COAGULATION OF VERY SMALL IRON GRAINS WITH "WEB-LIKE" STRUCTURES. P.A. Withey[a] and Joseph A. Nuth III[b], [a]Dept. of Physics and Engineering, West Virginia Wesleyan College, Buckhannon, WV 26201; [b]Astrochemistry Branch, Code 691, NASA - Goddard Space Flight Center, Greenbelt, MD 20771

We report the results of a further series of experiments on 20-50 nm - sized iron particles condensed from the gas phase in a condensation flow apparatus. These iron particles coagulate efficiently to form very long chains producing a "web-like" structure at the macroscopic level. It is discovered that these pure-iron chains and webs form even in the presence of weak ambient magnetic fields (<0.2 gauss). Remanance acquisition and alternating field demagnetization studies reveal that large magnetic fields are required to significantly alter the magnetization of these iron webs indicating that they are very magnetically hard. Iron particles in protostellar nebulae may have coagulated similarly and could have aided in the collection of surrounding nonmagnetic material to form even larger grains. We suspect that these particles should be efficient absorbers of microwave radiation and may be seen in the long-wavelength spectra of protostellar nebulae.

Experimental Procedure

Pure iron grains were produced in a condensation flow apparatus by bubbling iron pentacarbonyl [$Fe(CO)_5$] through a furnace kept at temperatures above 500 K using both helium and helium/hydrogen mixtures as a carrier gas at total pressures around 100 torr. The furnace was designed so as not to contribute any magnetic field in the system. A coil placed coaxial to the flow at the exit of the furnace was used to generate magnetic fields using a DC current ranging from 0.5 gauss (with no applied current) up to 20 gauss. The magnetic field within the chamber was reduced to below 0.2 gauss with the use of a Helmholtz coil. Iron concentration was varied by adjusting the helium bubbling rate. Iron web samples were collected on glass slides covered in nonmagnetic epoxy placed downstream from the furnace. The epoxy was then allowed to dry *in vacuo* capturing the web samples without air exposure to be later analyzed for magnetic properties.

Analyses

In previous work[1], optical microscopy, SEM, and TEM analyses indicated that these webs were made up of many kinked smaller strands containing hundreds of particles. Particle sizes were measured to be approximately 20-50 nm in diameter. In that previous study the heater was powered by an AC current of 500-1200 amperes which generated a magnetic field on the order of 100 gauss immediately outside the furnace where coagulation took place. It was expected that reducing the magnetic field may also reduce the magnetic strength of the webs, so the heater was replaced with one that would not contribute to the magnetic field, and a coil was placed just outside the furnace in order to control the magnetic field strength in the chamber. To our surprise, webs were able to form whether or not there was any magnetic field applied. With no current applied to the coil an external field of 0.5 gauss was present, which was reduced to below 0.2 gauss with the use of a Helmholtz coil. Even at these weak magnetic fields the webs formed were found to be extremely hard magnets. Remanance acquisition curves of samples produced in ambient fields of 0.5-20 gauss show that an external field of above 1000 gauss must be applied before showing any indication of loss of magnetization. For samples formed in magnetic fields of less than 0.2 gauss, loss of magnetization begins to be seen only after a 300 gauss field is applied, which is somewhat lower than for the webs produced in 0.5-20 gauss fields. However, even these web samples appear magnetically hard upon comparison to samples of small iron and nickel particles of the same approximate size trapped in copper lattices, where loss of magnetization is seen immediately on application of fields less than 50 gauss.

These results indicate that the iron webs have significant magnetic properties even though formed in the presence of little or no magnetic field. We hypothesize that the elemental iron released from dissociation of $Fe(CO)_5$ collect, growing into single domain particles of pure iron. Previous studies indicate that iron particles of this size (20-50 nm) should be single domain.[2] These particles behave as magnetic dipoles attracting each other, resulting in the formation of long strings of iron particles which macroscopically appear as "dustballs", "streamers", and "webs".

Discussion

Predictions of the magnetic field strengths produced by lightning discharges in the presolar nebula are in the range of 5-15 gauss.[3] However, this study suggests that iron particles in the presolar nebula would be magnetized on formation even with much weaker magnetic fields down to at least 0.2 gauss. Upon coming into contact with other similarly magnetized iron particles, structures characterizable as "streamers" or "webs" would coagulate from magnetic attraction. Interactions with oxygen would produce an iron-oxide layer on the outer edges, holding them together chemically as well as magnetically. This would not only produce an effectively larger sized grain but would also significantly increase the cross-section for coagulation of other magnetized grains. Single domain iron particles 20-50 nm in diameter present in protostellar nebulae could lead to a very efficient mechanism for coagulation of larger cm-sized grains. Magnetic dipole interactions between these particles would increase their effective grain radius by several orders of magnitude leading to the formation of fractal iron aggregates which could have enormously enhanced long wavelength absorption compared to an equal mass of iron spheres.[4] Evidence of these iron aggregates may have been observed in the long-wavelength spectra of modern protostellar nebulae.[5] Aggregates of single domain iron particles forming "web-like" structures could be large enough to act as a net sweeping up surrounding nonmagnetic material and could play a key role in the formation of larger grains.

[1] Nuth J. A. et al. (1994) *Icarus* **107**, 155-163.
[2] *For example*, Wasilewski P.J. (1981) In Meyers M.A. and Murr L.E., eds. *Shock Waves and High-Strain-Rate Phenomena in Metals* Plenum Publ., New York, 779-793.
[3] Levy E. (1988) In Kerridge J. and Matthews M., eds. *Meteorites and the Early Solar System,* Univ. of Arizona, Tucson. 697-711.
[4] Wright E. (1987) *Astrophys. J.* **320**, 818-824.
[5] Beckwith S. and Sargent A. (1991) *Astrophys. J.* **381**, 250-258.