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DUST DYNAMICS IN THE JOVIAN SYSTEM

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ABSTRACT

The Dust ballerina skirt is a set of well defined streams composed of nanometric sized dust particles that escape from the Jovian system and may be accelerated up to ≥200 km/s. The analysis done of the data obtained by Ulysses and Galileo spacecrafts throughout the Jovian system has confirmed that this dust comes from the ejections of Io´s volcanoes. The Ionian volcanoes eject a mixture of dust and gases of sulfur or sulfur dioxide, but though the speeds of the ejections seem to be just near a half of the escape velocity, part of the volcanic material escapes. In this thesis, it is demonstrated that, in order to escape from this satellite the dust particles, must accomplish at least three different conditions: first of all, grains must have a submicrometer size, grains must acquire a minimum electrostatic charge and third, they must be taken to certain altitude to be in contact with the surrounding plasma and being dragged. Additionally the rate of escaping dust is calculated. The driving of dust particles to great heights and later injection into the ionosphere of Io may give the nanometric dust particles an equilibrium potential, around some volts through electron capture, that allow the magnetic field to accelerate them away from Io.

RESUMEN

La falda de polvo de bailarina es un conjunto de *haces* bien definidos compuestos de partículas de polvo nanométrico que escapan del sistema joviano y que pueden ser acelerados por encima de ≥200 km/s. El análisis de los datos obtenidos por las sondas espaciales Ulises y Galileo en el sistema joviano ha confirmado que este polvo procede de las eyecciones de los volcanes de Ío. Los volcanes ionianos eyectan una mezcla de polvo y gases de azufre y dióxido de azufre y aunque las velocidades de eyección parecen ser apenas la mitad de la velocidad de escape de Ío, parte de este material eyectado en forma de polvo escapa. En este trabajo se demuestra que para que las partículas de polvo escapen de este satélite deben cumplir, al menos, con tres condiciones: Primero, el polvo debe tener un tamaño sub-micrométrico, segundo, estos granos de polvo deben estar cargados y, tercero, las partículas de polvo deben ser llevadas a una altura suficientemente grande para estar en contacto con el plasma circundante y ser arrastradas. Adicionalmente se calcula la tasa de polvo que escapa de Ío. Las plumas volcánicas llevan parte del polvo a muy grandes alturas y lo inyectan en la ionosfera de Io donde los granos de polvo nanométrico adquieren un potencial superficial estable de algunos volts por captura electrónica, que les permite ser aceleradas fuera de Ío a través del campo magnético joviano.

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INTRODUCTION
Dust in the Jovian System

Jupiter is a 71492 *km* ($1R_J$) planet, with a volume equivalent to thousand earths; it is surrounded by a huge (~$90R_J$, Acuña et al.,1982) magnetosphere bigger (>10^6*km*) in size than the Sun itself ($R_S \approx 10\ R_J$) and has, in the least, 61 satellites orbiting about it. Most of Jupiter's satellites are asteroid like moons but four, have sizes between our Moon and Mercury. These satellites are known widely as the Galilean satellites. Jupiter is also surrounded by an important amount of dust grouped in different ring or toroidal structures. All these elements together are known as the Jovian System.

Recently, the importance of dust has been recognized as a fundamental component, not only of the jovian system, but also of the whole Solar System and the Universe itself since the answer to some fundamental questions related to the origin of stars, planets and galaxies might be inside dust grains.

There are three main sources of dust grains in the Jovian System. The first source (not necessarily in order of importance) is meteorite impacts on Jupiter's moons. The second source may be considered as interplanetary dust source or outer source. The third source is the volcanic activity of Io, Jupiter's moon, of course an inner source.

Next, as examples, we describe briefly some dust populations of the Jovian System generated through the sources already mentioned.

i. Amalthea, Metis, Adrastea and Thebe (**Fig.1** and **Table 1**) are the four closest moons of Jupiter, they have radii only of some tens of kilometers (Table 1) and their origin might be parallel to the origin of Jupiter itself. Since they are too close to Jupiter they are also target of a wide amount of meteorites attracted and accelerated by this planet from the Interplanetary Medium. Every impact on the surface of these moons produces the ejection of a considerable amount of micrometric and sub-micrometric dust with enough speed to overcome their gravitational pull. Dust escapes from the moons but not from Jupiter so it spreads all along the orbits of these four moons building the so called Jovian Rings discovered by the Voyager missions in 1979. Four concentric dust rings on the equatorial plane of Jupiter compose this system. That is a toroidal *halo*, a well-defined *main* ring and *two gossamer* rings (**Fig.2** and **Table 2**). According to the estimations based on Galileo spacecraft dust data as it passed through the rings on November 2002, the particle density is around $\sim 10^{-3}$-10^{-4} m^{-3} (Krüger al., 2003) and dominated by micrometric particles.

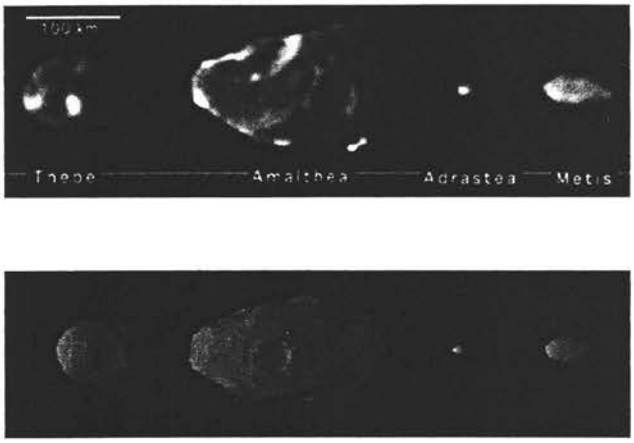

Fig.1 The four closest moons of Jupiter (Images: *NASA/JPL*).

TABLE 1. Physical properties of the four closest moons of Jupiter ($1R_J$ =71398km) after Burns et al., 2002.

MOON	Semimajor axis (R_J)	*e* [$\times 10^{-4}$]	*i* [grad]	Average radius. [km]	Surface escape velocity [m/s]	Geometric albedo
METIS	1.792	2	0.06	21.5	0.5-19	0.061
ADRASTEA	1.806	15	0.03	8.2	0-8	-
AMALTEA	2.54	31	0.39	83.5	30-82	0.090
TEBE	3.11	177	1.07	49.3	31-45	0.047

The Galilean moons (Table 3) are also subjected to meteorite impacts, but since their escape velocity is much larger ($\sim$2.4 *km/s*), most of the dispersed dust will be kept bounded to the moons and only a small fraction ($\sim 10^{-3}$) escapes. Those dispersed grains that achieve a near escape velocity form clouds that envelope the moons and those dust particles that escape spread all along the paths of these jovian moons forming a ring about Jupiter between Io's and Callisto's orbits (Table 4), concentrated basically along the orbit of Europa (Thiessenhussen et al., 2000). According to data, the meteorites that hit the moons have radii around ~0.5 to 1 μm, with fluxes of the order of ~1 *imp/min* and speeds near ~10 *km/s*. Although clouds have stationary masses, grains fall eventually onto the moons' surfaces in a matter of hours. On the other hand, the ring built with these particles is too tenuous to be detected optically (particle density~500 km^{-3}).

TABLE 2.Some properties of the dust that surrounds the galilean satellites (after Krüger et al. 2003).

SATELLITE	IO	GA	EU	CA
Cloud steady mass [ton]	50	70	120	250
Impactor flux[$\times 10^{-12}$ g/m²-s]	10	7	4	3
Dispersed mass in impacts [$\times 10^{5}$ g/s]	40	9	4	0.3
Fraction of dispersed mass that escapes [$\times 10^{-4}$]	1	2	8	40
Mass injected to the jovian space [g/s]	400	200	300	100

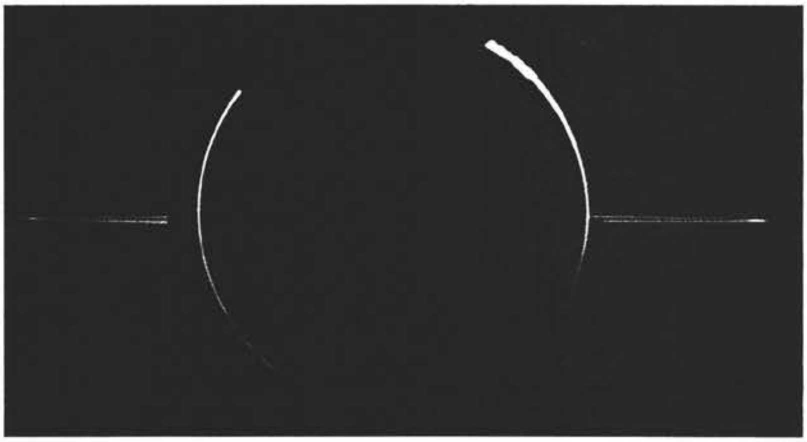

FIG. 2 The Jovian *rings* discovered by Voyager 1 in 1979 (NASA/JPL)

TABLE 3. Physical properties of the Jovian *rings* (after Ockert et al., 1999).

RING	Inner boundary [R_J]	Outer boundary [R_J]	Thickness [$\times 10^3$ km]	Optical depth [$\times 10^{-6}$ km]	Dust fraction
Halo	1.29	1.713	12.5	1	100
Main ring	1.706	1.804	~0.1	3	~50?
Amaltea's ring	≤1.804	2.546	1.3	0.1	100?
Thebe's ring	≤1.804	3.161	4.4	0.03	100?

ii. The disruption and later impact of comet Schoemaker-Levy 9 (*SL9*) onto Jupiter's atmosphere in 1994 generated an important amount of micrometric dust (~10^{11} to 10^{12} *kg*, Sekanina, 2001). This dust population forms now a tenuous belt of $5R_J$ width and similar orbital radii. According to models, this belt will be flattened eventually and will look just like the *main ring* at that $5R_J$ orbit.

Fig.3 Hubble Space Telescope image (H. Weaver, NASA/JPL) shows the 'string of pearls' comet Shoemaker-Levy 9 in March, 1994, 4 months before its collision with the planet Jupiter. This is the first collision of two solar system bodies ever to be observed, and the effects of the comet impacts on Jupiter's atmosphere were simply spectacular and beyond expectations. Comet *SL9* consisted of at least 21 discernable fragments with diameters estimated at up to 2 kilometers and around $\sim 10^{11} kg$ of micrometric dust particles.

iii. Io's amazing volcanic activity is now known to be an interesting and important source of nanometric dust as well as some ions and atoms for the Jovian System. Io's volcanism is activated by tidal dissipation due to the particular orbit of this satellite. Part of the material ejected through the volcanoes manages to escape and generates a plasma Torus around Jupiter. The Torus is composed of ions and electrons but has an important amount of dust that eventually escapes (~10nm) not only from the plasma Torus but also from the Jovian System itself in well-defined streams (Jovian Dust Streams). The whole set of dust streams is known as the Dust Ballerina Skirt since it composes an oscillating structure that concentrates in the magnetic equator.

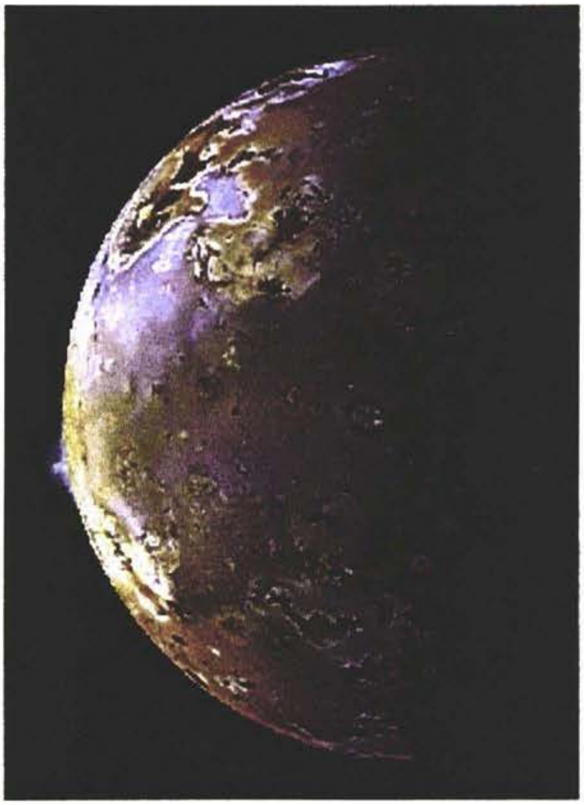

FIG.4 The Galileo spacecraft sighted prominent ejection from various volcanoes on Io, just like the one showed on the image where *Pillan Patera* emits a 140 *km* tall plume (Image: NASA/JPL).

CHAPTER ONE
The Jovian Dust Streams

Electromagnetic forces dominate the dynamics and distribution of the sub-micron sized dust particles in the Jovian System. Most dust particles in Jupiter's neighborhood get charged through different processes, but mainly due to radiation and the contact with the Jovian plasma. The influence of these electromagnetic forces over the dust grains will depend on its sizes and surface potentials. Certain grains, under certain circumstances may even be ejected from Jupiter to the Interplanetary Medium as witnessed by the Ulysses spacecraft as it approached and aimed its dust detector to the Jovian System at 5.4 AU heliocentric distance ($1AU \approx 1.5 \times 10^6$ km) on February 1992.

JOVIAN DUST STREAMS DETECTION

Pioneer 10 and 11 were the first spacecrafts to carry dust detectors and recorded, for the first time, dust particles, as they passed by Jupiter in 1973 and 1974. That finding motivated the search for a possible dust production mechanism in the following years (Johnson et al., 1980, Morfill et al., 1980 and Grün et al., 1980). More than a decade later, Ulysses spacecraft, a joint project between NASA and ESA, was aimed toward Jupiter in 1990 in order to achieve, through its gravity, an unusual orbit around the Sun. Ulysses spacecraft was also equipped with a dust detector, but 10^5 times more sensitive than Pioneer's that detected also dust from the Jupiter System.

The Ulysses dust detector, built by E. Grün and his colleagues, has an average detection area of 235 cm^2 and detects dust particles through the ionization generated by impacts on the target. Dust particles, charged or not, can be detected as they hit the target and generate a plasma cloud that is later separated in ions and electrons due to an electric field. Both currents are measured and, through them, mass and speeds are inferred.

When Ulysses was at $1AU$ from Jupiter at the beginning of 1992 and its dust detector was pointing directly to this planet, six particle bursts were detected in periodic collimated streams. According to the detector, the streams were composed by sub-micrometric dust grains (0.03μm to 0.14μm in radii, assuming a 1 g/cm^3 density) with masses around $1.6 \times 10^{-16} < m < 1.1 \times 10^{-14}$ g and speeds ranging from 20 km/s to 56 km/s. These streams were spaced 500R_J ($1R_J$=71398km) and occurred during several hours to two days at 28$\pm$3 *day* intervals (Grün et al.; 1993a; Grün et al.; 1993b).

The specific source of the dust was not identified, but it was clear that the dust came from the Jovian System, since the streams were narrow, collimated and concentrated near Jupiter and their periodicity indicated a single source (Grün et al., 1993b) as well. The first models proposed three potential *point* sources: The gossamer ring (Hamilton &

Burns, 1993) discovered by Voyager 1 in 1979, Io, the moon of Jupiter (Horanyi et al., 1993) whose huge volcanic plumes had been also discovered by the Voyager mission, or even the Schoemaker-Levy 9 (*SL9*) Comet (Grün et al., 1994) that disrupted itself on its way to Jupiter in 1992 and collided on its atmosphere in July 1994.

At the end of 1992, almost three years after being launched, the Galileo spacecraft entered also in the Jovian System, but to stay, since this Mission was devoted to study many aspects of the Jovian space. Galileo dust detector instrument, identical to Ulysses' dust detector registered the dust streams in its way to Jupiter and also when it was already orbiting it. This was a confirmation of the Ulysses data since the duration and intensity of the streams were similar.

Based on the analysis of the trajectories of the dust detected by Ulysses, Zook et al (1996) found that the mass and speeds inferred for the particles in the streams were not right. Speeds had been underestimated (~1 order of magnitude) and mass had been overestimated (~3 orders of magnitude). Particles are actually smaller ($\sim10^{-18}$ *kg*) and faster than 200 km/s and, therefore these values were out of the calibrated mass and impact ranges of the detectors (Grün et al., 1996) of both surveys. With this new finding SL9 was automatically discarded as a source since no particle produced in that comet would have such properties.

Already in 1995, based on an analytical analysis Maravilla et al (1995) had studied the trajectories of dust grains coming from the three sources and all results indicated that Io was the most likely source of the Jovian Dust Streams. Two years later and taking now Io as the source of the streams, Horányi, Grün and Heck (1997) modeled the Galileo dust measurements and successfully matched most of the features of the detected streams. *Finally*, a direct analysis of the periodicity of the streams detected by Galileo along 29 orbits by Graps et al (2000) found that the frequency is modulated by two intrinsic periods, ~10 and ~42 *hours*, that correspond to the rotation period of Jupiter and orbital period of Io respectively, confirming that the dust of jovian streams were generated in Io.

DUST ACCELERATION MECHANISM

The Jovian Dust Streams may be considered as a continuous flux of nanometric particles accelerated from the atmosphere of Io to the Interplanetary Space.

Almost a hundred hotspot volcanoes have been identified on the surface of Io where volcanism is activated by tidal dissipation. More than 15 of these volcanoes eject gas and dust explosively at speeds larger than 1 km/s generating spectacular plumes of more than 100 km in height, some observed also from Earth.

The surrounding jovian plasma co-rotates rigidly with Jupiter with angular velocity $\Omega\sim1.74\times10^{-4}$ *rad/s*, so that plasma particles along the Ionian orbit move with a tangential speed equal to 74.21 *km/s*. Since Io rotates around Jupiter in ~42 *hours*, its tangential speed is ~17.7 *km/s*. Particles that manage to reach the top of the highest plumes may be considered as particles injected into the jovian plasma with a speed ~57 *km/s* (Horanyi et al., 1993) which is the relative velocity between Io and the co-rotating plasma . This gradient of velocity and the charge will then ease the escape of the dust grains. Models suggest that fine dust from the volcanic ejections that manage to reach the cold regions of the plasma Torus will be charged negatively and will remain confined there. On the other hand the grains ($5\leq r\leq15$ *nm*) that enter the hot plasma Torus will be charged positively and will be accelerated ($v\geq200$ *km/s*) and pushed outwards by the corotational electric field (Horanyi et al., 1993a; Horanyi et al., 1993b).

TRIP FROM THE VENT TO THE TORUS

In order to escape from the Jovian System, grains must be positively charged and also be among certain size ($5 \leq r \leq 15$ nm), but these conditions apply for particles already out of Io's tenuous atmosphere and in the plasma Torus. Although we know that particles escape from Io through the volcanic ejections, it is not well defined how these particles escape, and how and where they are produced. In this work, we will try to define some of the conditions that particles need, in order to escape from Io and to a certain degree to fill the gap between two different steps: The generation and ejection of dust particles and the entering of these particles into the Ionian ionosphere.
Basically, we will try to answer some of the following questions:

Do DUST PARTICLES, in Io's volcanic plumes, GET CHARGED BEFORE being in contact with the ionosphere of this satellite?

If true: Which are those electrification mechanisms? And
What are the magnitudes of these charges? and
Which would be the consequences for the dynamics?

The answer to these questions will depend on the conditions of the plumes, some of which are known to a first approximation. The physical and chemical properties of the dust at locations where this dust is produced are very important features to develop a correct model. According to what is known from earth volcanism, charging processes might be something quite common inside the plumes and vents of volcanoes, which means that the main charging processes might not be those that take place in Io's ionosphere or the Jovian plasma.

On the other hand the study of dust coming from Io, may give us important information about the processes that take place in Io's internal layers.

CHAPTER TWO
Io, the moon of Jupiter

In the year 1610, Galileo Galilei, the great Italian astronomer, published the *Siderius Nuncius* –Sidereal Messenger- that was a series of important discoveries. One of these was a set of four stars that he conveniently baptized *Medici's Stars* honoring his sponsors. Galileo knew very well that those heavenly bodies were not stars, but satellites orbiting the largest of the planets, Jupiter.

In 1979, as the Voyager surveys passed by Jupiter, they had good images of these Medici's Stars (Io, Europa, Callisto and Ganimede), nowadays called Galilean Satellites. The intense activity of Io and the frozen surface of Europa were features never seen before. More than 20 years later, a new survey, now honoring Galileo with his own name, orbited Jupiter and had a more closer look at these moons and the whole Jovian System getting a wide amount of data including images with amazing details.

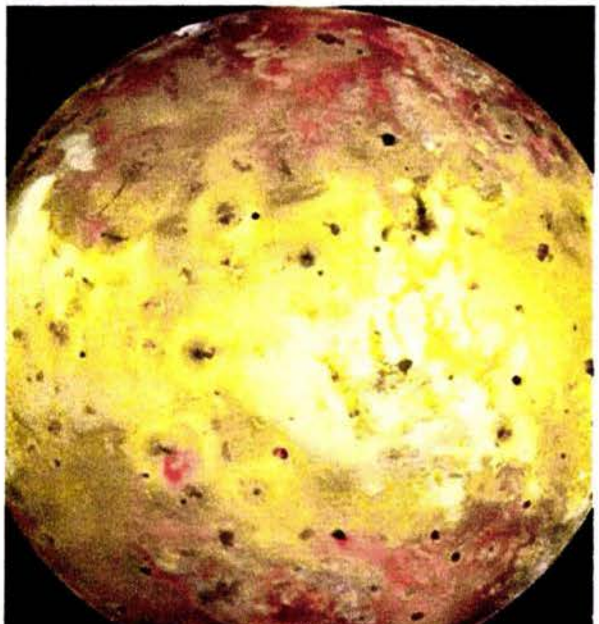

Fig.2.1 Composition of images of Io taken by the Galileo Survey on-board camera during a close fly-by in July 1999 (NASA-JPL).

THE SURFACE AND INTERIOR OF IO

Io (Fig.1) is a rocky body ~4% larger than our moon, with a diameter of 3630 km. Among Galilean Satellites, Io is the third in size and among all Jupiter's satellites the fourth in distance to Jupiter's centre (~4.22×10^5 *km* or ~$5R_J$). The mass of Io is $8.55\text{x}10^{22}$ *kg* and its bulk density ~3.57 g/cm^3. Io completes a revolution around Jupiter in a relatively short time, ~1.769 *days*, that is, its average tangential speed is near 18 *km/s* (~17749 *m/s*) in an orbit that lies right on the jovian equatorial plane. It is supposed, to a first approximation, that Io has gotten a differentiated interior like the Earth itself, composed essentially by a crust, an asthenosphere (a plastic layer where convection is possible), a mantle and a core. In some models a thin liquid layer is added between the astenosphere and the mantle.

In its first images of Io, Galileo saw a pizza like surface with yellow, orange and white areas, also red fields and even some small green spots. The first three-color features were explained as sulfur in its different forms and at different temperatures. On the other hand, red areas are explained as recent depositions of volcanic plumes that will tend later to yellow and the small green areas might be also sulfur, but mixed with other material or simply olivine.

Probably Io's crust is composed by Orthopyroxenes (*Fe/Mg* rich orthosilicate minerals, *Mg, Fe*$)_2SiO_4$, which are present in earth mafic and ultramafic lavas, McEwen et al, 2003), sulfur dioxide (SO_2) and other sulfur based materials (Nash et al, 1986). The idea of the silicate crust came out when the Galileo spacecraft observed the steepness of the volcanic calderas and detected temperatures (>650 *K*) far above the melting point of sulfur (~393 *K*, Pearl & Sinton, 1982). According to this, the sulfur crust might just be a coating due to SO_2 and *S* volcanic precipitations fed by local sulfur dioxide chambers inside the crust or even a global liquid sulfur ocean under the crust (Sagan, 1979, Nash et al., 1986 and).

This silicate crust might envelope a molten mantle made out also by silicates and with a solid *Fe/S* core in its centre corresponding to ~20% of the total mass of the satellite (Anderson et al., 2001 and Schubert et al., 2000b).

More than 115 mountains cover 3 % of Io's whole surface. Their origin is still not clear since they have an irregular distribution (McEwen et al., 2003), but it has been proposed that the large distance between them could be the result of huge low density *bodies* of different composition known as *plutons*, inside the crust that would mean that this crust itself is composed of different sub-layers, implying also that ultramafic volcanism may be concentrated at shallow depths (Keszthelyi & McEwen, 1997). Io's mountains have an average height around ~6 *km* and from 10 to 500 *km* wide bases. Their shapes are also diverse ranging from flat mesas and massive irregular structures to sharp peaks. The highest mountain is *Boosaules Montes* and has ~17 *km* in altitude.

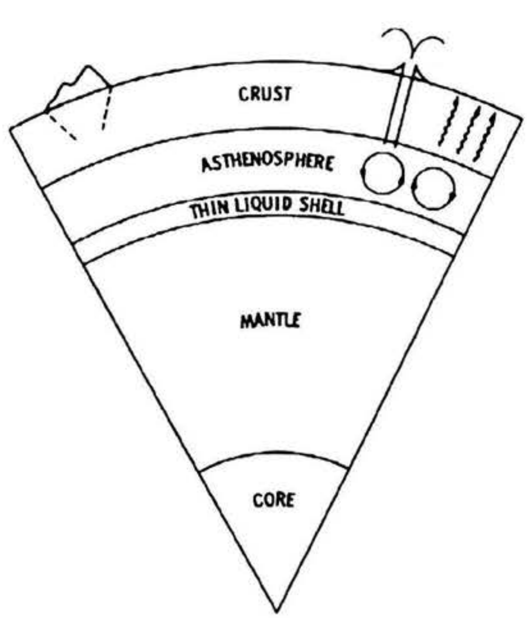

Fig.2.2 Hypothetical model of Io's interior (not at scale). Volcanoes and mountains lay on a Fe/Mg rich silicate crust coated by sulfur and sulfur dioxide. There are convective currents in the asthenosphere due to a heat gradient generated by tidal stresses. Eruptions and conduction bring heat to the surface (Image: Nash et al., 1986).

THE ORIGIN OF IO'S VOLCANISM

The orbital eccentricity of Io is kept through the balance of some interactions. The first and most important is the torque generated by its link with Jupiter that expands Io's orbit. Secondly, the resonance among Io, Europa and Ganymede, that modify its eccentricity and transfers angular momentum from one satellite to the other. Io is stretched in two senses, that is, the axis of a first tide points always to Jupiter and the axis of the second varies with Io's relative position in respect to the other satellites. This means a constant transference of energy, due to the continuous stretching and compressing, dissipated as heat into Io's body.

There could be radioactive material inside Io's core if we suppose an earth model, but since Io's tidal dissipation is a much more efficient heating mechanism than radioactive disintegration for the Earth, we suppose the tidal dissipation as the main source and cause of Io's intense volcanic activity.

A *minor* heat contribution may be added due to a second mechanism: electrical heating. Since Io and the Jovian magnetic field ($\mathbf{B}_J$) have different velocities, there is a voltage difference (Φ) through Io's diameter around ($\mathbf{v}X\mathbf{B}_J \approx$) 411 *keV* and also a current I that flows from Io to Jupiter along the field lines. To a first approximation the amount of dissipated heat per unit of time may be calculated through $P = Q / t = \Phi I$ (Joule effect). Roughly, $\Phi \sim 10^6$ *Volts*, $I \sim 10^6$ *A* (Nash et al., 1986) and though the dissipated heat power $\sim 10^{12}$ *watts* which means around ~0.02 W/m^2 or less than 1 % of the energy radiated through tidal dissipation.

IO'S VOLCANISM AND VOLCANIC PLUMES

The volcanic eruptions in Io are in some senses similar to those observed on Earth, that is, there are also lava flows, calderas and fire fountains just like in Hawaii; but these eruption are very different in some other senses. For example, Io's calderas are much larger (from some kilometers to several hundred square kilometers) and its lavas are, on the whole, much hotter (>1000 *K*) and with longer fluxes (e.g. for Amirani volcano, ~300 km) than lavas on Earth. The near hundred volcanoes identified on Io eject 100 times more lava per year than the more than 600 active volcanoes on Earth. Io's average heat flux is larger than ~2.5 W/m^2 (McEwen et al., 2003) and this is radiated almost constantly outwards in longer wavelengths than 5μm (Veeder et al. 1994) which is only comparable to the most active volcanic regions on Earth.

The highest temperatures detected on Io by the voyager missions are around 650 *K* and they are fully consistent with a sulfur volcanism model, but due to the limitations of the detectors, the Voyager missed small areas with higher temperatures. Unlikely, telescopic surveys in 1986, detected temperatures far above those measured by the Voyager which suggests, in the least, occasional silicate lava eruptions. Recently, through these telescopic observations as well as those of Galileo's survey it has been demonstrated that such hotspots are quite common on Io.

There are, at least, 30 geographic areas on Io's surface whose temperatures exceed ~700 *K*, among these some above ~1000 *K* and 12 different volcanic cones with lavas hotter than ~1700 *K* (McEwen et al., 1998). Due to these high temperatures, volcanic processes in Io fit a kind of volcanism known as ***hotspot volcanism***. Table 4 (McEwen et al., 1998) show the temperatures of some specific areas of Io's hotspots where the measured minimum temperature is 600K and the maximum more than 2600K.

TABLE 2.2. Hotspot's temperatures and areas observed during the eclipsing of Io (after McEwen et al., 1998)

HOTSPOT	LAT/ LONG	ORBIT	AREA [km^2]	T_{MIN} [*K*]	T_{MAX} [*K*]
Kanehekili-S	-17/36	G8	0.009	1195	1530
Kanehekili-N	-14/33	G7	>0.006	1335	1930
Janus	-4/39	G7	>0.21	840	1380
Amirani	23/116	G8	0.0006	1050	>2000
Svarog	-54/270	C9	>0.87	1095	1130
Acala	11/333	C9	0.019	1200	1430
Marduk	-27/209	E11	0.002	1365	1615
Pillan	-10/242	C9	0.03	1500	>2600
Pillan-N	-9/243	E11	0.0012	1330	1560
Pillan-S	-11/242	E11	0.029	1280	1320
Pele	-18/256	E11	0.575	1260	1290
Lei-Kung	37/203	E11	0.0016	1210	1265
Isum-N	33/205	E11	0.0012	1205	1655
Isum-S	30/207	E11	0.0025	1070	1530
----	22/238	E11	0.0002	1240	1915

The origin of *hotspot* volcanoes has not been determined, but according to the composition and chemical characteristics of lavas on earth volcanoes, they seem to have its origin in magma *bubbles* coming from the upper part of the nucleus that manage somehow to reach the crust. Since all these temperatures are above the melting point of sulfur in near vacuum, it is thought that silicate volcanic eruptions might be a fundamental part of the whole Ionian volcanism.

Additionally, it is observed that only a fraction of these Ionian hotspot volcanoes emit plumes. Both, Voyager and Galileo detected only 17 active volcanic plumes, 15 of which are displayed on Table 5 (McEwen et al., 1998).

TABLE 2.3 Active volcanic plumes on Io detected by the Voyager and Galileo surveys between 1979 and 1997 (McEwen et al., 1998).

	PLUME NAME	LAT/ LONG	DETECTION DATE [*month/y*]	HEIGHT (*km*)
1	Amirani	+24-+28,114	3,7/79, 12/96, 5/97	50-100
2	Volund	+23/177	3,7/79	50-100
3	Loki-W	+19/305	3,7/79	150-400
4	Maui	+19/122	3,7/79	50-150
5	Zamama	+18/173	6/96, 5/97	50-100
6	Loki-E	+17/301	3,7/79	20-150
7	Acala	+11/334	4,5,6/97	200-300
8	Prometheus	-2/152-4	3,7/79	50-100
9	Ra	-8/325	6/96, 12/96?	50-100
10	Pillan	-12/242	6,9/97	100-150
11	Kanehekili	-17/36	5/97	50-100
12	Pele	-18/256	3/79, 7/95?, 7/96, 12/96, 7/97?	300-460
13	Culann	-20/160	6,9/96?	0-50
14	Marduk	-27/210	3,7/79; 2,5,6,9/97	50-100
15	Masubi	-44//54	3,7/79	50-100

The shortest plumes are around ~50 *km* and the tallest 460 *km*. It is deduced from here that the three most violent volcanoes are Pele with 300-460 *km* tall plumes, Loki-W whose plumes range from 300 to 400 *km* in height and Acala with 200-300 *km* tall plumes.

Essentialy, these plumes are umbrella like structures made out of fine grain volcanic debris and gas whose origin might be at depths near ~1.5 *km* into Io's crust (Kieffer, 1982) where sulfur dioxide is heated at a ~40 *bar* pressure until it liquifies (~395 *K*). Sulfur dioxide vapours then force the liquid to the surface. This solid-liquid-gas mixture is accelerated upwards until it reaches the surface and expands violently into the thin atmosphere. Through this process the plume is cooled allowing further condensation as frost that will eventualy fall onto the surface.

According to their physical and chemical properties, plumes may be grouped in two large categories (Table 6). The first kind is characterized by huge plumes (>250 *km*) with short lifes (some days or months) or even intermitent and long periods (~10 years). These plumes are named Pele type plumes after the spectacular Pele plume. In fact, Pele is the hotspot with more constant temperatures during the years of observation in spite of his long eruption terms. Probably Pele might be associated with a lava lake. It has been found that Pele plumes are rich in sulfur and sulfur dioxide gases (Spencer et al., 2000), which suggests that it is composed only by gas and very fine particles with radii around ≤80nm.

The second global type of plumes are shorter (<120km), much more brilliant, with a longer life (several months or years), but low frequency of eruption (<3 years). This kind is known as Prometheus type named after the hotspot with the most persistent plume since the Voyager era (Geissler et al., 2003). Interestingly, during 20 *years*, Prometheus plume has migrated 85 *km* to the west; this characteristic seems to be common to other Ionian plumes.

TABLE 2.4 Properties of the 2 general types of Ionian volcanic plumes (McEwen et al., 1989).

PROPERTY	PELE TYPE	PROMETHEUS TYPE
Eruptive height	250-300 *km*	50-120
Diameter of plume deposits	1000-1500 *km*	200-600 *km*
Eruptive velocity	1 *km/s*	0.5 *km/s*
Eruptive duration	Days-months	Months-years
Frequency of new eruptions	10 y^{-1}	<3 y^{-1}
Associated surface temperatures	600-650 *K*	<450 *K*
Plume optical densities	Optically thin	Portions optically thick
Spectra of plume deposits	Relatively dark red	Bright white
Compositional association	S-rich, SO_2-poor	SO_2-rich
Global distribution	240-360°Long possibly 0°a 100° Long	+30° a -30° Lat
Geologic interpretation	S vaporized by molten silicates; Dominantly silicate crust.	SO_2 vaporized at low T(~400 *K*), perhaps by molten S, abundant SO_2 in crust.

ATMOSPHERE

It is said that Io possesess a quite tenuous atmosphere (McGrath 1997) produced as a whole of volcanic emissions and dominated though basically by sulfur dioxide SO_2 (Thomas et al. 2003), and related compounds such as *SO*, *O* and *S* in smaller amounts. Based on observation, it is calculated that the atmospheric pressure is of the order of ~10^{-9}-10^{-7} *bar* (Kieffer, 1982, Nash et al., 1986 and McGrath et al., 2003). The gases of the volcanic ejections maintain the atmosphere, but also the frost deposited onto the surface of previous the ejections that are sublimated by the solar radiation. Since, at nights, part of the atmosphere condenses again and fall back to the surface, it is then calculated that on the night side, the atmospheric pressure decreases up to 4 orders of magnitude, $\sim 10^{-11}$ *bar*. But in spite of being a variable atmosphere is although a real atmosphere if it maintains pressures above this former value which means a gas envelope dense enough to be controlled by molecular collisions and though obey the gas laws. It is also said that Loki and Pele emit around $\sim 10^{8}$ *kg/s* (Ip 1996) that would mean that those plumes could sustain each a local atmosphere of $\sim 10^{-7}$ *bar*.

IONOSPHERE

Unexpectedly, on December 7, 1995, when Galileo survey passed by Io at ~800 *km* from the surface, its plasma detectors revealed that it has crossed its ionosphere (Frank et al., 1996). Galileo identified this upper layer as a dense plasma ($\sim 18000 \pm 4000 cm^{-3}$) which, in comparison to the surrounding plasma ($\sim 3600 \pm 400\ cm^{-3}$) whose magnetospheric speed is ~57 *km/s*, is at rest with Io. This ionospheric plasma is colder ($\sim 10^{5}\ K$) than the *outside* plasma ($\sim 3\times10^{-6}$-$5\times10^{-6}\ K$) and has a composition that includes S^{+}, S^{2+}, O^{+} and O^{2+} ions.

It was found that the thermal speeds of ions are larger (~10 *km/s*) than Io's surface escape speed (~2.56 *km/s*) implying that this ionosphere is not gravitationally bound to Io. A possible mechanism that would explain why the ionosphere is not swept by the magnetospheric plasma might be the interaction between this ionosphere and the neutral atmosphere, that is, the ions will be kept at rest with Io if they experience a collision with a neutral atom or molecule along a gyroperiod in the local magnetic field.

Typically, it is considered that the Ionian ionosphere starts at 400km (Kliore et al., 1975 & Ip, 1996) above Io's surface. That height corresponds to the range of some known volcanic ejections.

Table 2.5 Properties of the Ionian ionosphere (after Frank et al., 1996)

Lower boundary	<400 *km* from the satellite's surface
Upper boundary	>900 *km* from the satellite's surface
Particle density	$\sim 18000 \pm 4000\ cm^{-3}$
Temperature	$\sim 10^{5}\ K$
Composition	S^{+}, S^{2+}, O^{+}, O^{2+} and SO_2^{+} ions
Thermal velocities (cool ions)	$\sim 10\ km\ s^{-1}$

THE PLASMA TORUS AND THE SODIUM NEUTRAL CLOUDS

The weak atmosphere generated through the violent volcanic processes and its interaction with the jovian magnetic field are two important factors that represent a continuous mass loss for Io. Part of the ejected material, composed by atoms and molecules of oxygen, sulfur and related compounds escape. The neutral particles that manage to escape will orbit next to the satellite until they are ionized through the impact of electrons or photons. Once ionized they will integrate to the jovian magnetic field and they will be accelerated up to the magnetospheric plasma speed, ~57 *km/s*. All these particles will form a toroidal structure along Io's orbit and on the jovian magnetic field equatorial plane known as the plasma Torus that co-rotates almost rigidly with Jupiter. Note that due to a 9.6° angle between the rotation and magnetic field axes, Io oscilates inside the Plasma Torus (Fig 2.3).

The Torus may be consider also composed of two regions: an internal –with respect to Io-cold region or *cold torus*, and a hot external region or hot torus. The temperatures of the *cold torus* are near 10^4 *K* and those at the hot torus are near 10^6 *K*.

If Io's orbit is $2.65\times10^6 m$ long and the Torus cross section around $\sim1R_J{}^2$ the volume of the Torus will be of the order of $\sim1.4\times10^{25} m^3$ (typical value). On the other hand if the supposed average particle density of the Torus is ~2000 *ions/cm³* with typical molecular weights around 20, then, the average mass for the Torus is $\sim9.3\times10^{25}$ *kg* (Thomas et.al., 2003). Even though this mass may be taken as stationary, the own variability of the system makes that this value differs up to 50% from the real figure. It is also possible that an important fraction (up to ⅔) of the mass ejected by Io escapes directly from the Jovian System and that most of the remaining mass that built the Torus stays only for 25 to 80 *days*.

Besides the atoms and molecules that are added continuously to the Torus, there is also a significant amount of sub-micrometric dust particles that escapes from Io and is added to the Torus as well. Their size and surface potential will define their permanence and dynamics inside the Torus. On the whole, it has been observed that nanometric particles (8-200 *nm*, Grün et al., 1998) with positive surface potentials of some volts will escape as part of the *Jovian Dust Streams*.

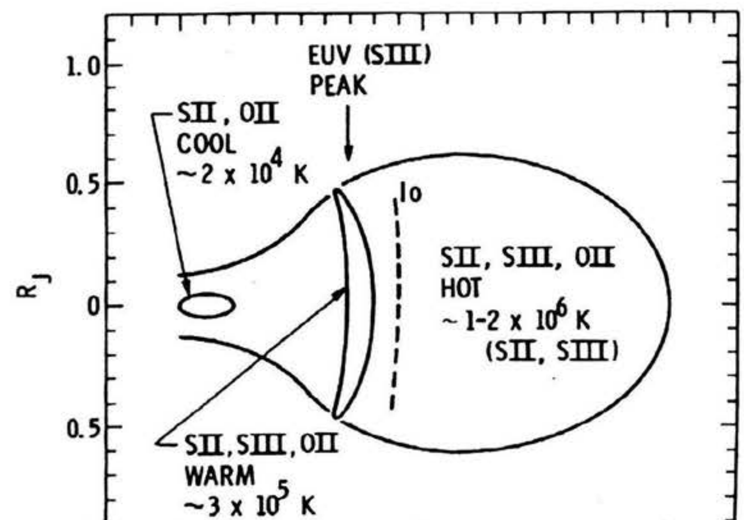

Fig.2.3 Plasma torus cross section where the different regions may be seen as well as the relative position of Io with respect to the Torus represented by dotted line. Io's orbit and the Torus have different inclinations, thus Io oscilates along the Torus (Smyth 1983).

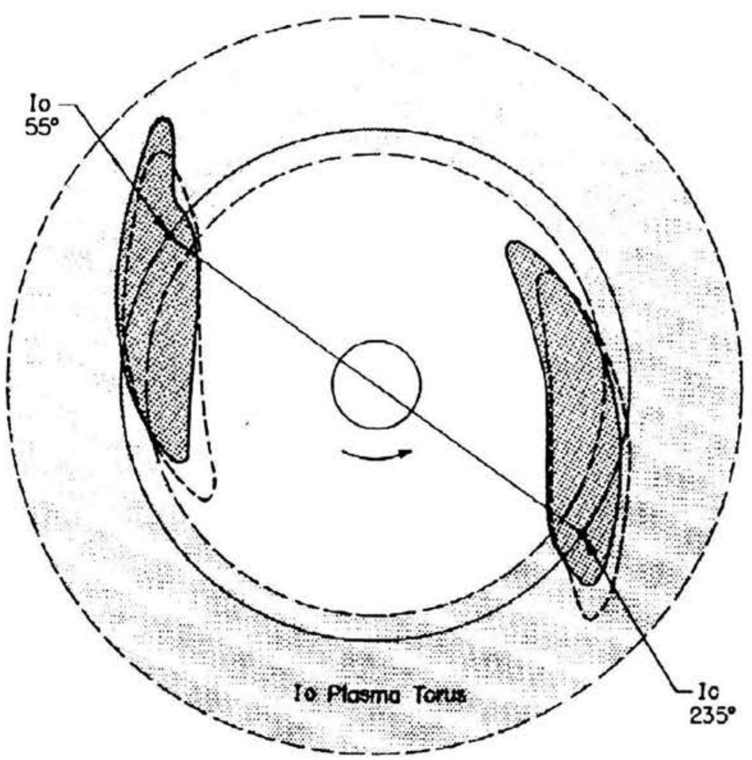

Fig.2.4 Schematic representation of the plasma Torus and the elongated sodium cloud around Io in two different positions of its orbit. Notice that the shape of the cloud varies (Smyth 1983)

The most abundant ions in the Torus are S^+, S^{2+}, S^{3+}, O^+ and O^{2+}, otherwise there are not too many measurements and neither the plasma detectors nor the spectrometers of the Voyager and Galileo surveys were able to distinguish the S^{2+} from O^+ (because they possess the same charge-mass ratio) or the O^+ from the O^{2+} (the single bright UV emissions detected were at 83.3 *nm*).

The Torus contains Sodium as well. In fact, sodium emissions are brighter than any other of the elements contained in the Torus and because of that it is very easily detected. But sodium is not spread throughout the Torus, but it is concentrated in an elongated cloud that surrounds and moves with Io (Fig 2.4).

CHAPTER THREE
Physical properties of Io's plumes

The meassurement of the physical properties of the plumes and volcanoes are quite important for the understanding of the volcanic processes. With the aid of the Galileo and Ulysses spacecrafts as well as the Hubble Space Telescope, the quality of the images Io's plumes improved greatly, but some –or many- properties are still uncertain or unknown. Since these properties, such as height, mass, density, ejection velocity, flight times and chemical composition are necesary for our study, this chapter is dedicated to them. Some known properties will be just displayed as reported by other authors, some will be inferred and some others will be estimated with base on those known properties. This will be done for most of the plumes, but our discussion will be centred on Pele, which is one of the most energetic volcanoes and is likely a source of dust to the interplanetary space.

DUST COMPOSITION & GENERATION

Possibly most of the material emitted by Io to its own surface or to space is ejected through the volcanic plumes (McEwen et al., 2003) which are basically composed of dust and gas. There are at least three lines of evidence that indicate the composition of the gas and dust: First, in the Plasma Torus it is possible to find sulfur, oxygen and sodium ions (Nash et al., 1986) and near Io, sulfur oxide and dioxide atoms and ions (Frank et al., 1996 and Kivelson et al., 1996). Second, Spectroscopy says that the thin atmosphere of Io is dominated by SO_2 and its disotiated subproducts SO, O and S; and also says that Io is covered by a *thick* layer of sulfur and sulfur dioxide (McEwen et al., 2003); and third, Io's crust and upper mantle should be composed of silicates, possibly, enriched with magnesium in order to explain such high temperature volcanism and superheated lava flows (McEwen et al., 1998). According to all these former ideas, grains must be made mostly of sulfur dioxide and sulfur, but there might be also some dust composed mainly of silicates such as Olivine. Olivine is an orthosilicate of magnesium with formula $(Mg, Fe)_2SiO_4$ in which the ratio may found to vary between forsterite (*Mg*-rich) and fayalite (*Fe*-rich). As reference it is added a table displaying sulfur and silicate properties.

Table 3.3 Properties of sulphur, sulphur dioxide and olivine

	Sulfur	Sulfur dioxide	Forsterite	Fayalite
Formula	*S*	SO_2	Mg_2SiO_4	Fe_2SiO_4
Colour (solid)	Yellow (etc.)	White	Green, yellow green, also white	Yellow to black
Density (solid) [g/cm^3]	2.0	1.6	3.21	4.30
Density (liquid) [g/cm^3]	1.8	1.5		
Melting point [*K*]	285-393, ~380 (10^{-5}*bar*)	198	2163±20	1205(~1*bar*)
Boiling point [*K*]	717 [1*bar*] 1000 [40 *bar*]	198 [0.01*bar*] 393 [40 *bar*]		

Although the ionian volcanism may differ from earth volcanism there might be some similarities between the hotest and most violent volcanic eruptions on Earth and those on Io. Hot spot temperatures in Io range from ~600 to >2600 *K* (McEwen et al., 1998), eruptions involve either sulfur or sulfur dioxide as the volatile phase that propells the plumes just like water vapour does it on Earth. Since the volatile content seems to be high, as the ejected material leaves the vent and faces an almost absence of atmosphere ($P \approx 10^{-7}$ *bar*) , there is a violent expansion that enables immediate condensation (plume phase) and so there is a disruption into fine dust and gas expelled at very high speeds >0.4 km/s (as calculated ahead in Table 3.2)

According to this, there are, at least, two mechanisms of dust generation in Io's volcanoes, here both will be supposed as the only mechanisms. These mechanisms are condensation/crystallization and coagulation. Crystallization may take place not only outside of the vent, but also inside of it depending on the temperatures and the ejected material. If it is right inside the vent, we say that magma lowers its temperature, due to a lowering of presure or the contact with colder material. On the other hand, outside the vent the ejected material will expand adiabatically into the thin atmosphere reducing its temperature drastically; that means that an important part of the material will condense almost immediatly (inside the plume). Even though the density of the plume is low as particles condense collisions may take place. If so, coagulation may also take place among smaller grains to generate larger grains.

Observations and models indicate that plumes are mostly composed of submicrometric grains and gas or even, as in the case of Acala (Geissler et al., 2001) mostly gas and very few dust particles. Micrometric grains do contribute to the optical depth of the plume but, since processes are so violent, most of the times, they are only a quite small fraction of the whole ejection.

It is uncertain the amount of solid sulfur in the vent but if temperatures are so high, the amount might be very small. Although laboratory data say that at very high temperatures the viscosity of sulfur increases notably which may favor its solidification in the vent in the case of the S_2 dominated Pele type eruptions, most of it solidify out of the vent due to the plume expansion. Sulfur may be ejected as a gas of molecules or atoms, depending of the temperatures or could even leave the vent in form of droplets if temperatures in the vent are somewhat below 1000K.

The ejected gases expand very fast and the temperature and pressure inside the plume drop also fast. According to Kieffer (1982), sulfur may crystallize at ~380K at a pressure of $\sim 10^{-5}$ bar which may be the conditions of some areas of the new plumes right after the gases have been decompressed. On the other side, Belton et al. (1996) states that when the temperature of the plume lowers to ~110 *K* sulfur dioxide gases cristallyze. According to models (Zhang et al., 2003), for the near 400 *km* plume of Pele, temperatures are below 400 *K*, above a radius of less than 20 km from the vent, and below 155 *K* above a ~50 *km* radius from the vent. This means –for Pele- that the dust would condense in less than a couple of minutes after ejection and would decouple from the gas at *low* heights *near* the vent at near ejection speed (eq.4). For any of the volcanoes on Io the gases are decompressed violently and then, for less energetic ejections the condensation temperatures are reached at lower heights.

If silicates are present in the plumes, the situation would be very different and silicate clast or dust may be present in the new plume from the beginning of the ejection because silicates may crystallyze at temperatures above 1000 *K*. Acording to the *Bowen series*, the series that are applied to the order in the sequence of crystallizations of the components of magmas, olivine is the first silicate to cristallize at ~2200 *K* as magma cools. If this is the case, silicate particles may be swept by the ejection from the walls of the vent and so the *new* plume could be composed of gases and vapors of sulfur dioxide and silicate solids particles.

Be it sulfur or silicate it is possible to consider the presence of dust almost from the begining of the ejection. Of course for silicates and for sulfides the charging conditions may vary depending on its history and chemistry.

HEIGHT & EJECTION VELOCITIES

As seen in Table 2.3, most Ionian plumes are above 50 *km* high, but Pele has a record among all since observations with the Hubble Space Telescope in 1996 found that its plume ranges from 300 *km* to 420 ± 40 *km* high (Spencer et al., 1997) ~12 times taller than the highest plumes generated on Earth. For example, one of the most violent eruptions recorded on the Earth was produced at Indonesian Tambora volcano in 1815, several 40 kilometer high plumes were generated as a product of the eruption (Sparks et al 1997).

To achieve such great heights dust and gases must be pushed with an enormous energy which means very high ejection velocities. These velocities are calculated as follows:

Let us consider a volcanic particle (be it a molecule or a dust particle) of mass *m* ejected with a vertical velocity of v_e from the surface of Io and whose velocity at a surface altitude H is v, conservation of energy gives,

$$\frac{mv_e^2}{2} - \frac{GmM_{Io}}{R_{Io}} = \frac{mv^2}{2} - \frac{GmM_{Io}}{R_{Io} + H} \tag{3.1}$$

or

$$v^2 = v_e^{\ 2} - 2GM_{Io}\left(\frac{1}{R_{Io}} - \frac{1}{R_{Io}+H}\right) = v_e^{\ 2} - \frac{2GM_{Io}H}{R_{Io}(R_{Io}+H)} \tag{3.2}$$

If the height of the plume is $H_{\max}$ (i.e. $v=0$, when $H = H_{\max}$), we get,

$$v_e = \sqrt{\frac{2GM_{Io}H_{\max}}{R_{Io}(R_{Io}+H_{\max})}} = v_{escape}\sqrt{\frac{x_{\max}}{1+x_{\max}}} \tag{3.3}$$

where $\sqrt{\frac{2GM_{Io}}{R_{Io}}}$ = velocity of escape from Io and $x_{\max} = \frac{H_{\max}}{R_{Io}}$.

Taking the mass and radius of Io as R_{Io}=1.815×10^{6}m and M_{Io}=8.92×10^{22}kg it is deduced from (3.3) the velocity of ejection of the Ionian volcanoes using the reported intervals of H_{max} for each volcano in Table 2.3. It is found, for example, that volcanoes such as Ra, Zamama or Volund have ejection velocities in the interval $0.41 \leq v_e \leq 0.58$ kms^{-1}. We observe that Pele and Loki-W are extreme cases; the former in the interval $0.96 \leq v_e \leq 1.15 kms^{-1}$ and the later in the interval $0.71 \leq v_e \leq 1.09 kms^{-1}$. Table 3.1 displays these results.

Table 3.1. Minimum and maximum ejection velocities for Ionian plumes after the height values reported by McEwen et al. (1998).

Plume Name	Height [km]	v_0 range [km/s]
Amirani	50-100	0.41-0.58
Volund	50-100	0.41-0.58
Loki-W	150-400	0.71-1.09
Maui	50-150	0.41-0.71
Zamama	50-100	0.41-0.58
Loki-E	20-150	0.27-0.71
Acala	200-300	0.81-0.96
Prometheus	50-100	0.41-0.58
Ra	50-100	0.41-0.58
Pillan	100-150	0.58-0.71
Kanehekili	50-100	0.41-0.58
Pele	300-460	0.96-1.15
Culann	0-50	0.00-0.41
Marduk	50-100	0.41-0.58
Masubi	50-100	0.41-0.58

Probably the highest ejection velocities of the plumes might be over the calculated values, but they are all well under the escape velocity from Io which is 2.56 *km/s*. Even Pele plume has less than a half of this velocity.

At first sight, it seems clear, out of the above discussion, that the volcanic eruptions will not provide enough energy to dust grains so that they can escape from Io. Since dust does escape from Io, and volcanoes are likely the source of this dust, this confirms that other forces probably electromagnetic are involved as it has already been stated, on the other hand the high temperatures present in the vents may allow the gas particles to interact each other with very high energies, so other processes might be involved.

TIME FROM THE VENT TO THE TOP OF THE PLUMES

For those visible particles in Table 3.1 and with a similar analysis as in eqs.(3.1) to (3.4), it is calculated the minimum and maximum flight times, that is, from the vents to the top of the plumes:

Table 3.2. Time intervals from the vent to the top of the plumes for visible particles emitted in some Io's plumes.

PLUME NAME	FLIGHT TIMES Min [minutes]	Max [minutes]
Amirani	4,1	6,1
Volund	4,1	6,7
Loki-W	7,9	16,4
Maui	4,1	7,9
Zamama	4,1	6,1
Loki-E	2,6	7,9
Acala	9,6	12,9
Prometeo	4,1	4,1
Ra	4,1	4,1
Pillan	6,7	7,9
Kanehekili	4,1	4,1
Pele	12,9	27.0
Culann	0	4,1
Marduk	4,1	4,1
Masubi	4,1	4,1

The average of the maximum flight time is of the order of ~8 minutes. The minimum time (ballistic) for the escaping grains to reach the Ionian ionosphere (~400 *km*) would be of the order of ~3 *minutes*.

CRATER AND VENT AREAS

Let us consider the area of the crater around 192 km^2 according to Strom & Schneider (1982) and Geissler et al. (2003), who reported a 24 km long and 8 km wide hotspot. The vent diameter is estimated around ~500 m (Cataldo et al., 2002) which corresponds to an area ~0.2 km^2 or 2×10^9 cm^2 supposing a circular vent.

VOLUME

For practical calculations the area of the vent is small in comparison to the size of the plume, so we take it as a point source in order to calculate its whole volume. The hotspot is surrounded by an almost circular ring formed by the expelled material and the envelope of the plume seen on the images is almost spherical, these facts indicate that the plume expands almost isotropicaly. The ring has an inner radius of 435 *km* and an external radius of 650 *km*. In Fig.3.1 we represent the plume as an hemispheric umbrella like structure. According to the specified dimensions and integrating its average volume is of the order of ~10^{16} m^3.

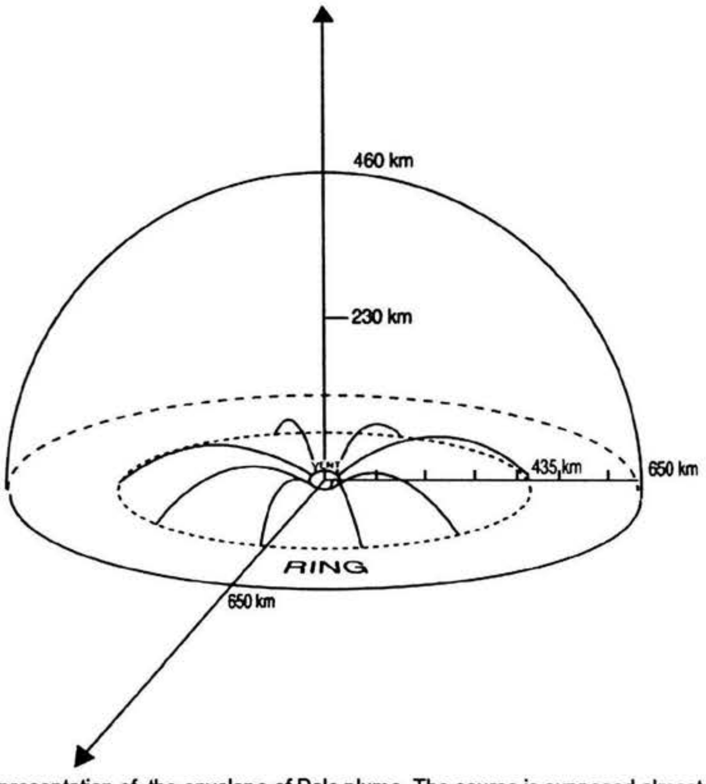

Fig.3.1 Schematic representation of the envelope of Pele plume. The source is supposed almost as a point source (not at scale) and the ejection as an hemispherical structure.

MASS AND DENSITIES

The results of table 3.1 indicate that the ejection speeds of Ionian volcanoes are approximately between 0.4 km/s and 1.2 *km/s*, but these numbers are just lower values related only to those particles observed. On the other hand, the dimensions of the ring deposits that surround the craters of volcanoes indicate also larger ejection speeds. In the case of Pele this ring has an oval shape that extends 435 *km* in the east-west direction and 650 km in the north-south direction. We can take 1 km/s as an average ejection speed for Pele and Loki as well.

Observations also suggest that the injection mass rate of Pele plume (and Loki's) is $\sim 10^{11}$ *g/s* (Johnson & Soderblom, 1982; Ip,1996; Spencer et al., 1997 and Cataldo et al., 2002) which means that the density of the gas in its vent is $\rho_{vent} = \Phi/(v_e A) \approx [(10^{11}\, g/s)/(10^5\, cm/s)(10^9\, cm^2)] = 10^{-3}\, g/cm^3$. If the gas is mainly sulphur ($m_o \sim 10^{-22} g$), the exiting particle density number n is roughly $\sim (10^{-3}\, g \cdot cm^{-3})/(10^{-22}\, g) = 10^{19}\, cm^{-3}$ or $10^{13} m^{-3}$.

The mass of the whole plume may be simply calculated through the ejection time on Table 3.3 as follows: Pele plume particles need ~27 min to reach the top of the plumes from the vent. This is also true for the volume element taken above which contains 10^{11} g. When the mass of this elemental volume reaches the top of the plume and falls back to the surface, the plume has a ***stationary*** mass around $2 \times 1620 \times 10^{11} g \approx 10^{14}\, g$.

Based on the former calculations, the mean bulk density of the whole plume is $\rho \sim 10^{14} g/10^{22}\, cm^3$ or $\sim\rho_{plume} = 10^{-8}$ *g/cm³*. Again, if this plume is composed only of sulphur, the particle mean density of the whole plume is $\sim 10^{14} cm^{-3}$. Zhang et al. in their simulations report a description of the stationary column density of Pele plume where vent and top molecular (SO_2) densities are $\sim 10^{12}\, cm^{-3}$ and $\sim 10^{6}\, cm^{-3}$ respectively, or a mean number density around $\sim 10^9\, cm^{-3}$.

Considering also that not only Pele or Loki, but all 17 plumes have similar rates of ejection it is possible to calculate the minimum rate at which the surface of Io is coated supposing that most of the mass ejection is made through the plumes and that most of this mass will fall back onto the surface. Both are valid suppositions supported by observation as we have seen. The 10^{11} g/s deposited onto the surface by Pele or Loki represent a volume rate of $V/t = (m/t)/\rho = (10^{11}\, g \cdot s^{-1})/(1.87 g \cdot cm^{-3}) = 5.3 \times 10^{10} cm^3/s$. If the total area of Io is $A = 4\pi(1815 \times 10^8 cm)^2 = 4.14 \times 10^{23} cm^2$, then the minimum deposition rate is $(V/t)/A = 1.28 \times 10^{-13} cm/s = 4 \mu m/year$. The average actual figure may be an order of magnitude larger if we take into account all plumes. In that case the sulphur or sulphur dioxide layer would be less than a meter thick, but that rate would be enough to cover the traces left by meteorites and let the surface look smooth as it seems to appear in the images..

All estimates –only for Pele- are summarized on the following table:

Table 3.4. Pele's estimated physical properties

Stationary Plume Mass	~10^{14} *g*
Ejection speed	~1 *km/s*
Mass ejection rate	~10^{8} *kg/s*
Plume Height	~300-460 *km*
Plume Volume	~10^{22} cm^3
Caldera area (Crater)	~192 km^2
Vent radius	~0.25 *km*
Vent area (circular vent)	~10^{9} cm^2
Vent bulk density	~10^{-3} g/cm^3
Vent particle density (sulfur)	~10^{19} cm^{-3}
Plume bulk density	~10^{-8} g/cm^3
Plume particle density (sulfur)	~10^{14} cm^{-3}
Hotspot surface temperature	~1260 - >1900 *K*

CHAPTER FOUR

Charging mechanisms for the dust ejected from Io's volcanoes

The dust grains from the volcanic plumes must be charged in order to be dragged by Io's surrounding plasma, escape from Io and be pushed away by the jovian electric field forces. In spite of the possibility that a certain amount of grains might get charged into the volcanic vents, the contact of neutral or charged grains with the ionospheric plasma will be definitive for their future dynamics. As we saw in chapter two, as Galileo passed through the Ionian ionosphere on December the 7th, 1995, it measured a 10 *eV* plasma with ion density about 18000 cm^{-3} in average. According to Frank et al. (1996), S^+, S^{2+}, O^+, O^{2+} and SO_2^+ ions are moving at 10 *km/s*, which is a speed faster than the escape speed from Io's surface.

CHARGING MECHANISMS IN THE IONOSPHERE

Into the ionospheric plasma grains are exposed to the bombardment of electrons, ions and photons. These encounters generate different scenarios depending on the intensity of the interaction. Electrons and ions may be captured by the grain, but if the impact is intense grain electrons, or even grain ions, may be dispersed. Photons, on the other hand, may add extra energy to grain electrons in order to escape.

These interactions will charge the grains or modify its charge. It is said, that all mechanisms may have a contribution and the charging of the grains is described as the sum of all these contributions, each represented by a current, as:

$$I = \frac{dQ}{dt} = \sum_i I_i \tag{4.1}$$

A useful way to deal and to understand the status of the charge in dust grains is to consider grains as one-plate capacitors with capacitance $C = Q / \varphi$, that may store a finite number of charges defined as $ne = Q$ and that generate a potential φ. The stored charge may be calculated with:

$$n \cdot e = Q = 4\pi\varepsilon_0 r\varphi \tag{4.2}$$

Where n is the number of fundamental charges e and $C = 4\pi\varepsilon_0 r$ is the capacitance with r the radius of the dust particle. And so, -if mks units- the number of charges for a micrometric sized dust grain is:

$$n = \frac{4\pi\varepsilon_0}{10^{-6} e} r\varphi \tag{4.3}$$

Or simplified as:

$$n \approx 700 r_\mu \varphi \tag{4.4}$$

In which r must be written in microns and φ in *volts*.

Some considerations must be taken into account regarding to the surface potential of the dust grains, since larger potentials have secondary effects on them. If positive, the particle experiences an outwards force that may activate the emission of ions *–ions field emission-* or may even disrupt it if it surpasses the mechanical resistance or tensile strength of the particle. If negative, electrons will begin to escape *–electron filed emission-* until the equilibrium potential is achieved. Therefore, the charging is limited by the intensity of the surface electric field, be it positive or negative, which is by practical purposes the quotient between the surface potential of the particle φ_s and its size r, or φ_s / r. This interval is written (Graps & Grün 2000) as follows:

$$|E_f| = \begin{cases} -10^9 V/m \ \ if \ \ Q < 0 \\ +2\times10^{10} V/m \ \ if \ \ Q > 0 \end{cases} \tag{4.5}$$

If the particle is disrupted in N fragments by a large positive potential, the charge Q would be redistributed on the remaining fragments by the rule $N^{2/3}Q$ where each fragment will have a net charge equal to $Q/N^{1/3}$, supposing them all identical in size,.

Basically four mechanisms are present in the ionosphere, but only one dominates due to the ionospheric properties, the physical properties of the dust grains and the conditions in which these are injected.

The main charging mechanisms are listed below and they be will be explained further ahead:

- *Electron capture*
- *Ion capture*
- *Secondary electron emission*
- *Photoelectron emission*

If all these currents are taken into account eq. (4.1) must be rewritten as:

$$I = \sum_i I_i = I_{e,i,moving} + I_{sec} + I_\nu \quad (4.6)$$

The dominant mechanism will be that which generates the largest currents and enables the dust grains to get charged in the shortest time. In general, this charging time may be obtained applying the basic equation:

$$\tau = \left|\frac{Q}{I}\right| = \left|\frac{4\pi\varepsilon_0 r\varphi}{I}\right| \quad (4.7)$$

Where I is defined by equation (4.6).

If we just consider the flux of electrons nv we can also write the charging time as:

$$\tau = \left|\frac{Q}{e \cdot I}\right| = \left|\frac{Q}{env\sigma_g}\right| \quad (4.8)$$

where σ_g is the cross section of the grains and v is the speed of particles for dust grains and electrons, ions or photons.

Electron and ion capture

The acquisition of electrons and/or ions is the most direct charging mechanism. For this mechanism the size of the grains is important, as well as the frequency of encounters which depend on the plasma density.

When electron and ion currents are the only charging currents, which seems to be our case, the equilibrium potential of a dust grain may be roughly calculated through the Spitzer (1941) equation considering only the temperature of the plasma and taking $T_e = T_i = T$:

$$\phi_{eq} = -\beta \frac{kT}{e} \quad (4.9)$$

Here β represents an experimental constant that depends on the composition of the plasma. If other mechanisms are present, Horanyi (1996) writes the electron/ion currents as:

$$I_{e/i} = 4\pi r^2 n_{e/i} \sqrt{kT_{e/i} / 2\pi m_{e/i}} \times \begin{cases} \exp(-e\varphi / kT_i) \\ 1 + e\varphi / kT_e \end{cases} \quad (4.10)$$

Secondary electron emission

As plasma electrons hit the dust particles with enough energy ($\geq 50\ eV$), these may disperse a certain amount of those electrons, which are bound to the atoms that compose the grains. These electrons are called secondary electrons, represent a positive charge mechanism and its number depends on the energy of the incident electrons and the chemical composition of the grain as well. Generally it is considered the ratio of emitted and incoming electrons, known as the *yield* or simply δ, as function of the electron incident energy. Experimentally it is known that the yield has a maximum value δ_M (from 1 to 10) for an optimum incident energy E_M (~100 to ~1000 eV) and based on this, Sternglass (1954) approximates the yield to:

$$\delta(E) = 7.4\delta_M\left(\frac{E}{E_M}\right)\exp\left[-2\left(\frac{E}{E_M}\right)^{1/2}\right] \tag{4.11}$$

Draine & Salpenter (1979) obtained δ_M=2.9 and E_M=420 eV for SO_x (silicate) particles and Horanyi et al (1997) obtained δ_M=3 and E_M=300 eV for SO_x (sulfide) particles.

Photoelectron emission

The exposition of grains to solar ultra-violet radiation makes them target of high-energy photons whose energy may be absorbed by electrons that escape generating a positive charging mechanism. The production of photoelectrons due to ultra-violet radiation from the Sun is approximated by:

$$I_\nu = \begin{cases} 2.5\times10^{10}\pi r^2 e\dfrac{\chi}{R^2} & if\ \phi < 0 \\ 2.5\times10^{10}\pi r^2 e\dfrac{\chi}{R^2}\exp(-e\varphi/kT_\nu) & if\ \phi \geq 0 \end{cases} \tag{4.12}$$

In this equation χ is the efficiency factor whose value is close to 1 for conductors (just like silicates) and close to 0.1 for dielectrics (just like sulphides). R represents the heliocentric distance in astronomical units, in this case R=5.2 AU. kT_ν may be approximated to ~1 to 3 eV as the average energy of photoelectrons.

THE CHARGING OF THE GRAINS IN THE IONOSPHERE

Since the ionosphere is said to lie above ~400 km from the satellite's surface and particles driven by some plumes just like Pele, Loki or Acala plumes reached their maximum heights at near that value, we can suppose that the dust particles are at rest with the ionospheric plasma.

In our case, since most of the ions are singly ionized, we can take the density of both species as equal. Even if the electron and ion densities are similar, the large speed of the electrons enables them to interact more frequently with the grains than ions.

In fact, the speed of the electrons is

$$v_e = \sqrt{3kT/m_e} = 2\times10^6 m/s \tag{4.13}$$

Besides, if grains are at rest with the plasma, the encounters with ions are reduced, making the electron capture a far more efficient charging mechanism than the ion capture.

Due to the characteristics of the ionospheric plasma, it is relatively direct to see that electron secondary emission and photoionization are not significant effects. In the case of the secondary electron emission, if we plot the yield versus the incident energy we see that, for SO_x, the yield has its maximum around 3 for incident energies between 270 and 350 eV. Taking now SiO_x, the maximum is around 2 for incident energies between 263 and 338 eV.

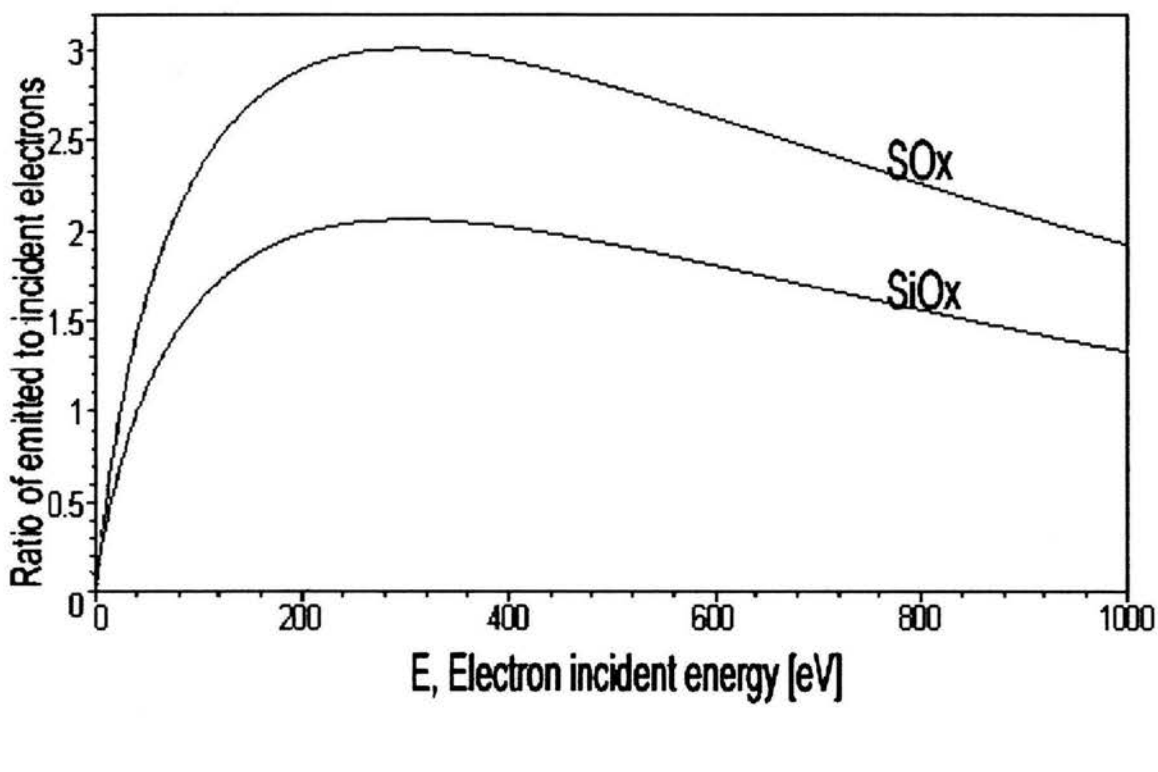

Fig. 4.1 Ratio of emitted to incident electrons –yield- as function of the incident energy of the electrons for SO_x and SiO_x particles. The ratio has a maximum around 3 for incident energies between 270 and 350 eV in the first case and around 2 for incident energies between 263 and 338 eV in the second case.

We draw, out of Fig.4.1, that, in Io, the energy of the ionospheric electrons is *low*, ~10 eV. This figure is, at least, an order of magnitude lower than those energies that would produce maximum emission of *secondaries*. In fact, for a 10 *eV* energy, $\delta \approx 0.5,\ 0.16$ respectively. We say that this plasma is too cold to produce an important amount of secondary electrons

As for the photoionization, equation (4.12) says that the photo-effect becomes less efficient as particles become smaller. For example, the photoelectron currents for a 0.1 μm particle would be $I_\nu \approx 10^{-5}$ and 10^{-6} *e/s* for silicate and sulphur/sulphur dioxide particles respectively. At this rate, a silicate particle would reach a φ=1 Volt potential in:

$$\tau = (4\pi\varepsilon_0 r_g \varphi\ e)/I_\nu = 70e/10^{-5} e/s = 7\times10^6 s = 81\ days \qquad (4.14)$$

For a sulphur/sulphur dioxide particle the charging time would be around 2 *years*. For both cases the time is quite long.

We conclude that the photoionization and the secondary electron emission are non efficient mechanisms for sub-micrometric particles in the ionosphere of Io. Therefore it is possible to discard them as important mechanism.

For electron capture the situation is quite different, for S^+ and O^+ plasmas, which are the main components of the ionospheric plasma of Io, β=3.6 and 3.9 respectively. This means that if other mechanisms are neglected and only thermal currents are considered, then from equation (4.9), for an injected sub-micrometric grain into a 10 eV ionospheric plasma, the equilibrium potential could be around –34 volts.

If the dust particle has r=0.1 μm, according to equation (4.4) it would need to capture 2380 *electrons* to reach the –34 *V* equilibrium surface potential. For this effect, the time in which that particle reaches equilibrium potential τ_{equil} or captures those 2380 *electrons* may be inferred from (4.8), that is:

$$\tau_{equil} = \left| \frac{2380e}{e\pi(1.8\times10^4/cm^3)(0.1\times10^4 cm)^2(2\times10^8 cm/s)} \right| = 2.1\ s \qquad (4.15)$$

Which is indeed a very short time that still confirms that electron capture dominates among the charging mechanisms.

Let us remark that the –34V potential is of the order of the negative threshold for the electron field emission given in (4.5), since the electric field, for the largest sub micrometric particle, is $-34V/0.1\times10^{-6}m = -3.4\times10^8 V/m$.

Let us also keep in mind that if particles are nanometric, the limit potential for electron field emission is $-10^9 Vm^{-1}\times10^{-9}m = -1\ Volt$, if they are 10 *nm* in size, then the potential is 10 *V* and for 0.1 *μm*, 100 *V*. Which means that the –34 *V* potential would not be applicable to very small particles just like those nanometric grains. Note also that the charging time and the size of the particle keep an inverse proportion such that $\tau \sim r^{-1}$, which leads to longer times as the particles become smaller.

Even taking into account those two considerations, the electron capture is nevertheless an efficient mechanism for these very small particles and the charging times are still small. In fact, using again (4.8), for a 10 *nm* sized particle and an equilibrium potential of 10 *V*, the charging time would be 6.1 *s*. For the smallest particle, 1 *nm* and a 1 *V* equilibrium potential, the charging time is of the order of 61 *s*.

There is still another issue related to the equilibrium potential that must be stressed, since this potential might be only an upper limit for charging purposes. Let us look at the Debye length which may be written as

$$\lambda_D = \left(\frac{kT}{4\pi nc^2}\right)^{1/2} = 740\left(\frac{kT}{n}\right)^{1/2} cm \tag{4.16}$$

where $c=3\times10^{10} cm/s$ is the speed of light, n the particle density in cm^{-3} and T is the temperature in kelvins. For our kT=10 eV and n=18000 cm^{-3} plasma, $\lambda_D = 17.4\ cm$. This means that the Debye spheres overlap, since the distance between the component particles of the ionospheric plasma is smaller than ~0.04 *cm*. At the end, and due to this overlapping, there is the possibility that each dust particle might collect very few electrons indeed meaning that in such case only a fraction of the dust particles that reach the ionosphere get charged. The minimum charge might be just one electron which would mean around ~ -0.1 *Volt* surface potential for a 10 *nm* particle. Even this potential, as we will see in the next chapter, would be enough for dragging purposes.

CHARGING IN THE VENT

This fast charging of the dust in the ionosphere also indicates that even if particles have already collected a certain potential by other means before being injected into the ionosphere, the final equilibrium potential in the ionospheric plasma would remain the same. It is not clear at all if grains reach the ionosphere charged or not and that is why, in order to have a more complete discussion, we will analyze briefly a possible charging mechanism near the surface of Io.

If it is true that particles reach the ionosphere already charged, the experience with terrestrial volcanoes points to a mechanism that would take place rather in the vents than in the plumes and which has possibly a direct connexion with high temperatures and clast/dust. In fact we could say that electric phenomena related to volcanic plumes are relatively common on Earth.

Among other examples of charged plumes we find reports from Mount St. Helens (Rossenbaum & Waitt, 1981), the Redoubt volcanoe (Hoblitt & Murray, 1990) or from the Hudson. According to some reports (Anderson et al., 1965) charges are present in the plumes particularly when violent and explosive eruptions loaded with solid particles (sizes from tenths to hundreds of microns, *black clouds*) take place. Anderson et al. (1965) report also that electric discharges are common near the vent and are present always immediately after the ejection suggesting the generation of the charge in the vent.

More recent reports (Miura & Koyaguchi, 1996) suggest that volcanic charged plumes are generally diferentiated in three parts (*PNP* model): an upper part with positively charged gas and aerosol, a middle with negatively charged fine ash (hundreth of a mililimiter in diameter) and a lower part with positively charged coarse ash particles (10^{-5} m in diameter). The positive lower part in the plumes was observable only when the plume activity was sufficiently strong (Miura et al., 2001) because positively coarse particles tended to fall out near the vent, but the middle negative part of the plume was predominant in most cases. In any case there seems to be a relationship between the sign of the charge and the size of the particles.

There is, of course no direct comparison between Earth's and Io's volcanoes since the scales are different and the origin of their particular volcanic processes are not the same, but Earth's volcanism might give us a hint of what is happening in Io's vents since these electric phenomena have two aspects that repeat in all cases and are present in the ionian volcanism: Intense eruptions (vulcanian, phreatomagmatic, etc) conected with high temperatures and the presence of solid particles in the vent.

It is direct to see that temperatures by themselves do not generate an important ionization in the ionian volcanic ejections, if there is not solid material involved, through the reckoning of the degree of ionization of the ejected gases.

Degree of ionization of the gas in the vents.

In fact any gas has got a certain degree of ionization which increases with temperature. The easiest approach to this idea is to obtain the ratio of ionized particles (n_i) in the gas to the neutral (n_n) particles through Saha's equation. That is:

$$\frac{n_i}{n_n} = 2.4\times10^{15}\frac{T^{3/2}}{n_n}\exp(-\frac{U_i}{kT}) \qquad (4.17)$$

where n_i and n_n are the ionized and neutral atom densities (atoms/cm^3), T is the temperature of the gas, U_i the ionization energy of the gas and k=8.6164×10^{-5}I is the Boltzman constant. For Pele hotspot (Table 3.3) the particle density in the vent is n_n=10^{19}cm^{-3} of sulphur (U_i =10.357 eV) gas. Then Saha's equation may be written as follows:

$$\left(\frac{n_i}{n_n}\right)_{Pele} = 2.4\times10^{-4}T^{3/2}\exp(-\frac{1.2\times10^5}{T}) \qquad (4.18)$$

plotted in Fig. 4.2. The plot covers the range of surface temperatures observed on Pele hotspot from 1260 to near 2000 K, but considering also that temperatures may be higher than 2600 K, as measured on some areas of Pillan patera. For the lowest temperature, 1260 K, the degree of ionization is low, $n_i/n_n \sim 10^{-40}$, but 2000 K and 2600 K this ratio becomes far larger, that is, $n_i/n_n \sim 10^{-25}$ and $n_i/n_n \sim 10^{-18}$ respectively. If the hotspot temperature rises to 3000 K the ratio is *only* $n_i/n_n \sim 10^{-16}$.

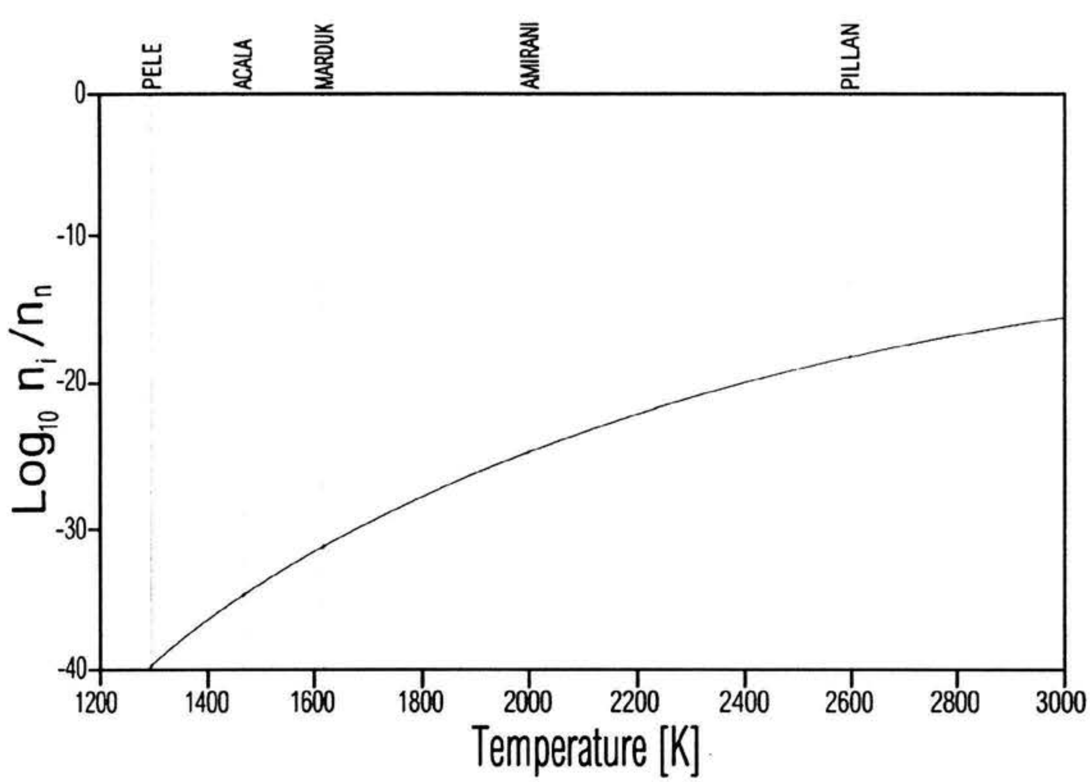

Fig. 4.2 Degree of ionization (in orders of magnitude) as function of the temperature in Pele type vent gases. Some plume maximum hotspot temperatures have been set as reference. According to measurements, the temperatures for Amirani and Pillan are larger than the values indicated (see Table 2.2).

How important is this degree of ionization may be found comparing the Debye length λ_D related to the cloud expelled by the vent with mean free path λ of the particles in the cloud.

For T=2000K and n~10^{19} cm^{-3} (cf. Table 3.3), with (4.16) $\lambda_D \approx 10^{-7}$ cm. On the other hand, if we consider ~1Å gas particle whose cross section is around $\sigma=10^{-16}$ cm^2, their mean free path is roughly $\lambda=10^3$ cm.

The gas does not behave like a plasma, and we can also consider this level of ionization poor and negligible. Then, high temperatures may play an *important* role as a charging mean only if there is solid material in the vent, which is uncertain due to high temperatures and the detection basically of sulphides, which condense at low temperatures. if refractory material is present, high temperatures may produce currents on these solids or emission of thermo-electrons through *thermionic emission* as we will see ahead.

Thermionic emission

Silicates, as refractory materials, may remain solid in the vent. Forsterite, for example, may crystallize above 2000 *K* and fayalite above 1000 *K*.

The basic physical circumstances involved in the *thermionic emission* are that at a given temperature, electrons may reach a large enough energy to escape from the grain, provided they are sufficiently near to the boundary surfaces and are moving in a suitable direction. The current generated by these escaping electrons may be approximated by

$$I_{th} = 4\pi r^2 f(T,\Phi)e \tag{4.19}$$

Where

$$f(T,\Phi) = \frac{4\pi m_e k_B^2 T^2}{h^3} \exp\left(-\frac{W}{k_B T}\right) \tag{4.20}$$

W is the work function, that is, the energy needed to free an electron. The work function is around ~5eV for silicates, but typically just some electron volts for metals. $4\pi m_e e k_B^2 h^{-3} = 1.2\times10^6\, Am^{-2}K^{-2}$ with $k_B = 1.38\times10^{-23} J/K$ is Boltzmann's constant, $h = 6.63\times10^{-34} j\cdot s = 8.61\times10^{-5} eV\cdot K^{-1}$ is Plank's constant, *e* and m_e are the charge and mass of the electron. The whole expression is the well known the *Richardson-Dushman* equation, which was first derived thermodynamically. In principle, the currents generated in a sub micrometric (r=0.1μm) silicate particle would be; if *T*=1300*K*, of the order of 0.03*e/s* and if *T*=1500*K*, of the order of 16 *e/s*. The charging of such grains would be limited by the recombination of the grains with the escaping electrons.

In this ideal scenario presented above, the escaping electrons would move at $\sim 3\times10^5\, m/s$ and since the density of the plume in the vent is 10^{19} cm^{-3}, the collision time between electrons and sub micrometric particles would be short $\tau_{col} = \lambda_e / v_e = 1/n\sigma v_e \approx 1\ ns$, meaning that although thermionic currents are a positive charging mechanism, grains could end with negative potentials once equilibrium is achieved.

Since the jovian magnetic field is present also along the neutral atmosphere of Io, if the particles could manage to leave the vent charged, the smallest particles could be accelerated to the jovian space almost from the lower parts of the plumes, making their escape easier.

CHAPTER FIVE
Escape of dust from Io and Jupiter

The conditions that dust grains must fulfill in order to escape from Io and from Jupiter are similar, but not the same. Our main goal on this chapter will be to demonstrate that the electrons collected by the dust grains from the plumes into the ionosphere of Io enable grains to escape from the satellite. The relationship between surface charge, size and composition of those dust grains is analyzed. Finally we compare the results with the conditions that grains must fulfill to escape from Jupiter and estimate the rate at which the Jovian dust streams are fed by Io.

ESCAPE OF DUST PARTICLES FROM IO

The dust grains injected in the Ionian ionosphere through the volcanic plumes need to have certain charge that depends on the mass, so that they can be dragged by the plasma that surrounds Io. The mass, of course depends on the radius r of the grain and its composition, defined through its density ρ. Since grains must defeat the gravitational attraction of Io, not any charge may suffice for that purpose. The grains that could be dragged by the jovian plasma must be those for which the electric force F_E due to the co-rotational electric field of the Jovian magnetosphere is greater than the gravitational pull of Io F_G. The limit, for calculation purposes may be written through the equilibrium equation:

$$\frac{F_G}{F_E} = 1 \qquad (5.1)$$

Where

$$\vec{F}_G = G\frac{m_g M_{Io}}{(R_{Io} + H)^2}\hat{r} \qquad (5.2)$$

This last expression is the gravitational pull that the grains of mass m_g experience at the top of the plumes of height H (M_{Io} and R_{Io} are the mass and radius of Io respectively). On the other hand:

$$\vec{F}_E = Q\vec{E} \tag{5.3}$$

is the electric force on the surface charge Q of the grains due to the co-rotational electric field $\vec{E} = c^{-1}(\vec{R}\times\Omega)\times\vec{B} = 0.113 Vm^{-1}$; where $\vec{R}$ is the position vector of the particle, Ω is the angular velocity of Jupiter (=1.74×10^{-4} rad/s), c is the speed of light (=3×10^{8} m/s) and $\vec{B}$ is the intensity of the jovian magnetic field. For a dipolar configuration $B = B_0(R_J/R)^3$, with $B_0 = 4.2\times10^{-4}T$ and $R = 5.20R_J$, the distance from Io to Jupiter in jovian radii.

Since the charge of the grains may be expressed through the surface potential just like $Q = 4\pi\varepsilon_0 r\phi$ and the mass of the grain as $m_g = (4/3)\pi r^3\rho$ supposing spherical grains of density ρ From equation (5.2), the largest grains, among those injected from the plumes, that could be dragged by the plasma, will have a maximum radius defined by:

$$r_g = \sqrt{\frac{3\varepsilon_0 E}{GM_{Io}}\left[\frac{(R_{Io}+H)^2|\varphi|}{\rho}\right]} \tag{5.4}$$

or factorizing all constant terms:

$$r_g = 2.246\times10^{-5}\sqrt{\frac{(R_{Io}+H)^2|\varphi|}{\rho}}\ \mu m \tag{5.5}$$

with $R_{Io}(=1815\pm5\ km)$ and H in *km*, ϕ in *volts* and ρ in *g/cm³*.

In chapter four it was demonstrated that the equilibrium surface potential for a sub micrometric grain injected into the Ionian ionosphere is –34 *V*. Let us suppose sub micrometric grains driven to the top of the 460 *km* Pele plume, composed by sulphur, sulphur dioxide or olivine. From (5.5), the maximum escape radii for these particles are:

For SO_2, 0.24 μm; for S, 0.21 μm and for Mg_2SiO_4, 0.17 μm.

For the same plume, but taking the lower limit of its height (*H*=300 *km*), the values would be 0.22 μm, 0.20 μm and 0.15 μm respectively.

These results are generalized on Fig 5.1 where all plumes have been considered. Averages for the same plot are summarized in Table 5.1. Some plumes are set as reference, taking their maximum heights. The largest grains that can escape from Io are those sulphur dioxide dust particles driven by Pele plume, with radii around ~0.24 μm. Meanwhile, the smallest ones are driven by Culan plume whose maximum height is about

50 *km* above the surface of the satellite. These are Olivine (forsterite) particles and have radii around ~0.24 μm.

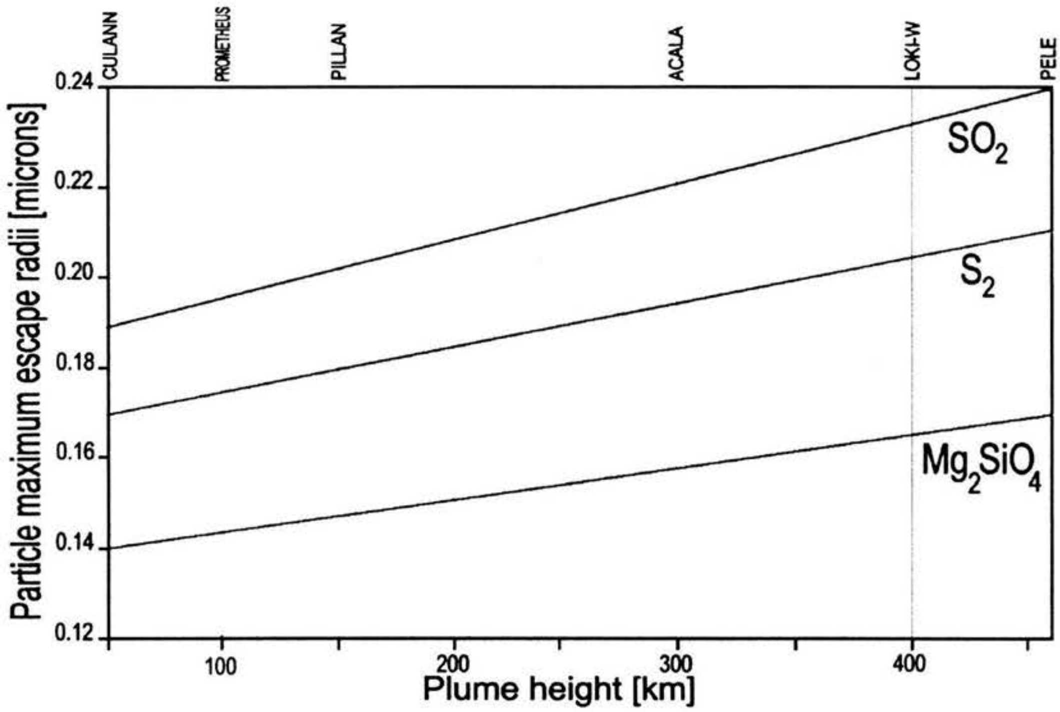

Fig. 5.1 Particle maximum escape radii versus plume height of Io's volcanoes for three different types of grains: Sulfur dioxide (1.6 $g\ cm^{-3}$), sulfur (2.0 $g\ cm^{-3}$) and olivine (3.21 $g\ cm^{-3}$). Grains are supposed charged at a -34 volt surface potential. Notice that the lower value is ~ 0.14 *microns* (olivine) and the upper is 0.24 *microns* (sulfur dioxide). Some plumes are set as reference taking their maximum reported heights (see Table 3.1).

Table 5.1 Average value of the maximum escape grain radii from Io's plumes considering a -34 V surface potential.

MATERIAL	r_{max} $[nm]$
SO_2	215
S_2	190
$MgSiO_4$	155

On the other hand, if we consider that dust particles may collect a minimum charge just like one electron, dust particle radius may be given through eq. (5.5) writing the surface potential in terms of the surface charge as:

$$r_g = 8.99 \times 10^{-3} \sqrt{\frac{(R_{Io} + H)^2}{\rho}}\ nm \qquad (5.6)$$

with R_{Io} and H in kilometers and ρ in g cm^{-3}.

In this case, for Pele plume we would have:

For SO_2, 1.32 *nm*; for *S*, 1.23 *nm* and for Mg_2SiO_4, 1.05 *nm*.

Of course, the dust particle radius, in comparison to our former calculation seems to be considerably reduced. Plotting now eq. 5.6 (fig.5.2) for the plume known ranges just like in figure 5.1, the possible maximum radii range may be clearly observed for most cases.

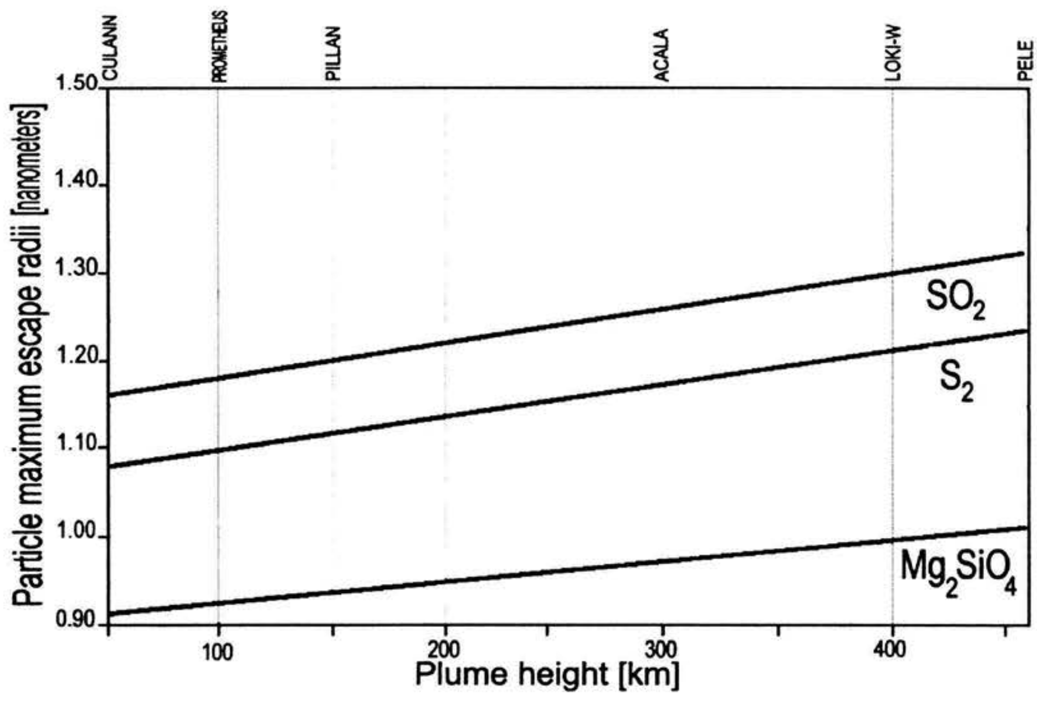

Fig. 5.2 Particle maximum escape radii versus plume height of Io's volcanoes for sulfur dioxide (1.6 *g cm*$^{-3}$), sulfur (2.0 *g cm*$^{-3}$) and olivine (3.21 *g cm*$^{-3}$) grains. Grains are now supposed charged with a minimum charge equal to one electron or an equivalent at ~-0.1 *volt* surface potential. Notice that the lower value is ~ 0.92 *nanometers* (olivine) and the upper is 1.32 *nanometers* (sulfur dioxide). Some plumes are set as reference taking their maximum reported heights.

Table 5.2 Average value of the maximum escape grain radii from Io's plumes considering a minimum surface charge equivalent to only one electron or ~-0.1 *volt* surface potential.

MATERIAL	r_{max} [nm]
SO_2	1.24
S_2	1.16
$MgSiO_4$	0.99

As we can see, if this is the case, only those very small particles from the volcanic ejections of Io may escape. Nevertheless, based on the whole analysis, the dust particles that escape indeed might be smaller than 0.1 *μm*, but larger than 1 *nm*; that is, the actual typical radius could be simply 10 *nm* which is an average in orders of magnitude

We must stress that the particles that are seen in the plumes have likely a radius, $r_g \geq 0.3$ μm, since smaller grains are poor backscatters of sunlight (Mendis et al., 1985). The theoretical radii obtained with equations 5.5 and 5.6 would scatter only ultraviolet radiation, in principle, we can consider those grains that escape from Io, invisible in other ranges of the electromagnetic spectrum. Due to the conditions of the plumes, as we saw on chapter three and according to observation most of the grains that condense in Io's plumes are micrometric or sub micrometric, although the last ones dominate (Collins, 1981).

ESCAPE OF DUST PARTICLES FROM JUPITER

The last escape stage of dust particles from Jupiter is the plasma Torus. It is important to notice here that all grains that escape have positive charge and small radii. Both cases are analyzed ahead.

Although dust grains escape from Io with a negative potential, the properties of the plasma inside the Torus, in most cases, favor a positive charging of dust grains in a matter of hours (Graps 2001) even if particles start being negative. On the other hand, there will be some aspects that may affect this charging process as it has already been demonstrated through the analysis of six years of the Galileo spacecraft data (Krüger et al., 2003a) which show that there is a strong dependence of the escape of particles on the position of Io in magnetic and inertial coordinates. This fact is reflected on a local time variation in the dust particle flux measured by Galileo. For example, it was seen that high fluxes occurred between 0 and 6 *h* (dusk) and between 15 to 18 *h* (dawn) in Jupiter local time; and fewer particles were measured between 8 and 15 *h*.

On the one hand, the plasma conditions are different for the Torus inside and outside of Io's orbit (cf. chapter two). Typical plasma temperatures for both cases are 10^4 and 10^6 K (1 and 100 eV) respectively. On the other hand, the asymmetries of the Torus have also a direct effect on the plasma conditions. That is, the whole plasma Torus is shifted by the dawn-dusk electric field of Jupiter about 0.15 R_J in the dawn direction (Barbosa & Kivelson, 1983; Ip & Goertz, 1983), that results in a higher plasma temperature in the dusk side.

To a first approximation it is seen that the charging history of the grains inside the Torus may be different for particles dragged from the side of Io facing Jupiter and from those dragged from the side facing away from Jupiter. Also there will be differences if particles are dragged when Io is at different positions along the Torus as numerical simulations indicate (Horanyi et al., 1997) since nanometric dust grains that start on the dawn side of Jupiter remain captured by the Io Torus for a longer time, while dust particles starting at the dusk side have got a larger probability to escape.

On the whole we may say that once dragged away from Io and accelerated to magnetospheric speed, dust will fast form a torus around Jupiter and along Io's orbit. Then, dust grains will be immersed into *plasmas* one or two orders of magnitude (≥100 eV) hotter than Io's ionosphere where secondary electron emission may become important so that incoming electrons may generate more than one outgoing electrons, making particles more positive or simply positive and more able to be pushed away by the co-rotating electric field as part of the Jovian Dust Streams.

Regarding to the size that dust grains may have in order to be pushed away from Jupiter, we introduce two equations that describe the largest and the smallest radii to compare these with the radii of the grains that escape from Io.

Krüger et al. (2003) calculated the minimum radius of grains (supposed spherical) that escape from Jupiter with the gyration of a charged grain along Jupiter's magnetic field lines $r_{gyr} = |\omega mc / QB|$ with $\omega = R\Omega - \sqrt{GM_J / R} = 5.724 \times 10^4 \, m/s$ the tangential speed of the particle in keplerian orbit, Ω is the respectively angular speed and R is the distance from Jupiter to Io. They assume a magnetic field for an aligned centered magnetic dipole, $|\nabla \vec{B} / B| = 3/R$, describing the motion of the grain bound to the magnetic field line with a guiding center approximation $r_{gyr} |\nabla \vec{B} / B| < 0.1$. After these assumptions, the minimum radius is written as $r_{\min} = [(0.1 \varphi B_0 R_j^3)/(300 \omega \rho 4 \pi c R^2)]^{1/2}$. The expression may be simplified as:

$$r_{\min} \approx 0.001 \sqrt{\varphi / \rho} \; \mu m \qquad (5.7)$$

with the surface potential in volts and the density in g/cm^3.

The radius of largest grain that can escape from Jupiter is obtained through the ratio L of the Lorentz force generated by the Jovian magnetic field and the gravitational pull of Jupiter experienced by the grain. The simplified expression is:

$$r_{\max} \approx \sqrt{0.0057 \varphi / \rho L} \qquad (5.8)$$

In this last expression it has been considered that if $L \geq 1/2$, the grain will escape from the circumjovian space to the interplanetary space in a parabolic or hyperbolic orbit (Hamilton & Burns 1993, Krivov et al., 2001).

According to both equations (5.6) and (5.7) the escape radii intervals for sulfur dioxide, sulfur and olivine particles would be:

Table 5.3 Escape radii intervals for sulfur dioxide, sulfur and olivine particles that leave the Jovian System.

MATERIAL	r_{min} $[nm]$	r_{max} $[nm]$
SO_2	1.8	189
S_2	1.5	169
$Mg_2 SiO_4$	1.2	133

There seems to be a coincidence between the radius of the particles that manage to escape from Io and from Jupiter, since the largest escape radii from Jupiter is similar to the largest escape radii from Io considering the largest possible equilibrium potential. On the other hand the smallest escape radii from Jupiter is similar to the largest escape radii from Io supposing the smallest possible equilibrium potential. In both cases, with a variation of only of ~10 %.

Even if most of the particles driven by the plumes are actually sub micrometric, on the whole, it is deduced that only a fraction of those particles will escape as the Jovian streams, but also, since the intervals match roughly, those particles dragged from the ionosphere of Io would seem to find its way almost *directly* from Io to the Interplanetary medium.

DUST EMISSION RATE FROM IO

A way to make an approximate calculation of the rate at which dust escapes to the Interplanetary Medium is to consider the characteristics of the detection and suppose that the emission of particles is quasi isotropic. Galileo and Cassini spacecrafts' dust experiments have detected the jovian streams only in regions near jovian equator because their paths have been constricted to such latitudes near Jupiter (Krüger et al., 1999), but the Ulysses spacecraft on the other hand, detected the streams in 1992 in the ecliptic and at ~30° in latitude and recently, on its second pass by Jupiter during the second half 2003, at ~80° in latitude (Krüger, private communication). The detection will be then influenced by an spherical expansion, that is, it will depend on the term $4\pi R^2$ where R is the distance from the particles to Jupiter or the distance where the detection takes place. The mass emission rate is expressed as the equivalent number of detector areas A_D –area of the detector- at detection distance r times the number of particles detected per second f -frequency of impacts on the detector- times the mass of a typical grain m_g, that is:

$$\Phi = \frac{dM}{dt} = (\frac{4\pi R^2}{A_D}) f m_g \tag{5.9}$$

Galileo's and Ulysses' detector's area is A_D =235 cm^2 (Graps et al., 2000). As for the impact rate, at the end of 1996 (4th November) when the spacecraft was near Callisto (30 R_J) the average impact frequency recorded for the streams was around $f \sim 0.1$ *imp/min*=1.67×10^{-3} *imp/s*. From Eq. (5.9) and from Table 5.2, for the mean smallest particle ~1.5 *nm* (~10^{-23} *kg*), the rate is 10^{-4} kg/s; and for the largest particle, 0.189 μm (~10^{-16} *kg*), the rate is around ~50 *kg/s*. The Dust Ballerina skirt is fed –in orders of magnitude- at an average rate of:

$$\Phi \sim 0.1\ kg/s \tag{5.10}$$

It has been calculated that Io produces a ton of material every second that feeding the jovian space (Spencer and Schneider, 1996), it has also been calculated that the Plasma Torus, where most of the emitted matter ends, has a mass that fluctuates between 10^5-10^6 *tons* (Bagenal, 1994). If we compare the amount of dust that escapes from Jupiter with the total amount of dust emitted to the Jovian space, it corresponds to only 0.01%.

CONCLUSIONS

Due to its wide and diverse population of dust, the Jovian system has become an important laboratory for dust studies. Many of the new ideas related to dust issues had their origin in the study of this system. An example of this is the discovery of Io's volcanism by the Voyager missions in 1979, by itself, an astonishing finding that settled new possibilities for the understanding of interplanetary dust, because of the later finding of the jovian dust streams by the Ulysses spacecraft in 1995. These streams were then an unexpected and interesting fact which changed the way of watching and understanding dust. Even though the connection between both facts was suspected almost from the beginning because of the existence of the plasma torus and the sodium cloud, the mechanisms that explained such streams were not clear on the whole.

Once identified Io and its volcanoes as the ultimate source of dust of the streams through the models developed and the periodicity printed in the dust detection it was seen that *both escapes*: the escape of dust grains from Io and the escape of the same dust grains from Jupiter, demanded a particular range of sizes and a certain electrostatic charge so, even if the spectacular volcanic ejections drove grains to really great heights, this fact, by itself, was not enough since the largest speed achieved by the ejections were at the end of 1995 their best a half of the escape velocity of the satellite.

We demonstrate along this job that the link between Io's dust and the circumjovian space is the Ionian ionosphere detected by the Galileo spacecraft. Our results indicate that the driving of dust particles to great heights by the large Ionian plumes and later injection into the ionosphere of Io may enable dust particles to collect quite efficiently electric charges and an equilibrium potential in a very short time that allow the magnetic field to accelerate them away from Io through the induced co-rotational electric field. Our interest along this job was to define the dominant charging mechanism for the dust particles, to calculate the equilibrium potential of the grains and the interval in which this charging takes place, as well as, the dependence of the grain size and surface potential to the escape from Io.

On the first place it was found that the electron capture is by far a more efficient charging mechanism than any other present in the Ionian ionosphere basically as a consequence of the particle density and temperature of the plasma. The collection of electrons needed to reach a negative equilibrium potential takes, at the most, a couple of seconds. There is also an important dependence to the grain sizes and thus to the composition of the grains.

These calculations were made supposing three possible types of materials, consequence of the chemical composition of Io's ejections and the type of volcanism identified and inferred on Io. The average maximum escape radius of those grains that collect charges and are able to be dragged by the surrounding plasma, is ~187 *nm* if we take the largest possible equilibrium potential. If the smallest potential is taken, the average radius is around 1.13 nanometers. If we consider the average of both last values in orders of magnitude we draw a typical radii of 10 *nm*. Interestingly, the sizes of dust grains obtained through this study match very well the values required for the particles to escape from the Jovian system. In fact the largest particles supposing maximum potential that are swept from the ionosphere of Io are ~10 % larger, in radius, than those larger particles that are pushed away from the plasma torus.

Since Earth volcanoes show electrification processes near or right in the vents because of the high temperatures and the presence of conductive material, thus it was explored that same mechanism with Io. Although the hotspot temperatures are high, silicate crystallization, and thus the presence of solid *clast* out of which dust may be formed is an actual possibility, but simple calculations demonstrate that the ionization of those solid silicates in such vents is poor even for the hottest hotspots just like in Pillan *patera* that reach temperatures above 2000 *K*.

Most –if not all- of the material deposited onto Io's surface or injected into the surroundings of this satellite is done through the volcanoes, be it lava flows or plumes. In fact, most of the emitted material ends on the surface eventually. According to our calculations the dragged grains would be swept from the plasma torus at a rate of 0.1 kg/s, which represents 0.01 % of the total mass emitted by Io.

Most of the calculations done along this job were centered on Pele volcanoe, since its spectacular plumes ranging from 300 km and 460 *km* high represent, to a first approximation, a direct source of dust for the jovian streams. To conclude we introduce a summary of the whole ejection history of this particular volcanoe, numbering the sequence of events that generate gases and dust in its plumes, accounting the trip from the volcanic chamber to the vent, then into the atmosphere and afterwards to the outside of Io and the Jovian System. Most of this history may be applied to the other Ionian volcanoes and their plumes.

1. The magma liquefies itself at 1.5-2 *km* depth below the surface of Io, where pressure is near 40 *bar*.

2. When *liquid magma* gets into contact with the *liquid underground* S / SO_2 (*underground lake or layer*), magma cools and S / SO_2 vaporizes. Both processes happen violently . If silicate magma is present there may be *clast* formation.

3. The magma, vapors and gases of sulfur dioxide reach the vent. In that process, the mixture decompresses to 10^{-2} *bar*. The temperature of the material leaving the vent is >1000 *K*. The mixture sweeps solid material (small amount) from the walls of the upper conduit and vent adding solid *clasts* to the future plume (these solids may be the result of sulfur solidification due to its high viscosity at high temperatures or even silicates that crystallize spontaneously below ~1700 *K*.

4. The mixture leaves the vent at ~1 $km\ s^{-1}$. The plume is formed as material expands almost isotropically. The pressure drops now to ~10^{-7} *bar* and temperature drops to ~85-130 *K* (night and day surface temperatures on Io) and though there is a temperature gradient along the plume.

5. The plume cools very fast. When vapor and gases are in a region of the plume where temperature has dropped to110 *K*, SO_2 condenses and clasts (dust) are generated and decouple from the gas. This happens above a radius of ~25-50 *km* from the vent. Only nanometric and micrometric size grains are formed because of the low density in the plume. Coagulation might take place in this stage.

6. Larger grains (in average >0.19 *μm*) will follow ballistic trajectories and will fall back to Io's surface. Smaller grains (in average <0.19 *μm*) will reach the ionosphere (n~18 000 cm^{-3} and $T \sim 10^5 K$).

7. Ionospheric 10 eV electrons are captured easily by the sub-micrometric dust grains in a couple of seconds, settling a negative potential that may be as large as -34 V or as small as -0.1 V . Due to their small size, these potentials are enough to let electromagnetic forces to dominate the grain's dynamics.

8. Sub-micrometric dust, depending on its charge will be accelerated to magnetospheric speed ~57 *km/s* and escapes from Io scattering themselves along its orbit.

9. Once in the Torus, grains will be under the properties of other kind of plasma, an order of magnitude hotter and less dense than the ionospheric plasma where particles may collect a positive surface equilibrium potential.

10. Part of the gas ejected from the Ionian volcanoes will be added to the Ionosphere and part to the neutral atmosphere. In the atmosphere gases will be condensed eventually in the night side of the satellite and will fall back to the surface eventually. The deposited solid material coating the surface will be evaporated again in the day side of the satellite and so on.

11. Inside the plasma Torus, grains larger than 150 *nm* or smaller than 5nm will remain bound to Jupiter. Grains among $5 \leq r_g \leq 150$ *nm* will escape from Jupiter in well defined *dust streams*.

APENDIX: ***JUPITER AND IO PHYSICAL PROPERTIES***

Table A1 Io Global Physical Prperties.

Radius	1815($\pm$ 5) *km*
Volume	$2.52\times10^{10}\,km^3$
Surface area	$4.15\times10^{7}\,km^2$
Mass	$8.92\times10^{25}\,g$
Relative mass to Jupiter	$4.703(\pm0.006)\times10^{-5}$
Density	$3.55g\cdot cm^{-3}$
Surface gravity	$180cm\cdot^{-1}$
Escape Velocity	$2.56km\cdot s^{-1}$
Orbital escape velocity	$\geq 7.18km\cdot s^{-1}$ Relative to Io surface
Semimajor axis	$4.216\times10^{5}\,km; (5.95R_J)$
Orbital period	42.456 *hr*
Mean orbital motion	203.2890 $deg\ day^{-1}$
Eccentricity	0.0041 (forced), $(1\pm2)\times10^{-5}$ (free)
Inclination	0.027 *deg*
Orbital velocity	17.34 $km\ s^{-1}$
Magnetospheric velocity	56.8 $km\ s^{-1}$
Magnitude	5.0
Albedo	0.6
Heliocentric distance	5.2 AU (7.78×10^{8} *km*)
Solar insolation	$\sim3\times10^{4}\,erg\ cm^{-2}\ s^{-1}$
Typical surface temperature	~135 *K*
Typical hotspot temperature	~300-650 *K*
Hotspot heat flor	$>5\times10^{13}$ *W*
Global average heat flor	>1.2 $W\ m^{-2}$
Global magnetic field (***B***) at Io	~2000 *nT*
Corotation electric field at Io	0.113 $V\ m^{-1}$ outward from Jupiter

Table A2 Jupiter Global Physical Properties.

Radius	71492 km (R_J)
Volume	$1.53 \times 10^{15} km^3$
Surface area	$6.42 \times 10^{10} km^2$
Mass	$1.90 \times 10^{30} g$
Density	$1.3 g \cdot cm^{-3}$
Escape Velocity at Io's orbit	$26\ km \cdot s^{-1}$
Semimajor axis	$778.3 \times 10^6 km; (5.203 AU)$
Orbital period	11.862 *years*
Rotation period	10.5 hr
Eccentricity	0.048
Inclination	1.30 *deg*
Magnitude	-9.40 V
Albedo	-2.70 V_0
Global magnetic field ($\lvert\vec{B}\rvert$)	~4.2 *Gauss*

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