Polluting white dwarfs with 2nd-generation asteroids formed in AGB outflows
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Evolution of low and intermediate mass stars

Background
White dwarfs, WDs are degenerate cores of < 8M☉ stars. Metals sink in their H/He atmospheres fast compared to their lifetimes (few days-1,000 years vs. billions of years)

White dwarf pollution refers to the presence of metals in their atmospheres: up to 50% of all white dwarfs are polluted [Koester+ 2014]

- Long WD lifetimes vs. short metal sinking timescales → accretion is ongoing
- Current pollution picture: white dwarfs feed on disrupted asteroids, scattered inwards by distant massive planets (1st generation planetary systems). Scattering planets have to be more massive than ~Neptune to send asteroids on star-grazing orbits, overcoming the effects of General Relativity [Pichon+ 2017]
- The pollution picture is unlikely complete because
  - the detected pollution is volatile-poor → why not from comets?
  - giant planets are not frequent around A and F stars (white dwarf progenitors) [Vigan+ 2021] and were even less frequent in the past, when the progenitors were evolving, in lower-metallicity environments

Formation of asteroids in AGB outflows
Asymptotic Giant Branch, AGB is a post-main-sequence evolutionary stage of < 8M☉ stars, when they lose most of their mass via turbulent outflows, becoming white dwarfs

- As seen in experiments and numerical simulations, small eddies tend to effectively concentrate dust of specific sizes in void spaces

Colors show gas vorticity, black points show dust grains

For Kolmogorov-like turbulence, spherically symmetric outflows and standard AGB values (Table 1), we can calculate this specific grain size s_{min} by equating dust advection (Epstein) stopping time to the eddy turnover time -

\[ s_{\text{min}} \propto \frac{\rho_{\text{gas}}}{\rho_{\text{dust}}} \]

\[ \tau_{\text{edd}} \sim H/R \sim 0.01 \rightarrow 1 \mu m \]

Observations: dust grains in AGB outflows are submicron [Ohnaka+ 2016]
- Kolmogorov prescription gives the characteristic size of forming dust clumps and their lifetimes - these values are ~ the eddy size and turnover timescale at Kolmogorov microscales

\[ t_{\text{edd}} \sim H/R \sim 100 \text{ km} \]

\[ t_{\text{edd}} \sim H/R \sim 0.1 \text{ hr} \]

- For the gravitational collapse of the dust clumps, 2 requirement must be met: (1) self-gravity overcomes the local stellar gravity and (2) turbulent diffusion. Simple calculations demonstrate that this is feasible: the maximal concentration factor of dust is \( c_{\text{min}} = 64 \pi R_{\text{dust}}^{3} / 9 \times 10^{5} \) [Desch & Cassidi 2000], raising the local dust volumetric density to the local Roche density (~10^4 g/cm^3) and suppressing turbulence (ratio of gas turbulent energy to dust self-gravity is ~ 1)

- This problem requires further investigation - turbulent concentration can be a process that seeds planetesimal formation, when a separate process takes the system to gravitational instability

- One of such processes is the growth of dust grains via coagulation. The dust growth timescales for 0.01-0.1 μm grains are short compared to the clump lifetimes

\[ t_{\text{growth}} \sim (\pi \sigma \delta t)^{-1} \sim 0.5 \rightarrow 5 \times 10^{-1} \delta \tau_{\text{edd}} \]

- number density of dust grains

- grains' cross-section

- grain's velocity dispersion (eddyl velocity at Kolmogorov microscale)

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Dynamics of 2nd-generation planetesimals
- N-body simulations of 2D WD systems in MERCURY [Chambers 1999] showed that collisions among planetesimals can occur during WD lifetimes
- Collision rate = proxy for collisional dust production. Interestingly, the n-body approach, often employed for similar problems, tends to overestimate the collision frequency

Future work: N-body simulations of 3D WD systems (WD + spherical halo of planetesimals)

- Poynting-Robertson drag can cause orbital decay of dust from a range of orbits

For perfectly absorbing grains and circular orbits, the orbital decay timescale \( \tau_{\text{cr}} \) is

\[ \tau_{\text{cr}} \sim \frac{a^{2} \tau_{\text{edd}}}{L} \]

- orbital radius

- speed of light

- grain mass

- WD luminosity (blackbody at 10,000 K)

- Future work: Touma+ 2019 investigated the dynamics of spherical halos of stars with black holes at the center, showing that stars can achieve high-eccentricity orbits in such systems - similar mechanism at play in polluted WD systems?