Cosmochlore—a new examination

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ABSTRACT. Examination of cotype cosmochlore from the Toluca meteorite confirms Laspeyres's observations (1897) in every respect, except that what he determined as iron was largely titanium. His data are completed by an electron-probe analysis and by full optical and X-ray data. Accepting the identity of cosmochlore and ureyite, the optical data of Frondel and Klein (1965) for the latter are partly in error or misprinted.

COSMOCHLORE was isolated from the Toluca meteorite by Laspeyres (1897), who obtained 73 mg from 585 g of the iron; his name, kosmochlor, was anglicized by Spencer (1897) and by Dana (1899). The mineral occurs as minute cleavage flakes, mostly less than 0.3×0.4 mm and no more than 0.1 mm thick. Laspeyres observed a second cleavage approximately at right angles to the flakes, and another, less frequent, in the same zone at approximately 105° to the flakes. Optically, the flakes extinguished with α', light yellow-green, at 12° 14′ to the cleavage cracks, γ', dark blue-green or emerald green; no optic axial figure was visible. Birefringence fairly strong ('Die Interferenzfarben.... ausserordentlich lebhaft'). Refractive index determinations were not possible with the techniques then available. Sp. gr. > 3.16; H. 5 to 6.

Although he had only 3.3 mg available for a chemical analysis, and his balance only weighed to 0.05 mg 'by estimation', Laspeyres attempted a *quantitative* analysis—a task that would tax a competent microanalyst with modern equipment. Unfortunately, he calculated his results to 0.01%, and derived a chemical formula $Ca_2Mg_2Fe_2Al_3Cr_9Si_{10}O_{44}$ or perhaps $R^{3+}_{14}Si_9O_{39}$, though, as he says, his figures must all be taken as $\pm 3\%$ at best, and hence as much as 7% of other components could have remained undetected; and this formula, which can only be regarded as a rough approximation, has been treated as established (see, e.g. Linck, 1938; Strunz, 1949).

Laspeyres mentioned that he had distributed nearly half his material to museums and universities [including the British Museum (Natural History)], and in 1964 the late R. J. Davis commenced an examination of this cotype material. He had established that cosmochlore is a clinopyroxene, and

preparations for an electron-probe analysis were under way when Frondel and Klein (1965) published their study of ureyite, a green sodium chromium silicate found in three meteorites, including Toluca. They rejected Laspeyres's name 'since its identity with $NaCrSi_2O_6$ can only be fortuitous' (one would have thought the occurrence of two distinct chromium silicates with essentially the same physical properties in the same meteorite far more unlikely), and because 'The name itself is undesirable, because of the ambiguity deriving from the suffix· *chlor*, which can mean chlorine-containing or, as was here the intent, green'—a very weak objection, since there are just as many minerals in which 'chlor' means green (as it does in chlorine itself) as there are in which it means chlorine-containing. A suggestion that cosmochlore 'has had no standing for 68 years' is hardly tenable since it was included as a valid species of uncertain composition by Linck (1938), Strunz (1949), and Hey (1955).

In 1968, Neuhaus published a study of holotype cosmochlore that confirms its identity with ureyite, and since Laspeyres's description of the mineral was certainly not 'so incorrect that a recognition of the mineral by means of it is impossible' (Dana, 1868), his name should have priority.

The present study, carried out on cotype material—two specimens presented to the British Museum (Natural History) by Laspeyres in February 1897—confirms the results obtained by Neuhaus and adds some further data.

The specimens consist of very small crystal grains, the largest 0.2×0.05 mm, on two glass slides: one, labelled 'BM 81869 Kosmochlor, braunes pleochr. Min., Chromit, Zirkon, Tolucaeisen, Min. Inst. Bonn', has about 100 grains of cosmochlore as well as the other materials mentioned, mounted in Canada balsam and under a glass cover-slip; the other slide is without a cover-slip and is labelled 'BM 81870 Kosmochlor, Zirkon, blaues pleochr. Min., Chromit, Tolucaeisen. Min. Inst. Bonn' and, besides the other minerals, has about two dozen cosmochlore grains mounted in Canada balsam.

TABLE I. *Optical data for cosmochlore*

	1	2	3	4	5
α	1.742*	—	1.740†	1.748†	1.765
β	1.765‡	—	1.756*	1.756†	1.778
γ	1.767*	—	1.762†	1.765†	1.781
α: [001]	22°‖	≈21°	22°‖	14°‖	13°§
β	‖[010]	‖[010]	—	—	‖[010]
2V$_\alpha$ { calc.	—	—	62°	93°	51°
{ meas.	34°¶		60° to 70°		53°

Pleochroism:

α	yellow**	yellow-green	dark green		yellow-green
β	emerald green	emerald green	yellow-green to yellow		grass-green
γ	dark blue-green	emerald green	emerald green		emerald green

* ±0.002.   † ±0.001.   ‡ calc.
§ γ: [001] (possibly a misprint).
‖ ±1°; also measured, for BM material, 19° for red, 20° for violet, using Wratten filters.
¶ $r < v$ strong.
** in thin fragments; green-yellow in thick ones.
1. BM 81869 and 81870 } Toluca cosmochlore.
2. Neuhaus, 1968
3. Toluca } Frondel and Klein, 1965, 'ureyite'.
4. Coahuila
5. Synthetic $NaCrSi_2O_6$, Ikeda and Yagi, 1972.

Optical properties. The refractive indices and maximum extinction angles, α:[001], of cosmochlore are in general agreement with those recorded for ureyite, but there are differences in the size of the optic axial angle and in the pleochroic formula (Table I). It is not clear whether the reported $2V_\alpha = 60$–$70°$ for ureyite was obtained by estimation, measurement, or calculation from the refractive indices of the Toluca material, which gives $2V_\alpha = 62\frac{1}{2}°$, though it should be noted that the refractive indices quoted for the Coahuila ureyite are those for an optically positive mineral.

The optic axial plane of cosmochlore is ‖(010) and the bisectrices are strongly dispersed. Complete, straight extinction is given by grains oriented with the incident light in the zone (100):(001), but other zones give incomplete oblique extinction, with abnormal red in thin fragments. Although a maximum angle α': [001] was measured as 22 ± 1° on a few crystals, angles of approximately 12° (as recorded by Laspeyres) and 17° were measured on others, and these could have been crystals lying on, or near, {210} and {110} respectively, which are the cleavages observed by Laspeyres. He observed a cleavage approximately at right angles to the flakes and another at 105° to them. From

Neuhaus's cell dimensions we calculate (110):($\bar{1}$10) 85° 7′ and (110):($\bar{2}$10) 104° 0′. The observed refractive indices, optic axial angles, and α: [001] listed in Table I lead to calculated extinction angles: on (110), $17\frac{1}{4}°$ (this study), 19° (Frondel and Klein, Toluca material), $13\frac{3}{4}°$ (Frondel and Klein, Coahuila material); on (210), 12° (this study), 14° (Frondel and Klein, Toluca material), $11\frac{1}{2}°$ (Frondel and Klein, Coahuila material).

Chemistry. A new electron-probe analysis of a grain from BM 81870 showed that there is an appreciable amount of Ti, not observed in the earlier electron-probe analyses; in Laspeyres's analysis this would be counted as Fe_2O_3 (see below). Since the mineral occurs as small inclusions in a meteoritic iron, we can safely assume that the iron is ferrous, and it is highly probable that the titanium is trivalent, especially as alabandine is present (Bunch *et al.*, 1970). The analysis (Table II) was performed using a Cambridge Instruments Geoscan microprobe fitted with an energy-dispersive detector. Accelerating voltage 15 kV, probe current 50 µA. Hypersthene from the Johnstown meteorite was run as a secondary standard. A first semi-quantitative analysis of two unpolished grains was carried out to check homogeneity; the material appears to be homogeneous, both as between

TABLE II. *Chemical data for cosmochlore*

	1	2	3	4	5	6
SiO_2	54.1	56.0	55.5	53.62	60	32
Cr_2O_3	26.0	22.6	30.6	27.02	14	39
Ti_2O_3	2.77	n.d.	n.d.	2.88	n.d.	—
Al_2O_3	0.87	n.f.	n.f.	—	n.d.	9
FeO	0.56	0.4	0.2	—	n.d.	9
MgO	1.46	5.4	0.8	1.63	6	5
CaO	1.59	3.7	1.7	2.28	7	6
Na_2O	12.8	11.6	11.6	12.57	13	n.d.
Sum	100.15	99.7	100.4	100.00	100	100

Atoms per 6 oxygen:

Si	2.02	2.07	2.06	2.00		
Cr	0.77	0.66	0.90	0.82		
Ti^{3+}	0.09	n.d.	n.d.	0.09		
Al	0.04	n.f.	n.f.	—		
$\sum$*	0.90	0.66	0.90	0.91		
Na	0.93	0.83	0.84	0.91		
Fe^{2+}	0.02	0.01	0.01	—		
Mg	0.08	0.30	0.03	0.09		
Ca	0.06	0.15	0.07	0.09		

n.d., not determined   n.f., not found   *$\sum$ (Cr, Ti, Al)
1. Toluca, BM 81870. R.H. anal.
2. Toluca } Frondel and Klein, 1965. 'Ureyite'.
3. Coahuila
4. [(Na{Cr, Ti}), (CaMg)]Si_2O_6, with Na:Mg::10:1 and Cr:Ti::9:1.
5. Toluca. Neuhaus, 1968.
6. Toluca. Laspeyres, 1897, on 3.3 mg; all figures ±3% at best.

TABLE III. X-ray powder data for cosmochlore, BM 81870, indexed using the cell dimensions of holotype material (Neuhaus, 1968)

I	d_{meas}	d_{calc}	hkl	I	d_{meas}	d_{calc}	hkl	I	d_{meas}	d_{calc}	hkl
5	6.36 Å	6.315 Å	110	4	1.720	1.723 / 1.721	421 / 150	1	1.438	1.434	620
4	4.39	4.382	020	3	1.650	1.651	042	6	1.391	1.396 / 1.395 / 1.391	351 / $35\bar{2}$ / 260
1	3.20	3.157	220	6	1.627	1.626	$22\bar{3}$	3	1.371	1.373 / 1.368 / 1.367	$26\bar{1}$ / $24\bar{3}$ / 223
10	2.97	2.965	$22\bar{1}$	6	1.601	1.604 / 1.601	$44\bar{1}$ / 151				
8	2.89	2.868 / 2.864	310 / $31\bar{1}$	2	1.577	1.578	440	5	1.320	1.315 / 1.314	$20\bar{4}$, $53\bar{3}$ / $71\bar{2}$
9	2.192	2.521 / 2.512	$11\bar{2}$ / 002	4	1.521	1.518 (600 / 350) / 1.517 / 1.515	$35\bar{1}$ / $60\bar{2}$				
7	2.463	2.454	221	5	1.501	1.500	$42\bar{3}$	5	1.294		
7	2.192	2.191 / 2.184	040 / 122	3	1.457	1.463 / 1.461 / 1.459 / 1.451	242 / 060 / $15\bar{2}$ / $51\bar{3}$	5	1.261		
7	2.109	2.105 / 2.103	330 / $33\bar{1}$					1	1.227		
5	2.023	2.020	420					1	1.194		
2	1.931	1.924	$24\bar{1}$					1	1.154		
								3	1.049		

grains and within a grain (Frondel and Klein found appreciable zoning).

X-ray data. An X-ray powder photograph of material from BM 81870 was in good agreement with Frondel and Klein's data for material from Coahuila, and indexed well with Neuhaus's cell dimensions for Toluca cosmochlore (Table III).

Conclusions. Since Laspeyres's observations have been confirmed in every respect, and are perfectly adequate for recognition of the mineral, his name must take priority. The pleochroism reported by Frondel and Klein (1965) is at variance with that found by all other observers, and is probably a misprint, as is the optical orientation reported for synthetic $NaCrSi_2O_6$ by Ikeda and Yagi (1972).

Though we do not know what methods Laspeyres employed in his gallant, if perhaps mistaken attempt at a quantitative analysis, it is not difficult to see how he might have arrived at the results he did. If he dissolved his Na_2CO_3 fusion in HCl and evaporated once to dehydrate silica (a not unusual practice at that date), much silica would remain in solution, to be precipitated by NH_3; this precipitate may have been treated with NaOH and bromine, dissolving Al and Cr (as chromate) and most of all the silica as well, to appear later as alumina and Cr_2O_3; if he simply leached the Na_2CO_3 fusion with water to dissolve chromate (which is not likely), an even larger proportion of the silica would be dissolved to appear as 'Cr_2O_3'. The 0.1 mg TiO_2 actually present would be included with his Fe_2O_3 (and it takes very little Fe_2O_3 to colour a precipi-

tate). His loss of 0.7 mg SiO_2 balances his excess of 0.4 mg Cr_2O_3 and his 0.3 mg 'Al_2O_3'; his 'Fe_2O_3' is 0.2 mg high and his CaO and MgO 0.1 mg each, probably from impurities introduced by reagents or glassware, and this excess of 0.4 mg led him to a good summation, so that he did not suspect the presence of 0.4 mg Na_2O (which he could not have determined anyway).

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