COSMIC-RAY EXPOSURE AND SHOCK DEGASSING AGES OF THE QUASICRYSTAL-BEARING KHATYRKA METEORITE M. M. M. Meier[1], L. Bindi[2], H. Busemann[1], P. R. Heck[3], A. I. Neander[4], C. Maden[1], M. Riebe[1], N. H. Spring[5,6], P. J. Steinhardt[7], R. Wieler[1]. [1]Institute of Geochemistry & Petrology, ETH Zurich, Switzerland (matthias.meier@erdw.ethz.ch); [2]Department of Earth Sciences, Università di Firenze, Italy; [3]Robert A. Pritzker Center, Field Museum of Natural History, Chicago, USA; [4]Department of Organismal Biology & Anatomy, University of Chicago, USA; [5]SEAES, University of Manchester, UK; [6]Department of Earth & Atmospheric Sciences, University of Alberta, Edmonton, CAN; [7]Department of Physics & Princeton Center for Theoretical Science, Princeton Univ., USA.

Introduction: Quasicrystals (QCs) are materials with quasiperiodic arrangements of atoms. They can have symmetries forbidden for true crystals, e.g., icosahedral symmetry for icosahedrite ($Al_{63}Cu_{24}Fe_{13}$), the first known natural QC [1], and 10-fold azimuthal symmetry in the case of the more recently identified decagonite ($Al_{71}Ni_{24}Fe_5$) [2]. Icosahedrite was identified in a mm-sized rock sample belonging to the collection of the Natural History Museum of the University of Florence. The QCs were found in regions rich in khatyrkite ($CuAl_2$) and cupalite (CuAl). Oxygen isotopes in the silicate part of the Florence sample show that it is extraterrestrial [3]. Its provenance was traced back to a Soviet prospecting expedition. A new expedition to Chukotka, Russia, in 2011 succeeded in retrieving ~10 more mm-sized grains, from >8 ka old sediments of a tributary of the Khatyrka river. The grains had the same O isotopic composition as the Florence sample, and some of them also contained khatyrkite [4]. These grains are now known as the CV_{ox} chondrite Khatyrka. While the origin and formation of khatyrkite in Khatyrka is still unclear, a shock impact origin has been suggested for the QCs [5]. Here we present He and Ne concentrations and isotopic compositions of six olivine grains from Khatyrka, in order to reconstruct its cosmic history and relationship to other CV chondrites.

Methods: We analyzed six forsteritic olivine (#Mg ~0.96) grains <50 µm in diameter, from fragment #126 [4]. The analysis of He and Ne in such small grains is possible due to a high-sensitivity compressor-source noble gas mass spectrometer connected to an ultra-low blank line at ETH Zurich [6]. Given the low mass of the grains (~0.75 µg total), weighing them was not possible. Instead, we used a µCT scanner with a voxel length of 5.47 µm to determine grain volumes, and calculated grain masses assuming a density of forsteritic (#Mg= 0.95±0.05) olivine (3.33± 0.06 g/cm^3). After micro-manipulator transfer of the grains to a sample holder for He-Ne analysis, they were loaded into the mass spectrometer and exposed to ultra-high vacuum for several days before being individually heated with a Nd:YAG laser (λ = 1064 nm) for 60 s to their melting point. He-Ne analysis was done using a protocol based on the one originally developed by Heck et al. [7]. We calculate cosmic-ray exposure (CRE) ages using a cosmogenic nuclide production model [8] for a carbonaceous chondrite matrix and forsteritic target chemistry.

Results: Results are given in Table 1. The reported volumes are 20% smaller compared to the ones given in an earlier abstract [9], due to an improved evaluation of grain volumes including a correction for variable voxel brightness near grain boundaries. All grains show cosmogenic ^{3}He and ^{21}Ne, corroborating an extraterrestrial origin. A fully cosmogenic origin was assumed for ^{3}He, while ^{21}Ne was corrected for atmospheric Ne (3-29% of measured ^{21}Ne) using a two-component deconvolution with cosmogenic and atmospheric Ne as end-members. Five grains have an average cosmogenic ^{3}He/^{21}Ne ratio of 3.6±0.3, except for grain 3, where it is 7.3±0.8. All six grains should have the same ratio, as they were irradiated by cosmic rays close to each other within the same mm-sized volume. Since grain 3 has, within uncertainty, the same mass and ^{3}He concentration as grain 1, yet shows a significantly lower ^{21}Ne concentration, we presume that it was not completely degassed in ^{21}Ne during analysis. A second laser shot onto grain 3 (melt residues) did not result in the release of additional He and/or Ne above detection limit.

#	Vol. (µm^3)	Mass (ng)	^{3}He/^{4}He ×10^{-4}	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne	^3He_c	$^{21}Ne_c$	R4 (Ma)
1	35800 ±2300	119 ±8	>470	3.6 ±2.5	0.42 ±0.08	6.6 ±0.3	2.3 ±0.1	<260
2	31200 ±2100	104 ±7	38 ±6	9.4 ±0.9	0.09 ±0.01	5.3 ±0.2	1.4 ±0.2	2750 ±660
3	37400 ±2400	125 ±8	400 ±250	11.2 ±1.7	0.13 ±0.02	6.6 ±0.2	0.9 ±0.1	270 ±80
4	47900 ±3000	160 ±10	330 ±150	5.5 ±2.0	0.40 ±0.06	9.9 ±0.3	3.0 ±0.1	400 ±120
5	44900 ±3800	209 ±17	>270	7.9 ±0.9	0.12 ±0.01	8.7 ±0.4	2.0 ±0.2	<350
7	29700 ±2500	99 ±9	>340	2.5 ±5.3	0.29 ±0.08	4.3 ±0.2	1.1 ±0.2	<310
t	227000 ±6700	756 ±23	-	8.1 ±0.6	0.18 ±0.01	41.3 ±0.7	10.6 ±0.4	-

Table 1: Volumes, masses, He, Ne isotopic composition, cosmogenic ^{3}He, ^{21}Ne amounts (in 10^{-15} cm^3 STP) and radiogenic ^{4}He retention ages ("R4", in Ma) of Khatyrka olivine grains. t = total.

As shown in Fig. 1, He is likely a two-component mixture of cosmogenic He (^{4}He/^{3}He = ~6) and radiogenic ^{4}He, similar to chondrules from the CV chondrites Leoville and Allende [10]. To calculate a (U,Th)-He age, we use U and Th concentrations of 14-22 and 49-77 ppb, respectively, measured in Allende chondrules [11]. All except grain 2 (2.8±0.7 Ga) have retention ages consistent with ~250-300 Ma.

To calculate the ^{21}Ne CRE age of Khatyrka, we need to determine a production rate, which depends on the position of the sample within the meteoroid and its radius, and thus requires a shielding indicator [8]. Since typical shielding indicators like the cosmogenic $^{22}Ne/^{21}Ne$ ratio or radionuclides are not available for the Khatyrka grains, we use $^{3}He/^{21}Ne$ instead. Elemental fractionation between He and Ne (e.g., diffusion losses) since the start of CRE must be minimal as the data points of the grains plot close to the radiogenic-cosmogenic mixing line in Fig. 1. The CRE age curves given in Fig. 2 are for an average cosmogenic ^{21}Ne concentration of 1.51×10^{-8} cm^3 STP/g (i.e., excluding partially degassed grain 3). At the $^{3}He/^{21}Ne$ ratio measured in the grains, the CRE age of Khatyrka is thus likely in the range ~2-5 Ma, although it could be higher if the meteoroid was very large (R > 5 m). The minimal meteoroid radius (based on $^{3}He/^{21}Ne$) is 0.5 m.

Three metallic grains, initially thought to be khatyrkites and analyzed for He and Ne in July 2015 [9], turned out to be samples unrelated to Khatyrka. At this point, we have not taken any measurements from khatyrkite found in the Khatyrka meteorite, although we plan to do so.

Discussion: Khatyrka likely experienced a strong shock ~250-300 Ma ago, but the (U,Th)-He clock was reset inhomogeneously, which is expected in the pressure range 10-35 GPa (S3-S5) [12]. This event might thus correspond to the >5 GPa, >1200°C shock event identified by [5] in Khatyrka. Only four CV chondrites have similar CRE ages: Allende [8], ALH 85006 [13], and Acfer 082 and 272 [14]. The former two both have U,Th-He ages >3.8 Ga. While the U,Th-He ages are <0.5 Ga for the latter two, this is likely due to solar heating [14], which is unlikely for Khatyrka given the nearly unfractionated He/Ne ratio (Fig. 1). Khatyrka is thus unique among CV chondrites for having a very short U,Th-He shock age of ~0.3 Ga. This might indicate that Khatyrka is derived from another parent asteroid than the other CVs with known cosmic histories.

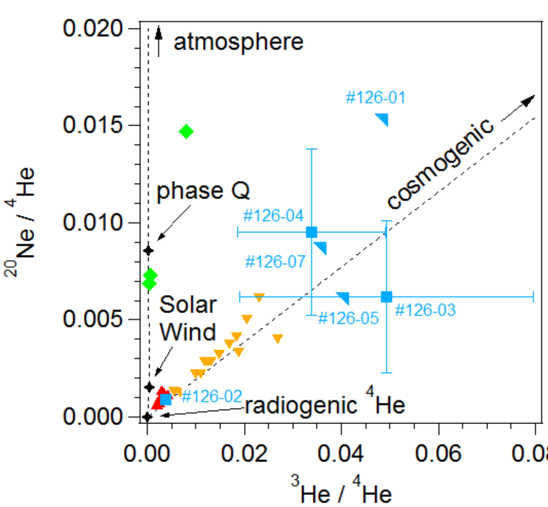

Fig. 1: Khatyrka olivines corrected for atmospheric Ne (blue; triangles are lower limits on both axes), CV chondrites Leoville (orange) and Allende (red) chondrules [10] and Acfer 082 and 272 (green) [14].

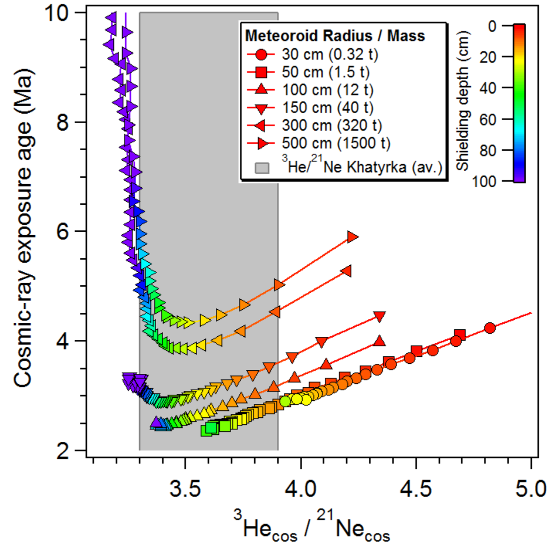

Fig 2: Ne-21 CRE ages of Khatyrka olivine as a function of $^{3}He/^{21}Ne$, for a range of meteoroid sizes, based on [8]. The shaded region represents the average $^{3}He/^{21}Ne$ ratio (of the five fully degassed grains) of 3.6±0.3. This range excludes very low shielding in small objects and very high shielding in large objects, and constrains the CRE age to 2-5 Ma.

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