons with sub-year voyage estimates. So we should not exclude outright the feasibility of manned missions to the Jovian system due to the distances involved.

Temperature is another matter to consider. Objects travelling through space experience temperatures that are quite extreme compared to what the same objects would experience on Earth. The effective temperature of space is extremely cold – approximately 3K [8]. When astronauts perform spacewalks above Earth, the spacesuit can have a temperature difference of up to 275° F from one side to the other, with one side of the spacesuit facing towards the Sun and the other facing out to the cold of deep space. In the Jovian environment with the Sun far more distant, even temperatures on the Sun facing side are extremely cold, with temperatures rarely rising above 170K on any of the Galilean moons.

The mean temperature on Callisto is estimated at 135K with a variation of ±50K [9]. The temperatures of Ganymede [10] and Io (discounting the extreme temperatures near hot spots and volcanic plumes) [11] are estimated at 110K, again with a variation of ±50K or so. That of Europa (due to its higher albedo) is lower, at 100K [10], again with a similar variation. While variation in temperature is not a concern here, the absolute temperature is of concern. For a manned mission to succeed, the spacesuits would require a durable thermal energy source to ensure sufficient comfort for astronauts. A significant design consideration of any base would require a reliable method of sustaining temperatures far higher than natural conditions.

An Overview of the Galilean Giants

Io

At a distance of 420,000 km, Io is the closest of the Galilean satellites to Jupiter – a proximity that results in making Io a highly active world. Tidal heating from friction generated within Io's interior under the gravitational influence of Jupiter and the other Galilean satellites leave the Ionian surface in a constant state of renewal with volcanic activity from more than 400 active volcanoes. Io is, in fact, considered the most geologically active object in the Solar System, and plumes rich in sulphur and sulphur dioxide regularly rise as high as 400 km above the surface.

We can disregard an extremely thin sulphur dioxide atmosphere as an inconvenience. However, a surface prone to explosive volcanism and extensive silicate lava flows, and exposed to high levels of Jovian radiation – estimated at 3,600 rem/day – far above dosages considered fatal for humans – make Io an unlikely satellite to visit. However, if the tidal heating on Io could be harnessed as a source of heat/energy (it has been estimated that the global total heat flow from Io is in the region of 1×10^{14} W [12]), this would provide a reliable energy source for a base in the region – if technical challenges such as providing sufficient radiation shielding could be overcome – either on one of the other Galilean giants or an orbiting space station.

It is also worth noting that, unlike most satellites, Io is composed of silicate rock with a molten iron or iron sulphide core, so this may provide mining opportunities. However, being hazardous as a region, we may have to rule out Io and any of its resources from practical considerations.

Europa

Europa is the smallest of the Galilean giants, with a radius of just over 1,500 km, but still one of the largest moons in the Solar System. It is just slightly smaller than Earth's Moon. With a possible sub-glacial water ocean [13] underneath its icy exterior, it has been suggested not just as a target suited for eventual human colonization, but also as a possible host to alien life forms.

The abundance of water is significant not only as a source of drinking water, but it could also be broken down to provide breathable oxygen. However, the colonization of Europa poses many difficulties. At 670,000 km from Jupiter, Europa receives 540 rem of radiation per day from the Jovian radiation belts, and this would be considered a fatal dose (> 500 rem). Humans would not survive at or near the surface of Europa for long without significant radiation shielding. It is also extremely cold on Europa – even colder than on the other Galilean giants – due to its high albedo – reflecting off most of the light and heat that reaches its surface. Also, although Europa has a great abundance of water, it is lacking in accessible minerals and irons. With the water ocean under the ice surface thought to be up to 100 km thick, all materials required for construction would need to be mined and transported from other satellites in the Jovian region.

Even overcoming these difficulties, one of the first dilemmas of setting up a base on Europa would be to not contaminate any primitive life that may already have a foothold there. Studies have indicated that the action of solar radiation on the surface of Europa might produce oxygen, which could be pulled down into the subsurface ocean by upwelling from the interior. If this process occurs, Europa's subsurface ocean could have an oxygen content equal to or greater than that of the Earth's – possibly providing a home to complex life [14]. Often considered a strong candidate for extra-terrestrial microbial-type life, if such were found, it could render Europa off-limits for colonization on the grounds of ethics due to the possible contamination/destruction of a delicate ecosystem. Conversely, human colonists coming into contact with such microbes could find that their immune systems do not offer a natural defense to alien microbes which evolved to become more durable to the natural conditions on Europa.

Discounting this, and with sufficient radiation shielding, Europa offers an intriguing location for a research base – having an abundant supply of drinking water and oxygen by extraction.

Ganymede

Ganymede is not only the largest of the Galilean giants, but is also the largest and most massive moon in the Solar System – larger in diameter than the planet Mercury, albeit with just 45% of Mercury's mass.

This results in an escape velocity of 2.741 km/s, somewhat larger than that of Earth's Moon, which has an escape velocity of 2.38 km/s. Therefore, the long-term effects on astronauts are least severe here due to weakened gravity environments.

Considerably further out than both Io and Europa, at over 1,070,000 km from Jupiter, Ganymede is also exposed to far lower levels of Jovian radiation when compared to Io or Europa. An unshielded colonist would receive about 8 rem of radiation per day on Ganymede, compared to what would be considered fatal doses of 540 rem/day on Europa or 3,600 rem/day on Io.

However, exposure of approximately 75 rems over a period of a few days is enough to cause radiation poisoning [15]. Astronauts on Ganymede would still require a significant level of radiation shielding in order to operate here, although much of this low-latitude region is partially shielded by Ganymede's magnetic field.

In considering potential off-Earth bases in the Solar System, a shielded underground base on Ganymede may be a reasonable long-term objective. Ganymede is the only satellite in the Solar System to boast a magnetosphere. This is thought to be produced by convection in a liquid iron core [16], where temperatures are estimated to be 1500-1750K. This internal heat source can counter the extreme cold conditions of 70-150K on the surface in an underground facility. Beneath a composition of silicate rock and water-ice in roughly equal proportions near its surface, Ganymede is also considered likely to have a salt water ocean far below its surface [17] due to magnesium sulphate and sodium sulphate salts which showed up in results from the Galileo spacecraft, along with detected signs of carbon dioxide and organic compounds [18], trace amounts of oxygen, and ozone. Such a salt water ocean could be not only a source from which ample drinkable water could be distilled, but also a source from which oxygen could be extracted. Furthermore, evidence of trace amounts of carbon dioxide and organic compounds suggests an intriguing world to analyze with a view to developing terraforming processes.

Also, it should not be overlooked that Ganymede has abundant resources in silicates and irons suitable for mining and construction, unlike many other satellites where water-ice dominates.

While aspirations such as mining and construction of permanent bases may seem far-fetched in our current age, foresight should be applied. This will ensure, where we attempt to initiate a foothold in such a remote region, that long-term prospects are considered, and that the region is the most suited to industrial progression. In this light, Ganymede weighs in with several advantages.

Callisto

The outermost of the Galilean giants, Callisto is almost 2,000,000 km from Jupiter, twice the distance of Ganymede from Jupiter, and hence the least affected by Jovian radiation. For this reason, Callisto was selected by NASA as the most suitable place to create a human base for future exploration of the Jupiter system when HOPE, Human Outer Planet Exploration, was presented. At that time, some of the objectives and requirements for such a pilot mission were explored [19].

Being darker, the surface of Callisto is warm relative to Europa and Ganymede (a darker surface reflects less light, and therefore retains more heat/energy), and it also benefits from a much thicker atmosphere [20]. The CO_2 component of Callisto's atmosphere was first detected by the Galileo mission's imaging spectrometer, NIMS, but recent modeling suggests an even more robust atmosphere. Interaction between a more substantial ionosphere and Jupiter's magnetosphere reduces electron impact, and the relatively thick atmosphere also protects the surface significantly from radiation flux. To put these figures in context, the surface pressure on Callisto is estimated at 7.5 pbar, while the estimated maximum surface temperature is 170K – still extreme conditions for any astronauts.

The escape velocity on Callisto is similar to that for Ganymede at 2.44 km/s. Therefore, again, the long-term effects on astronauts due to weakened gravity environments would not be as severe here as it would be on smaller worlds.

Callisto is a geologically inactive world, with no signatures of subsurface processes such as plate tectonics or volcanism. Not being subjected to tidal heating, Callisto has similarities with Ganymede in that it is also believed to have a subsurface ocean of liquid water. Hence, it would have an unlimited supply of drinking water and oxygen by extraction. Organic compounds have also been detected through spectroscopic measurements [20]. One proposition for Callisto may be the introduction of genetically-modified vegetation – robust to cold surface temperatures and capable of surviving in a weak CO_2 atmosphere, to grow here as renewable food sources.

As with Ganymede − and unlike Europa − Callisto has abundant accessible resources in silicates and irons that are suitable for mining and construction. A successfully established base here could be augmented over time into a more ambitious industrial base and colony if viable.

Vehicle and robot system concepts were explored toward achieving a successful first phase for the HOPE surface operation. The division of tasks between crew and robotics were analyzed for the exploration of all the Jovian satellites. It was concluded that a round trip of a crewed mission would require 2-5 years — albeit with significant advancement in propulsion technologies.

Perhaps the greatest challenge to establishing a base on Callisto relative to Ganymede, which is clearly the only other viable alternative in the region – involves questions of how to elevate the temperature of a base here to comfortable conditions in a self-sustainable process, and how to generate sufficient energy and electricity to meet the needs of such a base. Lacking an internal source of heat − and with little opportunity in the way of solar, tectonic, or other energy sources – presents an engineering trade-off with Ganymede's radiation shielding needs and complications.

Conclusions

While unmanned spacecraft have allowed us to learn a great deal about the Jovian system, a long term goal of human exploration to the region would allow us to learn a great deal more.

The Jovian system is a fascinatingly diverse region of our Solar System just awaiting mankind to explore it. In both Ganymede and Callisto, it has two bodies which could be considered to be viable options for a scientific base if specific engineering challenges can be overcome.

A study performed in recent years has suggested an initial manned round trip to the region could be achieved in 2-5 years, given sufficient advancement in propulsion technologies. It is doubtful anyone would argue that the diversity of the region is a far more appealing invitation to explore than alternatives such as Mars or the polar regions of Mercury. What we considered here is whether such a mission, leading to an eventual base, would be a viable option. In this light, we must conclude that there are options in the Jovian system that offer viable alternatives within our Solar System.

Acronyms and Abbreviations

AU	The Astronomical Unit 149,597,870,700 meters (the mean Earth-Sun distance).
Galileo NIMS	Near-Infrared Mapping Spectrometer, the Galileo mission's imaging spectrometer.
HiPEP	High Power Electric Propulsion (a NASA research project, c.2003-2004).
HOPE	Human Outer Planet Exploration (a NASA-led study on space exploration c.2003).
rem	Roentgen Equivalent Man, the US unit of measurement for a radiation dose.

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Bio

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