Primordial Capture of Dark Matter in the Formation of Planetary Systems

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Although Dark Matter (DM) apparently pervades the universe, it is rarely considered in the context of the formation of the Solar System and other planetary systems. However, a relatively small but non-negligible fraction of the mass of any such systems would consist of DM gravitationally captured during the collapse of the proto-planetary Nebula, subject to the very general assumption that DM particles have an individual mass $<<$ than the mass of the Earth. This process, much more efficient than the previously considered post-formation captures by three-body interactions (*1, 2*), would apply to both microscopic DM, such as axions or Weakly Interacting Massive Particles (WIMPs), and macroscopic DM candidates such as Compact Ultra-Dense Objects (CUDOs) and Primordial Black Holes (PBH).

"Primordial capture" occurs from the gravitational potential changes during the collapse of the proto-planetary nebula. Planetary systems result from the gravitational collapse of cold molecular clouds as the gas becomes gravitationally unstable, collapses, and fragments, with stellar systems forming out of the condensed fragments. Although free ranging DM particles would be minimally influenced by gas pressure changes directly, they of course would

respond to the gravitational changes caused by these fluid motions. The primordially captured material comes from the relatively small fraction of the DM population which by chance is moving sufficiently slowly to be caught and bound by the changing gravitational potential. A dark matter particle with a typical Halo velocity of 300 km s^{-1} would pass through a typical molecular cloud in $\sim$ 200,000 yr, much less than the gravitational collapse time and even faster than the pre-collapse supersonic turbulence (with typical velocities of $\sim$ 130 km s^{-1}) (*3*). Such Halo DM particles would be unlikely to be captured. On the other hand, a DM particle that happened to be situated inside a collapsing cloud with a relative velocity comparable to the local speed of sound (a few km s^{-1}) would be almost stationary relative to the cloud's shock waves and would experience a large change in the local gravitational potential as the gas flowed around it, rendering it subject to capture. For simple models of galactic DM velocity distributions and a cloud mass comparable to the Orion-A star-forming region, the total amount of primordially captured DM for a Sun-type star is $\sim 10^{-8}$ to 10^{-6} M$_\odot$ ($\sim 10^{22}$ to 10^{24} kg), depending on whether the star formed in the Galactic disk or the Halo.

While primordial capture is equally efficient for any DM particle, microscopic or macroscopic, the subsequent history of captured particles depends on their nature, and would be different for macroscopic CUDOs (which can interaction strongly with ordinary matter), PBH (which would consume ordinary matter), and microscopic DM (which does not interact strongly with ordinary matter). In addition, annihilating DM (either self-annihilating microscopic DM, or antimatter CUDOs) would be expected to have a greatly increased annihilation rates in the higher densities of a collapsed planetary disk. Several of these

cases may have left observable signatures in the Solar System in the course of its formation; this talk will examine three possible signatures of DM in the formation of the Solar System.

Primordially-captured annihilating DM might be able to account for many of the heating and high-energy radiation episodes in the early Solar System. Radiochemistry reveals that material in the early solar system was subjected to multiple episodes of high-energy radiation, which produced at least some of the "fossil" short-lived radionuclides (those with half-lives $< 10^7$ yr) (*4–7*). Short-lived radionuclides are frequently attributed to multiple supernova explosions adjacent to the proto-Solar nebula, but the evidence for supernova in the early Solar System may not be conclusive (*8, 9*) and the addition of DM annihilation provides both potentially an independent solution for the radionuclide observations and also tests of whole classes of DM theories.

In proto-planetary discs, the first step of planet formation is thought to be the conglomeration of dust particles into small (sub-meter) bodies, which then must grow through conglomeration into larger ones. In a proto-planetary disk the gas is subject to both pressure and gravity, and so does not follow a Keplerian orbit, creating a headwind for orbiting bodies, and causing meter-sized ordinary matter objects to rapidly spiral into the central star (*10, 11*). This rapid de-orbiting of meter-sized bodies, together with tendency of bodies of this size to fragment, rather than aggregate, at the collisional velocities expected in the proto-planetary disk, are together known as the "meter barrier" (*12–14*) in planetary formation. A population of sufficiently large macroscopic CUDOs in the primordial Solar nebula would resolve this issue, providing nucleation centers with sufficient mass and self-gravity to both avoid rapid de-orbiting

and accumulate dust and smaller bodies on their surface.

Primordial capture can also be used to derive severe restrictions in the mass range of PBH, as these would consume any ordinary matter objects they come in contact with, a process easily detectable in the Solar System. Capela *et al.* (*15*) considered primordial capture as part of stellar formation, and concluded that it can be used to exclude PBH with $\mathbf{M}_{PBH} > \mathbf{10}^{13}$ kg; by consideration of the consumption of planets and smaller bodies in the Solar System, this limit can be extended to arbitrarily small masses, independent of any Hawking radiation evaporation of the PBH.

References and Notes

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