A&A 387, L25–L28 (2002)
DOI: 10.1051/0004-6361:20020509

Astronomy & Astrophysics

# Search for decametric occultations of Io flux tube by Ganymede

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Received 5 December 2001 / Accepted 2 April 2002

**Abstract.** The satellite Ganymede sometimes occults the sources of the Jovian decameter radiation (DAM) associated with Io magnetic field line. The basic parameters of Ganymede occultations are calculated for 1990–2010. One of these events is found to coincide with a Io–A radio storm, which has been recorded in Nancay Observatory on 17 April 1994. In spite of the difficulty to identify the satellite shadow on sporadic DAM, the ratio of frequency emitted to calculated gyromagnetic frequency of electrons in the source is tentatively estimated as $f/f_{\rm c} \geq 1.11 \pm 0.02$. Formally, this limit contradicts the present generation theories where $f_{\rm c}$ in the DAM source is much closer to 1. Hence, improvements to the magnetic model (VIP4) or of the distortion of the Io flux tube are needed. Two possible shadows of the satellite are tentatively identified on the DAM frequency-time spectrogram. Multiple occultations are indeed possible in the Alfven wave model of Io-DAM interaction, and the lead angle of the emitting field line is not well known. That is why the tentative location of the radio source is made for both variants.

**Key words.** planets and satellites: individual – occultations – magnetic fields – radiation mechanisms: non-thermal

## 1. Introduction

It has been shown that the Galilean satellites can eclipse the sources of the Jovian decameter radiation (DAM) (Arkhipov 1997, 2001). Such occultations could help to precisely localize the regions of DAM generation and reveal the fine structure of the DAM sources. Moreover, the ratio of emission frequency to local cyclotron frequency of electrons in the source could be measured and used for evaluation of DAM theories.

The occultation method had been applied to the Jovian radio emissions only during the Galileo mission, at short distances and low frequencies (≤5.6 MHz; Kurth et al. 1997). In this way, new information could be obtained from Earth based observations.

That is why archive searches for DAM eclipses as well as new observations are very desirable. For this task the basic parameters of Ganymede occultations are calculated in this article.

## 2. Model assumptions

In accordance with present ideas on the radio emission generation, the following model is assumed for occultation calculations.

Jovian decameter radio emission is generated in fast extraordinary mode just above the local cyclotron frequency of electrons ($f_{\rm c}$) (see e.g. Zarka 1998). Even if $f \sim f_{\rm c}$, refraction probably becomes negligible at a short distance from the source, so that straight line propagation is an acceptable approximations for simplification of calculations. Of course, $f$ could be significantly above $f_{\rm c}$ (it is unknown a priori). However, our $f = f_{\rm c}$ approximation is still a useful asymptotic marker for prediction and practical search for occultations.

The Io-controlled emission is generated along or close to the magnetic field line connected with Io (Io flux tube – IFT; Fig. 1) (Carr et al. 1983). This IFT is calculated as an undisturbed magnetic line according to the VIP-4 model (Connerney et al. 1998). Of course, some delay of Io-Jupiter interaction must be taken into consideration. Thus the radio emitting field line is traced, which is formally connected with "effective" position of Io in the satellite orbital plane, at jovigraphic longitude $\lambda_{\rm Io} + {\rm d}\lambda_{\rm Io}$, where: $\lambda_{\rm Io}$ is the true Io longitude; and ${\rm d}\lambda_{\rm Io}$ is the lead angle. Here the corrections ${\rm d}\lambda_{\rm Io}$ are supposed with the two alternative methods:

(a) as approximation of difference between orbital longitudes $\lambda_{\rm Io}$ and the Io effective position, deduced from UV observations of IFT footprints (Clarke 1996): ${\rm d}\lambda_{\rm Io} \approx 14^\circ \sin(\lambda_{\rm Io}+59^\circ)+14^\circ$ (north); ${\rm d}\lambda_{\rm Io} \approx 2^\circ \sin(\lambda_{\rm Io}+160^\circ)+5^\circ$ (south). Uncertainty on the lead angle is of the order of several degrees.

(b) according to the analysis of DAM radiation pattern (Queinnec & Zarka 1998), ${\rm d}\lambda_{\rm Io} = 25^\circ$ (north) or $10^\circ$ (south) has been adopted.

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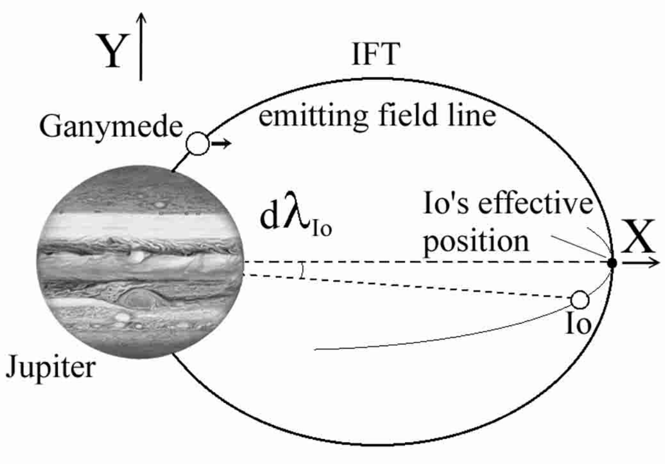

**Fig. 1.** Scheme of an occultation of the Io flux tube by Ganymede.

This dual strategy is reasonable, because the lead angle may be different in radio and UV, as the emitting electrons may not be exactly the same populations. As a result, the position of an Io-controlled DAM source is calculated as a point with $f = f_c$ on the magnetic line, which is connected with Io′s effective position.

The geocentric, differential coordinates of Jovian satellites are calculated with interpolation of ephemerides from *Bureau des longitudes* (`www.bdl.fr/ephem/ephesat/satformbis.html`). Although the errors of calculated positions are 0.001 $R_J$ ($R_J$ = 71 372 km is the equatorial radius of Jupiter), the real precision of eclipse prediction is limited by the lead angle uncertainty. Practically the error in visible coordinate of source is about the diameter of Ganymede (0.074 $R_J$).

## 3. Catalogue of occultations

To plan and analyze the observations, all IFT occultations by Ganymede have been calculated for 1990–2010 (see Table 1). Sometimes the Ganymede's centre occults IFT only with the UV lead angle, while it is impossible with the radio angle and vice versa. The following information is tabulated there for both versions (a) and (b) of lead angle: the date of occultation (day/month/year); the universal time of the event (UT; hour, min.); the frequency of the shadow center in dynamical spectrum of DAM (MHz); the central meridian longitude of Jupiter at occultation (CML, degree in system III 1965); the Io phase at occultation ($F_{Io}$, degree;); the hemisphere of occulted source (N- north; S- south); the geographical longitude ($\lambda_j$, degree); and latitude ($\varphi_j$, degree) of sub-Jovian point on the Earth at occultation.

To estimate the visibility of Jupiter for any observatory, the zenith angle of Jupiter could be calculated

$$Z_{obs} = \arccos[\sin\varphi_j \sin\varphi_o + \cos\varphi_j \cos\varphi_o \cos(\lambda_o - \lambda_j)] \quad (1)$$

where: $\lambda_o$ and $\varphi_o$ are the longitude and latitude of the observatory.

**Table 1.** The occultations of Io flux tube by Ganymede in 1990–2010.

| Date [dd/mm/yy] | UT [hh mm] | $f$ [MHz] | CML [deg] | $F_{Io}$ [deg] | N/S | $\lambda_j$ [deg] | $\varphi_j$ [deg] |
|---|---|---|---|---|---|---|---|
| 28/01/1994[b] | 06 58 | 27.1 | 70.4 | 36.1 | N | 349.2 | –14.6 |
| 18/02/1994[a] | 18 41 | 29.2 | 57.1 | 87.8 | N | 154.2 | –15.0 |
| 18/02/1994[b] | 18 47 | 33.1 | 60.3 | 88.6 | N | 152.9 | –15.0 |
| 19/03/1994[a] | 10 03 | 28.3 | 151.5 | 155.9 | N | 254.9 | –14.8 |
| 19/03/1994[b] | 10 31 | 29.3 | 168.4 | 159.8 | N | 247.9 | –14.8 |
| *17/04/1994[a] | 01 04 | 25.9 | 234.9 | 223.7 | N | 358.7 | –13.9 |
| *17/04/1994[b] | 01 16 | 25.1 | 242.7 | 225.5 | N | 355.4 | –13.9 |
| *24/04/1994[b] | 04 15 | 20.3 | 326.0 | 236.3 | N | 302.9 | –13.7 |
| 15/05/1994[a] | 14 24 | 28.3 | 257.4 | 278.5 | N | 127.6 | –12.8 |
| 15/05/1994[b] | 14 16 | 31.9 | 252.5 | 277.3 | N | 129.6 | –12.8 |
| 28/09/1994[b] | 16 20 | 32.0 | 265.9 | 241.3 | N | 330.3 | –15.4 |
| *21/01/1995[b] | 14 46 | 36.0 | 217.3 | 205.1 | N | 265.4 | –21.0 |
| *12/02/1995[a] | 03 41 | 34.7 | 246.8 | 264.7 | N | 53.6 | –21.5 |
| *12/02/1995[b] | 03 38 | 38.7 | 243.8 | 264.0 | N | 54.1 | –21.5 |
| 25/08/2000[b] | 06 01 | 22.3 | 189.4 | 239.7 | S | 4.5 | 21.0 |
| 15/09/2000[a] | 17 53 | 23.0 | 180.8 | 292.0 | S | 167.7 | 21.2 |
| 06/02/2005[a] | 21 55 | 38.1 | 248.4 | 277.7 | N | 92.8 | –6.0 |
| *27/11/2005[a] | 14 42 | 26.9 | 299.3 | 262.2 | N | 288.1 | –12.8 |
| *27/11/2005[b] | 14 41 | 27.5 | 298.8 | 262.0 | N | 288.2 | –12.8 |
| *07/02/2006[a] | 06 40 | 26.5 | 39.5 | 76.1 | N | 348.6 | –16.0 |
| *07/02/2006[b] | 06 43 | 30.1 | 41.5 | 76.5 | N | 347.8 | –16.0 |
| 07/03/2006[a] | 22 25 | 24.4 | 147.4 | 146.3 | N | 85.8 | –16.2 |
| 07/03/2006[b] | 22 55 | 25.4 | 165.4 | 150.5 | N | 78.3 | –16.2 |
| 29/03/2006[a] | 09 41 | 32.5 | 121.6 | 196.5 | N | 254.3 | –15.9 |
| 29/03/2006[b] | 09 45 | 31.9 | 125.0 | 197.3 | N | 253.1 | –15.9 |
| *05/04/2006[a] | 14 07 | 22.2 | 255.3 | 218.8 | N | 180.2 | –15.7 |
| *05/04/2006[b] | 14 24 | 20.2 | 265.4 | 221.1 | N | 176.0 | –15.7 |
| *12/04/2006[a] | 17 16 | 18.7 | 344.7 | 230.8 | N | 125.4 | –15.5 |
| *12/04/2006[b] | 17 13 | 19.8 | 342.6 | 230.3 | N | 126.2 | –15.5 |
| 26/04/2006[a] | 23 42 | 30.2 | 167.8 | 256.2 | N | 13.4 | –15.0 |
| *04/05/2006[a] | 03 41 | 19.4 | 285.9 | 275.3 | N | 305.1 | –14.8 |
| *04/05/2006[b] | 03 37 | 19.5 | 283.7 | 274.8 | N | 306.0 | –14.8 |
| 11/05/2006[a] | 06 20 | 18.2 | 357.4 | 283.4 | N | 257.4 | –14.5 |
| 01/06/2006[a] | 16 32 | 21.8 | 291.9 | 326.1 | N | 81.5 | –13.8 |
| 08/10/2006[a] | 16 01 | 37.2 | 238.6 | 281.3 | N | 328.4 | –17.0 |
| 22/07/2007[a] | 06 03 | 37.0 | 223.7 | 258.1 | N | 218.7 | –21.4 |

[a] The lead angle is taken from UV data.
[b] The lead angle is taken from radio data.

Obviously, such occultation is observable when a satellite eclipses the active DAM source, emitting towards the Earth. According to the maps of DAM occurrence for right- and left-hand polarizations separately (Carr & Desh 1976; Boudjada & Genova 1991), the most promising occultations are asterisked.

## 4. Search for DAM occultations

Unfortunately, no Jupiter observations were made on predicted dates with the UTR-2 radio telescope of the Institute of Radio Astronomy (Kharkov, Ukraine). The synoptic dynamic spectra of DAM from the archives of Nancay Observatory (`http://www.obs-nancay.fr/jupiter`) have thus been

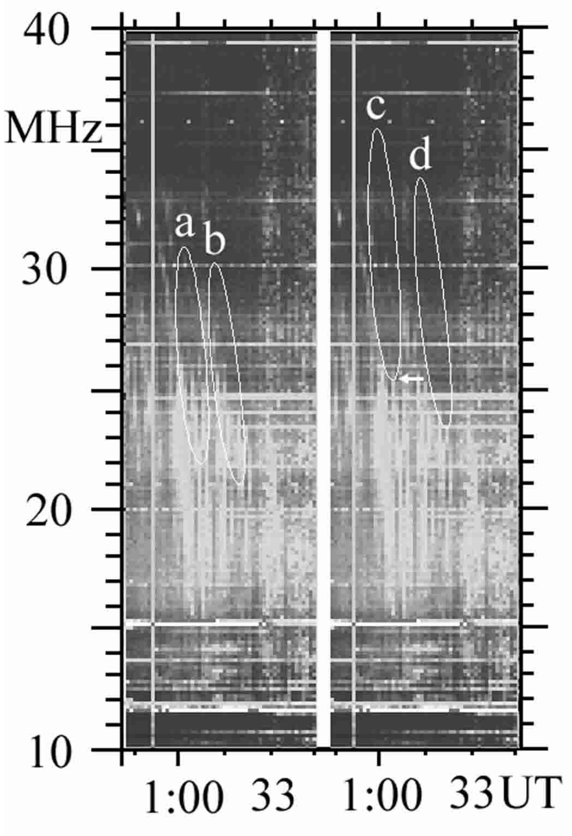

**Fig. 2.** Probable IFT occultations on the DAM dynamical spectrum of 17 April 1994 (right hand polarization). The predicted shadow contours with $f/f_\mathrm{c} = 1$ and $\mathrm{d}\lambda_\mathrm{Io} = 1°$ **a)** or $\mathrm{d}\lambda_\mathrm{Io} = 25°$ **b)** are shown as the light ellipsoids on the left panel. The candidates in the Ganymedes shadow are shown on the right panel: **c)** $f/f_\mathrm{c} = 1.15$ and $\mathrm{d}\lambda_\mathrm{Io} = -3°$; **d)** $f/f_\mathrm{c} = 1.11$ and $\mathrm{d}\lambda_\mathrm{Io} = 32°$.

used for the occultation search. As Ganymede occults some part of an emitting magnetic field line, the corresponding interval of frequencies must be shadowed in the DAM dynamical spectrum. Thus an elongated dark spot is formed in the spectrum, and this could be calculated. The typical dimensions of such a spot are 10 min and 9 MHz.

All corresponding Nancay spectra have been analysed (28/01/1994; 17.04.1994; 24/04/1994; 28.09.1994; 12.02.1995; 25.08.2000). Only on 17 April 1994 an Io–A storm (with right hand polarization) was recorded just in the predicted time interval of occultation. Both calculated contours of the Ganymede shadow, with the different lead angles (a) and (b), overlap the $L$-emission (Fig. 2, left). Of course, one possible explanation is the existence of several simultaneous radio sources, out of which only one is occulted by the satellite shadow. Conversely, there are two possible identifications of Ganymedes shadow above the Io-storm (Fig. 2, right). The most suitable ellipsoids are calculated with $f/f_\mathrm{c} = 1.15 \pm 0.01$ and $f/f_\mathrm{c} = 1.11 \pm 0.02$, $\mathrm{d}\lambda_\mathrm{Io} = -3°$ and 32° for (c) and (d) contours respectively. The search for interference fringes which should exist along the shadow borders (Arkhipov 2001) is impossible with the low resolution of the published spectrum.

In spite of the recognition problem, the spectrum of 17 April 1994 is of interest. Thus, $f/f_\mathrm{c} \geq 1.11 \pm 0.02$ for any identification of the shadow in the most probable range $-3° \leq \mathrm{d}\lambda_\mathrm{Io} \leq 32°$. Formally, this limit contradicts the hypothesis that $f/f_\mathrm{c}$ in the DAM source is much closer to 1. It is now believed (Zarka 1998) that DAM emission is produced close to the $X$ mode cutoff at

$$f \sim f_\mathrm{c}[\,1 + (f_\mathrm{p}/f_\mathrm{c})^2\,] \qquad (2)$$

where $f_\mathrm{p} = 8.99 \times 10^{-3}\,\mathrm{MHz}\,\sqrt{N_\mathrm{e}/\,1\,\mathrm{cm}^{-3}}$ is the plasma frequency of electrons and $N_\mathrm{e}$ is the electron density. Hence $f/f_\mathrm{c} - 1 \sim (f_\mathrm{p}/f_\mathrm{c})^2 < 3 \times 10^{-3}$ with $f_\mathrm{c} \sim 25\,\mathrm{MHz}$ and $N_\mathrm{e} < 1000\,\mathrm{cm}^{-3}$ in the DAM source when extrapolated from Voyager 2 radio occultation (Hinson et al. 1998). The DAM polarization suggests $N_\mathrm{e} < 10\,\mathrm{cm}^{-3}$ in IFT (e.g.: Shaposhnikov et al. 2000). Therefore, the found limit $f/f_\mathrm{c} = 1.11 \pm 0.02$ appears surprisingly high.

It is difficult to explain this result in terms of exotic lead angle ($\mathrm{d}\lambda_\mathrm{Io} < -3°$ or $\mathrm{d}\lambda_\mathrm{Io} > 32°$). Apparently, the $f_\mathrm{c}$ derived from magnetic field model could be underestimated. However, the gyromagnetic frequency, calculated using VIP4 and previous O6 GSFC models, has a quadratic difference of only 1.4 MHz along the Io magnetic shell at planetocentric distance of the occultation ($\simeq 1.14\,R_\mathrm{J}$). Hence, the standard error on calculated $f_\mathrm{c}$ is <1 MHz with VIP4, while the storm border exceeds the calculated $f_\mathrm{c}$ by >2.3 MHz. Another explanation of this discrepancy may be due to the additional magnetic field distortion by the electrical current which flows along the Io flux tube.

It has been strongly argued that Io–B DAM cannot arise from the instantaneous IFT only (Leblanc et al. 1994; Queinnec & Zarka 1998). It was proposed that the arcs of Io-controlled DAM are caused by a pattern of field-aligned currents, which are separated in longitude. These currents are carried by the Alfvenic disturbances as they bounce between the northern and southern ionospheres and the Io torus edge (e.g.: Bagenal & Leblanc 1988). Apparently, there are two arcs in the Io–A storm of 17 April 1994. Hence, a pair of radio sources could cause two shadows in the dynamic spectrum. This also justifies why both possible shadows are worth consideration.

The shadows border point with lowest frequency could be used for localization of the occulted radio source without any dependence upon the magnetic model. The universal time and frequency of this point is found for (c) ellipsoid by parabolic approximation of the storm border: $t_\mathrm{min} = 1\mathrm{h}\ 3.7\mathrm{m} \pm 0.3\ \mathrm{m}$ and $f = 25.16 \pm 0.14$ MHz (arrowed in Fig. 2). The tangential coordinates of the radio source with this frequency are:

$$X = X_\mathrm{G} = 0.565 R_\mathrm{J} \pm 0.003 R_\mathrm{J},$$

$$Y = Y_\mathrm{G} + R_\mathrm{G} = 0.883 R_\mathrm{J} \pm 0.001 R_\mathrm{J},$$

where: the $Y$ axis is directed from the center of Jupiter to its northern pole; $X_\mathrm{G}$, $Y_\mathrm{G}$ are the Ganymede coordinates for $t_{\min}$; $R_{\rm G} = 0.037 R_{\rm J}$ is the Ganymedes radius. For (d) ellipsoid: $t_{\min} = 1{\rm h}\,23.8{\rm m} \pm 1.3{\rm m}$; $f_{\min} = 23.4 \pm 0.4$ MHz; $X = 0.749 \pm 0.012\ R_{\rm J}$; $Y = 0.883 \pm 0.001\ R_{\rm J}$. Of course, these coordinates are tentative.

## 5. Conclusions

1. In 1990–2010 about 24 radio occultations of the Io flux tube by Ganymede could be observed from the Earth. Such phenomena are a promising and still unused tool to study the Jovian magnetosphere.
2. One of this events coincided with the Io–A radio storm, which was recorded in Nancay Observatory on 17 April 1994. The first attempt to measure directly the ratio of frequency emitted to calculated gyromagnetic frequency of electrons in the source leads to the limit of $f/f_{\rm c} \geq 1.11 \pm 0.02$. Formally, this limit contradicts the hypothesis that $f/f_{\rm c}$ in the DAM source is much closer to 1. One possible explanation is that the occultation is actually "hidden" by simultaneously emitting nearby radio sources (with $f/f_{\rm c} \sim 1$). Conversely, improvements to the magnetic model (VIP4) may be needed; or/and the distorsion of the Io flux tube must be taken into account.
3. Two candidate Ganymedes shadows are found on the DAM dynamic spectrum of 17 April 1994. Multiple occultations could be explained in terms of the Alfven wave model of Io-DAM interaction. However, the obtained coordinates of sources are tentative.
4. New observations of IFT occultations by Ganymede are desirable in 2005–2006.

*Acknowledgements.* I would like to express many thanks to Dr. Ph. Zarka, Dr. J. E. P. Connerney, Dr. J. H. Lieske, Dr. H. O. Rucker for their help with the literature and consultations. I also wish to thank Dr. L. Fleming for reading and commenting on the manuscript.

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