# A MODEL OF JUPITER'S DECAMETRIC RADIO EMISSIONS AS A SEARCHLIGHT BEAM

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**Abstract**

It has long been recognized that there is a marked long-term periodic variation in Jupiter's integrated radio occurrence probability. The period of the variation is on the order of a decade. Carr et al. [1970] showed that such variations are closely correlated with Jovicentric declination of the Earth ($D_E$). The range of the smoothed variation of $D_E$ is from approximately +3.3 to -3.3 degrees. This $D_E$ effect was extensively studied and confirmed by Garcia [1996]. It shows that the occurrence probability of the non-Io-A source is clearly controlled by $D_E$ at 18, 20, and 22 MHz during the 1957-1994 apparitions. We propose a new model to explain the $D_E$ effect. This new model shows that the beam structure of Jupiter radio emissions, which has been thought of like a hollow-cone, has a narrow beam like a searchlight, which can be explained by assuming that the three dimensional shape of the radio source expands along the line of the magnetic field. If we consider the sizes of the radio coherent region are 1000 m along Jupiter's magnetic field line and 200 m along the latitudinal direction, the equivalent beam pattern is 1 degree wide along Jupiter's magnetic field line and 5 degrees in latitude. As the searchlight beam is fixed with Jupiter's magnetic field, the pure geometrical effect of $D_E$ can be explained by this searchlight beam model.

## 1 Introduction

Although there is a long history of Jupiter radio observations since discovery in 1955, the emission mechanism of Jupiter's decametric radiation is not yet completely understood. This emission is generally believed to be produced by a mechanism related to cyclotron maser instability (see, for example, Wu [1985] and Treumann [2006], references therein).

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One of the unresolved problems of Jupiter's decametric radio emissions is the variation of occurrence probability with the order of a decade. The variation was first thought to be due to changes in solar activity (solar cycle). The Sun can influence the detection of Jovian decametric radiation by changing the local observing conditions, changing the density of plasma in the interplanetary medium and by changing conditions at the Jupiter radio source. Researchers have reported positive correlations with the magnetic sector structures in the solar wind, solar wind ram pressure and solar wind density. All of these correlations were found in short term (less than one month) variations of the occurrence probability of the non-Io-related sources [Barrow, 1978, Terasawa et al., 1978, Barrow et al.,1986]. Terasawa et al. [1978] speculate that shocks from the collision of fast and slow solar wind streams may enhance the non-Io-related emission source.

The period of the variation was also close to the orbital period of Jupiter (11.86 years). Carr et al. [1970] showed that such variations are closely correlated with Jovicentric declination of the Earth ($D_E$). The range of the smoothed variation of $D_E$ is from approximately +3.3 to -3.3 degrees. If this is the case, the observed variation appears to be a pure geometric effect caused by changes in the beam cross section seen from the Earth. The shape and angular dimensions of the part of the emission beam accessible to the Earth is shown in Figure 6a in Carr et al. [1970]. However the detail of the beam model has not been proposed so far. In this paper, we propose a new type of beam model a so called "searchlight beam model" to explain the $D_E$ effect.

## 2 The $D_E$ Effect

Carr et al. [1970] showed that three parameters of Jupiter's decametric emissions which apparently undergo cyclic variations with periods of the order of a decade are the mean occurrence probability for an apparition, the Central Meridian Longitude (CML) and the effective width of Source A. The period of the cyclic variations was close to the orbital period of Jupiter (11.86 years). One quantity that varies with the Jovian orbital period is the Jovicentric declination of Earth or $D_E$. Jupiter's axis is inclined by 3.1° to a perpendicular to its orbital plane. Jupiter's orbital plane is inclined by 1.3° to Earth's orbital plane. The combination of the two effects causes Earth to vary in Jovicentric declination by ±3.3°. $D_E$ varies with the 11.86 year orbital period of Jupiter as well as the 1 year period of Earth in its orbit. The $D_E$ effect is a geometrical one, resulting from the fact that the ground-based radio observers see different parts of a narrow emission beam that corotates with Jupiter. Each of these parameters was found to be more closely correlated with $D_E$.

Garcia [1996] extensively studied and confirmed this $D_E$ effect. Figure 1 shows the plots of seasonal averaged sunspot number, $D_E$ and occurrence probability at 18, 20 and 22 MHz for non-Io-A spanning the years from 1957 to 1994. The radio observations used in this study were mainly taken by Yagi antennas located at the University of Florida Radio Observatory (UFRO). The occurrence probability of the non-Io-A source varies in close step with $D_E$ as seen in Figure 1. Garcia [1996] reports that the changes in source width and location for non-Io-A are very large over the roughly 7 degree range of $D_E$. The high CML edge of the non-Io-A source also has a very strong dependence on $D_E$.

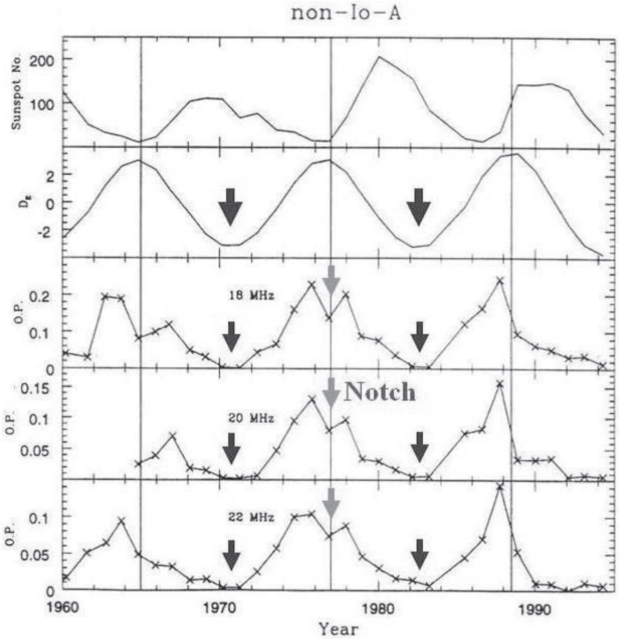


*Figure 1: Plots of seasonal averaged sunspot number, $D_E$ and occurrence probability (O.P.) at 18, 20 and 22 MHz for non-Io-A during the period from 1957 to 1994. The vertical lines mark the dates of highest $D_E$. The arrows indicate the minimum of $D_E$ and the notch. (after Garcia [1996])*

## 3 Model of a Searchlight Beam

Dulk [1967] proposed a conical sheet beam model for Jupiter's radio emissions. If the radiation is confined to a conical sheet, the radiation is detected from Earth when it crosses the plane of this sheet. However such a simple model can not explain the observed variations within a $D_E$ range of $\pm 3.3°$, because the conical sheet will always be intersected by planes $\pm 3.3°$ from the equatorial plane and it will not have a noticeable effect in the occurrence probability. We need a model of the beam pattern which captures these variations with Jovicentric latitude.

We propose a new model to explain the $D_E$ effect. This new model shows that the beam structure of Jupiter radio emissions, which has been thought of like a hollow-cone, has a narrow beam like a searchlight. The searchlight beam is an intensified part of a conical sheet beam. Figure 2 shows the searchlight beam superimposed on a conical sheet. As shown in Figure 3, the three dimensional structure of coherent radio source extending along the magnetic field line is considered to be the radio source of the searchlight beam. In this model we consider the simple assumption of the radio coherent length ($d$) to determine the size of the beam ($\theta$) by the equation of $\theta \approx \lambda/d$. Where $\lambda$ is the emitting wavelength. This equation is generally used to show the directivity pattern in the case of phase coherent antenna.

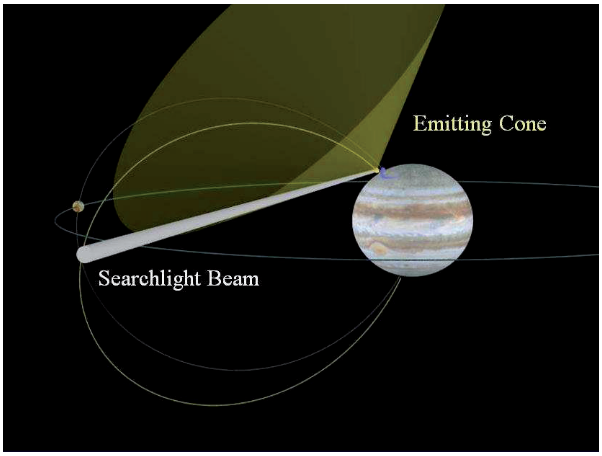


*Figure 2: A searchlight beam model of Jupiter's decametric radio emissions. The searchlight beam is the intensified part of a conical sheet beam (Emitting Cone).*

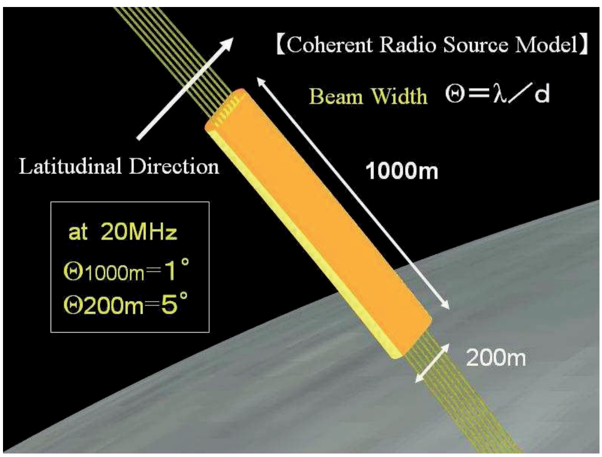


*Figure 3: A coherent radio source model to explain the searchlight beam. The three dimensional structure of the Jupiter radio source expands along the line of Jupiter's magnetic field.*

A "notch" as shown in Figure 1 at the points of maximum $D_E$ is confirmed. There exists an upper edge of the beam such that at high De (>2.7°) the occurrence probability starts to drop off again. This notch would be hard to explain by a simple cone but a searchlight beam model can illustrate the effect. So we use 5 degrees as the parameter of the radio source dimension perpendicular to the magnetic field direction.

If we consider the dimensions of the radio coherent region are 1000 m along Jupiter's magnetic field line and 200 m along the latitudinal direction, the equivalent beam pattern at 20 MHz emitting frequency is 1 degree wide along Jupiter's magnetic field line and 5 degrees in latitude. In this case the sharp beaming effect in the latitudinal direction can be considered. Figure 4 shows the cross section of initial beam pattern perpendicular to the plane of radio coherent region. The emitting ray is refracted upward by the local plasma conditions. As the searchlight beam is fixed with Jupiter's magnetic field, the pure geometrical effect of $D_E$ can be explained by this searchlight beam model. The important point of this model is to take into account the latitudinal dimension of the coherent radio region which may be associated with the shape of the current system along Jupiter's magnetic flux tube.

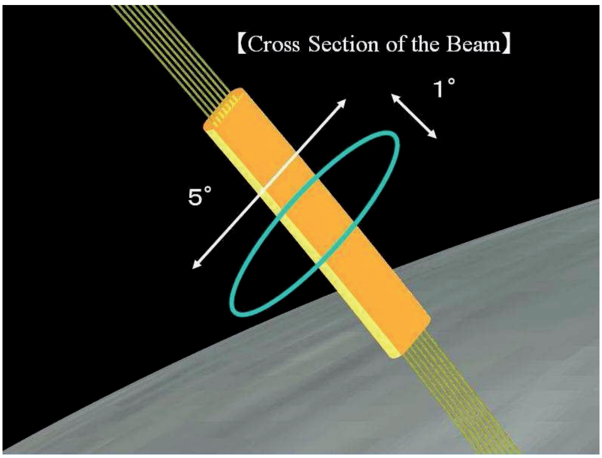


*Figure 4: Cross section of the searchlight beam based on the dimension of coherent length of 1000 m by 200 m at 20 MHz.*

This is the reason why one part of a conical sheet beam is intensified toward the equatorial plane. And also this searchlight beam model does not conflict with the previous idea of the conical sheet. As the radio observations of Jupiter are mainly on the equatorial plane, the full shape of conical sheet beaming has not yet been confirmed especially at the higher frequency of 20 MHz. This model is also based on the simple beam width equation. In the case of a much lower frequency than 20 MHz with constant coherent length, the equivalent size of the beam would be expected to be larger.

Recently Mutel et al. [2008] reported the first direct measurements of the angular beaming patterns of terrestrial auroral kilometric radiation (AKR) by using the four-spacecraft Cluster array. They showed each individual AKR burst radiates in the form of tangent plane beaming rather than filled or hollow cone beaming. The tangent plane beaming model suggests that AKR emission is confined to a plane containing the magnetic field vector at the source, and is refracted upward. This resulting beam pattern has very similar features to the searchlight beaming model.

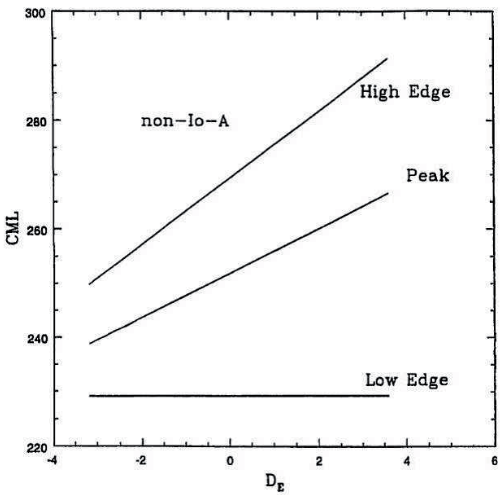


*Figure 5: The best fit lines to the high and low CML edges and peak of non-Io-A source at 18 MHz for each apparition during the period from 1957 to 1994. The high and low CML edges are defined by the full-width-half maximum longitude of the occurrence probability. (after Garcia [1996])*

## 4 Delta Zone Effect

If the searchlight beam model is correct, we have to explain the cyclic changes of the central meridian longitude (CML) and the effective width of non-Io-A source. Garcia [1996] showed the high CML edge of the non-Io-A source at 18 MHz has very strong dependence on $D_E$, but the low CML edge has no change with $D_E$ as shown in Figure 5. This means the parameters of the effective width and the peak-point of the non-Io-A source have a relationship with $D_E$. This non-uniform effect along the longitude can be explained by the delta zone effect displayed by the computer graphics in Figure 6. This delta zone effect is caused by the magnetic anomaly of the Jupiter polar region, because Jupiter's magnetic field has non-dipolar terms of much higher order. A number of magnetic field models based on various combinations of the Pioneer and Voyager magnetometer data have been developed (see, for example, Acuña et al. [1983], Connerney [1993], references therein). One of the latest model, named the VIP4 model [Connerney et al., 1998], incorporates data on the terrestrially observed infrared measurements of the positions of the Io flux tube as well as the in situ measurements by spacecraft.

Figure 6 shows the color coded magnetic surface contour of the north polar region from the view of 180° CML based on this VIP4 model. The red lines indicate the active magnetic flux tubes (L-shell = 5.9) intersecting Io's orbit from 170° to 220° CML every 10°. The L-shell value of the sources of the non-Io-A has been thought to extend along L-shell $\geq$7 field lines [Zarka, 1998; Clarke et al., 2004, and references therein]. The measurement by the modulation lane method shows the source L-shell value is close to 5.9 inside the Io plasma

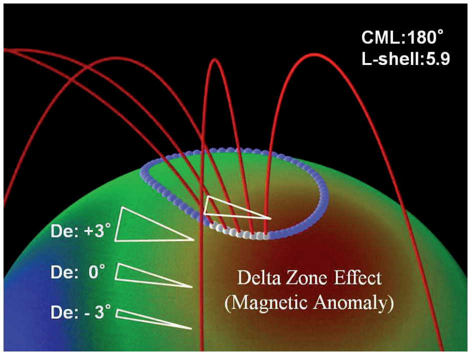


*Figure 6: Delta zone effect is shown by the triangular shape of white lines. The effective area of the shape of the triangle depends on the $D_E$.*

torus region [Imai et al., 2002]. If we assume the L-shell of the radio emitting source at 20 MHz is around 6, the radio sources are located at the gyro-frequency points of 20 MHz along the red lines in Figure 6. From Figure 6 the non-linearity of the Jupiter's magnetic field parameters, the so called magnetic anomaly, along the longitudinal direction can be considered. If we take into account the extension of the radio emitting region along the latitudinal direction, the two dimensional effective area of the radio emitting region seen from the observer may be changed by the geometrical effect. The shapes of the triangle, corresponding to the effective area, in Figure 6 indicate the dependence on $D_E$. The vertical dimension of the triangular shape corresponds to the number of radio sources which have the same beaming direction. This delta zone effect is one candidate to explain the cyclic changes of CML and the effective width of the non-Io-A source.

## 5 Conclusion

In this paper we show the long-term periodic variation of the occurrence probability of Jupiter's decametric radio emissions is caused by the $D_E$ effect which is related to the pure geometrical effect of sharp radio beaming. We propose the searchlight beam model which can explain this sharp beaming especially in a latitudinal direction. The three dimensional structure of the radio source is the important key parameter to produce the searchlight beam of Jupiter's decametric radio emissions. We calculate the beam pattern by using the dimensions of the radio coherent region. The calculated results show the existence of sharp beaming in the latitudinal direction. As the searchlight beam is the intensified part of a conical sheet beaming toward the equatorial plane, it does not conflict with the previous idea of the conical sheet model. We also propose the delta zone effect to explain the cyclic changes of CML and the effective width of the non-Io-A source. We believe that the searchlight beam model is very important in understanding the beaming of the planetary radio emissions.

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