**CANDIDATE COSMIC SPHERULE FROM THE NOVEMBER 2019 SAINT LOUIS BOLIDE** R. C. Ogliore[1], T. L. Daulton[1], L. Vacher[1], N. Liu[1], R. Korotev[2], R. P. Harvey[2], M. Fries[3]. [1]Department of Physics, Washington University in St. Louis, St. Louis, MO 63130, USA, [2]Department of Earth and Planetary Sciences, Washington University in St. Louis, St. Louis, MO 63130, USA, [2]Department of Earth, Environmental, and Planetary Sciences, Case Western Reserve University, Cleveland, OH 44106, USA, [3]NASA JSC.

**Introduction:** Approximately $4\times10^7$ kg of extraterrestrial material arrives at the Earth's surface every year [1], of which $\sim$10–100 kg (parts per million) is recovered in witnessed meteorite falls. It is challenging to find meteorites and often nothing is found from even a large bolide [2]. A meteoroid with a pre-atmospheric size of one meter and mass of 2,000 kg may result in only a few stones between 10 grams and 1 kg—the rest of the mass will either be vaporized or will make it to the ground as sub-mm spherical particles, called cosmic spherules. Cosmic spherules have been recovered from sea sediments using magnetic rakes for 150 years [3]. However, the collection of such spherules from observed bolides is quite rare [4, 5], and contamination from anthropogenic sources can be confused for extraterrestrial material. Despite the challenges, the recovery of even microscopic material from observed fireballs will allow cosmochemists to better link Near Earth Objects (NEOs) with a specific meteorite type. Here we discuss a potential cosmic spherule from an observed 2019 bolide and compare to a confounding pollutant: fly ash from coal power plants.

**Methods:** At 8:51 pm local time on November 11 2019 a bright bolide appeared near St. Louis in eastern Missouri, USA (Figure 1). This is AMS fireball event 5566-2019.

Figure 1: Weather camera view seconds prior to bolide (left) and at peak brightness (right).

The meteoroid's entry speed was estimated to be 15.3 km/s from video footage. Bolide terminus was $\sim$100 km west of St. Louis, above Bridgeport, Missouri. The geostationary lightning mapper onboard the GOES 16 weather satellite estimated the total energy to be $1.2\times10^{10}$ J, and therefore the meteoroid's estimated mass was 100 kg. We analyzed video footage of the fireball with the nearly full moon in the frame and, assuming a luminous efficiency of 3.4%, calculated a similar energy and mass. Radar returns consistent with falling meteorites were found in imagery from one nearby weather radar [6]. The meteorite strewn field was calculated based on the radar returns, prevailing winds, and the trajectory and assumed masses of falling meteorites (Figure 2).


Figure 2: Strewn field calculation. Pink line is bolide path; white rectangles indicate search area. Red is the predicted area for $\sim$kilogram meteorites, yellow is the predicted area for sub-gram meteorites.

We searched for meteorites in the strewn field on the morning of November 13 in the region near the radar returns and where stones of a $\sim$10 grams were expected to land. It snowed in the area $\sim$12 hours before the bolide and $\sim$5 cm of fresh snow covered the ground. In addition to visually searching for meteorites, we used a neodymium magnet attached to a hiking pole to recover magnetic (I-type) cosmic spherules. We swept the magnet through the snow for a total of $\sim$2 hours during the search. We did not find any meteorites, and brought the magnet back to the lab. We "rubber stamped" the magnet with carbon tape attached to a one-inch SEM stub. Then we acquired backscattered electron images of the carbon tape in a Tescan Mira3 FEG-SEM with brightness/contrast set so that only Fe-rich particles were non-black. We acquired $\sim$54,000 images and automatically identified 1,500 images with some non-black pixels and manually searched these images for cosmic spherules.

The most promising cosmic spherule candidate we identified was a $\sim$10 $\mu$m diameter sphere with dendritic surface texture. It was composed of Fe and O based on qualitative SEM-EDS analysis. We used the Wash U FEI Quanta 3D FIB to extract a lamella for TEM analysis (Figure 3).

The area we searched is 47 km northwest of the 2.4 GW Labidie coal power plant. Fly ash is mostly removed from the stacks of modern coal plants like Labidie, but some still may make it to the ground in the sur-

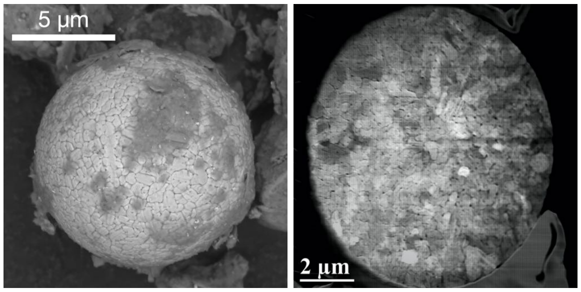


Figure 3: Left) BSE image of candidate cosmic spherule (5 kV). Right) TEM HAADF image of extracted FIB section.

rounding area. Other industrial operations in the area may also contribute to fly ash. To distinguish this candidate cosmic spherule from possible contaminant fly ash, we also analyzed particles of National Bureau of Standards coal flyash (SRM 1633a) [7]. We analyzed surface textures, internal textures, and qualitative elemental compositions using SEM-EDS techniques.

**Results:** The candidate cosmic spherule FIB section showed a fine-grained texture with a few bright subgrains in HAADF imaging (Figure 3). Quantification of the composition of these grains by EELS is forthcoming. SEM-EDS and TEM-EDS analyses showed mostly Fe and O with minor Ni.

Fly ash spherules have many different textures, some of which look very similar to our candidate cosmic spherule. BSE mosaics of thousands of intact fly ash particles [8] and polished fly ash [9] are available for viewing online. An iron-oxide fly ash spherule with similar texture as our candidate cosmic spherule is shown in Figure 4. The external textures for many iron-oxide fly-ashed spherules are similar to our candidate cosmic spherule, but the internal textures differ. Our candidate cosmic spherule contains subgrains with varying HAADF brightness, smaller sizes, and more rounded shapes, compared to BSE images of polished fly ash spherules. SEM-EDS of a polished iron-oxide fly ash spherule shows that it is mostly $Fe_2O_3$ with 0.1–1 atom percent Al, Si, and Ca that is concentrated in veins between iron oxide (Figure 5). Nickel is less than 0.1 atom percent (though Ni can be $>1\%$ in oil fly ash [10], which was not studied here).

**Discussion:** The external texture of iron-oxide fly ash spherules are very similar to the cosmic spherule we found from the November 2019 St. Louis fireball. However, the Al, Si, and Ca veins present in fly ash are not present in our candidate cosmic spherule. The candidate cosmic spherule contains subgrains of varying HAADF brightness and black void spaces which are not present in the fly ash. Forthcoming TEM-EELS analyses of subgrains in the candidate cosmic spherule will help determine if it originated from the Nov 11 St. Louis meteoroid. Bona fide I-type cosmic spherules may contain measurable Ni and subgrains of sulfides including pentlandite.

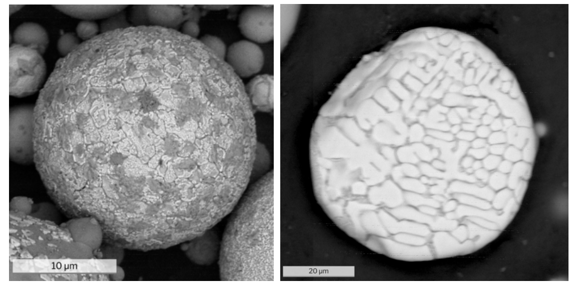


Figure 4: Left) BSE image of fly ash spherule with similar texture as our candidate cosmic spherule. Right) BSE image of a different fly ash spherule, in cross-section after polishing.

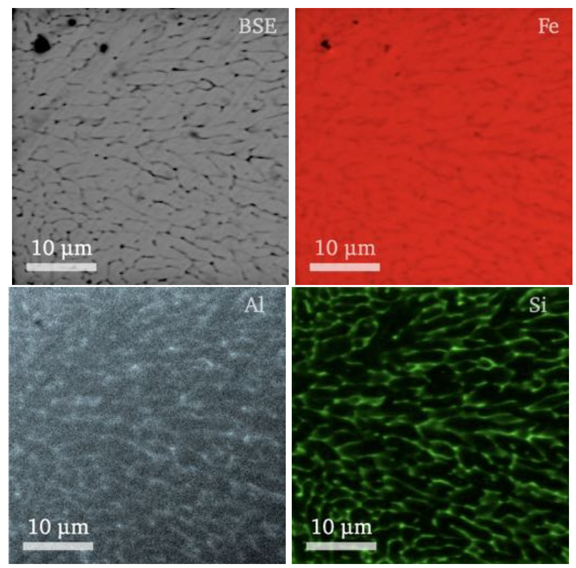


Figure 5: BSE and X-ray images of a polished iron-oxide fly ash spherule.

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