MA-143 Report

Synchrotron X-Ray Scattering from Nanoparticle-Containing Fireballs

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Ball lightning is a spherical "fireball" which may range in size from a few centimeters to about one meter in diameter, floating in the air like a balloon, and emitting intense light within a variety of spectral ranges, from dim red to intense white. Its occurrence in nature during thunderstorms has been reported by thousands of observers. One of its strangest properties is its long lifetime, ranging from seconds to many minutes, without any apparent external source of energy. Philosophers and scientists, from Lucius Seneca to Niels Bohr, have studied the phenomenon, but none was able to come up an unambiguous theory explaining all its observed characteristics and variability. A recent theory by Abrahamson and Dinniss assigns their formation to the evaporation of carbon and silicon when a conventional lightning strike the ground. Subsequently, nanoparticles containing these materials are formed, and their oxidation by ozone, which is also formed by conventional lightning, provides the source of energy sustaining the fireball.

Two years ago we have managed to create artificially in the laboratory "fireballs" of a few-cm diameter and sub-second lifetimes (Dikhtyar and Jerby, *Phys. Rev. Lett.* **96** 045002(2006)). This was accomplished by using a novel microwave drill technique (Jerby et al., *Science* **298** (2002) 587) where microwaves are focussed by a pointed rod into a solid substrate made from glass, silicon, germanium, alumina or other ceramics. The energy from the microwaves then produces a molten hot spot in the substrate. When the "microwave drill" is pulled away from the solid, it drags some molten material and creates a tiny hot drop. The ignition of this drop creates a floating, quivering, intense-light-emitting fireball. The exact composition and internal structure of the fireball was not, however, known at that stage. During the last two years we have improved the method to yield longer lifetimes and larger fireballs. An example of the chamber, with a fireball inside, is shown in Fig. 1. The fireball is clearly floating in the air.

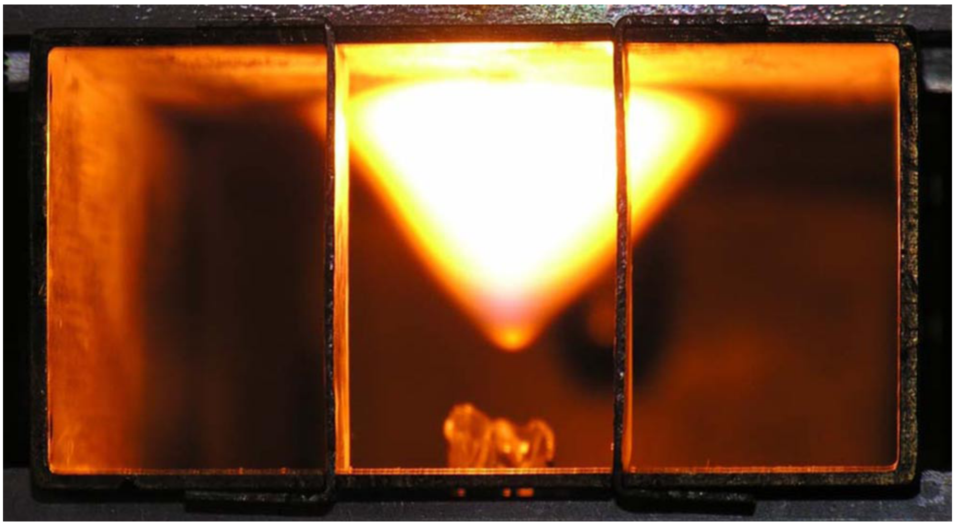

Figure 1: The fireball floating in the microwave cavity.

To find out the internal structure of the fireball, we had to go to the ESRF where small angle x-ray scattering (SAXS) could be done on fireballs created in situ. Here, the intensity and highly-focused beam available at the ESRF was crucial for a successful measurement.

We have carried out SAXS scattering measurements on the fireball [Mitchell et al. *Phys. Rev. Lett.* **100**, 065001 (2008)]. This, by itself, constitutes a novel application of SAXS to a new phase of matter: the plasma. The background subtracted and normalized SAXS intensity as a function of the scattering vector is shown in Figure 2. The data can be well described by relatively simple models originating in SAXS from colloids. The results show that these fireballs contain hot nanoparticles, with a mean size of 50 nm and a volume fraction of about 10^{-7}. They have been found to last for about 2 seconds after the microwave is shutdown. Hence, the fireball can be considered to be a "dusty plasma" ball consisting of an ensemble of charged nanoparticles. This finding is similar to the theoretical model proposed for lightning balls by Abrahamson and Dinniss.

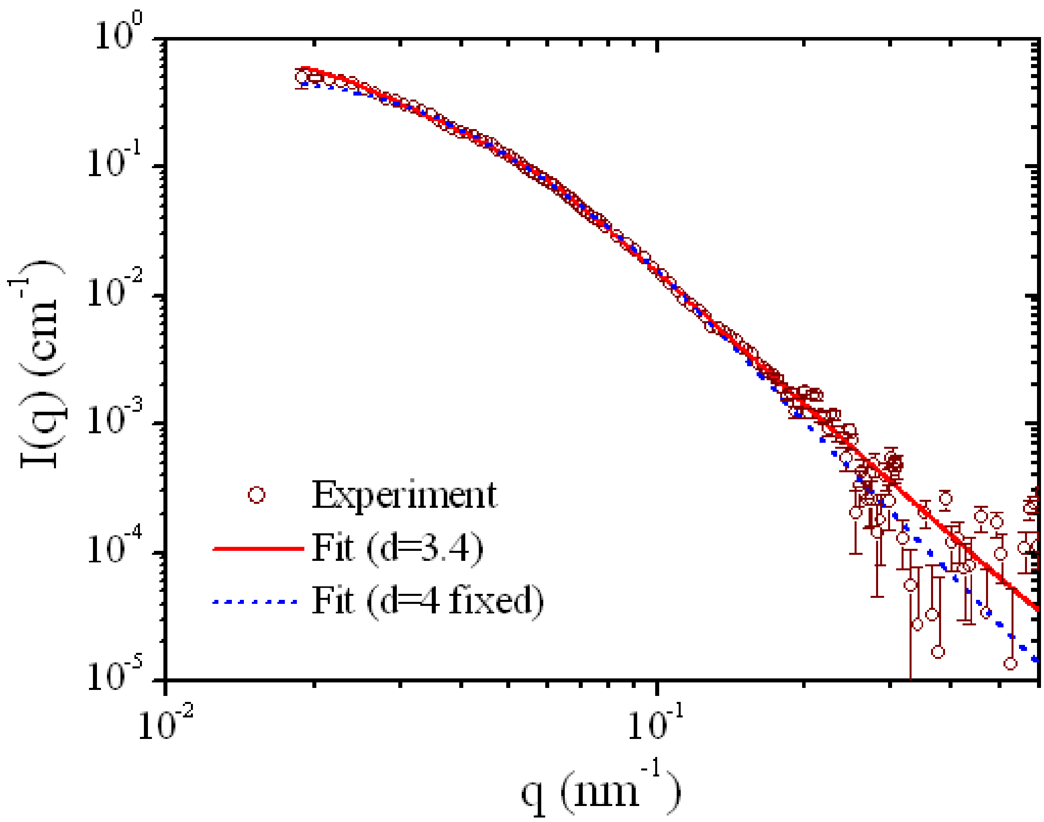

Figure 2: Normalized SAXS intensity $I(q)$ *as a function of momentum transfer, q, for a typical fireball in our experiment.*

While our experiments do not yet provide a full explanation of the formation and structure of fireballs, they do provide a better understanding of the ball-lightning enigma, and contribute as well to the development of practical applications of fireballs, and in particular to the direct production of nanoparticles from a solid substrate. The high intensity and low emittance, providing sharp focusing, at the ESRF is crucial for these and future experiments. Improvements in X-ray instrumentation, especially the SAXS detector, has allowed a quantitative investigation of this extremely dilute (volume fraction $\approx 10^{-7}$) non-equilibrium system. Moreover, the results demonstrate the prospective for *in situ* investigations of microwave-material (including biological specimens) interactions and microwave generated plasmas in particular.