CHONDRITE ORIGINS IN NEBULAR FIEFDOMS OF THE EARLY SOLAR SYSTEM. H. J. Melosh[1], P. A. Bland[2], G. S. Collins[3], B. C. Johnson[4], D. A. Minton[1], M. Caffee[1] and J. Bae[5]. [1]EAPS and Physics Departments, Purdue University, West Lafayette, IN 47907, jmelosh@purdue.edu, [2]Dept. Applied Geology, Curtin University, GPO Box U1987, Perth, Western Australia, 6845, Australia, P.Bland@curtin.edu.au. [3]IARC, Dept. of Earth Science & Engng, Imperial College, London, SW7 2AZ, UK, g.collins@imperial.ac.uk. [4]Dept. Earth, Environmental and Planetary Sciences, Brown University, Providence, Rhode Island, 02912, USA, brandon_johnson@brown.edu. [5]DTM, Carnegie Institution, 5241 Broad Branch Road NW Washington DC, 20015, jbae@carnegiescience.edu.

Introduction: The ultimate origin of the many classes of chondrite meteorites has been a vexing problem since they were first recognized more than 150 years ago. Three years ago Johnson et al. [1] proposed an impact jetting origin for chondrules. That model was criticized on the grounds that it did not provide a basis for compositional complementarity between chondrules and matrix materials, a problem that has recently been exacerbated by the discovery of complementary matrix/chondrule W isotopic abundances [2]. Connelly et al.'s [3] finding that individual chondrules in the same chondrite may differ in age by millions of years, suggesting long term storage of chondrules, further complicates this issue.

The Puzzle of Complementarity: The origin of chondrules was the subject of a conference convened in February, 2017, at the Natural History Museum in London. At that conference new evidence was presented supporting the concept of complementarity. That is, while neither chondrules nor matrix alone represents the primitive chemical composition of the (non-gaseous) solar nebula, the sum of the two does approximate that composition [4]. Complementarity has been controversial in the past, but new data on tungsten isotopes reported by the Münster group [2] strongly supports this concept.

There are multiple classes of chondritic meteorites, perhaps as many as a dozen (depending on which classification is used). Each class has its own distinctive chemical, mineralogical and isotopic composition. Complementarity is claimed to hold within each class separately, so that the matrix of one class of chondrite is complementary only to chondrules in its own class and not to chondrules from meteorites in another class. It holds only if the matrix and chondrules of each class are considered together.

The puzzle is to explain how such an arrangement could arise. This is a subset of an even higher-level puzzle of why there are so many classes of chondrite in the first place. A further complication arises from the recently perfected ability to date individual chondrules. It now appears that individual chondrules even in the same chondrite may differ in age by several million years [3]. This, too, has generated controversy, because it is difficult to understand how chondrules that originated from both the beginning and near the end of the chondrule-forming era can have come together in the same final resting place.

Fiefdoms of the Early Solar System: If we accept both complementarity and the age dispersion among chondrules, and, fold those into the existence of many different kinds of chondrites, what does that tell us about the early solar system? Here we propose that these puzzles can be resolved if the different chondrite classes arose in long-lasting, quasi-independent domains in the early solar system that we here call "fiefdoms", a term deriving from feudal Europe, where the economy centered around small, nearly independent political units, each governed by a local oligarch whose hegemony discouraged contact with neighbors. In our framework, each fiefdom within the solar nebula inherited a distinctive chemical and isotopic composition from its location in the early solar system. As the primordial chondrules and dust accreted first into planetesimals, then into planets, these bands remained mostly distinct, exchanging only small amounts of material with their neighbors, until the gas dissipated and gravitational interactions later mixed the distinct regions into the solar system we see today [5].

This postulate is inspired by recent ALMA observations of multiple isolated dust bands in the outer part of protoplanetary discs, such as the iconic HL Tau or TW Hya [6,7]. Although these dust bands are observed only at great distances from their host stars (10 to 100 AU), we hypothesize that in the (currently unresolvable) inner disk, similar dynamical processes led to a radial separation of dusty domains imbedded in a gas-rich nebula, a separation perhaps enforced by interaction with growing planetary embryos.

Pressure Bumps: While current models do not provide a widely accepted dynamical basis for the confinement of dust to narrow zones (even in the case of HL Tau and TW Hya the confinement mechanism is controversial), it has long been understood that "pressure bumps" in the nebular gas can confine dust and solid particles in narrow zones. Whipple [8] showed that, in the usual case of gas pressure that declines with increasing radius from the central star, solid particles following Keplerian orbits face a headwind in the gas and so tend to drift inwards towards the star. However, if for some reason (usually the presence of an embedded planet) the pressure gradient is locally reversed, Keplerian dust and planetesimals experience a tailwind that accelerates them outward. Local "bumps", reversals of pressure, thus tend to confine solids into a narrow band. This construct is widely used to explain the observed dust bands in protoplanetary disks. Observationally, while the dust is confined to a band, the gas distribution is more uniform. When the gas is lost from a dissipating nebula, this confinement is removed and gravitational interactions would cause the solids to disperse and mix on a dynamical time scale of a few hundred thousand years. Within these bands quite large planetesimals (Moon size and larger) can grow very rapidly through the related processes of streaming instability and pebble accretion [9].

Stable Rings? It has been well understood that a massive planet (more than approximately 20 Earth masses at the current Jupiter's location) can open a radial gap around its orbit in a protoplanetary nebula [10]. Recently, Bae et al [11] showed that, in addition to the main gap within which a planet orbits, the planet can open additional gaps throughout the disk as the spiral arms driven by the planet interact with the disk. Between the gaps form rings that can possibly be stable for long-term storage of chondrules. For a 20 Earth-mass proto-Jupiter in a minimum-mass solar nebula, it is suggested that 4 pressure bumps interior to proto-Jupiter's orbit could form and two outside [12]. Desch et al [13] invoke a similar mechanism to explain the abundance of CAI's in chondrites. However, the full dynamical problem of the distribution of pressure, gas and solids in a protoplanetary nebula with embedded massive, accreting planetesimals still needs more clarification.

Proposal: In spite of this lack of a solid dynamical foundation, we propose that many of the outstanding problems of meteorite origins, including complementarity, the existence of many distinct chondrite groups and the age dispersion of chondrules in a single meteorite, are resolved if the nebular disk was divided into relatively independent zones in which accretion in the gas-rich disk took place in multiple bands, "fiefdoms" in our terminology [14]. Differences in chemical composition, oxygen isotope composition and physical structure would be the consequence of slightly different environments with respect to the early sun. Accretion, collisions and overall increase in the size of protoplanets would initially be confined to each narrow region, until dissipation of the nebular gas and the dominance of gravitational interactions that promote mixing on sub-Myr time scales.

Implications: In addition to resolving these puzzles of meteorite composition, our proposal offers simple resolutions to two other planetary puzzles. The first is the surprising similarity, if not identity, of the isotopic compositions of the Earth and Moon [15]. While much ingenuity has now been applied to explaining how this similarity could persist through the now-favored impact origin of the Moon, it has long been understood that the simplest explanation is if the proto-Earth and impactor were nearly identical in composition. Most accretion scenarios, however, gave no rationale for such a close match. However, if the impactor ("Theia") and the proto-Earth grew to planethood in the same fiefdom, they would both have received material from the same chemical and isotopic reservoir and a near-identity of composition would be the natural consequence.

Second, going further afield, one of the Kepler mission's many surprises was the large number of dynamically cool multi-planet systems, in which three or even five planets orbit so nearly in the same plane that they all occult their star from Earth's perspective. But such a system might be a natural outcome of a fiefdom arrangement in which the damping gas remained in the system longer than in our solar system. In this case intra-fiefdom growth would have proceeded to the point that nearly all of the solids were swept up into a single planet, which, upon dissipation of the nebular gas, was already in a stable dynamical configuration with its neighbors.

While many of these arguments are qualitative, and there is no complete dynamical model at present that supports the separation of the solid-rich inner part of the solar nebula into independent bands (fiefdoms), we believe that the evidence from the chondritic meteorites strongly implies the existence of such a structure in the early solar system.

References: [1] B.C. Johnson, D.A. Minton, H.J. Melosh, M.T. Zuber (2015), Nature. 517, 339–341. [2] G. Budde, T. Kleine, T.S. Kruijer, C. Burkhardt, K. Metzler (2016) PNAS. 201524980–6. [3] J.N. Connelly, M. Bizzarro, A.N. Krot, A. Nordlund, D. Wielandt, M.A. Ivanova (2012) Science 338 651–655. [4] D. C. Hezel and H Palme, EPSL 254, 85-93 (2010). [5] F. E. DeMeo and B. Carry, Nature 505, 629-634 (2014). [6] S.M. Andrews, D.J. Wilner, Z. Zhu, T. Birnstiel, J.M. Carpenter, L.M. Pérez, et al. (2016), ApJ. 820 1–5. [7] K. Zhang, E.A. Bergin, G.A. Blake, L.I. Cleeves, M. Hogerheijde, V. Salinas, et al. (2016), ApJ. 818 1–7.. [8] F. Whipple, in *From Plasma to Planet*, 211-232 (1972). [9] Chambers, ApJ *825*(1), 63 (2016). [10] Lin and Papaloizou, ApJ, v309 p846 (1986); Takeuchi, Miyama, Lin, ApJ, v460 p832 (1996), Lambrechts and Johansen, A&A *572*, A107 (2014). [11] J. Bae, Z. Zhu and L. Hartmann, ApJ, 850, 201 (2017). [12] J. Bae and Z. Zhu, arXive:1711.08166v1 [astro-ph.EP] (2017). [13] S. Desch, A. Kalyaan, and C. M. O'D. Alexander, arXive:1710.03809v1 [astro-ph.EP] (2017). [14] H. J. Melosh, P. A. Bland, G. S. Collins and B. C. Johnson, MetSoc LPI Contrib. No. 1987, Abs. #6239 (2017). [15] H. J. Melosh, Phil. Trans. Roy. Soc. A, 372,30168 (2014).