The Origin of the IMF from Core Mass Functions

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We examine the initial mass functions (IMFs) of stars produced by different molecular core mass functions. Simulations suggest that more massive cores produce more stars, so we propose a model in which the average number of stars formed in a core is equal to the initial number of Jeans masses in that core. Small-N systems decay through dynamical interactions, ejecting low-mass stars and brown dwarfs which populate the low-mass tail of the IMF. Stars which remain in cores are able to competitively accrete more gas and become more massive.

We deduce the forms of the core mass functions required to explain the IMFs of Taurus, Orion, IC 348 and NGC 2547. These core mass functions fall into two categories - one which peaks at a few $M_\odot$ to explain Taurus and NGC 2547, and one that peaks at around $0.2M_\odot$ to explain Orion and IC 348.

Keywords: Stars - formation, Stars - mass function

1 Introduction

All stars form in dense molecular cores (eg. André et al. 2000). Observations of the densest cores, known as prestellar cores (Ward-Thompson et al. 1994), show that their mass functions are remarkably similar to the IMF of field stars (Motte et al. 1998; Testi & Sargent 1998; Motte et al. 2001). This suggests that the form of the IMF may be directly related to the form of the core mass function (CMF).

Most stars $>1M_\odot$ exist in binary or multiple systems (eg. Duquennoy & Mayor 1991). Most of these multiple systems must form as such, since it has been shown that dynamical evolution is unable to significantly alter the initial binary properties or population (Kroupa 1995). Therefore many cores must produce multiple objects and so the IMF cannot be a simple mapping of the CMF.

In a previous paper (Goodwin et al. 2004c) we showed that the IMF of Taurus could be explained if all of the stars in Taurus formed from cores of a few solar masses, a CMF similar to
that observed by Onishi et al. (2002). In this contribution we investigate the effect of changing the CMF on the IMF and multiplicity of star forming regions.

2 Multiple star formation in cores

Recent studies have shown that within massive (>5\(M_\odot\)) turbulent cores, multiple star formation is the norm (Bate et al. 2002, 2003; Delgado Donate et al. 2004; Goodwin et al. 2004a,b). A significant population of low-mass stars and brown dwarfs is formed by ejections from unstable multiple systems in these cores.

Delgado Donate et al. (2003) modelled the origin of the IMF by assuming that fragmentation in cores is scale-free: i.e. that all cores produce the same number of objects (stars and brown dwarfs) and that the masses of these objects scale with the mass of the core. By convolving the outcome of star formation in a 1\(M_\odot\) core with a core mass function (CMF) they obtained an IMF. However, Goodwin et al. (in preparation) find that the number of objects that form depends strongly upon the mass of a core, with low-mass cores being far less able to form multiple objects than more massive cores. Fig. 1 shows the average number of objects that form in cores of different masses but with the same initial thermal and turbulent virial ratios (the ratio of the initial thermal or turbulent energy to the initial potential energy). The average number of objects that form is approximately one per initial Jeans mass (∼1\(M_\odot\)).

Given that most stars form in multiple systems and the number of stars forming in a core might be expected to increase with the mass of the core, we propose a simple model for the formation of stars within cores and the relationship of stellar masses and multiplicities to the core mass (the core-to-star relationship):

- Cores form an average number of objects (stars and/or brown dwarfs) approximately equal to the initial number of Jeans masses in the core (eg. Goodwin et al. in prep).
- Multiple systems with \(\geq 3\) members are initial unstable and will decay to a stable system within a few \(\times 10^4\) yrs through the ejection of low-mass stars and brown dwarfs (cf. Reipurth & Clarke 2001; Bate et al. 2002; Sterzik & Durisen 2003; Goodwin et al. 2004a).

The initial mass function (IMF) is then due to the convolution of the core mass function (CMF) and the core-to-star relationships in these different cores.
Figure 2: The IMFs of Taurus (histogram, from Luhman et al. 2003a) and NGC 2547 (points, from Jeffries et al. 2004). NGC 2547 has been normalised to contain the same total number of stars as Taurus for ease of comparison.

We assume a form for the CMF - in this case a log-normal which may have different variances above and below the mean - and randomly sample cores from that CMF. A core then produces $N_*$ objects where $N_*$ is drawn from a gaussian of mean $M_{\text{core}}$ (where $M_{\text{core}}$ is the core mass in solar masses) with $\sigma = 2$. $N_*$ is then rounded to the nearest integer $\geq 1$.

If $N_* \leq 3$ then $N_*$ stars are formed of mean mass $\epsilon M_{\text{core}}/N_*$ (we assume that the core-to-star efficiency $\epsilon = 0.75$ in all cases).

If $N_* > 3$ then $N_* - 3$ stars are ejected with masses drawn uniformly from a logarithmic distribution between $0.02 M_\odot$ and $0.1 \epsilon M_{\text{core}}$. The remaining three stars then distribute the rest of the mass in the core between themselves such that their individual masses are $\epsilon (M_{\text{core}} - M_{\text{ej}})/3$ (where $M_{\text{ej}}$ is the mass of ejected stars).

3 Results

3.1 The IMFs of Taurus and NGC 2547

Both Taurus (Luhman et al. 2003a) and NGC 2547 (Jeffries et al. 2004) have similar MFs. Both of these MFs show a significant peak at $\sim 1 M_\odot$, with a rapid drop above this peak, and a rather flatter decline into the brown dwarf regime, as illustrated in Fig. 2 (where the MF of NGC 2547 has been normalised to have the same total number of stars as Taurus for ease of comparison). The similarity between the two MFs is clear.

Fig 3 shows the results of applying our model to a log-normal CMF of mean $\log M_{\text{core}} = 0.5$ and $\sigma_{\log M_{\text{core}}} = 0.1$ (illustrated by the dashed-line in Fig 3) which is a reasonable approximation to the CMF of Taurus as observed by Onishi et al. (2001). The hashed histogram is the observed IMF of Taurus (Luhman et al. 2003a) and it compares well to the open histogram given by our model. The open circles show the contribution to the IMF from ejected stars and brown dwarfs. The binary fraction is very high in our model as the vast majority of stars have formed in multiple systems, only the ejected component has a low multiplicity. This again compares well with the high observed multiplicity in Taurus (Duchêne 1999).

This agrees well with the results of Goodwin et al. (2004c), the IMF is a combination of a peak of bound systems with average stellar mass $\approx 1 M_\odot$ which remain bound in the cores, and a flat low-mass tail of ejected brown dwarfs and low-mass stars.
3.2 The IMFs of Orion and IC 348

Orion has an IMF that is very similar to the field (Muench et al. 2002). Fig. 4 shows the fit to the Orion IMF given by a CMF of mean $\log M_{\text{core}} = -0.8$ and $\sigma_{\log M_{\text{core}}} = 0.3$ (lower) and $= 0.7$ (upper).

Figure 4 reproduces the IMF of Orion well with a wide, flat peak between 0.1 and 0.6$M_\odot$, falling at both ends, with an approximately Salpeter slope at high-masses. Fig. 5 shows the binary fraction as a function of primary mass. This model fits the observed field binary fractions quite well, except at lower masses where it is assumed that all ejected stars and brown dwarfs are single (which is not always the case, a low fraction of ejected stars are multiples, see Goodwin et al. 2004b).

IC 348 has an IMF that is very similar to Orion except that it is relatively deficient in brown dwarfs (Luhman et al. 2003b). Fig. 6 shows the fit to the IMF of IC 348 using a CMF of mean $\log M_{\text{core}} = -0.8$ and $\sigma_{\log M_{\text{core}}} = 0.1$ (lower) and $= 0.7$ (upper). This is almost identical to the CMF used to model Orion, but the lower extent of the CMF is far smaller (0.1 compared to 0.3 in the Orion CMF). Almost no brown dwarfs are formed in cores in IC 348, they are all the result of ejections from higher-mass cores.

4 Conclusions

Using a simple model of fragmentation in cores we are able to match the IMFs of Taurus, NGC 2547, Orion and IC 348 with different core mass functions.

The IMFs of Taurus and NGC 2547 are well-fitted with a CMF that peaks at a few solar masses, which matches the observed CMF of Taurus (Onishi et al. 2002). This CMF reproduces the peaks in these IMFs at $\sim 1M_\odot$. Most solar-type stars are formed in multiple systems, explaining the very high observed binary fraction in Taurus (Duchêne 1999).

To fit the IMFs of Orion and IC 348 requires CMFs that peak at only a few tenths of a solar mass. The lack of brown dwarfs in IC 348 as compared to Orion can be explained by a CMF that does not extend as far into the brown dwarf regime in IC 348. The binary fractions in Orion and IC 348 are close to those observed in the field.
Figure 4: The IMF of Orion (solid line, from Muench et al. 2002) is well-fitted by the open histogram produced by the CMF shown by the dashed-line. As in fig. 3 the circles show the contribution to the IMF from ejected stars.

Figure 5: The binary fraction of stars in the model of Orion as a function of primary mass (Open circles). The error bars show the observations of the field binary fraction adapted from Sterzik & Durisen (2003).
Figure 6: The IMF of IC 348 (hashed histogram, from Luhman et al. 2003b) is well-fitted by the open histogram produced by the CMF shown by the dashed-line. As in fig. 3, the circles show the contribution to the IMF from ejected stars.

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