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Probing brown dwarf formation mechanisms with Gaia

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Abstract. One of the fundamental questions in star formation is whether or not brown dwarfs form in the same way as stars, or more like giant planets. If their formation scenarios are different, we might expect brown dwarfs to have a different spatial distribution to stars in nearby star-forming regions. In this contribution, we discuss methods to look for differences in their spatial distributions and show that in the only nearby star-forming region with a significantly different spatial distribution (the Orion Nebula Cluster), this is likely due to dynamical evolution. We then present a method for unravelling the past dynamical history of a star-forming region, and show that in tandem with *Gaia*, we will be able to discern whether observed differences are due to distinct formation mechanisms for brown dwarfs compared to stars.

Key words. Stars: formation – Galaxy: open clusters and associations – Stars: kinematics and dynamics

1. Introduction

One of the outstanding questions in star formation is whether brown dwarfs (BDs) form more like stars, or more like giant planets (Chabrier et al. 2014). One way of addressing this question is to compare the spatial and velocity distributions of stars and (BDs) in star-forming regions; any differences could indicate that the formation mechanisms are different.

Whilst this may appear to be a straightforward question to address, two issues complicate the picture. Firstly, methods for comparing the spatial distributions of objects are diverse and range from comparing the slopes of mass spectra as a function of distance from the centre of a star-forming region, to measuring the relative concentration or local surface density around BDs compared to stars. The latter two methods of measuring mass segregation can give contradictory results, especially if the morphology of a star-forming region is complex. The former method is fatally flawed when used in substructured star-forming regions, as it requires the definition of a 'centre' – impossible in a region such as Taurus (Parker et al. 2011).

Secondly, early dynamical evolution in star-forming regions is known to alter the spatial distributions of stars, and could be responsible for any observed difference is the spatial distributions of stars and BDs. In this scenario, we would need to know the amount of dynamical evolution that has occurred in the past to assess whether any differences in spatial distributions are a relic of the star and BD formation process(es) in the star-forming region in question.

2. Spatial distributions of stars and BDs

2.1. Quantifying spatial differences

In this section, we discuss the spatial distributions of stars and BDs in three star-forming regions with different densities and using two different measures of mass segregation. Classically, mass segregation is the over-concentration of massive stars in a cluster, and can be indicative of ongoing energy equipartition in a stellar system.

We determine the relative spatial distribution of stars to BDs using the minimum spanning tree (MST) $\Lambda_{\rm MSR}$ ratio (Allison et al. 2009b), which compares the MST length of random stars in a region to the MST length of a chosen subset of stars (or in this case, BDs). We then compare the median local surface density around the BDs to the median local surface density of all objects in the region, the $\Sigma_{\rm LDR}$ ratio (Maschberger & Clarke 2011; Parker et al. 2014).

2.2. Spatial distributions in Taurus, ρ Oph and the ONC

We measure $\Lambda_{\rm MSR}$ and $\Sigma_{\rm LDR}$ in the low-density ($\tilde{\Sigma}$ = 5 stars pc^{-2}) Taurus association, medium density ($\tilde{\Sigma}$ = 75 stars pc^{-2}) ρ Oph region, and the higher density Orion Nebula Cluster (ONC, $\tilde{\Sigma}$ = 1000 stars pc^{-2}).

In Taurus there are hints that the BDs have a more sparse spatial distribution compared to stars, but the differences are not particularly significant (Parker et al. 2011). In ρ Oph, there is no preferred spatial distribution (Parker et al. 2012). In the ONC, however, the BDs appear to be more sparse than the higher mass stars. This could be due to dynamical evolution; the most massive stars in the ONC are mass segregated (Allison et al. 2009b), although the timescale to mass segregate down to beyond the hydrogen-burning limit (and hence reach full energy equipartition) is probably of order a Hubble time (and certainly orders of magnitude longer than the age of the ONC). However, the destruction of primordial binaries which contain BDs may result in the ejection of BDs at greater velocities (and hence traveling further and becoming more distributed) than the low-mass stars.

3. Dynamical evolution

Can the observed spatial differences between stars and BDs in some star forming regions be explained by dynamical interactions? In the ONC, the mass segregation of the most massive stars can be explained in the cluster formed from the collapse of a subvirial, substructured star forming region (Allison et al. 2009a). Many star forming regions are observed to be subvirial (e.g. Peretto et al. 2006), and substructure is ubiquitous (e.g. Cartwright & Whitworth 2004; Arzoumanian et al. 2011; Gouliermis et al. 2014).

However, it is unclear whether these initial conditions also lead to the preferential ejection of BDs over low mass stars. It is important to note that comparing the spatial distribution of BDs to massive stars that are already mass segregated will in most cases give the erroneous result that the the BDs are 'inversely mass segregated'.

In Parker & Andersen (2014) we followed the evolution of the spatial distribution of brown dwarfs compared to low mass stars in *N*-body simulations of substructured, subvirial regions undergoing cool-collapse (Allison et al. 2009a). We measured the $\Lambda_{\rm MSR}$ ratio, which compares the overall spatial concentration for BDs compared to stars; and the $\Sigma_{\rm LDR}$ ratio, which compares the local density around BDs compared to stars. We compared this to the ratio of stars to brown dwarfs as a function of distance from the cluster centre, $\mathcal{R}_{\rm RSS}$ (e.g. Andersen et al. 2011); an observed decrease in this ratio from the centre would indicate that more BDs are on the outskirts.

The *N*-body simulations contained 1500 stars and BDs drawn from a Maschberger (2013) IMF, and binary properties as observed in the Galactic field. The initial spatial distributions of the stars and BDs were identical to each other. We then evolved the star forming regions for 10 Myr, during which time a smooth, centrally concentrated cluster similar to the ONC formed.

In Parker & Andersen (2014) we found that in a suite of twenty identical simulations (differing only in the random number seed used to generate the initial conditions), 6/20 show the BDs to be more spread out according to all three diagnostics: $\Lambda_{\rm MSR}$, $\Sigma_{\rm LDR}$ and $\mathcal{R}_{\rm RSS}$. In a larger fraction of simulations, the BDs appeared more spread out in two of the three diagnostics. However, in many simulations these measures were transient, and only presented themselves as being significant for a small fraction of the full dynamical evolution.

Based on these simulations, we conclude in Parker & Andersen (2014) that the observed difference in spatial distribution of BDs compared to stars could be due to the dynamical evolution, rather than differences in the outcome of the star/BD formation process(es). (We also note that more complete observations would be highly desirable in order to ascertain whether the observed differences are actually real.)

4. Dynamical histories of star forming regions with *Gaia*

Whilst we have shown that dynamical interactions could be responsible for the observed differences in spatial distributions between stars and brown dwarfs, we often have very little information on the previous evolution of the star forming region or cluster, which makes in difficult to conclusively attribute spatial differences to dynamics.

However, if we also utilise other measures of spatial structure, and ultimately kinematical information from *Gaia* and its associated ground-based spectroscopic surveys, we will be able to calibrate suites of simulations to observed diagnostics, and determine the initial kinematic and spatial distributions of these regions. This would allow us to assess whether a region has been so dense in the past that dynamics could have been responsible for any observed difference between stars and BDs.

To do this, we combine measures of mass segregation $\Lambda_{\rm MSR}$ and local surface density $\Sigma_{\rm LDR}$ for the *most massive stars in the region, rather than the BDs* with the spatial structure of the region, the $\mathcal{Q}$-parameter (Cartwright & Whitworth 2004; Cartwright & Whitworth 2009). Regions with substructure have $\mathcal{Q} < 0.8$, and centrally concentrated regions without substructure have $\mathcal{Q} > 0.8$. Dynamical interactions rapidly erase substructure (Parker & Meyer 2012; Parker et al. 2014) so any region with $\mathcal{Q} > 1$ has likely undergone significant dynamical evolution (Parker & Meyer 2012).

Furthermore, if a region has a high local density initially ($>$ 100 stars pc^{-2}) then the $\Sigma_{\rm LDR}$ ratio becomes significantly higher than unity for the massive stars, irrespective of the initial velocity dispersion. On the other hand, $\Lambda_{\rm MSR}$ only becomes significantly greater than unity in subvirial collapsing regions.

Combining all three measures, a subvirial region which collapses to form a dense cluster will have $\mathcal{Q} > 1$ and $\Sigma_{\rm LDR} > 1$ and $\Lambda_{\rm MSR} > 1$, whereas a supervirial region which has expanded will retain some stucture $\mathcal{Q} < 0.8$ and have $\Sigma_{\rm LDR} > 1$ and $\Lambda_{\rm MSR} \sim 1$. It is the former scenario which has likely produced the ONC.

A more quiescent (i.e. low local densities) region, even if in the process of collapsing, will have a $\mathcal{Q}$-parameter < 1, and $\Sigma_{\rm LDR} \sim 1$ and $\Lambda_{\rm MSR} \sim 1$. In such a region, if the distribution of BDs is different to stars, then it is unlikely that dynamical interactions alone are responsible and one can conclude that star formation and brown dwarf formation are different.

The *Gaia* satellite, and its associated ground-based spectroscopic surveys will be able to deliver kinematical information on stars on the outskirts of unobscured star clusters, which can then be compared to tailor-made numerical simulations.

In a preliminary study, Allison (2012) compared the dynamical evolution of star-forming regions that formed clusters, but with subtle differences in the initial conditions. In one set of simulations, the star-forming regions were subvirial, with a high amount of substructure, and in the other set the regions were in virial equilibrium and the stars were arranged in an almost-uniform spherical distribution.

Allison (2012) showed that the more substructured, subvirial regions ejected more stars into an outer halo, and those stars were ejected with higher velocities, than the virialised, smoother regions. At first glance, it appears that *Gaia* would be able to readily distinguish between these initial conditions. However, the addition of primordial binaries causes this result to be diluted, because the binaries effectively act as extra substructure in the simulations.

A more in-depth analysis of the velocity space in these simulations is required to fully understand the capabilities of *Gaia* in respect of discerning the initial conditions of star formation in exposed (open) clusters. However, any information that is present in the velocity space will compliment the spatial distribution analyses discussed in this article.

5. Conclusions

Current observations of star-forming regions have largely shown that the spatial distributions of stars and brown dwarfs (BDs) are very similar, if not indistinguishable. In several regions, most notably the Orion Nebula Cluster, the BDs have a slightly more sparse spatial distribution. However, this can be explained by the star-forming region have undergone dynamical evolution, which scatters the BDs to the outskirts.

Using the full 2D spatial information for *all* members in a region can place limits on the amount of dynamical evolution which has taken place, allowing us to assess whether any observed difference between the stars and BDs is likely due to their formation mechanisms being distinct. Further kinematical information from *Gaia*, its associated ground-based spectroscopic surveys and independent proper-motion studes (e.g. Bouy et al. 2013) will also place strong constraints on the dynamical histories of star-forming regions, and by extension, the brown dwarfs within.

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