Quantifying kinematic substructure in star-forming regions with statistical tests of spatial autocorrelation.

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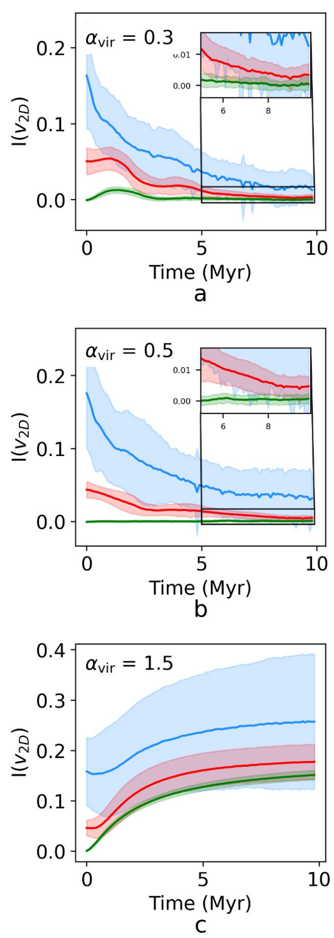

Figure 2. Moran's I of velocity vectors vs time for regions with different initial conditions.

Introduction

With the advent of Gaia large quantities of high quality kinematic data have become available. The kinematic structure of star forming regions provides a valuable window into their evolutionary history, and into star formation as a whole. However understanding the kinematic structure of star forming regions is is a challenging task due to the high-dimensional and often messy nature of these datasets. This is further complicated by human biases which can lead us to see what we expect to see. As such interpreting these datasets by eye is not reliable, statistical methods are required to quantify kinematic structure in star forming regions.

Moran's I is a statistical method of quantifying spatial autocorrelation. It is primarily used in geosciences in order to study the spatial distribution of different phenomena. Here we apply it to quantify the spatial autocorrelation of kinematic parameters in star forming regions. It is applied to simulated star forming regions which are generated to mimic the kinematic properties expected by different models of star formation, and we demonstrate that this method can differentiate between them.

The simulations are performed using the *N*-body code STARLAB (Portegies Zwart et al. 1999, 2001). Regions that formed via the monolithic model are simulated by Plummer spheres in virial equilibrium (i.e. neither expanding nor collapsing). Regions that formed via the hierarchical model are simulated by synthetic regions with spatial and velocity substructure initialised in a collapsing (subvirial) state. The algorithm that is used to generate these fractals is publicly available and is found at https://github.com/r-j-arnold/gen_fractal_star_clusters.

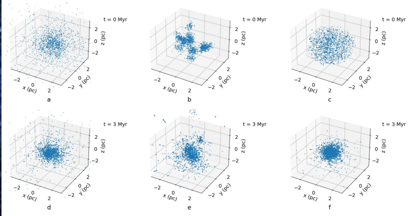

Figure 1. Regions with different initial conditions before (top row) and after (bottom row) being evolved for 3 Myr.

Conclusions

- We demonstrate that the Moran's I statistic can be used to detect signatures of primordial kinematic substructure (or its absence) long after such signatures are impossible to discern by eye due to dynamic evolution.

- We further demonstrate that it can distinguish between regions that formed in bound vs unbound states at ages up to (and likely beyond) 10 Myr.

- The results for the monolithic model analogue show that the measured Moran's I of the velocity vectors is expected to be very close to zero (within 0.015 even in cases with extreme observational biases).

- Because the results for the monolithic model occupy such a narrow band if the Moran's I statistic is applied to observations of real star forming regions and consistently shows results outside it (0 ± 0.015) it can confidently be said that the data is inconsistent with the monolithic model.

- Further, if the data has mild or moderate observational biases, and an age smaller than 6 or 5 Myr respectively, then the observed Moran's I of the velocity vectors in simulations is not degenerate. Therefore it is possible to determine whether the data best fits the hierarchical model, monolithic model, or neither.

Results

Fig. 1 shows simulated Plummer spheres (left column), fractals with spatial and velocity structure (middle), and fractals with only velocity substructure (right column). They are shown at t = 0 in the top row and after being evolved for 3 Myr in the bottom row. From this it is apparent that after being evolved for 3 Myr all the regions have formed centrally concentrated balls and it is virtually impossible to distinguish them by eye. The Moran's I statistic is applied to the velocity vectors and the results for different initial condition types are plotted in different colours in Fig. 2. From this it can be seen that the Moran's I statistic can differentiate between regions that formed with different initial condition types and bound (top two panels) and unbound (bottom panel) formation states.

Mild, moderate and severe artificial observational biases are applied to the results for the monolithic and hierarchical model analogues. These biases are outlined in the table below:

	Completeness per cent	Contamination per cent	Velocity error km s^{-1}
Mild	50	10	0.25
Moderate	30	20	0.5
Severe	10	30	1.0

The results are presented in Fig. 3. The results for the monolithic model analogue are shown in green, and the hierarchical model analogue in blue. It is apparent that observational biases reduce the measured spatial autocorrelation of the velocity vectors (i.e. I(v_{2D})), and increase the noise on the results. However in the case of mild and moderate observational biases it is still possible to use Moran's I to differentiate between regions that formed via the hierarchical vs monolithic model at ages where that can not be done by eye (>3 Myr).

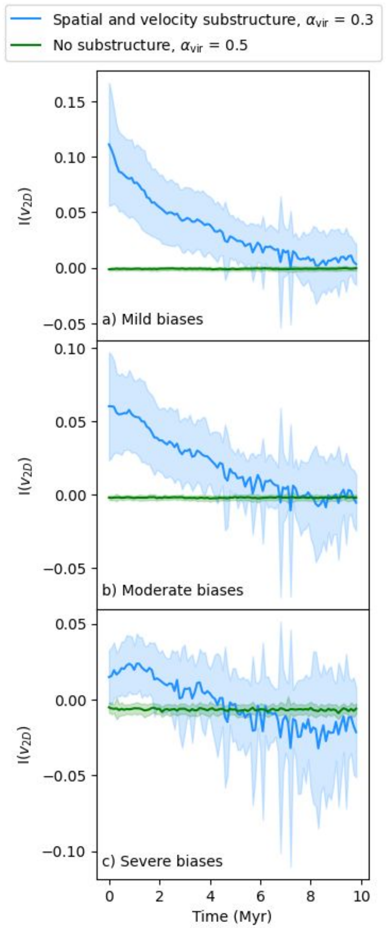

Figure 3. Moran's I of velocity vectors vs time for simulations mimicking the monolithic and hierarchical models under different simulated observational biases.