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Coordinated observations of PHEMU at radio wavelengths

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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. Measurements of the radio flux density variation occurred during the mutual occultations of Io by Europa and Ganymede were carried out during the PHEMU09 campaign at K- and Q-band. Flux density variations observed for the first time at radio wavelengths are consistent with the typical optical patterns measured when partial occultations occurred. The flux density drops indicate a non-linear dependence with the percentage of overlapped area.

Key words. Planets: Occultations – Planets: Jupiter – Satellites: Europa, Ganymede, Io – Radio continuum: Solar System

1. Introduction

Twice every 11.8 years Jupiter transits the nodes of its orbit. When the inclination of the orbital planes of Galilean satellites with respect to the planet's equatorial plane is very small, the satellites either occult or eclipse each other, depending on whether they are collinear with the Earth or with the Sun, respectively. This phase typically lasts for a few months. These occultations or eclipes are referred to as mutual phenomena or PHEMU (Fig.1). Their observations 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 centres on Io's surface (73 hot spots plus the Ra Patera plume), and 23 additional sites that were identified as probable active volcanic centres. 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's activity because they most likely represent the major pathways of magma to the satellite surface.

Imaging of Io at NIR wavelengths (from 1 to 5 micrometers) has revealed a higher num-

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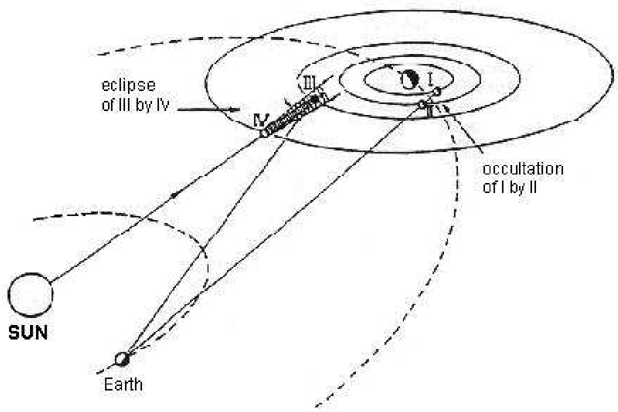

Fig. 1. Mutual events (occultation and eclipses) between Jupiter satellites. Credits to: J.-E. Arlot, IMCCE/CNRS

ber 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.

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 sur-

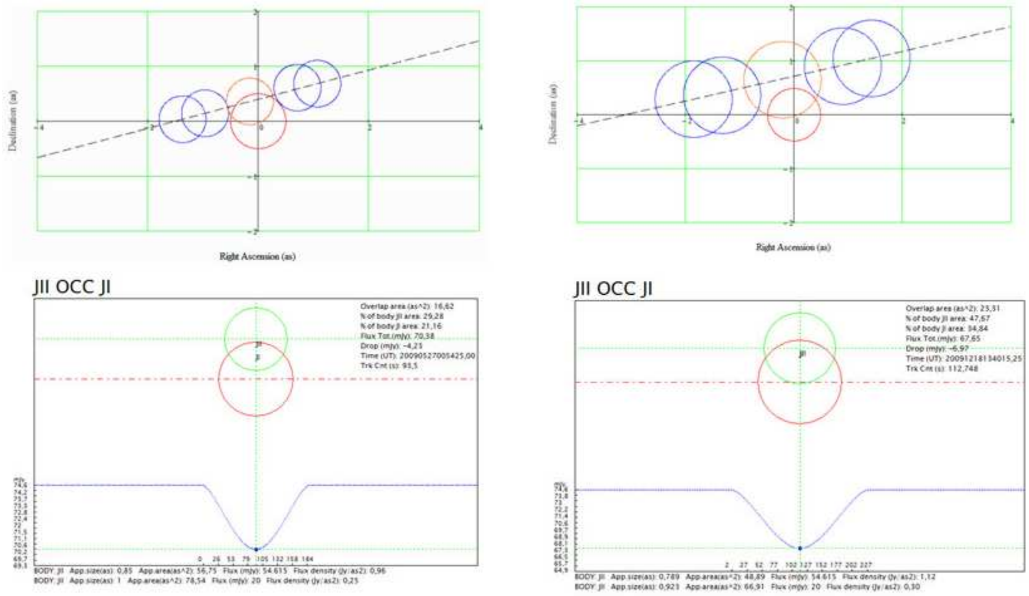

Fig. 2. Top: astrometric maps of the 2OCC1 PHEMU events occurred on June 10 (left-hand) and December 18 (right-hand) 2009. Bottom: numerical model of the occultation curves (see text for details).

face 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 radii of satellites, the mean flux densities, the impact parameter and the time duration (Pluchino 2010). Fig. 2 shows the simulations performed for the 2OCC1 PHEMU event which occurred on June 10 (left-hand) and December 18 (right-hand) 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 (4 lateral circles) and orange (upper central) circles indicate sides and central positions, respectively of Io during the occultation. Red (lower central) circles indicate the position of Europa during the maximum of the occultation. In the bottom of the figure the numerical model of the occultation curves computed by the software is shown.

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 Istituto di Radioastronomia (Pluchino et al. 2011), Bologna 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 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

Table 1. 11 Io's occultation events occured from May 2009 to March 2010. 22 different scans were recorded on radioastronomy bands S, X, K and Q. A total of 15 partial and 7 annular events were observed. The table shows the 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 indicate partial and annular occultation respectively.

Phenomena	**Date of max.**			**Time of max.**			**Mag.**	**Dur.**	**Satellite distance**	**Elevation at**		
										Md	**Nt**	**Eff**
	Y	M	D	h	m	s		s	RS	°	°	°
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

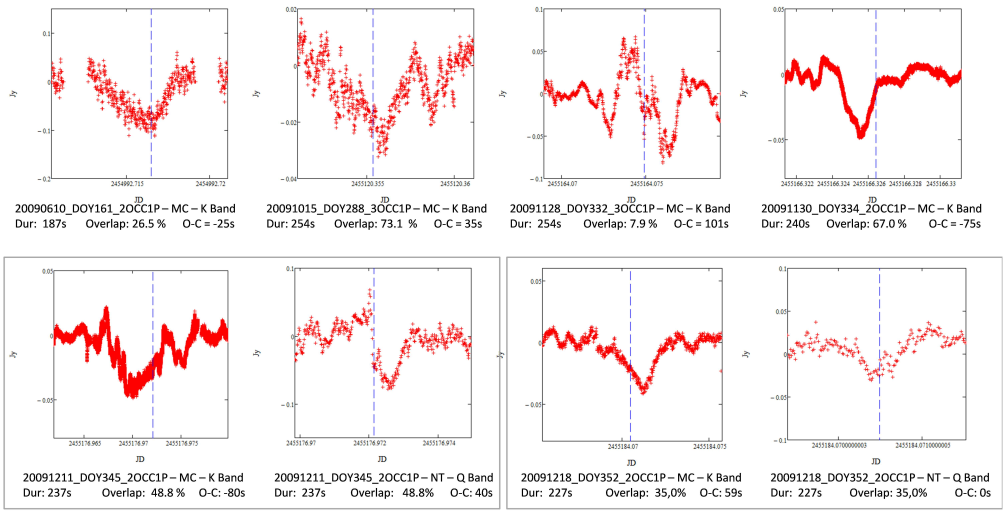

Fig. 3. Radio flux density measurements of a subset of 8 PHEMU events observed with the Medicina and Noto antennas. The plots show the flux density variation (in Jy) during the occultations. The blue (dotted) line indicates the calculated minimum instant of the event. On the bottom of each plot is showed information as data, type of event, station ID, radio receiver, duration in seconds, satellite dishes overlap and O-C (Observed-Calculated) measured.

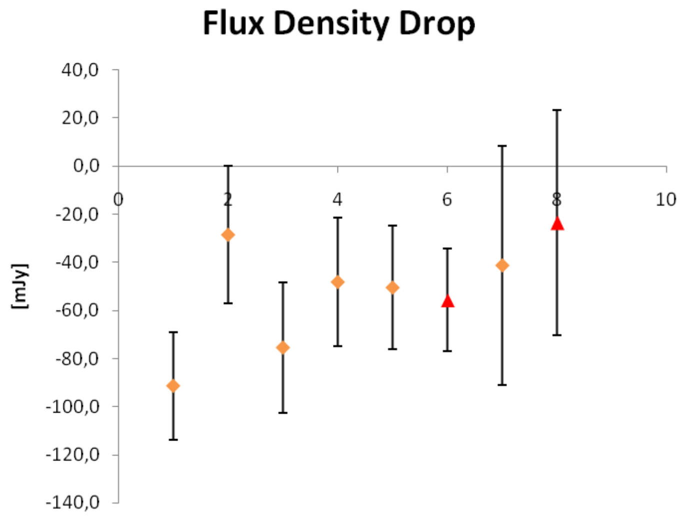

Fig. 4. Some flux density drop measurements (mJy), obtained at K and Q-Band, with the Medicina and Noto antennas, during a subset of 8 Ios occultations events. Diamonds are flux density drops measured at 22 GHz (K band), triangles are the measurements at 43 GHz (Q band).

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 Pluchino et al. (2010). 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 yielded a flux density of (0.5 ± 0.1) Jy for Io, (0.6 ± 0.3) Jy for Europa, and (0.6 ± 0.3) Jy for Ganymede. The distance between the flux density calibrator and Io ranged from 2.6° to 40′. Different types of OFF-source measurements were also performed during occultations in order to subtract background noise and to monitor the stability of the receiver gain. The OFF-source measurements (obtained with a RA offset of 1°) were subtracted from the ON-source to also remove possible contributions of the Jupiter radio emission in the side lobes of the antenna beam. Since the beam width at 43 GHz is approximately 1′ we can exclude at this frequency the strong contribution of Jupiter inside the antenna 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. Effelsberg observations were mostly performed with the 9-mm secondary focus system (ν = 32 GHz) in beamswitch mode. Only on Nov 16, the 2.8-

cm secondary focus receiver (ν = 10.45 GHz) was used. After some cross-scans for the flux density and position calibration, the measurements were done by tracking ON- and OFF-positions with a similar strategy as in Medicina and Noto.

3. Results

As can be seen in Fig. 3, during the observed occultations, a trough of the flux density was measured in good agreement with the model. Besides, the minimum value of the flux density resulted time-shifted by few tens of seconds. This is called O-C (Observed-Calculated) parameter, also observed at optical wavelengths. Some O-C parameter measurements, in our preliminary analysis, are not in a plausible range. These cases will be studied in more detail.

The analysis of the flux density drops of 8 PHEMU events (see Fig. 4), observed at K- and Q-Band showed a weak correlation with the percentage of Io's surface involved with the occultation. Further analysis is still in progress and will better explain any inhomogeneous distribution of the brightness temperature of the involved satellite surfaces. The observing campaign is now ended. A numerical model is under development which is able to simulate the diffusion of the electromagnetic radiation near the satellite limb, in order to better explain some interestings structures and anomalies in the observed occultation patterns.

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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. et al. 1999, Icarus, 140, 243
McEwen, A.S. et al. 1997, Geophysical Research Letters, 24, 2443
Pluchino, S. 2008, IRA Internal Report 421/08
Pluchino, S. 2010 *European Planetary Science Congress* 2010, held 20-24 September in Rome, Italy. 2010, p.248
Pluchino, S. et al. 2010 *Galileo's Medicean Moons: their impact on 400 years of discovery, Proceedings of the International Astronomical Union* IAU Symposium Vol. 269, p. 245-249 (2010)
Pluchino, S. et al. 2011, Memorie della Societa Astronomica Italiana Supplement, 16, 152
Spencer, J.R. et al. 1994, Icarus, 107, 195
von Kap-herr, A. 1977 *Technischer Bericht* Nr. 40, MPIfR Bonn