Molecular cloud evolution simulation with dendrogram

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About me

Name: Kotora Sasaki

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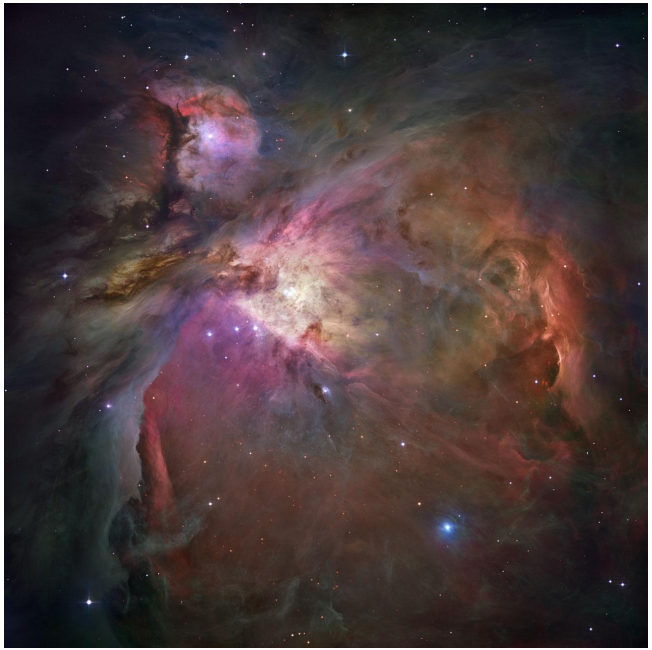
Hobbies: listening and playing music !

Introduction: star formation from molecular clouds

Among the various types of interstellar matter in the universe, molecular clouds are responsible for star formation. However, the process of star formation by molecular clouds remains a mystery.

To understand star formation, it is necessary to construct a consistent scenario.



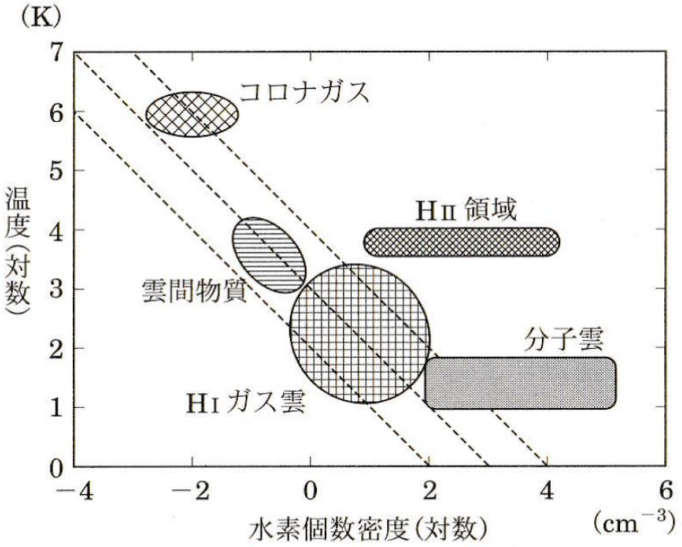
Molecular clouds and ionized regions of M42
(NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team)

Introduction: importance of considering simulation

It is difficult to understand the star formation process from only observational data:

- In the 10 million years of time it takes to form a star, the observational data only looks at that one moment in time.
- Direct observation of star formation is difficult due to the thick optical gas at the site.

➔ Especially in the field of star formation, studies using not only observations but alsc simulated data are very important.

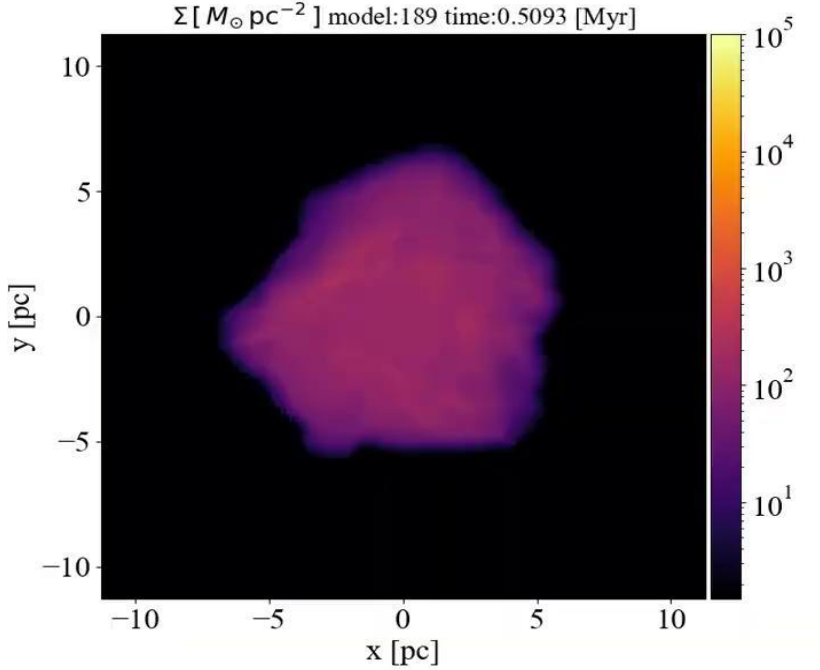


天文学辞典(日本天文学会)

Introduction: previous work

In the simulations, no structural indicators for gravity contraction have been identified.

If such indicators were known, it would make comparisons with observed data easier.



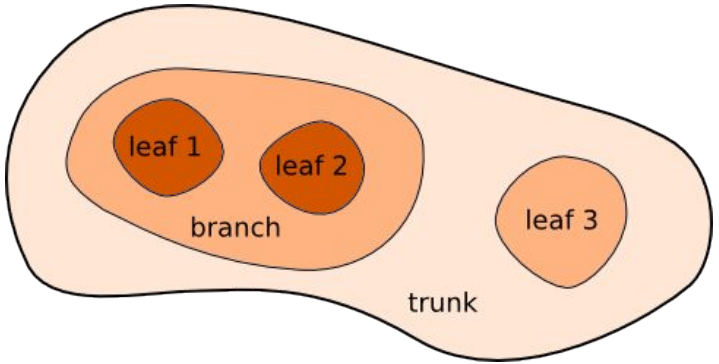
A density-uniform fluid corresponding to a giant molecular cloud being compressed by self-gravity. (Fukushima-san)

Method: use dendrogram for analysis

The dendrogram in the astrodendro package is used for the analysis.

The dendrogram classifies data into leaves, which are the smallest structures, and branches, which have internal structures.

In the data, the more gas is gathered, the more complex the internal structure.

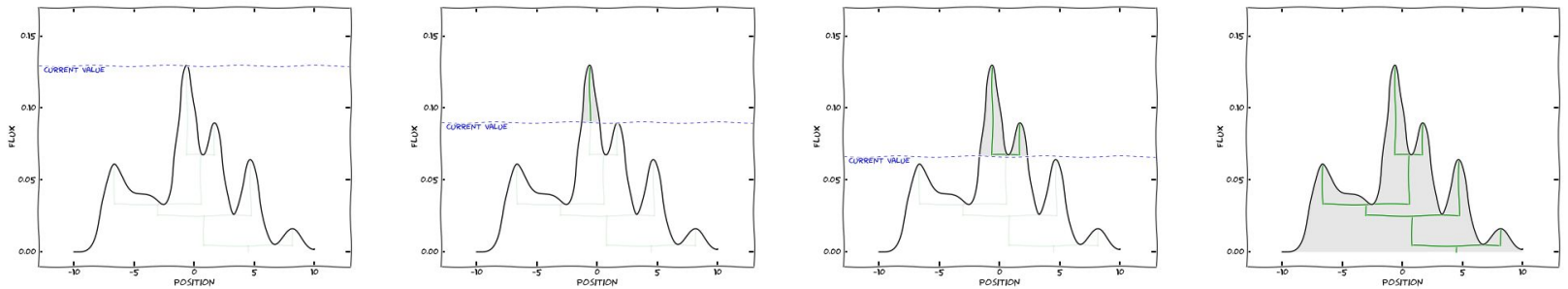


https://dendrograms.readthedocs.io/en/stable/

Method: how the dendrogram algorithm works

In the dendrogram algorithm, the tree is built from the pixel/voxel with the highest value in the dataset and gradually other pixels/voxels are added.

In the figure, the current value descends from the maximum value, and the first leaf is generated with that value as the peak. When the current value reaches the second peak, the second leaf is generated independently. In the third figure, the two leaves are merged into a branch. Eventually, we end up with a single tree in this example.



https://dendrograms.readthedocs.io/en/stable/algorithm.html

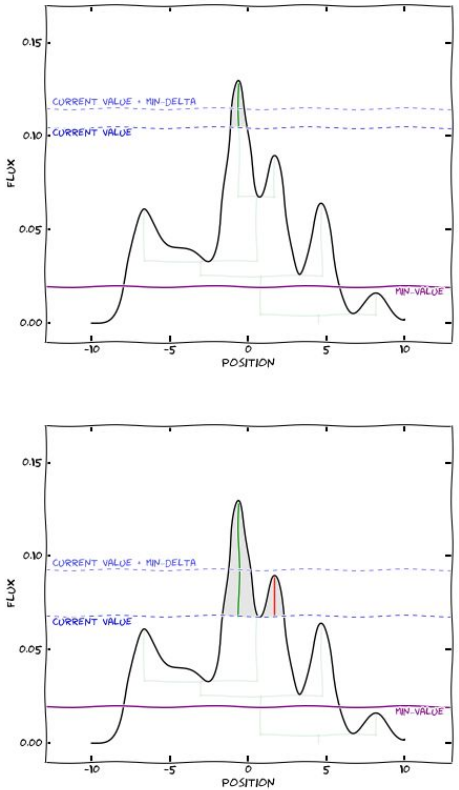
Method: three parameters of the dendrogram

When running the dendrogram, the following three parameters are required:

min_value: any value lower than this will not be considered in the dendrogram.

min_delta: how significant a leaf has to be in order to be considered an independent entity. The significance is measured from the difference between its peak flux and the value at which it is being merged into the tree.

min_npix: the minimum number of pixels/voxels needed for a leaf to be considered an independent entity.



https://dendrograms.readthedocs.io/en/stable/algorithm.html

Method: simulation data

Data: numpy arrays with the gas mass in the velocity-position-position coordinates

Real time:

- m400: 0.5702 Myr
- m1000: 1.104 Myr
- m2200: 1.703 Myr
- m2800: 2.188 Myr

Size: (39, 64, 64)

1cell = 1.4 pc, 0.65 km/s

About simulation:

- Self-gravitational AMR (M)HD + Sink particles
- No magnetic field

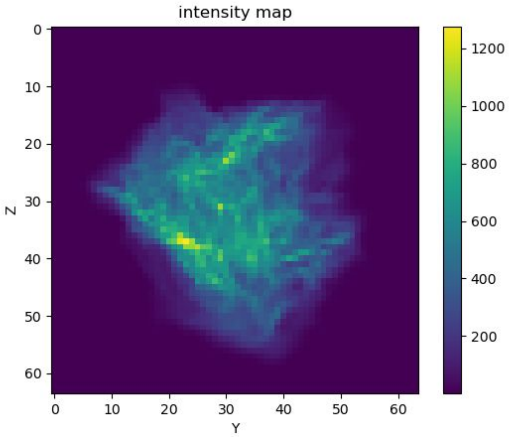
(Matsumoto 2007, 2015)

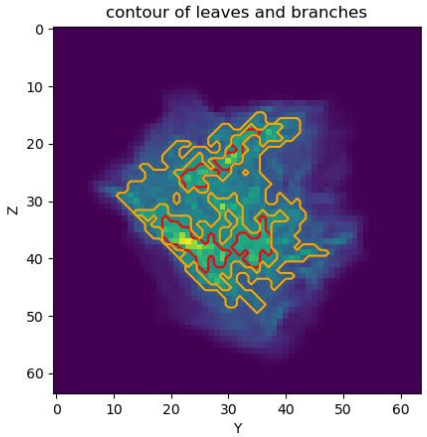
- Non-Equilibrium chemistry
  - H, H2, H+, H-, H2+, e, CII, OI, OII, OIII, CO
- Heating and Cooling
  - Photoionization and photodissociation heating
  - Line cooling (CII, CO, OI, OII, OIII), dust cooling
  - Chemical heating and cooling
- Metal transfer

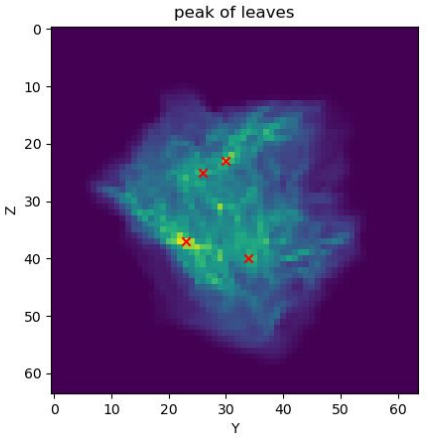
(Sugimura et al. 2020, CO network:Nelson & Langer 1997)

Results: m400 (intensity map)

min_value = 400, min_delta = 120, min_npix = 15

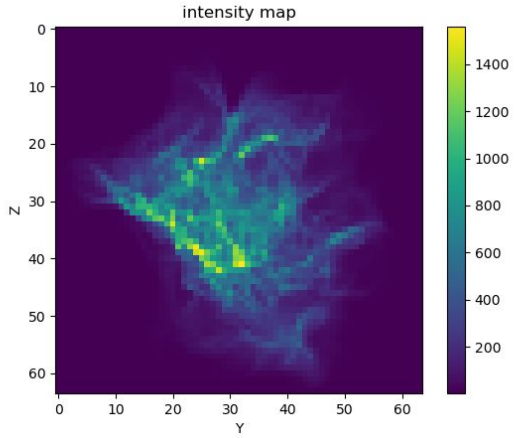


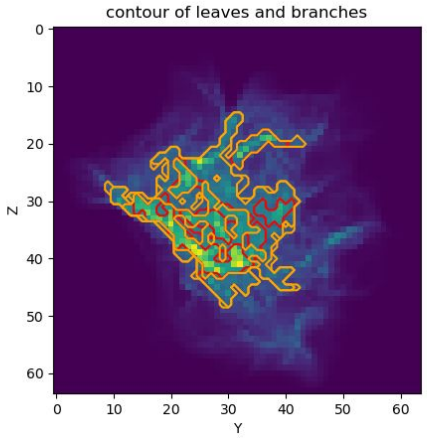


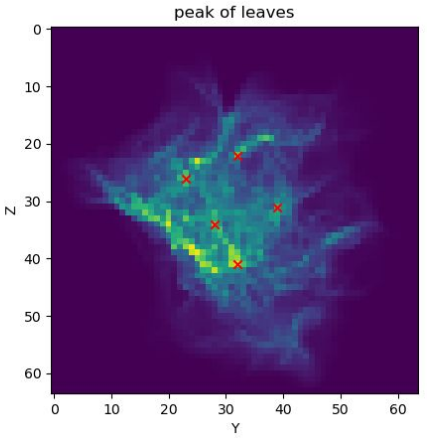


Results: m1000 (intensity map)

min_value = 400, min_delta = 120, min_npix = 15

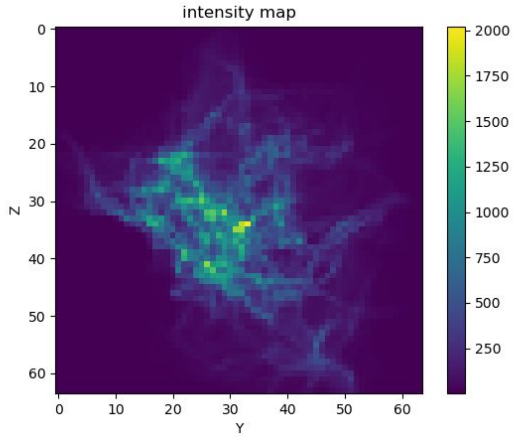


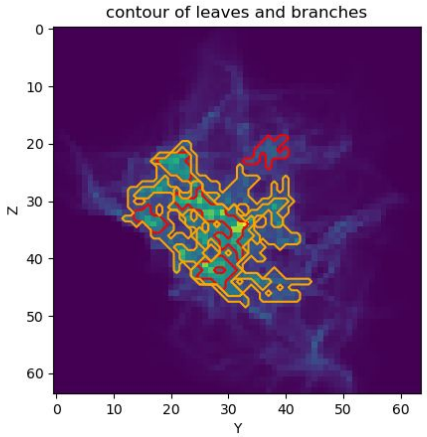


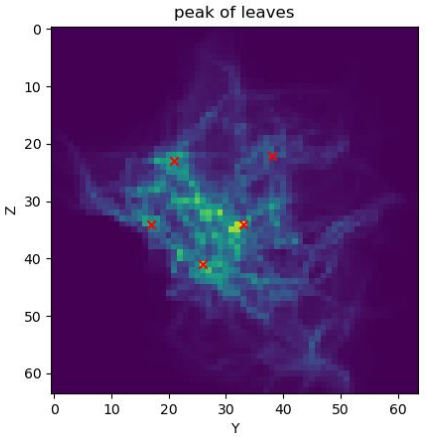


Results: m2200 (intensity map)

min_value = 400, min_delta = 120, min_npix = 15

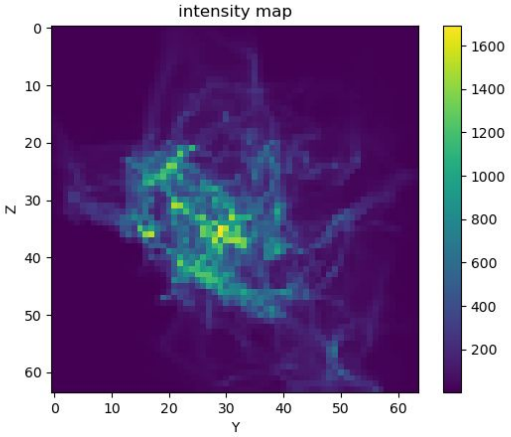


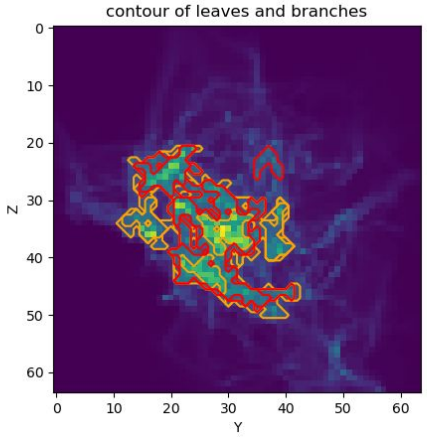


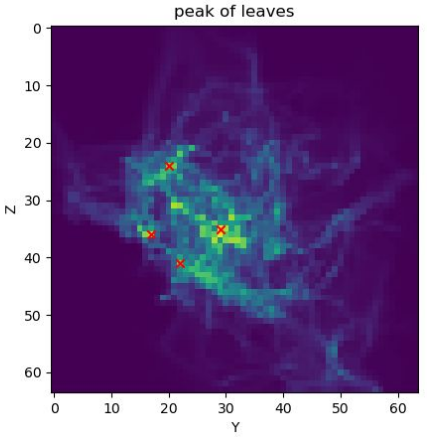


Results: m2800 (intensity map)

min_value = 400, min_delta = 120, min_npix = 15

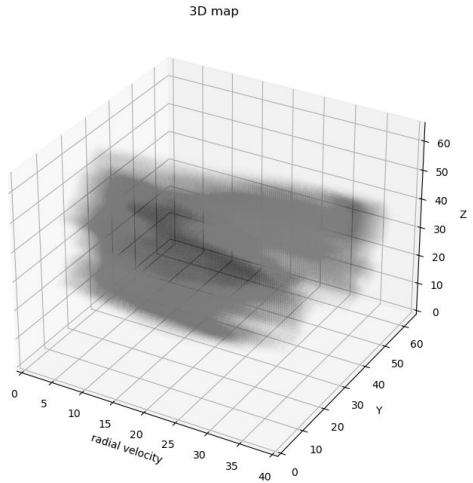


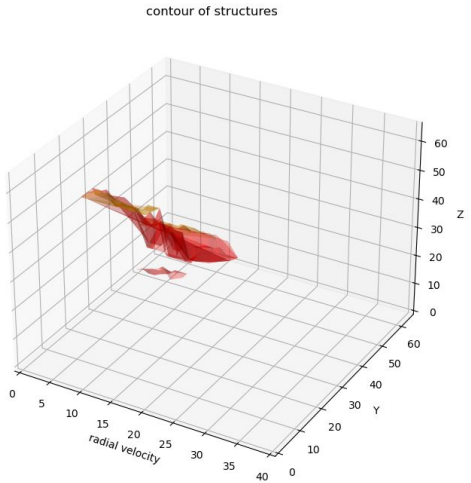


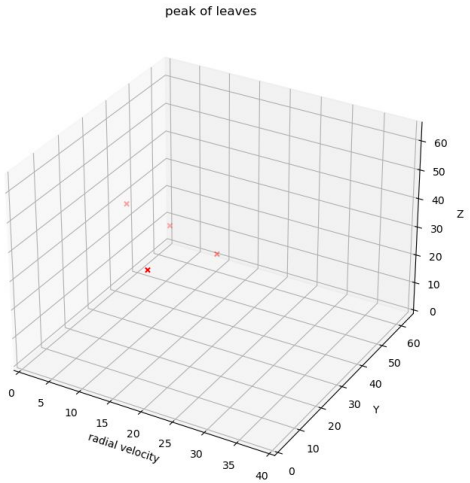


Result: m400 (3D)

min_value = 90, min_delta = 20, min_npix = 50

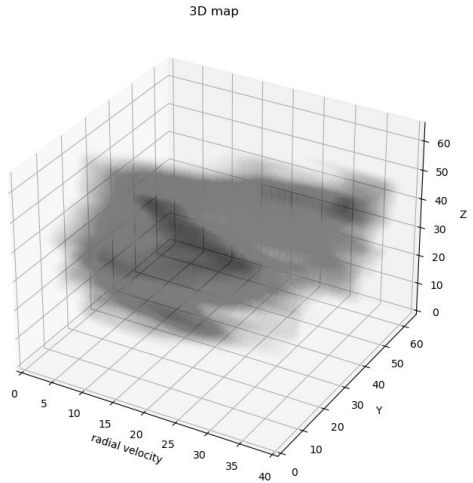


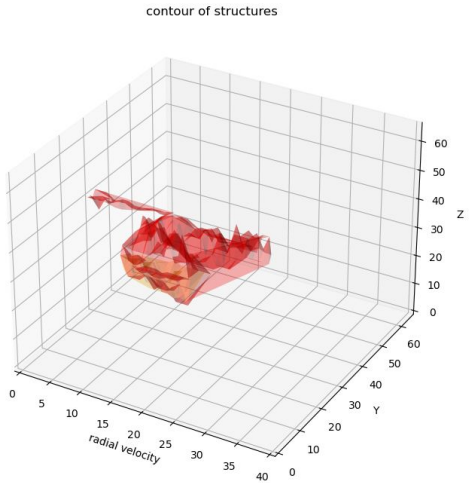


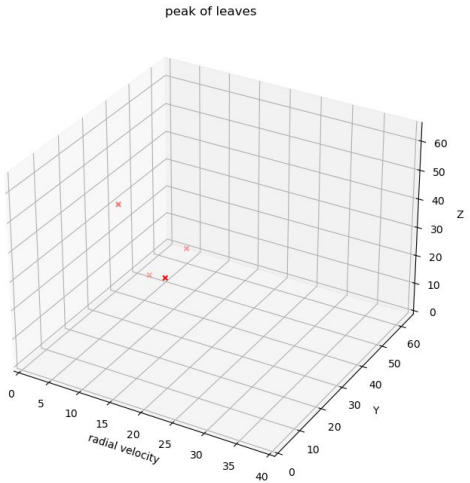


Results: m1000 (3D map)

min_value = 90, min_delta = 20, min_npix = 50

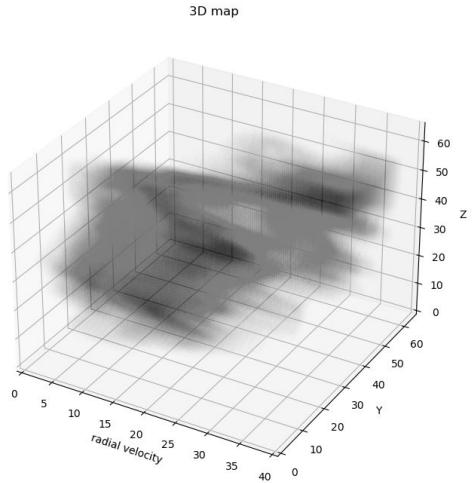


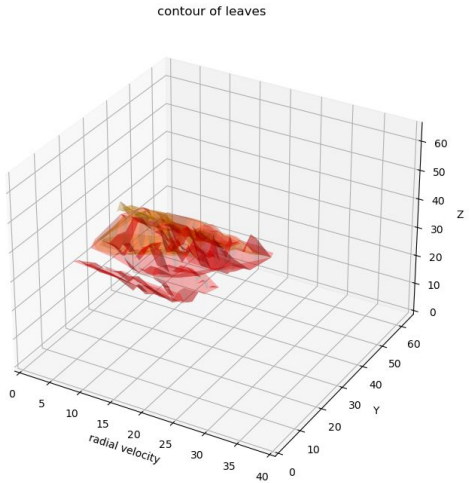


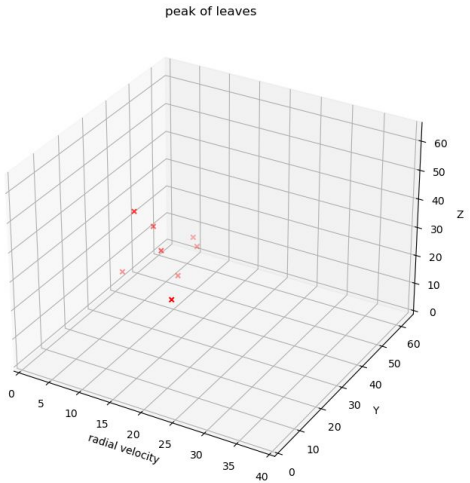


Results: m2200 (3D map)

min_value = 90, min_delta = 20, min_npix = 50

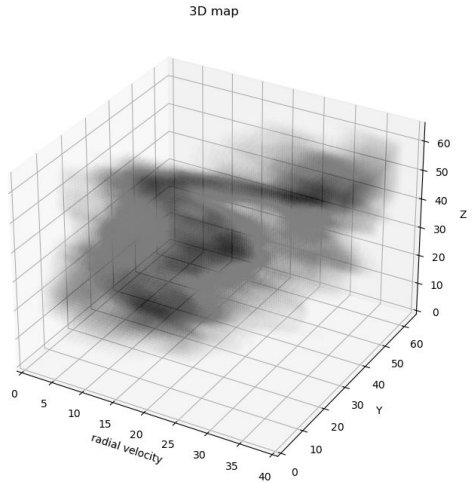


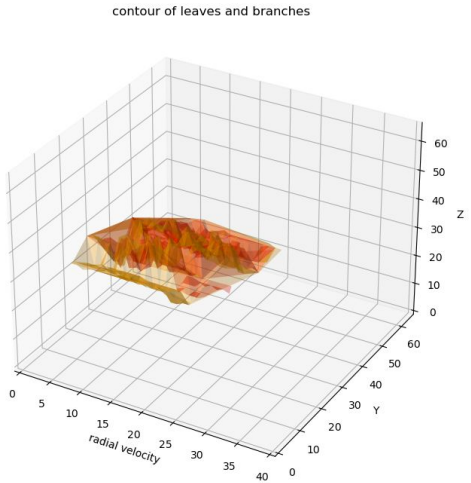


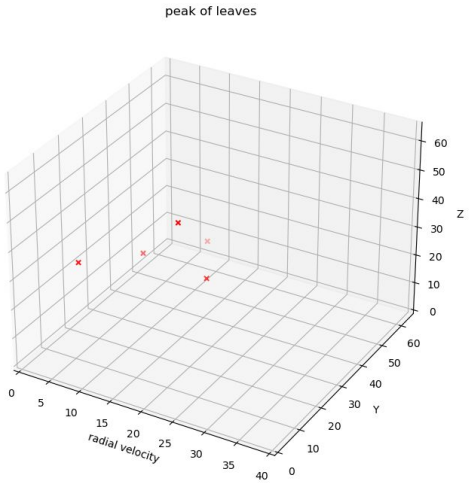


Results: m2800 (3D map)

min_value = 90, min_delta = 20, min_npix = 50



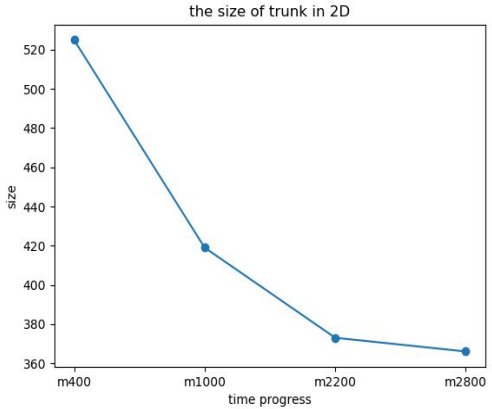


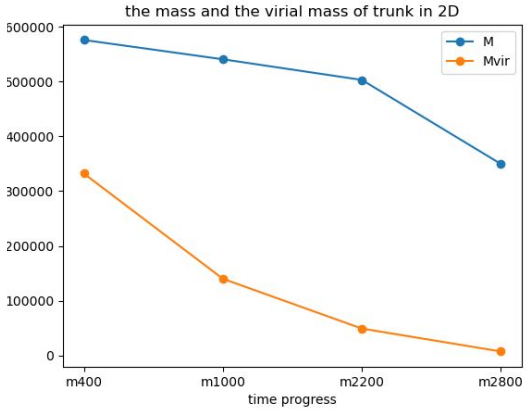


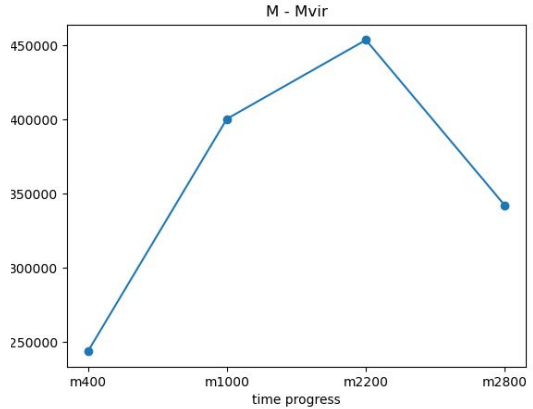
Discussion: size and mass variation in 2D

In the 2D analysis results, The rate at which the trunk contracts gradually slows as time develops. As for the difference between mass and virial mass, it is increasing from m400 to m2200 but decreasing to m2800.

➔ The increased effect of internal pressure from m2200 to m2800 may have resulted in a decrease in the rate of trunk contraction.

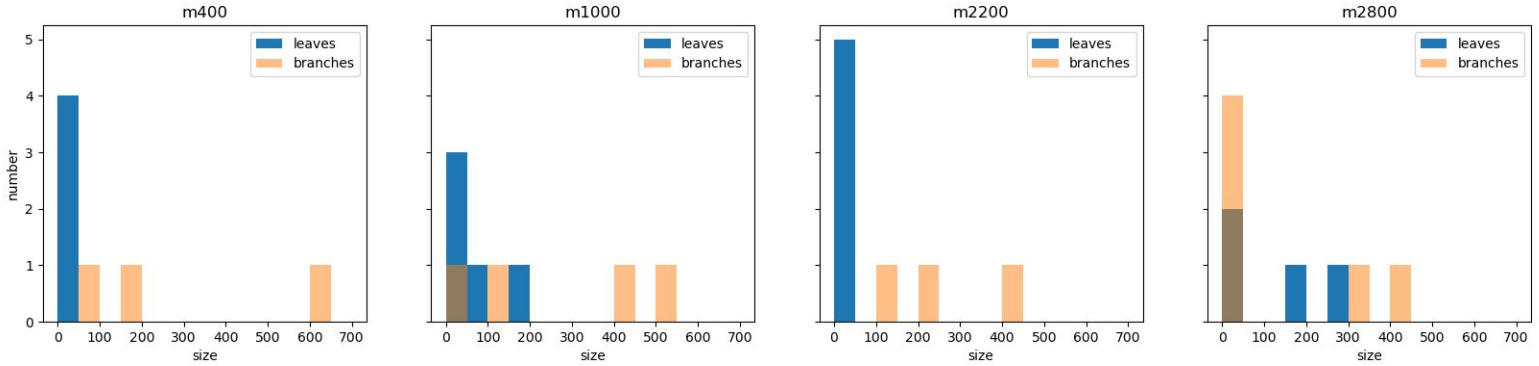






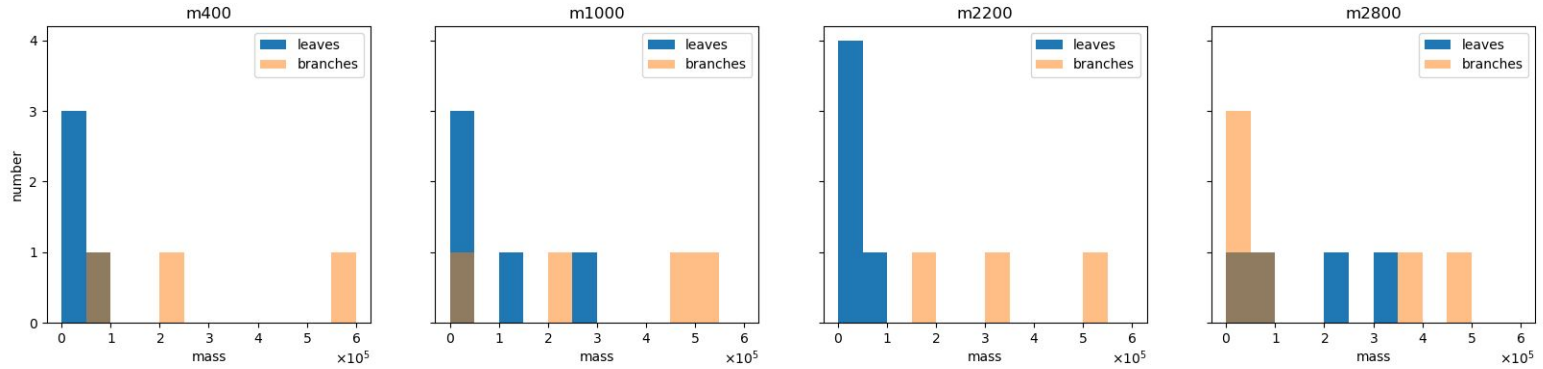
Discussion: size of structure in 2D

- Trunk shrinkage can be seen.
- The size of smaller structures appears to be alternately increasing and decreasing.



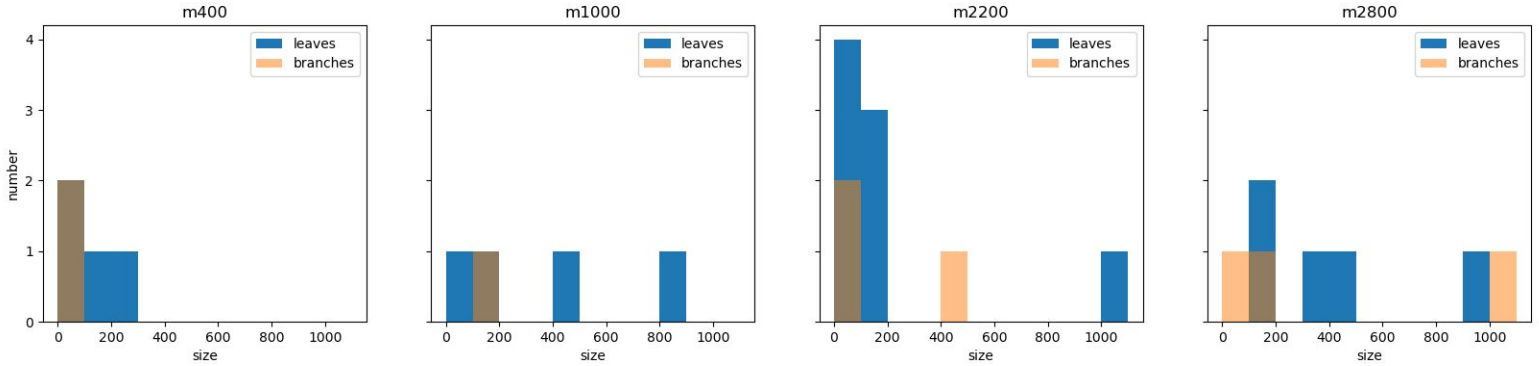
Discussion: mass of structure in 2D

- The filament structure has developed and the internal mass of the trunk has decreased.
- The size of smaller structures appears to be alternately increasing and decreasing.



Discussion: size of structure in 3D

- The size of smaller structures appears to be alternately increasing and decreasing.
- A relatively large structure has arisen and is growing (especially from m2200 to m2800).



Discussion: mass of structure in 3D

- The mass of smaller structures appears to be alternately increasing and decreasing.
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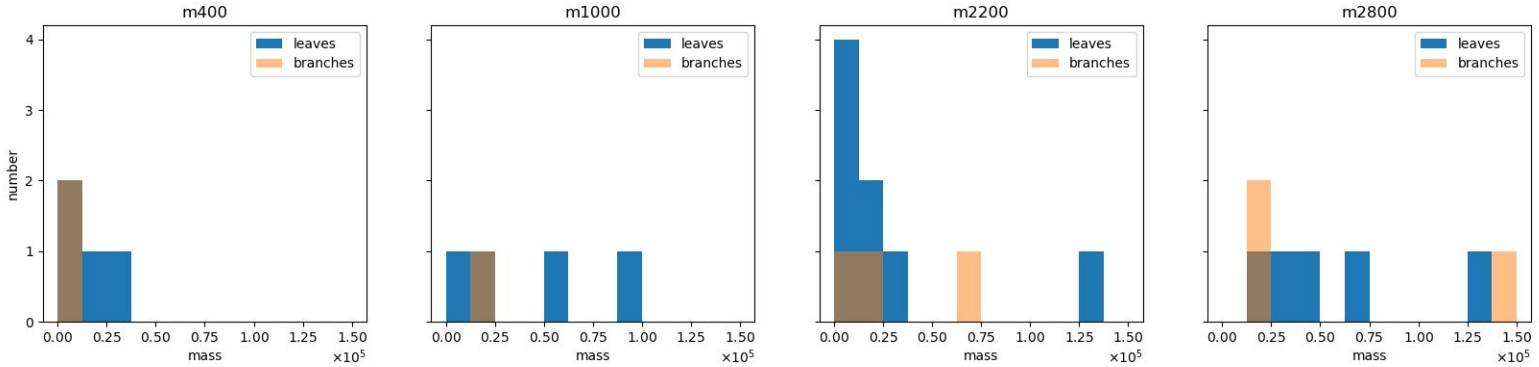
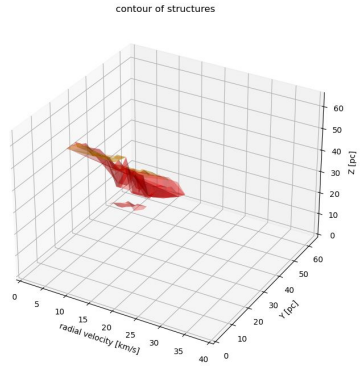
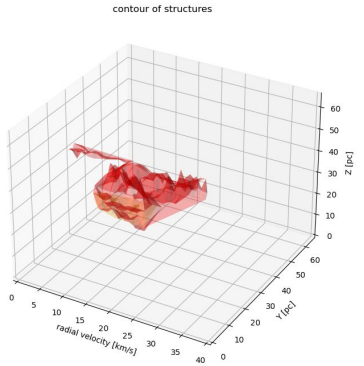


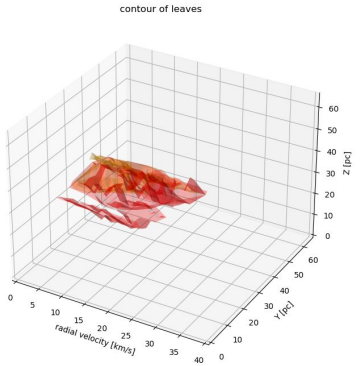
Discussion: estimated gas cloud evolution depiction

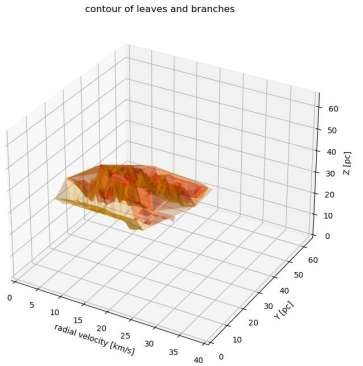
As a whole, the gas cloud contracts and develops a filamentary structure, while inside, smaller structures expand and contract.

➔ The overall contraction subsides and a large structure is created inside.









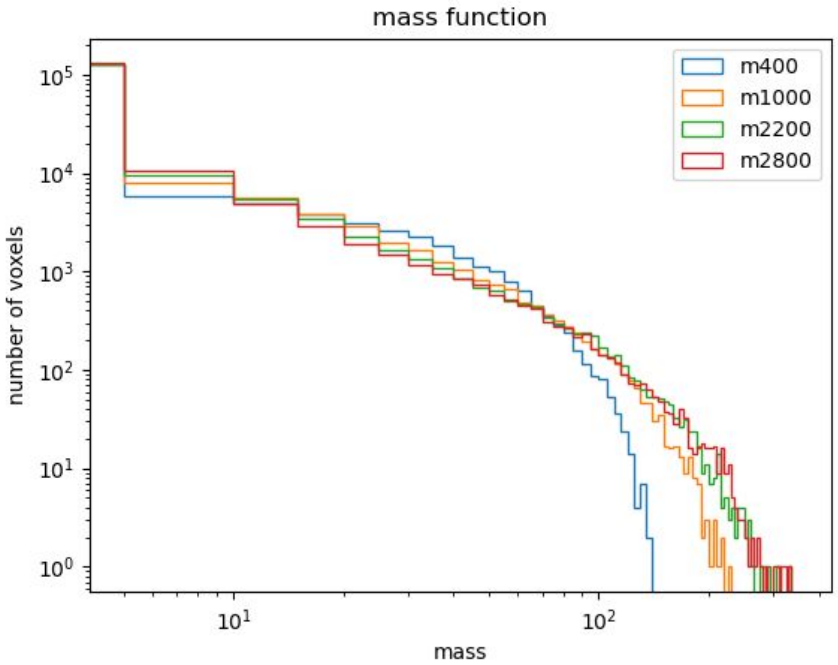
Discussion: comparison with mass function

- The large and small mass portions increase with time evolution.

➔ Filament structures are developing.

- The mass function shows that the speed of mass increase is gradually slowing down.

➔ The overall speed of contraction of the cloud is gradually slowing down.



Summary

- In order to understand the process of star formation by molecular clouds, simulated gas cloud data were analyzed.
- Specific structures inside the molecular cloud were identified from dendrogram analysis.
- The molecular cloud evolution scenario can now be estimated more accurately.

Future work:

- Dendrogram analysis at other points in time and at other parameters
- Temperature-related analysis using BDF
- Comparison with observed data