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Polarimetry of M-type asteroids★

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ABSTRACT

Aims. Results of a polarimetric program at Complejo Astronómico El Leoncito (Casleo), San Juan, Argentina are presented. The aim of this campaign is to estimate the polarimetric properties of asteroids belonging to the X taxonomic class. In this paper results of the campaign for M-type objects are presented.
Methods. The data have been obtained with Casprof and Torino polarimeters at the 2.15 m telescope. The Casprof polarimeter is a two-hole aperture polarimeter with rapid modulation and the Torino polarimeter is an instrument that allows simultaneous measurement of polarization in the U-, B-, V-, R-, and I-bands.
Results. The campaign began in 2000, and data on a sample of 26 M-type asteroids were obtained. Most of these objects were polarimetricaly observed for the first time. Combining these data with those available in the literature, an estimate of the polarimetric parameters and albedo for 12 objects is presented. Furthermore, the data show that asteroids 21 Lutetia and 77 Frigga have a large inversion angle and 441 Bathilde a deep polarization minimum, implying a controversial taxonomic classification as M-type for these objects. Also, the polarimetric parameters estimated for the M-type asteroids showing in their spectra the 3 μm band and classified as W-type by Rivkin et al. (1995, Icarus, 117, 90; 2000, ApJ, 145, 351) could be different from those without that feature.

Key words. minor planets, asteroids – techniques: polarimetric

1. Introduction

The M-type asteroids are members of an asteroid class introduced for the first time by Zellner & Gradie (1976) and proposed as a taxonomic class by Tholen (1984, 1989). These asteroids represent a group of objects that has been originally suggested to be composed by metal, but they were historically difficult to interpret due to the apparent lack of diagnostic mineral absorption features in their visible and near-infrared reflectance spectra. Derived from the larger group of X-class asteroids that represent spectrally featureless, moderately "reddish" objects in the 300 to 1100 nm region (Tholen 1984), the M-type asteroids are distinguished by their moderate albedos (~0.07 to 0.30). The other members of the X-class, the E- and P-type asteroids, exhibit higher and lower albedos, respectively (Tholen 1984). Then, the X-class was originally described as being spectrally degenerate, and could only by subdivided into the E-, M- and P-types based only on albedo. However, Rivkin et al. (1995, 2000) discovered a 3 μm band in the spectra of M- and E-type asteroids, Burbine et al. (1998) detected absorption bands in the visible range on the surface of E-type asteroids, also observed later by Fornasier & Lazzarin (2001), Busarev (1998) found absorption bands on M-type asteroids, and the SMASSII spectra (Bus 1999; Bus & Binzel 2002) reveal variations among their members, allowing us to divide them into several sub-classes based solely on spectral features. Recently, Clark et al. (2004) extended these spectroscopic studies to the near-infrared and Hardersen et al. (2005) found absorption features in the 0.9 μm spectral region for six M-type asteroids.

Since the albedo is a valid criterion to sub-classify X-class objects and one of the most important methods used in practice for determining asteroid albedos is polarimetry, an extensive polarimetric observing campaign was developed since 2000, and is presently under way, to obtain polarimetric observations of X-class asteroids to improve their taxonomic classification and to shed light on their polarimetric properties. Polarimetry is a technique that is a powerful tool for the investigation of physical properties of atmosphereless bodies. In particular, this technique provides two main results for asteroids: first, the relation between the minimum polarization and the inversion angle of the phase-polarization curve is a powerful diagnostic of asteroid surface texture (Dollfus & Zellner 1979; Dollfus et al. 1989). Using laboratory measurements of meteorites and lunar and terrestrial samples, these authors concluded that asteroids are covered by regolith layers with a broad mixture of particle sizes. The second important result is an estimation of the asteroid albedos using the polarimetric slope – albedo and minimum polarization – albedo relationships (Zellner & Gradie 1976). The radiation reflected by asteroids is in a general state of partial linear polarization. The observations allow us to determine the so-called Stokes parameters of the incoming light, from which the values of the degree of linear polarization P and the position angle of the polarization plane can be determined at different epochs. The position angle is usually defined relative to the orientation of the scattering plane, that is the plane containing the asteroid, the Sun, and the observer. A classical result of polarimetric studies of atmosphereless solar system bodies is that the orientation of the plane of linear polarization of the light received from these objects is,

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as a general rule, limited to two cases: it is either parallel or normal to the scattering plane. In polarimetry, the results of observations are usually expressed using the P_r parameter, defined as the ratio:

$$P_r = \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel}, \quad (1)$$

where $I_\perp$ and $I_\parallel$ are the intensities of the scattered light polarized along the planes perpendicular and parallel to the scattering plane, respectively. It can be shown that $P_r = P\cos(2\theta_r)$, where θ_r is the angle between the position of the polarization plane and the normal to the scattering plane.

In the present paper results of the X-class polarimetric campaign for M-type objects are presented. The observations are described and the results are discussed in Sects. 2 and 3, respectively. Finally, in Sect. 4 the conclusions are presented.

2. Observations

The observations presented here have been carried out using the Casprof and Torino polarimeters at the 2.15 m telescope of Complejo Astronómico El Leoncito (Casleo), San Juan, Argentina. The Casprof polarimeter is a two-hole aperture polarimeter with rapid modulation provided by a rotating achromatic half-wave retarder and a Wollaston prism polarizing beamsplitter. The complementary polarized beams are detected with photomultipliers operating in pulse-counting mode and the acquisition and guiding are accomplished with a CCD camera viewing the sky surrounding the entrance aperture. The Torino polarimeter was described in Piirola (1988) and Scaltriti et al. (1989), but it is important to recall that this instrument allows simultaneous measurement of polarization in the U-, B-, V-, R-, and I-bands, using five separate photomultipliers and a set of dichroic filters. Since the received signal is in general exceedingly low in the U-, B-, and I-bands of the Torino polarimeter, only V data have been used in practice in the data reduction. From the analysis of several standard stars, the instrumental polarization of both polarimeters is found to be fairly constant and always below 0.1%.

The targets were observed during short runs some weeks apart to obtain measurements during the same apparition at different phase angles. To check the performances of the instrument we observed a few bright asteroids for which polarimetric data were already available in the literature during a few nights. In these cases, the observations always fit the previous known phase-polarization curves of these objects.

Observing nights were generally assigned around the new Moon to minimize the contamination of sky polarization by moonlight. In all cases, the smallest diaphragm allowed by the observing conditions was used to minimize the contribution of sky background. Each night a minimum of two zero-polarization and one high-polarization standard stars were observed to allow for the determination of instrumental polarization. The standard stars' data were obtained from Turnshek et al. (1990) and Gil-Hutton & Benavidez (2003).

The targets have been observed consecutively a minimum of four times each night with individual exposure time long enough to reach acceptable signal-to-noise ratios ($S/N > 50$). The measurements for each retarder position were coadded to improve the S/N ratio and the errors were evaluated assuming a Poisson distribution. After a correction for instrumental polarization, the Stokes parameters were obtained using reduction programs specially designed for each polarimeter.

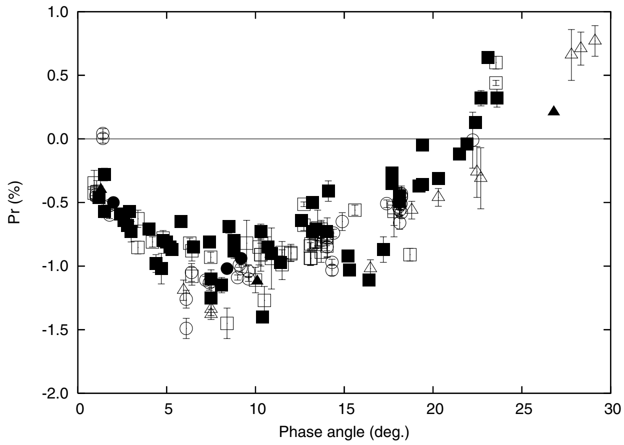

Fig. 1. Polarimetric observations for M-type asteroids. Data for 21 Lutetia are indicated by triangles, for 16 Psyche by circles, and for all other objects by squares. In all cases the filled marks are data taken during this campaign.

3. Results

Data on 26 M-type asteroids during different observing runs between June 2001 and October 2005 are presented here. The observed asteroids, observation date, total integration time in seconds, phase angle, position angle of the scattering plane, degree of linear polarization and its error, position angle in the equatorial reference frame and its error, and P_r are shown in Table 1. Although most targets could be observed at a single phase angle, comparing the data obtained with the available polarimetric measurements of asteroids of the same taxonomic type allows us to draw interesting conclusions on their surface properties. On the other hand, to enlarge the polarimetric database of M-type asteroids, observations of 13 objects classified as M-type were obtained from the Small Bodies Node at NASA's Planetary Data System (`http://pdssbn.astro.umd.edu/sbnhtml/asteroids`) and from Zellner & Gradie (1976), Belskaya et al. (1985, 1987a,b, 1991), Broglia & Manara (1992), Cellino et al. (1999, 2005), and Fornasier et al. (2006). Since data obtained with an R filter is normally of good quality and generally compatible with V filter data, observations in both filters from these sources were taken into account. Figure 1 shows all the polarimetric observations of M-type asteroids considered here.

Previous analysis of asteroidal phase-polarization curves showed similar behavior for asteroids of the same taxonomic class (Goidet-Devel et al. 1995), but the data plotted in Fig. 1 show that some M-type objects have peculiar phase-polarization curves with a great dispersion mainly in the region of phase angle $\alpha > 15°$. A particular case of a peculiar phase-polarization curve is the asteroid 21 Lutetia, a target of the Rosetta Mission, which was classified as M-type on the basis of its IRAS albedo. The observations show remarkable differences in comparison with other M-type asteroids. Using the semi-empirical model of phase-polarization curves proposed by Piironen et al. (2000), Kaasalainen et al. (2001a,b), and Muinonen et al. (2002):

$$P_r(\alpha) = A_0\left[\exp\left(-\frac{\alpha}{A_1}\right) - 1\right] + A_2\alpha, \quad (2)$$

where A_0, A_1, and A_2 are constant coefficients, a minimum of the phase-polarization curve of $|P_{\min}| = 1.21 \pm 0.01\%$ at $\alpha_{\min} = 8.67°$, a slope of the linear region of the phase-polarization curve

Table 1. Polarimetric observations of M-type asteroids obtained in the X-class campaign at Casleo.

Asteroid	Date UT	$T_{\rm int}$ s	α °	$\theta_\odot$ °	P %	σ_P %	θ °	σ_θ °	P_r %
16 Psyche	2003 May 05	720	2.0	63.0	0.50	0.01	60.0	0.7	−0.50
	2004 Jul. 15	360	8.4	68.5	1.04	0.01	74.3	0.04	−1.02
	2004 Aug. 26	720	9.2	77.4	1.00	0.01	87.5	0.2	−0.94
21 Lutetia	2003 May 04	720	1.3	10.2	0.40	0.01	9.4	0.8	−0.40
	2004 Aug. 26	720	26.8	74.6	0.24	0.01	178.2	1.6	0.21
	2004 Oct. 15	360	10.1	82.4	1.15	0.02	75.8	0.4	−1.12
22 Kalliope	2004 May 18	360	6.5	100.0	0.85	0.01	103.2	0.05	−0.85
	2005 Sep. 02	360	7.4	164.4	0.81	0.01	160.9	0.4	−0.81
	2005 Oct. 04	720	14.0	44.3	0.74	0.01	47.9	0.4	−0.73
69 Hesperia	2005 Apr. 08	360	17.7	106.4	0.28	0.02	111.5	2.3	−0.27
75 Eurydike	2001 Jun. 25	720	19.4	106.3	0.21	0.03	144.3	4.0	−0.05
	2001 Jul. 21	720	23.6	108.5	0.36	0.07	32.2	5.5	0.32
	2005 Apr. 09	720	1.2	77.4	0.48	0.04	85.6	2.4	−0.46
	2005 Apr. 10	720	1.5	85.6	0.57	0.05	83.2	2.5	−0.57
	2005 Jun. 08	1080	18.1	112.3	0.50	0.11	116.0	4.2	−0.49
77 Frigga	2004 May 18	720	15.2	112.2	0.97	0.04	122.0	1.2	−0.92
	2005 Jun. 08	720	7.5	94.4	1.27	0.14	89.7	3.2	−1.25
	2005 Sep. 02	1440	19.2	89.4	0.43	0.04	77.2	3.0	−0.37
	2005 Sep. 04	1440	19.4	89.5	0.41	0.04	76.2	3.1	−0.36
92 Undina	2004 May 18	360	18.1	76.5	0.45	0.06	79.1	3.1	−0.45
	2004 Jul. 15	360	2.9	107.0	0.57	0.03	108.4	1.5	−0.57
	2004 Aug. 25	720	12.6	72.5	0.65	0.01	77.5	0.5	−0.64
	2005 Sep. 04	720	17.7	79.6	0.36	0.02	75.6	1.4	−0.35
97 Klotho	2003 May 05	720	21.9	111.1	0.06	0.02	134.9	10.2	−0.04
	2004 May 18	360	5.0	76.5	0.84	0.03	6.9	0.8	−0.81
	2004 Jul. 16	720	16.4	111.6	1.12	0.04	114.4	1.0	−1.11
	2004 Aug. 25	1080	17.2	102.3	0.95	0.10	118.1	3.0	−0.87
	2005 Sep. 02	720	15.3	89.4	1.07	0.04	81.4	1.0	−1.03
	2005 Oct. 04	720	20.3	82.5	0.33	0.04	77.7	1.2	−0.31
125 Liberatrix	2004 Oct. 15	720	1.5	0.7	0.30	0.05	170.4	4.3	−0.28
132 Aethra	2004 Jul. 15	720	7.5	129.7	1.10	0.07	128.7	1.8	−1.10
	2004 Jul. 17	720	8.1	126.0	1.15	0.06	127.5	1.6	−1.15
135 Hertha	2004 Aug 25	720	22.4	67.0	0.15	0.01	172.6	2.1	0.13
	2004 Oct. 15	360	4.8	80.8	0.80	0.01	79.2	0.3	−0.80
	2004 Oct. 16	360	5.2	79.7	0.85	0.02	80.0	0.4	−0.85
161 Athor	2005 Sep. 04	1080	23.1	70.0	0.64	0.02	160.3	0.7	0.64
184 Dejopeja	2004 May 17	360	8.8	95.2	0.99	0.06	109.2	3.5	−0.88
	2004 Jul. 15	720	11.4	94.6	0.97	0.05	97.4	1.5	−0.97
	2005 Sep. 02	1080	2.4	69.4	0.60	0.04	72.0	2.1	−0.59
201 Penelope	2005 Apr. 09	720	2.8	150.5	0.70	0.03	144.2	1.0	−0.68
250 Bettina	2001 Jul. 21	720	10.7	75.6	0.94	0.08	62.6	2.3	−0.85
	2001 Jul. 22	720	10.9	76.2	1.00	0.05	63.3	2.2	−0.90
322 Phaeo	2005 Apr. 10	1440	4.4	75.0	0.98	0.07	72.0	2.1	−0.98
337 Devosa	2005 Jun. 08	720	4.7	0.2	1.02	0.12	3.0	3.4	−1.02
338 Budrosa	2005 Jun. 08	720	3.0	62.6	0.77	0.08	72.1	3.0	−0.73
347 Pariana	2004 Jul. 16	720	21.5	107.0	0.25	0.04	76.7	5.1	−0.12
	2005 Sep. 02	1080	5.8	179.7	0.65	0.04	179.6	1.7	−0.65
	2005 Oct. 02	1440	13.2	51.1	0.74	0.03	51.9	1.4	−0.73
	2005 Oct. 04	1440	13.4	52.4	0.71	0.04	52.4	1.6	−0.71
369 Aeria	2005 Jun. 08	720	2.6	166.9	0.64	0.04	163.7	1.9	−0.64
382 Dodona	2005 Apr. 09	360	5.3	166.6	0.87	0.04	162.4	1.2	−0.87
441 Bathilde	2005 Sep. 04	1440	10.4	92.7	1.42	0.03	88.3	0.5	−1.40
558 Carmen	2001 Jun. 25	720	10.3	67.1	0.92	0.06	86.0	2.0	−0.73
	2005 Apr. 09	720	8.8	82.9	0.81	0.03	86.4	1.1	−0.80
	2005 Apr. 10	720	8.5	81.7	0.74	0.05	71.6	1.8	−0.69
	2005 Jun. 08	1440	14.1	120.9	0.41	0.08	119.3	5.2	−0.41
757 Portlandia	2005 Apr. 09	720	13.2	120.9	0.52	0.04	127.6	2.0	−050
758 Mancunia	2005 Sep. 04	1080	4.0	37.9	0.71	0.03	37.1	1.3	−0.71
1146 Biarmia	2004 Oct. 16	1080	22.7	80.7	0.56	0.06	143.1	2.9	0.32

of $h = 0.108 \pm 0.001\%/°$, and an inversion angle of $\alpha_0 = 24.83°$ were found for this asteroid (Fig. 2). The large inversion angle of the polarization curve for this object suggests a controversial classification as M-type.

Two other M-type asteroids with enough observations to find a solution for their phase-polarization curves are 16 Psyche (Fig. 3) and 347 Pariana (Fig. 4). For 16 Psyche the fitted polarimetric parameters are $|P_{\rm min}| = 1.03 \pm 0.02\%$ at $\alpha_{\rm min} = 7.99°$,

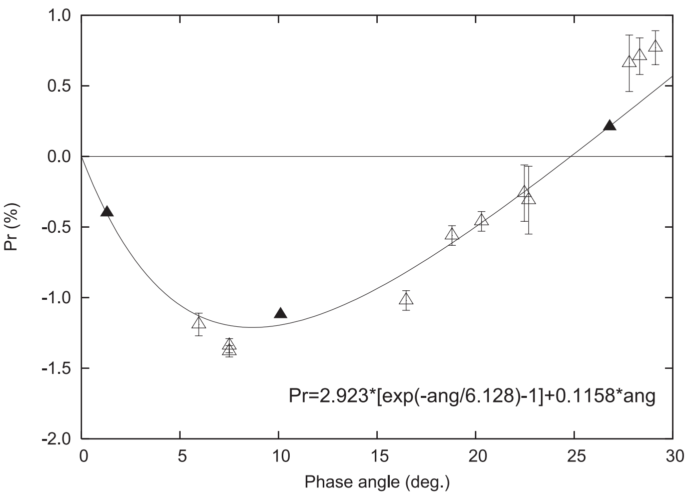

Fig. 2. Polarimetric observations of 21 Lutetia. Filled marks are data taken during this campaign.

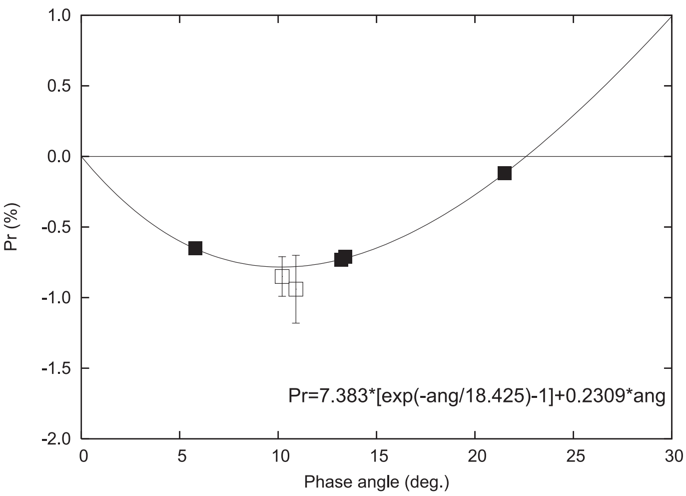

Fig. 4. Polarimetric observations of 347 Pariana. Filled marks are data taken during this campaign.

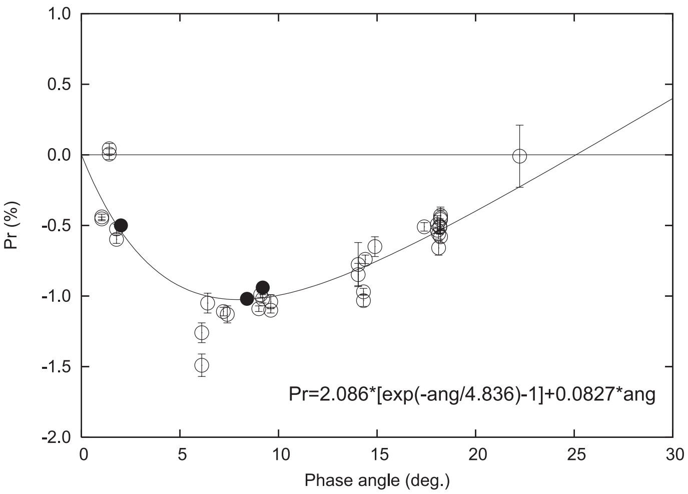

Fig. 3. Polarimetric observations of 16 Psyche. Filled marks are data taken during this campaign.

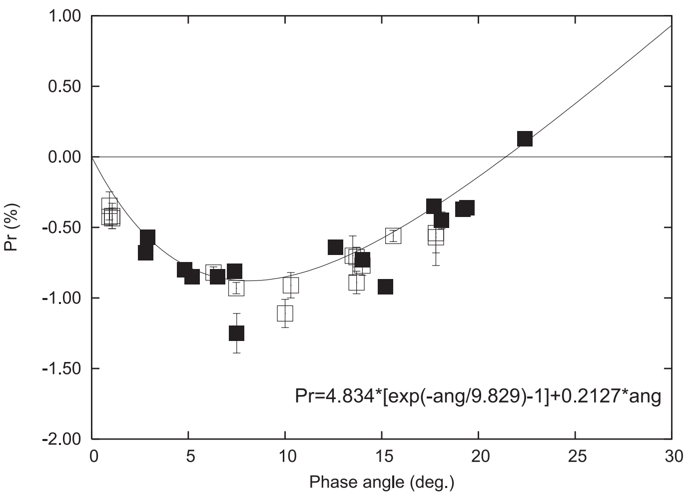

Fig. 5. Polarimetric observations of M-type asteroids classified as W-type by Rivkin et al. (1995). Filled marks are data taken during this campaign.

$h = 0.080 \pm 0.001\%/^\circ$ and $\alpha_0 = 25.08^\circ$, and in the case of 347 Pariana the polarimetric parameters found are $|P_{\min}| = 0.78 \pm 0.03\%$ at $\alpha_{\min} = 10.15^\circ$, $h = 0.113 \pm 0.001\%/^\circ$ and $\alpha_0 = 22.59^\circ$. The large inversion angle and low polarimetric slope for 16 Psyche could be a result of the data paucity for $\alpha > 18^\circ$ and the low weight of the alone point at $\alpha = 22.2^\circ$, so the fitted values for h and α_0 could be far from the real ones and should be taken with caution.

Rivkin et al. (2000) suggested separating the M-type asteroids into two groups taking into account the presence or absence of a 3 μm feature on their spectra, an evidence of hydrated minerals in the asteroid surface. These authors suggested forming a new W-type group with the M-types showing this feature. Seven M-type objects observed during this campaign are members of this new group (21 Lutetia, 22 Kalliope, 77 Frigga, 92 Undina, 110 Lydia, 135 Hertha, and 201 Penelope) and ten objects that do not show the 3 μm feature were also observed (16 Psyche, 75 Eurydike, 125 Liberatrix, 161 Athor, 184 Dejopeja, 216 Kleopatra, 337 Devosa, 758 Mancunia, and 785 Zwetana). The phase-polarization curves obtained by a fit of the semi-empirical model to the polarimetric observations of asteroids in each group are shown in Figs. 5 and 6, respectively, where the data for 16 Psyche and 21 Lutetia were not taken into account to allow any comparison between the groups and these well observed asteroids. The fit of the observations to the phase-polarization curve for the W-type group ($|P_{\min}| = 0.88 \pm 0.02\%$ at $\alpha_{\min} = 8.12^\circ$, $h = 0.101 \pm 0.001\%/^\circ$ and $\alpha_0 = 21.41^\circ$) only provide a polarimetric parameter h that is similar to Lutetia's value. If data for the asteroid 21 Lutetia is included in this group the polarimetric parameters change to $|P_{\min}| = 0.89 \pm 0.03\%$ at $\alpha_{\min} = 7.37^\circ$, $h = 0.077 \pm 0.001\%/^\circ$ and $\alpha_0 = 22.93^\circ$. The difference in the polarimetric parameters including 21 Lutetia in the W-type group or not could be a consequence of the dispersion and low weight of the observations around $\alpha = 10^\circ$ or a result produced by different polarimetric properties of 21 Lutetia in comparison with the other M-type asteroids, mainly its large inversion angle. One of the objects in this group, the asteroid 77 Frigga, shows a polarimetric behavior similar to 21 Lutetia: the polarimetric behavior of this object is characterized by a noticeable negative polarization at phase angles of 7.5 and 15.2°, implying a large inversion angle and a controversial classification as M-type. In the case of the no W-type group, the phase-polarization curve fit gives $|P_{\min}| = 0.99 \pm 0.08\%$ at $\alpha_{\min} = 8.24^\circ$, $h = 0.146 \pm 0.004\%/^\circ$ and $\alpha_0 = 19.64^\circ$, which are similar to those obtained for 16 Psyche (with the exception of h and α_0 due to the forementioned problem with the fit for this asteroid).

Table 2. Estimated polarimetric parameters for M-type asteroids.

Asteroid	$\|P_{\min}\|$	$\alpha_{\min}$	h	α_0	Albedo	
	%	°	%/°	°	Pol.	IRAS
22 Kalliope	0.83 ± 0.04	7.45			0.18 ± 0.02	0.14
75 Eurydike			0.103 ± 0.017	20.15	0.22 ± 0.06	0.15
77 Frigga	1.25 ± 0.14	7.50			0.10 ± 0.02	0.14
97 Klotho			0.174 ± 0.018	22.12	0.12 ± 0.03	0.23
132 Aethra	1.13 ± 0.03	7.80			0.12 ± 0.01	0.17
184 Dejopeja	0.93 ± 0.06	10.10			0.15 ± 0.02	0.19
250 Bettina	0.88 ± 0.08	10.80			0.17 ± 0.02	0.26
441 Bathilde	1.41 ± 0.12	9.40			0.09 ± 0.01	0.14
558 Carmen	0.75 ± 0.06	9.20			0.21 ± 0.03	0.12
16 Psyche	1.03 ± 0.02	7.99			0.13 ± 0.01	0.12
21 Lutetia	1.21 ± 0.01	8.67			0.11 ± 0.01	0.22
21 Lutetia			0.108 ± 0.001	24.83	0.20 ± 0.04	0.22
347 Pariana	0.78 ± 0.03	10.15			0.19 ± 0.02	0.18
347 Pariana			0.113 ± 0.001	22.59	0.19 ± 0.04	0.18
W-types (no 21)	0.88 ± 0.02	8.12			0.17 ± 0.01	
W-types (no 21)			0.101 ± 0.001	21.41	0.22 ± 0.05	
no W-types (no 16)	0.99 ± 0.08	8.24			0.14 ± 0.02	
no W-types (no 16)			0.146 ± 0.004	19.64	0.14 ± 0.03	
all M-types (no 16 or 21)	0.91 ± 0.07	8.57			0.16 ± 0.02	
all M-types (no 16 or 21)			0.121 ± 0.004	20.92	0.18 ± 0.04	

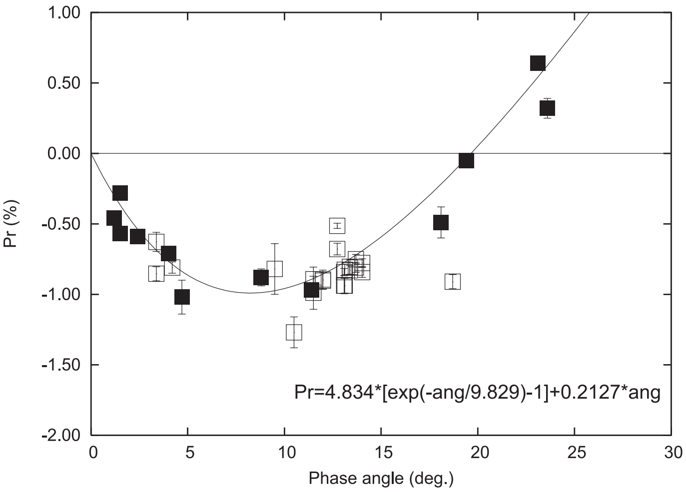

Fig. 6. Polarimetric observations of M-type asteroids not classified as W-type by Rivkin et al. (1995). Filled marks are data taken during this campaign.

If data for 16 Psyche is included in this group the polarimetric parameters only change slightly to $|P_{\min}| = 1.04 \pm 0.03\%$ at $\alpha_{\min} = 8.43°$, $h = 0.139 \pm 0.004\%/°$ and $\alpha_0 = 20.62°$. The two points with noticeable negative polarization at phase angles of 10.5 and 18.7° in Fig. 6 are observations of 216 Kleopatra and 785 Zwetana, respectively, taken from the literature. In the first case, the polarimetric measurement was taken from Belskaya et al. (1987a) and is considerably more negative than a series of observations of the same object at $11 < \alpha < 14°$ ($P_r \sim 0.85$), looking like an observational error. In the second case, the observation is from Fornasier et al. (2006), who also suggest that this object could have a behavior similar to that shown by 21 Lutetia with a possible large inversion angle. In all the cases the observations were also fitted with the phase-polarization curve model proposed by Lumme & Muinonen (1993) and a third order polynomial (Goidet et al. 1992), but the polarimetric parameters obtained are always coincident within the nominal error bars. The single polarimetric observation of 441 Bathilde at $\alpha = 10.4°$ obtained in this campaign agrees very well with a previous observation by Belskaya et al. (1987a) at $\alpha = 8.4°$ ($P_r = 1.45 \pm 0.12\%$) and is indicative of a deep polarization minimum and a low albedo for a M-type asteroid.

The polarimetric albedo of an asteroid may be estimated by two empirical relations linking the geometric albedo p and both h and $P_{\min}$. These relations are expressed by means of very simple mathematical forms:

$$\log p_v = C_1 \log h + C_2 \quad (3)$$
$$\log p_v = C_3 \log P_{\min} + C_4, \quad (4)$$

where C_1, C_2, C_3, and C_4 are constants. The slope-albedo relationship (Eq. (3)) is found to be almost independent of grain size and texture, and linear for $p \geq 0.05$–0.04, making the slope of the linear region of the phase-polarization curve a useful indication of albedo for a wide range of surface types. On the other hand, the $P_{\min}$-albedo relationship (Eq. (4)) displays more scatter than the slope-albedo relationship due to the sensitivity of $P_{\min}$ with grain size, surface texture, taxonomic type, and the difficulty of defining the exact value of $\alpha_{\min}$ for each object based only on scarce data. The polarimetric albedo can be found using the slope-albedo relationship for the M-type asteroids observed at least three times near α_0, and the $P_{\min}$-albedo one for the objects having at least two observations near $\alpha_{\min}$. Alternatively, the asteroid polarimetric parameters could be obtained from the fitted phase-polarization curve. The set of constants proposed by Cellino et al. (1999) was used in Eqs. (3) and (4) ($C_1 = -1.118 \pm 0.071, C_2 = -1.779 \pm 0.062, C_3 = -1.357 \pm 0.140$ and $C_4 = -0.858 \pm 0.030$), and the results are listed in Table 2, where IRAS albedos from Tedesco et al. (2002) were included for comparison.

4. Conclusions

During an extensive polarimetric campaign to improve the classification of X-class asteroids, 26 M-type objects were observed at different phase angles (17 of them for the first time) increasing the M-type asteroids polarimetric database. For 12 objects the observations, combined with data from the literature, allow us to obtain the polarimetric albedo and some parameters of the phase-polarization curve. Due to the lack of observations for phase angles greater than 18° it was impossible to obtain a good fit for the phase-polarization curve of the asteroid 16 Psyche. Since the slope-albedo relationship provides the most confident result to obtain the polarimetric albedo of an asteroid, it is necessary to observe this object at large phase angles to find reliable values for α_0 and h.

The asteroid 21 Lutetia shows a peculiar phase-polarization curve with a large inversion angle for an M-type asteroid. Also, the asteroid 77 Frigga shows a noticeable negative polarization, implying a large inversion angle and a controversial classification as M-type. On the other hand, 441 Bathilde presents a polarimetric behavior that is indicative of a deep polarization minimum and a low albedo for an M-type asteroid.

The polarimetric parameters of the asteroid group with the 3 μm feature on their spectra (W-type of Rivkin et al. 2000) appear different from those of the group without that feature. The main differences between both groups are in the polarimetric slope h, which also means a difference in their mean albedo ($p = 0.22$ and $p = 0.14$, respectively), and in the inversion angle α_0, which is larger for the W-types. Nevertheless, it is difficult to decide if this difference is statistically meaningful with the few observations obtained at phase angles larger than 20°, and more and better data are needed to reach a conclusion about this difference.

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