Evolution of early Protoplanetary systems embedded in gaseous disks under perturbation of passing-by stars.

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Outline.

- Numerical approach for our research: SPH tee-based code

$$\rho_i = \sum_j m_j W(\vec{r}_{ij}, h)$$

- Protoplanetary disks.

- Disks in Open clusters: Close encounters.
Protoplanetary Disks in open clusters.

Motivations:

- Very poor amount of work have been done for binary and multiple systems, still we we don’t have clear answers on how planets can form

- Disks in open clusters (Hernández & al 2010; Mann & al. 2015)

- HARPS-N radial velocity measurements: Observation of the first multi-planet system in an O.C. (M44) (Malavolta & al., 2016)

- Solar system formation in OC (Pfalzner 2013)

- Binary stars ev. in O.C. not substantially affected (Parker & al. 2009)

- A Binary System in the Hyades Cluster Hosting a Neptune-sized Planet (David R. Ciardi & al. 2018)
Tree-SPH Algorithm.

Gaseous systems – small number of point mass objects.

- Stars
- Gas

Small N-body system

Lagrangian approach (SPH + TREE structure)


Pinto L.D. & al. (2018 - submitted)

Tree-SPH Algorithm.

\[ \rho_i = \sum_j m_j W(\vec{r}_{ij}, h) \]

Tree-SPH Algorithm.

\[ P(\vec{r},t), \ \rho(\vec{r},t), \ T(\vec{r},t), \ v(\vec{r},t) \]

- **Smoothing Length** \( h \), defines the resolution of interpolation.
- At least ~50 neighbour particles are needed.

\[
\begin{align*}
\frac{d\rho}{dt} + \rho \vec{\nabla} \cdot \vec{v} &= 0 \\
\frac{d\vec{v}}{dt} &= -\frac{1}{\rho} \vec{\nabla} P + \vec{f} \\
\frac{du_i}{dt} &= \frac{P}{\rho^2} \frac{d\rho}{dt}
\end{align*}
\]

\[ P = f(T, \rho, ...) \rightarrow P = \frac{\rho}{m} KT = (\gamma - 1) \rho u \]

\[
\begin{align*}
\rho_i &= \sum_j m_b W_{ij} \\
\frac{d\vec{v}_i}{dt} &= -\sum_j m_j \left( \frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2} + \Pi_{ij} \right) \vec{v}_i W_{ij} \\
\frac{d\vec{u}_i}{dt} &= \frac{1}{2} \sum_j m_j \left( \frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2} + \Pi_{ij} \right) \vec{v}_j \cdot \vec{v}_i W_{ab} \\
P_i &= (\gamma - 1) \rho_i u_i \\
\frac{d\vec{r}_i}{dt} &= \vec{v}_i
\end{align*}
\]

- **CPU time** ~ \( N \), \( \text{Tree-SPH Algorithm.} \)

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*Monaghan’s papers (1989, 1992, 2005)*
Tree-base scheme for self-gravity

Far “cluster” multipole potential field expansion with respect to its M.C.

\[ \phi(\vec{r}) = -\frac{MG}{r} - \frac{1}{2} \frac{G}{r^5} \cdot \vec{r} \cdot Q \cdot \vec{r} \]

\[ \ddot{a}_i = - \frac{MG}{r^3} \cdot \vec{r} + \frac{G}{r^5} (Q \cdot \vec{r}) - \frac{5}{2} \frac{G}{r^7} (\vec{r} \cdot Q) \cdot \vec{r} \]

\[ M = \sum_i m_i \]

\[ \vec{R}_C = \frac{1}{M} \sum_j m_j \vec{r}_j \]

\[ r = ||\vec{r}_C - \vec{r}|| \]

\[ Q|Qij = \sum_i 3 \cdot (x_i - x_{ic})(x_j - x_{jc}) - \delta_{ij}||\vec{r} - \vec{R}_C||^2 \]

Close cluster: NO quadrupole approximation

Advantage in time consuming ~ N LOG(N)

Cache friendly implementation.

Shared Memory parallelization with open-MP modules.

Data race problem easily fixed:
Private memory allocation for $\ddot{a}, \dot{T}$ needed
( every thread needs 32 Bytes per particle)

Interaction with point-mass objects.

Individual timestep. $\Delta t \propto \Delta t_{\text{max}} \cdot 2^{-n}$

Different methods.

- Gas: 2nd order Velocity-Verlet
- Stars: 14th order RK

Correction terms for variable smoothing length and gas self-gravity added

$$\frac{dv_i}{dt} = -\sum_j G m_j \frac{1}{2} \left(a_{soft}(r_{ij}, h_i) + a_{soft}(r_{ij}, h_j)\right) \cdot \frac{r_{ij}}{r_{ij}} - \sum_j G m_j \frac{1}{2} \left(\frac{\xi_i}{\Omega_i} \nabla_i W(h_i) + \frac{\xi_j}{\Omega_j} \nabla_i W(h_j)\right) + \sum_j m_j \left(\frac{P_i}{\rho_i^2 \Omega_i} \nabla_i W(h_i) + \frac{P_j}{\rho_j^2 \Omega_j} \nabla_i W(h_j)\right)$$
Disk Model.

Simple Flared Disk around a single star.

- Optically thin
- Geometrically Thin
- Vertical Isothermal approximation
- Stellar radiation dominates
  Thermal evolution (accretion negligible)
- Velocity field: \( v_\theta \sim \sqrt{\frac{G M_{\text{star}}}{R}} = R \cdot \Omega_{\text{kep}} \)
- Surface density: \( \Sigma \sim r^{-3/2} \)
- Disk self gravity.
- Euler Equations:

\[
\begin{align*}
\frac{d \rho}{dt} + \rho \vec{V} \cdot \nabla \rho &= 0 \\
\frac{d \vec{V}}{dt} &= -\frac{1}{\rho} \nabla P + \vec{f} \\
\frac{du}{dt} &= \frac{P}{\rho^2} \frac{d \rho}{dt} \\
P &= f(T, \rho, \ldots)
\end{align*}
\]

- Same model for Circumbinary Disks

\[
\begin{align*}
\rho(z) &= \rho_0 \cdot \exp \left( -\frac{z^2}{2H^2} \right) \\
H &= \frac{c_s}{\Omega_{\text{kep}}} \propto T^{1/2} R^{3/2}
\end{align*}
\]
Gravitational field from other stars perturbs the disk.

Several simulations at different impact parameters and relative v orientation with respect to the disk midplane.  
( Luis Diego Pinto, Roberto Capuzzo Dolcetta, Stefano Cattolico, in prep.)

\[ M_d = 0.01 M_{SOL} \quad 5 \, \text{AU} < R < 100 \, \text{AU} \quad \text{impact parameter } b = 300 \, \text{AU} \]

Passing-by star \( M_2 = M_1 \)

4 e~0 orbiting planets
Direct integration.

**Scientific goal:** to investigate the perturbation of a non isolated disk, embedded in an open cluster.

- Mass loss
- Radial cut off

**Impulsive perturbations:**
- from **passing by** stars
- **strong** but **instantaneous**
- disks can be abundantly truncated in a short timescale (<< T crossing)

**Cumulative perturbations**
- from **background** stars
- **weak** but **secular**
- disks can be substantially truncated in a long timescale (>> T crossing)

(Rosotti & al., 2014)
Thank You!!!