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Formation of Solid H_2 in the ISM

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H_2 Phase Transition + Gravity = Substellar H_2 Bodies

Introduction

- Observations of various ices and of comets
  → Phase transition processes are happening in cold regions
- Fragmentation of gravitationally unstable fluids in a phase transition
  → Formation of cold, substellar sized bodies[1,2]

H_2 condensation conditions

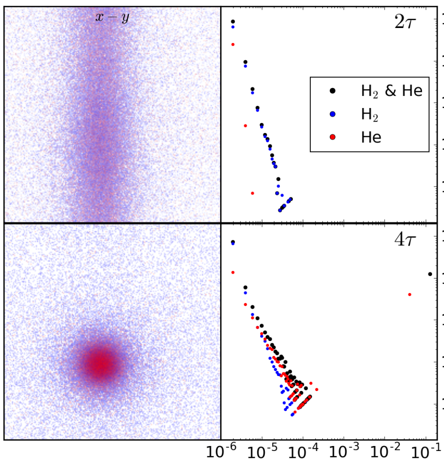
- During the plane-parallel contraction of star formation
- Dense substellar structures such as cometary knots

Motivation

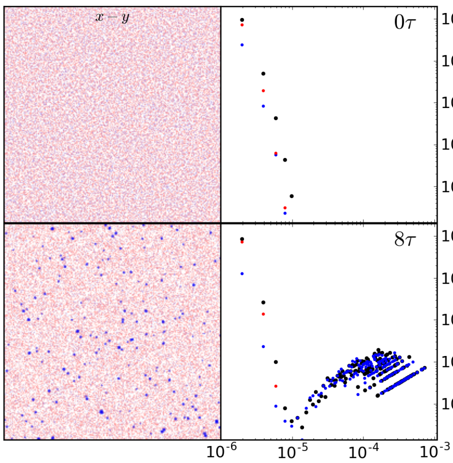
- Formation of solid H_2 during star formation
- Solid H_2 as dark baryons
- Formation of solid H_2 in clumpuscules
- Formation of solid H_2 in cometary knots
- Comets as remnants of solid H_2

Conclusions

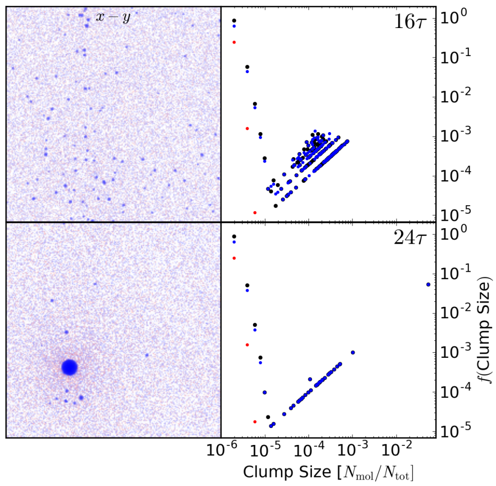
- Fluids in a phase transition are always gravitationally unstable
  → Jeans length vanishes
- H_2 phase transition + gravity:
  Gas $\xrightarrow[\text{transition}]{\text{phase}}$ grains $\xrightarrow{\text{gravity}}$ comets / planetoids
- Sheet-like collapse
  → Fastest collapsing geometry
  → Temperature increase by only a factor of 2
  → Smallest opacity increase
- H_2 phase transition can be reached during sheet-like collapse, if
  $T_0 < 15\,\mathrm{K}$ without cooling
  $T_0 < 30\,\mathrm{K}$ with cooling
- H_2 condensation
  → Inefficient star formation
  → Difficult to detect, dark baryons?



Ideal gas with 75% H_2 + gravity ($L > \lambda_{\mathrm{Jeans}}$)
→ Formation of gaseous He-planetoid



Phase transition with 25% H_2, without gravity
→ Formation of solid H_2-oligomers



Phase transition with 75% H_2 + gravity ($L < \lambda_{\mathrm{Jeans}}$)
→ Formation of solid H_2-planetoid

Physics

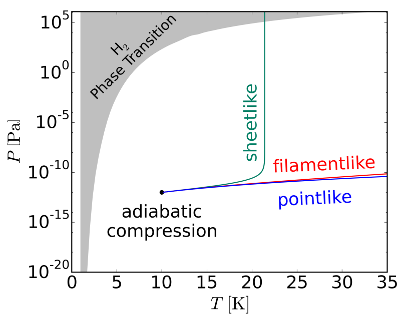
- Phase transition fluid: $(\partial P/\partial \rho)_s = 0$
  - Increase of density does not increase pressure
  - Increase of density increases fraction of condensed matter
  → Fluids in a phase transition are gravitationally unstable at any scale
- Virial theorem using the inter-molecular Lennard-Jones potential energy $E_{\mathrm{LJ}} = E_{\mathrm{a}} + E_{\mathrm{r}}$ and gravitational potential E_{G}:

$$0 = \underbrace{2E_{\mathrm{kin}} + 12E_{\mathrm{r}}}_{>0} + \underbrace{6E_{\mathrm{a}} + E_{\mathrm{G}}}_{<0}$$

→ Unvirializable density domain if $6|E_{\mathrm{a}}| > 2E_{\mathrm{kin}} + 12E_{\mathrm{r}}$
→ Formation of H_2 clumps up to $T \approx 600\,\mathrm{K}$

Sheetlike Collapse

- Fastest collapsing geometry[3]
- Remains optically thin
- Temperature increase by a factor of ≤ 2.1
- Phase transition if $T < T_{\mathrm{c}} \equiv 33\,\mathrm{K}$
  - $T_{\mathrm{c}}/2.1 \approx 15\,\mathrm{K}$
  → Phase transition if $T < 15\,\mathrm{K}$

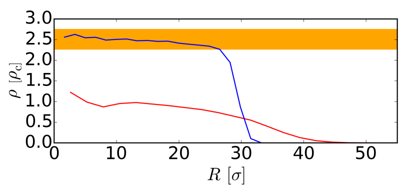


Simulations

- Widely used Molecular dynamics code: LAMMPS[4]
- Combination of Lennard-Jones and gravitational potential
- Use of Super-Molecules:
  - 1 Super-Molecule $= \eta$ molecules
  - Invariance of E_{kin}, E_{LJ}, E_{G}

Planetoid Densities

- Rocky H_2 planetoid
- Gaseous He planetoid
- Laboratory condensed H_2



References

(1) Füglistaler A., Pfenniger D. 2015, Astronomy & Astrophysics, 578, A18
(2) Füglistaler A., Pfenniger D. 2016, Astronomy & Astrophysics, 591, A100
(3) Zel'dovich, Y. B. 2016, Astronomy & Astrophysics, 5, 84
(4) Plimpton S. 1995, J Comp Phys, 117, 1-19

Acknowledgements. This work is supported by the STARFORM Sinergia Project funded by the Swiss National Science Foundation. We thank the LAMMPS team for providing a powerful open source tool to the scientific community.