**H₂ Phase Transition + Gravity = Substellar H₂ 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\(^1,2\)

**H₂ condensation conditions**

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

### Motivation

- Formation of solid H₂ during star formation
- Solid H₂ as dark baryons
- Formation of solid H₂ in clumpuscules
- Formation of solid H₂ in cometary knots
- Comets as remnants of solid H₂

### Conclusions

- Fluids in a phase transition are always gravitationally unstable → Jeans length vanishes
- H₂ phase transition + gravity:
  - Gas → grains → comets / planetoids
- Sheet-like collapse → Fastest collapsing geometry → Temperature increase by only a factor of 2 → Smallest opacity increase
- H₂ phase transition can be reached during sheet-like collapse, if \( T_c < 15 \) K without cooling
- H₂ condensation → Inefficient star formation → Difficult to detect, dark baryons?

### Physics

- Phase transition fluid: \( \frac{\partial p}{\partial \rho} = 0 \)
  - 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 \( E_{\text{LJ}} \), and gravitational potential \( E_G \):
  \[ 0 = 2E_{\text{kin}} + 12E_{\text{LJ}} + E_G \]
  → Unvirializable density domain if \( 6|E_{\text{LJ}}| > 2E_{\text{kin}} + 12E_G \)
- Formation of H₂ clumps up to \( T \approx 600 \) K

### Sheetlike Collapse

- Fastest collapsing geometry\(^3\)
- Remains optically thin
- Temperature increase by a factor of \( < 2 \)
- Phase transition if \( T < T_c \approx 33 \) K
- Phase transition if \( T < 15 \) 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 \( E_{\text{kin}}, E_{\text{LJ}}, E_G \)

**Planetoid Densities**

- Rocky H₂ planetoid
- Gaseous He planetoid
- Laboratory condensed H₂

### References

3. Zel’dovich, Y. B. 2016, Astronomy & Astrophysics, 5, 84

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