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Surface composition of Hungaria asteroids from the analysis of the Sloan Digital Sky Survey colors

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ABSTRACT

Aims. We present the results of a taxonomic classification defined using multiband photometry of Hungaria asteroids. The aim of this work is to analyze the compositional diversity of this population.

Methods. Photometric observations of 334 Hungaria asteroids were taken from the Moving Object Catalog of the Sloan Digital Sky Survey. By means of least squares fitting, a linear function was found to describe the flux data of the Sloan observations and the slope of each spectrum. Each spectrum was then normalized to 6230 Å. The taxonomic type of each object was found by calculating the dissimilarities between the individual spectra and the mean spectra representing the different classes.

Results. We found that a large number of objects in our Hungarias sample are X-types as expected (59% of the sample), but we also found a large number of C-type (26%), and S-type (9%) asteroids and a small number of objects belonging to other taxonomic types. The C-types are not formed originally in this region of the inner main belt, and their presence in this zone could be an indication that there is a dynamical mechanism that is responsible for transporting objects from the the main belt to the inner Solar System.

Key words. minor planets, asteroids – solar system: general

1. Introduction

The Hungaria dynamical group is composed of high-inclination asteroids orbiting at about 1.9 AU, just inside the inner edge of the asteroid main belt. They occupy a region that has complex dynamics which is surrounded by the 5:1 and 4:1 mean motion resonances with Jupiter and the ν_5 and ν_{16} secular resonances, (Scholl et al. 1986). According to their location in the inner asteroid belt, the members of this group might be the sources of the asteroids that must be replenishing the short-living Mars-crosser population (Michel et al. 2000). The Hungarias are currently clustered in the orbital element space due to long-term dynamical processes, but Williams (1989, 1992) and Lamaitre (1994) identified some dynamical clustering in the proper elements space, possibly indicating the presence of families.

The location of the Hungaria group in the inner edge of the main belt would seem to favor a mineralogy associated with E- or M-type taxonomical classes, especially considering that 6 of the 13 E-types classified by Tholen (1989) are in this region. These taxonomic types were originally introduced into the Tholen taxonomy (Tholen 1984), were described as being spectrally degenerate, and could be subdivided based on albedo only. The superficial mineralogies implied by each of these types are considerably different: enstatite or other iron-free silicates for the E-type, and metal with possibly traces of silicates or metal plus enstatite for the M-type (Gaffey et al. 1989). These two types were included in the X-class of the taxonomy proposed by Bus & Binzel (2002b) due to their spectral similarity.

Several works have shed light on the diverse characteristics of the X-class spectra: a 3 μm band in the spectra of M- and E-type asteroids (Rivkin et al. 1995, 2000); absorption bands in the visible spectra of the surface of E-type asteroids (Burbine et al. 1998; Carvano et al. 2001; Fornasier & Lazzarin 2001); absorption bands in the spectra of M-type asteroids (Busarev 1998; Hardersen et al. 2005); small absorption bands in the near-infrared (Clark et al. 2004a), and mineralogical differences between E-type asteroids (Clark et al. 2004b). It is noteworthy that the SMASSII spectra revealed variations in the diverse X-class spectra, allowing them to be divided into several subclasses based solely on spectral features (Bus 1999; Bus & Binzel 2002b).

Carvano et al. (2001) completed a spectroscopic survey of asteroids in the Hungaria group. They observed 29 objects and found that 18 showed a slightly red featureless spectrum that was classified as X-type; they also found 8 S-type, 2 C-type, and 1 A-type asteroids. Since the albedo is a valid criterion for subclassify X-type objects and one of the most important techniques to determine asteroid albedos is polarimetry, Gil-Hutton et al. (2007) performed a extensive polarimetric observing program of Hungaria asteroids. They measured the albedo of 18 Hungarias and found that several asteroids do not have polarimetric properties compatible with E-type objects. This results suggests that the compositional distribution in the group is not as peculiar as has been assumed and the number of high albedo asteroids is compatible with that observed in the inner main belt.

Both Carvano et al. (2001) and Gil-Hutton et al. (2007), studied small samples of asteroids but reached similar conclusions about the compositional distribution of Hungaria asteroids. A compositional analysis of a statistically significant number of members of this group would provide invaluable data for assessing the reality of the dynamical grouping and existence of collisional families, and help to develop a more robust understanding of the transport mechanisms operating between the main belt and planet-crossing orbits.

Impotant sources of data about Hungaria asteroids are large photometric surveys, such as the *Sloan Digital Sky Survey* (SDSS). A sub-product of the SDSS is the *Moving Objects Catalog* (MOC), which in its third release provides five band photometry for 43 424 asteroids of which 15 472 have been observed twice or more (Ivezić et al. 2001; Jurić et al. 2002). For analyzing the surface composition of asteroids and performing a taxonomic classification, multiband photometry is not as precise as spectroscopy, but the amount of data that the SDSS-MOC provides contrast significantly with the aproximately 2300 asteroids observed by major spectroscopic surveys that provide publicly available data sets; such as the SMASS (Xu et al. 1995; Bus & Binzel 2002a) and the S^3OS^2 (Lazzaro et al. 2004). While these spectroscopic surveys reached an average absolute magnitude of $H \sim 11$, the SDSS-MOC increased this value to $H \sim 15$, providing taxonomic information of a large population of very small asteroids, for which spectroscopic observations can only be obtained using very large telescopes.

In this paper, we search for photometric data of Hungaria asteroids in the SDSS-MOC to identify the spectral characteristics of members of this group and to distinguish between objects belonging to different taxonomic classes. However, we note that due to the aproximation only that few band photometry can provide to a spectroscopic classification, this analysis provides only an indication of the taxonomic type of an asteroid. In the following section, we describe the methodology applied to search the database. In Sect. 3 we present the results, and in Sect. 4 we discuss them and outline the conclusions.

2. Methodology

The SDSS photometry is based on the *u, g, r, i, z* system of filters (Fukugita et al. 1996; Stoughton et al. 2002), with band centers at $\lambda_u \simeq 3540$ Å, $\lambda_g \simeq 4770$ Å, $\lambda_r \simeq 6230$ Å, $\lambda_i \simeq 7630$ Å, and $\lambda_z \simeq 9130$ Å, and bandwidths of $\Delta\lambda_u \sim 570$ Å, $\Delta\lambda_g \sim 1380$ Å, $\Delta\lambda_r \sim 1380$ Å, $\Delta\lambda_i \sim 1530$ Å, and $\Delta\lambda_z \sim 1350$ Å. The photometric observations are performed almost simultaneously in the five filters. Each entry in the MOC corresponds to a single observation of a moving object and provides the apparent magnitudes *u, g, r, i, z* with their corresponding errors. Of the 204 305 entries contained in the third release of the MOC, we only considered 67 637 observations that are effectively linked to know asteroids (Jurić et al. 2002). These observations corresponded to 43 424 unique bodies. We then selected only candidates in the Hungaria region, i.e. with semimajor axes in the range 1.77 AU $< a <$ 2.06 AU, inclinations between 16° and 30°, and perihelion distances larger than 1.66 AU.

To analyze these observations, we computed the reflectance flux or albedo $F(\lambda)$ at each band center using the observed colors corrected by the solar contribution, $C_{u-r} = (u-r) - 1.77$, $C_{g-r} = (g-r) - 0.45$, $C_{r-i} = (r-i) - 0.10$, and $Cr - z = (r-z) - 0.14$, where the values of the solar colors were taken from Ivezić et al. (2001). The albedos at each band center, normalized to the albedo at the r band, were defined to be $F_u = 10^{-0.4C_{u-r}}$, $F_g = 10^{-0.4C_{g-r}}$, $F_i = 10^{-0.4C_{r-i}}$, and $F_z = 10^{-0.4C_{r-z}}$.

To estimate the relative errors $\Delta F/F$, we used a second order approach $\Delta F/F = 0.9210\Delta C \times (1 + 0.4605\Delta C)$, where ΔC are the color errors computed to be the root mean squared sum of the corresponding magnitude errors. In the case of F_r, its error was estimated to be $\Delta C_r = \sqrt{2}\Delta r$. We then discarded data of "bad" observations, i.e. observations for which $\Delta F/F$ was larger than 10% in the *g, r, i*, and *z* bands, and larger than 20% in the *u* band.

3. Results

Using our selection method, we obtained a final sample of 395 observations corresponding to 334 Hungaria asteroids (2 objects with four observations, 3 with three, and 49 with two observations). The spectra derived from these observations increase the size of the spectroscopic database of Hungaria asteroids tenfold.

The taxonomic type of each object was found by calculating the dissimilarities between the individual spectra and the mean spectra representing the different classes. For this purpose, the dissimilarity is defined as the Euclidean distance:

$$d_i^2 = \frac{\sum_{k=1}^{n}(P_{ik} - Po_k)^2(\sigma_{ik}^2 + \sigma_{ok}^2)^{-1}}{\sum_{k=1}^{n}(\sigma_{ik}^2 + \sigma_{ok}^2)^{-1}}, \tag{1}$$

where d_i is the distance between the ith and a mean spectrum, P and P_0 represent the individual channel making up the individual and mean spectrum, σ is the error in the channel, and the total number of channels is n. The mean spectra of each taxonomic class were obtained from Table 3 of Bus & Binzel (2002b), resampled and convolved with the SDSS filter set. Since the SDSS u filter has a central wavelength that is shorter than those considered by the Bus & Binzel taxonomy, this filter is not used to find the spectral dissimilarity. Although using this method we would be able to assign each asteroid to one of the 26 taxonomic types proposed by Bus & Binzel (2002b), we instead define broader subclasses of asteroids to limit the uncertainty caused by using photometry to complete out classification. We propose five classes to classify the asteroids in our sample: a broad X-class (including X, Xe, Xc and Xk types), a broad D-class (including D, T, K, L and Ld types), a broad C-class (including C, Cb, Cg, Ch, Cgh and B types), a broad S-class (including S, Sk, Sq, Sl, Sa and Sr types), and a broad O-class (including O, R and Q classes), which have 188, 13, 82, 27, and 7 objects, respectively.

Only five of the 334 Hungaria asteroids from our sample were previously observed spectroscopically: (1727) Mette, (3169) Ostro, (3447) Burckhalter, (4116) Elachi and (13111) Papacosmas. Table 1 summarizes the taxonomic classification proposed for these objects by different authors, and Tables 2 to 6 list our sample separated into the broad taxonomic classes proposed in this work.

A group of 16 objects from our sample cannot be classified using this methodology because the photometric data provided by the SDSS-MOC result in a dissimilarity too large for a correct taxonomic classification.

4. Discussion

We have analyzed the spectral characteristics of a sample of Hungaria asteroids based on photometric data obtained from the SDSS-MOC. We have determined the taxonomic types of 318 objects using broad taxonomic classes to estimate their classification. We have applied a method that cannot provide a taxonomic classification as rigorous as that provided by spectroscopic data, but which provides a good measure of the spectral characteristics of an object and enables some distinction to be made between the proposed broad classes.

Even though only 5 objects in our sample were previously observed spectroscopically, in almost all cases there are a good agreement with our results. The only exception is the asteroid (3169) Ostro: this object was previously classified into four different taxonomic types by several authors and there is no consensus opinion about its classification (see Table 1). This peculiar

Table 1. Taxonomic classification of Hungaria asteroids spectroscopically observed.

Asteroid	Class(a)	Class(b)	Class(c)	Class(d)	Class(e)
1727	S				S
3169	TS	C	Xe	C/Cb	D
3447		Xe		X/Xe	X
4116		S	Sl	S/Sl	S
13111				Sl	L

(a) Tholen (1989); (b) Carvano et al. (2001); (c) Bus & Binzel (2002b); (d) Lazzaro et al. (2004); (e) this paper.

Table 2. List of candidate broad X-class Hungaria asteroids.

3447	62157	105846	1998 UB28	2002 EY128
4531	65288	106120	1999 RO30	2002 GO6
4765	65836	106458	1999 TJ233	2002 OC3
5378	66064	106700	1999 VA83	2002 OV7
5558	66108	107126	1999 XJ105	2002 RW238
5579	66150	107741	1999 XQ164	2002 TC57
8825	66195	109598	1999 XS141	2002 TU59
15822	71798	114797	2000 EY200	2002 UG34
16426	72938	115931	2000 GJ4	2002 VF66
16669	73804	119012	2000 GK169	2002 VP14
18890	74511	119022	2000 RF91	2003 AM72
21261	74590	119023	2000 RR36	2003 AP80
21688	76832	119961	2000 RX36	2003 AS71
24702	76848	121121	2000 SC24	2003 AW22
25339	76873	121349	2000 VY38	2003 BJ49
27568	77917	121842	2000 WD9	2003 FD3
29298	77918	123304	2000 YT16	2003 FN3
33326	78857	123305	2001 AJ28	2003 HQ53
34745	79135	123600	2001 AL19	2003 QC39
37471	80101	123846	2001 BM38	2003 QL71
37634	80108	123954	2001 BP10	2003 SA145
39866	82080	124121	2001 CH35	2003 SA315
40264	82144	129626	2001 CU37	2003 SE105
43334	82151	129627	2001 DJ3	2003 SH35
44588	84057	130162	2001 DP92	2003 SU127
47143	85563	133055	2001 EY16	2003 TS11
49670	86402	136951	2001 HC63	2003 TU
51112	90041	137053	2001 QT102	2003 YO117
52384	90162	137057	2001 RO47	2003 YZ20
53422	90164	138197	2001 SS276	2004 BA58
53452	90206	141488	2001 SZ275	2004 BN103
53530	92166	143662	2001 TE147	2004 BX26
56337	92336	143737	2001 TU36	2004 BY121
56343	95741	146108	2001 UR165	2004 FD147
56351	99285	148315	2002 AD130	2004 HL62
58747	101745	153954	2002 BT21	2004 JA6
58897	104770	154646	2002 EJ	
59978	105122	1998 SD33	2002 ER5	

object was observed by Descamps et al. (2007), who obtained its lightcurve and measured a flux variation that could be explained by assuming a tightly bound binary or a contact binary, similar to the Trojan asteroid (624) Hektor. Due to the different taxonomic types proposed for this object, it is impossible to define a taxonomic class for (3169) Ostro and spectra at different rotational phases will be required to improve our understanding of its behavior.

As expected, we found a large number of broad X-class asteroids (∼59% of the sample) but also a significant number of objects in other taxonomic classes, in good agreement with the results of Carvano et al. (2001) and Gil-Hutton et al. (2007). Among them, there was a group of broad S-class

Table 3. List of candidate broad D-class Hungaria asteroids.

3169	26916	53424	104125	2003 CQ3
4116	31182	63605	107636	
13111	37635	99286	150483	

Table 4. List of candidate broad C-class Hungaria asteroids.

5384	67238	124122	2001 OA42	2003 SK251
5871	78023	130091	2001 QA288	2003 SN32
11437	80027	133036	2001 TP16	2003 SO85
23452	82069	137037	2001 XR68	2003 SW253
24778	82077	137972	2002 AK198	2003 TU7
30958	86405	138195	2002 AU2	2003 WU157
31351	91590	141490	2002 BD2	2004 BU68
41685	96573	146695	2002 CW16	2004 CP114
45950	97757	1996 XO32	2002 FB33	2004 DQ39
46513	105211	1999 RM30	2002 QM6	2004 FL31
51371	106829	1999 RP14	2002 RK191	2004 FT31
56358	107642	1999 YU	2002 SX41	2004 GJ15
56360	111693	2000 HY34	2003 AR59	2004 GY11
60374	114842	2000 SJ11	2003 DV21	2004 QK3
63762	119018	2000 SS163	2003 FL8	
63815	119026	2000 XC39	2003 QL105	
66109	123958	2001 DL14	2003 SD221	

Table 5. List of candidate broad S-class Hungaria asteroids.

1727	76928	101727	148709	2003 WK127
5577	82074	104737	2001 OG54	2004 BM111
7579	90211	105626	2002 CX217	2004 RL24
9165	96298	131419	2002 RB27	
56338	97335	141530	2003 AM80	
73610	99277	146946	2003 AQ72	

Table 6. List of candidate broad O-class Hungaria asteroids.

23615	138259	2001 OF36	2004 RW109
129991	2000 EX5	2003 RY7	

candidates (∼9%), which is a taxonomic class typical of objects in the inner asteroid belt; we also however detected a non negligible number (∼26%) of broad C-type asteroids, whose presence in this region it is not easy to explain. If we compare the osculating element histograms for the broad X- and C-class groups (Fig. 1), they show a similar shape, imply that the two populations are mixed together and occupy the same region of space. Since the broad C-types objects could be primitive objects similar in surface composition to carbonaceous chondritic meteorites that could have undergone little or no heating (Gradie et al. 1982; Bell et al. 1989), the inner asteroid belt is not the place where objects with broad C-type spectrum were formed and there must be a mechanism responsible for their presence in this region.

An interesting possibility to explain the excess of C-type objects in the Hungaria region is a space weathering effect. Lazzarin et al. (2006) showed that the spectral slope of a fresh X-type object could be confused with that of a C-type with an old surface, so if the slopes obtained for objects classified in these taxonomic types are similar and the C-types that we found are small objects, their presence in this region could be the result of a catastrophic disruption of a X-type object, being fresh X-type fragments and not C-types. To determine if this scenario is valid, a comparison between the mean spectra of the classified objects in our broad C- and X-class is shown in Fig. 2, where it can be

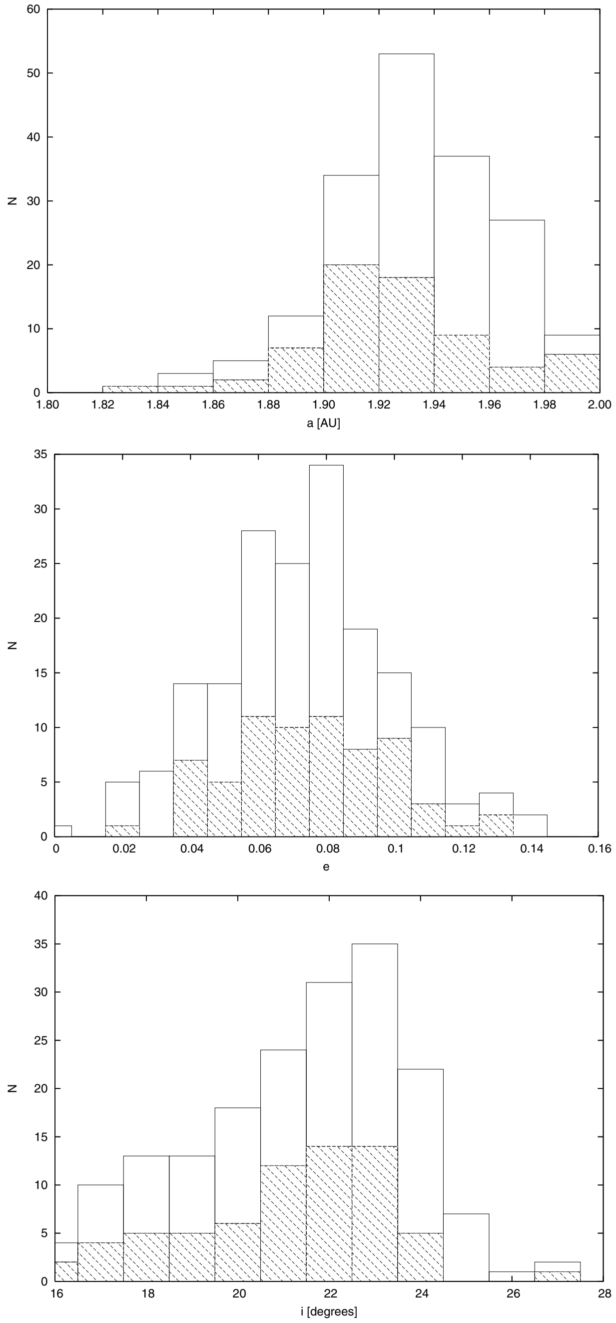

Fig. 1. Distribution of semi-mayor axis, eccentricity and inclination for objects in X- and C-classes. The blank boxes indicate objects belonged to the broad X-class, while the dashed boxes are for the broad C-class objects.

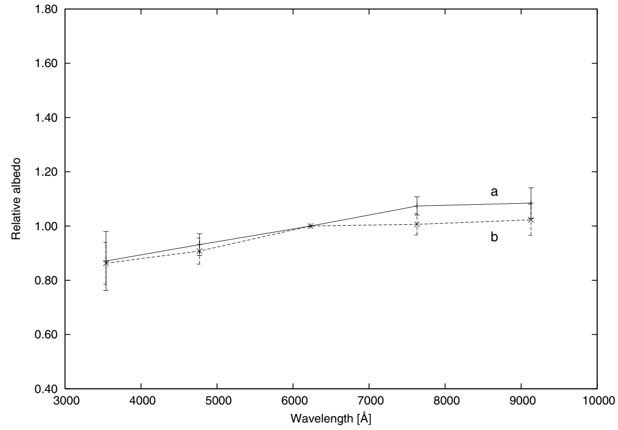

Fig. 2. Mean spectrum of the objects classified in the broad X and C-class using the dissimilarity method explained in the text. The mean spectrum of the broad X-class objects is indicated by "a" and that of the broad C-class objects is indicated by "b".

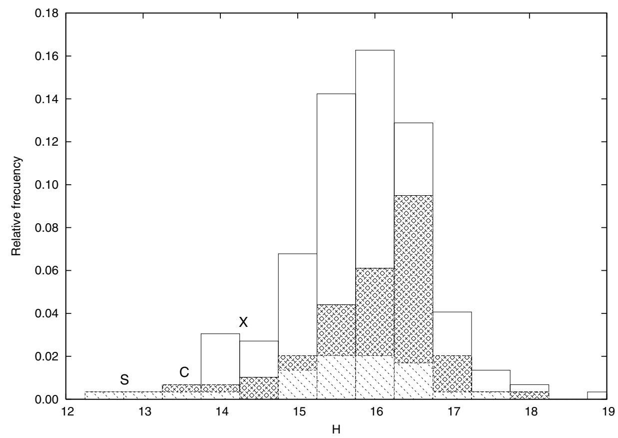

Fig. 3. Comparison between the absolute magnitude histograms for objects classified in the broad X-, C-, and S-class.

seen that the dissimilarity method can detect the UV absorption band shortward of 5500 Å for C-types and the occasional shallow absorption feature longward of 8500 Å, which is characteristic of X-types spectra (Bus & Binzel 2002b). We conclude that the method used to classified these objects can therefore distinguish well between those two broad taxonomic classes.

On the other hand, to test for an excess of C-types among the smaller objects it is possible to compare between the absolute magnitude histograms of objects classified in the broad C- and X-class. Those histograms are shown in Fig. 3, and were compared using a Kolmogorov-Smirnov test, which indicate that both distributions are similar at a 95% level imply that there is no preference for the smaller objects to be classified as C-types.

A more interesting possibility is a transport mechanism. In the Solar System the existence of asteroids in Mars-crossing orbits (Michel et al. 2000) and near-Earth asteroids (Gladman et al. 2000) is strong evidence of a dynamical process of transport from the asteroid belt to the inner Solar System. A possible scenario to explain the presence of broad C-type asteroids in the Hungaria region is that suggested by Gladman et al. (1997) and Migliorini et al. (1998). These authors found that the bodies injected by collisions into the main resonances of the asteroid belt could not sustain the observed population of large diameter Earth-crossers, but that was instead necessary to take into account an important contribution of Mars-crossers to the multikilometer Earth-crosser population. Michel et al. (2000) found in their simulations that several objects arriving at the inner asteroid belt from the intermediate asteroid belt ($a > 2.1$ AU) that become a Mars-crosser, could increase their inclinations and evolve temporarily as a Hungaria asteroid. It would then be possible to find objects placed temporarily in the Hungaria region with short dynamical lifetimes (Michel et al. 2000) that are not original members of the group. If this dynamical scenario is true, it could explain the presence of objects classified in this work as broad D- or O-classes in the Hungaria zone which are not taxonomic types usually found in the inner asteroid belt.

An important point to consider is that in the Hungaria region we have found a large number of broad C-type objects than S-types. If the proposed transport mechanism is at work, the number of C- and S-type objects must be almost identical since the transport process has no preference for one taxonomic type or the other. It is not easy to explain this large difference in the number of objects, but it is possible that a relatively large C-type object coming from the intermediate asteroid belt, arrived at the Hungaria region and had a disruptive collision, forming a large number of broad C-class objects that we observe today in this zone. In fact, there is a larger number of small C-type objects than S-types for $H > 15$, while for the largest objects ($H \leq 15$) the number of asteroids with similar absolute magnitude is almost identical for both classes (see Fig. 3), which is the expected result following a disruptive process.

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