THE KHATYRKA METEORITE: A SUMMARY OF EVIDENCE FOR A NATURAL ORIGIN OF ITS REMARKABLE Cu-Al METAL ALLOYS. G. J. MacPherson[1] (macphers@si.edu), C. Lin[2], L. S. Hollister[3], L. Bindi[4], C. L. Andronicos[5] and P. J. Steinhardt[2]. [1]Dept. of Mineral Sciences, Smithsonian Institution, Washington D.C. 20560 USA; [2]Dept. of Physics, Princeton University, Princeton, NJ 08544, USA; [3]Dept. of Geosciences, Princeton University, Princeton, NJ 08544 USA; [4]Dipartimento di Scienze della Terra, Università di Firenze, I-50121 Florence, Italy; [5]Div. of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907 USA.

Introduction: The first report [1] of naturally-occurring quasicrystals (QC), and our subsequent documentation of their extraterrestrial origin within the Khatyrka CV3 (ox) meteorite [2-4], have provoked much controversy, because the QC and their associated metal phases are alloys of copper and aluminum. The dominant scientific community reaction to our results has been to regard these metals as man-made, despite our growing evidence to the contrary. The arguments boil down to two. First, metallic aluminum is unexpected to occur in nature because of the extreme reducing conditions required. In fact, the conditions required for pure Al are far more reducing than those in the early solar nebula or even those required by the assemblages in enstatite chondrites. Second, from a cosmochemical perspective, copper and aluminum are so dissimilar in their expected condensation behavior and chemical affinities that the two elements virtually never occur together in meteorites. In short, the argument against a natural origin is that because these things can't happen, they didn't. Our contrary view, based on all the evidence, is that if things did happen, they can happen. Here we summarize all of our findings to date (including new results) that strongly indicate a natural origin for the alloys. At the end we pose a challenge to the community to come up with a viable model for how the metals are man-made, yet accounting for all of our observations.

Key observations: The evidence against the meteorite-metal assemblage being man-made, either as accidental contamination or deliberately (i.e. a hoax), is of two basic kinds: (a) the grains were recovered by us from several undisturbed clay layers, one of which is 6700-~8000 years-old, and (b) the metal and meteoritic material are not accidentally juxtaposed but are intimately mixed and contain clear evidence of high-temperature and high-pressure chemical interaction between the two, and these reactions occurred where shock heating caused melting of both the meteorite silicates and the Cu-Al alloys.

Documented prehistoric source of the grains. Most of the studied grains were recovered during our expedition to the Chukotka region of eastern Siberia in 2011 [3]. The grains were extracted from dense, undisturbed, fluvial (well-sorted) clay layers exposed along the banks of the Listvenitovyi stream. The layers vary in composition, from serpentine-derived to schist-derived, and are rich in charcoal fragments. Figure 3 of reference [3] shows the field occurrence of one of the serpentine-rich (blue) layers, and our methods of grain extraction. Grains later shown to contain the Cu-Al alloys were photographed individually in the field, two of which are described in [3]. Finally, a bulk sample of one serpentine-rich clay layer was shown to be 6700-8000 years old based on radiocarbon dating [3]. Therefore, grains that we personally extracted from undisturbed ancient clay layers contain the exotic alloys and thus the latter cannot possibly be accidental contamination.

The metal and meteoritic material are co-genetic. Evidence given in [3] shows unambiguously that the Khatyrka meteorite itself is an oxidized CV3 chondrite that is similar, but not identical, to Allende. It contains chondrules, CAIs, and the characteristic barrel-shaped olivines of CV3 matrices. Oxygen isotope analyses of the CAI and coarse olivine crystals are typical of CV3 phases. In the first Khatyrka samples we studied, those illustrated in [3], the Cu-Al alloy grains seem mostly to just sit next to meteoritic material without any obvious interaction. However, we subsequently learned from studying additional samples that Khatyrka experienced extreme but heterogeneous shock [4]. Recent noble gas measurements show that a major degassing event occurred on the Khatyrka parent body within the past ~200 Ma [6]; this may or may not have been the event responsible for the shock features we observe. The shock event was sufficiently intense to form both stishovite and ahrensite (the iron-rich form of ringwoodite) [4], and locally caused melting of both the meteoritic silicates and the Cu-Al alloys (Fig. 1). In these examples, the metal-silicate contacts exhibit striking reaction textures in which aluminum in the Cu-Al alloys is oxidized and overgrown by reaction rims of Mg-Al spinel, and conversely oxidized iron in the silicate melt is reduced to beads of pure iron metal (Fig. 2). We previously showed [5] similar reactions at the contact between Cu-Al alloys and a CAI. Furthermore, there are several examples of grains of metal phases totally enclosed in stishovite and other silicates and oxides.

Discussion: Our careful field collection of the material, and our subsequent detailed studies of some of the collected grains, rule out any possibility of accidental contamination of meteoritic material by man-

made alloys. And unless prehistoric peoples indigenous to Siberia were far more technologically advanced than we know, it is unlikely that the alloys themselves were made 8000 years ago. There remain two possibilities. There is of course the possibility that an alien spacecraft crashed on the CV3 parent asteroid sometime in the past and that was the source of the metal. Barring that fanciful idea however, the alternative is a deliberate hoax, which seems to be the preferred model of some in the cosmochemistry community. How such a hoax might have been accomplished is hard to imagine, requiring access to equipment capable of producing the extreme shock pressures. For reasons noted above, the hoax would necessarily have been perpetrated after our recovery of material from Siberia. Also and most telling, the original material in which the natural QC were found was not known at that time to be meteoritic in origin. Yet, subsequent oxygen isotopic analyses of the associated silicates revealed clear ^{16}O excesses. Lastly there is the issue of motive. No QC-containing material has to our knowledge been put up for sale at any price, and in any case the cost of synthesizing such tiny (mm-sized) grains seems hardly worth the effort. Our collective conclusion, after nearly five years of study, is that the Khatyrka + Cu-Al-alloy assemblage is natural. We do not yet understand what unique set of circumstances led to the assemblage, but to repeat: if something did happen, it can happen and it is up to us to figure out how.

A Challenge: We recognize that the arguments summarized above may not satisfy some persistent doubters. We therefore challenge anyone to come up with a plausible and specific non-natural hypothesis for the origin of the Cu-Al alloys. Such a model has to address all of the constraints noted above, including not only mechanism but also (if a hoax) a plausible motive. Although we are planning further tests, it would be informative for those plans to have plausible models for a non-natural origin—even one—that can explain the collection of observations above. We have sought for five years to find such a model and failed to come up with one. If anyone has one that satisfies these conditions—and that is *testable*—we would be happy to hear it.

References: [1] Bindi L. et al. (2009) *Science 324*, 1306-1309; [2] Bindi L. et al. 2012 PNAS 109, 1396-1401; [3] MacPherson G.J. et al. (2013) *Meteoritics & Planet. Sci*. *48*, 1499-1514; [4] Hollister L.S. et al. (2014) *Nature Comm.* (DOI: 10.1038/ncomms5040); [5] Hollister L.S. et al. (2015) LPSC, Abst. #2394; [6] Meier M.M.M. et al. (2015) *78th Ann. Meeting of the Meteoritical Society (2015)*, Abst. #5035.

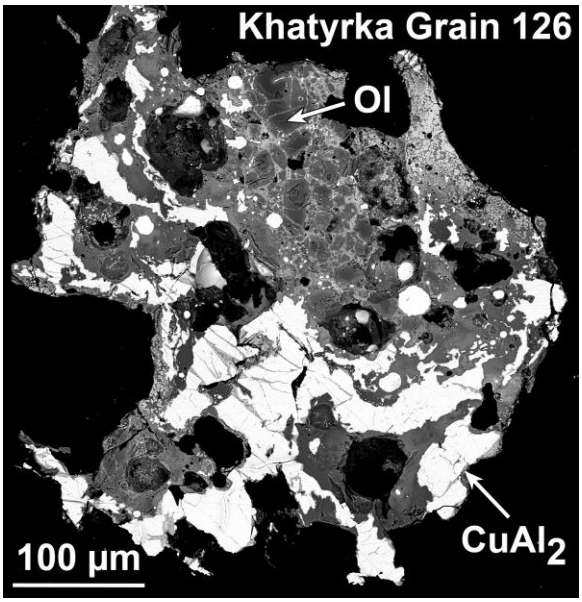

Fig. 1. BSE image of Khatyrka Grain 126. The Cu-Al alloys (white, mostly khatyrkite $CuAl_2$)) are highly irregular and even cuspate in shape, suggesting both mixing of immiscible melts and reaction between the two.

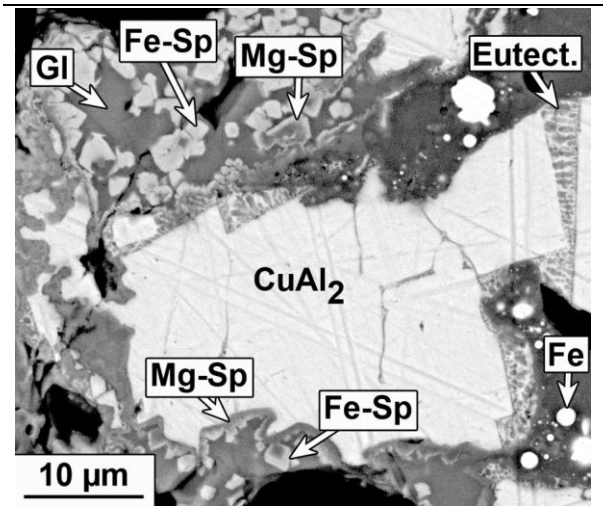

Fig. 2. BSE image of $CuAl_2$ that is rimmed by spinel (Mg-Sp), and with tiny beads of pure Fe metal (Fe) along its boundary. These features document simultaneous oxidation of metallic aluminum and reduction of oxidized iron in the silicate melt (now glass, Gl). Where Fe metal beads are absent, the Mg-rich spinel is mantled by iron-rich spinel (Fe-Sp), indicating extreme variations in redox conditions in the vicinity of the $CuAl_2$. "Eutect." is a eutectoid intergrowth of khatyrkite and an unknown fine-grained phase that is mostly Al.