Chapter 1

Review of Earlier Works on Jovian Decametric Radio Emission and the Scope of Present Investigation

1.1 Introduction

Jovian radio emission was first serendipitously discovered at decametric (DAM) wavelengths by Burke and Franklin (1955) at the frequency of 22.2 MHz. Since that time, Jupiter has proven to have a wealth of complex radio emission (Fig. 1.1) mechanisms among the zoo of solar system radio emissions. Of these complex radio emission spectra we have sorted out DAM region of spectra for our interest. Jovian DAM has been systematically monitoring for half century since its discovery from different terrestrial stations of varying latitude and longitude (Thieman, 1979). As the emission can be detected from ground based stations from the upper cut-off frequency 39.5 MHz (Fig. 1.2) down to terrestrial ionospheric cut-off frequency, around 5 to 10 MHz and peak of the intensity of emission at around 8 MHz, it has been felt to investigate the emission from stations above ionosphere of the Earth e.g. Earth orbiters (Kaiser, 1977) Radio Astronomy Explorer (RAE1 & RAE2) and recently with radio and plasma wave instrument (WAVES) on the Wind spacecraft (Bougeret et al., 1995). Then successively Jupiter's magnetosphere has been viewing in-situ by the spacecrafts (Smith et al., 1974; Smith et al., 1975; Acuna & Ness, 1976; Warwick et al., 1979a, 1979b; Alexander et al., 1981; Gurnett et al., 1992; Gurnett et al., 1996; Menietti et al., 1998a, 1998b; Barrow et al., 1996; Kaiser et al., 2000) Pioneer 10 and 11, Voyager 1 and 2, Galileo, Ulysses and Cassini and all have noticed that as the terrestrial observations, there are
Figure 1.1 Status of Jovian radio emission (boldface) among the spectra of solar system radio emissions in the decameter-to-kilometer range, normalized to a distance of 1 A.U. (except for the sky background - Kraus, 1986). The figure displays average spectra of the auroral radio emissions of the five "Radio-planets". Peak levels are ~ one order of magnitude above these averages. Jovian S-bursts fluxes can reach $10^{-16}$ Wm$^{-2}$Hz$^{-1}$. Grey-shaded regions labeled "SED" and "UED" (Saturn/Uranus Electrostatic Discharges) — range of intensities of these planetary lightning-associated radio emissions. (adapted from Zarka, 1992).
Fig. 1.2 JUPITER'S DECAMETRIC RADIATION: At frequencies < 40 MHz
After that the range showing synchrotron and thermal range of spectrum
[courtesy Imke de Pater (UC Berkeley)]
different sources emitting radio emissions from the magnetosphere of Jupiter in the DAM range. The occurrence probabilities of detecting the emission depend strongly on the values of the Jovian central meridian longitude (CML), phase of Jupiter's Galilean satellite Io (Io-DAM) and related with same CML, but, independent of Io-phase (non-Io DAM), and the Jovicentric declination (DE) of the Earth respectively. Klecker et al. (2003) analysing Galileo spacecraft data show that Callisto, and to a lesser extent, Ganymede, influence Jovian radio emission as well. Ever since Bigg (1964) identified the dramatic correlation between the orbital positions of the Galilean moon Io and the observed occurrence probability and intensity of Jupiter's sporadic decametric (DAM) radio emission, investigators have tried to understand the mechanism underlying this effect (Kaiser & Alexander, 1977; Carr et al., 1983). The emissions occur in episodes called “storms”. A storm can last from a few minutes to several hours. Three types of bursts can be received during a storm. The L- bursts (L for long) that vary slowly in intensity with time and the S- bursts (S for short) or millisecond bursts which are sporadic spikes and N-bursts (N for Narrow band). Sometimes all the three types of bursts can be detected simultaneously. The emission is believed to beam into a thin hollow cone (Dulk, 1967). Radio- spectral observations (Carr et al., 1983; Boischot et al., 1981) by Voyager1&2 spacecrafts, Wind / WAVES data and Nancay-data (Fig.1.3) (Lecacheux et al., 1998) showed that the emission has a distinctive arc-like appearance on a frequency- time spectrogram (Queinnec & Zarka, 1998). These types of phenomenon have also been confirmed from the data of radio and plasma wave science (RPWS) instrument (Kaiser et al., 2000) on Cassini during the approach to Jupiter. These arcs like features are believed to be generated at the local electron cyclotron frequency via the cyclotron maser mechanism (Aubier et al., 2000; Wu & Lee, 1979; Zarka, 1998), which produces radiation nearly perpendicular to the local magnetic field (Piddington & Drake, 1968). Usually, two types of arcs can be
Fig. 1.3 $Io-B$ dynamic spectrum based on the total power, recorded by Voyager spacecraft on 16th July, 1979.

Vertical axis – frequency in MHz; Horizontal axis – top: time in UT, middle: system III longitude, bottom: $Io$ - phase

[http://www.astro.ufl.edu/~imai/voyager/gif/v2h197.gif]
identified, $\text{Io}$-controlled and non-$\text{Io}$ controlled. $\text{Io}$-controlled arcs are produced by a system of Alfven Waves excited by $\text{Io}$ (Wiles et al., 1994; Goldreich & Lynden Bell, 1969; Neubauer, 1980; Hill et al., 1983). Non-$\text{Io}$ controlled emissions are independent of $\text{Io}$'s position and are highly variable. Evidence already exists that the solar wind plays a role in controlling the non-$\text{Io}$ radiations (Pontius, 2002; Barrow, 1978; Teraswa et al., 1978; Levitskij & Vladimiskij, 1979; Barrow, 1979; Barrow, 1981; Pokorney, 1982; Penkulu, 1983; Bose et al., 1983; Bose et al., 1985; Woch et al., 1988; Bose & Bhattacharya, 2000, 2001, 2002, 2003); and from the simultaneous observations using the Cassini and Galileo spacecraft data Gurnett et al. (2002) show that radio emission in the Hectometric (HOM) range and DAM range of non-$\text{Io}$ origin as well as extreme Ultraviolet auroral emissions from Jupiter are triggered by interplanetary shocks propagating outward from the Sun. Analysing the data from Galileo, Menietti et al. (1999) showed that non-$\text{Io}$ DAM emission from Jupiter has local time effect.

In this paper we have considered periodic modulation of Jovian DAM and $\text{Io}$ related source locations and their characteristic features e.g., Polarization, $L$-bursts, $S$-bursts, $N$-bursts, Modulation lane and the shape of the beam in a greater detail. Emphasis is also laid to the non-$\text{Io}$ related features. Dynamics of the field-aligned current sources both at the Earth and the Jupiter has also taken into consideration. Finally, mechanism of emission from the Jovian magnetosphere has been discussed critically.

1.2 Periodic Modulation of Radio Emission

The role of Jupiter and $\text{Io}$ in their mutual interaction and the nature of their coupling were first elaborated in greater detail by the two Voyager flybys in 1979. Subsequent exploration of this system by ground-based and Earth-Satellite-borne observatories and by the Galileo orbiter mission in 1995 and latest in-situ observation by Cassini in 2000 has improved our
understanding of the highly complex electro dynamical interaction between \textit{Io} and Jupiter manifold. Gurnett and Goertz (1981) proposed that the electro dynamic interaction between \textit{Io} and Jupiter’s magnetic field could launch an Alfven wave along the field lines near \textit{Io}. This would undergo multiple reflections at Jupiter’s northern and southern polar ionosphere causing a standing wave current system extending down stream and moving with \textit{Io} (Fig. 1.4). They estimated that at least nine reflections would be generated and each of these is associated with a discrete decametric radio source. The calculated longitudinal spacing between successive reflections in \textit{Io}’s rest frame would be 5.8° with an error of factor of 2.

Precise calculations by Bagenal (1983) using an offset tilted dipole magnetic field model and a plasma density model of the \textit{Io} plasma torus derived from Voyager1 measurements (Bagenal & Sullivan, 1981) revealed that the actual spacing would vary with longitude in the plasma torus due to changing in the local Alfven wave speed and the orientation and intensity of the magnetic field. It was concluded that the average longitudinal spacing between successive reflections would be 10°. If both north and south directed Alfven waves are taken into consideration, this spacing would be expected to produce an average temporal separation between adjacent spectral arcs of 35 min.

Smith and Wright (1989) gave an alternative explanation of the Alfven wave interaction between \textit{Io} and the Jovian magnetic field. They argued that Wentzel-Kramers-Brillouin (WKB) approximation assumed by Gurnett and Goertz (1981) in their model is inappropriate owing to the enormous increase in Alfven wave speed near the torus boundary leads to significant wave reflection (Neubauer, 1980) with only 30\% of the wave energy arriving at the polar ionosphere. This limits the number of ionospheric reflections of the Alfven downstream of \textit{Io} and hence reduces the extent of the standing wave current system in Smith and Wright’s model (Smith & Wright, 1989).
Fig. 1.4 Standing Alfvén wave current system down stream of Io and the associated hollow emission cones corresponding to Io-related source

the magnetic field disturbance created by Io's orbital motion through the Jovian magnetic field manifests itself as an oscillation of the global magnetic field downstream of Io. They showed that this magnetic field disturbance could be quantitated by using a series of Eigen mode solutions to the Sturm-Liouville equations. The solutions revealed a quasi-periodic (Wright & Smith, 1990) form with an average longitudinal separation between points of maximum magnetic field disturbance at high latitudes of approximately 60 where the DAM emission is generated. Staelin et al. (1988), using the voyager dynamic spectral data measured an average time interval of 3-4 min. between adjacent arcs, equivalent to approximately 0.50 of Io phase. Also the time interval between arcs was randomly distributed in time, conforming to a Poisson distribution of intervals. In order to account for this discrepancy, they argued that many reflections of the Alfven wave must occur, extending completely around Jupiter many times and thus overlapping to produce smaller apparent arc spacing. Using a completely different approach, Bagenal and Leblanc (1988) reformatted the Voyager dynamic spectral data into epochs at fixed central meridian longitude and varying Io phase to stimulate what an observer at fixed Jovian longitude would observe as the standing wave current system and the associated emission cones are carried past by Io's orbital motion. They noted periodic gaps in the 'reconstructed' spectrographs, which were attributed by them to the spaces between Alfven wave reflections. To simulate correctly these gaps using a model of the Alfven wave wake downstream of Io, they increased the accepted values of plasma density (Bridge et al., 1979; Bagenal, 1994) in the Io plasma torus by 36%. Bagenal and Leblanc's assumption may be corroborated by the observation made by Galileo Space craft's data. Galileo measured ion plasma densities that were about 50% greater than those observed by Voyager at the same distance (Frank et al., 1979; Prang et al., 1996). Again to explain the multiplicity of closely spaced arcs observed, each Alfven wave reflection had to be associated
with multiple arcs instead of a single arc, a feature not yet explained properly for current theories of DAM generation (Queinnec & Zarka, 1998; Aubier et al., 2000; Wu & Lee, 1979; Zarka, 1998)

Wilkinson (1989) suggested that Alfven wave reflections might be identified not with individual arcs but with certain long duration arc structures as noted in the Voyager dynamic spectral data by Boischot et al. (1981). These arc structures contain substructure made up of individual arc-shaped segments, which are observed inside a single arc-shaped envelope and are readily distinguished from normal arcs. They have been referred to as “Principal arcs” (Maeda & Carr, 1992) or Io-caused emission (ICE) (Riddle, 1983) structure. These ICE structure should be generated when magnetic field lines corotating with Jupiter were stimulated for producing radio emission as they passed by Io. Wilkinson (1989) developed an empirical principal arc-model in which the emission cone angle varied with frequency in the manner as suggested earlier by Goldstein and Thieman (1981). This model was used to simulate principle arcs seen in the Voyager dynamic spectral data (Maeda & Carr, 1992). Further, although the principle arcs identified by Riddle (1983) were all located either in the Io-A or Io-C region, the principal arc model could also account for some of the intense Io-related spectral arcs associated with the Io-B source. In searching evidence of the multiple principle arcs from sources within the extended standing wave current system down stream of Io in the Voyager dynamical spectral data Wilkinson (1989) was able to identify a small number of examples in both the Io-A and Io-B regions and, from these, deduced an angular spacing between successive Alfven wave reflections in the Io plasma torus of between 9.8° and 14.8°, in satisfactory agreement with the 10° spacing predicted by Bagenal (1983). A serious limitation of this study was that both magnitude of the emission cone angle and its evolution
with time, both of which have a vital role on the accuracy of the result, were essentially unknown at the time.

Wilkinson (1998) hypothesized that if multiple radio beams are generated by the Alfvén wave interaction between Io and Jupiter and these beams are swept sequentially past the observer by Io’s orbital motion, then the probability of receiving the emission will vary periodically with time showing maximum when each beam is directed towards the observer (Fig. 1.4). Multiple (Vertex early) arcs might be observed (Wilkinson, 1998) in the frequency-time spectrogram taken close to the planet. But if observations are taken at a single frequency using a ground-based telescope, the effects of ionospheric and interplanetary scintillation will break up the arc emission. Such a periodicity should be observable as a periodic variation in L-burst activity with time. Bagenal and Leblanc (1988) in their study, found periodicity in the Voyager dynamic spectral data and from this a longitudinal spacing between successive Alfvén wave reflections in the Io plasma torus of 13° was deduced. In the theoretical model of Wright and Smith (1990) a low frequency modulation of the dominant quasi-periodic magnetic field perturbation is predicted when Io is in the upper portion of the torus as it is during Io-B storms. Moreover, this low-frequency modulation could account for the apparent splitting of the Io-B source into two components, Io-B1 and Io-B2, as described by Leblanc (1981). Thus it seems plausible that two major periodicities could be present simultaneously in the data. Interestingly, in the Io-B data of Bagenal and Leblanc (1988) there are examples of intense multiple principal arc emission where the angular spacing between the arcs expressed in Io-phase is much less than 13°. The multiple reflecting Alfvén wave model (Queinnec & Zarka, 1998; Menietti et al., 1999; Crary & Bagenal, 1997) may be supported by the observation of Prange' et al. (1996) where they detected for the first time with the Hubble Space Telescope Faint Object Camera (HST/ FOC) far-ultraviolet (FUV H2
bands) spots at the \textit{Io}-flux tube (IFT) footprints (FIG-1.5). Similarly, infra-red (IR) observations (Fig.1.6) (Connerney et al., 1993) from NASA’s infra-red telescope showed single intense IR spot located 15°-20° of longitude down stream of the \textit{Io}-foot print. Comparing these results with Jovian DAM radio bursts Prange \textit{et al.} (1996) and Zarka \textit{et al.} (1997) have built a scenario of the electron precipitations along the IFT for interpreting Jovian S-bursts and energy budget for the said phenomena.

An alternative explanation for the observed periodicity and the imaging data is that all of the DAM radio emission is generated in a single source at or near the \textit{Io} foot print and is beamed into multiple directions (Wilkinson, 1998). This explanation also consider the significant longitudinal extent of the Jovian DAM radio sources without requiring multiple Alfven wave reflections down stream of \textit{Io}. Further, both the diffraction theory of Lecacheux \textit{et al.} (1981) and the lasing theory of Calvert (1982) provide a potential mechanism for explaining how multiple radio beams can be generated by a single source. However, polarization measurements during long-lasting \textit{Io}-B storms (Lecacheux \textit{et al.}, 1991;Leblanc \textit{et al.}, 1994; Dulk \textit{et al.}, 1994) reveal that the measured emission cone angle does not vary over a period of several hours, a feature in accordance with the multiple emission beam models as in these models it would be expected that the emission cone angle should vary with time since \textit{Io}'s position with respect to the observer changes.

1.3 \textit{Io}-and non-\textit{Io} related source locations and their characteristic features

1.3.1 Source locations and polarization

The long-term Earth-based observations (Thieman, 1979) show three prominent peaks of emission probability depending on which longitude of
Figure 1.5 shows an ultraviolet picture of the aurora and the Io footprint auroral emissions taken by the Space Telescope Imaging Spectrograph (STIS) aboard the Hubble Space Telescope (HST) in 1998. The bright high latitude structures are emissions of molecular hydrogen excited by impact of impinging magnetospheric particles.
Figure 1.6: Infrared image at 3.4 m of Jovian aurora and the lo footprint emissions Jupiter taken with NASA’s Infrared Telescope Facility (IRTF) at Mauna Kea in 1995, Hawaii, using the NSFCAM facility imager (Connerney and Satoh; 2000). It shows the thermal emission of H formed by molecular hydrogen ionized by impinging particles.
Jupiter faces the Earth (central meridian longitude or CML). These sources are usually labelled sources A (around 240° CML), B (around 150° CML), and C (around 330° CML). The exact location and magnitude of the peaks of probability varies slowly depending on frequency in the 15 MHz – 40 MHz frequency range. Below 15 MHz there is a sudden shift in the picture to two peaks of probability, one around 180° CML and one around 330° CML. Hence to investigate the phenomena, observations from above the ionosphere have been continuing by Earth orbiters (Kaiser, 1977) and spacecrafts (Bougeret et al., 1995; Smith et al., 1974; Smith et al., 1975; Acuna & Ness, 1976; Acuna & Ness, 1976; Warwick et al., 1979a, 1979b; Alexander et al., 1981; Gurnett et al., 1992; Gurnett et al., 1996; Menietti et al., 1998a, 1998b; Barrow et al., 1996; Kaiser et al., 2000).

Spacecraft observations of this transition region are limited. The Voyager Planetary Radio Astronomy (PRA) (Warwick et al., 1979a, 1979b; Boischot et al., 1981) experiment had good coverage from 50 KHz up to 40 MHz, but suffered from internal spacecraft interference in the frequencies near 5 MHz. Also, the data are limited since Voyager flew by quickly and observed Jupiter only from very limited sectors of Jupiter's local time regions. Dependence of the phenomena on frequency or local time is difficult to determine by such observations by Voyager spacecrafts. Genova et al. (1987) analysing Voyager data observed that Jovian radio emission in the range of HOM & DAM are well correlated. The probability of observing non-\textit{Io} DAM from Nancay is shown to be highly variable. These variations correspond well to fluctuations of HOM activity, influenced by the solar wind, observed by Voyager. They concluded from this result that the same source regions, at high latitudes in the Jovian magnetosphere, and that the altitude extent of the source covers several planetary radii. They have found no such effect for the \textit{Io}-dependent emission, which is seen to be consistent with a source close to the field line. Galileo spacecraft as an orbiter around Jupiter observes the planet with its Plasma wave instrument.
at all local times (Menietti et al., 1998) and at frequencies up to 5.6 MHz but, unfortunately no higher. Still these observations help to bridge the uncertainties in the observations made by ground based observations and Voyager spacecrafts and provide a more complete picture of the transition region. Data from the Unified Radio and Plasma Wave (URAP) experiment (Stone et al., 1992) on the Ulysses Spacecraft were used to determine the direction, angular sizes and polarization of the radio sources for remote sensing of the heliosphere and the jovian magnetosphere. URAP observations of Jovian radio emissions have greatly improved the determination of source locations and consequently our understanding of the generation mechanism(s) of planetary radio emissions. The study of the observed wave-particle interactions will improve our understanding of the processes that occur in the solar wind and at the Jupiter and of radio wave generation. But, the instrument to frequencies less than 1 MHz limited these studies. The hectometric (HOM) frequency exists approximately in the range 200 kHz < f < 2 MHz, where as the DAM frequency range extends approximately from 1 MHz < f < 40 MHz (Carr et al., 1983; Ladreiter and Leblanc, 1991). Menietti et al. (1998) have analysed some of the radio emission data of HOM and lower DAM frequency range returned by Galileo during the first two Ganymede flybys (G1 & G2). They have shown that HOM emissions appear to be the low frequency extensions of DAM arcs, with source regions along either Io or Ganymede flux tube. While the uncertainties associated with the technique are many in practice due to the fact that the spacecraft is moving and the source regions vary in location, frequency, and amplitude with time. As a result data analyses do not allow a precise source location, the HOM / DAM emission observed near the G1 and G2 encounters are consistent with a gyro resonant source region with correction for refraction due to the Io- torus plasma to understand the results. Cassini Radio and Plasma wave instrument (RPWS) (Kaiser et al., 2000) and the radio and plasma wave instrument (WAVES) on the WIND
spacecraft (Bougeret et al., 1995) in Earth orbit simultaneously observed DAM emission in the ranges from 3.6 KHz to 16.1 MHz and 1MHz to 14MHz respectively. It has been revealed from terrestrial and extraterrestrial observations that occurrence probability of decametric radio emission (Boischot et al., 1987; Lecacheux et al., 1998; Queinnec and Zarka, 1998) from Jupiter within a narrow frequency range is a function of the system III(1965) central meridian longitude (CML) and the orbital position of the innermost Galilean satellite Io relative to the observer (Io phase) Fig1.7. There are four zones of CML within which the occurrence probability of the Jovian storm activity near 22 MHz is comparatively high. According to the classification of Carr et al. (1983), they are called sources A, B, C and D. Each source consists of Io-related and Io-unrelated (non-Io) components according to whether Io’s position has a strong influence or weak or non-existent influence respectively. Io-B emission occurs only when the Io-phase is in the range 40° – 110° and CML range 15°– 240°, Io-A and Io-C emission when the phases of Io are 180° – 260° and 200° – 260° and CML ranges 180° - 300° and 280° - 60° respectively, where as Io-D emission occurs for the 95- 130 range of Io-phase and 0° – 200° CML range. Similarly the non-Io related sources are located for the range of Io-phase from 0° – 360°, but CML range 80°-200° for non-IoB, 200°-300° for non-IoA and 300°-360° for non-Io - C source respectively (Fig.1.8). Lecacheux et al. (1998), Queinnec & Zarka (1998) and Aubier et al. (2000) confirmed the source locations (Carr et al., 1983) in the co-ordinate space of CML-Io phase (ΦIo) Boischot et al. 1987) investigated the structure and the position of Jovian sources of DAM radio emission by studying the interplanetary scintillations (IPS) using broad band dynamic spectra obtained at Nancay between 15-40 MHz and arrived at the conclusion that Io and non-Io emissions are radiated, at each frequency, by very small sources in a very thin hollow conical sheet at large angle to the magnetic field lines. According to them the sources are spread spatially with
Fig. 17 Relative probability of occurrence of DAM against central meridia longitude

Fig 1 8(a) Dynamic spectral behaviour of non-lo sources (A, B, C)

1 8(b) lo(A, A', B, C, D) source location in the co-ordinate space of lo-phase and Central meridian longitude $\lambda_{\text{III}}$.

1.8(c, d, e, f) dynamic spectral behaviour of lo sources (B, A, D, C)
frequency. They also observed that there is no preferred line of force involved in the non-Io emission, and as a result they inferred that electrons do precipitate all the time at every longitude, approximately near the L-shells corresponding to the orbit of Io. Io in its motion interacting with that electron enhances the emission from an extended region around the Io-flux tube (IFT). The emission anisotropy of the regions of different sources has been explained as evidence of the beaming of Jovian decametric radiation from the local magnetic field. Geometry of A, B, and C, D actually correspond to only two physically distinct source regions, each viewed along one side or the other of their widely opened beaming pattern. The observed dominant right-hand polarization of Io-A and Io-B emissions thus suggest that they originate from a source region in the northern hemisphere, while left hand polarization of Io-C and Io-D emissions favour a southern hemispheric sources. Northern and Southern hemisphere emission has been separated by their polarization, but, this is valid only for the higher frequency emissions, for frequencies below 15 MHz the polarization is more mixed. Genova and Aubier (1985) detected in their 3.5 months of observing only 26 cases of unambiguous left – handed – polarized emissions. The emissions correspond to two different particular patterns in the CML-Φ, diagram, corresponding to the Io-D and Io-C regions of occurrence. The measurements showed that the left –hand emissions reach lower maximum frequencies than the northern emissions, which indicate the asymmetries in the Jovian southern and northern magnetic fields. Queinnec and Zarka (1998) combining data coverage of the range 1-40 MHz from the Waves experiment on the Wind Spacecraft and from the Nancay Decameter Array studied arc shapes over the entire frequency range (3 MHz to 37.5 MHz) and revealed that Io-B and -D sources are observed when Io is near Jupiter’s dawn limb (as viewed from the Earth), while Io-A and -C sources correspond to the dusk limb. Porquerusse and Lecacheux (1978) gave first evidence of a narrow
beaming of DAM emission by analyzing simultaneous observations, from Nancy observatory and from space (French Soviet Experiment Stereo-5 aboard Mars 5 spacecraft). Voyager spacecrafts PRA team analysing the frequency-time \((f-t)\) dynamic spectrum (Warwick \textit{et al.}, 1979a, 1979b) discovered that most of the Jupiter’s DAM emissions in the range from a few to 40 MHz is organized into thin “arc” like structures.

Dulk (1967) and Piddington (1967) introduced a hollow cone beam model interpret the phenomenology of \(Io\)-related source A (\(Jo-A\)) and source B (\(Jo-B\)) emissions. Assuming a tilted dipole magnetic field and an emission cone half angle of \(79^\circ\). Dulk (1967) established that the two CML regions for which parts of the hollow cone beam are aligned with Earth are at source A and B longitudes. Also assuming that the emission is observed only when \(Io\) is close to the longitude of the cone apex, Dulk was able to account in a rough way for the active \(Io\) phase regions for \(Io-A\) and \(Io-B\) emission. Basic elements of the Dulk beam model have been utilised in most subsequent attempts to model the \(Io\)- related emission (Hill, 1983, Thieman, 1979; Hashimoto & Goldstein, 1983; Wang, 1985). Dynamic spectral plots of the broad band radiation received by the two Voyager spacecraft showed that decametric storms typically consists of multiple groups of nested-arc-like structure (Warwick \textit{et al.}, 1979a; Boischot \textit{et al.}, 1981; Goldstone and Thieman, 1981; Leblanc, 1981; Maeda and Carr, 1992; Riddle, 1983; Lecacheux \textit{et al.}, 1991; Leblanc \textit{et al.}, 1994; Dulk \textit{et al.}, 1994; Prang \textit{et al.}, 1996). Some authors have proposed models in which each spectral arc results geometrically from the rotation of families of hollow cone beams of different frequencies threaded by an activated flux tube (Warwick \textit{et al.}, 1979a; Goldstein and Thieman, 1981; Genova and Aubier, 1985; Pearce, 1981; Staelin, 1981).

Maeda and Carr (1984) identified instances in which the ground stations and both Voyager spacecraft recorded the same emission event
from non-\textit{IoA} storms. They demonstrated that the events are due to rotation of a continuously emitted curved-sheet beam of radiation, which could be approximated by a limited sector of a hollow cone. They further showed that the beam could not have been a full hollow cone and that the source of emission in each case was located at northern auroral zone latitudes. Maeda and Carr (1988) further found that the beams of the \textit{Io}-related source \textit{Io-A} and \textit{Io-B} (as well as non \textit{Io-A}) could be approximated by a hollow cone sector. Maeda and Carr (1988) presented the results of the analysis of two spacecrafts’ observations of the same spectral arc events over wide frequency range together new information on the locations and emission beam geometry of \textit{Io}-related sources. Boischot \textit{et al.} (1981) noted than in many storms there is a single arc that is distinguishable from neighbour arcs by its higher intensity and characteristics shape. Riddle (1983) suggested that this principal arc is directly related to the flux tube passing through \textit{Io}. It is implicit in Riddle’s conclusion that \textit{Io} somehow has stimulated the other arcs in the vicinity in a less direct manner than was the principal arc. Maeda and Carr (1992) observed that in most \textit{Io-A} storms a principal arc could similarly be identified, more on the basis of higher intensity than distinctive shape. From the Queinnec and Zarka’s (1998) analysis of \textit{Io} controlled DAM arcs, it reveals that \textit{Io} arcs, especially \textit{Io-A}, -B, -C and-D arcs have a well defined structure in the frequency-time plane (Fig. 1.9) and last for hours. From their work it has been seen that \textit{Io-A}, -B, -C and-D sources reveal different morphologies. \textit{Io-A} emissions occur as families of 5-7 individual negatively drifting arcs; \textit{Io-B} arcs are made of an intense positively drifting part followed by a much weaker negatively drifting arc preceded by a broad band fringe-like pattern. \textit{Io-C} arcs have an opposite curvature (“Vertex late”) and weaker arcs are nested inside the main one; \textit{Io-D} emissions appear as an isolated arc, so called “Vertex early”(fig.1.9a-bottom spectra) (Genova and Aubier, 1978) with complex high frequency morphology. It has also been revealed from their work that
Fig. 1. (a) Dynamic spectra of Io-controlled arcs over the whole frequency range recorded in combined WIND spacecraft and Nancay DAM array data recorded on May 8–9, 1995:

Top: Io-B arcs (f_min - f_max = 8–37.5 MHz; Intensity) ~ 7–13 dB, RH-polarized) between 00:00 – 02:50 (UT)

Bottom: Io-D arcs (f_min - f_max = 3–23 MHz; Intensity) ~ 7 dB, LH-polarized) between 22:40 – 01:40 (UT)
(i) Io-A emissions are not an isolated arc as Io-B, -C and -D ones but rather a series of a few individual negatively drifting arcs (Fig. 1.9c), lasting a total of 2-hours. Their intensity is -7 dB above the background (in Nancay data); (ii) Io-B arcs with high sensitivity reveal an "inverted U" shape (Fig. 1.9a-top spectra), with an intense positively drifting part (main arc) with fluxes up to > 10 dB followed by a much weaker negatively drifting arc (late arc) with intensity -10 dB; (iii) Io-C emissions consist of a main arc with mirror-C shape (Fig. 1.9b) including weaker arcs nested inside the main one and intensity > 7 dB. Genova and Aubier (1987) studied the dynamic spectra (Fig. 1.10) recorded by Voyager spacecrafts PR A experiment. They analysed two component of the emissions, greater and lesser arcs (Aubier and Genova, 1985) which were seen above and below 15 MHz respectively and observed Io-B, -A, -A' and -C events and the non-Io-B, -A and -C events. They also showed that the high frequency cut-off of the sources of non-Io and the Io emissions are not very different. According to them the high frequency (≥ 25 MHz) radio source region is located at high latitudes. From their analysis they were not able to identify the exact position of the source region of the non-Io emissions. They predicted that the radiation could be produced along field lines intersecting Io's orbit at higher latitudes than the foot of the Io-field lines, mainly in the region magnetically connected to the magnetospheric tail (Connerney et al., 1981) which could be consistent with the fact that the non-Io emissions, and not the Io ones, are subject to the influence of the solar wind (Barrow, 1978; Teraswa et al., 1978 Levitskij & Vladimiskij, 1979; Barrow, 1979; Barrow, 1981; Pokorney, 1982; Penkulu, 1983; Bose et al., 1983; Bose et al., 1985; Woch et al., 1988; Bose & Bhattacharya, 2000, 2001, 2002, 2003). The solution of a source on a field lines linked to the magnetospheric tail can be verified from the local-time effect on the non-Io emissions. This phenomenon has been verified by Barrow (1981) and recently by Bose & Bhattacharya (2000, 2001, 2002, 2003) and also the phenomenon has been supported by
Fig. 1. 9(b) Dynamic spectra of Io - C arcs over the whole frequency range recorded in combined WIND spacecraft and Nancay DAM array data recorded on May 7 – 8, 1995:

\[ f_{\text{min}} - f_{\text{max}} = 3.5 - 20.5 \text{MHz}; \quad \langle \text{Intensity} \rangle \sim 8 \text{dB} \text{, LH - polarized} \]

between 23:10 – 01:10 (UT)**
Fig. 1. (continued)

Fig. 1. Fig. 9(c) Dynamic spectra of Io-A arcs over the whole frequency range recorded in combined WIND spacecraft and Nancay DAM array data recorded on September 22, 1997: ( $f_{\text{min}} - f_{\text{max}} = 2 - 31$ MHz; $\langle \text{Intensity} \rangle = 7$ dB, RH - polarized) between 19:40 - 21:40 (UT)**

**(In the Figs 1.9(a - c): Horizontal lines - man made interference (fixed frequency), Vertical lines - Nancay data calibrations or radio emissions from terrestrial lightning. Gray Scale of the displayed data covers a dynamic range of about 3 dB above the background.)

[Adapted from Queinnec and Zarka, 1998]
Fig. 1.10 Dynamic spectrum of Jupiter's decametric radio emissions as observed by Voyager: it is characterized by a complex, highly organized structure in the frequency-time domain. It depends on Jovian longitude, and Io phase. Poor spatial resolution, but good spectral resolution. Note the arcs (timescales of sec.): L-bursts, drift in frequency by up to +150 kHz/s. [Carr et al. 1983]
Menietti et al. (1999) from the Galileo data. Menietti et al. (1998) analysed the radio emission data from the plasma wave high frequency receiver (101kHz < f < 5.6 MHz), which includes hectometric (HOM) and lower DAM frequency range, returned by Galileo during the first two (G1 and G2) Ganymede (Jovian – satellite) flybys to determine the spin plane direction to apparent source locations of the radio emission in the Jovian environment. They came to the conclusion from their analyses that both the Io and Ganymede flux tubes are possible source regions of the HOM / DAM arc signatures. They first identified from their analyses that Ganymede has the expected orbital phase for the vertex-early arc curvature in the dynamic spectrum of lower frequency range of HOM / DAM radio emission. Also they showed that HOM / DAM arcs all appear to propagate from high latitudes of Jupiter, consistent with gyro-resonant source regions. They identified also some statistical significant events from the source regions at a lower or higher altitude than required for a gyro resonant source. They interpreted such events due to refraction from asymmetries (Desch et al., 1994; Schneider et al., 1997; Thomas et al., 1996) in the Io-torus or from source regions requiring an alternative free energy electron beams source.

We analysed the probability of occurrence of non-Io Jovian decametric radiation (NIJDR) at different solar conditions. In an 11-year solar cycle it is seen that polar coronal whole size (PCHS) changes with solar conditions. In the Jovian local time (JLT) scale occurrence probability of NIJDR varies linearly with PCHS. The above observation leads us to the fact that the high correlation of occurrence probability with PCHS might be due to interaction of Jupiter magnetosphere with solar wind. We know that IMF lines originated from sun carry the solar charged particles and, with the rotation of sun the IMF sweeps different planetary magnetosphere through different sectors. So, attempts are made to examine the phenomena of different sector boundary crossing the Jupiter’s magnetosphere. Though the data of
sector-boundary crossing has been recorded at 1 AU, we can extrapolate the data to 5.2 AU, as the structure is stable in the solar planetary frame. The analysis shows that in local time frame occurrence probability from different sources at different frequencies is more when IMF sector boundary crosses Jupiter’s magnetosphere. At 11.4h JLT non-\( \dot{\text{o}}\)-A source emits radiation, whereas non-\( \dot{\text{o}}\)-B at 11.7h JLT and non-\( \dot{\text{o}}\)-C do not show such distinctive feature. In this context the recent observations of Gurnett et al. (2002) may be mentioned here they report simultaneous observations using the Cassini and Galileo spacecraft of radio emissions of non-\( \dot{\text{o}}\) origin in the frequency range from 0.5 to 5.6 MHz and extreme ultraviolet auroral emissions from Jupiter. Their results show that both of these emissions are triggered by interplanetary shocks propagating outward from the Sun. When such a shock arrives at Jupiter, it seems to cause a major compression and reconfiguration of the magnetosphere, which produces strong electric fields and therefore electron acceleration along the auroral field lines, similar to the processes that occur during geomagnetic storms at the Earth.

1.3.2 Evidence for Beaming and Cone half angle

Poquerusse and Lecacheux (1978) gave first evidence of a narrow beaming of DAM emission by analysing simultaneous observations, from Nancay observatory and from space (French-Soviet experiment Stereo-5 aboard Mars 5 spacecraft) Voyager spacecrafts PRA team analysing the frequency-time (f-t) dynamic spectrum (Warwick et al., 1979a, 1979b; Alexander et al., 1981) covered that most of the Jupiter's DAM emissions in the range from 1.3 MHz to 40 MHz is organized into thin “arc” like structures, lesser arcs below 15 MHz and greater arcs at higher frequencies. Kaiser et al. (2000) identified Jovian non-\( \dot{\text{o}}\) DAM arc beams that simultaneously illuminated both Cassini and Wind spacecrafts and they clearly classified non-\( \dot{\text{o}}\) A and B arcs. Also the results supports the presence of the both senses of curvature at nearly all longitudes for non-\( \dot{\text{o}}\)
emissions as observed by Leblanc (1981). Kaiser et al. (2000) have shown that hollow cones have their vertices along a Jovian magnetic field line rotating with the planet’s period of 9.92 hours, or along a flux tube threading through the satellite Io and rotating with a period of 1.77 days. The altitude of the hollow cone along the field line or flux tube is fixed where the extraordinary (X) mode cut off frequency equals the radiation frequency. As the flux tube or field lines co-rotates past the observer, radiation from cone walls will pass by the observer, who will see the arc-like structures in ten dynamic spectrum. Arc-like structures in Jovian Dam spectrum can be realized when the leading wall of the cone passes (Vertex early or open parenthesis "(" and then when the trailing wall passes (vertex late or close parenthesis ")") (Fig.1). Lecacheux et al. (1998) studied two Io controlled events, each one as a composition of two dynamic spectra recorded at Nancay (in a bandwidth from 40 MHz to 14 MHz) and by Wind / WAVES experiments (14 MHz to 1 MHz) to evaluate the beam geometry in the frame of available models and usual assumptions in the emission mechanisms. Now it is widely accepted that the Jovian decametric arcs are caused by the rotation past the observer of a thin curved sheet beam, which is approximately in the form of a hollow cone. There is a systematic variation of cone opening angle with respect to frequency (Goldstein and Thieman, 1981; Goldstein and Goertz, 1983). The alternative possibility is that the emission is broadly beamed such that both spacecraft were within the beam at the same time, and that the observed arc structure results from a frequency-dependent time variation of the intrinsic source intensity rather than from the sweeping of a narrow frequency-dependent beam of constant intensity across the observer. If arcs were the results of intrinsic source intensity variations, the propagation-corrected arc centroid time for Voyager 1 would have been the same as that for Voyager 2 at every frequency. On the contrary, if the arc structure were due to the rotating frequency dependent hollow cone beam, the corrected arc centroid times
Fig. 1.11 Represents the confinement of emission to the walls of the cone. As the field line or flux tube rotates with the planet through the field of view of the observer or probe, a pair of arcs is observed in the frequency-time plane, with the leading wall causing a "vertex early" (or open parenthesis) arc and the trailing wall causing a vertex late (or closing parenthesis) arc. The vertex of each cone is at extraordinary cutoff frequency which is essentially the same as the electron gyrofrequency:  \( f = \frac{eB}{2\pi mc} \), \( B \) – magnetic field strength at the vertex of the cone, \( e \) – the electronic charge, \( m \) – mass of the electron, \( c \) – velocity of the light) [adapted from Kaiser et al., 2000]
for each frequency would be different at the two spacecraft. It is seen from Fig.1.12 that the later is the case. Two curves for Voyager1 and Voyager 2 are sharply different on each of the two dates. The corrected centroid times at all frequencies above the cross over frequencies are earlier for Voyager1 than Voyager 2. The observed arc structure could not have resulted from an intrinsic variation in source intensity. It reveals from Fig1.12 that at each frequency the radiation was emitted in a thin curved-sheet beam with different curvatures at different frequencies, its thickness being not greater than the separation between the two spacecraft (about 6") as viewed from Jupiter. At all the frequencies above the cross over frequency one part of the beam was aligned with Voyager 1 first, and another part of the same beam was aligned with Voyager 2.

The analysis of the results presented in Fig.1.12 is same as the basic assumptions made by Goldstein and Thieman (1981) in their beam model development. The assumptions are as follows:

(i) The curved sheet beam at each frequency is a sector of a hollow cone with its axis tangent to the $lo$-excited flux tube at the emission point where the observed frequency is equal to the electron gyro-frequency.

(ii) Emission occurs simultaneously at all the frequencies, continuing for time intervals longer than the durations of individual spectral arcs.

(iii) The hollow cone-opening angle is not constant with frequency.
Fig 1.12 Frequency of Jovian DAM radio source vs. propagation corrected event time observed by Voyager 1 and Voyager 2

(iii) The time frequency drift pattern of the individual arc is due to
(iv) the sweeping motion of the multicone beam pattern with respect to the observer.

As a result the alignment of the thin beams at different frequencies with the observer are at different times. It reveals from Fig. 1.13(a) that the multi-cone beam pattern and the time frequency arc owing to successive cone alignments with the observer Fig. 1.13 (b). The sweeping of the beam pattern is for the relative motion of the \( f_0 \)-excited tube flux with respect to the observer. As shown in Fig. 1.12, the corrected centroid times of the Voyager 1 arc are coincident with those of the Voyager 2 arc at frequencies from 12 to 16 MHz on Feb. 1 and at about 20 MHz in Feb. 4. This clearly indicates that all such frequencies the emission towards Voyager 1 and Voyager 2 left Jupiter simultaneously. One may assume that the radiation frequency is slightly greater than the electron gyro-frequency at the emission point and the radiation at each frequency is emitted in a thin hollow cone, the axis of which is tangent to the magnetic field at the emission point. On the co-rotating celestial sphere the cone half angle is estimated by calculating the angular distance between the station position and the position representing the field vector with the aid of the O4 field model at the source. Goldstein and Thieman (1981) assumed a cone half-angle variation in which the cone half-angle increases from the lower frequencies to the so-called nose frequency and then decreases toward higher frequencies to account for the arc structure. Most of the authors (Genova and Aubier, 1985; Green, 1984; Leblanc et al., 1993) agree that the hollow cone half angle can be estimated from Voyager data as between 70° and 80°. Lecacheux et al. (1998) analysed the entire frequency spectrum of the Jovian DAM emission by combining the simultaneous observations of the frequency range of 1 MHz to 13.8 MHz from Wind / WAVES and 10 MHz to 40 MHz data from Nancay Decametric Array. From
Fig. 1 13(a) Representing a schematic view of the beam-model where the source at each frequency is located in the Io-excited flux tube and the emitted radiation along a sector of a hollow cone. Beam cross section at frequencies $f_1$, $f_2$, or $f_3$ has been represented by shaded portions respectively.

1 13(b). Frequency vs. Time plot
the whole spectrum they selected two representative \textit{Io}-controlled events \((\textit{Io-B} / \textit{D} \text{ and } \textit{Io-Q})\) and analysed in terms of the available models (Dulk, 1967; Goldreich and Lynden Bell, 1969, Goldstein and Thieman, 1981; Piddington, 1967; Leblanc, 1981; Pearce, 1981) of the Jovian environment. From their analyses it reveals that in case of the \textit{Io-B} / \textit{D} event at frequencies below 20 MHz may fit the models about 87°. But they were unable to explain the \textit{Io-C} event with the existing model of beam geometry. As a result they proposed that the departure from the theory can be resolved, provided the existing maser-cyclotron theory can accept the wave propagation effects, occurring close or inside the radio source region, since the \textit{Io-DAM} source follows the motion of \textit{Io} surrounding which the magnetic field topology is complex. Under the above concept they arrived at the conclusion that the source altitude, the principle curvatures of the reflecting surface as well as orientation of the radiated beam with respect to this surface, are continuously changing functions of the active field line position. The emission beam in some cases can even suffer substantial refraction when directed towards the reflecting surface, implying different kinds of intensity modulations like edge effects or interfering phase paths and all of these considerations may help to resolve the said discrepancy and unexplained feature. They observed the phenomena both at higher frequencies as well as at frequencies below 3 MHz where the refraction effects may occur in the \textit{Io}-plasma torus as suggested by them. Jovian emission mechanism theories (Zarka et al., 1997; Smith, 1976) predicted that hollow cone radiation beam emissions should be confined to the thin walls of the cone. As a result hollow cone arc theories demand the measure of the thickness of the cone walls for interpreting the dynamic spectrum. Most workers have considered the duration of a given arc as a measure of its thickness. It is possible to observe an arc simultaneously (after correcting light travel time difference) by two spacecrafts provided their angular separation as observed from Jupiter is less than the cone wall
thickness. However, if the angular separation of two spacecrafts is greater than the wall thickness, then it is not possible to observe the arcs simultaneously by the spacecrafts, but will be delayed by the amount of time it takes for the cone attached to a Jovian magnetic field line or Io-flux tube to rotate through the angle after correcting for light travel time. Kaiser et al. (2000) carried out Stereoscopic Radio observations of Jupiter by Cassini and Wind/ WAVES RAD2 spacecraft during two intervals in 1999. First in the month of January '99 when the Jovian longitude difference between two spacecraft was about 5.4° apart, whereas in the month of August-September '99 the angle ranged from 0° to about 2.5°. With these separations, the instantaneous widths of the walls of the hollow conical radiation beams of some of the DAM arcs were measured suggesting that the typical thickness of the hollow conical beam is about 1.5° with an uncertainty of about 0.5°. This result supports the findings of the previous workers (Boischot et al., 1981; Queinnec and Zarka, 1998; Prang et al., 1996) who got such result by analysing the data based on the duration of a given arc at a single frequency and equating it either to the Io-flux tube (IFT) period (Queinnec and Zarka, 1998, Prang et al., 1996) or the Jupiter's rotation period (Boischot et al., 1981). Observations of Kaiser et al. (2000) showed that the arcs are associated with Io or IFT, which are rotating at a slower rate than that of the Jupiter's rotation period. Though Kaiser et al.'s (2000) result support that of the previous worker's (Boischot et al., 1981; Queinnec and Zarka, 1998; Prang et al., 1996) result, but they are hesitant to conclude the thickness of all arc cone walls is 1.5°, as they observed small number of events with Cassini- Wind spacecrafts. Hence, they suggested the possibility that the thickness may be a function of refraction in the immediate source region, and this may well vary from one location to the next. They also expect that their observations and suggestion may be verified with the planned solar terrestrial rotation observatory (STEREO) mission (launch in 2005).
1.4 Different important features of Jovian Decametric Dynamic
spectra

In the dynamic spectra of Jovian decametric radio emission the most
commonly observed components are the long (L) bursts which are seen in
the range from a few 10ths of seconds to a few seconds. Study of the
dynamic spectra of DAM emission with high-resolution spectrograph reveals
the existence of many micro features in the spectra besides the L-bursts.
Among the various features, the short (S) bursts (Ellis, 1974; Riihimaa,
1977; Desch et al., 1978; Leblanc et al., 1980), the modulation lanes
(Riihimaa, 1971; Genova et al., 1981), the arc structure (Warwick et al.,
1979b; Boischot et al., 1981; Leblanc, 1981). Another class of fine
structured emission consists of narrow-band events, which were first
pointed out by Warwick (1963), Riihimaa (1964), Warwick and Gordon
(1965)

1.4.1 L - bursts

Riihimaa (1978) observed dynamic spectra of Jupiter's L - burst with
high resolution radio spectrograph of operation range close to 21-23 MHz
and sensitivity of the order of 10^21 Wm^-2 Hz^-1 from 1963-1977 in the
Nancay observatory. He recorded the storms from Io-A, -B, -C, Non-Io-A,
-B, -C and observed that the L - bursts (Fig.1.14a,b,c,d) are characterized
by their emission envelope. The duration of envelopes varies from one to a
few seconds increasing towards the opposition of Jupiter to reach a
maximum in the vicinity of 10 to 20 days before and after opposition.
Modulation lanes appear within the emission envelopes. The magnitude of
the frequency (f) vs. time (t) slopes of lanes is determined by CML of
Jupiter, and partly by the longitude of Io. The sign of the slopes depends on
CML only. The same types of observations were also recorded with fixed
frequency spectrograph by Douglas (1964), Douglas and Smith (1967) Slee
and Higgins (1968) and Pataki (1969) they indicated that the 1 second
Fig. 1.14a Dynamic spectrum of Jovian Io -A (L burst) decametric radio emission recorded on August 9, 1998 at 8h 36m 20s UT.

The emission consisting of L - bursts with the features —

(i) Spectrum structures —complex, The intensity of the bursts is Modulated by irregular-shaped structures drifting from high to low frequencies

(ii) polarization of emission — almost pure RH circular

(iii) Horizontal lines at a constant frequency are radio station interference.

[ ufro1.astro.ufl.edu /io-B.htm]
Fig. 1.14(b): Dynamic spectrum of Jovian Io-B (L-burst1) decametric radio emission recorded on June 20, 1997 at 10h 12m 50s UT.

The emission, consisting of L – bursts with the features —

(i) frequency range — 17 to 27 MHz.
(ii) Structures — drifting from high to low frequencies at about 40kHz/sec are present.
(iii) Polarization of emission — RH elliptically.
(iv) The faint horizontal line — about 27 MHz is radio station interference. [ufro1.astro.ufl.edu/Io-B.htm]
The emission, consisting of $L$ - bursts with the features —

(i) frequency range — 20 to 31 MHz
(ii) Structures — two sets of drifting features
(iii) (a) the low frequency drift — about 180 kHz/sec;
     (b) the high frequency drifts — about 60 kHz/sec.
(iv) Polarization of emission — RH elliptical.
(v) The diagonal deflection is a sweeper station. Horizontal lines at a constant frequency are radio station interference
    [ ufro1.astro.ufl.edu /Io-B.htm]
The emission, consisting of $L$-bursts with the features:

(i) Frequency range: 18-22.5 MHz.
(ii) Polarization of emission: LH elliptical
(iii) The diagonal deflection is a sweeper station. Horizontal lines at a constant freq are radio station interference.

[ufro1.astro.ufl.edu/~o-B.htm]
components of the Jovian DAM bursts is produced due to inter planetary scintillation. \(L\)-bursts are most commonly observed in the dynamic spectra of Jovian DAM emission where as the \(S\)-bursts accounts for a relatively small fraction (10%).

1.4.2 \(S\)-bursts

Kraus (1956) reported first the existence of groups of very short \((S)\) pulses in the Jovian DAM emission. The duration of such pulses varies form 200 ms to 1ms and such pulses were later called \(S\)-bursts(Fig.1.15). The spectra of such pulses in frequency range 18-23 MHz studied by Riihimaa (1964) and also by Ellis (1974) in the range 8-17 MHz. Riihimaa (1966), Baart et al. (1966), and Barrow and Bart (1967) observed the \(S\)-bursts from \(Io-B\) and -\(C\) sources. Riihimaa (1977) confirmed statistically the above observations in the range 18-23MHz. He classified the \(S\)-bursts appeared in the Jovian DAM dynamic spectra as shown in the Fig.1.16. Riihimaa has assigned a small alphabet to each type of structure to distinguish one \(S\)-burst from another. The analysis of Riihimaa structure (Riihimaa, 1991) occurrences in \(S\)-patterns (Boudjada et al., 1995a,b) showed that more than 70% of the bursts are similar to the types a, b, e / f and g / h on an average constant frequency duration of 15ms. The negative drift rate is found nearly similar to -31MHz / sec. Boudjada et al. (2000) analysing Riihimaa structures e.g. type q or type n and some times partially recorded type for type a more precisely showed that individual \(S\)-bursts of those type are composed of 3 parts(by decomposing these into R-up,R-center and R-down) Fig.1.17 (Boudjada et al., 2000). Both bursts (\(L\)-and \(S\)-bursts) can occur in same storm where a transition from \(L\) - to \(S\)-bursts is observed followed by a return to \(L\)-burst (Leblanc \textit{et al}., 1980; Riihimaa and Carr, 1981; Boudjada \textit{et al}. 1995a).It has been observed (Boudjada \textit{et al}., 2000) that in the CML- \(Io\)-phase diagram there are two high probability regions of Jovian milli-second radio bursts \(Io-B\) and -\(C\) sources. In both cases
Fig. 1.15: Dynamic spectrum of Jovian decametric \textit{Io-B} (S \& L bursts) radio emission recorded on September 6, 1997 at 4h 33m 40s UT.

Two bands of emissions are present —

Upper Spectra — the low frequency band consists of S - bursts
Middle Spectra — the high frequency band consists of narrow band L - bursts
Lower Spectra — the horizontal lines at around 27 MHz are Citizens Band (CB) radio stations [ ufro1.astro.ufl.edu//o-B.htm]
Fig. 16 Dynamic spectra of Riihimaa classified individual $S-$ bursts from a catalogue of observations made in Oulu (Finland) from 1974 to 1989. The drift rate $-25$ MHz s$^{-1}$ with a frequency bandwidth 3MHz.

[adapted from Boudjada et al, 2000]
Fig 117 Decomposition of type and n-type $S$ - bursts into R - up, R - center and R - down parts [ adapted from Boudjada et al., 2000 ]
positions of the satellite-\textit{Io} are on the age of the planet with regard to the observer at $90^\circ$ for $\textit{Io-B}$ $250^\circ$ for $\textit{Io-C}$. An example of $S$-bursts observed at the observatory Graz-Lustbuhel is displayed in the Fig.1.18 (Galopeau \textit{et al.}, 1999). Queinnec and Zarka analysed statistically the bandwidth, flux density, power, energy, and polarization of Jovian $S$-bursts from high-resolution observation performed in Nancay using an acousto-optical spectrograph. From their observations it reveals that the $S$-burst flux density are found to follow a power low distribution with an average index -2, with an average rated power of $10^9$W subject to sudden variations at a time scale of minutes. The density of $S$-burst occurrence in the $f-t$ plane is found to be $\sim 0.3$. The average flux density normalized at 1Au is $4 \times 10^{-26}$Wm$^{-2}$Hz$^{-1}$ and observed $S$-bursts corresponds to dominant right-hand elliptical polarization. Spectral variation of this polarization ratio is suggested by the observation whose interpretation in terms of radio beaming angle is also consistent with earlier studies. They observed that $S$-bursts are polarized mainly with right-hand polarization, but the ratio of the right and left-hand polarization varies from storm to storm (Litvinenko \textit{et al.}, 2003). Rucker \textit{et al.} (2004) analysed in depth the microstructure inherent in the $S$-bursts by means of the newly developed waveform receiver and connected to the decameter world largest radio telescope UTR-2 (Kharkov) yielded waveform measurements of Jovian $S$-bursts, which have been analysed by wavelet analysis method. The outcome their investigation is the detection of clear signatures of micro second ($\mu$s) modulations, providing the evidence of a super fine burst structure with the following parameters:

(a) Instantaneous frequency band of one separated $\mu$s pulse of 100 to 300kHz,

(b) Time duration of one separated $\mu$ - pulse of 6 to 15 $\mu$s, and

(c) Time interval between closest subsequent $\mu$s pulses is 5-to25 $\mu$s.
Fig 1.18 Presents high resolution dynamic spectra of Jovian S - bursts recorded in the Graz-Lustbühel observatory.

Each pixel has time and frequency resolutions of 4ms × 20kHz.

Colour coded Intensity range:
(i) Yellow : -115dBm, (ii) Red : -65dBm,

The average drift rate is -20 MHz s⁻¹

[adapted from Rucker et al., 1992]
The apparent frequency drift of a millisecond burst evidently results from sequentially decreasing frequencies of subsequent sub pluses, each representing an island of phase coherent gyrating electron bunches.

1.4.3 N-band bursts

Warwick (1963), Riihimaa (1964), Block (1965), and Warwick and Gordon (1965) pointed out narrow band events (Fig.1.19) in the Jovian DAM dynamic spectra. Later on Riihimaa (1968a) studied the occurrence of N-band emission in the Io–CML diagram. He pointed out that the N-band events are relatively infrequent phenomena which occur more frequently when Io–phase in between 210°–300° for a large range of CML (110°–360°) and he also pointed out that the event consists either of groups of S-burst trains or of bands splitting events separated by 100–200 kHz. Riihimaa and Carr (1981) described narrow band L-emission intersected by S-bursts in the range of 21–23 MHz. Boischot et al. (1980), Leblanc and Rubio (1982) observed N-band emission at the upper frequency limit of the broad band DAM emission in a small area of the Io–B region, in the Io-CML diagram. In some cases they observed that the intensity of the upper frequency broad band is reinforced and the gap between the narrow band and broadband is constant and very regular. The splitting is observed either at the upper frequency of S-bursts or at the cut off frequency of the broadband continuum emission. They thought such phenomenon as an emission “splitted” at the upper frequency, due to an interference or a diffracting pattern. They also noticed in the Voyager PRA record of Io–DAM in the frequency range 1MHz–40MHz that the narrow band of the splitting is always polarized in the same as the broadband emission. It is important to note that the splitting in the Io-B and –C regions are observed with R–H and L–H circular polarizations respectively. The ratio of its bandwidth over the frequency of occurrence is equal to about 10⁻². The
The emission, consisting of N (narrow band) emission, with the features —

(i) Frequency range & structures — drifting slowly between 20 and 22 MHz

(ii) Polarization of emission — pure RH circular

(iii) The horizontal lines around 27 MHz are Citizens Band (CB) radio stations

[ ufr01.astro.ufl.edu /io-B.htm]
splitting appears exactly similar to that observed on the high-resolution record of Nancay. Boudzada et al. (2000) studied the relationship between some typical $S$-burst events chosen from Riihimaa catalogue (Riihimaa, 1991) and the Jovian $N$-band emissions. Their analysis of the temporal evolution of the Jovian narrow band involves the presence of fine structures i.e. the $S$-bursts, with short time duration of about few tens of milliseconds. Each $S$-burst duration and the short time scale of the gap in the $N$-band account for a mechanism totally intrinsic to the radio source. Oya and Oya (2002) analysed 65 $S$-burst events in the dynamic spectra of Jovial DAM radiations in the period from 1983 to 2000 using high time resolution radio spectrograph with a time resolution of 2 ms and the bandwidth of 2MHz. Within the occurrence of 65 $S$-bursts they identified 26 events as the $S-N$ burst events, which are characterized by the interaction between the $S$-burst emissions and the $N$-band emissions. In the dynamic spectra of the $S-N$ burst, emission trend with negative and slower frequency drift named as “Trailing Edge Emissions “ (TEE), which are often follows the appearance of $S$-bursts. A typical $S-N$ burst phenomenon with complex features has been shown in the Fig 1.20. The duration time of TEE was about 0.1 s. Oya and Oya (2002) arrived at the conclusion from their analysis of the microscopic view of the dynamic spectra (Fig.1.21) that there is no correlation between the drift rates of the $S$-bursts and associated TEE. The drift rate of the $S$-burst depends on the frequency while there is no such dependence for the drift rate of the TEE. In the dynamic spectra the TEE phenomenon smoothly connected to the $N$-burst reflecting the fact that the center frequency, bandwidth and the drift rate of the TEE coincide with those of the $N$-burst at the merging point (fig.1.22). Arkhipov et al. (2002) explained the Riihimaa classified $S$-bursts and $N$-band spectra in terms of a helical motion of radio sources with a small group velocity of emission.
Fig. 1.20 Dynamic spectrum of \( S-N \) bursts in a frequency range of 20.5 - 22.5 MHz recorded on 20th September, 1986 from 17:44:31 to 17:44:35 (UT) at Tohoku University.

Nature of polarization (RH/LH) are indicated by small arrows. In the spectrum there are some periodic interruptions (shown by large arrows) due to recording system. [adapted from Oya et al., 2002]
Fig. 1.21 Characterization of dynamic spectra presented in Fig. 1.20 by six parameters:
(a) S-burst drift rate (MHz/sec), (b) Trailing Edge Emission (TEE),
(c) Time interval from the appearance of S-burst to the appearance of TEE,
(d) S-burst frequency range (MHz), (e) Time interval of appearing N-burst after the disappearance of S-burst, (f) Time interval between the appearance of S-burst and disappearance of TEE (msec).
[adapted from Oya et al., 2002]
Fig. 1.22 (a) part of the dynamic spectrum (Fig. 1.20) and the temporal variations (b-d) of the center frequency, the drift rate, and band width. [adapted from Oya et al., 2002]
1.4.4 Modulation Lanes

It has been mentioned earlier that, since the discovery of Jovian DAM in 1955, there are inherent three types of bursts (e.g. L-bursts, S-bursts, and N band events) in the Jovian dynamic spectra of DAM emission. Of these three types L-bursts of 1sec duration when observed with ground based instruments has been generally seen to be modulated by interplanetary scintillations (IPS) (Douglas and Smith, 1967; Slee and Higgins, 1968; Genova and Leblanc, 1981). Riihimaa (1970) discovered in L-bursts groups of lanes drifting in the time frequency plane. These drifting lanes feature are called modulation lanes. Later he studied these features extensively in 20 - 23 MHz frequency range. In large bandwidth dynamic spectra of Jovian DAM emission with the Nancay Array Boischot et al. (1980) and later Genova et al. (1981) identified three types of "Lanes - like" modulations. Each type has definite spectral and occurrence characteristics. The three types are -

(i) Terrestrial ionosphere scintillations

(ii) Modulation lanes as discovered by Riihimaa

(iii) High frequency lanes (he lanes)

(i) The modulation of terrestrial ionospheric origin bears the following Spectral characteristics

(a) These types are superimposed with other usual spectral features (Arcs, IPS, modulation lanes) in the dynamic spectra

(b) Whole emission frequency range are strongly modulated by this feature

(c) Frequency displacement has been observed in the simultaneous
records of right and left hand polarizations

(d) Frequency drift and spacing of this type vary with time and frequency. Though in most cases the variation is slow and continuous and their frequency drift can have both signs, negative drifting can be seen about 75% of the time of duration of such feature.

These types of modulations are irregular and which can be observed between two sequences of "smooth" lanes. A typical value of the frequency drift is ~20 kHz⁻¹ at 20 MHz; of the frequency spacing between two lanes ~ 0.5 - 1 MHz; of the time spacing ~ 1 min (Geneva et al., 1981). As this fringe type of phenomenon has been seen to be superimposed to the normal dynamic spectrum indicates that it might be originated close to the Earth, after the radio emission of Jovian origin has suffered the modulation effects close to Jupiter and in the interplanetary medium. According to Riihimaa (1976) this type of fringes are called "broadband lanes", the spacing of such lanes greater than about 500 kHz. Genova et al. (1981) interpreted that dynamic spectra in the DAM range of Jovian origin may suffer diffraction by semi periodic ionospheric F-zone inhomogeneties during their passage through ionosphere and as a result this type of features can be seen. A fluctuation in the F-zone dimension and / or velocity can give rise to the variability of different parameters. Several such ionospheric lenses may be responsible for irregular pattern of such type of fringes.
(ii) The modulation lanes of Jovian origin

These categories was discovered by Riihimaa (1970) and also observed by Genova et al. (1981) with Nancay Array. Riihimaa distinguished three kinds of modulation lanes in his study with Jovian dynamic spectra of DAM in the frequency range of 20 - 23 MHz. Genova et al. (1981) observed such feature with with Nancay's broadband spectrograph Array and tabulated the main properties of such lanes as -

(a) A great stability of their whole appearance during 10 min to 1 hour

(b) They generally cover the whole emission frequency range

(c) Their curvature, similar for \( L_2 \) and \( L_4 \) lanes: their absolute drift rate decreases towards lower frequencies

(d) The absence of marked qualitative difference between the two channels of circular polarization

(e) There modulation depth, variable from storm to storm, is few db

\( L_2 \) Lanes are observed for \( 60^\circ < \text{CML} < 260^\circ \) at all \( \phi_{io} \) and particularly in the \( Io - B \) source (B1 and B2); \( L_4 \) lanes are observed for \( 60^\circ < \text{CML} < 310^\circ \) at all \( \phi_{io} \) and in the \( Io - C \) regions (Fig. 1.23). \( L_3 \) lanes appear almost in the \( B_2 \) region.

(iii) High Frequency Lanes

Genova et al. (1981) observed this kind of modulation for the first time. The feature tend to cover smaller frequency range in the highest frequency part of the emissions and due to this feature this type of modulation was named as ' high frequency (hf) lanes ''. These modulations are not as regular as the other two types mentioned earlier and have a small
Fig. 1 23 Dynamic spectra recorded at Nancay Observatory showing three types of modulation lane. Smooth ionospheric modulations drift negatively with a large modulation depth. (b) $L_\alpha$ modulation lane structure composed of $L_\alpha$ positively drifting and $L_\eta$ negatively drifting lanes. The negatively drifting modulations cross over the vertex early arcs of the $L_\eta$ source spectral arcs. (c) High frequency
modulation depth often less than 3 db), but they always have the same spectral characteristics. Frequency drift of such spectra is always negative within -5 and -50 kHz s\(^{-1}\). The curvature of the spectra is opposite to that of L\(_4\) modulation lanes and as a result the drift rate increases with frequency: the most probable value is between -10 and -25 kHz s\(^{-1}\) at 25 MHz and -5 and -20 kHz s\(^{-1}\) at 29 MHz. The characteristics, and particularly the drift rate of such modulation do not show any significant variation along one particular storm. Their occurrence do not show any seasonal or local time dependence as that of Terrestrial Ionospheric origin, but is strongly dependent on the position in CML - \(\phi_t\) co-ordinate system: they occur almost only in Io-B region and in another region including both Io-A\(^{'}\) region and the low CML part of Io-A source. Lecacheux et al. (1981) proposed that the arc pattern of such spectra have its origin in diffraction by a density hole located permanently in Io torus. Slight inhomogeneities in the density gradient on the sides of the hole might be the site of creation of such type of modulation in the arc intensities like hf-lanes. But this reason is not sufficient to explain the hf-lanes observed in Io-B source. Though Imai et al. (1997) interpreted the DAM modulation lanes in terms of radiation scattering due to FAC inhomogeneities in the Io plasma torus but that model can not explain lanes with opposite drifts with respect to Io torus rotation. According to the model proposed by Arkhipov (2003) FAC inhomogeneities of the magnetospheric plasma above the Jovian ionosphere generate such modulation lanes.

1.5 Identification of Field-aligned currents in the terrestrial and Jovian Magnetosphere and its consequences

The growing awareness of the function of field-aligned currents (FAC) in magnetosphere-ionosphere coupling has allowed a conceptional framework within which the plasma wave may be understood widely.
Barbosa et al. (1981) interpreted high altitude satellite data of impulsive electrostatic waves due to FACs in the context of temporal events associated with geomagnetic storms and substorms. Extensive investigations of the magnetospheric tail plasma sheet (Gurnett et al., 1976) at high altitudes / latitudes (Gurnett and Frank, 1977) revealed the persistence of a characteristic wave mode in certain regions where FACs were suspected to flow. This type of the emission termed as broadband electrostatic noise (BEN), has the nature of being very impulsive with large peak-to-average field ratios, \( E_{\text{max}} \sim 10 \text{ mV/m} \) and extends over frequencies from 10Hz to several kHz with power law dependence. The peak intensity occurs at about 10 to 50 Hz\(^{-1} \). When intensity-time profiles of the spectrum analyser are displayed this mode can be distinguished from other magnetosphere noise by the usually sharp prominence out of the lower intensity surrounding noise (e.g. auroral hiss etc.) and it is localized to narrow portions of the orbit when the satellite is not rapidly changing in magnetic local time. Thus the noise is confirmed to discrete field lines (auroral) at high latitudes or the edges of the plasma sheet in the magnetotail (Gurnett et al., 1976). If any ambiguity occurs in the identification of BEN, the presence of magnetic noise bursts removes that doubts. Many theories described the generation of BEN to current driven instabilities of the plasma distribution (Ashour-Abdulla and Thorne, 1978; Huba et al., 1978; Gray and Eastman, 1979). They exploited the terrestrial BEN – FAC association phenomenon to the Jovian magnetospheric plasma wave events. Matsumoto et al. (1999) observed during the analysis of the data from the deep magnetotail of terrestrial magnetosphere by the Plasma Wave Instrument and Comprehensive plasma Instrument on board the GEOTAIL spacecraft that it experienced multiple crossings of the plasma sheet boundary layer, BEN and Langmuir wave alternatively. The dynamic spectra are very bursty in time, and their waveforms are showing a series of electrostatic solitary waves (ESW). The ESW, are observed in the
presence of a hot thermal electron distribution function. Omura et al. (1999) studying ESW and the corresponding GEOTAIL electron velocity distribution functions observed a series of ESW in the plasma sheet boundary layer of the Earth's magnetotail where enhanced fluxes of high energy electrons are flowing along the ambient magnetic field. Kasahara et al. (2001) waveforms of BEN in ion heating region observed by Akebono and found that the waves are classified into continuous noise and impulsive noise. They showed the spatial distribution of the continuous noise statistically dependent on local time, geomagnetic activity, and the season. They analysed intensity-time profiles of plasma wave measurements by the Voyager1 (V1) plasma wave system (PWS) spectrum analyser having channel width from 10Hz to 56.2KHz. They compared the Jovian spectra with terrestrial observations and indicated eight BEN events near the edges of the plasma sheet during both inbound and outbound journey of V1 through the Jovian magnetosphere. The intensity decreases with increasing distance beyond $10R_J$, and the noise was not detected in the outer magnetosphere beyond $30R_J$. The emission below 1kHz has shown distinctly a power law dependence ($\sim f^{-2.5}$). Gurnett and Frank (1977) and Gurnett et al. (1979) characterize terrestrial BEN having a slope of $f^{-2.2}$ and this is deemed to correspond well with the Jovian emission. This finding led Barbosa et al. (1981) to conclude that there is a positive evidence for FAC in the middle magnetosphere of Jupiter. Using global magnetohydrodynamic (MHD) simulation of the interaction of Jupiter's magnetosphere with the solar wind Walker and Ogino (2002) investigated the effects of the solar wind on the structure of currents in the Jovian magnetosphere. In their simulation they assumed that the current sheet is weaker on dayside than the night side with some local regions where the current density decreases by more than 50 percent. As a result there is a non-uniform distribution of current along the azimuth. The current sheet contains also strong radial "corotation enforcement" currents. Almost at all
local times the outward radial currents are observed but there are some regions where the direction of currents is toward the Jupiter. In the local afternoon and evening regions the current pattern is especially complex. The FAC pattern is also complex in the near equatorial magnetosphere. They simulated the currents from the inner boundary to the ionosphere and observed the expected configuration for the ionosphere to drive corotation. At lower latitudes the currents are away from Jupiter and at higher latitude the currents are toward the Jupiter. The Upward FACs map to larger distances on the night side (40-60\(R_J\)) than on the dayside (20-30\(R_J\)). They tried to observe the effect of solar wind dynamic pressure and IMF on the simulation study on the structure of the currents and arrived at the conclusion that the current sheet and FAC were slightly stronger with higher pressures, but the IMF had a stronger effect on the currents with the strongest currents for northward IMF with a lag in time in responding by the magnetosphere. Nichols and Cowley (2003) suggested a model assuming the values of effective Pedersen Conductivity of the Jovian ionosphere and the mass outflow rate of iogenic plasma on which the amplitude and spatial distribution of the coupling currents flow between Jupiter's ionosphere and middle magnetosphere investigated the dependence of the solutions for the plasma angular velocity and current components on the parameters over wide ranges. In doing so they considered two models of the magnetosphere – dipole alone, and an empirical current sheet field based on Voyager data and the key feature of their model is that the current sheet field lines map to a narrow latitudinal strip in the ionosphere, at approximately 15\(^\circ\) co-latitude. From their analysis it is observed that the major distinction between the solutions for the dipole field and the current sheet concerns the behaviour of the FACs - in the dipole model at moderate equatorial distances the direction of the current reverses, and the current system wholly closes if the model extends to infinity in the equatorial plane and to the pole in the ionosphere. In the approximate current sheet model, however, the FAC is
unidirectional, flowing consistently from the ionosphere to the current sheet for the sense of the magnetic field of the Jupiter. In the later model current closure must then occur at higher latitudes, on field lines outside the region described by the model. The absolute values of the currents are also higher for the current sheet model than for the dipole with the same parameters, by factors of approximately 4 for the field-perpendicular current intensities, approximately 10 for the total current flowing in the circuit, and approximately 25 for the FAC densities.

FACs at Jupiter have been inferred from radio observation of DAM emission (Carr et al. 1983). Jovian DAM controlled by Io has long been assumed to be associated with FAC resulting from the electro-dynamic interaction of the satellite with the Jovian ionosphere. Barbosa (1983) raised a question after the Voyager spacecraft findings of local time dependence of non-Io DAM (Alexander et al., 1981) about the process involved in FAC generated DAM emission from corotation dominated Io-flux tube on the L-shell near L=6. In this regard it is to be mentioned that Io-dependent emissions do not exhibit local time effects (Carr et al., 1983; Bose & Bhattacharya, 2002). As far as it is known that there has never been any evidence of spatial relation between two DAM emissions. Barrow (1983) showed other several FAC systems associated with iogenic plasma transport and for one of them they showed theoretically a FAC dissipative output of ~60 tera-watt. They argued that the corotation breakdown region outside of 18R_J is more susceptible to the influence of the solar wind and dawn-dusk asymmetries of the magnetospheric configuration. They solicited that any variation of solar wind parameters is more likely affect a FAC system in the middle magnetosphere than one at Io's orbit. Correlation studies of Terasawa et al. (1978), Oya and Morioka (1998) and recently by Bose and Bhattacharya (2002, 2003) supported the fact that Io-independent DAM is very much dependent on different solar parameters and which is
also supported by Galileo spacecraft data (Menietti et al., 1998). Further evidence of this interaction is now available in-situ detection of a propagating Alfvén wave close to the Io flux tube, the infrared (IR) and the ultraviolet (UV) imaging of the ionospheric emission at the foot of the Io flux tube. These observation are interpreted in the frame of two models, the "Unipolar inductor model" (Fig. 1.24) proposed by Goldreich and Lynden Bell (1969) after DAM modulation discovery and the "Open loop Alfvén wave model" (Fig. 1.25) proposed by Neuber (1980) and Goertz (1980) based on the detection of the magnetic perturbation and plasma density perturbation by Voyager 1 close to the Io flux tube. These two models actually represent two versions of the same interaction between Io and the magnetized torus but non-explicitly include a process that accelerates particles along the field lines. The relative motion of Io in the co-rotating plasma torus disturbs the magnetic field of Jupiter. The propagation of the perturbation away from Io is usually described as a propagation of low frequency magneto hydrodynamic (MHD) waves. Most of the energy will propagate along the Io flux tube as Alfvén waves. The magnetic perturbation induces a field-aligned current that propagates down towards the Jovian ionosphere along the Io flux tube. Basic difference of the two models is the location of the field-aligned current closure. In the unipolar inductor model, the current closes in the Jovian ionosphere as a Pedersen current while in the open loop Alfvén wave model, the current closes at the front of the Alfvén wave as polarization current. Both the models are required to explain different features of emissions from Jovian magnetosphere. On one hand, the observation of Io-related DAM emission usually favours the unipolar inductor model as it is able to provide a large lead-angle (the ionospheric foot of the Alfvén wing leads Io by an angle called the lead angle) close to 15° that would explain the observed asymmetry in radio emissions on the other hand, the open loop Alfvén wave model can explain the DAM spectra show a "multiple-arc" modulation
Fig. 1.24 The classical unipolar inductor model first invoked by Piddington and Drake (1968) and Goldreich and Lynden-Bell (1969) to explain Io-controlled radio emissions from Jupiter. The labels indicate the many ways in which wave-particle interactions and plasma instabilities are expected to affect the microscopic processes along the field-lines threading the Io sheath and ionosphere. Related processes should be important at other satellites of Jupiter.
Figure 1.25 – The open-loop Alfven wave model.

Sketch of the magnetic field distortion caused by Alfven waves that are generated by the Io-torus interaction. The waves propagate along the Jovian magnetic field $B_0$ in the plasma reference frame. These Alfven waves form an Alfven wing whose local angle $\theta_A$ to the Jovian magnetic field varies with the local plasma condition (from Hill et al., 1983).
pattern (arcs in a time-frequency diagram), which are usually interpreted as multiple bounces of standing Alfvén waves trapped between the torus and the Jovian ionosphere (Prang et al., 1996, Crary and Bagenal, 1997). Far-field effects of the Io-Jupiter interaction include acceleration and precipitation of electrons into Jupiter's ionosphere leading to UV, IR and radio emissions at/near the Io Flux Tube (IFT) footprints (Bhardwaj et al., 2001). Remote observations are well adapted to study these electromagnetic signatures; whose existence demonstrates that Io's influence extends down to Jupiter's ionosphere. They are complementary to in-situ observations close to Io. Besides these observations (IFT footprints and observations close to Io), nothing is known about the disturbance induced by Io except for some indirect information from radio emission. Galileo and Hubble Space Telescope (HST) observations have shown similar but less energetic effects to occur at the footprints of the other Galilean satellites (Hospodarsky et al., 2001). Studying right handed polarized Io-DAM arcs from the northern hemisphere, Queinnec and Zarka (1998) observed radio fringes with ~2 minute spacing preceding the main arc (Fig.1.26), and explained the phenomenon by multiple reflections of the Alfvén wave perturbation between Jupiter's ionosphere and the external boundary of the torus (Gurnett and Goertz, 1981; Bagenal and Leblanc, 1988) for which they could estimate a reflection coefficient of ~95%. Their counterpart of the faint extended in UV and IR trails of spots separated by 1° to 2° detected downstream of Io's foot prints, and which could be interpreted in terms of wave reflections (Delamire et al. 2003), wake reacceleration (Hill and Vasyliunas 2002). Connerney and Satoh (2000) have observed multiple features at the foot of the Io flux tube in \( H_3^+ \) imagery with approximately 4 to 5 degrees separation between subsequent spots. Multiple features are infrequently observed but on several occasions a pair of emission features has been observed in both \( H_3^+ \) imagery (Connerney and Satoh 2000) and in the UV (Clarke et al. 2002). Queinnec and Zarka
Fig. 1.26 Alfvén wave perturbation between Jovian ionosphere and the external boundary of the \( \text{Io-torus} \) and corresponding features

(a) \( \text{Io-DAM dynamic Spectrum arcs} \)

(b) Intensity distribution over 1MHz band at 23Mhz, showing the main arc proceeded by fringes with ~ 2 min spacing

--- indicates intensity ratio from one fringe to the next

(c) \( \text{Io-Jupiter interaction deduced from (a) and (b)} \)

* --- represents most of the energy is deposited at the first arrival of the perturbation to the ionosphere.
(1998) also proposed an alternative scenario for the weak radio arc following the main arc (Fig. 1.26a,c), in which accelerated electrons “leak” from the Alfvénic perturbation on their way to Jupiter, and produce—after mirroring—low intensity radio emission in a narrow band just below the maximum surface gyrofrequency. Combining ground-based Nancay observatory data and WIND -WAVES spacecraft observations, Io- DAM arcs can be observed from ~ 40 MHz down to ~1 - 2 MHz (Fig.1.26a), i.e. from just above the ionosphere to 1 - 2 $R_J$ above it. The low-frequency cut-off in the dynamic spectra of DAM arcs is seen to lie between 1 and 2 MHz, whereas the minimum electron gyro frequency is ~ 60kHz. Zarka et al. (2001) have proposed that Io-DAM is produced along field lines threading through the dense, stagnating plasma wake discovered by Galileo (Gurnett et al. 1996); the vertical extent of the wake can then lead to quenching of the cyclotron-Maser mechanism below 1-2 MHz, provided that it contains protons with a concentration >1-3%. Using the O6 and VIP4 field models Zarka (1998) proposed 3D modelling over the full 1 – 40 MHz frequency range (Fig. 1.26a) and showed that the arc shape appeared in the dynamic spectra of Jovian DAM is quantitatively consistent with the emission coming from a single flux tube fixed in Io’s frame, leading Io by ~10° - 30°. The detailed arc shape can be obtained from the combination of nonplanar field line topology with radio emission beaming in a conical sheet of 70°± 5° aperture (half-angle) and ~2° thickness (Kaiser et al. (2000). The Jovian radio emission-beaming angle must slightly decrease with increasing frequency (Lecacheux et al.1998) and also it is observed that the arc shape can vary with the beaming angle.

All the above theoretical and experimental discussions have been based on the strong control of the DAM emissions by the satellite Io through standing Alfven waves (Bagenal and Leblanc, 1988; Neubauer, 1980). Erkaev et al. (2002) Have tried to draw attention to the less
intensive slow mode magnetohydrodynamic (MHD) waves, which received less attention on such interaction. Though in different publications (Kopp, 1996; Krisko and Hill, 1991; Linker et al., 1991; Wright and Schwartz, 1990) these types of waves were investigated to the vicinity of Io. But, none proceeded further to investigate the consequences of propagation of such waves into the strong magnetic field region above the ionosphere. Erkaev et al. (2002) using the experimental data of the plasma pressure (Fig.1.27) in the vicinity (∼ 0.5\(R_i\)) i.e. 900 km of Io provided by the Galileo space craft (Frank et al. 1996) and extrapolating the trend of the curve with a Gaussian function predicted that the real enhancement of the gas pressure must be in the range 6 – 8\(R_i\) in the warm plasma of the torus around Io and estimated the consequences of the slow wave propagation processes along the Io-flux tube (L ∼ 6) due to such enhancement. During its orbital motion Io is followed by a wake of disturbed plasma pressure. In the reference frame fixed to Io, these wings look like a steady structure. However, in a frame of a given magnetic flux passed by Io, the plasma perturbations are not steady i.e the plasma pressure is a function of time. They assumed also that the relaxation time of attaining equilibrium of the background plasma parameters of the magnetic flux tube should be much less than the period of Io - motion along its orbit as well as for the Io-Jupiter interaction. From the physical point of view as slow mode wave is guided along the magnetic field and propagates inside a dipole flux tube with progressively decreasing cross section (within a distance of 7.13\(R_i\) the cross section decreases by 380 times) the magnetic pressure increases by \(1.5\times10^5\) times. As a consequence, the flow velocity has to increase toward Jupiter rather than to decrease as it is usually observed after a regular explosion phenomenon. With such physical picture Erkaev et al. (2002) described the slow mode wave mechanism (Fig.1.28) as a pressure pulse produced near Io generates two slow MHD waves propagating along the IFT in the opposite directions- one towards the northern and the other towards the southern
Fig. 1.27 Extrapolation of the plasma pressure with Gaussian functions. • - data points obtained by the Galileo spacecraft. [adapted from Erkaev et al., 2002]
Fig. 1.28 Schematic view of the development of a nonlinear slow-mode wave and a field-aligned electric field due to a pressure pulse at Io. Parameter S represents the distance measured along the Io-flux tube. [adapted from Erkaev et al., 2002]
ionosphere of Jupiter. These slow mode MHD waves are quickly converted by steepening mechanism due to supersonic flow behind the shock front into non-linear waves. The velocity of the wave behind the shock increases in its course of propagation to Jupiter and attains the values of the order of the initial Alfv'enic velocity (~ 150 km s⁻¹) near Io. As a consequence the plasma flow streaming along the Io flux tube has to generate a field aligned potential difference (~1kV) due to the Alfv'en mechanism (Serizava and Sato, 1984). By this way slow mode wave mechanism as proposed by Erkaev et al. (2002) can take a competitive part to explain the phenomena like Io-controlled aurora and radio emissions together with the generally accepted Alfv'en wings model. Though the arrival of Alfv'en wave at the Jovian ionosphere take the leading role of explaining the existing phenomena e.g. trailing spots as mentioned earlier have been interpreted as arrivals of reflected Alfv'en waves (Connerney et al., 1999). Erkaev et al. (2002) claimed that one of such bright spots in the tail might be connected with the arrival of the slow shock. Queinnec and Zarka (1998) pointed out that the maximum emission frequency of some parts of the DAM emission, in particular the Io-B radiation; require a 30° – 50° lag of the source field line and the instantaneous Io flux tube. The propagation time of Alfv'en waves considering this lag would require unrealistically increasing plasma density (more than 10 times higher than that used by Bagenal, 1983). but, this can be estimated without considering such inflated plasma density with the Arkaev et al. (2002) model. According to them the consequence of the slow shock propagation is a strong plasma flow behind the shock front, which in turn leads to a field – aligned potential difference of the order of 1kV. The said 30° – 50° lag in longitude can easily be interpreted, as the non-linear wave is much slower than an Alfv'en wave. Under such consideration they claimed the slow wave mechanism could be considered as responsible for some parts of the DAM emissions.
1.6 Critical analysis of the energy budget of electromagnetic emissions in the Io - Jupiter electrodynamical coupling

It is conceived from the previous articles that complicated electrodynamical coupling of Io with its plasma torus and Jovian magnetosphere evolves multi-wavelength emissions from Jovian atmosphere. It is also verified that the electrodynamical interaction between Io and the Jovian magnetosphere results in FAC via Alfvén wave propagation that runs from Io along Jovian Magnetic field lines and closes through the Jovian ionosphere (~ 65° north and south latitude) at each foot of IFT. As a result particles carrying the FAC impacting the atmosphere of Jupiter produces auroral like spots and radio waves. In the following Table-1.1, the budget of the emitted power is being displayed –

Table 1.1 – Budget of emitted power in multi-wavelength spectra from Io – Jupiter interactions

<table>
<thead>
<tr>
<th>Electromagnetic Spectrum Region</th>
<th>Emitted power limit in watt (W)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infra-Red (IR)</td>
<td>( \sim 3 \times 10^{10} - 10 \times 0^{10} )</td>
<td>Zarka et al., 1997</td>
</tr>
<tr>
<td>Ultra Violet (UV)</td>
<td>( \sim 5 \times 10^{10} ) &amp;</td>
<td>Bhardwaz et al., 2001</td>
</tr>
<tr>
<td>Radio-waves</td>
<td>( \sim 10^9 - 10^{10} )</td>
<td>2001</td>
</tr>
</tbody>
</table>

The total electromagnetic power $\sim 10^{11}$ W, is thus remarkably larger in comparison to Earth's total auroral power concentrated in IFT footprints, the dimension $\sim 60 \times 200$ K$m^2$ area which is typically larger than the size of the Io (diameter 3640Km) projected onto the planet. Saur et al. (2004) provides the information that IR and UV emissions require precipitated power of $\sim 3 \times 10^{11}$ W in the form of 10 – 100 keV electrons, while the cyclotron-maser mechanism of radio emission with an efficiency about 1%, implies a precipitating power of $10^{11}$ – $10^{12}$ W in the 1 – 10 keV range. If the electron energy is distributed in the appropriate energy ranges, the above result conforms to the dissipation of $10^{12}$ W per hemisphere in the Io-Jupiter interaction. In this respect Crary (1997a,b) attempted to compute electron precipitations triggered by Io, and observed that despite the reflection of the Alfvén wave, Io interaction still conveys power to the high latitudes. The wave’s finite parallel electric field produces an electron beam through the repeated Fermi acceleration mechanism. Most of the accelerated particles come from low latitudes and being coupled with the wave pushed along in front of it, until too much of its energy has been reflected and ultimately ceases to support the Fermi acceleration. Crary (1997a) showed that by this mechanism the electron beam would have riches by a flux of approximately $8 \times 10^{24}$ electrons per second. According to his model the total power of the beam would be $\sim 10^{11}$ W with an average (maximum) energy of 75 (500) keV – the estimate leads to the fact that the previously mentioned energy range (1-10 keV) of electron corresponds to a power $\sim 10^{9}$ W will not fulfil the above requirements in the radio-wave emission range.

Williams et al. (1996, 1999) observed the behaviour of the energetic particles during the Io's wake flyby by Galileo electron particle detector (EPD) and Plasma wave subsystem (PLS). It is revealed from their analysis that the energetic electro pitch angle distribution evolved from a
pancake distribution to a butterfly distribution function as Galileo spacecraft approaches near to Io. Near closest approach, in the wake of Io, the distribution suddenly turned into an intense bi-directional beam aligned with the magnetic field with energies in the range $\sim 0.1$ to $\sim 200$keV and power of a few $10^{10}$W (Williams et al., 1999; Frank and Patterson, 1999,2000). In principle such beams could provide enough power for the footprint electromagnetic emissions if they extended to sufficiently high magnetic latitudes. Mauk et al. (2001) raised question about the relation of such energetic electron beam with the footprint emissions. The question of the acceleration process to meet the requirement of the energy budget still remains open. Although the planetary rotation is thought play a role (e.g. via the centrifugal force) in particular acceleration and auroral processes, especially for rapidly rotating planet as Jupiter, no such correlation can be found between the auroral radio power and the planetary rotation (angular momentum or typical corotation electric field) (Zarka et al., 2001b). Chust et al. (2001) throw some light on this controversy by considering a two-step energization process taking advantage of the mass – loading electric field followed by Landau accelerations by low frequency plasma waves which might be excited by Alfv’en currents. In support to this class of scenario the detection of very intense ULF electromagnetic waves detected by Galileo/ PWS in the southern Alfv’en wing may be mentioned. Still the quantitative estimation of energization is required to be developed.

1.7 Characterization of jovan decametric radio emission mechanism and its related intriguing parameters

Combining observational results and modelling it has been possible to characterize the emission mechanism and some of its features. Observational aspects of the DAM emission have been used to calculate the radio rotational period of the planet, determine the location of the sources, beaming angle and the thickness of the emission cone. The use of
modulation lanes and the study of $N$-bands and microstructure of the $S$-bursts are revealing more interesting aspects of the plasma interaction with the magnetosphere.

Observational phenomena and few modelling have been discussed in the previous articles and some indication of the mechanism of emission has also been mentioned. In this article some discussion on mechanism of radio emission and its propagation with special emphasis on modulation lane, generation of N-bursts and microstructure of S-bursts will be reviewed.

Considering the high radiation power of DAM with the maximum energy up to $10^{11}$W, contribution of coherent plasma wave processes including "wave- particle interactions" is essential to explain the generation mechanism. Two wave particle mechanisms have been proposed to explain the strong DAM emissions; one is "direct mechanism". In the direct mechanism the Cyclotron Maser Instability (CMI) (Wu and Lee, 1979) have been proposed to explain the radiation of auroral kilometric radiation (AKR). The right-handed extraordinary (R-X ) mode waves are generated directly through the cyclotron type resonance condition under the relativistic effect of the high-energy electrons. On the other hand, the indirect mechanism of the Mode Conversion (MC) mechanism (Oya, 1971; 1974) also been proposed; left hand ordinary mode waves are generated through the mode conversion process along the propagation path of the plasma waves. Now, it is important to evaluate how these mechanisms work for the generation of DAM on the basis of the identification of propagation modes of DAM.

1.7.1 Propagation mechanism of Jovian DAM from the source to the observer

For investigating the propagation mode of Jovian DAM observed initially from terrestrial stations and later on from different spacecrafts, observers need to search the mode of polarization of such radiation, which
traverses a long way crossing the different plasma environments in the Jovian magnetosphere, interplanetary space and for the ground observer through the terrestrial ionosphere. In the first stage it was found (Carr et al., 1965; Green & Sherill, 1969; Riihimaa, 1979b) that emission of the so-called A and B sources is mainly RH polarized, whereas that of the C and D sources is LH polarized. The polarization is basically in the elliptic mode and the major axis of polarization ellipse is almost perpendicular to the plane between the magnetic field and emission in the region of probable localization of sources and they inferred from their observations that DAM emission corresponds to the X-mode in the generation region.

In the second stage of observation with ground based Radio-Telescope at the Nancay Radio Astronomy Observatory observers (Boudjada & Lecacheux, 1991; Lecacheux et al., 1991; Dulk et al., 1992) measured all four stokes parameters to calculate the full set of polarization parameters (degree of polarization, degree of linear ($\eta$) and circular ($\rho$) polarizations, and the orientation of polarization ellipse) of the emission as a function of both frequency and time. Dulk et al. (1994) reported by analysing complete polarizing state of 37 radio storms from all Io-related sources (A, B, C, D) and two non-Io events of Jovian DAM with the spectro-polarimeter at Nancay that emission from all of the sources is 100% elliptically polarized at all frequencies in the measured range of 10 – 38 MHz, but the degree of linear and circular polarization differs for different Io and non-Io related sources. The results of observation of Dulk et al. (1992,1994) have been summarized in the Table1.2
Table 1.2 – degree of polarization of different sources at 20 MHz

<table>
<thead>
<tr>
<th>Sources</th>
<th>Linear (n)</th>
<th>Circular (r_c)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>lo - A</td>
<td>+0.66</td>
<td>-0.72</td>
<td>Dulk et al. (1994)</td>
</tr>
<tr>
<td>lo - B</td>
<td>+0.87</td>
<td>-0.49</td>
<td>observed at the frequency</td>
</tr>
<tr>
<td>lo - C</td>
<td>+0.74</td>
<td>-0.67</td>
<td>≈20MHz</td>
</tr>
<tr>
<td>All sources</td>
<td>+0.51</td>
<td>+0.85</td>
<td></td>
</tr>
<tr>
<td>L bursts*</td>
<td>+0.87</td>
<td>_</td>
<td>Dulk et al. (1992)</td>
</tr>
<tr>
<td>S bursts*</td>
<td>+0.80</td>
<td>_</td>
<td>at f ≥20MHz</td>
</tr>
</tbody>
</table>

+ve sign - represents LH polarized & -ve sign for RH polarized

It is interesting to note that in the case of all sources the observed emission basically LH polarized of which the degree of circular polarization is more than that of linear polarization, whereas polarization characteristics are different for different individual sources. Further from the observation of Dulk et al. (1992) it reveals that there is almost no difference in ellipticity of L – and S– bursts. There do exist different controversial models for location and modes of polarization of Jovian DAM radio emission. As according to...
Warwick (1970) elliptical polarization results from linear mode coupling which occurs within the Jovian ionosphere, at the point where the radiation, originally generated in the $X-$ mode towards the planet, is reflected. Whereas Goertz (1974) suggested that the linear mode coupling (LMC) occurs in the Jovian magnetosphere in some "limiting polarization zone" (LPZ) defined as the region of the magnetosphere in which the rate of change of polarization of $X-$ and $O-$ modes equals the rate of change of phase difference between the two modes. Beyond this point, the observed polarization of the emission is identical the ray path. According to Goertz model, the axial ratio (ellipticity of radiation) and inclination of a polarization ellipse which depends on the angle between the magnetic field line and a ray path in the LPZ, changes due to rotation of the planet and radiation frequency. Zhelznyakov (1970,1995) developed extensively and independently the theory of LMC in an inhomogeneous magnetized plasma to study the solar radio emission polarization. From their model it reveals that existence of LPZ does not suffice for effective LMC and formation of the observed elliptical polarization. According to Zhelznyakov theory for effective coupling the said LPZ must lie in the "transitional region" (TR), the region of transition from quasitransverse (QT) to quasilongitudinal (QL) propagation or vice versa, i.e. LPZ in the region of radical change of mode polarization takes place. For the explanation of the experimental data Lecacheux et al. (1991) proposed two possibilities of mode conversion:

Two linear, characteristic (normal) modes with coherent phases are generated in the source of DAM emission due to MASER generation mechanism, and then without mode coupling the normal modes propagate in any part of the path to an observer.

Only one mode is generated by a MASER mechanism, and the second normal mode is created by strong mode coupling while the emission propagates in a near-vacuum medium.
MASER mechanism rejects the 1st possibility. So, Lecacheux et al. (1991) proposed the second version for the explanation of the elliptical polarization of DAM radiation according to which one elliptical mode is generated at the source region and the same mode is retained all the way for its propagation to the observer.

Shaposnikov et al. (1997) proposed a model based on LMC assuming inhomogeneous magnetized plasma of the Jovian magnetosphere for the observed polarization of DAM emission. They pointed out the following serious drawback of the LMC of Lecacheux et al. (1991):

(i) Near the source of the emission extremely low plasma density is needed – this does not fit well with the high level of radiation from the source,

(ii) Frequency and time independence of the observed polarization cannot be understood,

(iii) Difference of the ellipticity of emission from B, A and other sources cannot be realized,

(iv) Different generation mechanisms (e.g. electro cyclotron maser instability (ECMI) and plasma mechanisms) for DAM emission is not in agreement with this model.

Details of dynamic spectra of S-bursts and narrow band emission can be explained well by plasma model developed by Zaitsev et al. (1986); Shaposhnikov & Zaitsev (1996); Shaposhnikov et al. (1996).

The above mentioned model needs high electron density in the source region, more than that as considered by the model of Lecacheux et al. (1991). The ECMI theory can explain well the dynamical spectra of
$L - \text{bursts and predicts that the axial ratio (T) of the polarization ellipse is the function of the angle (θ) of propagation relative to the magnetic field in the source region. According to the standard ECMI theory proposed by Melrose and Dulk (1991) } T = |\cos θ| \text{ and the modified ECMI theory of Willes et al. (1994) } T = |\cos^3 θ|. \text{ Willes et al (1994) modified the standard ECMI theory by considering the contribution of mildly relativistic electrons streaming along converging field lines as the source of ECMI, but this modification does not contribute too much to solve the discrepancy of finding 'θ'.}

Shaposhnikov et al. (1997) pointed out that the existing drawbacks of interpretation of observed polarization as a consequence of strong linear mode coupling carries information directly from the source region on the mechanism of emission. They suggested that the observed polarization does not carry information directly and solely on the source region, but on the TR as well, which may not coincide with the source region. In their model they have considered plasma density and magnetic field distribution along the ray propagation path in calculating the efficiency of linear mode coupling. They simplified their analysis by segmenting the propagation path of emission into quasi transverse (QT) propagation, quasi longitudinal (QL) propagation, transition region (TR).

According to Zheleznyakov's (1970, 1995) effective coupling takes place only on TR to justify the so-called elliptical polarization. The location of TR in the Jovian magnetosphere varies with the emission frequency and time. The place of TR in the magnetosphere is mainly defined by a height of emission source and the angle θ between the direction towards an observer and the magnetic field in the source. At different frequencies (f) the DAM source regions are located at heights corresponding to gyrofrequency level $\ell_0 = f$. This is the reason why both the ray path height and θ changes with frequencies. Moreover, due to planetary rotation and the lack of magnetic...
field symmetry relative to planetary spin axis the angle $\theta$ will vary with central meridian longitude (CML). The ellipticity of emission escaping from the Jovian DAM is completely defined by the angle $\theta$ in the source. Thus, for every given DAM radio emission storm occupying some region in frequency – time space. Shaposhnikov et al. (1997) with their model identified a number of TR regions located in a certain domain of Jovian magnetosphere where the linear mode coupling may take place. These type of TR zones are defined as “interaction region” of the magnetosphere (IRM) for a given emission storm. The distribution of plasma density and the position of IRM in the magnetosphere are very much Jovian magnetic field model dependent. Shaposnikov et al. (1997) tested their model with Jovian dipole field model where the magnetic momentum coincides with the spin momentum of the planet and assuming sources of the DAM emission at different frequencies ($f$) are located along the same magnetic field lines, belong to $L$-shells passing through the satellite $Io$, at heights associated with gyrofrequency ($f_{ce}$) level. Under such circumstances only one $X$-mode is expected to be excited in the sources, approximately perpendicular to the magnetic field lines where the condition of QT propagation is fulfilled. The geometry of the problem is presented in the Fig.1.29. According to their model magnetospheric plasma density variation in IRM is the cause of variation of ellipticity of polarization of the observed DAM emission storm, but not on frequency and time. From this finding it was inferred that ellipticity of DAM emission would be dependent on CML rather than $Io$'s position. This result is not in accordance with the observation of Dulk et al. (1994) – the propagation of the event occurred with $Io$ – phase near or within $Io$-$B$ range, but the CML of the observer in the $Io$-$A$ – range is similar to $Io$-$A$ events. Besides, the properties of the polarization of $Io$ and non -$Io$ are very much alike. Observing such discrepancy between their model and the observed result of Dulk et al. (1994) they put forward the following points to be taken into account for re-evaluation of their model—
Fig. 1.29 Schematic view of Shaposhnikov et al. (1997) model for fixed time.

Source location - at each frequency along the magnetic field line.

\( f_{\text{max}} \) — maximum frequency;

\( f_{\text{min}} \) — minimum frequency

The "transitional region" (TR) for emission at a frequency \( f \) is located along the ray path from the corresponding source near the point.
Magnetospheric background plasma density as a function of time due to internal (satellites \(Io, Ganymede\)) and external (solar wind origin) sources,

Improved magnetic field model (O4/ O6 / VIP4 etc.) to be used. Since for such field models, it is hardly to be expected that the IRM for B and A sources be symmetrically located relative to the plain defined by the point of the observer and the Jovian rotation axis, different plasma densities occur in the IRM of these sources.

Misawa and Oya (1999) analysed \(Io - DAM\) to identify the expected magnetoionic wave mode and source conditions with 3-D tracing assuming radiation of \(X\) – and \(L - O\) mode waves from both northern (N) and southern IFT and investigated conditions of wave which meet with the observed occurrence characteristics. For 3D tracing analyses they used the following models of magnetosphere and ionosphere –

Magnetospheric models-

(a) GSFC O6 – model; (b) JPL 13 E2 model

Ionosphere models –

Two types of electron density models with the same height (900 km) whose peak electron densities are \(6 \times 10^5\text{cm}^{-3}\) and \(2 \times 10^7\text{cm}^{-3}\) where a peculiarly ionised condition induced by precipitating particles in the Jovian polar ionosphere has been taken into account for later model,

Topside (600km height) ionosphere model –

(a) Rare density model, (b) Moderate density model

It is observed that later model smoothly combine the ionosphere density model with the magnetospheric density model.
Using the models mentioned above they determined the origin of polarization at the region where plasma continuity is terminated. They applied a criterion of plasma continuity proposed by Cohen (1960) and estimated axial ratio values of the elliptically polarized Io – DAM along the ray paths. From their analysis it is revealed that the R-X mode wave which is radiated almost perpendicularly to the local magnetic field from the northern polar region, is selected as a preferable Io – DAM wave based on the observed characteristics of the occurrence probability and polarization. Required conditions for the origin of R-X mode Io- DAM wave is that the electron density in and near the source region is quite low and there should have some energy supply process in the Io – related source regions.

During its passage from Jovian magnetosphere to the observer at the Earth DAM radio wave has to cross the Jovian magnetosphere (source region (S*) – interaction region of magnetosphere (IRM) – Io-plasma torus (IPT)), interplanetary plasma region and ionosphere of the Earth. As a result it suffers Faraday rotation (FR) of the polarization ellipse corresponding to different ambient plasma condition. Using spectropolarimeter observations performed at the Nancay Observatory Shaposnikov et al. (1999) derived a theory of the wave ellipse orientation allowing to get the total amount of Faraday rotation en route from the source of emission till the ground based observer. In this long path of 4.2AU the Jovian DAM elliptic plane of polarization suffers maximum Faraday rotation in the gigantic magnetosphere filled with inhomogeneous plasma and in the terrestrial ionosphere. Except a small domain close to the source region the approximation of quasi-longitudinal (QL) propagation occurs along the entire emission ray path. In the interplanetary medium there is almost a complete absence of rotation due to very low density of plasma and magnetic field. Shaposhnikov et al. (1999) investigated the phenomenon in each sector separately. In this investigation they
considered the O4 magnetospheric model with their earlier theory (Shaposhnikov, 1997) of linear mode coupling. In the ‘S’ region only the elliptical polarization of Jovian DAM can be observed. In the IRM region they estimated the rotation, which is found to be approximately between 20 - 40 degrees for different “sources” to be distinguished in the CML - Io phase diagram. Beyond IRM the polarization is expected to remain constant due to low level of the magnetospheric plasma density. Due to the enhanced density in the Io – plasma torus (IPT) a noticeable rotation of the polarization is very much probable. Dulk et al. (1992) estimated the contribution of the IPT to the Faraday rotation of 18 MHz DAM radiations from about \(-2\pi\) to \(2\pi\) radians depending on CML. For the calculation of FR the following assumptions are made –

Existence of the frequency dependence of rotation of the polarization ellipse with the considerations of torus latitude inhomogeneity for the sources placed along the magnetic flux tube close to the limb.

Different inclinations of the Jupiter spin axis to the Earth – Jupiter line for CML = 110° for simulating the characteristic scale of plasma torus in homogeneity in a given region penetrated by the ray paths of a given emission storm,

a limited region of IPT composed of an inhomogeneous plasma slab immersed in the homogeneous magnetic field parallel to the surfaces of the plasma (Fig.1.30).

assumed also that the rays cross the slab under a constant angle to the plasma surfaces i.e. the ray path has no curvature.
Fig I 30 Schematic model of Shaposhnikov et al. (1997) for the propagation of Jovian DAM radio wave from sources to a ground-based observer. X – denotes the ray path of the extraordinary wave, O – corresponds to the ordinary wave, QTR – quasi transverse region, QLR – quasi longitudinal region of propagation, TR – transitional region, VR – region of vacuum propagation, IRM & IPT – interaction region of the magnetosphere and the Io plasma torus, $B_j$ – planetary magnetic field, $n_c$ – magnetospheric plasma density, $h$ – height.
Fig. 1.31 Typical modulation lane [adapted from Imai et al., 1997]
Plasma distribution by a Gaussian function $n_e = n_i \exp \left( \frac{-h}{R_J} \right)$ with characteristic scale height ‘$h$’ (∼ $R_J$, the Jovian radius), along field lines (along an axis $h$ in Fig. 1.30), taking into account frequency, $f \approx f_{ce} \sim \left( \frac{R_J}{h} \right)^3$.

Under the above considerations they found 1% error of finding the rotation measure.

The main rotation of the elliptic plane of polarization of Jovian DAM occurs in the Earth’s ionosphere. Different authors give the estimation as large as about (70 – 90)% out of the total amount of FR.

In the Earth’s ionosphere the frequency dependence of the emission path is minimal due to the fact that at a particular time the range of the path traversed by the emitted ray is much smaller than the characteristic scale of ionosphere in homogeneity and can be neglected. However, the ray path splitting has been taken into account. They tested their model with the above assumptions using Nancay spectropolarimeter data during the quiet ionosphere conditions in the interval of time 01-30 UT and 02-30 UT of 8th Sep, 1987 with no interferences above 15 MHz, but in the frequency band between 19 – 36 MHz. In this range the signal from Jupiter is found to be much stronger than the sky background. From their analysis it is observed that the FR varies as a function of emission frequency ($f$). They estimated values of FR in IRM (∼ 25°) and total rotation in the IPT and Earth’s ionosphere (∼ 64°) with their model for Io-B source ($f$ = 30 MHz) using Jovian magnetospheric O4 model and found that the result is almost consistent with experimental values. Winglee (1986) studied FR of DAM emission in the IPT and found a constant rotation in the said region. In such estimation they assumed that IPT have both cold and energetic components and there is no frequency dependence of emission. The existence of such hot and dense plasma component has been confirmed.
from Galileo spacecraft data (Erkaev, 2002), but Shaposhnikov did not consider such phenomenon in his model.

However, due to the natural cut-off frequency (≈ 39.5 MHz) of Jovian DAM the observation frequency band cannot be extended significantly towards the high frequencies. But the result can be tested by extending the frequency band towards the lower frequency band (around 10 MHz) using ground-based observation with certain improvement of measurement accuracy. The problem of extension towards the lower frequency has been eliminated by the data of Wind satellite, which carries antennae, and receiver system enabling the measurements of the full set of the polarization parameters. The frequency difference between nearby Faraday fringes is expected to be as large as about 0.5 MHz at a frequency of ~10 MHz. From the treatment of Shaposhnikov et al. (1999) with the experimental data it is revealed that different approximate formulae give different estimation of both the rotation measure en route from the Jovian emission source till the ground-based observer and the value of the polarization angle at the emission point.

1.7.2 Model of DAM modulation lane

In the art 1.4.4 the observational and characteristic features of modulation lanes have been mentioned. Here a glimpse of a quantitative model proposed by Imai et al. (1992a,b, 1997) will be presented. In this model it is assumed that the modulation lanes are an interference pattern produced by the passage of the DAM radiation through an essentially 2-D screen located near Io’s orbit close to the longitude of the sub-Earth point. The screen is assumed to be composed of approximately equally spaced Field-aligned columns of enhanced or diminished plasma density. Typical modulation lane (Fig.1.31) of the Io-B DAM source with positive \( f \) \( f \) slopes of about 190 kHz-s\(^{-1}\) recorded at the University of Florida Radio Observatory by means of a sensitive dynamic spectrograph utilizing a 640-
Fig.1.32 Modulation lane model (Imai et al., 1997) of the Jovian Io–B DAM source.
IFT - Io Flux Tube; PEFT - Previously Enerziged Flux Tube; Curved red striations
- Interference screen not to scale. [adapted from Imai et al., 1997]
dipole antenna array. The main purpose of their model was to calculate \( f_1 - f_2 \) slopes as a function of CML distribution of observed slopes. For this they assumed that emitted rays from Jovian radio source propagating towards Earth penetrate the interference screen consisting of parallel, approximately equally spaced, field aligned columns of enhanced or depleted plasma density. The screen is located (Fig. 1.32) at approximately 180° from superior geocentric conjunction at Io's orbit. The free parameters of the screen are the spacing of the plasma enhanced or plasma depleted columns, and the magnitude of this excess (deficit) of column plasma density above (below) the undisturbed background value. During the passage through the enhanced plasma columns radiation is scattered at higher intensity than that passing through the lower – density plasma between columns. As like as optical gratings, intensity maxima occur in those directions for which the path differences from successive enhanced – scattering columns to the wave front differ by zero or an integer number of wavelengths (\( \lambda \)). Similarly intensity minima occur for directions in which path differences are odd numbers of half wavelength. Above the density of the undisturbed plasma they found that to produce the required scattering angle the necessary enhancement of plasma density is 200 electrons - cm\(^{-3}\). The average density of the undisturbed plasma measured by Voyager and Galileo spacecraft is about 2000 electrons - cm\(^{-3}\) in the plasma torus. Using Fresnel Zone theory (Davis, 1969) the relation between the distance \( d \) from one column centre to the next and the distance \( R \) between the Jovian Radio source and the interference screen which is required for maximum fringe pattern modulation depth is

\[
d = 2\sqrt{(R + \lambda/2)^2 - R^2} \approx 2\sqrt{R\lambda} \quad \ldots \quad \ldots \quad (1.2)
\]

As the interference screen has been considered to be located at Io's orbit, \( R = 5.5 \, R_j \) for the assumed frequency \( \xi = 22 \text{MHz}, \ \lambda = 13.6 \text{m} \). Putting these values in the equation (1.1) the value of \( d \) comes out to be 138 km,
which should be the distance between column centres that would give the maximum fringe modulation depth. Dividing this depth by the relative velocity \( v_c - v_s \) (~ 67 km/s) between the plasma column system \( (v_c \approx 74 \text{ km/s}^{-1}) \) and \( v_s \) (~ 7 km/s), the velocity of the typical source \( (\text{Io-A / Io-B}) \) following \( \text{Io's} \) orbital motion in the direction perpendicular to the Jupiter - Earth line. The time intervals between successive modulation maxima at fixed frequencies comes about typically 2s which is the same as calculated most probable observed time spacing between modulation lanes. Though they assumed constant separation \((d)\) of the modulation lanes, but actually it is observed to vary in different modulation patterns. They calculated the slope \((\alpha)\) of the modulation lane dynamic spectra (Fig.1.33) using the relation

\[
\alpha = -\frac{\left( v_c - v_s \right) (f_{\text{max}} - f_{\text{min}})}{\left( h_2 - h_1 \right)} \quad \ldots \ldots \quad (1.3)
\]

Where \( f_{\text{max}} \) and \( f_{\text{min}} \) are the maximum and minimum frequencies corresponding to the points \( h_2 \) and \( h_1 \) respectively and the defined positive \( x\)-direction is considered to be perpendicular to the line of sight to the Earth and parallel to the Jovian equator, in the direction of increasing system III longitude. Using the relation it is observed that \( h_2 - h_1 < 0 \) for \( \text{Io-B} \) and \( >0 \) for \( \text{Io-A} \) sources respectively and accordingly the slope for \( \text{Io-B} \) should be +ve and that for \( \text{Io-A} \) is -ve. The model proposed by Imai et al. (1992a,b) is seen to fit well to the observed data. With the modified model Imai et al. (1997) extended the calculations by using additional data and expanding ranges, i.e. wider ranges of CML, cone half angles, and the inclusion of southern hemispheric sources \((C \& D)\) with the previously included northern hemispheric sources \((A \& B)\) and also non-\text{Io} sources.

It reveals from their modulation lane model, based on cyclotron maser instability source region, that an interference pattern produced by the passage of DAM emission through a plasma structure near the orbit of \text{Io}
Fig. 1.33 shows the origin of the slope of a modulation lane from the source region: (a) for $I_o - B$, and (b) for $I_o - A$. Each plot - projection on a plane perpendicular to the line of sight, x axis - in the direction of increasing longitude (to the left), y axis - not shown in the figure, being positive to the north (i.e., upward), vertical bands - plasma column intersections with the defined plane, diagonal line - projected positions of the source points within a single PEFT that are simultaneously emitting at their respective frequencies. [adapted from Imai et al., 1997]
close to the sub-Earth point is very much encouraging to interpret new and detailed information regarding the Jovial DAM radio sources observed in the different dynamic spectra. In the said model (Imai et al., 1997) they used successively with O4 & O6 models and found that their model is very much sensitive to the Jovian magnetospheric model.

Recently Arkhipov (2003) proposed a new algorithm to interpret Riihimaa's (1979) empirical diagram of f-t drift rates of the modulation lanes. The proposed model clearly explains all the point clusters of the diagram and observed that the cone–half angle of DAM radiation is about 70°.

1.7.3 Generation mechanism of S- bursts, N- bursts

In the art 1.4.1, 1.4.2 and 1.4.3 different characteristic features of L-bursts, S- bursts and N- bursts have been reviewed. Here generation mechanism of the phenomena will be reviewed. Among the three types of bursts L- burst is commonly observed component and there is no complication about their generation mechanism. But, it is believed that S-burst structure is intrinsic to the emission process and is thus capable of yielding important information concerning its nature. The existing models developed to explain the observed characteristics (drift rates, periodicity of structures, burst time duration, occurrence probability...) are being reviewed below:

(i) Ellis (1965) proposed a model to explain the negatively drifting property of S-bursts. This model is based on energetic electron bunches, which originate in the Jovian magnetosphere close to the satellite Io and radiating when they stream outwards with adiabatic motion along magnetic field lines in the Jovian magnetosphere from their mirror points and as a result the observed negative drift rates are observed.
The recent investigation (Boudjada et al. 1997; Gafopeau et al. 1999) shows that fixing the initial pitch angle and the electron speed as proposed by Ellis cannot fit the instantaneous drift rate of one individual S-burst. Boudjada et al. (2000) proposed that the drift rates of S-bursts might be related to a mechanism inherent and solely depending on the temporal variation of the narrow band.

(ii) Calvert et al. (1988) explained the equally spaced discrete components in the S-burst as an effect due to longitudinal oscillation modes of the natural radio laser. However, this model does not take into consideration the presence of the narrow band events with the studied S-burst event.

(iii) Louren (1997) proposed filamentary models to explain narrow band structures and spectral fine structures related to the spatio–temporal organization of the emission source with regard to the observer. From the analysis of dynamic spectra by Boudjada et al. (2000) it reveals that narrow band features because of the short time scales (a few tens of milliseconds) and the individual S-burst duration (in few hundred of milliseconds), are intrinsic to the source contrary to the predicted filamentary structures.

Both the above models can be considered to explain part of the observed features but not the global observed phenomenon. Boudjada et al. (2000) proposed a model for S-bursts taking into account the inherent effects (e.g. refraction effects, oscillation of the emitting wave planes etc.) inside, or close to the source region, which generates the narrow band emissions.

From the above discussion it is clear that there should have some intrinsic relation between S- and N-bursts, since in the dynamic spectra of S-N bursts, and S-bursts appears as slopping line (Fig. 1.34 & 1.35)
Fig. 1.34 Illustration of the structure of $S-N$ burst from the analysis of dynamic spectrum shown in Fig. 1.20
[adapted from Oya et al., 2002]
Fig. 1.35 Different segments of dynamic spectrum of 20 September, 1986 characterizing complicated interactions of S-N burst (indicated by arrows) [adapted from Oya et al., 2002]
crossing a \(N\)-burst. Oya \textit{et al.} (2002) studied the characteristics of \(S-N\) burst event by using high-resolution spectra with the bandwidth of 2 MHz. From the characteristics of the \(S-N\) burst event they proposed a following generation mechanism of the \(S\)-bursts.

From the analysis of 65 \(S\)-burst events including 26 identified events of \(S-N\) burst events from \(Io-B\) source recorded in high time resolution spectrograph of Tohoku university from 1983 – 1999 Oya \textit{et al.} (2002) discarded the proposal of Louren (1997) and Zarka (1998) of geometrical control of \(S\)-bursts and suggested that the acceleration mechanism of bunched electrons that are responsible for the generation of the \(S\)-bursts is closely related to the formation process of the electrons which generate the \(N\)-bursts. Assuming the radiations take place at the electron cyclotron frequencies they estimated that the altitude range of the source, emitting \(S\)-bursts from 5 - 38 MHz, is from a few thousands km to \(3 \times 10^4\) km. The acceleration region of the bunched electrons is supposed to be distributed in this altitude range along the IFT. The spatial extent of the source of few thousand km will emit radiation in the frequency range of a few MHz frequency. The observed frequency drift rates can be justified by considering bunched electrons moved parallel to the magnetic field with the speed in the ranges from 0.06c (0.9 keV) to 0.13c (4.1 keV). Oya \textit{et al.} (2002) explained the phenomenon through the schematic view of the mechanism in the Fig1.36. The sequence of the phenomena is initially there is a TEE phenomena – a new region of \(N\)-burst is generated and moving upward along IFT, simultaneously, the newly formed bunched electrons move with 0.1c speed upward. These high speed electrons merges with the \(N\)-burst region in the high altitude and as a result the \(N\)-burst event disappears. According to them in the \(S-N\) burst events, two kinds of potential drops seems to appear along the IFT. One potential drop is created first at a high altitude, which forms the quasi steady \(N\)-burst.
Fig. 1.36 summary of the result of analyses of Oya et al. (2002)
Subsequently at the lower altitude, the other potential drop appears suddenly, and then bunched electrons being accelerated by this electric field produces the $S$-burst. Oya et al. (2002) found that the bandwidth of the trailing edge emission (TEE) is narrower than 100kHz; the spatial extent of the acceleration region of $S$-burst electrons along the magnetic field line is very thin (<100km). Sudden neutralization of the positive charge of the double layer type electric field existing in the $N$-burst region by the arriving electron beam of $S$-bursts may be the cause of the destruction of the $N$-burst source region. Then, the potential drop disappears until the second potential drop moves up to the original point. Unstable potential drop in the lower altitude start to move up with a fairly fast speed, but lesser than $S$-burst electrons. They also concluded from their analyses that the acceleration region of the bunched electrons, responsible for the $S$-burst event, are not located neither close to the Jovian ionosphere nor near $Io$, but extented in a wide altitude range from a few thousands km to $3 \times 10^4$ km above the Jovian ionosphere. The proposed model is required to be verified with large number of data of $S- N$-bursts including the dynamical nature of the $Io$ plasma torus and considering other models of Jovian magnetospheric field.

Misawa (2000) investigated the condition for generation of $Io$-DAM emissions by 3D ray tracing technique. He performed the analysis with this technique for the case of both R - X and L - O mode emissions using the VIP4 model of Jovian global magnetic field. Comparing the simulated occurrence probability (OP) of $Io$-DAM waves from the ground with the recorded $Io$-DAM from terrestrial stations he arrived at the conclusion that initial wave condition (magnetoionic wave mode, ray direction, and source position) at the source region is not sufficient to explain the observed OP, but additional conditions are required for the wave generation.
1.8 Scope of the Present Investigation

Investigations on some aspects of non-\textit{Io} radio signal in decametric range and cosmic rays from Jupiter have been carried out by the author for the last two and half decades. The proposed dissertation will give a description of the investigations undertaken with the discussion of the results obtained thereof.

The earlier part of the chapter presents an overview of the Jovian DAM radio emission up to the recent years. Evidences for periodic modulation of Jupiter's DAM radio emission is considered first. Information of \textit{Io}- and non-\textit{Io} related source location and their characteristic features of emission, e.g., polarization, shape of the beam, \textit{L}-bursts, \textit{S}-bursts, \textit{N}-bursts, modulation lanes etc. Dynamics of the field-aligned current sources both at the Earth and Jupiter has also taken into consideration. Propagation from Jupiter to terrestrial stations and energy budget of the electromagnetic radiation from Jovian magnetosphere has also been discussed. Finally, mechanism of emission from the Jovian magnetosphere has been discussed critically.

Chapter 2

A description of different experimental set up for the study of Jupiter has been given in this chapter. Methodology for observing the Jovian atmosphere is outlined and the equipments developed and constructed in different International Observatories for the purpose are reviewed. Additional instruments used for collecting the data are critically discussed and finally the techniques employed for registration of Jovian data are discussed at length. Also the techniques and instrumentation of collecting solar plasma data are reviewed in brief.
Chapter 3

A comparative study of the proposed models of the magnetic field in the Jovian magnetosphere and the results obtained thereof are made. The utility of the models with some interesting findings are discussed and their limitations are clearly pointed out.

Chapter 4

This chapter investigates the local time dependence of decametric radio emission from Jupiter observed from Earth stations and examines the phenomenon at different solar activity conditions. The results exhibit that, at different solar activity periods, all non-Jo sources show high occurrence probability of decametric (DAM) radio emission corresponding to high polar coronal hole size, and at the time of crossing of interplanetary magnetic field sector boundary to the Jovian magnetosphere, occurrence probability shows high intensity. The results have been critically interpreted by considering the interaction of solar wind with the Jovian magnetosphere.

Chapter 5

The purpose of the chapter is intended to throw light on the interaction between solar plasma with Jovian magnetosphere by studying correlation between DAM radio emission from the Jupiter with different solar plasma parameters and also with the Interplanetary magnetic field feature, the Heliospheric current sheet extent. Significance of the correlation is tested with usual statistical technique. Also we have performed Chree superposed epoch analysis with lag-days correction for the observed solar plasma parameters at 1AU considering high values of occurrence probability of DAM radio emission of non-Jo origin from Jupiter as epoch days. The results of Chree analysis support the correlation study.
Chapter 6

In this chapter the short term periodicity in Io- and Non- Io DAM has been searched with each of twelve apparition Jovian DAM data using Chree Superposed analysis technique. The said technique applied initially with solar wind velocity considering high value of OP as key day and later with OP with sector boundary crossing of interplanetary magnetic field ( IMF ) as key day. It reveals from the analysis that there is a hidden periodicity of 8/9 days (~4 to 5 times of Io's rotational period (1.77 days) about Jupiter) in case of Io – DAM and 25/26 days (synodic period of Sun observed from its equatorial plane) that for non – Io DAM. Usual statistical technique has been applied to test the significance of the result obtained.

Chapter 7

Contribution of cosmic rays from neutron-monitor and multi – directional meson telescope data after necessary corrections have been subjected to Chree analysis. It reveals that there is a thirteen (13) month periodicity ( synodic period of Jupiter ) with 99% confidence level. Also solar diurnal variations of cosmic – rays show a definite increase during the interval 160° ≤ θₑ ≤ 260° which corroborates the previous investigations. This analysis further reveals that the amplitude for the favourable period is larger than those for the unfavourable period. The analysis indicates that a part of the increased intensity of cosmic rays observed at terrestrial stations are of Jovian origin.

Chapter 8

This chapter reports that some recent observations of Jovian signal in the DAM range as received at Kalyani ( LAT- 22° 57' 00";LONG – 268° 20'00" ) by using dipole antennae and the results have been examined with the standard available software and it reveals that the signal is of Jovian non – Io origin.