JOVIAN DECAMETRIC OCCULTATIONS BY CALLISTO IN 2001–2010

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Abstract

Sometimes the satellite Callisto occults the sources of the Jovian decameter radiation (DAM). The basic parameters of such events and the diffraction patterns of Callisto's shadow in the DAM dynamic spectrum are calculated for 2001–2010. The J. Lieske's theory of the Callisto motion and the VIP-4 magnetic model are used. Obtained tables and dynamic spectra would be a guide for DAM observations. As an observational result, the precise location of DAM sources and their dimensions can be used for evaluation of DAM theories and magnetic models.

1 Introduction

It has been shown that the satellite Callisto can eclipse the sources of the Jovian decameter radiation (DAM) [Arkhipov, 1997]. Such occultations could precisely localize the regions of DAM generation and reveal the fine structure of the DAM sources. Moreover, the ratio of emission frequency and 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). Thus, two sets of possible source regions were found from the Ganymede occultation of the hectometric radio source [Kurth et al., 1997c]. Nevertheless, Earth based observations can localize DAM sources more precisely, at better spatial resolution. In this way, the new information could be obtained on previously unprobed innermost parts of Jovian magnetosphere.

Unfortunately, the archives search for old DAM eclipses was unsuccessful. That is why the new observations are very desirable. For the planning of such experiments, the basic parameters of DAM occultations are calculated in this article.

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2 Model assumptions

In accordance with popular ideas, the following model is assumed for occultation calculations.

Jovian decameter radio emission is generated as R-X mode just above the local cyclotron frequency of electrons (f_c) [Carr et al., 1983]. For the first approximation, we can ignore the uncertain refraction. Indeed, at electron number density of of $N < 1000$ cm^{-3} above the Jovian ionosphere [Strobel and Atreya, 1983], we have $(f_p/f_c)f < 0.0001$ at $f_c = 30$ MHz, where f_p is the plasma frequency of electrons. Therefore, the refraction is negligible at $(f - f_c)/f_c$ $0.01 >> (f_p/f_c)f$. Hence, $f = f_c$ approximation seems appropriate for simplification of calculations. Of course, f could be significantly above f_c (it is unknown a priori). However, our $f = f_c$ approximation is still the useful asymptotic marker for prediction and practical search for occultations.

The Io-controlled emission is generated along the magnetic field line connected with Io (Io flux tube - IFT) [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 that line is traced, which is formally connected with effective position of Io in the satellite orbital plane, at jovigraphic longitude L + dL (where: L is the true Io longitude and dL is the leading angle). There are great discrepancies between estimations of the leading angle, varying from 15° to 70° [Genova and Aubier, 1985]. Here the corrections dL are found as approximations of differences between L and the longitudes of IFT footprints observed in UV [Clarke, 1996]: dL=14°* sin(L+59°)+14° (North); dL=2° sin(L+160°) + 5° (South). 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 the Io effective position.

Apparently, the non-Io emission is generated along magnetic lines which are connected with auroral zones. The most intense polar emissions are found between the magnetic lines, traced from 12 R_J (Jovian radii) and 30 R_J [Satoh and Connerney, 1999]. Accordingly, the non-Io DAM source is assumed as a point with $f = f_c$ on the magnetic line, traced from the magnetic equator at (12+30)/2=21 R_J distance. The VIP-4 magnetic model [Connerney et al., 1998] is used for location of DAM sources.

The geocentric, differential coordinates of Io and Callisto are calculated with interpolation of ephemerides from Bureau des longitudes (Paris, J. H. Lieske theory). Although the errors of calculated positions are 0.001 R_J, the real precision of eclipse prediction is limited by the leading angle uncertainty ($\approx 1.5°$ or 0.03 R_J) in the source longitude for Io-controlled DAM. This maximum error in visible coordinate of source is about the radius of Callisto. Therefore, the predicted centre of occultation usually would be inside of real Callisto's shadow in the DAM dynamical spectrum.

3 Phenomenology of DAM occultations

As Callisto occults some part of an emitting magnetic line, corresponding intervals of frequencies must be shadowed in the DAM dynamical spectrum. Thus the elongated dark

spot is formed in the spectrum. The typical dimensions of such details are 7–20 min. and 2–5 MHz. Some examples of such shadows with diffractional fringes are shown in Figure 1.

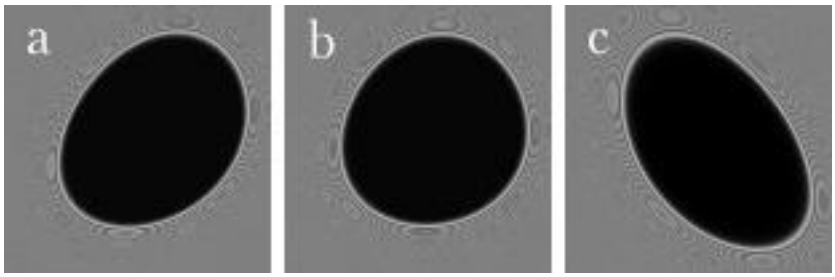

Figure 1: The calculated shadows of Callisto in the DAM dynamic spectrum of 27 June 2001: (a) the "perpendicular" occultation of a non-Io-A source (its cone of radiation opens at a 90° angle about the field line); (b) same occultation of a non-Io-A source, but at the 80°-angle of its radiation pattern; (c) the occultation of the Io flux tube.

The different form of the shadow depends on the angle α between projections of the emitting magnetic line and Callisto's motion. Obviously, this angle is measurable: $\alpha = arcsin(A/B)$, where: A is the maximum of instantaneous shadow dimension in frequency; B is the total dimension of the shadow in frequency. The model of Jovian magnetic field with the Callisto coordinates permits finding that point on the line of sight, where calculated α is equal to observed one. This unique method for 3D-location of DAM sources is useful especially for non-Io emissions, which could be generated on sufficiently different magnetic lines.

To model a realistic view of DAM occultation, the dynamical spectra of an IFT eclipse (29 August 2010) and the corresponding Jovian radio storm (8 September 1999; UTR-2 synoptical observation) are multiplied. The result is shown in Figure 2 (left). In reality, the shadow could be of low contrast because of other, non-occulted sources. The following algorithm is proposed for the search for DAM eclipses. The dynamical spectrum is smoothed by the sliding window in a kind of circle, then the result of this procedure is subtracted from the initial image. Thus the pixels, which are brighter than the smoothed level, are considered as "white", and others are considered "black". This clipping permits us to see details of extremely low contrast (Figure 2, right).

The diffraction fringes may be used for estimation of monochromatic source dimension. For example, the fringes of the 27/06/2001 IFT occultation have been calculated for unresolved sources (Figure 3a). This spectrum is multiplied with the radio storm of 08/09/1999 (Figure 3b) in the scale of Jovian synoptical observations on the UTR-2 radio telescope. Obtained realistic spectrum of the fringes is filtered (Figure 3c) to show the first 4 fringes. The first maximum is smoothed at 200 km-sources; the fourth one disappears at 100 km-dimension.

Of course, the Poisson spot could image the DAM source in dynamical spectrum with $\sim$ 4 km-resolution [Arkhipov, 1997]. However, the number integration of the Fresnel–Kirchhoff equation leads to a Poisson spot amplitude of 1–3% of the shadow background. The dynamical compression of 0.018 and 1 km-irregularities of Callisto's limb were taken into account. So, the observation of the Poisson spot is problematical.

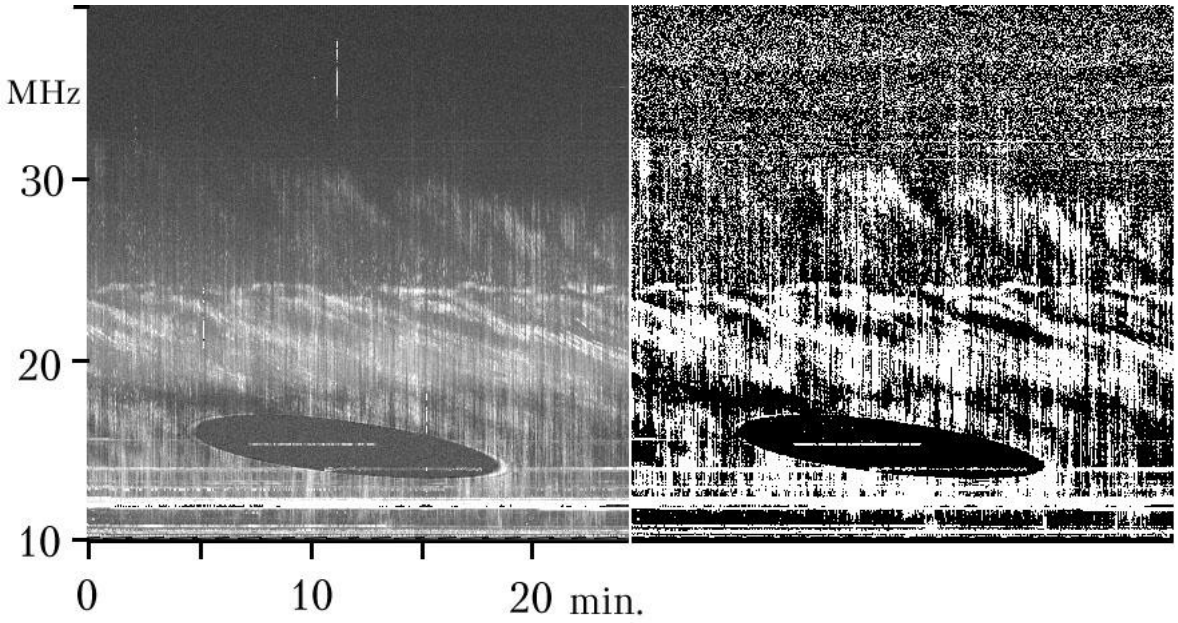

Figure 2: The modeling of Callisto's shadow from Io flux tube at 29 August 2010 on a corresponding radio storm of DAM (8 September 1999; observed at UTR-2 radiotelescope, IRA, Kharkov): - the realistic view of DAM occultation in the dynamical spectrum (left); - the filtered dynamical spectrum for revealing the shadow and its details of low contrast (right).

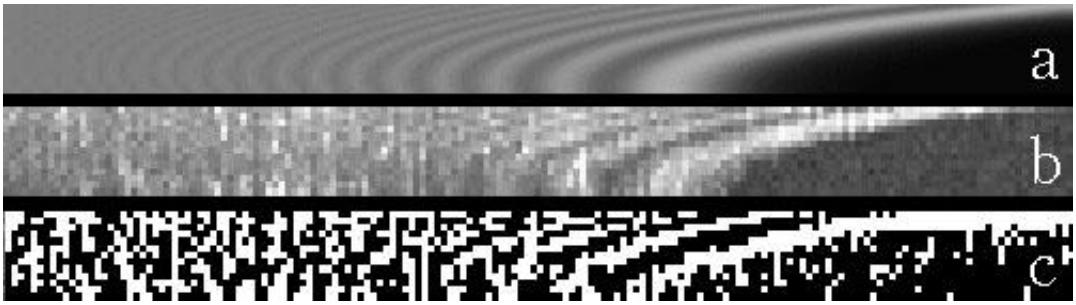

Figure 3: The simulation of diffraction fringes near Callisto's shadow in DAM dynamical spectrum (the occultation of Io flux tube at 27 June 2001): (a) the computed fringes for the unresolved DAM sources; (b) the realistic view of these fringes in DAM dynamical spectrum at UTR-2 observations; (c) the filtered dynamical spectrum reveals up to 4 fringes.

4 Catalogue of occultations

To plan the observations, 281 possible DAM occultations by Callisto have been calculated for 2001–2010. Obviously, such an event 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 and Desch, 1976; Boudjada and Genova, 1991], the promising occultations are selected. However, the occultations under 10 MHz are rejected because of radio and ionospheric interference. Moreover, the non-Io events above 25 MHz are ignored also because of low DAM probability there.

Table 1: The occultations of Io-controlled Jovian decameter radiation by Callisto in 2001–2010.

Date	UT	MHz	CML	Fio	N/S	Lj	aj
27/06/2001	08 02	17.6	223.0	224.8	S	51.0	23.1
02/09/2001	17 39	22.3	207.0	247.7	S	215.8	22.8
01/11/2004	08 01	13.6	266.2	230.3	N	26.3	-2.1
04/12/2004	22 50	11.4	6.9	225.3	N	137.3	-4.4
26/07/2005	13 19	9.9	329.1	243.5	N	48.9	-3.8
16/07/2007	20 00	10.5	185.9	234.9	N	15.7	-21.5
13/08/2010	02 59	14.6	180.8	101.2	S	357.7	-0.3
29/08/2010	19 35	15.2	313.4	258.8	S	91.8	-0.9
20/11/2010	21 27	24.7	281.5	251.3	S	334.2	-3.9

The result of this selection is presented as a catalogue of occultations (Tables 1 and 2). The following information is tabulated there: - 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 III 1965 system); - the Io phase at occultation (Fio , degree;); - the hemisphere of occulted source (N - North; S - South); - the geographical longitude (Lj , degree); and latitude (aj , 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: Zj=arccos[sin(aj)* sin(ao)+cos(aj)*cos(ao)*cos(Lo-Lj)], where: Lo and ao are the longitude and latitude of the observatory.

The formal errors of tabulated results are $\sim$ 10 s and $\sim$ 10 kHz for time and frequency respectively.

It is assumed for non-Io emissions, that the magnetic field in the DAM source is perpendicular to the line of sight. Thus the couple of "perpendicular" occultations is calculated for one of Callisto's lower conjunctions. At some unknown/arbitrary angle of the conical radiation pattern, the non-Io emission could be eclipsed inside the time interval limited by these "perpendicular" occultations. Hence the tabulated, "formal", non-Io occultations must be considered as the limits of time intervals for possible eclipses. The exact moment of non-Io eclipse is unpredictable because of unknown longitude of the emitting magnetic line.

5 Conclusion

1. DAM occultations by Callisto seem to be observable and detectable.
2. The position of Callisto's shadow in dynamical spectrum of DAM could elucidate the origin of radio emissions.
3. The 3D-location of non-Io sources is determinable from the shape of the Callisto shadow in DAM dynamical spectrum.

Table 2: The occultations of non-Io Jovian decameter radiation by Callisto in 2001–10/2006.

Date	UT	MHz	CML	Fio	N/S	Lj	aj
12/02/2001	14 03	11.3	310.1	191.7	S	67.2	19.9
12/02/2001	15 50	13.1	14.8	206.7	S	40.4	19.9
18/03/2001	03 26	13.1	356.9	176.0	S	196.8	20.7
18/03/2001	05 21	14.2	66.7	192.2	S	167.9	20.7
03/04/2001	23 18	15.2	242.4	357.1	S	245.8	21.2
04/04/2001	00 19	16.3	279.0	5.7	S	229.7	21.2
24/05/2001	12 34	17.6	317.5	192.5	S	8.0	22.6
24/05/2001	14 01	20.3	10.1	204.8	S	346.2	22.6
10/06/2001	09 41	20.8	248.0	24.3	S	38.6	22.9
10/06/2001	10 34	22.0	279.9	31.8	S	25.4	22.9
21/12/2004	15 36	13.0	142.5	22.2	N	231.3	-5.2
21/12/2004	17 57	14.5	227.8	42.1	N	196.0	-5.2
24/01/2005	03 04	9.9	126.3	352.6	N	28.2	-6.1
24/01/2005	05 49	11.3	226.0	15.9	N	347.0	-6.1
09/02/2005	20 56	10.9	304.0	159.3	N	104.7	-6.0
09/02/2005	21 57	9.3	341.0	167.9	N	89.3	-6.0
31/03/2005	16 02	9.0	99.9	217.4	N	124.8	-4.2
31/03/2005	18 33	11.2	190.9	238.9	N	87.1	-4.2
17/04/2005	07 13	10.5	181.2	4.5	N	238.3	-3.4
17/04/2005	09 35	9.6	267.0	24.5	N	202.8	-3.4
03/05/2005	02 31	12.8	266.1	151.0	N	351.5	-2.7
03/05/2005	23 48	10.6	312.1	161.8	N	332.4	-2.7
20/05/2005	13 30	14.6	338.5	295.8	N	108.9	-2.3
20/05/2005	14 18	13.1	7.5	302.5	N	96.9	-2.3
12/08/2005	05 33	15.9	83.2	33.3	N	150.7	-4.8
12/08/2005	07 01	19.1	136.0	45.6	N	128.9	-4.9
14/09/2005	22 58	15.7	274.4	49.5	N	222.9	-7.3
15/09/2005	00 03	13.0	314.1	58.8	N	205.5	-7.3
21/11/2005	08 50	11.2	263.8	73.2	N	20.7	-12.4
21/11/2005	10 13	9.2	313.9	85.0	N	359.9	-12.4
08/12/2005	03 28	8.6	105.4	243.2	N	87.8	-13.5
08/12/2005	06 17	10.4	207.4	266.9	N	45.6	-13.5
01/09/2006	10 12	11.0	220.7	268.7	N	88.5	-15.0
01/09/2006	12 07	9.2	290.2	285.0	N	59.9	-15.0
05/10/2006	01 41	11.9	342.3	268.8	N	187.7	-16.8
05/10/2006	02 34	10.8	14.4	276.3	N	174.4	-16.8
21/10/2006	22 21	11.6	256.6	95.6	N	225.4	-17.7
21/10/2006	23 48	9.5	309.0	108.0	N	203.7	-17.7

Table 3: The occultations of non-Io Jovian decameter radiation by Callisto in 11/2006-2010.

Date	UT	MHz	CML	Fio	N/S	Lj	aj
07/11/2006	17 26	9.8	113.2	270.0	N	286.2	-18.6
07/11/2006	20 09	11.7	211.9	292.9	N	245.4	-18.6
11/12/2006	11 54	11.9	343.5	293.9	N	343.4	-20.2
11/12/2006	12 48	10.8	15.9	301.4	N	330.1	-20.2
28/12/2006	08 49	11.7	267.7	124.2	N	16.7	-20.9
28/12/2006	10 08	9.6	315.4	135.3	N	357.0	-20.9
14/01/2007	03 32	10.0	112.4	294.7	N	82.9	-21.4
14/01/2007	06 14	11.8	210.4	317.5	N	42.4	-21.4
16/02/2007	20 16	12.0	283.7	306.6	N	165.5	-22.0
16/02/2007	21 24	9.9	325.1	316.3	N	148.3	-22.0
05/03/2007	13 21	10.9	71.5	106.6	N	254.5	-22.2
05/03/2007	04 56	12.8	129.1	120.1	N	230.7	-22.2
22/03/2007	08 38	12.0	299.5	284.1	N	309.8	-22.3
22/03/2007	09 38	10.1	336.2	292.7	N	294.6	-22.3
11/05/2007	08 28	11.6	265.0	20.3	N	261.5	-22.2
11/05/2007	09 48	9.5	313.5	31.7	N	241.5	-22.2
27/05/2007	22 48	11.9	315.9	159.0	N	28.8	-22.0
27/05/2007	23 43	10.3	349.5	166.8	N	14.9	-22.0
13/06/2007	12 40	12.3	349.4	294.6	N	161.9	-21.8
13/06/2007	13 33	11.2	21.5	302.2	N	148.7	-21.8
16/07/2007	17 03	12.1	78.4	209.6	N	60.2	-21.5
16/07/2007	18 38	14.4	136.4	223.2	N	36.2	-21.5
02/08/2007	10 12	13.9	228.9	12.2	N	145.3	-21.4
02/08/2007	11 51	11.7	288.9	26.2	N	120.5	-21.4
04/09/2007	19 50	14.5	142.6	327.3	N	329.6	-21.7
04/09/2007	22 03	16.4	222.7	346.0	N	296.5	-21.7
08/10/2007	10 38	18.3	240.3	323.1	N	77.8	-22.3
08/10/2007	12 00	15.8	290.0	334.7	N	57.3	-22.3
25/10/2007	05 10	19.2	77.2	132.0	N	146.2	-22.6
25/10/2007	06 23	22.1	121.2	142.4	N	128.0	-22.6
27/11/2007	23 27	24.6	299.7	155.2	N	207.1	-23.1
28/11/2007	00 10	20.6	325.8	161.4	N	195.3	-23.1
14/12/2007	19 57	24.6	208.0	341.1	N	246.9	-23.2
14/12/2007	21 25	24.7	261.2	353.4	N	224.9	-23.2
10/07/2010	18 31	21.5	303.2	153.4	S	158.6	0.0
10/07/2010	19 42	24.7	346.3	163.5	S	140.7	0.0
15/09/2010	08 02	17.5	296.3	22.5	S	246.3	-1.8
15/09/2010	09 18	20.1	342.0	33.2	S	227.4	-1.8
01/10/2010	22 09	18.7	338.5	1 60.5	S	16.2	-2.6
01/10/2010	23 39	21.6	33.3	173.2	S	353.5	-2.7

4. The diffraction fringes around the Callisto's shadow are detectable. They could be used for the estimation of DAM source dimension. Unfortunately, the observation of the Poisson spot is very problematical.

5. The catalogue of DAM occultations by Callisto is compiled for 2001–2010. Obviously, such eclipses are sufficiently frequent for practical utilization.

It would be a pity if such unique chances for DAM studies will be lost again. An international co-operation for DAM occultation patrol is very desirable.

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References

Arkhipov, A. V., Jovian decametric eclipses by the Galilean satellites, in *Planetary Radio Emissions IV*, edited by H. O. Rucker, S. J. Bauer, and A. Lecacheux, Austrian Academy of Sciences Press, Vienna, 129–132, 1997.

Boudjada M. Y., and F. Genova, The left–hand polarization sense of the Jovian decameter radiation, *Astron. Astrophys. Suppl. Ser.*, **91**, No.2, 453–467, 1991.

Carr T. D., and M. D. Desch, Recent decametric and hectometric observations of Jupiter, in Jupiter, edited by T. Gehrels, University of Arizona Press, Tucson, 693–735, 1976.

Carr, T. D., M. D. Desch, and J. K. Alexander, Phenomenology of magnetospheric radio emissions, in Physics of the Jovian Magnetosphere, edited by A. J. Dessler, Cambridge Univ. Press, Cambridge, 226–284, 1983.

Clarke, J. T., Far–ultraviolet imaging of Jupiter's aurora and the Io "footprint", *Science*, **274**, No. 5286, 404–409, 1996.

Connerney, J. E. P., M. H. Acuna, N. F. Ness, and T. Satoh, New models of Jupiter's magnetic field constrained by the Io flux tube footprint, *J. Geophy. Res.*, **103**, No. A6, 11929–11939, 1998.

Genova, F., and M. G. Aubier, Io–dependent sources of the Jovian decameter emission, *Astron. Astrophys.*, **150**, No.1, 139–150, 1985.

Kurth, W. S., D. A. Gurnett, S. J. Bolton, A. Roux, and S. M. Levin, Jovian radio emissions: an early overview of Galileo observations, in *Planetary Radio Emissions IV*, edited by H. O. Rucker, S. J. Bauer, and A. Lecacheux, Austrian Academy of Sciences Press, Vienna, 1–13, 1997c.

Satoh T., and J. E. P. Connerney, Jupiter's H+3 emissions viewed in corrected jovimagnetic coordinates, *Icarus*, **141**, 236–252, 1999.

Strobel, D. F., and S. K. Atreya, Ionosphere, in Physics of the Jovian Magnetosphere, edited by A.J. Dessler, Cambridge Univ. Press, Cambridge, 51–67, 1983.