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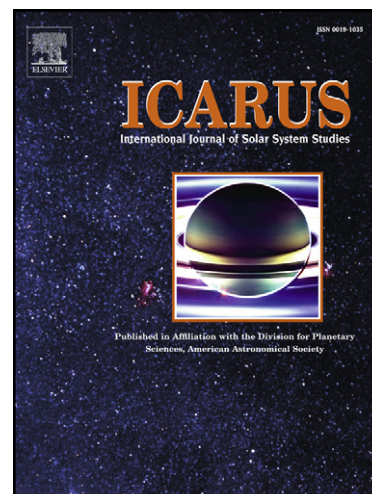
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**Polarimetric evidence of close similarity between
members of the Karin and Koronis dynamical
families[†]**

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Abstract

We present the results of a campaign of polarimetric observations of small asteroids belonging to the Karin and Koronis families, carried out at the ESO Cerro Paranal Observatory using the VLT-Kueyen 8-meter telescope. The Karin family is known to be very young, having likely been produced by the disruption of an original member of the Koronis family less than 6 My ago. The purpose of our study was to derive polarimetric properties for a reasonable sample of objects belonging to the two families, in order to look for possible systematic differences between them, to be interpreted in terms of differences in surface properties, in particular albedo. In turn, systematic albedo differences might be caused by different times of exposure to space weathering processes experienced by the two groups of objects. The results of our analysis indicate that no appreciable difference exists between the polarimetric properties of Karin and Koronis members. We thus find that space weathering mechanisms may be very efficient in affecting surface properties of S-class asteroids on very short timescales. This result complements some independent evidence found by recent spectroscopic studies of very young families.

Keywords: Asteroids, Polarimetry, Asteroids, surfaces.

1 Introduction

The Karin family is an extremely young cluster of objects with an estimated age of less than 6 My ago (Nesvorný *et al.*, 2006). Since it is located, in the space of orbital proper elements, inside the big Koronis family, it is extremely likely that the Karin family was produced by the collisional disruption of a parent body that was originally a member of the Koronis family. Karin members should be therefore second-generation fragments deriving from the body that produced the Koronis family more than one Gy ago. The much longer estimated age of Koronis is based on the Galileo probe observations of the cratering record on (243) Ida and its small satellite Dactyl.

We remind that Koronis members belong to the populous *S* taxonomic class, that according to many authors is believed to include the parent bodies of Ordinary Chondrites (Chapman, 1996a, 1996b; Clark *et al.*, 2002). We also remind that the Koronis family does not represent an exception to the general observational evidence that families are quite homogeneous in compositions, since the reflectance spectra of members of the same family are generally found to be very similar (Cellino *et al.*, 2002).

If the above inferences are correct, a comparative analysis of the properties of Karin and Koronis members is in principle an ideal tool to study the observable effects of different times of exposure to space weathering processes affecting the surfaces of objects of nearly identical composition.

According to current knowledge, the effect of exposure to space weathering effects on *S*-class asteroid surfaces is twofold. On one hand, the spectral reflectance properties tend to progressively change, leading to an overall reddening of the spectrum, and to a relative decrease in depth of the silicate absorption feature around $1\mu\text{m}$ in wavelength. A preliminary spectroscopic analysis of a sample of objects belonging to another very young family, Iannini, suggested that the characteristic time scale for space weathering evolution of spectral reflectance might be of the order of 570 ± 220 Millions of years (Willman *et al.*, 2008). Spectroscopic observations of several members of the Karin family gave in the past controversial results. In particular,

available data seemed to indicate that these objects tend to exhibit a less reddish spectral trend with respect to typical S-class asteroids (Chapman *et al.*, 2007). At the same time, however, it was found also that the $1\mu\text{m}$ absorption band might be quite shallow, more than would be expected for fresh surfaces not heavily modified by space weathering mechanisms.

More recently, a more comprehensive spectroscopic survey of members belonging to some among the youngest families identified so far, including those of Datura, Lucascavin and Karin, led Vernazza *et al.* (2009) to conclude that the reddening of the surfaces of asteroids belonging to the S class is an extremely rapid process, occurring during the first 10^6 years since family formation.

The present paper focuses on another expected effect of exposure to space weathering, namely a progressive decrease of the albedo of the surface. As in the case of spectral reddening, this additional effect is thought to occur as a result of separation and deposition of nanophase iron (Hapke, 2001; Noble *et al.*, 2001). The albedo of asteroid surfaces may be determined by means of polarimetric observations. A comparison of the observable polarimetric properties of Karin and Koronis members, therefore, can be very interesting. If the space weathering process would act relatively slowly, one should expect to find evidence of systematic differences between the polarimetric properties of objects having ages of 6 My and 1 Gy, respectively. On the

other hand, if the space weathering mechanism is capable of modifying very efficiently the geometric albedo, reaching some kind of saturation over very short timescales, as suggested by the spectroscopic results quoted above, and also confirmed by some laboratory experiments (Brunetto and Strazzulla, 2005; Brunetto *et al.*, 2006), no strong differences should be expected for the two samples. Since we cannot be sure that the process of detectable reddening and that of detectable modification of polarimetric properties should have necessarily identical time scales, it is very interesting to investigate the polarimetric properties of different members of the Koronis and Karin families, and to compare them. This is exactly the subject of this paper.

2 Asteroid Polarimetry

The basic idea of our analysis is to derive phase - polarization data for objects belonging to the Karin and Koronis families, in order to look for some possible systematic difference between the behaviour of the members of the two groups. If present, such differences may be interpreted in terms of different properties of the surfaces of the members of the two families. In particular, we have tried to obtain polarimetric data in ranges of phase angles which may be useful to derive evidence of some systematic difference in surface albedo.

For those who are not familiar with asteroid polarimetry, we remind that

the light we receive from asteroids is in a state of partial linear polarization. The observations show that the polarization plane is normally found to be, with very good approximation, either parallel or perpendicular to the Sun - asteroid - Earth plane (the scattering plane), depending on the value of the phase angle. The results of polarimetric observations are usually expressed using the P_r parameter, defined as the ratio

$$P_r = \frac{I_{\perp} - I_{\parallel}}{I_{\perp} + I_{\parallel}}$$

where I_{\perp} and I_{\parallel} are the intensities of the components of scattered light with the electric field vector oscillating in the planes perpendicular and parallel to the scattering plane, respectively. If we indicate as θ the angle between the position angle of the linearly polarized beam and the position angle of the plane perpendicular to the scattering plane at the epoch of the observation, we can also write that the relation between the measured degree of linear polarization P and the P_r parameter is given by:

$$P_r = P \cos(2\theta)$$

The advantage of using P_r , is that, according to its definition, the absolute value of P_r gives directly the degree of linear polarization, while its sign specifies the orientation of the polarization plane (either parallel or normal to the scattering plane).

The polarimetric properties of asteroids are generally described through

an analysis of the variation of P_r as a function of different illumination conditions, described by the value of the phase angle. The latter is defined as the angle between the directions to the Sun and to the observer, as seen from the asteroid. Typical phase - polarization curves of asteroids are characterized by an interval of phase angles for which P_r has negative values, the so-called negative polarization branch. The extreme value P_{min} of the negative branch is normally reached between 8 and 10 degrees of phase. P_r changes sign at an *inversion angle* usually occurring around 20 degrees of phase. Around the inversion angle, the variation of P_r as a function of phase is usually well described by a linear relation, and its slope computed at the inversion angle is conventionally indicated as h . A classical result of laboratory experiments and astronomical observations is that there is a relation between the slope h and the surface albedo. Another, though less strict, relation exists also between albedo and P_{min} . These relations are conventionally expressed in very simple mathematical form, as

$$\log(p_V) = C_1 \log x + C_2$$

where x is either h or P_{min} , and the values of the two constants C_1 and C_2 vary accordingly. The most recent calibration of the albedo - polarization relation (namely the values to be used for the two coefficients in the above formula) has been published by Cellino *et al.* (1999), and we will use it in our present analysis. We note that older calibrations exist in the literature,

and are still used by several authors. This is a source of confusion, and it is clear that one urgent goal in asteroid polarimetry is to converge to a unique and updated choice of the calibration coefficients. IAU Commission 15 has appointed a Working Group of specialists with the goal of solving this problem as soon as possible, but it is clear that many new observations are needed to fulfil this task.

Summarizing, polarimetry provides information on some properties of surface regolith which can hardly be obtained by means of other techniques. In particular, polarimetry is one of the best available techniques for the determination of the geometric albedo, mainly for small objects, with particularly useful applications to near-Earth objects (Cellino *et al.*, 1999, 2005a, 2005b; Delbò *et al.*, 2007). The polarimetric behaviour is also thought to be related to other properties, including the typical sizes of regolith particles (Dollfus *et al.*, 1989), and/or the distances of light scatterers in the crystalline structure of the surface material, and its refractive index (Masiero *et al.*, 2009). The major problem in asteroid polarimetry is that it is not easy to develop a comprehensive analytical theory based on current knowledge of light scattering properties, to quantitatively explain in details the whole body of observational evidence. Some of the commonly exploited relations between polarimetric properties and physical parameters are still at least partly empirical, although important advances have been done in re-

cent years on the theoretical side (Muinonen *et al.*, 2002a; Shkuratov *et al.*, 2002). According to these studies, the most important phenomenon determining the observed polarimetric properties of atmosphereless Solar System bodies is coherent backscattering.

On the other hand, it is well established that asteroids belonging to different taxonomic classes exhibit differences in the details of their phase - polarization curves, and this is interpreted in terms of corresponding differences in regolith particle properties, including primarily albedo (Penttilä *et al.*, 2005). It is thus very interesting in principle to compare the polarimetric properties of bodies having likely the same mineralogical composition, but having been exposed for very different times to space weathering effects that are known to produce observable effects on the properties of regolith particles, including spectral reflectance and albedo.

3 The Choice of the Targets and the Observations

In planning our observations, we had to satisfy a few fundamental requirements: first, we had to observe a reasonably large sample of objects belonging to the Karin family, and over a time span possibly sufficient to derive reasonable estimates of the slope h of the phase - polarization curve. Since these asteroids are very small (a few km in diameters) and faint (apparent magnitudes fainter than 20) the choice of the telescope to whom to

address our observing proposal was practically obliged. These are objects whose state of polarization can be measured only by using telescopes in the 8-meters class or beyond, conveniently equipped for polarimetric observations. In our project, we were successful in getting observing time at the 8-meters Kueyen telescope, one of the four 8-meters telescopes of the European Southern Observatory (ESO) located at Cerro Paranal (Chile). In particular, we got four full nights, on June 6 and 23, and on July 4 and 23, 2006. The observations were carried out using the FORS1 instrument in polarimetric mode. Information on this instrument and observation mode are available at <http://www.eso.org/instruments/fors1>.

In addition to the sample of Karin asteroids, an equivalent sample of objects belonging to the Koronis family had also to be selected for observations during the same nights. We note that the Koronis family includes many objects that are much larger and brighter than the Karin members. But due to our desire of observing objects in the same size interval, our choice of Koronis targets was also limited to a sample of quite faint objects. The reason for choosing objects in the same size range for both families was to avoid in principle the danger of observing objects having possibly systematic differences in their physical properties. In this respect, objects having the same size and composition may be expected to be intrinsically identical, and any systematic differences between their observed surface properties might be

reasonably interpreted as being essentially due to different space weathering exposure ages.

Of course, we cannot rule out *a priori* the possibility that some of the Koronis objects in our sample might also be in principle second-generation fragments. However, it is very unlikely that any of them might be as young as the extremely fresh Karin objects. In other words, we are confident that in our analysis we compare the albedos of freshly-born asteroids with those of objects intrinsically similar if not identical to them, but having much more mature surfaces.

In Table 1 we give the full list of targets observed during our four nights. For each object we give the observational circumstances, the absolute magnitude H (taken from the JPL-Horizon web page, available at URL <http://ssd.jpl.nasa.gov/sbdb.cgi>) and we specify whether they belong to either the Koronis or Karin families. As for the listed values of H , we note that it has been recently pointed out that catalogue values of this parameter tend to be affected by considerable errors, and in particular the actual objects are usually found to be fainter than predicted on the basis of the nominal H values (see, for instance, Cellino *et al.*, 2009).

In our VLT observations, we used standard procedures already applied in a previous campaign (Delbò *et al.*, 2007) for data acquisition, calibration and reduction. The acquisition of flat fields and observations of polarimetric

Table 1: List of Targets and Observational circumstances.

number	Designation	H	JD	Family	Date	UT time	r (AU)	Δ (AU)	α
7028	tachikawa	13.2	2453921.7091145832	KO	2006-07-05	05:01:07.500	2.769766228	1.815736468	8.98
9988	eric templebell	12.8	2453921.7650868753	KO	2006-07-05	06:21:43.506	2.957308268	2.000359216	8.11
11298	gide	14.1	2453908.8046239587	KO	2006-06-22	07:18:39.510	3.004799739	2.049289857	8.01
13360	1998 ud8	12.6	2453891.6841435414	KO	2006-06-05	04:25:10.002	2.815818621	1.889154344	10.27
13360	1998 ud8		2453908.7017591665	KO	2006-06-22	04:50:31.992	2.810403960	2.021947590	15.45
13360	1998 ud8		2453921.6394502083	KO	2006-07-05	03:20:48.498	2.806482925	2.155175539	18.26
13360	1998 ud8		2453938.6439989582	KO	2006-07-22	03:27:21.510	2.801626203	2.356509665	20.47
13382	1998 xc4		2453938.7136843749	KO	2006-07-22	05:07:42.330	2.967683506	2.032217265	9.26
13765	nansmith	14.2	2453891.6564381248	KA	2006-06-05	03:45:16.254	3.050892093	2.137090582	9.90
13765	nansmith		2453908.6785302083	KA	2006-06-22	04:17:05.010	3.050229878	2.285839875	14.57
13765	nansmith		2453921.6053008330	KA	2006-07-05	02:31:37.992	3.049354659	2.430483422	17.03
13765	nansmith		2453938.6209720834	KA	2006-07-22	02:54:11.988	3.047713682	2.646692258	18.92
13807	1998 xe13	13.7	2453891.7396210413	KA	2006-06-05	05:45:03.258	2.879224309	1.937080015	9.14
13807	1998 xe13		2453908.7229166664	KA	2006-06-22	05:21:00.000	2.867051612	2.056744246	14.51
13807	1998 xe13		2453921.6575886114	KA	2006-07-05	03:46:55.656	2.857780533	2.181781131	17.49
13807	1998 xe13		2453938.6665566666	KA	2006-07-22	03:59:50.496	2.845584134	2.375278497	19.95
14071	gadabird	13.9	2453891.7633160413	KO	2006-06-05	06:19:10.506	2.757499168	1.744203323	1.35
14071	gadabird		2453908.7789872917	KO	2006-06-22	06:41:44.502	2.751154296	1.777679859	7.57
14071	gadabird		2453921.6843634723	KO	2006-07-05	04:25:29.004	2.746603501	1.850933496	12.24
14071	gadabird		2453938.6936458331	KO	2006-07-22	04:38:51.000	2.740990786	1.997589773	17.02
15205	1978 vc4	14.3	2453938.7735302085	KO	2006-07-22	06:33:53.010	2.907604020	1.947181982	8.00
15578	2000 gw69	13.4	2453921.9160812497	KO	2006-07-05	09:59:09.420	2.814157822	1.877323081	9.87
16313	1199 t-1	14.6	2453908.8847685419	KO	2006-06-22	09:14:04.002	2.666921540	2.174954405	21.28
16313	1199 t-1		2453921.8557522916	KO	2006-07-05	08:32:16.998	2.668605403	2.024436756	19.49
16313	1199 t-1		2453938.8588772919	KO	2006-07-22	08:36:46.998	2.671449444	1.854166604	15.60
16748	1996 pd9	13.8	2453891.8816318749	KO	2006-06-05	09:09:32.994	2.731276542	2.334325196	21.32
16748	1996 pd9		2453908.8592131250	KO	2006-06-22	08:37:16.014	2.722919845	2.118907934	19.60
16748	1996 pd9		2453921.8197608334	KO	2006-07-05	07:40:27.336	2.717020758	1.971467574	17.18
16748	1996 pd9		2453938.8329802081	KO	2006-07-22	07:59:29.490	2.709952863	1.814529770	12.44
22398	1994 wf1	13.6	2453908.5131861111	KO	2006-06-22	00:18:59.280	3.164337356	3.246557845	18.18
22398	1994 wf1		2453921.5017050970	KO	2006-07-05	00:02:27.320	3.163996285	3.418417966	17.21
22398	1994 wf1		2453938.5082168961	KO	2006-07-22	00:11:49.940	3.162863981	3.624638486	15.36
22682	1998 qu47	13.8	2453891.5767620830	KO	2006-06-05	01:50:32.244	2.941047557	2.274588290	17.00
22682	1998 qu47		2453908.5929339584	KO	2006-06-22	02:13:49.494	2.945682920	2.487858376	19.29
23912	1998 su128	13.7	2453891.5521267708	KO	2006-06-05	01:15:03.753	2.875890318	2.232490941	17.80
23912	1998 su128		2453908.5681943754	KO	2006-06-22	01:38:11.994	2.866420318	2.431974488	20.04
23912	1998 su128		2453921.5328356386	KO	2006-07-05	00:47:16.999	2.859215073	2.594852368	20.76
24121	achandran	14.1	2453908.5389699168	KA	2006-06-22	00:56:07.001	2.864080523	2.853932467	20.47
24121	achandran		2453938.5315798335	KA	2006-07-22	00:45:28.498	2.862171431	3.225620078	17.97
26875	1994 af10	14.1	2453891.9113164581	KA	2006-06-05	09:52:17.742	2.684070864	2.397068359	22.12
26875	1994 af10		2453908.9130672915	KA	2006-06-22	09:54:49.014	2.681070046	2.181239903	21.09
26875	1994 af10		2453921.8854899998	KA	2006-07-05	09:15:06.336	2.679294929	2.027835719	19.28
26875	1994 af10		2453938.8925406253	KA	2006-07-22	09:25:15.510	2.677663348	1.855225798	15.39
45257	1999 yc14	14.7	2453891.7137122918	KA	2006-06-05	05:07:44.742	3.017610598	2.086659639	9.21
48312	2002 np3	14.9	2453891.6290133335	KA	2006-06-05	03:05:46.752	2.868931782	2.067677163	14.68
48312	2002 np3		2453908.6508679166	KA	2006-06-22	03:37:14.988	2.858684830	2.239891709	18.33
48312	2002 np3		2453938.5916722915	KA	2006-07-22	02:12:00.486	2.840625904	2.604294604	20.93
51068	2000 gw156	15.2	2453891.8151620831	KA	2006-06-05	07:33:50.004	2.695411101	2.236323829	21.24
51068	2000 gw156		2453908.8306712499	KA	2006-06-22	07:56:09.996	2.692330265	2.032067838	19.02
51068	2000 gw156		2453921.7909433329	KA	2006-07-05	06:58:57.504	2.690451632	1.896460285	16.17
51068	2000 gw156		2453938.8066397221	KA	2006-07-22	07:21:33.672	2.688610179	1.759103053	10.84
69880	1998 sq81	14.4	2453891.6022337498	KA	2006-06-05	02:27:12.996	3.022834226	2.269908483	14.91
69880	1998 sq81		2453908.6214697920	KA	2006-06-22	02:54:54.990	3.025237444	2.468543879	17.90
69880	1998 sq81		2453938.5601041671	KA	2006-07-22	01:26:33.000	3.028248651	2.870428594	19.60
76686	2000 hn72	14.8	2453921.7328394442	KA	2006-07-05	05:35:17.328	2.888541758	1.917167529	7.33

standard stars are part of the standard ESO calibration procedure and were carried by ESO staff. The asteroid and standard star images were corrected for bias and master flat, and the cosmic rays removed. Linear polarization measurements were obtained in the V-band at 8 position angles of the $\lambda/2$ retarder plate (0° , 22.5° , 45° , 67.5° , 90° , 112.5° , 135° and 157.5°). In the data reduction procedure, for each position of the half-wave plate, photometric measurements of the recorded Ordinary and Secondary rays were performed. To each polarimetric measurement we assigned a corresponding SNR value by taking the minimum value of SNR found for the photometric measurements of the Ordinary and Extraordinary ray for each of the 8 positions of the $\lambda/2$ retarder plate.

We want to make it clear that in this campaign we were not interested in deriving detailed and very accurate polarimetric information for each individual object. Having at disposal only four nights covering a maximum time span of one month, we could not hope to be able to obtain in any case a satisfactory phase angle coverage for each single object. Moreover, due to the faintness of the targets, we were aware that the error bars of the single polarimetric measurements should be expected *a priori* to be fairly large. Obtaining very accurate measurements for objects so faint would require quite long integration times, not compatible with the need of observing a sufficiently large sample of targets to be repeatedly measured during the

nights at our disposal, over a variety of phase angles. Our main purpose, therefore, was to infer the evidence of a possible *systematic difference* between the phase - polarization curves of Karin and Koronis family members, in a statistical sense.

In other words, in this paper we do not look in details at the phase - polarization curves obtained from a few observations of each individual object. Instead, we are mostly interested in merging together all the observations of a sample of members of the Karin family, observed in a range of phase angles, to be compared with an analogous set of measurements obtained for a sample of Koronis members of approximately the same size. The results of this exercise are given in the following Section. We also note that, since our goal here is simply to compare average phase - polarization curves of two different samples of objects, this analysis is exempt from all kind of problem usually encountered in asteroid polarimetry, related to the uncertainty in deriving absolute determinations of the albedo, as a consequence of uncertainties in the calibration of the albedo - polarimetric slope (or P_{min}) relation (see, for instance, Delbò *et al.* 2007).

4 The Results

Table 2 summarizes the results of our polarimetric observations for each object in our target list. In Fig. 1 the above results are graphically shown

Table 2: Results of polarimetric observations

number	Designation	Family	$\alpha(^{\circ})$	$P(\%)$	$err(P)$	$PA(deg)$	$err(PA)$	θ (deg)	$P_r(\%)$	$err(P_r)$	SNR
7028	tachikawa	KO	8.98	0.60	0.05	97.6	2.5	94.7	-0.59	0.05	468.1
9988	eric templebell	KO	8.11	0.71	0.09	71.9	3.5	98.8	-0.68	0.09	290.0
11298	gide	KO	8.01	0.80	0.07	88.9	2.6	83.5	-0.78	0.07	340.4
13360	1998 ud8	KO	10.27	0.70	0.08	105.6	3.2	96.3	-0.68	0.08	813.9
13360	1998 ud8	KO	15.45	0.28	0.09	100.0	9.5	99.5	-0.26	0.09	410.4
13360	1998 ud8	KO	18.26	0.21	0.23	95.6	30.9	103.3	-0.19	0.23	186.4
13360	1998 ud8	KO	20.47	0.11	0.09	54.6	23.0	37.0	0.03	0.09	360.0
13382	1998 xc4	KO	9.26	0.64	0.06	86.4	2.8	85.2	-0.63	0.06	406.1
13765	nansmith	KA	9.90	1.00	0.22	115.3	6.3	83.1	-0.97	0.22	161.3
13765	nansmith	KA	14.57	0.07	0.12	77.2	56.2	59.7	-0.03	0.13	189.1
13765	nansmith	KA	17.03	0.70	0.42	176.1	16.9	21.6	0.51	0.42	60.4
13765	nansmith	KA	18.92	0.56	0.22	4.0	11.0	13.8	0.50	0.22	115.9
13807	1998 xe13	KA	9.14	0.96	0.13	109.4	3.9	89.6	-0.96	0.13	369.3
13807	1998 xe13	KA	14.51	0.78	0.11	111.5	3.9	85.9	-0.77	0.11	355.9
13807	1998 xe13	KA	17.49	0.82	0.34	91.9	11.8	105.4	-0.70	0.34	104.2
13807	1998 xe13	KA	19.95	0.93	0.17	129.5	5.2	67.5	-0.66	0.17	219.4
14071	gadabird	KO	1.35	0.33	0.06	166.7	5.6	97.2	-0.32	0.06	556.3
14071	gadabird	KO	7.57	0.98	0.05	114.1	1.6	86.3	-0.97	0.05	465.8
14071	gadabird	KO	12.24	1.21	0.10	118.1	2.4	77.2	-1.09	0.10	246.2
14071	gadabird	KO	17.02	0.61	0.09	102.0	4.6	89.4	-0.61	0.09	261.2
15205	1978 vc4	KO	8.00	0.75	0.09	72.0	3.3	90.4	-0.75	0.09	285.7
15578	2000 gw69	KO	9.87	0.73	0.14	84.7	5.8	79.4	-0.68	0.14	279.8
16313	1199 t-1	KO	21.28	0.28	0.14	11.7	14.3	145.2	0.10	0.14	258.1
16313	1199 t-1	KO	19.49	0.41	0.19	177.4	14.4	158.4	0.30	0.20	225.6
16313	1199 t-1	KO	15.60	0.26	0.09	80.0	10.0	74.5	-0.22	0.09	286.8
16748	1996 pd9	KO	21.32	0.21	0.09	14.6	13.1	144.4	0.07	0.10	374.9
16748	1996 pd9	KO	19.60	0.09	0.06	51.5	19.3	106.8	-0.07	0.06	429.3
16748	1996 pd9	KO	17.18	0.52	0.06	52.4	3.5	105.8	-0.44	0.06	410.5
16748	1996 pd9	KO	12.44	0.73	0.04	75.8	1.6	83.8	-0.71	0.04	619.1
22398	1994 wf1	KO	18.18	0.58	0.22	63.0	10.6	40.0	0.10	0.21	117.1
22398	1994 wf1	KO	17.21	0.67	0.42	135.3	16.9	68.2	-0.48	0.41	62.1
22398	1994 wf1	KO	15.36	0.66	0.37	127.0	15.7	76.9	-0.59	0.37	68.1
22682	1998 qu47	KO	17.00	0.91	0.16	127.8	5.0	76.0	-0.80	0.16	223.7
22682	1998 qu47	KO	19.29	0.04	0.11	38.8	79.6	15.6	0.03	0.11	236.6
23912	1998 su128	KO	17.80	0.31	0.21	129.1	18.9	75.3	-0.27	0.21	172.4
23912	1998 su128	KO	20.04	0.22	0.09	55.4	11.7	32.2	0.10	0.09	278.7
23912	1998 su128	KO	20.76	0.13	0.19	1.0	42.4	21.5	0.10	0.19	130.0
24121	achandran	KA	20.47	0.50	0.38	58.4	20.7	35.2	0.17	0.36	119.5
24121	achandran	KA	17.97	0.46	0.55	71.5	34.8	48.1	-0.05	0.56	76.2
26875	1994 af10	KA	22.12	0.29	0.19	173.8	20.0	164.1	0.25	0.19	181.5
26875	1994 af10	KA	21.09	0.29	0.09	150.6	9.2	187.8	0.28	0.09	271.6
26875	1994 af10	KA	19.28	0.03	0.09	82.0	99.6	76.4	-0.03	0.09	283.0
26875	1994 af10	KA	15.39	0.68	0.06	70.3	2.5	90.7	-0.68	0.06	275.4
45257	1999 yc14	KA	9.21	1.26	0.20	109.4	4.6	97.3	-1.22	0.20	175.0
48312	2002 np3	KA	14.68	0.59	0.31	49.0	15.6	28.9	0.31	0.32	111.3
48312	2002 np3	KA	18.33	0.69	0.17	79.6	7.1	59.2	-0.33	0.17	145.2
48312	2002 np3	KA	20.93	0.86	0.31	51.9	10.7	31.6	0.39	0.32	79.5
51068	2000 gw156	KA	21.24	0.35	0.14	13.0	11.1	147.1	0.14	0.14	255.6
51068	2000 gw156	KA	19.02	0.36	0.13	56.4	10.6	103.5	-0.32	0.13	191.6
51068	2000 gw156	KA	16.17	0.57	0.14	112.7	7.0	227.6	-0.05	0.14	180.4
51068	2000 gw156	KA	10.84	0.60	0.05	79.2	2.4	83.9	-0.59	0.05	343.7
69880	1998 sq81	KA	14.91	0.46	0.28	143.5	16.9	60.1	-0.23	0.27	129.3
69880	1998 sq81	KA	17.90	0.71	0.14	138.5	5.7	64.2	-0.44	0.14	179.5
69880	1998 sq81	KA	19.60	0.96	0.22	140.9	6.8	59.8	-0.47	0.22	111.2
76686	2000 hn72	KA	7.33	0.72	0.19	61.6	7.6	94.6	-0.71	0.19	196.8

in the form of a plot of P_r versus phase angle, using different symbols to indicate members of the Karin and Koronis families.

As it can be seen, many of our polarimetric measurements are affected by large error bars, since the objects were very faint. The plot appears to be noisy, with no clear difference between the Karin and the Koronis members, since the objects are mixed in the plot and the two groups do not show any systematic shift with respect to each other. The Koronis members appear to have on the average slightly smaller error bars and are less dispersed. This can be a consequence of the fact that, as can be seen looking at Table 1, the Koronis members in our sample were on the average a little brighter than the Karin members, though not so much as to imply a significant systematic difference in size. Even in the case of the Koronis members, however, at least in a few cases, like one observation of (14071) Gadabird around 12 degrees of phase, the scatter of the measurements is certainly not negligible, but we believe that this is due primarily to the faintness of the object, rather than to a clear difference in the behavior of the phase-polarization curve.

In order to better represent the polarimetric behaviour of the two groups, we decided to remove from our analysis all the objects whose signals were affected by exceedingly large errors. In particular, we limited our analysis by considering only observations characterized by SNR better than 150. This led us to consider a sample of 25 observations of Koronis asteroids, and

16 observations of Karin asteroids. Note that, in the case of the Koronis members, this led to reject only four measurements out of 29. The selected measurements are separately shown in Figures 2 and 3.

As can be seen in Figure 2, the single phase-polarization data were fitted by a curve having the following mathematical expression:

$$P_r = A_0 \left(\exp^{-\alpha/A_1} - 1 \right) + A_2 \alpha \quad (1)$$

where α is the phase angle. The above expression, first proposed by Piironen *et al.* 2000, has been adopted by several authors in recent years to represent in an analytical way the phase - polarization curves of asteroids and other Solar System bodies (Kaasalainen *et al.*, 2001; Muinonen *et al.*, 2002b; Gil-Hutton, 2007).

The data shown in Fig. 2 are noisy, and the nominal accuracy of the coefficients of the best-fit curve that we find is poor. However, the best-fit curve for our sample of small Koronis members does not differ significantly from that of typical phase - polarization curves exhibited by well-observed *S*-class asteroids of larger size. As an example, we show in Fig. 4 the available polarimetric data for the asteroid (39) Laetitia, with superimposed the best-fit curve obtained for our Koronis sample. It can be seen that the curve fits reasonably well the available data for Laetitia (taken from the Asteroid Polarimetry Database available at the NASA Planetary Data System repository, at URL <http://pds.jpl.nasa.gov/>).

In principle, a similar curve might be computed also for the Karin objects displayed in Fig. 3, but we have checked that the lack of polarimetric measurements at phase angles below 8 degrees, produces a visually strange behaviour at small phases, where the fit is not constrained by any actual observation. However, since our main goal is to check whether the asteroids belonging to the Koronis and Karin families display a behaviour that can be quantitatively found to be different, we preferred to take a more direct approach. In Fig. 5 we plot again our Koronis and Karin data (already shown separately in Figs. 2 and 3, together with the best-fit curve found for the Koronis sample. In order to quantify the visual impression that no systematic difference can be seen between the two groups of data, we made a Kolmogorov-Smirnov test, to check the hypothesis that the Karin data distribution can be issued from the same law of distribution that produces the Koronis sample. The test was carried out by using some standard IDL routines¹. The result of this exercise is that the above hypothesis cannot be rejected, with a confidence level of 97.7%. Of course, we are aware that this kind of statistical test has little sense when applied to a small sample of data like the one we are using here, and this would not improve even by adding the limited number of data points with SNR worse than 150. Yet, we mention this result, since it seems to confirm our subjective conclusion that

¹available at <http://idlastro.gsfc.nasa.gov/ftp/pro/math/kstwo.pro>

our polarimetric measurements of Karin and Koronis samples do not exhibit any kind of strong, systematic difference. We also note that we computed a best-fit curve by using together all the Karin and Koronis observations with SNR better than 150. Again, we found that the resulting best-fit curve turns out to be practically identical to that already found for Koronis members, only, and shown in Fig. 2. Since there are not apparent differences, in the above Figure we only show the best-fit curve obtained for the Koronis sample.

Although we recognize that we have not at disposal a big sample of measurements, we have in any case computed the resulting values of the h slopes for the phase-polarization curves of our two samples. As quoted above, the value of h is known to be an important diagnostic of the surface albedo. Again, we could not find any systematic difference about the two families. In the computation of the polarimetric slope, we excluded all the observations made at phase angles smaller than 16° or having nominal SNR worse than 150. In this way, we selected a sample of 14 measurements for the Koronis sample, and of 9 measurements for the Karin sample. We computed linear least-squares fits, weighting the observations with the inverse of the nominal error of P_r . For the Koronis and Karin family members, we found for the slope the values $h_{KO} = 0.105 \pm 0.018$ and $h_{KA} = 0.110 \pm 0.027$, respectively. The small nominal errors of the derived slopes suggest that,

even if the phase - polarization curves of different individual objects within the two samples can be not absolutely identical (as one might guess by looking in details at the data shown in Table 2), the differences are in any case quite marginal, and are probably mainly due to observational uncertainties. Therefore, we can conclude that no difference in polarimetric slope is found in our analysis. Adopting the Cellino *et al.* (1999) calibration coefficients of the h - albedo relation, the corresponding albedo turns out to be 0.21 ± 0.04 for the Koronis sample, and 0.20 ± 0.06 for the Karin sample. These values are relatively high for the S class, but not beyond the observed range of variation for this class. Note also that the uncertainty in the above albedo values mainly comes from corresponding uncertainties in the calibration of the slope - albedo relation (as already noted in another situation by Delbò *et al.* 2007).

To summarize, we find that our two samples of Koronis and Karin polarimetric measurements are not statistically distinguishable and can be fitted by a single phase-polarization curve.

5 Discussion

The results of our observing campaign indicate that the phase - polarization curves of members of the very young Karin family cannot be distinguished from those of equal-sized members of the much older Koronis parent family.

When we started this project, a few years ago, our expectation was that we would possibly detect some clear and measurable difference between the two groups, as a consequence of quite different times of exposure to space weathering effects. We have found that this is not the case, and our results are in agreement with recent indications coming from asteroid spectroscopy (Vernazza *et al.*, 2009), suggesting that space weathering effects may substantially affect the properties of asteroid surfaces over very short time scales. In the case of the present investigation, this time scale is of the order of less than about 6 My.

According to our analysis it seems that the Karin family, in spite of being so young, is already an “old” one from the point of view of the time scales needed to modify the albedo by means of space weathering mechanisms. If space weathering mechanisms are so efficient, the only possibility to achieve what was the original goal of our observing campaign would be to carry out polarimetric observations of other, younger, families, like those of Iannini (Nesvorný *et al.*, 2003), or the even younger families more recently found by Nesvorný and Vokrouhlický (2006) (Datura, Emilkowalsky, Lucascavin families). These families, which may be even younger than 1 My and are generally formed by objects belonging to the *S* taxonomic class, might be sufficiently fresh as to exhibit some clue of a transition from surfaces not yet strongly altered by space weathering processes, at least for what con-

cerns surface properties (like the geometric albedo) derivable by means of polarimetry.

Of course, we are fully aware that spectroscopic observations by Vernazza *et al.* (2009) indicate that spectral reddening effects seem to be already present and detectable in times as short as one Million of years.

A timescale of only 1 My for the space weathering-driven reddening of the surfaces, might in principle raise some difficult problems. In particular, it would seem not easy to explain the fairly abundant presence of apparently intact, or poorly reddened spectra among near-Earth objects (Binzel *et al.*, 2001). In the past, some results based on an analysis of the timescales needed to produce near-Earth asteroids by means of direct injection into resonances in family forming events (Gladman *et al.*, 1997; Zappalà *et al.*, 1998) had been criticized due to the fact that the resulting timescales, of the order of 2 or 3 My, turned out to be in conflict with the cosmic ray exposure ages of meteorites. A longer timescale was thought to be necessary to solve this problem, and the generally accepted solution is now the one involving a longer Yarkovsky-driven drift in semi-major axis, needed to reach neighboring resonances after collisional events. If the timescale for spectral reddening of asteroid surfaces is even shorter than 1 My, it becomes in principle quite difficult to explain the existence of apparently intact OC-like surfaces among near-Earth asteroids. A very elegant explanation of this

apparent conundrum, however, has been found very recently by Binzel *et al.* (2010). In particular, the above authors demonstrated that all known NEAs exhibiting OC-like spectra have had some close approach with the Earth during the last 200,000 years. Due to tidal interactions these close-approach events are thought to have produced a general re-shaping of the objects, and a consequent general re-juvenation of the surfaces. Although some details of this scenario are not yet completely clear, it seems that we have now at disposal an explanation of the presence of very fresh asteroidal surfaces which have been found so far uniquely among the NEA population, and not among main belt objects.

Our present results tend to be in agreement with the above-mentioned general scenario, since we have found that space-weathering mechanisms affecting the albedo, or more generally surface properties giving a polarimetric signature, seem to occur on time scales shorter than 6 My for small main belt asteroids belonging to the *S* class, a value which is fairly short, though still less extreme than the spectral reddening timescale found in recent investigations.

We think that our results are interesting in many respects. One reason is that it is commonly assumed that polarimetric properties may be diagnostic of the typical sizes of surface regolith particles (see, *e.g.*, Dollfus *et al.*, 1989). It is also generally believed, moreover, that the presence of a dusty regolith

is considered to be a necessary pre-requisite for an efficient switching on of the space weathering engine (See, e.g., Chapman 2004). On the other hand, what kind of regolith may we expect to be present on the surfaces of bodies as small and young as Karin members? This question is also related to the results of polarimetric observations of the asteroid (25143) Itokawa, the target of the Hayabusa space mission. *In situ* images of this object suggest that very little regolith seems to be present on the surface, yet its polarimetric properties, according to observations by Cellino *et al.* (2005b) are not different with respect to those of other, bigger and certainly regolith-covered *S*-class asteroids. In this respect, our new polarimetric observations of the Karin family complement and extend previous results on Itokawa, suggesting that “normal” polarimetric properties are found also for objects that might be suspected to be regolith-poor. A possible explanation of this apparent paradox has been recently proposed by Masiero *et al.* (2009).

Of course, we cannot rule out the possibility that the development of a regolith layer may be faster than expected. In the case of Karin family members, moreover, this might also be possibly related to their peculiar environment in the same region of the orbital element space occupied by the big Koronis family. This might possibly tend to enhance the rate of relatively gentle collisions with particles belonging to the dust band associated with the Koronis family, or with the Karin family itself (Nesvorný *et al.*, 2003). Inter-

family collisions among Karin members for a very short time after family formation might be a another possible source of relatively intense surface reprocessing, according to the results of Dell'Oro *et al.* (2002). If this can be proven to be true, we would have a result that might be assumed to hold in general for all objects produced by energetic collisional phenomena.

We do not want to rule out *a priori* the possibility that our basic assumption that the Koronis members in our sample should be much older than the sample of observed Karin objects, might be wrong. If all the objects in our sample were very young, including both Karin and Koronis family members, no difference should be expected *a priori* in their surface properties. However, it seems to us that this possibility is very unlikely, since a very young age of the Koronis objects in this size range would require explanations that contradict available evidence (unacceptably high inter-family collision rates, an overall family age in disagreement with the cratering rate of Ida and Dactyl, etc.).

We are also aware that the overall quality of our results is severely affected by limits in accuracy of our polarimetric measurements. It is clear that further observations should be certainly useful to strengthen the conclusions of our analysis. Having at disposal a longer observing time distributed among a larger number of nights, the error bars of the measurements could be significantly decreased. However, we are convinced that our present re-

sults are already statistically robust. No real difference can be detected between the polarimetric behaviour of the Karin and Koronis members that we have observed, and our sample is not negligible. For this reason, although this result is exactly the opposite of what we originally hoped to find, we conclude that Karin and Koronis family members are, in terms of polarimetric properties, essentially identical in spite of their very different ages. We hope that this result may be useful to trigger further theoretical efforts in the field of light scattering phenomena and space weathering of the surfaces of rocky bodies.

From the point of view of asteroid polarimetry, our observing campaign at VLT constitutes also *per se* a significant achievement. We have been able to measure the degree of linear polarization of a sample including some of the smallest main belt asteroids ever observed by means of polarimetric techniques (apart from a few tiny, but very close near-Earth asteroids like Itokawa and Apophis). The feasibility of these measurements has been satisfactorily proved, and it is clear that the availability of more observing time would have allowed us to decrease the error bars of our measurements. In any case the obtained results are important and constitute in our opinion a very good use of VLT time. The whole field of asteroid science will take profit by a more systematic use of this observing facility for well focused observing programs.

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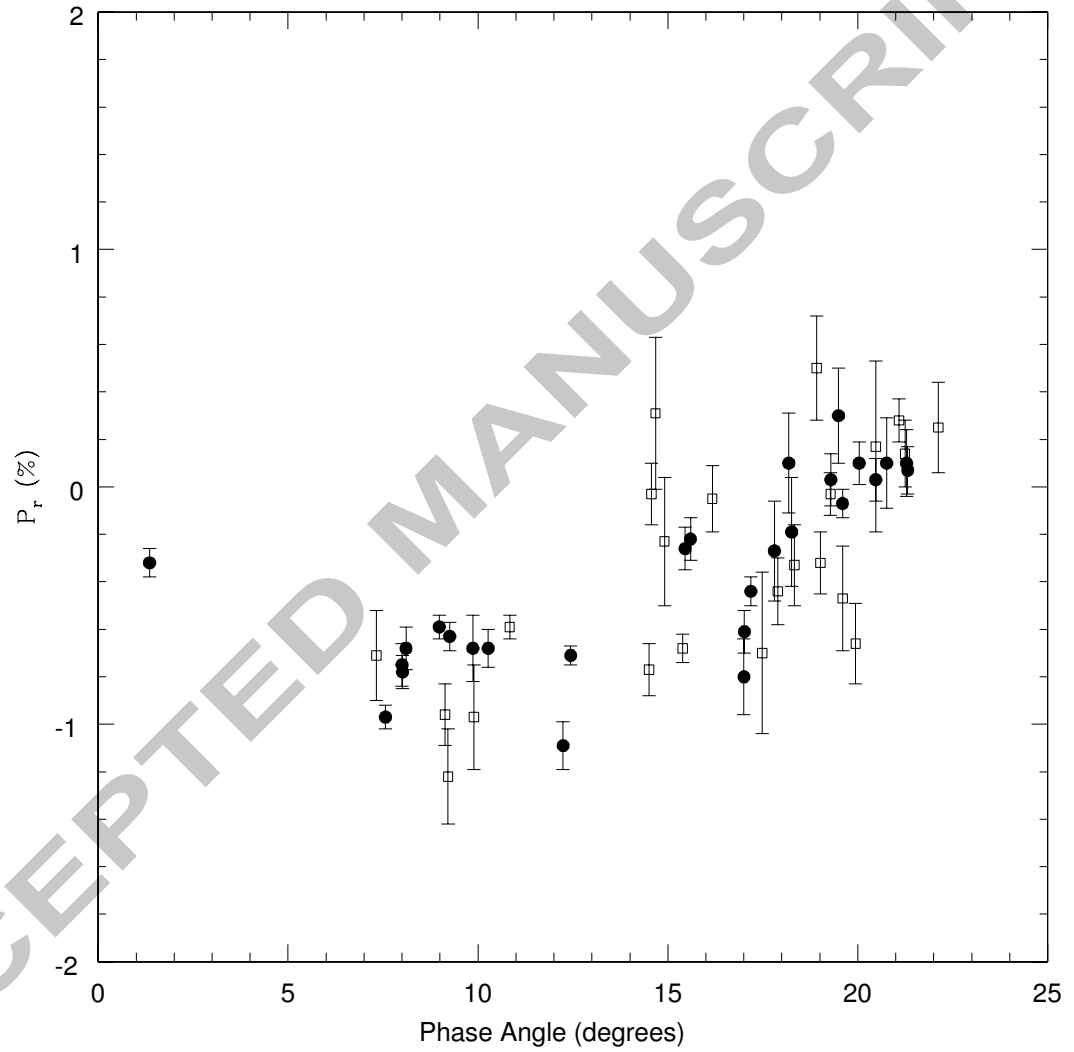


Figure 1: Measured phase - polarization data using the whole sample of observed Koronis (full symbols) and Karin (open squares) members.

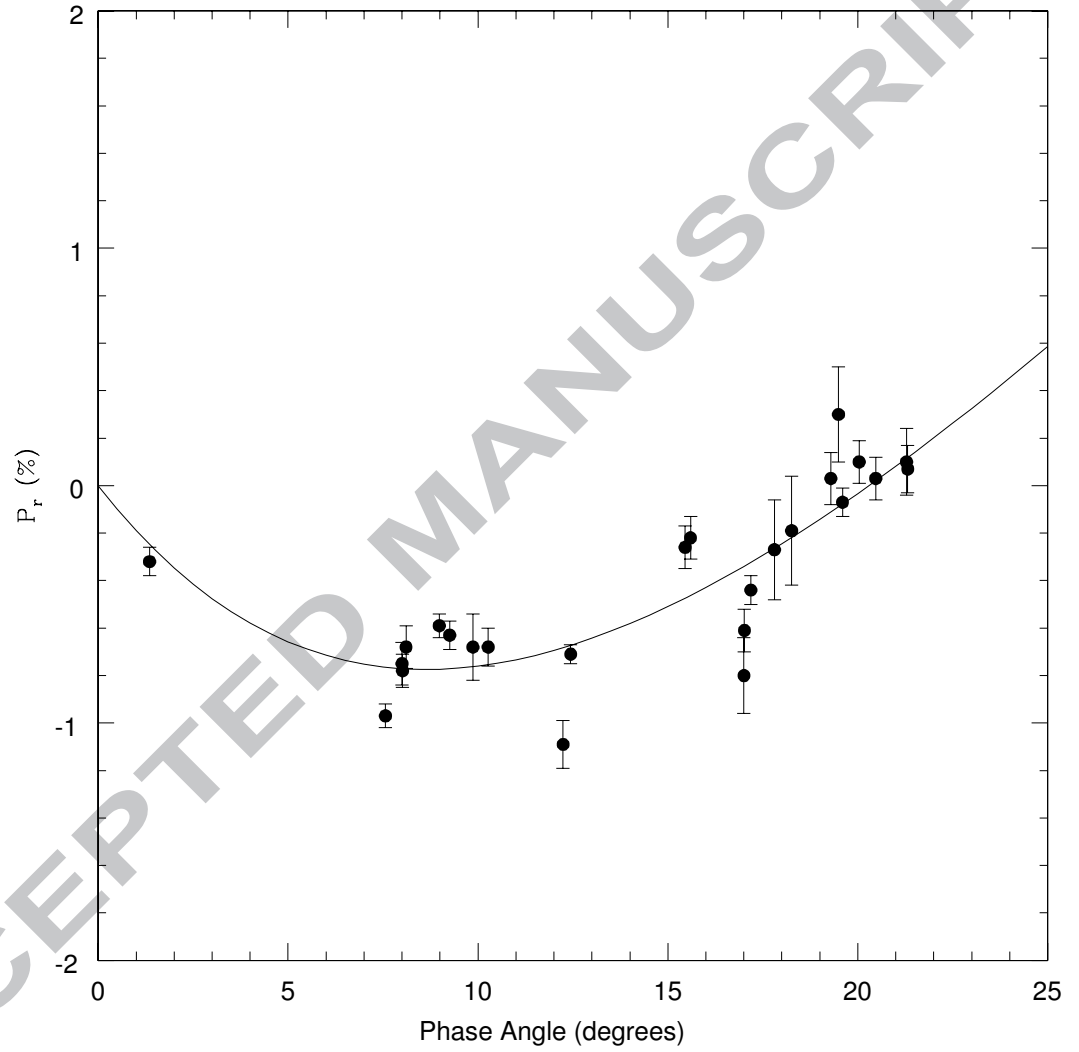


Figure 2: Phase - polarization measurements including only the Koronis family members for which the SNR of the observations was better than 150. The best-fit phase-polarization curve according to Equation 1 is also shown.

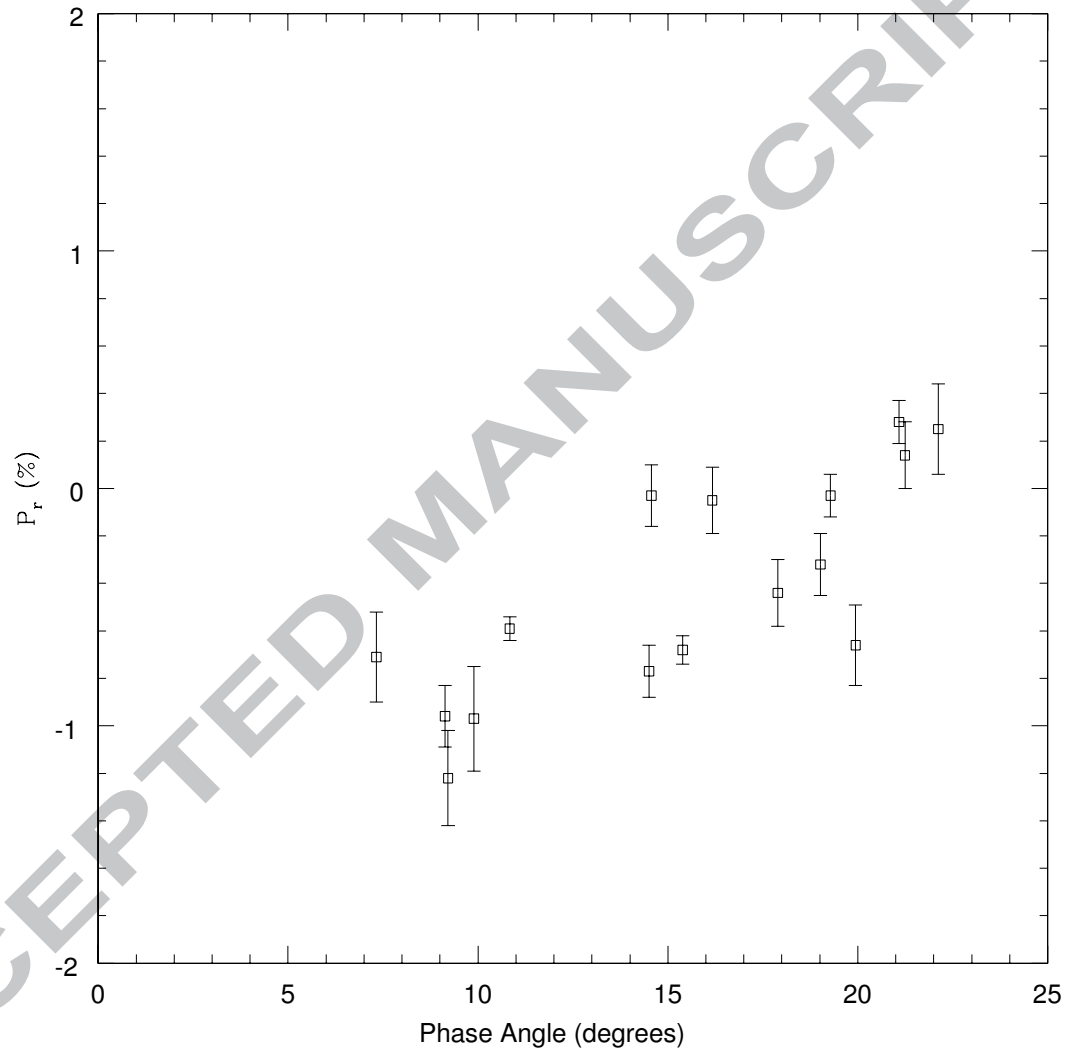


Figure 3: Phase - polarization measurements including only the sample of observed Karin family members for which the SNR of the observations was better than 150.

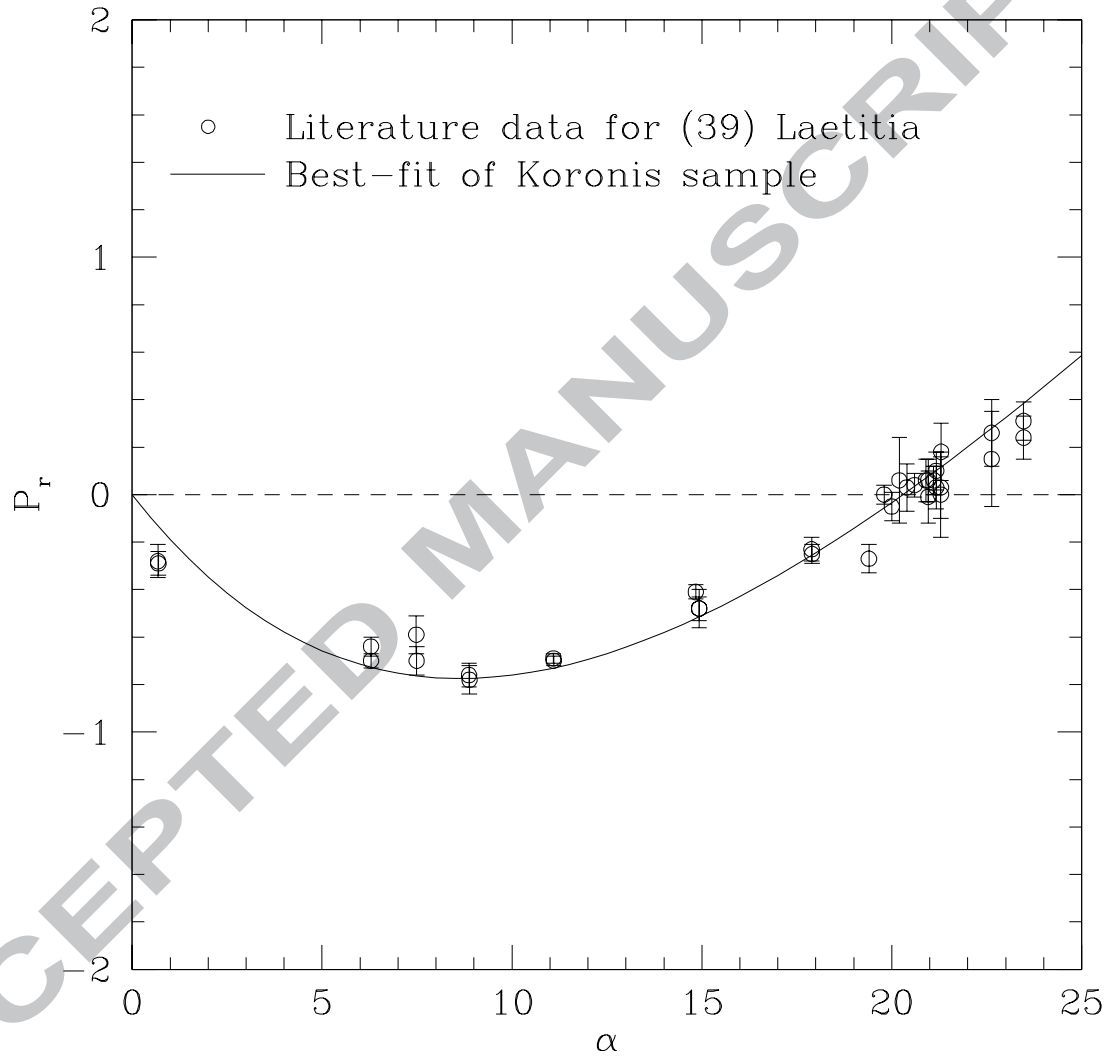


Figure 4: Published phase - polarization measurements of the big *S*-class asteroid (39) Laetitia are shown together with the best-fit curve referring to our sample of Koronis family members shown in Fig. 2.

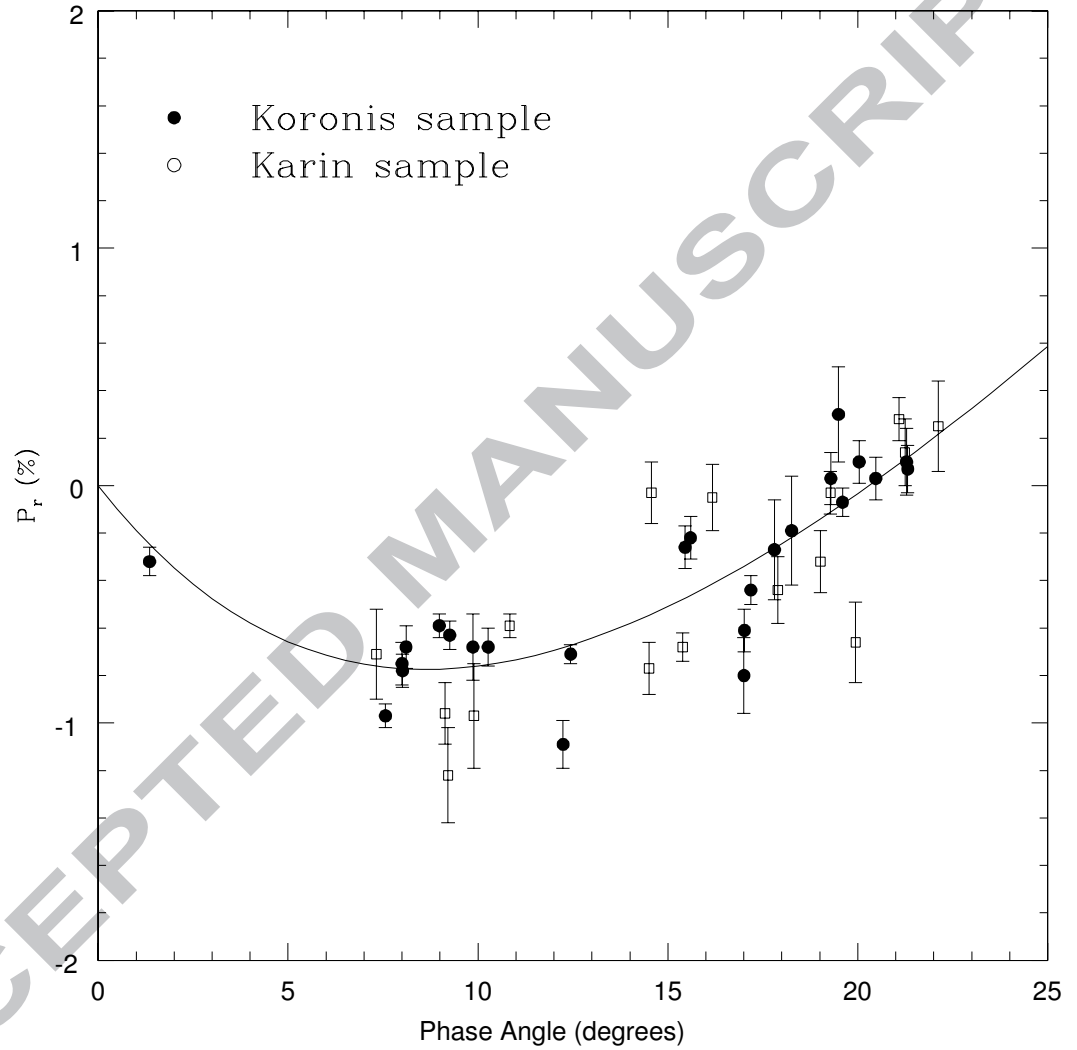


Figure 5: Phase - polarization measurements for the Koronis (full symbols) and Karin (open squares) members for which the SNR of the observations was better than 150, plotted together with the best-fit phase-polarization curve found for the Koronis family members.