Simulating the birth environment of circumstellar discs

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English summary

Circumstellar discs are structures of gas and dust that surround young stars. It is in these discs where planets will eventually form, so studying their evolution is important to understand the formation of planetary systems. Our own solar system began as a circumstellar disc, spinning around the Sun. These discs develop shortly after their host stars, and in their early years they are immersed in the leftovers of star formation. This environment can be very hostile to the young discs. Most stars form not in isolation but in groups, so nearby stars can pass close to the discs and truncate them, removing their outer layers. If the encountering star has a disc of its own, the two discs might even exchange material. If there are massive stars in the vicinity, the ultraviolet radiation coming from them can heat the surface of nearby discs enough to evaporate material from them, in a process known as external photoevaporation. Even radiation from the host star itself can remove material from the inner regions of the discs, in what is called internal photoevaporation. As they move through the gas in the environment, the ram pressure can strip mass from the outer regions of the discs and harden their surfaces. And, if there happens to be a supernova explosion nearby, the discs in the neighbourhood can be completely destroyed by the blast.

Circumstellar discs also expand due to their inner evolution. Mass flows from the outer parts of the discs to the inner regions, and this matter is accreted, or consumed, by the host star. The outer regions, due to conservation of angular momentum, expand outward. When unperturbed, discs drive material into the star and expand consistently until they are completely drained of mass. In isolation, this process should last around 10 million years. However, observations show that discs disappear much faster than that. This effect can be related to two things. First, planet formation might start very early in the life of a disc, so the mass is quickly used in forming rocky planets and the cores of gas giants. Second, the environmental effects described above might also act rapidly in decreasing the mass of the discs. If the environment is playing an important role, it can literally mean life or death for planetary systems: if the discs lose their mass shortly after their birth, planets simply do not have enough time to form. Constraining the effects of the environment on circumstellar discs will help determine a time scale within which planets must form.

This thesis investigates how the environment affects the evolution of the young circumstellar discs, with the focus being on two particular processes: truncating encounters with other stars, and external photoevaporation caused by the radiation from massive stars in the vicinity. All the work performed in this thesis is based on computational simulations of the astrophysical processes described above. We use the Astrophysical MUltipurpose Software Environment, AMUSE[2], to bring together codes to model stellar dynamics, stellar evolution, disc evolution, and photoevaporation. The quantification of the effects of these mechanisms is performed by analysing the distributions of disc masses, sizes, and their lifetimes at the end

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[2] `http://amusecode.org`

of the simulations. All the code developed for this thesis is open source and freely available online[3].

In Chapter 2 we model clusters with 1500 stars where all stars have circumstellar discs. We model the evolution of the discs using a semi-analytical approach, and we look to study how the presence of interstellar gas in the clusters affects the rate of dynamical encounters and disc truncations. We model three types of clusters: one where gas is present during the entire simulation, one without gas, and one where gas is present initially but is expelled halfway through the simulations. The discs are subject to dynamical encounters which can truncate them, and we study how the gas affects the final size distribution of the discs. We find that the results for the three type of regions are relatively similar, since the intrinsic evolution of the discs make them expand faster than they are truncated by encounters. In the models where we consider slowly growing discs, we obtain disc size distributions that are comparable to those observed in real star forming regions.

In Chapter 3 we introduce a new model for the discs that allows us to also implement external photoevaporation. In these new simulations, all low mass stars (less than 2 times the mass of the Sun) have a circumstellar disc, and stars more massive than that emit ultraviolet radiation. This radiation evaporates material from the discs. In these simulations, the discs are subject to their inner evolution, dynamical truncations, and external photoevaporation. We model regions with 100 stars and evolve them for 2 million years. We find that the mass lost from the discs due to external photoevaporation is tens of times higher than that lost by dynamical truncations. This means that external photoevaporation is a much more relevant process in determining final disc mass and size distributions. We also find that photoevaporation is extremely efficient in destroying the discs: around 60% of the discs are dispersed within the first 100.000 years of evolution, and by 2 million years only 10% to 20% of the initial discs are left. This means that in regions with massive stars where discs are subject to photoevaporation, planet formation must start very soon after disc formation. Otherwise, the discs are simply not massive enough to form planets.

Using the same model developed for Chapter 3, in Chapter 4 we simulate a series of clusters with 1000 stars and different radii, ranging from 0.5 parsec to 5 parsec (one parsec is almost 3.3 lightyears, 210,000 times the distance between the Earth and the Sun, or 31 trillion kilometers). In this way, we explore a larger range of stellar densities. We look to determine how the stellar density of a region affects the lifetimes and masses of the discs. We find that disc masses decrease sharply with increasing stellar density. In particular, in regions where the density is higher than 100 stars pc^{-2} it is difficult for discs massive enough to form planets to survive for long. We compare our final disc mass distributions and stellar densities to those of observed star forming regions, and we find that both simulations and observations follow a similar trend.

In the first four chapters of this thesis, we consider all the stars in the simulations to form at the same time, and to be initially distributed in a spherical configuration. However, we know that in reality the star formation process results in stars with distributions that are more fractal and filamentary. In Chapter 5 we go one step back from the previous simulations and begin by modelling a simple approximation of the star formation process. This results in two main differences from the previous simulations: the initial spatial distribution of the stars is not be spherical, and not all stars form at the same time. After each star forms, we assign a disc to it which uses the same model as in Chapters 3 and 4. To the inner disc evolution, external photoevaporation, and dynamical encounters, we add the effects of internal photoevaporation and dust evolution inside the discs. We evolve the simulations for 2 million years after the last star has formed. We find that a star formation process that is

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[3] `http://github.com/franciscaconcha`

extended in time allows for the younger discs to live for longer. When star formation ends, the gas left over from the process is expelled from the region. This expulsion makes the clusters expand as they try to regain equilibrium, which reduces the stellar density and the effects of radiation. At the end of these simulations, there are more discs left, and they are more massive than in the previous chapters. The newly implemented dust model also results in the discs having more mass in solids than in previous simulations, which is an important reservoir for the formation of planets.

The results of the simulations performed for this thesis show that the environment is extremely important in determining the survival of circumstellar discs and that the surroundings of these discs constrain the time available for planets to form. These conclusions are also supported by observational surveys of young discs in star forming regions. In particular, external photoevaporation is efficient in quickly destroying circumstellar discs, and so it greatly limits the amount of material and time available to form planets. These results have important consequences for the study of planet formation.

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