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Formation of cyclone and anticyclone in Jupiter: A battle of great red spot and red storm

Abstract

The formation of Jupiter and its different regions including its great red spot are first outlined. The boundaries of the zones and belts of the planet display complex turbulence and vortex phenomenon and the structure as a whole is dominated by the behavior of fluid mechanics. These characteristic patterns have been considered at length. The principle for the formation of cyclones in the Northern and Southern hemisphere is explained. The energy needed to power all the turbulence in the atmosphere of Jupiter is produced by the heat released from the planet's core. The Great Red Spot, an anticyclone storm situated at 22° south of Jupiter's equator and the red storm properties are examined considering the associated environmental factors and possible encountering. The storms and lightning experienced on Jupiter have also been compared to those on Earth.

Key Words

Red storm; Jupiter; Cyclones; Great red spot; Lightning.

INTRODUCTION

Jupiter is the largest planet in our Solar System with radius 11.3 Earth radii, mass equivalent to 317 Earth masses and mean density 1.3 gm/cc, close to that of water. New Horizons is a NASA robotic spacecraft mission launched on January 19, 2006, directly into an Earth-and-solar-escape trajectory with an Earth-relative velocity of about 16.26 km/s. In this paper the formation of cyclone in Jupiter as viewed through the spacecraft New Horizons are first summarized. The boundaries of the zones and belts of the planet are considered focusing the characteristic patterns[1]. The principle for the formation of cyclones in the Northern and Southern hemisphere is examined looking at meteorological parameters like temperature and pressure at the core of Jupiter and at its top. Jupiter's Great Red Spot (GRS) is an atmospheric storm that has been strong in Jupiter's southern Hemisphere for at least 400 years. Both the Great Red Spot and the red storm properties associated with the planet are analyzed besides environmental factors and probable encountering.

JUPITER FINDINGS THROUGH NEW HORIZONS

New Horizons' Long Range Reconnaissance Imager (LORRI) was able to take first photographs of Jupiter on September 4, 2006. The spacecraft began further investigation of the Jovian system in December 2006[2]. While at Jupiter, New Horizons' instruments made refined determinations of the orbits of Jupiter's inner moons, especially Amalthea. The probe's cameras found volcanoes on Io and studied all four Galilean moons in detail. It also made long-distance studies of the outer moons Himalia and Elara. Imaging of the Jovian system started on September 4, 2006[3]. The craft also observed Jupiter's Little Red Spot and the planet's magnetosphere and tenuous ring system[4]. Figure 1 shows Jupiter through infrared camera.

New Horizons further provided the first close-up examination of Oval BA, a storm character that has informally become familiar as the "Little Red Spot", owing to the red appearance of the storm. It was still a white spot when the spacecraft Cassini flew by. We have presented in Figure 2 (a) the enhanced view of

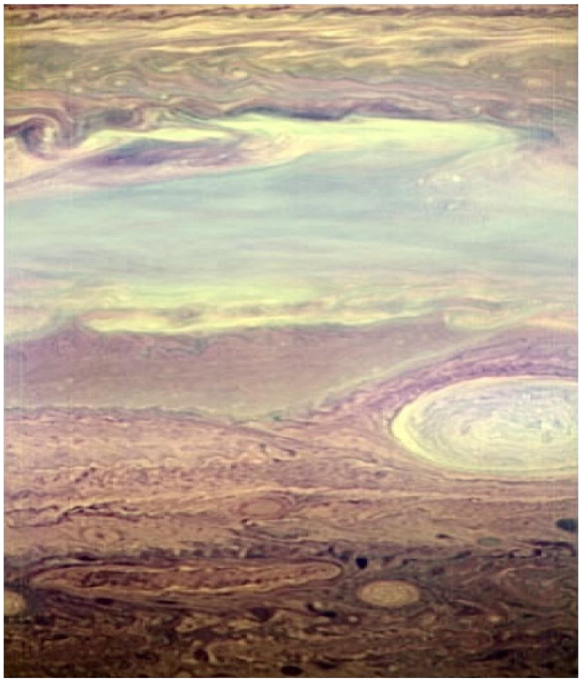

Figure 1 : Jupiter as viewed through infrared camera identifying volcanoes on Io [http://en.wikipedia.org/wiki/File:NH_Jupiter_IR.jpg]

Jupiter's "Little Red Spot" by the New Horizons space probe while Figure 2 (b) exhibits New Horizon's image of Jupiter's Himalia.

ATMOSPHERIC FEATURES AND FORMATION OF CYCLONES

Different gases have different condensation temperatures. Hydrogen compounds condense at temperatures less than 150K while condensation of rocks takes place at temperatures between 500-1300K and metals at 1000-1600K. The frost line is the distance in the solar nebula from the protostar where ices like hydrogen compounds can condense, whereas only metals and rocks can condense inside this line. Jovian planets are formed though a mechanism called accretion. In fact, accretion is the process when microscopic solid particles are condensed and grown into planets. These microscopic particles are attached together through electrostatic forces and not through gravitational attraction because these particles are very small. But as they grow in mass, their gravitational forces will increase and eventually accelerate their growth further. Formations of Jovian planets are created beyond the frost line causing availability of ices to create them. The formation of Jupiter including other Jovian worlds began with the build-up of ice-covered dust in the outer, cold solar nebula. Figure 3 shows the block diagram of the formation of Jovian planets. The figure clearly shows how the gases condense into icy particles are finally formed into Jovian planets after coming out through different steps.

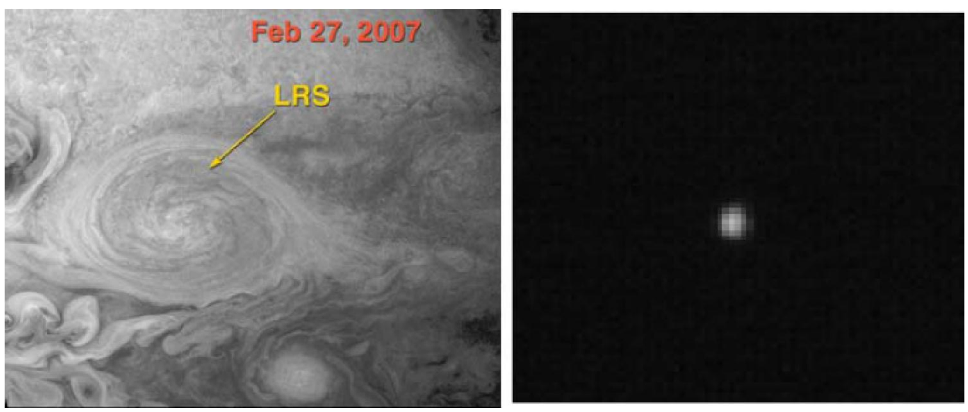

Figure 2 : (a) Enhanced view of Jupiter's "Little Red Spot" by the New Horizons space probe; (b) New Horizon's image of Jupiter's Himalia [http://pluto.jhuapl.edu/soc/view_obs.php]

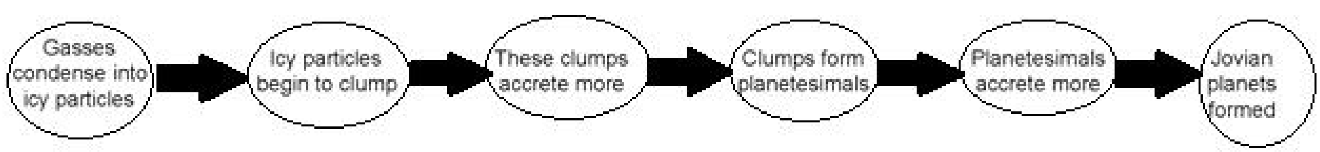

Figure 3 : The block diagram of the formation of Jovian planets

The photograph 4 reveals interestingly the formation of a Jovian planet which is essentially formed by going through four different steps as indicated in the figure.

Due to gravity, the heavier elements sink to the core of proto-Jupiter and hence expected the core region to be rocky and the lighter elements (H and He) remain in the atmosphere. The exterior of Jupiter is determined by its brightly colored latitudinal zones. Owing to differential rotation, the equatorial zones and belts rotate faster than the higher latitudes and poles.

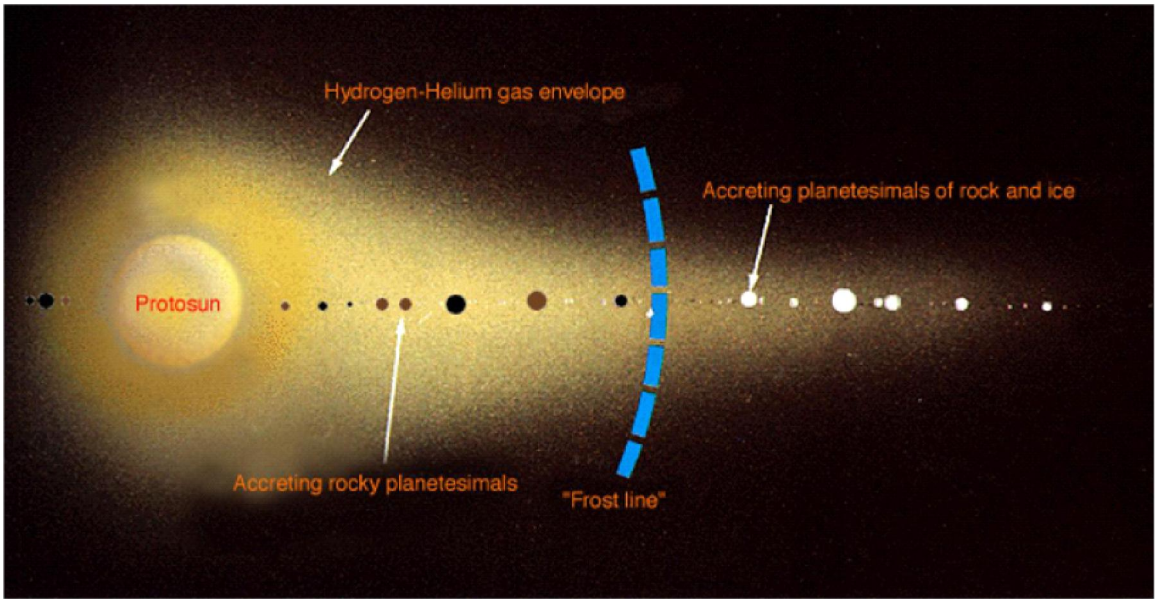

Figure 4 : Formation of a Jovian planet [http://www.physics.uc.edu/~hanson/ASTRO/LECTURENOTES/F04/OUTERDEBRIS/Page15.html]

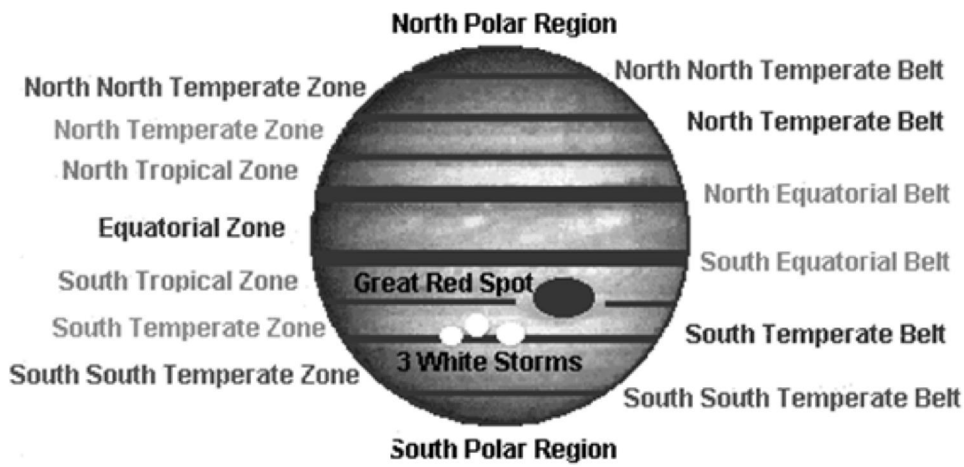

Figure 5 : The different regions of the Jupiter including its great red spot (http://abyss.uoregon.edu/~js/ast121/lectures/lec19.html)

In Figure 5 we have exhibited the different regions of the Jupiter including its great red spot. The banded structure of Jupiter's atmosphere consists of a series of lighter-colored zones and darker belts crossing the planet. The intensity and latitude of both the zones and belts vary during the year but the general pattern is always present. These variations cause convective motion in the planet's atmosphere. The zones lie above upward-moving convective currents in Jupiter's atmosphere while the belts are the downward part of the cycle as reproduced in Figure 6.

The stream breaks up into individual elements, known as eddies which are responsible to develop cyclones[5,6]. Cyclones are developed basically due to the Coriolis effect where the lower latitudes travel faster than the higher latitudes and thus producing a net spin on a pressure zone. On Jupiter the cyclones are regions of local high or low pressure spun in such a fashion. The direction of the spin differs in the two hemi-

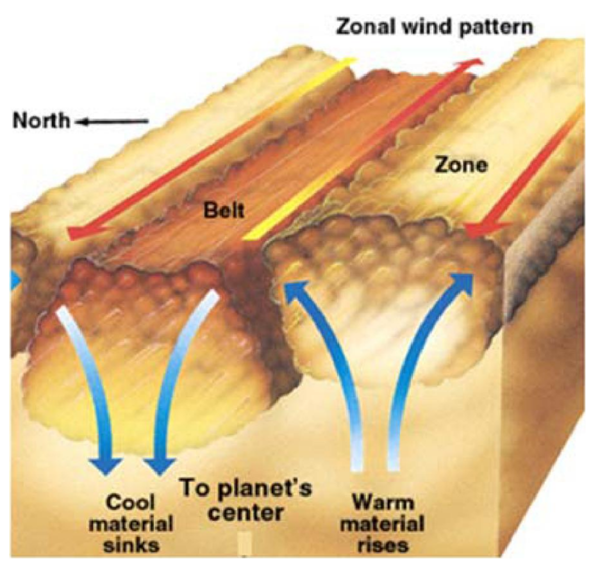

Figure 6 : Jupiter's convection pattern showing the 'cool material sinks' and warm material rises' on either sides of the planet's center (http://wisp.physics.wisc.edu/astro104/lecture20/lec20_print.html)

spheres where clockwise spin is in the North and counter-clockwise spin is in the South. In the North, brown ovals are low pressure cyclones/storms while in the South white ovals are high pressure cyclones/storms. Both of them can last on the order of tens of years. The well known Great Red Spot is a large high pressure storm which lasted over 600 years.

The principle for the formation of cyclones in the Northern and Southern hemisphere is shown in Figure 7. In the formation of storms on Earth, the energy to power comes from sunlight. But Jupiter being too far from the Sun, it receives very little energy. The energy required to power all the turbulence in the atmosphere of Jupiter is produced by the heat released from the planet's core. In fact, Jupiter has a very small solid core owing to its highly flattened shape and also because it has a very high rotation rate.

The difference in the appearance between zones and belts is owing to the differences in the opacity of the clouds. Ammonia concentration is higher in zones which is responsible to the appearance of denser clouds of ammonia ice at higher altitudes. This in turn leads to their lighter color. On the contrary, in belts clouds are thinner and are located at lower altitudes. The upper troposphere is colder in zones and warmer in belts[7]. The origin of Jupiter's banded structure is not yet well known, though it may be similar to that of Earth's Hadley cells. The simplest interpretation is that when air enriched in ammonia it raises in zones. Due to expansion and cooling it forms high and dense clouds. The North Equatorial Belt (NEB) is one of the most active belts on the planet which is characterized by anticyclonic white ovals and cyclonic "barges". This is alternately called as "brown ovals".

THE GREAT RED SPOT AND THE RED STORM

The Great Red Spot (GRS) is an anticyclone storm situated at 22° south of Jupiter's equator; Earth Observations from Earth establish a minimum storm lifetime of 183 years to 348 years[9,10]. The storm is sufficiently large and observable through Earth-based telescopes. The actual spot has been observed continually since 1878[11]. An infrared image of GRS taken by the ground based Very Large Telescope is shown in Figure 8(a) while the visible wavelength image of red storm as observed in Jupiter's southern hemisphere is shown in Figure 8(b).

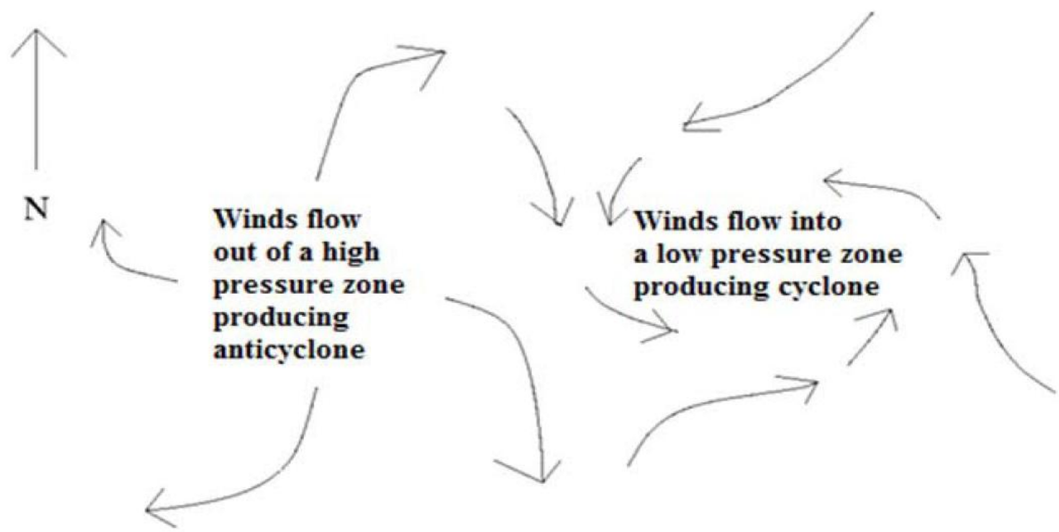

Figure 7 : Principle for the formation of cyclones and anticyclone respectively in the Northern and Southern hemisphere [http://www.nhn.ou.edu/~jeffery/astro/astlec/lec015.html]

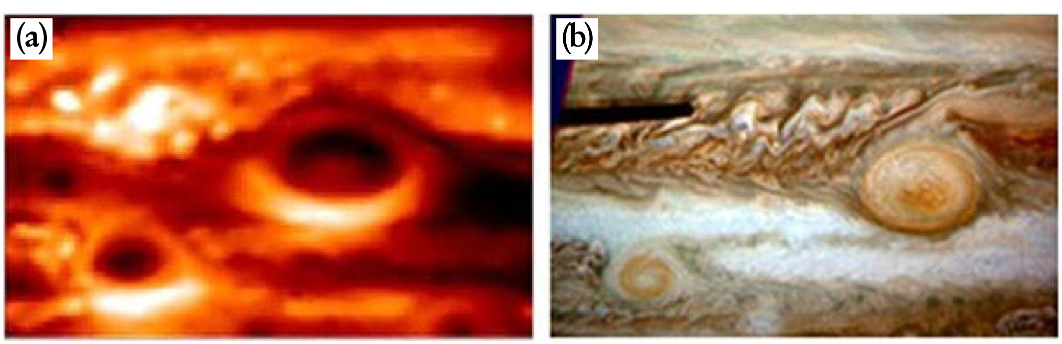

Figure 8 : (a) Infrared wavelength images of the Great Red Spot and (b) the visible wavelength images of Red Storm (http://hubblesite.org/newscenter/archive/releases/2006/19/image)

The GRS rotates counterclockwise with a period of about six Earth days[12]. The spot is sufficiently large to contain two or three planets the size of Earth. Infrared data have indicated that the Great Red Spot is colder and higher in altitude in comparison to most of the other clouds on the planet[13]. The cloud tops of the GRS are nearly 8 km above the surrounding clouds[13] and it is spatially confined by a modest eastward jet stream to its south and a very strong westward one to its north[14]. Astronomers, in 2010, imaged the GRS in the far infrared and observed that its central, reddest region is warmer than its surroundings by about 3 to 4 K. The warm air mass is situated in the upper troposphere in the pressure range of 200–500 mbar and the warm central spot slowly counter-rotates causing a weak subsidence of air in the center of GRS[15]. The observations exhibit that the reddest color of the Great Red Spot corresponds to a warm core within the comparatively cold storm system. Images reveal dark lanes at the edge of the storm where gases are descending into the deeper regions of the planet. These types of data provide a sense of the circulation patterns within the Solar System's best-known storm system.

The Great Red Spot's reddish color has not yet been determined properly but is assumed, in general, that the color may be due to the complex organic molecules, red phosphorus and sulphur compound. The Great Red Spot (GRS) varies greatly in hue, from almost brick-red to pale salmon, or even white. The reddest central region is warmer than the surroundings indicating that the Spot's color is affected by environmental factors[15].

Red storm in Jupiter's southern hemisphere, officially named as Oval BA, looks to some extent similar in form to the Great Red Spot and so affectionately referred to as "The Little Red Spot" or "Red Spot Jr." or simply "Red Jr.". Formation of three white oval storms that subsequently merged into Oval BA can be traced to 1939, when the South Temperate Zone was rent by dark features. This effectively split the zone into three long sections which was labeled by Jovian

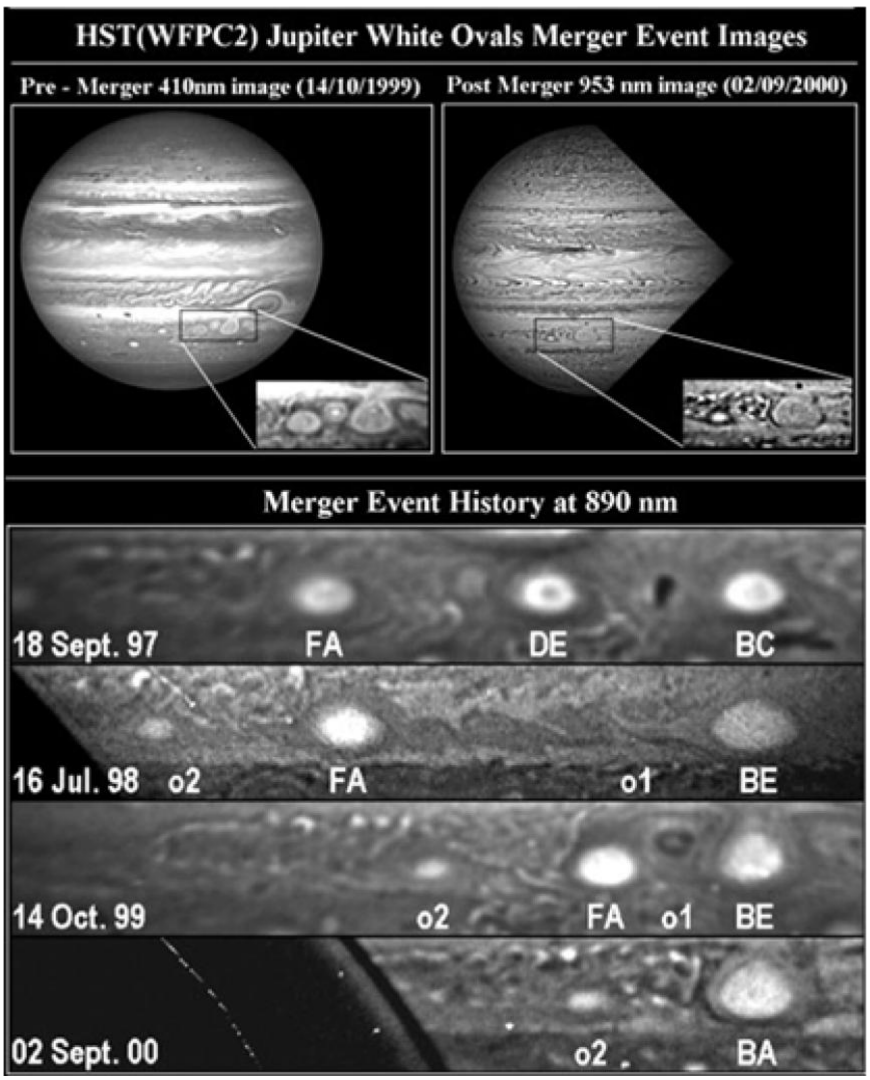

Figure 9 : Formation of Oval BA from three white ovals [Credit: NASA/ESA]

observer Elmer J. Reese[16] as the dark sections AB, CD, and EF. The rifts expanded into the white ovals FA, BC and DE[13] out of which Ovals BC and DE merged in 1998, forming Oval BE. Further, BE and FA merged together forming Oval BA[17]. Figure 9 reveals the formation of Oval BA from three white ovals. This feature in the South Temperate Belt was first found in 2000 after the collision of three small white storms which has intensified since then[17].

Storms and lightning

The storms experienced on Jupiter are largely similar to thunderstorms on Earth. They show themselves through bright clumpy clouds about 1000 km in size. They appear from time to time in the belts' cyclonic regions, particularly within the strong westward (retrograde) jets[8]. In contrast to vortices, these storms are short-lived phenomena whose strongest one may exist for several months. However, their average lifetime is only about 3–4 days[8]. These storms are believed to be due to moist convection within Jupiter's troposphere. Storms are found tall convective columns (plumes). They carry wet air from the depths to the upper part of the troposphere, where it condenses in clouds. A typical value of the vertical extent of Jovian storms is about 100 km. They extend from a pressure level of about 5–7 bar, where the base of a hypothetical water cloud layer is located, to as high as 0.2–0.5 bar[17].

Always the storms on Jupiter are associated with lightning. The imaging of the night side hemisphere of Jupiter as obtained by the spacecrafts Galileo and Cassini revealed regular light flashes in Jovian belts and near the locations of the westward jets. This is particularly true at 51°N, 56°S and 14°S latitudes[8]. On Jupiter lighting strikes are on an average a few times more powerful than those on Earth though they are less frequent. However, the light power emitted from a given area is similar to that on Earth[8]. A few flashes have been identified in Polar Regions, making Jupiter the second planet after Earth to show polar lightning[18,19]. Figure 10 shows lightning on Jupiter's night side as imaged by the Galileo orbiter in 1997. The storms occurred some 50 to 75 kilometers beneath the outer cloud layer, with lightning strikes hundreds of times more powerful than those on Earth. Each column shows a different storm. The images were taken with exposures of 90 seconds, with a two-minute interval between them.

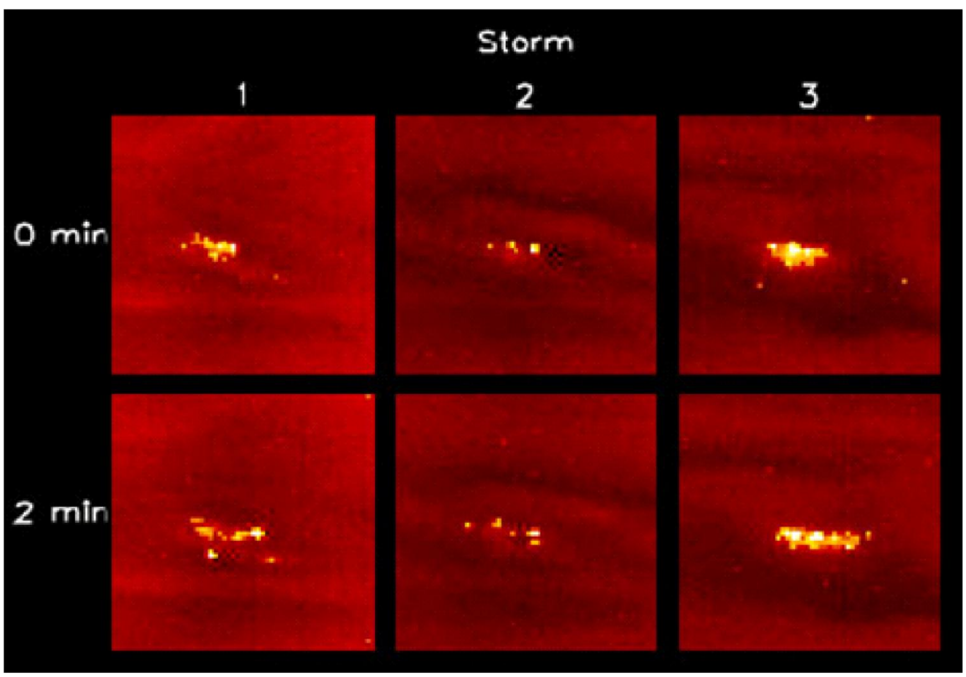

Figure 10 : Lightning on Jupiter's night side, imaged by the Galileo orbiter in 1997 (http://apod.nasa.gov/apod/ap971216.html)

ENCOUNTER AMONG GREAT RED SPOT, OVAL BA AND "BABY RED SPOT"

An interesting feature in the South Temperate Belt, Oval BA, was first seen in 2000 after the collision of three small white storms and has increasing since then. In August 2005, Oval BA slowly began to turn red[20]. Christopher Go discovered the color change on February 2006 and found that it had reached the same shade as the Great Red Spot[20]. Based on this fact, NASA writer Phillips suggested that it be called "Red Spot Jr." or "Red Jr."[21]. A team of astronomers, in April 2006, thought that Oval BA might converge with the GRS that year as they observed the storms through the Hubble Space Telescope[21]. The storms pass each other about every two years but their passings in 2002 and 2004 did not produce any new findings. Simon-Miller, of the Goddard Space Flight Center, predicted the storms would have their closest passing in 2006[18] and in fact the two storms were photographed on July 20, 2006 when they were passing each other by the Gemini Observatory without converging[22].

Oval BA is gradually getting stronger according to findings made with the Hubble Space Telescope in 2007. Also the wind speeds have reached 618 km h^{-1} which is nearly the same as in the Great Red Spot. This is in reality far stronger than any of the progenitor storms[23,24]. In July 2008, its size was about the diameter of Earth: nearly half the size of the Great Red Spot[25] (http://www.sciencedaily.com/releases.htm).

The South Tropical Little Red Spot (LRS) is nicknamed as the "Baby Red Spot" by NASA[26]. This popularly called Baby Red Spot encountered the GRS in late June to early July 2008. In the course of a collision, the smaller red spot was shredded into pieces. The remnants of the Baby Red Spot first orbited and thereby consumed by the GRS. The last of the remnants having a reddish color was identified by the astronomers but had disappeared by mid-July. The remaining pieces further collided with the GRS, which finally merged with the bigger storm. The rest of the pieces of the Baby Red Spot had completely disappeared by August 2008[26]. During this period of encountering Oval BA was present nearby but played no significant role to destruct the Baby Red Spot[26]. Figure 11 reveals an encounter that happened for a short period in June 2008 among Oval BA, Great Red Spot and "Baby Red Spot". The three natural-color Jupiter images shown in the figure were made from data acquired on May 15, June 28, and July 8, 2008 by the Wide Field Planetary Camera 2 (WFPC2). Each of the images covers 58 degrees of Jovian latitude and 70 degrees of longitude.

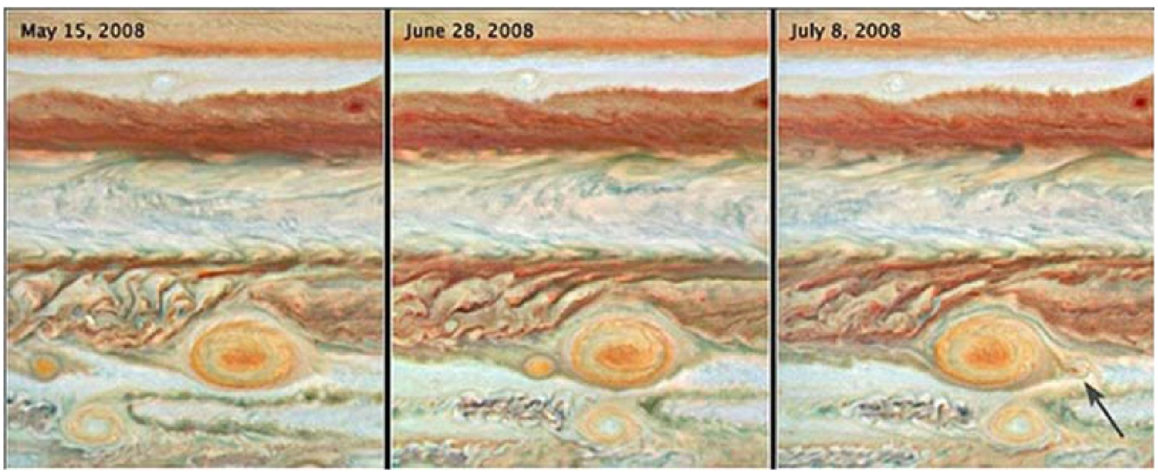

Figure 11 : Oval BA (bottom), Great Red Spot (top) and "Baby Red Spot" (middle) during a brief encounter on May 15, June 28 and July 8, 2008; the arrow in right hand image indicates that the baby red spot was deformed (pale color) and has been spun to the right of the GRS (http://hubblesite.org/newscenter/archive/releases/2008/27/image)

The time series marked in the figure reveal the passage of the "Red Spot Jr." in a band of clouds below the Great Red Spot. The Oval BA or the so called "Red Spot Jr." first appeared on Jupiter in early 2006 when a previously white storm was converted to the appearance of red. But this was not true for the "baby red spot" which appeared in the same latitudinal band as the GRS. In course of time the baby red spot went closer to the GRS, as evident from the picture sequence until it is caught up in the anticyclonic spin of the GRS. From the final image recorded on July 8, 2008 it appears that the baby red spot has been deformed with pale in color and has been spun to the right of the GRS.

CONCLUSION

The reason why Oval BA turned red is not yet clearly understood. According to a 2008 investigation by Pérez-Hoyos, the most likely mechanism may be an upward and inward diffusion of either a colored compound or a coating vapor which may interact subsequently with high energy solar photons at the upper levels of Oval BA. Others believe those small storms and their associated white spots on Jupiter turn red when the winds become sufficiently powerful for drawing certain gases from deeper within the atmosphere causing a change of color when those gases are exposed to sunlight[27]. It may be mentioned that the Oval BA should not be confused with the South Tropical Little Red Spot (LRS), another major storm on Jupiter. Interestingly, the new storm, previously a white spot in Hubble images, turned red in May 2008 which was clearly analyzed and found that characteristics are dissimilar from Oval BA[28,29].

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