Chondrule Formation: Nebular Gas Confinement of Impact Splashes

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What are “chondrules” & why would we care?

Chondrules are ~0.1⋯1 mm-size once-molten silicate spherules out of which many meteorites are predominantly made (see image).

They must have formed during the first 10 Million years of the Solar System through flash-heating events.

It is one of the biggest unresolved debates in meteoritics as to what these flash-heating events might have been. One thing is sure: they must have been very common.

Identifying what energetic process has molten such a high fraction of the meteoritic material may shed light on the processes underlying planet formation.

Chondrule formation: meteoritical constraints

From decades of laboratory measurements of meteorites, the following constraints on the chondrule-formation process have been found (among many more):

- After they were molten, chondrules must have rapidly cooled (within a few hours).
- Chondrules and matrix (=the ‘dust’ between the chondrules) are chemically complementary: together they are solar (Hezel & Palme, 2010, Earth and Planetary Science Letters, 294, 85)
- Chondrules must have formed in dense environments, so dense that they were likely gravitationally bound clumps of material (Alexander & Ebel, 2012, Meteoritics and Planetary Science, 47, 1157)
- Sometimes chondrules were pressed together while they were still plastic, i.e. not perfectly solidified yet (Metzler, 2012, Meteoritics and Planetary Science 47, 2193)
- Chondrules managed to stay in the asteroid belt for ~ 5 million years, despite their dynamic tendency to rapidly drift inward toward the sun.

Various classic models and their problems

There exist many models of chondrule formation, e.g.:

(1) Flash heating by nebular shocks (e.g. Morris & Desch 2010)
Problems: Low density environment, hard to cool down rapidly enough, complementarity hard.

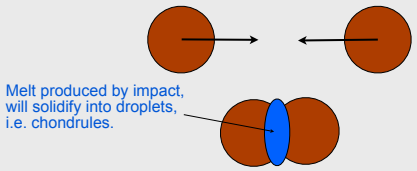
(2) Flash heating by nebular lightning (e.g. Gibbard et al. 1997)
Problems: Nebula too conductive, lightning very localized, low density.

(3) Low-velocity impacts between 26Al pre-molten planetesimals, causing melt-sprays (e.g. Zook et al. 1980)
Problems: Works only once, only for equal-sized bodies (must penetrate the crust)

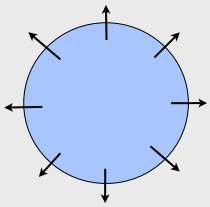
(4) High-velocity impacts between planetesimals, causing impact-melt sprays (Urey 1956)
Problems: Hard to re-accrete debris, hard to maintain high velocities.

OUR MODEL: Impact splash + ambient gas

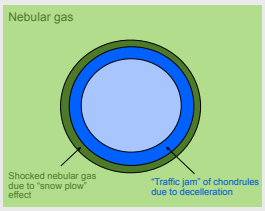
Collision between ~10 km size planetesimals a at few km/s:



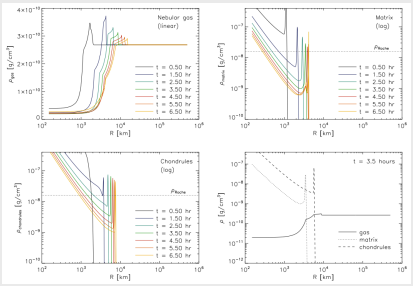
Without nebular gas: Material disperses. No re-accretion.



With nebular gas: Dense shell forms, and creates planetesimals



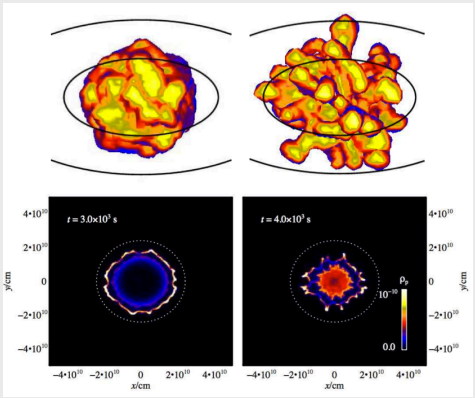
1-D Spherically symmetric model



The front chondrules hit the gas first, and will decelletate. The later chondrules will run into the first ones. A dense shell forms with density above the Roche density, meaning the shell will fragment into gravitationally bound objects.

3-D Model

Because the dense debris is decelerated by tenuous nebular gas a Rayleigh-Taylor instability sets in, making dense bullets, which are dense enough to be bound.



Conclusion

Including the decelleration by the nebular gas can produce a dense compressed environment in which chondrules cool. The density is high enough to cause gravitational contraction and re-accretion. This scenario may answer some of the previously mentioned issues with chondrule formation models.

Feel free to ask questions. We are very interested in a debate!
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