Jupiter and Io: The unique celestial couple

Marykutty Michael
Engineering Physics and Astronomy, University of Virginia, Charlottesville, VA 22903, USA

Jupiter and its satellites constitute a miniature solar system. Io, Europa, Ganymede and Callisto, the largest among the Jovian satellites are called the Galilean satellites after their discovery by Galileo Galilei in 1610. Io is the innermost Galilean satellite and according to Greek mythology Io was the dearest of Zeus (Jupiter), while the other three were also named after his lovers.

The Io-Jupiter system is unique. While Io is the most volcanically active planetary body, Jupiter is the largest planet, has the strongest magnetic field, fastest spin, biggest and most powerful magnetosphere, and has a very dense atmosphere. The study of this moon-planet system is exciting as Io is involved in active and continuous electrodynamic interaction with its parent planet. Being able to describe this system will advance our understanding of basic plasma-neutral-surface interactions, and will help us understand the behavior of interacting pairs existing at other places in our solar system and in extra solar planetary systems.

The mass of Jupiter is more than the total mass of all other planets.

Before attempting to analyze the Jupiter-Io system, differences from the Earth-Moon system are outlined. Jupiter is 5.2 times farther from the Sun than Earth, and has an equatorial radius of 71400 km (R_J), which is 11 times that of Earth, and a volume that is 1400 times that of the Earth. The mass of Jupiter is more than the total mass of all other planets. Jupiter, with a 10-hour day, is the fastest rotator among planets. The Jovian atmosphere is mostly made of molecular hydrogen and helium with sulfur, oxygen and nitrogen in small amounts. Jupiter's magnetic moment is about 20,000 times greater than that of Earth, with magnetic field direction opposite to that on Earth and inclination of 9.6°, which is close to 11° tilt on the Earth. The general form of Jupiter's magnetosphere resembles that of Earth with dimensions about 1200 times greater.

While the magnetic field of Earth is generated by the iron core, the Jovian magnetosphere is generated by the motion of magnetic material inside the liquid metallic shell. At about 1000 km below the cloud top, the hydrogen atmosphere becomes thicker and finally changes phase to become liquid hydrogen. Because of the tremendous pressure, under the liquid hydrogen layer, a layer of metallic hydrogen layer exists which causes the Jovian magnetic field. The Earth's field is reasonably well represented by a dipole but at Jupiter the quadrupole and octupole moments are significant producing a pointed and bullet shaped magnetosphere. The power for populating and maintaining the magnetosphere of Jupiter comes principally from the rotational energy of the planet and the orbital energy of Io, whereas the power source for Earth's magnetosphere is principally the solar wind.

As stated in the beginning, Io is the innermost among the Galilean satellites and is the fourth largest natural satellite in the solar system with radius of 1815 km, 2% larger than the Moon. Io orbits Jupiter at a distance of 5.9 R_J from Jupiter, which is well within Jupiter's intense magnetosphere, while our Moon is at a distance of 60 R_E (R_E is the radius of Earth) from Earth, which is well outside the Earth's magnetosphere. That means while Io constantly couples with Jupiter's magnetosphere, the Moon does not. Io is volcanically active, while the volcanoes on Moon ceased between 3-4 billion years ago. The volcanoes on Io emit an SO_2 rich material, which is one of the major sources of its SO_2 atmosphere. The Moon has a very thin collisionless atmosphere with He, Ar, Na, K, Ne etc as the constituents. Table 1 gives the important physical parameters of Jupiter and Io and a comparison with those of Earth and Moon. A detailed review on Io is presented in *Spencer and Schneider* (1996). In the present article a few of the most important issues of Jupiter-Io are addressed. Why are there volcanoes on Io? What is the role of Jupiter in producing these volcanoes? Do these volcanoes help produce an atmosphere at Io? How does this atmosphere interact with the Jovian magnetosphere and produce the torus, neutral clouds and aurora? In the following sections these fascinating questions will be discussed in order to obtain an insight into this unique planet-moon system.

▼ **Table 1:** Important physical parameters of Jupiter and Io.

Parameter	Jupiter (Earth)	Io (Moon)
Radius	71400 (6400) km	1815 (1736) km
Volume	1.4×10^{15} (1.1×10^{12}) km^3	2.5×10^{10} (2.2×10^{10}) km^3
Mass	1.9×10^{27} (6×10^{24}) kg	8.9×10^{22} (7.3×10^{22}) kg
Density	1326 (5515) kg m^{-3}	3530 (3340) kg m^{-3}
Gravitational acceleration	23.1 (9.8) m s^{-2}	1.8 (1.6) m s^{-2}
Escape velocity	59.5 (11.2) km s^{-1}	2.5 (2.4) km s^{-1}
Orbital period	4330 (365) days	1.7 (27) days

The Jovian system has been visited by a number of spacecrafts: Pioneer 11 and 12, Voyager 1 and 2, Ulysses, Galileo and most recently by Cassini. Pioneer 11 and 12 arrived at the Jovian system in 1973 and 1974, respectively, while Voyager 1 and 2 have visited Jupiter and its satellites in 1979. The Ulysses is the first spacecraft to explore interplanetary space at high solar latitudes whose encounter with Jupiter occurred in 1992. The Galileo spacecraft has been orbiting around Jupiter since 1995 and in December 2000 the Cassini spacecraft passed through the edge of the Jovian magnetosphere.

Volcanism and internal structure of Io

Volcanic activity: Io is the only body outside the Earth, to exhibit active volcanism on a massive scale. It can provide a picture of active volcanic processes that ceased elsewhere in the solar system. The volcanism on Io was discovered by the Voyager spacecraft in 1979. The recent observations of this amazing body by the Hubble Space Telescope (HST) and the Galileo spacecraft have shown that Io is dotted by hundreds of volcanic centers. Volcanic activity on Io is so relentless that there are no signs of impact craters on its surface, as they are rapidly filled in with volcanic material soon after they are formed. The extensive volcanic activity on Io generates dramatic changes to it's surface over very

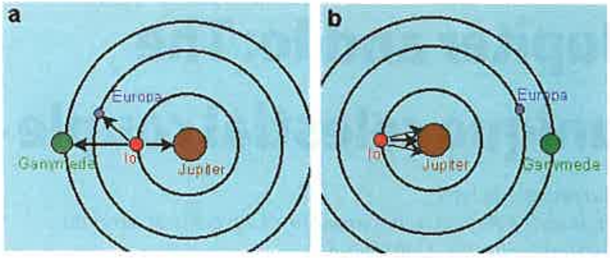
Article available at http://www.europhysicsnews.org or http://dx.doi.org/10.1051/epn:2003301

short timescales. Volcanic material is ejected with speeds of 1 km s^{-1}, which is nearly half the required escape velocity on Io, compared to the 100 ms^{-1} ejecta speed for volcanoes on Earth. The higher ejection speed combined with the lower gravity gives volcanic plumes up to 300 kilometers above the surface of Io. These eruptions closely resemble geysers on Earth. The recent observations showed that the temperature of the hot spots on Io ranges up to 2000 K. Such lavas were common in the early history of the Earth (~2.0 to 4.5 billion years ago) when the Earth's internal heat content was much greater.

The heat source that produces volcanic activity on Earth is the energy released from the decay of radioactive materials within the interior, as well as from heat left over from Earth's formation. But tidal heating produced by Jupiter and the other Galilean satellites is responsible for the massive volcanism on Io. Being an enormous planet, Jupiter exerts a tremendous gravitational force on Io, which orbits relatively close to the giant planet. The relative closeness is seen by comparing the orbital distances of moon and Io from their respective parent planets. As stated in the beginning, Io orbits Jupiter at a distance of 5.9 R_J while Moon's orbit is 60 R_E from Earth. Any object placed in the gravitational field of another will experience forces that tend to distort it, because the attraction is stronger on one side than on the other side. If the body is liquid, it will assume a somewhat elongated shape with the long axis pointed toward the gravity's source. If the body is rigid, it will gradually assume a stable elongated shape and becomes phase locked to the parent planet. However, if the gravitational field changes the body will flex in response. This flexing produces friction and heat inside the body. This is what is happening at Io. Although Io is phase locked to Jupiter, it is in orbital resonance with Europa and Ganymede (for every orbit of Ganymede, Europa makes two and Io makes four orbits). Jupiter pulls Io inward toward itself, while the gravity of the outer moons pull it in the opposite direction. A cartoon explaining this pull by Jupiter and the other satellites is shown in Figure 1. At one point of time Jupiter is at one side of Io and the other satellites are on the other side as in Figure 1a. Later Jupiter and the other satellites are on the same side of Io as in Figure 1b. As a result, Io is subjected to varying tidal forces that cause Io's solid surface to bulge up and down as much as 100m, while the ocean tides on Earth have average excursions of the order of 10m. This friction generates enormous amounts of heat and pressure within Io, causing molten material and gases to rise through fractures in the crust and to erupt onto the surface.

...extensive volcanic activity on Io generates dramatic changes to it's surface

Figure 2 is a picture of Io in enhanced color taken by Galileo. The surface colors are due to the volcanic activity and the subsequent lava flow. Sulfur gas (S_2) was recently detected above one of the Io's volcanoes by the Hubble Space Telescope (HST). This compound is stable at the very high temperatures inside the volcano, but once it is ejected and lands on the cold surface, the sulfur atoms rearrange themselves into larger molecules of three or four atoms (S_3 and S_4), which give the surface a red color. Eventually the sulfur atoms rearrange themselves into their most stable configuration (S_8), which is yellowish in color. SO_2 frost explains the presence of the white patches. The recent observations of high temperature lava suggest the presence of silicates, which are confirmed by the presence of Mountains.



▲ Fig. 1: (a). Jupiter is on one side of Io while Europa and Ganymede are on the other side and Io is pulled from both sides. 1(b). Jupiter, Europa and Ganymede are on the same side of Io and is pulled to the same side.

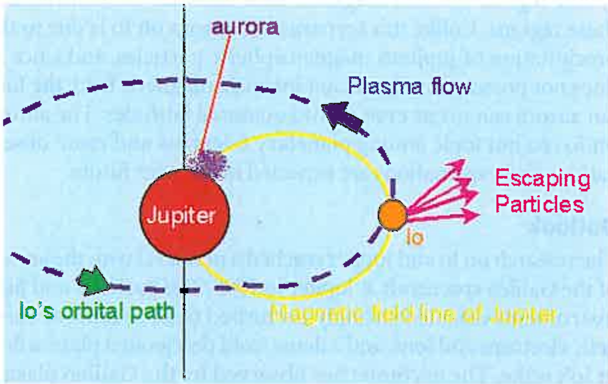
Internal structure: The gravity-field measurements taken by the Galileo spacecraft have shown that the interior of Io is gravitationally separated. That is, dense materials while in the molten state sink to the center of the satellite to form the core and less dense elements rise toward the surface. Io is believed to have a dense core composed of iron and iron sulfide with a radius of approximately 900 km, which extends about halfway to the surface. It is likely that the core is formed either from internal heating processes during the early stages of the moon's formation, or as a result of the ongoing tidal heating that drives the volcanic activity at the surface. Surrounding the core is a mantle of partially molten rock, which is overlain by a relatively thin, rock crust. The *Journal of Geophysical Research*, volume 106, issue E12, December 25, 2001 has provided a special section on the geology and geophysics of Io including the latest observations.

▲ Fig. 2: The enhanced color image of Io taken by Galileo spacecraft in 1996 (http://galileo.jpl.nasa.gov).

Atmosphere of Io

The nature of an atmosphere on Io has been of interest ever since the discovery of an ionosphere by the Pioneer spacecraft in 1973. SO_2 is the major constituent in the atmosphere of Io, and was observed in infrared by Voyager, in ultraviolet by HST and Galileo, and in millimeter wave by ground-based observations. SO has been observed in the millimeter wave by its rotation lines and S_2 in ultraviolet. The photochemical products of SO_2, Na, K, Cl, and NaCl are also present in Io's atmosphere. The sources of SO_2 in the atmosphere of Io are volcanic activity, sunlit sublimation of surface SO_2 frost, and sputtering. The major sources are the first two, but the relative importance is poorly understood.

Io's atmosphere is observed to be patchy and time variable. This property of the atmosphere supports the concept of volcanic origin. Volcanoes produce localized atmospheres with pressures that decrease rapidly with distance from the source. Sublimation

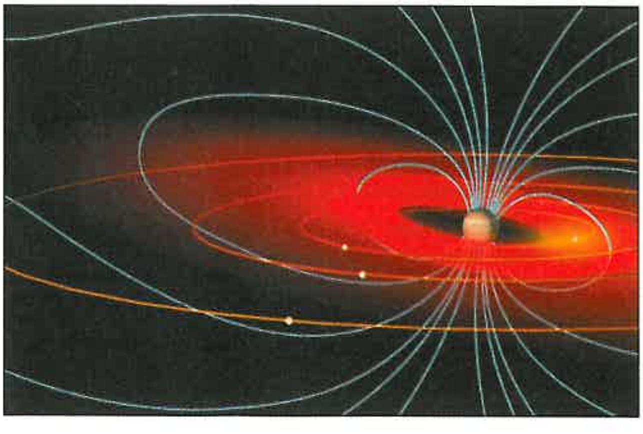


▲ Fig. 3: Schematic of Io Jupiter system. The magnetic field line of Jupiter, which passes through Io, is the Io flux tube (IFT). The escaping particles which are ionized travel with the magnetic field lines around Jupiter and forms the Io plasma torus as in figure 4 and those which are not yet ionized form a neutral cloud as shown in figure 5.

of SO_2 frost is responsible for the existence of a more distributed atmosphere. Although the sublimation atmosphere can reach the nightside, volcanoes are a direct source of the atmosphere on the night side where the temperatures are very low. Surface sputtering is considered the least important source of atmosphere. Energetic ions which reach Io's surface can cause the ejection (sputtering) of molecules from the surface. Though sputtering is not very efficient in producing an SO_2 atmosphere, it might be important for ejecting more refractory species such as Na to be discussed below. A detailed review about the atmosphere of Io is given in *Lellouch* (1996) and the latest atmospheric model is discussed in *Moses et al.* (2002).

Jovian magnetosphere, Io torus and neutral clouds

Since Io resides in the magnetosphere of Jupiter, ions of sufficient energy on colliding with Io's atmospheric species transfer their energy to the atmospheric particles. These particles can then escape from the atmosphere of Io if they get energy greater than the escape velocity. A schematic plan of the escape of particles from the atmosphere of Io is shown in Figure 3. Particles escape at a rate of 1000 kg s^{-1} from the atmosphere of Io. Some of these escaping atoms and molecules become ionized and are therefore trapped by the Jovian magnetic field lines, which drag them along. These ions form a doughnut-shaped region along the orbit of Io around Jupiter known as the Io plasma torus, which is shown in red color in Figure 4.



◀ Fig. 4: Jupiter, Io, Europa, Ganymede and Callisto. The satellite on the right side of Jupiter is Io. The doughnut-shaped red structure along the orbit of Io around Jupiter is the Io plasma torus. The blue lines are the magnetic field lines of Jupiter. This cartoon was prepared by *John Spencer* of Lowell Observatory.

The torus is populated with sulfur and oxygen ions, which are the photochemical products of SO_2 with sodium, potassium and chlorine ions in trace amounts. As the orbital velocity of Io is less than the rotational velocity of the Jovian magnetospheric plasma the Jovian field lines and the associated plasma stream past Io at a relative speed of 57 km s^{-1}. This flow sets up a potential difference of ~400 kV across Io resulting in a current of ~10^6 A that closes through the Jovian and Ionian ionospheres. The magnetic field lines which connect Io to Jupiter define the Io Flux Tube (IFT) which is the yellow line connecting Jupiter and Io in figure 3. The ejected gas from Io, which has not yet been ionized, forms a huge atmosphere near Io known as the neutral cloud. Figure 5 shows an image of the Na component of the cloud, which is connected with Io as it orbits Jupiter. In this figure Io is represented by the small dot inside the crossbars. Clouds of neutral oxygen, sulfur and chlorine also are present. Although the density of sodium is very small, it is easy to detect (Figure 5) due to the strong resonant scattering, when illuminated by sunlight, of the yellow sodium D lines.

Auroral emissions from Jupiter and Io

Electromagnetic radiation emanating from the polar regions of a planet is known as aurora. These auroral emissions are generally produced by the excitation of the upper atmospheric atoms and molecules by energetic electrons and ions precipitating down from the planet's magnetosphere. The occurrence of aurora is a topic of its own and a meticulous review on the aurora of the outer planets is given in *Bhardwaj and Gladstone* (2000).

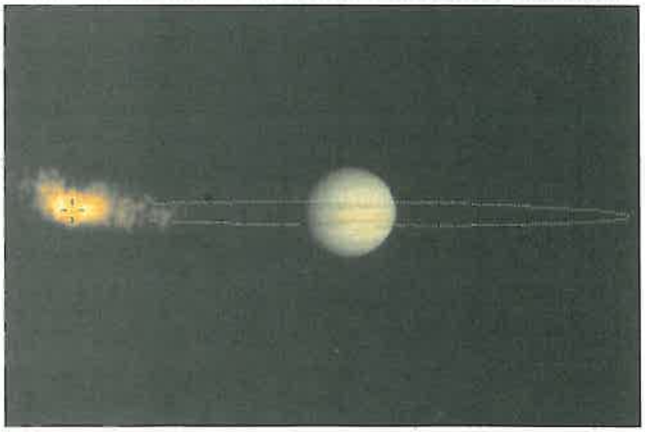
The aurora at Jupiter is very interesting as it hosts a variety of different kinds of auroral processes from that on Earth. Here we restrict our discussion to the auroral processes at Jupiter, which are associated with Io. Aurora spot like emissions were observed at Jupiter where the Jovian magnetic field lines that pass through Io touch Jupiter's atmosphere. These spot like emissions are called Io flux tube footprints and is a direct signature of the complex electrodynamical interaction between Io and Jupiter. The first direct evidence of the Io Flux Tube (IFT) footprint was obtained in a near infrared (H_3^+) image of Jupiter's emission at 3.4 μm in 1992 by ground based observation. The H_3^+ ion is formed in Jupiter's auroral ionosphere by the ionization of H_2 by an electron or an ion followed by conversion to H_3^+. This H_3^+ ion is vibrationally excited and returns to the ground state by emitting the near infrared radiation of 3.4 μm. The ultraviolet IFT footprints were first detected by HST in 1994 in the H_2 Lyman and Werner bands. These emissions are produced by the collisional excitation of the atmospheric H_2 molecules by precipitating charged particles. The IFT footprint in the visible region was observed for the first time by Galileo spacecraft in 1998. Figure 3 shows the auroral radiation from Jupiter where the Io flux tube touches Jupiter.

The Jovian magnetospheric plasma also produces emissions from Io. Spectacular emissions were observed from Io in visible, ultraviolet and x-ray wavelengths. Emissions in the visible were observed by Voyager, ground-based telescopes, Galileo, HST, and Cassini. The first observations by the Voyager 1 spacecraft occurred in 1979. The ground based telescopes have been observing the neutral oxygen emission at 630 nm from Io since 1990. Galileo spacecraft detected visible emissions in the blue (380-440 nm), green (510-605 nm) and red (615-710 nm) band, which appeared to be correlated with Jovian magnetic field orientation at Io. The blue emissions were observed close to the equator, the red emission along the limb and the green emissions were concentrated on the night side. The probable sources of these emissions are SO_2 bands in the blue region, oxygen lines of 630 and 634 nm in the red region and oxygen line of 557.7 nm and sodium lines of 589 and 589.6 nm in the green region. Cassini has observed visible emissions from Io in late 2000 and early 2001 on its way to Saturn. The wavelength filters used in the Cassini spacecraft range from 235 to 730 nm.

Ultraviolet emissions from Io were observed for the first time in the late 1980's. In the early 1990's HST observed neutral oxygen and sulfur emissions in the ultraviolet region. The important line emissions among them are oxygen lines at 130.4 nm and 135.6 nm and sulfur lines at 147.9 nm and 190 nm. The spatial structure of these emissions were studied in detail by the Space Telescope Imaging spectrograph onboard HST in 1997. These observations have shown that Io's UV emissions are correlated with the orientation of the Jovian magnetic field near Io suggesting the role of magnetospheric plasma in producing these emissions. A detailed study of the interaction of Jovian magnetic field-aligned electrons with the atmosphere of Io producing these emissions is given in *Michael and Bhardwaj* (2000) and *Saur et al.* (2000).

Ultraviolet emissions from Io were observed for the first time in the late 1980's.

X-rays from Io were observed by the Chandra x-ray observatory in 1999 and 2000. These emissions are suggested to be produced due to the bombardment of Io's surface by hydrogen, oxygen and sulfur ions of energies greater than 10 keV. Aurora on planets like Jupiter and Earth are produced due to the precipitation of charged particles from the planet's magnetosphere to the upper atmosphere and are mostly confined to the high latitudes (polar regions), as the magnetic field lines are concentrated at these regions. Unlike this scenario, the aurora on Io is due to the precipitation of Jupiter's magnetospheric particles, and since Io does not possess any significant intrinsic magnetic field, the Ionian aurora can occur even at the equatorial latitudes. The aurora on Io is a hot topic among planetary scientists and more observations and explanations are expected in the near future.



▲ Fig. 5: The image of Io's neutral sodium cloud seen from Earth shown together with Jupiter and a schematic drawing of Io's orbit to scale. The location and size of Io is indicated by the orange dot within the cross bars (Goldberg, B.A. et al. *Science*, vol. 226, p.512, 1984)

Outlook

The research on Io and Jupiter reached a new level with the arrival of the Galileo spacecraft at Jupiter in 1995. The particles and field instruments detected strongly perturbed fields, beams of energetic electrons and ions, and a dense, cold decelerated plasma flow in Io's wake. The asymmetries observed by the Galileo plasma wave instrument during the various flybys suggest that the Io's ionospheric plasma density is being strongly influenced by the magnetospheric plasma flow around Io. Detection of emissions at the Io footprint in Jupiter's auroral atmosphere in the infrared, ultraviolet, and visible wavelengths revealed that the particles associated with Io reach Jupiter. The *Journal of Geophysical Research*, volume 106, issue A11, November 1, 2001 has given a special section on the studies of Io including the latest results from the Galileo spacecraft. Two spacecrafts, Cassini and Galileo were in the vicinity of Jupiter in the early 2001, which is the first ever conjunction of two spacecrafts at an outer planet. Observations of these two spacecrafts were complemented by nearly simultaneous images from the Earth orbiting Hubble Space Telescope and Chandra X-ray observatory. The results of all these observations are reported in various papers in the issue of *Nature*, volume 415, February 28, 2002.

An analogy of the Io-Jupiter system is now being applied to extra-solar planets and binary stars consisting of magnetic and non-magnetic white dwarfs. More importantly the vibrant volcanism and extreme heat flow of Io may help us understand the early stages of Earth. The study of this exciting system is attracting young scientists from a broad range of disciplines and our understanding is advancing swiftly.

Acknowledgement

The author's work is supported at the University of Virginia by NASA's Planetary Atmospheres Program

References

[1] Bhardwaj A., and Gladstone G.R., Auroral emissions of the giant planets, Reviews of. Geophysics, vol.38, p.295, 2000.

[2] Lellouch, E., Io's atmosphere: Not yet understood, Icarus, vol.124, p.1, 1996.

[3] Michael M., and Bhardwaj A., FUV emissions on Io: Role of Galileo-observed field-aligned energetic electrons, Geophysical Research Letters. Vol.27, p.3137, 2000.

[4] Moses, J.I., M.Y. Zolotov, and B. Fegley, Photochemistry of a Volcanically Driven Atmosphere on Io: Sulfur and Oxygen Species from a Pele-Type Eruption, Icarus, vol. 156, p.76, 2002.

[5] Saur, J., F.M. Neubauer, D.F. Strobel, and M.E. Summers, Io's ultraviolet aurora: Remote sensing of Io's interaction, Geophysical Research Letters, vol. 27, p. 2893, 2000.

[6] Spencer, J.R., and N.M. Schneider, Io on the eve of Galileo mission, Annual Review of Earth and Planetary Sciences, vol. 24, p.125, 1996.