**WHY ARE CHONDRULES RARE OR ABSENT IN THE RYUGU SAMPLE?** W. Herbst[1] and J. P. Greenwood[2], [1]Astronomy Dept., Wesleyan University, Middletown, CT 06457, wherbst@wesleyan.edu, [2]Earth & Environmental Sciences Dept., Wesleyan University, Middletown, CT 06457, jgreenwood@wesleyan.edu.

**Introduction:** The rarity, or absence altogether, of chondrules in the Ryugu sample returned by the Hayabusa2 mission [1] was surprising to many, although predicted by us [2]. Evidently, chondrules were either never present within this C-type asteroid sample or they were destroyed by some unspecified process. Here we reiterate the arguments that led to our successful prediction and explain why we expect that chondrules (and chondrites) will be rare objects on all asteroids. If verified by future missions this would imply that chondrules were never abundant in the Solar System and have no substantial role to play in planet formation. That said, they would remain important objects to study because of what they can reveal about conditions in the early asteroid belt.

**The macroporosity of rubble pile asteroids**: Small asteroids are mostly or entirely gravitationally bound granular aggregates that have been called "rubble piles" for decades [3]. If the pile has a bulk density $\rho_{bulk}$ and is composed of grains (i.e., boulders, cobbles, pebbles, etc.) with a common density of $\rho_{grain}$ then these quantities are related to the porosity ($\phi$) of the pile, its fraction of empty space, as follows:

$$\rho_{bulk} = \rho_{grain}(1 - \phi). \qquad \mathbf{(1)}$$

In planetary science, $\phi$ is generally called the *macroporosity* to distinguish it from the porosity of the grains themselves, dubbed microporosity. Until recently this equation has been used to estimate $\phi$ from the measured bulk density of an asteroid by assuming a grain density based on the spectral analog meteorite class [4]. Since bulk densities are often much lower than grain densities, this method commonly yields estimates for $\phi$ that are quite large, ~40%, as was the case for Ryugu.

Granular aggregates are important features on Earth and sophisticated models of their porosity have been developed. The most successful of these in terms of predictive power is based on linear-mixture packing theory [5]. These models show that porosity values as high as 40% are only possible for piles with a narrow range of grain size. When there is a substantial size range, the phenomena of sifting and occupation act to greatly reduce the porosity of any homogeneous pile. Sifting is the filling-in of space by small grains and occupation is the replacement of void spaces by large boulders. While grain shape and other factors play some role, the principal determinant of porosity in a homogeneous pile is its grain size distribution.

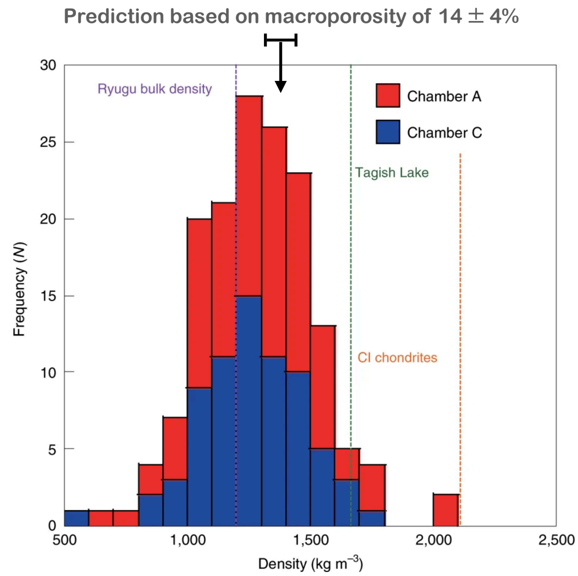


**Fig. 1**. Densities of grains from the surface of Ryugu returned by the Hayabusa2 mission [1]. At the top is our prediction for the average grain density on Ryugu based on its calculated microporosity of 14 ± 0.04% and an assumption of homogeneity [2].

Close-up images of small asteroids reveal surfaces with a large range of grain size. If they are reasonably homogeneous, they could not possibly have macroporosities as large as 40%, due to sifting and occupation [2,5]. That means that the low bulk densities exhibited by small asteroids are not caused by inefficient packing, i.e. large $\phi$. *Low bulk densities must be caused primarily by low grain densities of constituent boulders.*

We illustrate our approach with the example of Ryugu. Michikami et al. [6] used surface photographs from a variety of heights to determine its surface grain (boulder) size-distribution. We [2] showed that the resulting volume-frequency distribution is well represented as a lognormal function with a sigma of 2.4 ± 0.1. We then applied linear-mixture packing theory to estimate the porosity of the asteroid assuming it is homogeneous. Our result, $\phi = 0.14 \pm 0.04$, combined with the measured bulk density of Ryugu, $\rho_{bulk} = 1.19$ gm cm$^{-3}$, leads via Eq. **1** to an estimate for the density of the rocks composing the asteroid, $\rho_{grain} = 1.38 \pm 0.07$ gm cm$^{-3}$. In Fig. **1** we compare this estimate to the measured densities of grains from the surface of Ryugu returned by the Hayabusa2 mission.

As can be seen, the agreement is excellent, supporting the assumption of homogeneity and the macroporosity calculation. Grott et al. [7] obtained a similar value for the macroporosity of Ryugu in a related, but independent study.

**The rarity or absence of chondrules**: There is a strong correlation between the density of primitive material and its chondrule abundance, as shown in Fig. 2, which is based on the data in Table 1 of [1]. Regardless of the physical cause of this correlation it predicts that chondrules will be rare in low density material. If microporosities of 15% are representative of small asteroids then their low bulk densities indicate they are made of low-density boulders which, as Fig. 2 shows, are likely to contain few, if any, chondrules.

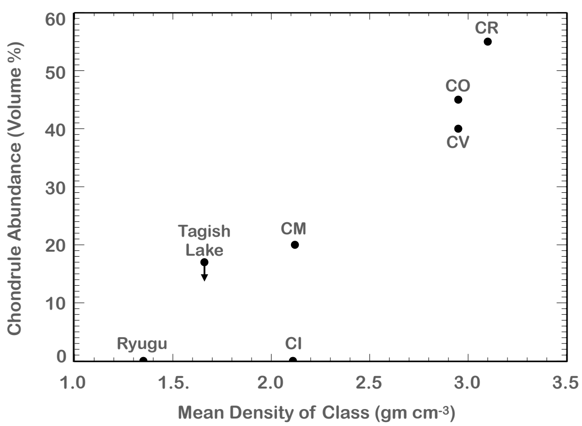


**Fig. 2**. Chondrule abundance as a volume percentage correlates well with the mean density within CC meteorite classes. The Ryugu surface sample extends this correlation to even lower densities. Data plotted are from Table 1 of [1].

**The lithification of chondrites and formation of chondrules**: How did the strong correlation shown in Fig. 2 arise? The density and tensile strength of a meteorite is a measure of how well-lithified it is, i.e. the degree to which its microporosity has been reduced by exposure to heat, pressure or chemical processes. Ryugu material is so poorly lithified that it does not have the tensile strength to survive passage through the Earth's atmosphere [1]. Lithification of primitive, undifferentiated material in the asteroid belt is difficult [e.g. 8]. There is insufficient steady pressure available, even at the center of Ceres, to be important. Without exposure to high temperature, one might expect primitive objects to be poorly lithified and, we believe, that is exactly what the Hayabusa2 results reveal. We believe that the Ryugu sample will turn out to be quite representative of preserved primitive material beyond the Earth's surface. It will be of low density, low tensile strength and lack chondrules, because it was never exposed to the brief blast of high temperature melting needed to lithify it substantially and produce chondrules.

By contrast, it appears that chondrites on Earth are those (rare) objects that *were* exposed to the brief heat blasts recorded in chondrule textures. A crude estimate of the fraction of material that was lithified by exposure to these heat blasts comes from the fraction of mass flux at the top of the Earth's atmosphere represented by chondrites, ~0.1% [9,10].

What does this mean for chondrules? It suggests that the heat blasts required for their formation affected only a minor fraction of primitive material, meaning that chondrules were never widespread in the Solar System and, consequently have no important role to play in planet formation. It cautions us against using some properties of chondrites (e.g. their densities) to assess the properties of asteroids, even when they have similar reflectance properties and compositions. Chondrites are a biased sample of the preserved primitive material in the solar system, a sample in which the best-lithified fraction has been seriously overrepresented. Chondrules, we argue, are a feature of that population, whose importance has been seriously overestimated. We predict that chondrules will be rare on all asteroids.

How did the chondrules form and the chondrites lithify? Our theory is they were exposed to brief heat blasts from volcanic activity at the surface of large planetesimals as they orbited within accretion disks. For details please see [2, 11, 12].

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