Galileo's Medicean Moons: their impact on 400 years of discovery
Proceedings IAU Symposium No. 269, 2010
C. Barbieri, S. Chakrabarti, M. Coradini & M. Lazzarin, eds.

doi:10.1017/S1743921310007490

Study of mutual occultation phenomena of the Galilean satellites at radio wavelengths

S. Pluchino[1], E. Salerno[1], G. Pupillo[1,2], F. Schillirò[1], A. Kraus[3], K.-H. Mack[1]

[1] INAF - Istituto di Radioastronomia, via Gobetti 101, I-40129 Bologna, Italy
[2] INAF - Osservatorio Astronomico di Torino, Strada Osservatorio 20, I-10025 Torino, Italy
[3] Max-Planck-Institut für Radioastronomie, Auf dem Hgel 69, D-53121 Bonn, Germany

Abstract. We present preliminary results for our study of mutual phenomena of the Galilean satellites performed at radio wavelengths with the Medicina and Noto antennas of the Istituto di Radioastronomia - INAF, and with the Effelsberg 100-m radio telescope of the Max-Planck-Institute for Radioastronomy, Bonn. Measurements of the radio flux density variation during the mutual occultations of Io by Europa and Ganymede were carried out during the PHEMU09 campaign at 22 GHz and 43 GHz. Flux density variations observed at radio wavelengths are consistent with the typical optical patterns measured when partial occultations occur.

Keywords. Occultations, Planets and satellites: individual (Europa, Ganymede, Io, Jupiter), Radio continuum: solar system

1. Introduction

Twice every 11.8 years Jupiter transits the nodes of its orbit. Since the inclination of the orbital planes of Galilean satellites with respect to the planet's equatorial plane is very small, for a few months during these passages, the satellites either occult or eclipse each other, depending on whether they are collinear with the Earth or with the Sun, respectively. These events are referred to as mutual phenomena or PHEMU (Figure 1). Their observation can be used, for instance, to derive corrections of the orbital parameters or to study the surface properties of the involved Jovian satellites. A typical example is given by the activity of Io's volcanoes. The Galileo mission has revealed 74 active volcanic centers on Io's surface (73 hot spots plus the Ra Patera plume), and 23 additional sites that were identified as probable active volcanic centers. There are two types of hot spot activity in terms of duration: persistent (active for periods longer than one year) and sporadic (events that persist up to 3 months) (Lopes-Gautier *et al.* 1999). The persistent hot spots are particularly important for the study of Io activity because they most likely represent the major pathways of magma to the satellite surface. Imaging of Io at shorter IR wavelengths (from 1 to 5 micrometers) has revealed a higher number of hot spots whose temperatures are typically included within the range of 650 K and 750 K reaching sometimes even higher values (Spencer *et al.* 1994, McEwen *et al.* 1997). Variations of the hot spot activity in terms of power output have been measured with ground-based optical and IR observations. Occultation phenomena were used to study the temperature of the Loki volcano - the most powerful volcano in the solar system - that is known to undergo periods of brightening and to be the site of giant outbursts. Optical and infrared data obtained during an occultation at a wavelength of 4.8 microns showed a large drop/jump of the flux density simultaneously with the disappearance/reappearance of Loki behind the limb of the occulting satellite (Howell 1998, Arlot *et al.* 2006). So far mutual phenomena, and in particular mutual satellite occultations, have been rarely studied at radio wavelengths. The major problem in observing the Galilean satellites with single dish radiotelescopes is in fact the strong Jovian radio-emission that may fall within the primary beam pattern of the antenna. The Jupiter flux density observed with the Very Large Array (VLA) radio interferometer is about 10 Jy at 6 cm and 35 Jy at 2 cm (de Pater *et al.* 1984). Observations of occultations by Jupiter do not provide the high angular resolution possible in mutual events whereas they can be obtained when Io is in eclipse and therefore radio flux density measurements are more sensitive to faint hot spots. Since no thick atmosphere surrounds the Galilean satellites, the observations of these phenomena are extremely accurate for astrometric purposes. In the case of Io, flux density variability depends on the wavelength, the time and the location on the surface of the hot spots. Ground-based observations at radio wavelengths are therefore extremely important in order to collect further information on the characterization, localization and time evolution of Io's volcanoes.

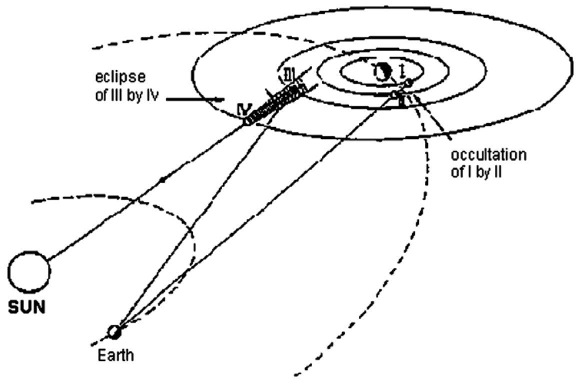

Figure 1. Mutual events (occultation and eclipses) between Jupiter satellites.

2. Observations of PHEMU at radio wavelengths

The total flux density of the eclipsed satellite measured by a ground-based radiotelescope is defined as the integral over all points of its surface, each considered as a source. Taking into account the fraction of brightness due to each point (including hot-spots), the resulting integral is calculated as sum over finite satellite surface elements. By partitioning the surface of the eclipsed satellite into a number of finite elements and assuming that radio flux density is isotropically irradiated by the satellite surface in all directions, the flux density sent by a surface element toward a ground-based observer will then be proportional to the area of this element, its brightness temperature, and the cosine of the angle between the normal to the surface of the current element and the direction of the ground-based observer. For each occultation event, a numerical model was computed and displayed by a customized software which was able to simulate the flux density variation by setting as input parameters the satellites radii, the mean flux densities, the impact parameter and the time duration. Figure 2 shows the simulations performed for the 2OCC1 PHEMU events occurred on June 10^{th} (on the left) and December 18^{th} (on the right) 2009. At the top of the figure the astrometric maps of the PHEMU events are shown. The maps were derived from JPL ephemeris values of the Jovian satellites. Blue and orange circles indicate side and central positions respectively of Io during the occultation. Red circles indicate the Europa position during the maximum of the occultation.

https://doi.org/10.1017/S1743921310007490 Published online by Cambridge University Press

In the middle of the figure the numerical model of the occultation curves computed by the software is shown.

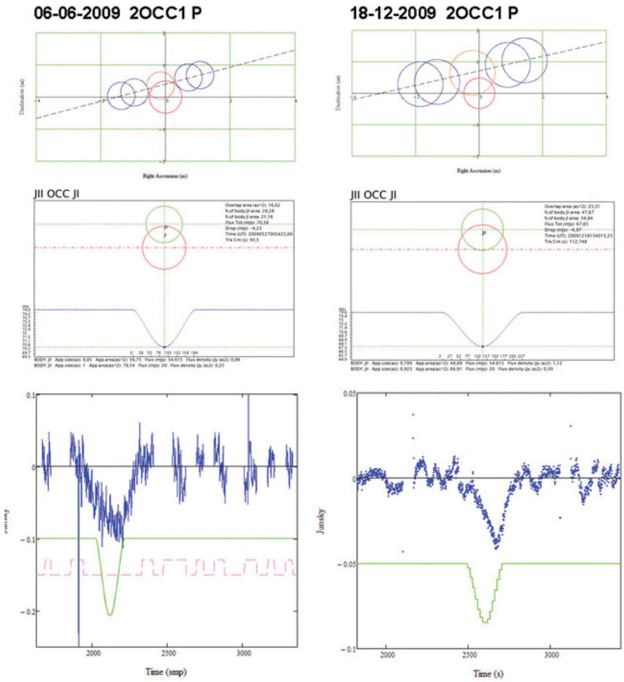

Figure 2. Top: astrometric maps of the 2OCC1 PHEMU events occurred on June 10th (on the left) and December 18^{th} (on the right) 2009. Middle: numerical model of the occultation curves (see text for details).

A summary of the occultation events observed during the PHEMU09 campaigns is presented in Table 1. Observations were performed with the Medicina and Noto 32-m antennas of the Italian Istituto di Radioastronomia and with the 100-m radiotelescope of the Max-Planck-Institute for Radioastronomy, Bonn. Observational frequencies were 43 GHz at Noto, 22 GHz at Medicina and 10 or 32 GHz (according to the weather conditions) at Effelsberg.

At Medicina and Noto data were recorded with the Mark IV backend used for the Very Long Baseline Interferometer (VLBI) observations. At Effelsberg data were taken with the Digital Backend used for continuum observations. Data acquired by the Italian antennas were post-processed with the Advanced Software Tools for Radio Astronomy (ASTRA) (Pluchino 2008). Data collected at Effelsberg were analyzed with the CONT2 subpackage of the Toolbox package for the analysis of single-dish radio observations (von Kap-herr 1977).

Radio occultation measurements require to point the occulted satellite (Io in this case) and to track it while it is occulted by the other one (Europa or Ganymede). Assuming an event-length nodding cycle with a block integration time of 1 s per point, we sampled the occultation curves with a number of ON-source total power measurements equal to the expected duration of the event in seconds. Absolute flux density calibrations were performed by using the radio source J2131-1207 characterized by flux densities of 1.2, 0.55 and 0.49 Jy at 5, 22 and 43 GHz respectively. The averaged difference of the calibrated ON-source and OFF-source gave as a flux density of 0.5 ± 0.1 Jy for Io, 0.6 ± 0.3 for

https://doi.org/10.1017/S1743921310007490 Published online by Cambridge University Press

Table 1. List of observed events. In column one, n. 1 indicates the Io satellite, n. 2 and 3 indicate the Europa and Ganymede satellites, respectively. P and A indicates partial and annular occultation respectively.

Phenomena	**Date of maximum**			**Time of maximum**			**Mag.**	**Dur.**	**Satellite distance**	**Elevation at**		
										Md	**Nt**	**Eff**
	YYYY	MM	DD	h	m	s		s	RS	deg	deg	deg
2 OCC 1 P	2009	6	10	5	11	43.	0.152	187	2.2	+29	+35	+24
2 OCC 1 P	2009	6	17	7	17	46.	0.064	145	2.0	+12	+14	+11
3 OCC 1 P	2009	10	8	17	51	6.	0.030	184	3.3	+25	+33	+18
2 OCC 1 A	2009	10	15	17	21	44.	0.426	221	1.5	+24	+33	+18
3 OCC 1 P	2009	10	15	20	30	33.	0.071	254	3.9	+25	+30	+20
2 OCC 1 P	2009	10	22	19	30	19.	0.426	223	1.7	+27	+33	+22
2 OCC 1 A	2009	11	16	15	14	29.	0.426	234	2.6	+25	+33	+18
2 OCC 1 A	2009	11	23	17	30	54.	0.426	238	2.8	+28	+34	+23
3 OCC 1 P	2009	11	28	13	46	42.	0.025	254	5.4	+20	+28	+14
2 OCC 1 P	2009	11	30	19	48	53.	0.388	240	3.1	+12	+14	+10
2 OCC 1 P	2009	12	11	11	18	38.	0.281	237	3.5	+07	+13	+01
2 OCC 1 P	2009	12	18	13	40	16.	0.201	227	3.7	+27	+35	+20
2 OCC 1 P	2009	12	25	16	3	14.	0.123	206	4.0	+28	+35	+24
2 OCC 1 P	2010	1	1	18	27	34.	0.054	169	4.2	+10	+11	+09
2 OCC 1 P	2010	3	21	10	8	35.	0.397	1882	1.4	+38	+46	+32
2 OCC 1 P	2010	3	28	9	1	15.	0.400	1980	1.3	+32	+31	+30

Figure 3. From the left: the 32-m Medicina, 32-m Noto and 100-m Effelsberg radiotelescopes.

Europa and 0.6 ± 0.3 Jy for Ganymede. The distance between the flux calibrator and Io ranged from 2.6 deg to 40 arc min. Different types of OFF-source measurements were also performed during occultations in order to subtract background noise and to monitor the stability of the receivers gain. The OFF-source measurements (obtained with a RA offset of 1 deg) were subtracted from the ON-source to also remove possible contributions of the Jupiter radio emission in the side lobes of the antenna's beam. Since the beam width at 43 GHz is approximately 1 arcmin we can exclude at this frequency the strong contribution of Jupiter inside the antenna's main lobe, whereas any contribution into the secondary side lobes would attenuate the signal by a factor of 100. Due to the proper motion of the satellites, we performed an accurate tracking by constantly pointing the antenna according to the coordinates provided by the JPL Horizon Solar System Dynamics facilities. The 22 GHz receiver at Medicina allowed us to integrate with a bandwidth of 2 GHz, dual polarization, obtaining a sensitivity of approximately 12 mJy with an integration time of 0.68 s achieved with an original sampling interval of 40 ms. Recent observational tests performed with the 43 GHz receiver at Noto on the Jupiter satellites showed the feasibility of the high-frequency front-end for this kind of measurements.

https://doi.org/10.1017/S1743921310007490 Published online by Cambridge University Press

3. Results

We have studied PHEMU of the Galilean satellites at radio wavelengths by using the radio occultation technique. Figure 4 shows two examples of the flux density variations measured during occultations. Signals are total power, already ON-OFF corrected and calibrated. Blue curves indicate the flux density measured at 22 GHz by the Medicina antenna during the 2OCC1 PHEMU events occurred on June 10th (on the left) and December 18th (on the right) 2009. Signal integrations were performed over the entire available bandwidth. Green curves indicate the expected flux density variation according to the numerical model.

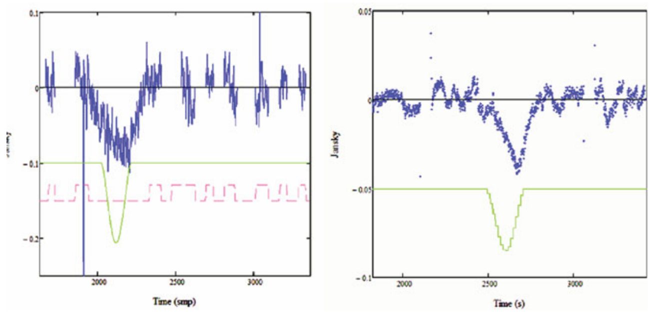

Figure 4. Radio flux density measurements of the 2OCC1 PHEMU events occurred on June 10th (on the left) and December 18th (on the right) 2009. In green: expected flux density variation according to the numerical model. In blue: flux density measured at 22 GHz by the Medicina antenna.

As can be seen in the graph, during the observed occultations, a trough of the flux density was measured in perfect agreement with the expected variation. Besides, the minimum value of the flux density resulted time-shifted by few tens of seconds in accordance with O-C (Observed-Calculated) variations (~1 min) also observed at optical wavelengths. The observational campaign is still ongoing and a numerical model, which is able to simulate the diffusion of the electromagnetic radiation near the satellite limb, is under development in order to better explain structures and possible anomalies in the measured flux density curves.

References

Arlot, J.-E. *et al.* 2006 *A&A*, 451, 733

de Pater, I., Brown, R. A., Dickel, J. R. 1984 *Icarus*, 57, 93

Howell, R. R. 1998 *Proceedings of the 29th Annual Lunar and Planetary Science Conference, Houston, Texas, March 16-20, 1998.*, 57, 93

Lopes-Gautier, R., McEwen, A. S., Smythe, W. D., Geissler, P. E., Kamp, L., Davies, A. G., Spencer, J. R., Keszthelyi, L., Carlson, R., Leader, F. E., Mehlman, R., Soderblom, L. 1999 *Icarus*, 140, 243

McEwen, A. S., Simonelli, D. P., Senske, D. R., Klaasen, K. P., Keszthelyi, L., Johnson, T. V., Geissler, P. E., Carr, M. H., Belton, M. J. S. *Geophysical Research Letters*, 24, 2443

Pluchino, S. 2008 *IRA Internal Report 421/08*

Spencer, J. R., Clark, B. E., Toomey, D., Woodney, L. M., Sinton, W. M. 1994 *Icarus*, 107, 195

von Kap-herr A. 1977 *Technischer Bericht Nr. 40, MPIfR Bonn*