CHAPTER 2

Theory

2.1 Planetary Aurora

Aurora is caused by the collisions of energetic particles with planet's atmospheric particles at high altitude. Planetary magnetosphere is formed by the interaction between interplanetary magnetic field, which is dragged along the solar wind, and planet's magnetic field. In magnetosphere there are several regions, which are bow shock, Magnetosheath, plasmasheet, Magnetopause, and Manetotail (Fig. 2.1). Most energetic charged particles (mostly electrons) flow from magnetotail toward the planet. Some charged particles travel along the planetary magnetic field lines, and impact with atmospheric particles in planetary ionosphere. The collisions excite atoms or molecules in atmosphere, from which the electromagnetic waves are emitted, and form the main oval aurora.

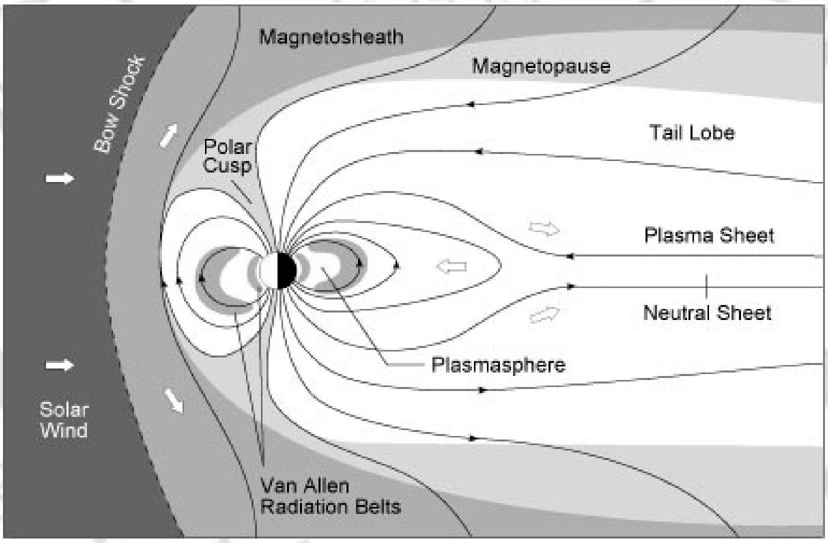


Figure 2.1: The sketch of interaction between solar wind and planetary magnetosphere (Lang, 2015).

As seen in Fig. 2.1, bow shock is the boundary of planetary magnetosphere, which is created when two streams of gas collide. The speed of solar wind suddenly drop in this regions. The gas flow behind the shock downstream is subsonic in the region, which is called “magnetosheath”. The flow of plasmas in the magnetosheat are deviated surround planet. The location, where pressure of solar wind balances the pressure of planetary magnetic field, is called “magnetopause”. We can estimate the distance of magnetopause from planet by

$$\frac{r_{\text{mp}}}{R_{\text{P}}} = \left(\frac{B_{\text{P}}^2}{2\mu_0 \rho_{\text{sw}} u_{\text{sw}}^2}\right)^{1/6}. \tag{2.1}$$

Where r_{mp} is radius of magnetopause, R_P is radius of planet, B_P is magnetic field strength at equator of planet, and $\rho_{sw} u_{\text{sw}}^2$ is solar wind dynamic pressure. The thin plane of plasma locating in the equatorial plane is called “plasmasheet”. In the case of terrestrial magnetosphere, plasmasheet contains both hot plasma and electrons, whose temperatures (T_e) correspond to energy about 1 keV.

Solar wind dynamic pressure varies as solar wind’s density and velocity. Plasma density normally decreased as a square of distance from the sun. Originally the speed of solar wind is supersonic. When the flow travels through the bow shock near magnetosphere, the plasma velocity rapidly drop, as well as the drop of the density and temperature. The downstream subsonic plasma therefore cause turbulance flow in plasmasheet, creating Alfvénic disturbance, and alfvén wave accordingly. The speed of the Alfvén wave is defined as:

$$C_A^2 = \frac{B_0^2}{\mu \rho_0}. \tag{2.2}$$

C_A is Alfvén speed.

Earth’s aurora mainly influenced by charged particles from solar wind. Solar wind drags solar magnetic field lines outward, which become “Interplanetary Magnetic Field” (IMF) lines, from the sun and impacts Earth’s magnetic field with average velocity around 400 km/s. Some particles travel toward the poles, and consequently cause the auroral emission. In Earth’s atmosphere, mostly atomic and molecular nitrogens and oxygens are excited due to collisions with the solar wind particles, and later emit energy for returning to ground state. The emitted energy is in the form of electromagnetic waves. Atomic oxygens are excited and emit spectrum at 630 nm (red) or 557 nm (green). After charged particles impact atomic and molecular nitrogens in atmosphere, excited nitrogens would emit either blue or red light (Fig. 2.2). Earth's aurora appearing in the north is called Northern Light or Aurora Borealis. On the other hand, the aurora appearing in the south is called Southern Lights or Aurora Australis.

Figure 2.2: Earth's aurora (Ichoku, 2015).

2.2 Motion of charged particles in magnetosphere

Charged particles travel along magnetic field by gyrating along magnetic field line. This motion is called gyromotion (or cyclotron motion), shown in Fig. 2.3.

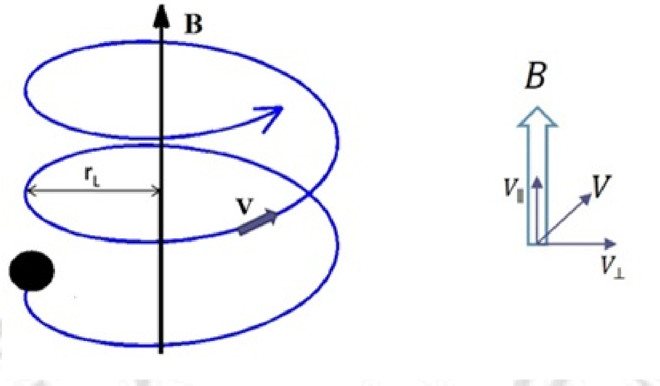


Figure 2.3: (left) A charged particle gyrates along magnetic field line modified from CAS (2015). (right) Two components of particle's velocity are perpendicular component $(V_\perp)$ and parallel component $(V_\parallel)$ to the field line.

Radius of gyro motion is defined as

$$r_L = \frac{mV_\perp}{qB}. \tag{2.3}$$

Where, r_L is gyro radius, m is mass of particle, q is charge of particle and B is magnetic field strength.

For an assumption of planetary magnetic field as a dipole field, the field lines converge and are strongest at the poles.When charged particles travel along the field lines from equator (B_0) to polar region (B) the perpendicular velocity changes due to the variation of magnetic field strength, according to the first adiabatic invariance,

$$V_\perp^2 = (\frac{B}{B_0})V_{\perp 0}^2. \tag{2.4}$$

In polar region, the magnetic field strength increases from B_0 to B and accordingly perpendicular velocity ($V_\perp$) increases from initial value at equator ($V_{\perp 0}$). When charge particle travels into polar region, the parallel velocity ($V_\parallel$) will decrease due to the conservation of energy. Therefore, if kinetic energy is assumed to be constant,

$$V_\perp^2 + V_\parallel^2 = V_{\perp 0}^2 + V_{\parallel 0}^2. \tag{2.5}$$

where $V_{\parallel 0}$ and $V_{\perp 0}$ are velocities in two components at initial or reference point. $V_\parallel$ and $V_\perp$ keep changing when B is continuously increasing along magnetic field line toward polar region.

As a result, at high altitude in polar region, the parallel velocity could decrease to zero and only perpendicular velocity would remain. In that case, the particles are trapped at a moment and then return to the opposite direction toward the region of weaker field as seen in Fig 2.4. On the other hand, if a particle still has parallel velocity, it will penetrates into planetary ionosphere and impact with atmospheric particles. Eventually the aurora is created.

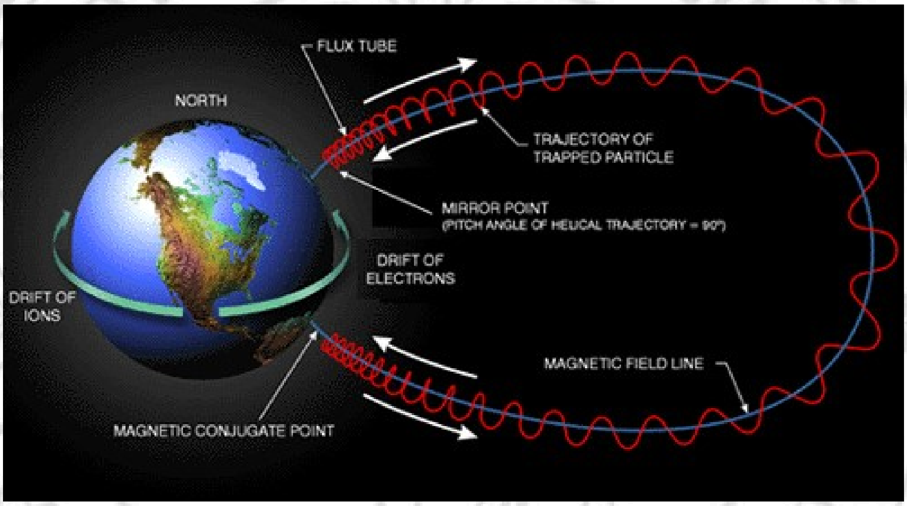
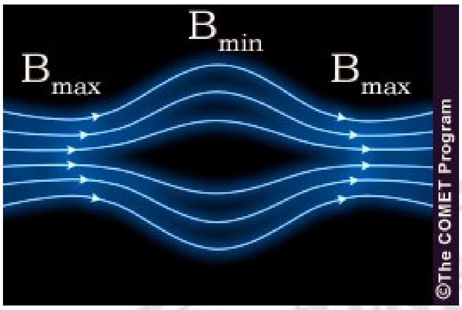


Figure 2.4: Particles moves back and forth inside magnetic, which is bounded by two regions of strong and weak magnetic field (Jursa, 2015).

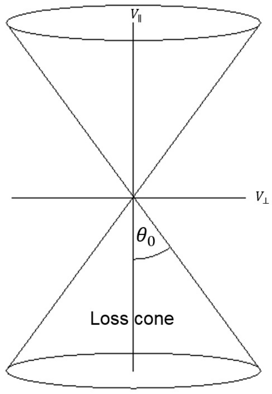
For the particles that are trapped and travel at high altitudes between north and south poles, their motions are called “magnetic mirroring”, in which the region is called “magnetic bottle”, as seen in Fig. 2.5a. In Fig. 2.5b the angle between particle’s velocity and magnetic field line, or pitch angle (θ), in which the mirrored particles are able to escape the magnetic bottle, is called “loss cone”. Therefore the condition, which the particles would be trapped inside the magnetic bottle, is

$$sin\theta_0 > (\frac{B_0}{B_{max}})^{1/2}. \tag{2.6}$$

Particles can escape from magnetic bottle when pitch angles (θ_0) is less than $sin^{-1}(\frac{B_0}{B_{max}})^{1/2}$. B_{max} is magnetic field at polar region, where auroral emission is detected.



(a)



(b)

Figure 2.5: (a) Magnetic bottle occurs when magnetic field lines converge at polar region, whose magnetic field strength (B_{max}) is much stronger than magnetic field at equator (B_{min}). (b) Loss cone is the angle defined by angle θ, in which the direction of particle's velocity allows the mirrored particles to be able to penetrate into planetary atmosphere modified from Hutchinson (2015).

2.3 The interaction between planetary magnetic field and satellite

Jupiter has a very large and strong magnetic field. The major influence on Jovian magnetosphere is the planet's rotation. Jupiter's rotation of about 10 hours drags magnetic field lines to be firmly fixed with its motion. Plasma pressure in Jupiter's magnetosphere is very large. This pressure is confined around equator plane. Plasma density and pressure increase in the layer of plasmasheet, in which embeds Jovian's four largest moons, Io, Europa, Ganymede and Calisto. Those moons are also called "Galilean satellites". Io is nearest to Jupiter among the Galilean satellites and mostly affected by Jupiter's magnetosphere. The direct evidence of interaction between planetary magnetic field and satellite is found in planetary aurora region. The aurora feature, which is called "magnetic footprint", is the interaction evidence and clearly seen right by the main auroral oval with lower latitude, shown in Figure 2.6.

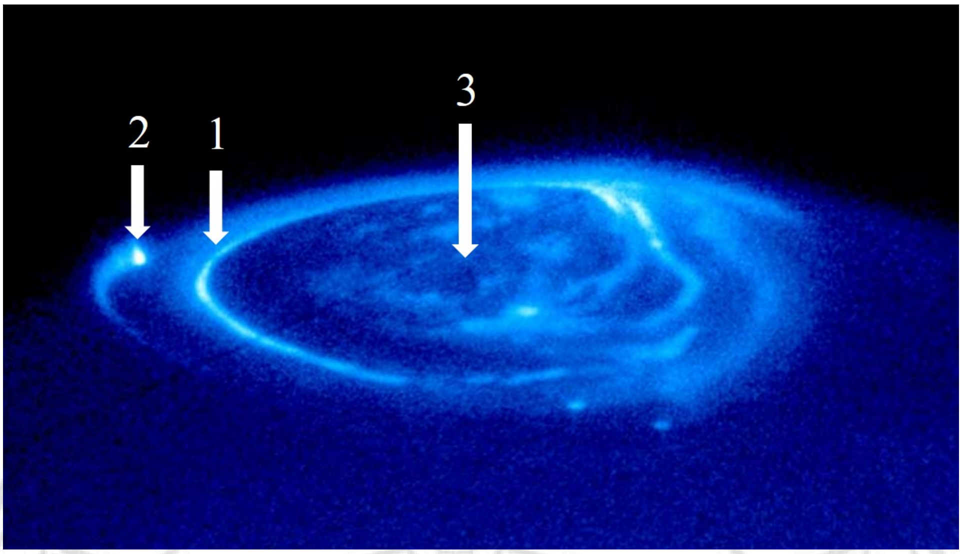


Figure 2.6: Aurora on Jupiter [NASA/ESA, John Clarke (Boston University)]. Number 1 indicates Jupiter's "main oval aurora". Number 2 indicates Io's magnetic footprint. Number 3 indicates polar emission, which is influenced by solar wind.

As for the main focus of this research, Io provides large amount of charges particles to Jupiter magnetosphere via volcanic eruptions. Those charged particles are ionized components of SO_2 spewed from Io's surface forming the satellites atmosphere. Io's neutral atmosphere is ionized mainly by photoionization and charge-exchange processes. These charged particles can travel along Jupiter magnetic field lines, and finally penetrate into Jupiter's atmosphere, creating the bright aurora at the foot of magnetic flux tube, and becoming magnetic footprint. The ions and electrons ejected from Io's volcanoes accumulate around the orbital path of Io. This accumulation of plasma is called "Io plasma torus", shown in Fig .2.7.

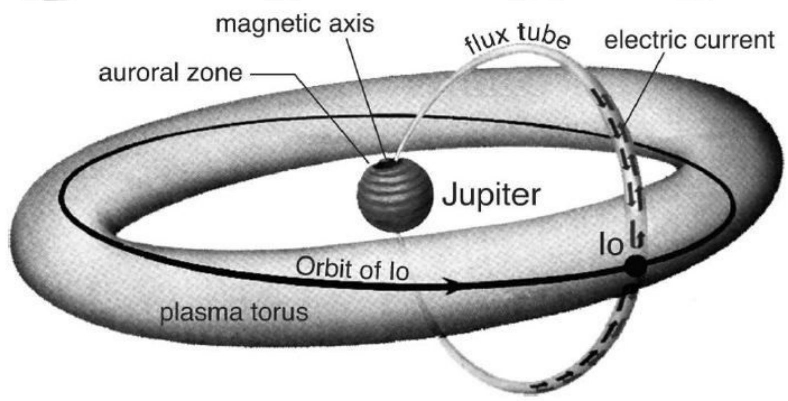


Figure 2.7: Sketch of Io plasma torus (Saur et al., 2004).

Io orbits around Jupiter with velocity 17 km/s (1.77 days period). Jupiter's rotation period about 10 hours causes the plasma torus to rotate with velocity 74 km/s at Io's orbit. Therefore the torus plasma flows past Io with relative velocity of 57 km/s. The fast flow of upstream plasma interact with Io's atmosphere. As a result, Jupiter's magnetospheric plasmas constantly sweep Io's atmosphere out as Io orbits around Jupiter. Plasma torus consists of the ions components of SO_2 , i.e., O^+, O^{++}, S^+, S^{++}, etc. The torus was divided into two regions (Cravens, 2004): (1) inner cold torus (S^+) with electron density $\sim$ 1,000 cm^{-3} and ion temperature (T_i) and electron temperature (T_e) $\sim$ 1 eV, (2) outer warm torus (O^+, S^{++}) with electron density $\sim$ 2,000 cm^{-3}, $T_i \sim$ 100 eV and $T_e \sim$ 5 eV.

At Io, the plasma flows from upstream to downstream by going around the interaction region. The field lines and plasma flow are diverted around Io, creating a structure called Alfvén wing (Fig. 2.8). The boundary of Alfvèn wing starts from the upstream boundary toward the region of magnetic field lines diversion behind the interaction region (black lines). In Fig. 2.8 for cross section view of Alfvén wing , B is Jupiter's magnetic field, and u is the plasma flow speed at the upstream region. Open arrow head represent current flowing on the side radially away from Io (solid lines) and current flowing closer to Io (dashed lines). Inside the Alfvén wing, there is strong perturbation, which is called Alfvén disturbances. Alfvén disturbances is much stronger than the weaker perturbation at the region outside the Alfvén wing.

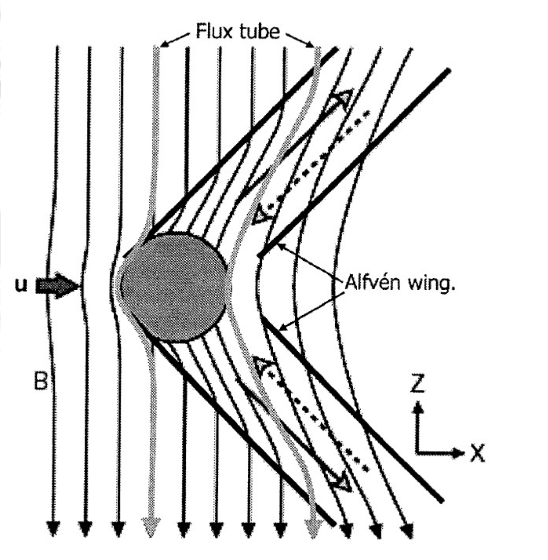


Figure 2.8: Schematic Alfvén disturbances and Alfvén wing down stream of Io (Kivelson et al., 2004).

Wave in the downstream regions is changed into slow mode to restore the pressure equilibrium. The field lines not only deviate in the regions near Io, but also happened at above and below around Alfvén wing. The gray lines are flux tubes representing the region that electric current was created between Jupiter and Io. The power output in this region has high concentrations called "Io Flux Tube". The currents flow in flux tube away from Jupiter, across magnetic field line along with Alfvèn waves at Io and then flow back along magnetic field lines toward Jupiter (blue line on left of Fig. 2.9). This flow can be explained by $\mathbf{J} \times \mathbf{B}$ forces.

2.4 Io's magnetic footprint

Charged particles from Io travel along magnetic field lines of Jupiter and impact with atmospheric particles creating aurora at the foot of magnetic flux tube. This spot emission is well known as "Io's magnetic footprint" or IFP. IFP was divided into three parts: (1) the main Alfvén wing (MAW) spot connects Jupiter ionosphere to the interaction region at Io. (2) The Tran-hemispheric Electron Beam (TEB) spot is a result of accelerated electrons along magnetic field lines. Lastly, an emission caused by some particles, which are reflected in plasma torus due to the density gradient, is called (3) Reflected Alfvèn Wing spot (RAW). The diagram of connection between Io and Jupiter's ionosphere is shown in Figure 2.9.

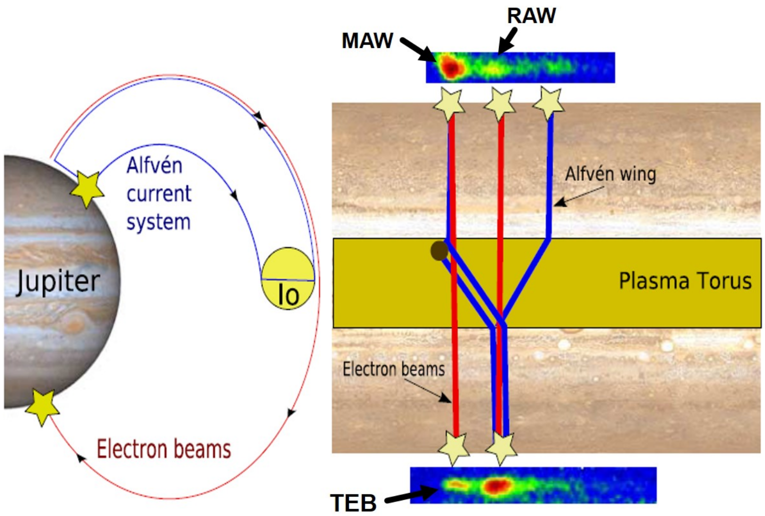


Figure 2.9: The diagram of connection between Io and Jovian ionosphere, where Io footprints are represented by stars (Bonfond et al., 2008).

Figure. 2.9 illustrates aurora at the foot of magnetic flux tube. Charged particles are picked-up along Alfvén wings (blue line) creating MAW spot. Electron acceleration along magnetic field lines (red line) creates TEB spot. Arrows along the blue lines in Figure. 2.9 (left) represent direction of current, which is called “Birkeland current system ($J_{||}$)”.

2.5 Previous Studies

Bigg (1964) presented the first evidence of interaction between Jovian magnetosphere and Io. Observations of Io’s influence on Jupiter were detected by the Voyager 1 and Voyager 2 Jupiter flybys in 1979. Io was discovered to have a number of eruptions of the volcanoes which cause Io to be the most active satellite in our solar system. In addition, strong electrodynamic interactions between Io and Jupiter’s magnetic field were directly observed by Voyager 2 (Ness et al., 1979).

Previous study presented strong connection between Io’s magnetic footprint brightness and the density of the plasma torus (Wannawichian et al., 2010). The result showed that the brightness of Io’s footprint varies with location of Io in plasma torus. Interaction between Io’s atmosphere and Jupiter’s magnetospheric plasma is strongest when Io is in the center of the plasma torus. Ten years observation of HST showed variation of IFP with two emission peaks, i.e., first peak at Io’s system III longitude $\sim 110°$, and second peak at $\sim 290°$, as seen in Figure 2.10.

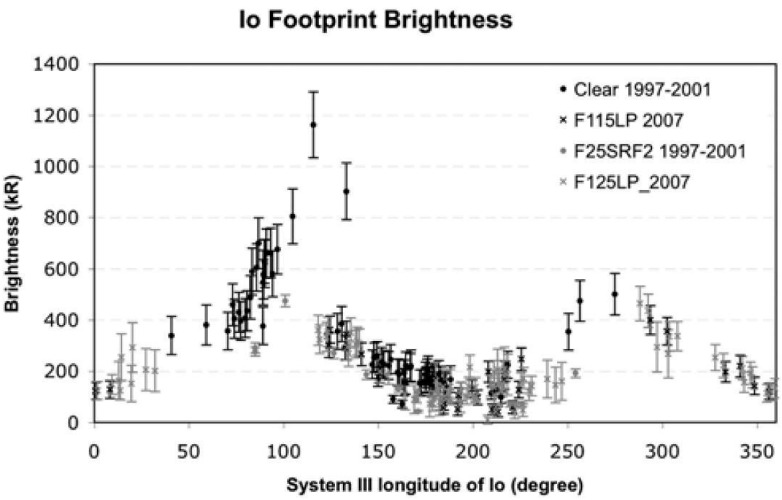


Figure 2.10: Io’s footprint brightness corresponding to the location of Io (λ_{III}). The brightness peaks appear at $\sim 110°$ and $\sim 290°$ (Wannawichian et al., 2010).

Shown in Figure 2.11, the data from observations by Hubble Space Telescope since 1997 to 2009 was studied by Bonfond et al. (2013). While the interaction between Io and Jupiter's magnetosphere appears to be very strong when Io is in the center of plasma torus, the brightness of north magnetic footprint varies with different trend and not as bright as south magnetic footprint. The brightness was not only controlled by Io's location; but the magnetic field asymmetric between two hemispheres could also play a very important role.

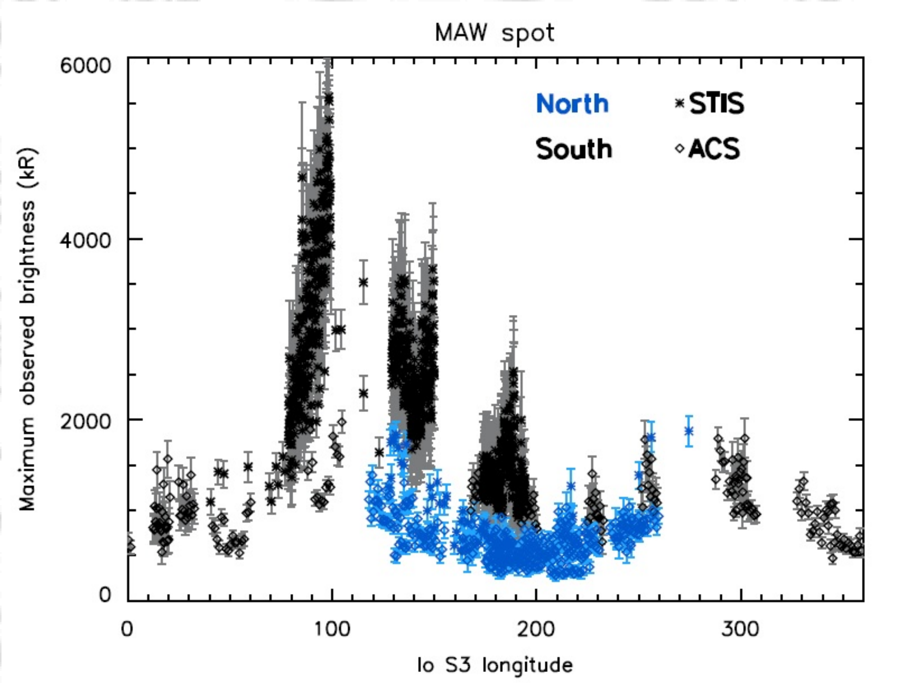


Figure 2.11: The brightness variation of MAW spot. Black symbols represent the footprint's brightness in southern hemisphere and blue symbols represent the footprint's brightness in northern hemisphere (Bonfond et al., 2013).

The effects of the volcanic eruption from Io was studied by Yoneda et al. (2013). The result indicate that the intensity of Jupiter's radio emission (HOM) was decreased when Io has more volcanic eruptions. The model of previous study by Nichols and Cowley (2003) and Tao et al. (2010), present that the increasing of plasma from Io results in the field-aligned current between ionosphere and Jupiter's magnetosphere to decrease. This correspond to the decay of Jupiter's hectometric radio emission (HOM) in previous study by Yoneda et al. (2013), shown in Fig 2.12.

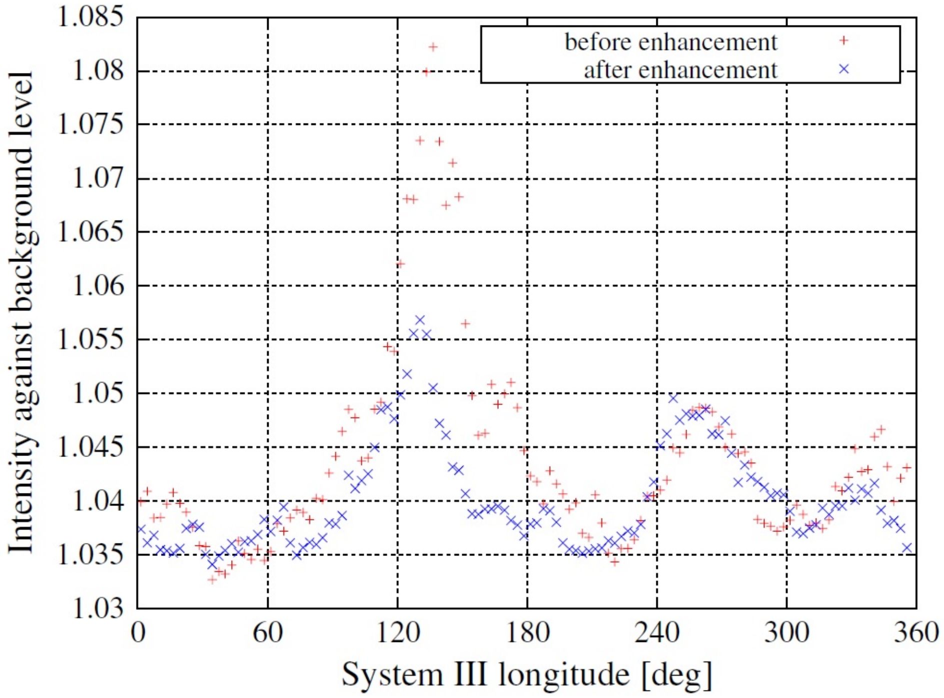


Figure 2.12: This picture show intensity of HOM (Jupiter's hectometric radio emission) as a function of Jupiter's system III longitude (Yoneda et al., 2013). Red crosses is the emission before eruption (1-23 May 2007) and blue crosses is the emission after eruption (7-29 June 2007) of Io's volcanos.