Face-to-face Encounter of the Space Craft Juno with Jupiter having strong source of Radio Signal: a survey

Shankar Prasad Mitra[1*], Debasmita Dutta[2] and Asit B. Bhattacharya[3]

[*1]Department of Physics, Techno India University, West Bengal, Kolkata 700009, India

[2]Department of Electronics and Communication Engineering, Techno India University, West Bengal, Kolkata 700009, India

[3]Head Department of Electronics and Communication Engineering and Dean of Research, Techno India University, West Bengal, Kolkata-700091, India

[*1]shankarmitra35@gmail.com
[2]Debasmitadatta98@gmail.com
[3]bhattacharyaasitbaran@gmail.com

Abstract— **Jupiter has been one of the biggest mysteries of solar system over years and astronomers rigorously trying to reveal its secrets. Since the accidental discovery of Jupiter's radio signal in 1955 scientists continuously observing the planet in radio, UV and IR frequency. After ground based study for a long period, the researchers feel the necessity of a close look to the planet to solve the mystery of our solar system, origin and evolution of the gas giant, its dynamic magnetosphere, interior structure, atmospheric dynamics, chemical composition and its intense aurora. In pursuance of these aspects of astrophysics the space research institute NASA and Jet Propulsion Laboratory (JPL) added a new feather in the form of a fastest man made, solar powered space craft Juno. In this paper, we have critically discussed the different types of signal and radio burst that emits from Jupiter and their mechanism considering the vital role of its nearest moon Io followed by the exploration with earlier space probes and an overview of the new mission Juno. The space craft Juno is a highly equipped instrument with titanium made body having a unique polar orbit to reach very close to the planet than else before. After a five-year long journey Juno started to interact with the planet by crossing the bow shock and magnetopause several times through which the purpose of observing Jupiter's magnetic field has been solved. We have emphasized the radio and plasma wave observations in Jupiter's polar magnetosphere during Juno's first perijove pass on August 27, 2016 (DYO 240), electron energy spectrogram and the plasma wave signals from Jupiter's ionosphere that observed by Juno.**

Keywords— ***Radio signal, dynamic magnetosphere, aurora, and radio burst, plasma wave, electron energy spectrogram***

I. INTRODUCTION

The study of the largest planet Jupiter of the solar planetary system has special importance as it covers a strong source of radio signal, contributing the planet earth by different means. Dipole antenna is a simple instrument for analyses of Jovian Radio signal for ground based study. For better understanding of the planet we need a close look to it. A solar powered spacecraft Juno, launched on August 5, 2011 provides formation of Jupiter, the inside mechanism of the planet including the size of its dense core, the movement of the deep interior, the physical processes that power the auroras and about its pole. In this paper we have focused on the characteristic changes in the received radio signal by Juno when it reaches to the close vicinity of Jupiter.

II. BACKGROUND STUDYAND RADIO TELESCOPIC RESEARCH

In 1610 Galileo Galilei discovered the four largest moons of Jupiter which are Io, Europa, Ganymede and Callisto using a telescope considered as the first telescopic observation of moons other than Earth's [1]. In 1660s using a new telescope Cassini discovered some spots and colorful bands on Jupiter. He observed that the planet appeared oblate and was able to estimate the rotation period of the planet [2]. In 1690 Cassini further observed that the atmosphere undergoes differential rotation [3] and a prominent oval-shaped feature in the southern hemisphere of Jupiter, the so called Great Red Spot. The pharmacist Schwabe produced the earliest known drawing to find the details of the Great Red Spot in 1831 [4]. The Red Spot was reportedly lost from sight on many occasions between 1665 and 1708 before becoming famous in 1878. It was recorded as fading in 1883 and also at the start of the 20th century [5]. In 1955 a mysterious signals from space were accidentally discovered by radio astronomers Burke and Franklin [6] and they realized that Jupiter was in the beam of the cross antenna at all the time when signals were recorded at the operating frequency of 22.2MHz and there were some special longitudes of Jupiter where the radio emission was much more likely to be heard than others. These longitudes were like "landmarks" on a planet which mean that Jupiter does not spread radio waves in every direction but rather it beams the radio waves into space. We know that Radio waves can be polarized or unpolarized but most of the radio waves from Jupiter are polarized which signifies that these waves are coming from a zone where magnetic field is present. This was in fact one of the first evidence that Jupiter has a magnetic field [7].

After collecting years' worth of data scientists discovered that radio signals transmitted from Jupiter in three forms.

(i) *Decametric radio bursts:* This nonthermal radiation (λ ~10 m) arises due to charged particle, emitted from volcanic moon Io, get accelerated under the influence of the strong magnetic field [8] of Jupiter called synchrotron emission [Fig 1]

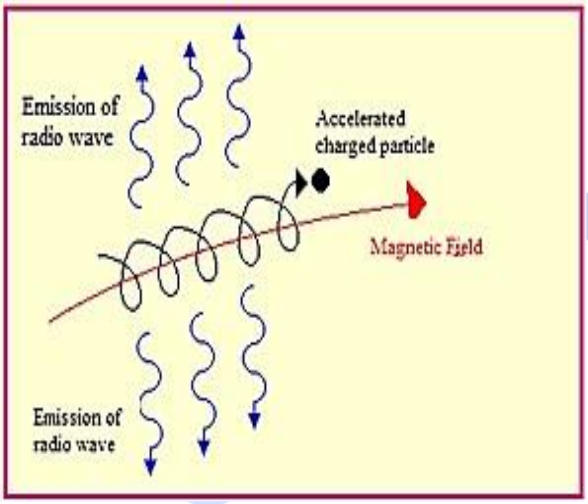

Fig 1 Synchrotron Emission:A charged particle encounters a strong magnetic field and accelerated along a spiral path following the magnetic field and produces synchrotron radio emission

(ii)*Decametric radio emission:* The volcanic emission of Io forms a torus-shaped belt around Jupiter's equator [Fig 2]. This ring of charged particles spiraling in Jupiter's intense magnetic field produces cyclotron emission [9]. The decametric radio waves have frequencies in the range between 10 and 40 MHz. It was first observed by Drake and Hvatum in 1959 [10]. The radio emission pattern is not isotropic. They waves are emitted along a thin hollow cone. Io-controlled Decametric Radiation (Io-DAM) emissions are only observable when the emission cone is illuminating the observer.

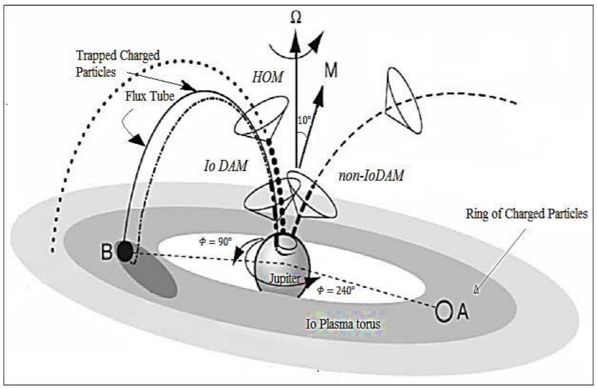

Fig.2 Radio emissions are emitted by the accelerated electrons along magnetic field lines in the Jovian aurora regions. In the plasma wake of Io for Io-DAM emissions or in the plasma disk for non-Io-controlled Decametric Radiation (Non-Io-DAM) and Hectometric Radiation (HOM) emissions (A and B represents two position of Io for azimuthal angle 90°and 240° respectively)

(iii) **Thermal radiation** which arises mainly from the heat in the atmosphere of Jupiter [11].

III. JUPITER'S MAGNETOSPHERE

A magnetosphere is the sphere of influence of the magnetic field of a planet that surrounds planets and affects the region around it which is produced by a planet having sufficient amount of magnetic material, producing a substantial amount of current. The internal pressure of the magnetic field of a planet when interacts and balanced by the external pressure of the solar wind, a magnetosphere is formed. The size of a planet's magnetosphere depends on both the strength of the magnetic field and the strength of the solar wind. Jupiter's internal dynamo generates its intense magnetic field with a dipole moment nearly18000 times stronger and about 10 times greater than that of our Earth [12].

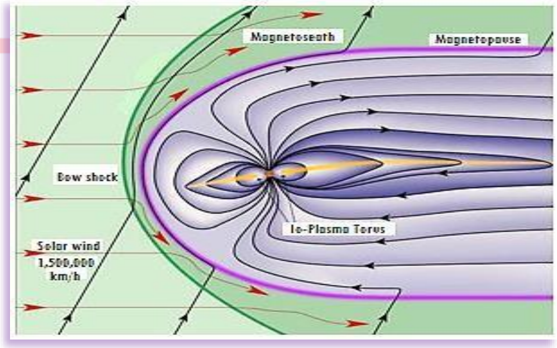

Fig. 3 Jupiter's magnetosphere is formed by balancing the external pressure of the solar wind with the internal pressure of the magnetic field of a planet

In our solar system the Jupiter's magnetosphere is the largest and most powerful. The region where the ionized solar wind is abruptly decelerated and heated by the obstruction created by Jupiter's magnetic field called bow shock (BS).Downstream this region there is a turbulent flow called the magnetosheath which separates bow shock from the magnetopause (MP) region [Fig 3].As discussed above the existence of Jupiter's magnetic field was first known from the observations of radio emissions and was directly observed in 1973 by the spacecraft Pioneer 10.Jupiter's internal magnetic field is produced by electrical currents in its outer core, which is made up of liquid metallic hydrogen. Another fact that charged particles emitted from volcanic Io surface get trapped by the Jupiter's magnetic field and generates strong currents around the poles of the planet which creates Jupiter's auroras. It can be observed in almost all parts of the electromagnetic spectrum i.e. X-rays, UV, visible and IR. Jupiter's magnetosphere is very dynamic because of three factors:(i) very strong planetary magnetic field, (ii) rapid rotation of the planet and (iii) the low density of the solar wind at the orbital position of Jupiter. The magnetosphere of Jupiter is shaped by the solar wind which continuously pushes back Jupiter's magnetic field [Fig.3].

IV. EXPLORATION WITH SPACE PROBES

Jupiter is the largest planet of our solar system and probably formed first, it is very much like the Sun in composition. We have lost the history of Earth, but not Jupiter's. To learn more about Jupiter we need a close look to the planet for which some spacecrafts have been sending there in last few decades. In 1973, the first spacecraft Pioneer 10 was send, followed by Pioneer 11 space probe [13, 14].The closest approach of different space crafts and the corresponding distances [15] are presented in Table 1.

TABLE I. THE CLOSEST APPROACH OF DIFFERENT SPACE CRAFTS AND THE CORRESPONDING DISTANCES

Spacecraft	***Closest approach***	***Distance***
Pioneer 10 (flyby)	December 3, 1973	130,000 km
Pioneer 11 (flyby)	December 4, 1974	34,000 km
Voyager 1 (flyby)	March 5, 1979	349,000 km
Voyager 2 (flyby)	July 9, 1979	570,000 km
Ulysses (gravity assist)	February 8, 1992 February 4, 2004	408,894 km 120000000km
Galileo (orbiter)	Orbit insertion December 8,1995	
Cassini (gravity assist)	December 30, 2000	10,000,000 km
New Horizons (gravity assist)	February 28, 2007	2,304,535 km
Juno (Orbiter)	Orbit insertion July 5, 2016	

V. OVERVIEW OF THE NEW MISSION JUNO BY NASA

In 1995, NASA's spacecraft Galileo has dropped a probe into Jupiter's atmosphere which yields a surprising result that Jupiter's composition was different from that scientists thought and their theories of planetary formation proved to be wrong. Today scientists have some major unanswered questions about this giant gaseous planet and it is believed that the clue of origin of our solar system hidden beneath the clouds and massive storms of Jupiter's upper atmosphere. To reveal the story a space craft was launched by NASA on August 5, 2011 from Cape Canaveral Air Force Station [16] Juno is the fastest man made solar powered spacecraft. Juno's primary goal is to search for clues about of the formation and evolution of the planet Jupiter. The Juno Mission also serves the objective of understanding Jupiter's gravity and magnetic fields, atmospheric dynamics and composition the coupling between the interior atmosphere and magnetosphere that determines the planet's properties and drives its evolution taking the advantage of its unique elliptical polar orbit using long-proven technologies on the spinning spacecraft. The spacecraft will also observe physical processes that power the auroras. [17, 18] The understanding of the origin and evolution of Jupiter will help us to understand the origin of our solar system and other planetary systems around other stars.

VI. JUNO'S FLIGHT TRAJECTORY

Earth flyby: The spacecraft Juno was built by Lockheed Martin and is operated by NASA's Jet Propulsion Laboratory (JPL). After launching on August 5, 2011, the spacecraft traveled for two years in an elliptical heliocentric orbit around Earth. Then Juno slingshot itself towards the Jovian system using Earth's gravity to pass by Earth in October 2013 (gravity assist) [19].

Jupiter's orbit insertion (JOI): Solar powered Juno is the second spacecraft to orbit Jupiter after the nuclear powered Galileo orbiter. Juno completed its five-year journey to Jupiter on July 5, 2016after traveling a total distance of nearly 2.8 billion kilometers [20]. Strong gravitational field of Jupiter accelerated the spacecraft to around 210,000 km/h [21].Then an insertion burn in its main engine for 2,102 seconds decelerated Juno by 542 m/s [22] for changing its trajectory from a hyperbolic flyby to an elliptical polar orbit having a period of about 53.5 days [23]. The spacecraft successfully entered in its orbit around Jupiter on July 5, 2016 at 03:53 UTC [24]. During almost next 20 months of science phase of the mission, the spacecraft will execute a close flyby above Jupiter's cloud tops every 14 days. The spacecraft will orbit Jupiter 37 times and at the end of the last orbit it will be de-orbited into the planet [25].

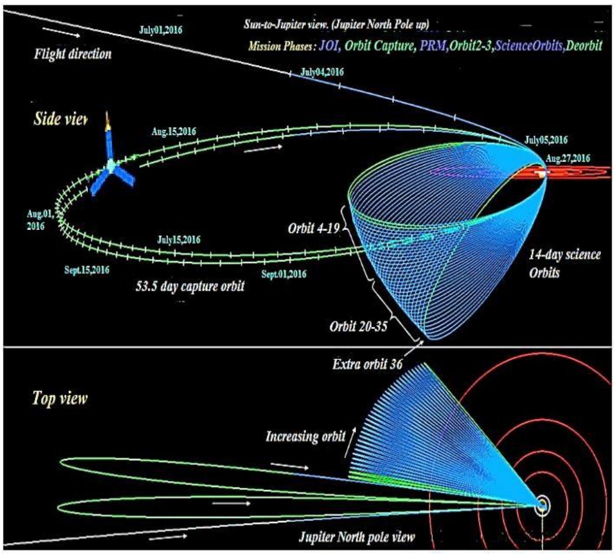

Fig. 4 Mission orbits diagram. The tilt of Juno's orbit relative to Jupiter changes over the course of the mission, sending the spacecraft increasingly deeper into the planet's intense radiation belts (Credit: NASA/JPL)

Mission summary:

TABLE II. FROM LAUNCH TO DEORBIT [20, 23, 24, 25, 26-35]

Launch	August 5, 2011
Deep Space Maneuvers	August/September 2012
Earth flyby gravity assist	October 2013
Jupiter arrival	July 2016
Period of orbiter of Juno	20 months(37orbits)
Perijove 1	August 27, 2016
Perijove 2	October 19,2016
Perijove 3	December 11,2016
Perijove 4	February 2, 2017
Perijove 5	March 27,2017
Perijove 6	May 19,2017
Perijove 7 (fly-over the GRS)	July 11, 2017
End of mission (deorbit into Jupiter)	February 2018

VII. SCIENTIFIC INSTRUMENTSUSED FOR JUNO

TABLE III. INSTRUMENTS OF JUNO AND THEIR SCIENTIFIC OBJECTIVES [36-50]

Name of the Instrument	*Scientific Objective*
Microwave Radiometer (MWR)	It is a multi-wavelength microwave radiometer which will measure the abundance of water and ammonia in the deep layer of Jupiter’s atmosphere up to 200 bar.
Jovian Infrared Auroral Mapper (JIRAM)	It is an image spectrometer. Its goal is to probe the upper layers of Jupiter's atmosphere (to a pressures of 5–7 bars) at infrared wavelengths (2–5 μm) using an imager and a spectrometer to study the dynamics, chemistry in Jupiter’s atmosphere and perhaps to determine how Jovian hot spots formed.
Magnetometer (MAG)	It is used to map the magnetic field of Jupiter and to determine the dynamics of Jupiter's interior and the three-dimensional structure of the polar magnetosphere and its auroral region.
Gravity Science (GS)	It is an experiment and instrument of Juno to monitor Jupiter's gravity using the high-gain K-band and X- band. It will give a map of Jupiter's gravitational field which will help us to understand the interior of Jupiter.
Jovian Auroral Distributions Experiment (JADE)	This instrument will return data in situ on Jupiter's auroral region and magnetospheric plasmas, by detecting and measuring electrons and ions in this region.

Jupiter Energetic-particle Detector Instrument (JEDI)	It is used to collect data on "energy, spectra, mass species (H, He, O, S), and angular distributions" that will help us to study the energies and distribution of charged particles. It can detect particle 30 keV to 1 GeV, whereas JADE, another instrument on the spacecraft, will observe particle below30 keV. It is also designed to study the concept that energy from Jupiter's rotation is converted into its atmosphere and magnetosphere.
Radio and Plasma Wave Sensor (WAVES)	It is designed to detect radio spectra (50 Hz to 40 MHz) and magnetic fields (plasma spectra 50 Hz to 20 kHz) in the auroral region to identify the auroral currents that define Jovian Radio Emissions and acceleration of the charged particles in the auroral region.
Ultraviolet Spectrograph or Ultraviolet Imaging Spectrometer (UVS)	It is an imaging spectrometer that observes the ultraviolet range of light (70 nm to 200 nm) for remote observations of the aurora, detecting the emissions of gases (hydrogen) in the far-ultraviolet range. Its main focus is to find the source of aurora emissions of Jupiter
JunoCam (JCM)	It is the visible-light camera, not one of the core scientific instruments of Juno. All images taken by JCM will be available on NASA's website.

VIII. INTERACTION OF JUNO WITH JUPITER'S MAGNETIC FIELD

The spacecraft Juno faced for the first time the Jupiter's Bow shock just once on 24th June 2016, day of year (DOY) 176 when it was at a distance of 128 RJ, (Fig 5) where RJ = Jupiter's radius = 71,492 km.

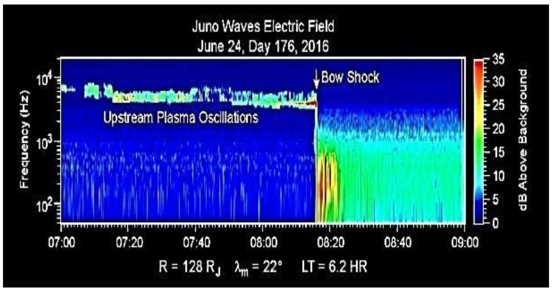

Fig. 5 This chart presents data recorded by Waves instrument of NASA's Juno spacecraft on June 24, 2016 as the spacecraft crossed the bow shock just outside of Jupiter's magnetosphere (Image credit: NASA/JPL-Caltech/SwRI/Univ. of Iowa)

The above figure (Fig 5) a frequency-time spectrogram with abscissa representing total elapsed time of two hours and ordinate representing frequency (in hertz). The vertical bar to the right of the chart indicates the color coding which is used to indicate wave amplitudes as a function of wave frequency in decibels (dB) above the background level detected by the Waves instrument. Each step of 10 decibels marks a tenfold increase in wave power. We know Jupiter's magnetic field is tilted about 10 degrees from the planet's axis of rotation.

In the spectrogram λ_m= 22° indicates that at the time these data were recorded, the spacecraft was 22 degrees north of the magnetic-field equator and the "LT" indicates the local time on Jupiter at the longitude of the planet directly below the spacecraft, with a value of 6.2.Before reaching the bow shock the Waves instrument has recorded plasma oscillations of frequency just below 10 KHz. It shows a low density of electron in the region just outside Jupiter's bow shock. [51] On the very next day, June 25, 2016 the Waves instrument witnessed the crossing of the magnetopause. This frequency-time spectrogram, (Fig 6) is obtained from the data recorded by the Waves instruments of Juno at a distance of 114 $R_J$at λ_m = 12°

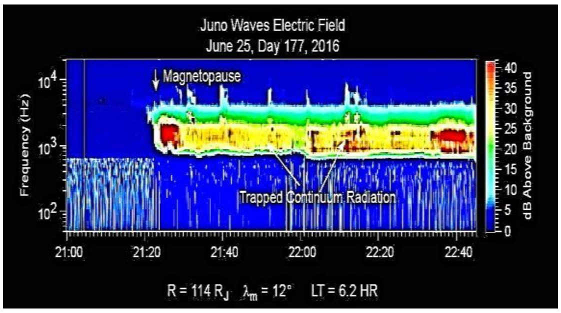

Fig 6 Encounter of Juno with Jupiter's magnetopause (Image credit: NASA/JPL-Caltech/SwRI/Univ. of Iowa)

Here (Fig 6) "Trapped continuum radiation" indicates that waves transit into the lower density of the Jovian magnetosphere. In the next 5 days from

June 25to June29, 2016 [DOY 177 to 181] Juno crossed magnetopause (MP) multiple times spanning at radial distances of 74 to 114 R_J, before orbit insertion (JOI) on 4 July (DOY 186). During DOY 199 to 210 it reaches the radial distances of 92 to 112 R_J, and on DOY 213 it was nearly at 113 R_J, and on DOY 221 to 224 it reaches at a distances of 102 R_J to 108 R_J. Juno resides at distances of >92 R_J for little more than 29 days. Now on the course to continuous approach towards Jupiter the space craft goes into the orbit around Jupiter on July 4, 2016 where the Science instruments detected changes in the particles and fields around the spacecraft as it transit from an environment dominated by the interplanetary solar wind to Jupiter's magnetosphere. Juno transit through the Jovian magnetosphere multiple times (Fig. 7) in which the measured magnetic field magnitude is compared with a magnetospheric model derived from earlier flybys. The variation in magnetic field magnitude throughout most of the 10-day interval centered on closest approach to Jupiter (1.06 R_J) at 12:53 UT is well understood based upon prior knowledge of the planetary magnetic field [52] and the Jovian magnetodisc [53]. The planetary magnetic field calculated using VIP4 spherical harmonic model [54] is also shown here with the gray line. From Juno's first perijove pass a magnetic field of 7.766 G was observed (Fig 7).

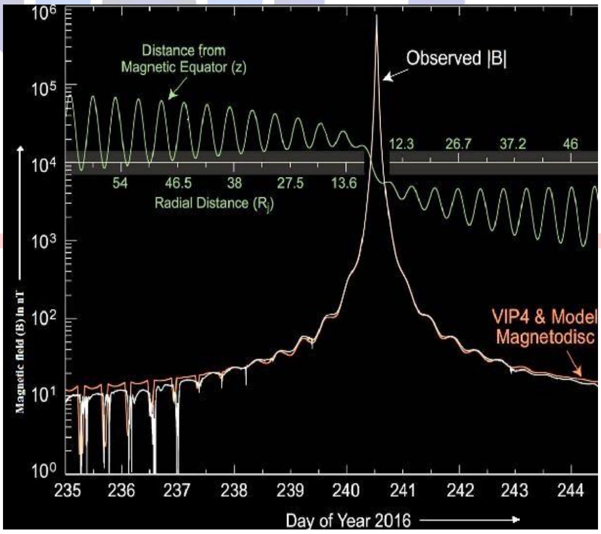

Fig 7 Measured magnetic field magnitude (white, solid) and distance above the magnetic equator (gray) as a function of time and distance from Jupiter during Juno's first perijove pass

IX. RADIO AND PLASMA WAVES DETECTION BY WAVE INSTRUMENT OF JUNO

During the first perijove of Juno across the magnetic field lines around Jupiter's auroral region a strong auroral radio emissions at low altitudes was faced by it. According to plasma theory, the electron cyclotron frequency, f_{ce}(Hz) = 28|B| (nT). The radio emissions are generally confined to frequencies at or above f_{ce}, which probably produced by the cyclotron maser instability (CMI) at frequencies at or just below f_{ce} [55]. The intensity peak of the graph near the frequency line f_{ce} [Fig 8(A) and 8(B)] indicates that Juno passed very close to the source regions for the emissions.

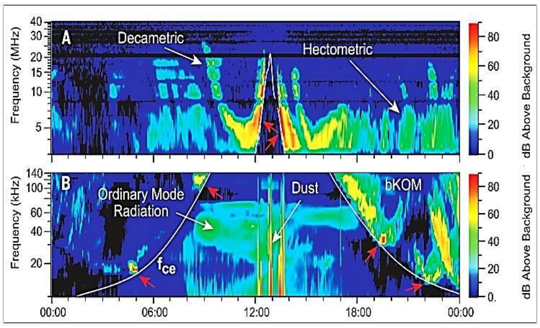

Fig. 8 Radio and plasma wave observations in Jupiter's polar magnetosphere during Juno's first perijove pass on August 27, 2016 (DYO 240) (Image credit: NASA/JPL-Caltech/SwRI/Univ. of Iowa)

The white curve in the figures represents the electron cyclotron frequency and the red arrows in Fig 8(A) and Fig 8(B) identify emissions observed with increasing intensity just above f_{ce}. The electric and magnetic components are plotted in Fig 9(A) and Fig. 9(B) respectively at frequencies below 20 kHz.

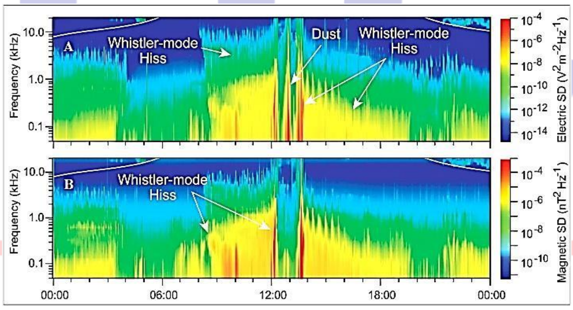

Fig. 9 Plot of electric and magnetic components Radio and plasma wave observations in Jupiter's polar magnetosphere during Juno's first perijove pass on August27, 2016 (DYO 240) (Image credit: NASA/JPL-Caltech/SwRI/Univ. of Iowa)

In the above frequency-time spectrogram (Fig 9) just after 12:00 and near 13:30 UT there are two intensity peak of emission which ensures Juno's passage over Jupiter's main auroral region. These features are called auroral hiss [56] and correspond to features in the energetic electron distributions. These waves exist at frequencies below the lower of electron cyclotron frequency (f_{ce}) and electron plasma frequency (f_{pe}). The electron density (n_e) can be determined by using the relation $n_e = (f_{pe}/8980)^2$, where n_e is expressed in cm^{-3} and f_{pe} in Hz.

X. INTERACTION OF JUNO WITH CHARGED PARTICLES

On August 27, 2016 i.e. on the same day when the previous observation was taken the electron and ion observations obtained by Juno are presented in Fig.10. In the electron energy spectrogram in Fig10 there is a broad bright region between about 4:00 and 8:00 UT represents a period of time when the spacecraft dipped into Jupiter's radiation belts where Juno encounters high electron and ion intensities [57]. The energetic electron data measured by JEDI are plotted in Fig 10.

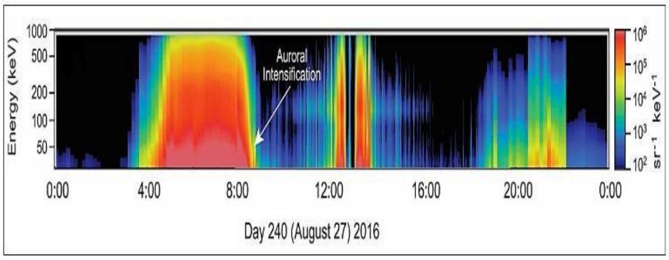

Fig. 10 Electron energy spectrogram obtained during Juno's first perijove pass (Image credit: NASA/JPL-Caltech/SwRI/Univ. of Iowa)

In Fig11 (A) and 11(B) the lower energy plasma data for ions and electrons are represented which are measured by Jovian Auroral Distributions Experiment (JADE).

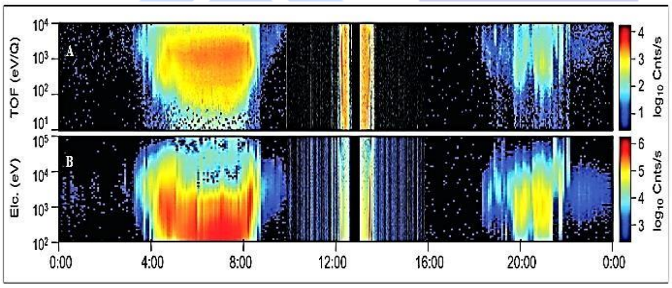

Fig. 11 Ions and electrons spectrogram obtained during Juno's first perijove pass (Image credit: NASA/JPL-Caltech/SwRI/Univ. of Iowa)

NASA's Juno spacecraft has observed plasma wave signals (Fig 12) from Jupiter's ionosphere. In the figure bellow (Fig 12) there is a frequency-time spectrogram which shows an increasing plasma density as Juno descended into Jupiter's ionosphere during its close pass by Jupiter on February 2, 2017. The intensity of the waves is displayed based on the color scale shown on the right. The actual observed frequencies of these emissions approach 150 kHz, which is above the human hearing range.

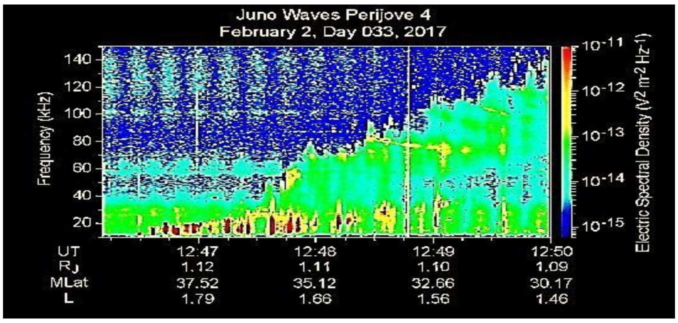

Fig 12 Plasma wave signals from Jupiter's ionosphere observed by the space craft Juno (Credit: NASA/JPL-Caltech/SwRI/Univ. of Iowa)

XI. CONCLUSSIONS

Juno is equipped with latest technologies so better observations, analysis is expected compared to the previous space crafts. Juno has provided observations of fields and particles in the polar magnetosphere of Jupiter on basis of which its magnetic field has been predicted using VIP4 model. Juno has been the witness of the tossed up plasmas from the ionosphere of Jupiter providing a mechanism to populate its magnetosphere. It also provides information about the interaction between ionosphere and magnetosphere of Jupiter and an idea of ion density around Jupiter's atmosphere is developed. We also understand the mechanism that precipitating energetic particles associated with Jovian aurora are different from the energy distributions that power the auroral emissions at Earth.

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