Chapter 7
Concluding Issues

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We have now presented a survey of the results of a range of gas dynamical and stellar dynamical simulations: these model the formation of stars in clusters and trace the evolution of clusters over the first few Myr of their existence. So far we have mainly focussed our observational comparisons on the statistical properties of the stars (and multiple systems) formed within the clusters and have not attempted any detailed comparisons between simulations and individual clusters. We now turn to this issue, discussing how simulations compare with observations of the youngest gas-rich clusters. We then discuss more generically whether the properties of field stars bear the imprint of an origin in a clustered environment and then re-focus the argument by trying to assess what can be said about the birth environment of the Sun.

7.1 Modelling Individual Clusters

7.1.1 Gas-Free Studies

The most popular object for N-body studies is the Orion Nebula Cluster (ONC) since it is well-studied observationally, relatively nearby and, by the standards of clusters within 500 pc of the Sun, relatively populous (containing $\sim$4000 stars within a region $\sim$5 pc across). Dynamical studies that have attempted to constrain the early history and future evolution of the ONC through models that match its current properties (at an age of $\sim$2 Myr) include Kroupa et al. (2001); Scally and Clarke (2001, 2002); Scally et al. (2005); Proszkow et al. (2009); Allison and Goodwin (2011).

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These modelling attempts indicate considerable degeneracy with respect to initial conditions: because the cluster is dense (with central densities of $10^5\,\mathrm{pc}^{-3}$, McCaughrean and Stauffer 1994; Hillenbrand and Hartmann 1998) the associated dynamical times are short and this allows ample time for traces of initial conditions to be erased. For example, it is easy to accommodate a variety of clumpy, sub-clustered origins for the ONC despite its present day smoothness (Scally and Clarke 2002; Allison et al. 2010). It is therefore not a good testbed with which to either confirm or refute the hypothesis of hierarchical cluster assembly that is suggested by hydrodynamical simulations of cluster formation (e.g. Bonnell et al. 2008). On the other hand, it is well known from simulations of cluster merging on a larger scale (Fellhauer and Kroupa 2002) that kinematic signatures of sub-clustering are considerably more durable than traces in the spatial distribution of stars. Here however, current modelling efforts are frustrated by the lack of kinematic data (see below).

The observational situation in the ONC is that the stellar population is well characterised by the seminal studies of Hillenbrand and Hartmann (1998) as recently updated by Da Rio et al. (2012). Moreover, recent investigations (Fűrész et al. 2008; Tobin et al. 2009) have also provided a good measure of the stellar radial velocity distributions in the ONC. There are however two problems with interpreting kinematic data (see also Mathieu Chap. 13). Firstly, the only proper motion data available is that of Jones and Walker (1988). In this study, any net contraction or expansion of the cluster was subtracted from the data because of an uncertainty in the absolute plate scale between the two epochs. Secondly, it is hard to interpret the radial velocity data unambiguously. Fűrész et al. (2008) and Tobin et al. (2009) report a velocity gradient along the major axis of the cluster (the ONC is mildly flattened on the sky with an aspect ratio of 2−3:1; Hillenbrand and Hartmann 1998). Although these authors interpret their kinematic data in terms of a collapsing filament it is equally compatible with a state of expansion.

These difficulties mean that we do not currently have a good measure of the virial state of the cluster nor of whether it is expanding or contracting: this is evidently a matter that will be addressed by *Gaia* over the coming years.

Another system which has proved a fruitful object for dynamical modelling is the nearby η Cha association, which is somewhat older and considerably sparser than the ONC. At an age of 6−7 Myr it contains 18 systems within a parsec. The core of the system contains 4 stars with masses in excess of $1.5\,\mathrm{M}_\odot$; there are apparently no stars associated with η Cha which have masses less than $0.1\,\mathrm{M}_\odot$. This mass distribution is conspicuously top-heavy with respect to the canonical IMF (Kroupa et al. 1993) and raises the question whether such a distribution can be explained in terms of dynamical evolution: specifically, has the missing complement of brown dwarfs been ejected from the cluster by two-body relaxation? Becker et al. (2013) studied this hypothesis in detail via a suite of N-body simulations which started from a range of densities and virial states; they concluded that (assuming a normal IMF) there is *no* dynamical history that can simultaneously account for both the concentration of massive stars in the core and the observed lack of brown dwarfs. η Cha thus represents a rare case of a system in which there is good evidence for a deviant initial mass function (IMF) (i.e. one whose discrepancy cannot simply be ascribed to finite sampling effects).

7.1.2 Embedded Star-Forming Regions

We now turn to the issue of how well simulations reproduce the properties of regions that are still heavily embedded in their natal gas. Figure 7.1 compares the results of the simulation of Bonnell et al. (2008) with *Herschel* maps of Aquila by Könyves et al. (2010) and Bontemps et al. (2010). The resemblance is striking, at least superficially: both show a clustered core of stars and a further population of sources organised along filaments which (in the simulations) are in the process of infalling into the cluster core. In Aquila, the distributed population in the filaments is younger (pre-stellar); this is consistent with the simulations, where the stars in clusters are those that formed first (Maschberger et al. 2010).

One of the first embedded regions to be qualitatively compared with simulations is the core of ρ Ophiuchus. Figure 7.2 (from André et al. 2007) presents a millimetre map of the L1688 region that is colour-coded according to line-of-sight velocities of pre-stellar gas condensations derived from N_2H^+ measurements. These condensations (designated as 'MM' objects in Fig. 7.2) are organised in groupings (A–F).

Does this image bear out the predictions of hydrodynamical modelling? André et al. (2007) drew attention to the rather small global velocity dispersion of the cores in the region and used this to argue that '...the condensations do not have time to interact with one another before evolving into pre-main sequence objects'. This data

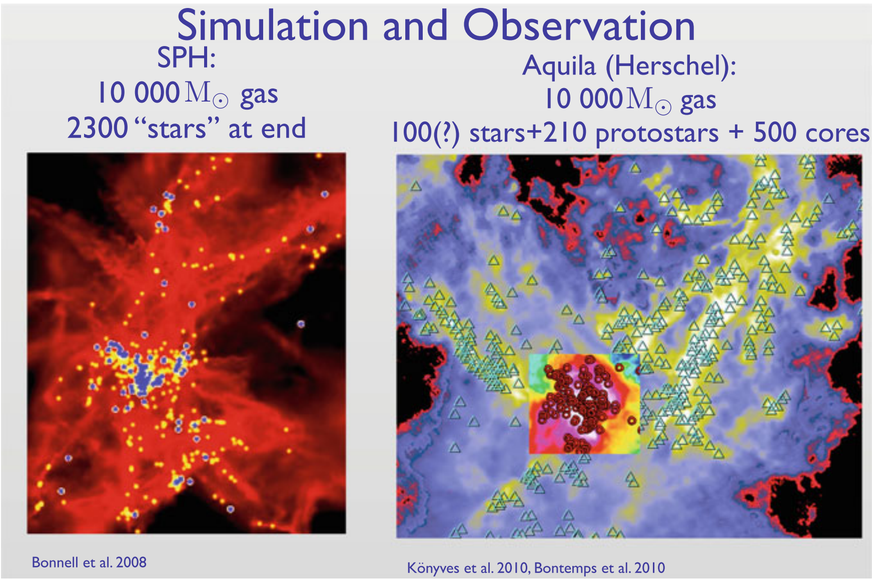

Fig. 7.1 Comparison between the SPH simulation of Bonnell et al. (2008, *left*) and *Herschel* maps of Aquila (*right*). In the *left panel* the *yellow filled circles* represent stars while the *blue filled circles* denote brown dwarfs. In the *right panel* the stars and protostars from the survey of Bontemps et al. (2010) are represented by the *red circles* in the central inset while pre-stellar cores from the survey of Könyves et al. (2010) are denoted by *blue triangles*

has thus been used to argue for a quasi-static picture of clump collapse which is apparently at odds with the dynamical picture emerging from simulations. If cores indeed lacked significant relative bulk motions and did not exhibit orbital motions in the local potential, then this would be remarkable result, raising questions about what processes could stop cores from responding to the local gravitational field.

Closer examination of the numbers however reveals a situation which, reassuringly, is broadly compatible with the simulation results. The measured one-dimensional velocity dispersion ($0.4\,\mathrm{km\,s^{-1}}$) corresponds to a three-dimensional velocity dispersion of $0.7\,\mathrm{km\,s^{-1}}$; this is roughly the free-fall velocity given the masses and sizes of the core groupings (labelled A–F in Fig. 7.2). Moreover the crossing timescale within such groupings is rather short (a few times 10^5 years): such cores will thus be able to traverse their natal groupings on a timescale comparable with their internal collapse times. In addition, the Ophiuchus map also provides observational support for hierarchical cluster formation as manifest in the simulations: the velocity differential ($\sim 1\,\mathrm{km\,s^{-1}}$) between the groupings to the NW and SE is such that these may well merge on a timescale of ~ 1 Myr.

The detailed comparison between simulations and the structure and kinematics of *gas* in embedded regions is still relatively in its infancy: see Offner et al. (2009) for an analysis of the relative kinematics of the gas and stars in simulations and Kirk et al. (2010) for an observational study of the relative kinematics of dense cores and distributed gas in Perseus.

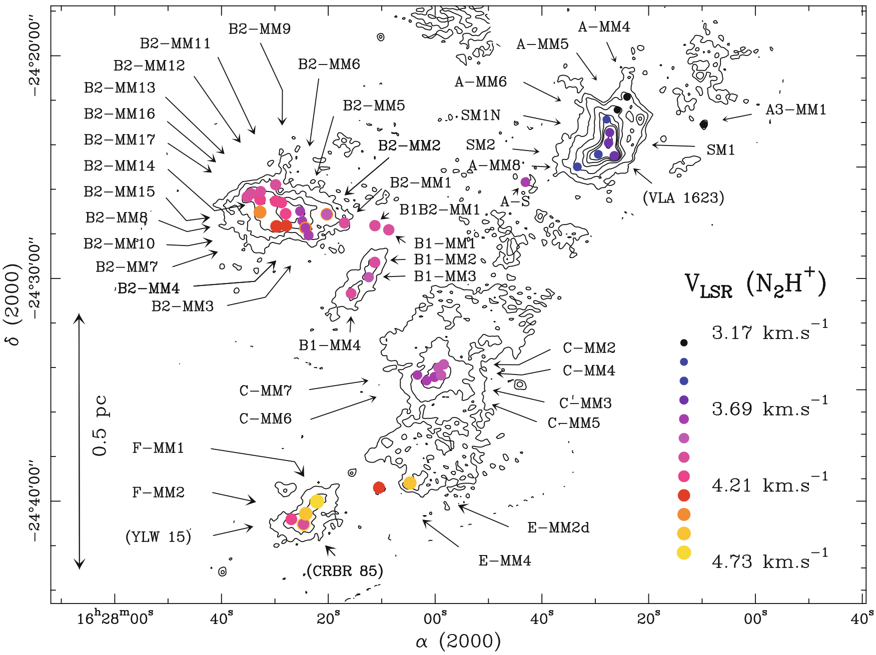

Fig. 7.2 1.2 mm map of the core of ρ Ophiuchus showing the clustering of pre-stellar condensations and their kinematic properties as traced by N_2H^+(1–0) emission. Figure from André et al. (2007)

7.2 Imprint of Cluster Origin on Field Star Populations

There has been much discussion over the years as to whether there is any difference in the properties of stars that form in clusters (which may subsequently dissolve) compared with those that form in isolation. This question however has to be updated to reflect recent observational and theoretical insights. Firstly, there is considerable observational evidence that *most* stars in star-forming regions are ‘clustered’ in some sense (Lada and Lada 2003; Bressert et al. 2010) whatever the dynamical status of these groupings: under these circumstances it is hard to define a control sample with which the cluster population should be compared. Secondly, simulations point to cluster formation as being a hierarchical process so that stars mostly form in small-N groupings which then—depending on the environment—follow an upward progression through the cluster merger tree, being incorporated into successively larger structures (Maschberger et al. 2010; see Fig. 7.3). This implies that it is hard to define what is meant by a star ‘born in a cluster’.

Instead we have to frame some more nuanced questions. These include ‘Are there properties of stars (in general) which bear evidence of dynamical interactions in their early history?’ as well as ‘Are there properties of stars that depend on the scale of the cluster in which they at some stage find themselves situated?’ Here we shall look at the latter question with regard to a possible imprint on the IMF.

It is long been noted that the maximum stellar mass within young clusters has a generally positive correlation with the cluster mass. This must at least in part be a statistical effect—i.e. if one thinks of a star formation event as drawing stars from an underlying distribution then one is more likely to select stars high up in the steep (Salpeter) tail of the distribution if one is selecting a large number of objects. The magnitude of this effect can be readily quantified (see below) in order to assess whether (for an assumed universal IMF) the statistics of maximum stellar mass versus N conform with expectations.

Weidner and Kroupa (2004, 2006) have argued that the data do *not* conform with the statistics of random drawing and argue that instead there is an additional *systematic* dependence of maximum stellar mass on cluster mass. The sign of the claimed dependence is positive (i.e. it has the same sign as the stochastic effect described above) so the effects within individual clusters are rather subtle. Nevertheless, there are profound differences between these two hypotheses when one stacks up an integrated IMF (averaged over all clusters: henceforth termed the IGIMF). In the case of random drawing, the IGIMF is of course identical to the input IMF by construction. In the case of there being a systematic, cluster mass dependent upper mass limit per cluster, the effect of stacking up an ensemble of truncated power-laws is that the IGIMF can end up being steeper than the input IMF. The magnitude of this effect depends not only on the assumed relationship between maximum stellar mass and cluster mass but also on the assumed *cluster* mass function: a pronounced influence on the IGIMF requires the integrated population to be dominated by small-N clusters, so that (for a power-law cluster mass function) the slope needs to be steeper than -2 to have any significant effect.

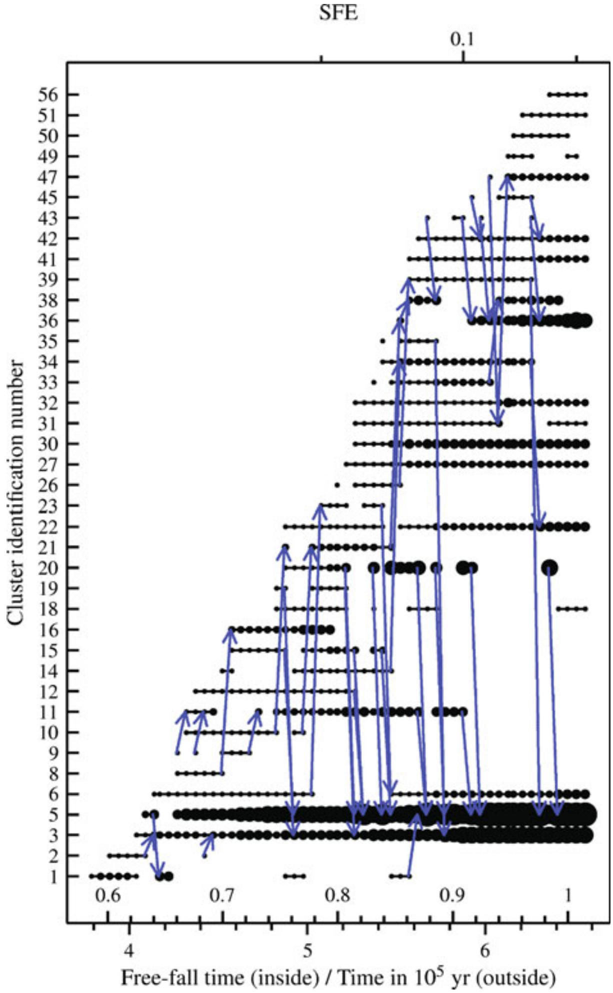

Fig. 7.3 An illustration of hierarchical cluster assembly within the simulations of Bonnell et al. (2008). Clusters identified via the minimum spanning tree are depicted with the symbol size representing the mass of the most massive star and the arrows represent cluster merging events. Figure from Maschberger et al. (2010)

The issue of the IGIMF is important because, on the scale of entire galaxies, it controls the normalisation between observed star formation diagnostics (produced by massive stars) and the overall star formation rate. It is hard to assess this relationship a priori on galactic scales because of the large number of observational uncertainties (in addition to the IGIMF) which be-devil the analysis (see Elmegreen 2006; Pflamm-Altenburg et al. 2007; Selman and Melnick 2008 for contrasting conclusions on the empirical status of the IGIMF, as well as the discussion in Reid Chap. 16, Sect. 16.6).

Fortunately, however, we can attack the problem from the other end by assessing the direct observational evidence for truncated IMFs within clusters: this can be achieved by using simple binomial statistics to work out the expected distribution of the maximum stellar mass as a function of cluster membership number N and then enquiring where the observed datapoints are located with respect to the centiles of the predicted distribution. Note that it is important to consider the data in this way instead of comparing the data with the *expectation value* (i.e. mean) of the maximum stellar mass at a given N. This is because the predicted distributions are very asymmetric: the median is much less than the mean and this implies that with sparsely sampled datasets the data values are likely to be significantly less than the mean in the majority of samplings. This does *not* mean, on its own, that the IMF is necessarily truncated.

The results of this exercise are shown in Fig. 7.4; taken at face value, they are entirely consistent with the results of random selection. However, there are a couple of notable features about the observational data. Firstly, the position of the datapoints with respect to the centiles depends on the selection criteria employed: i.e. whether the data involved a measurement of stellar maximum mass in already identified clusters (green and blue points) or instead the identification of clusters around already identified massive stars (red points). Unsurprisingly, the latter points tend to lie higher on the centiles; this emphasises the importance of unbiased target selection in constructing such a diagram. Secondly, it is worth noting that the most observationally

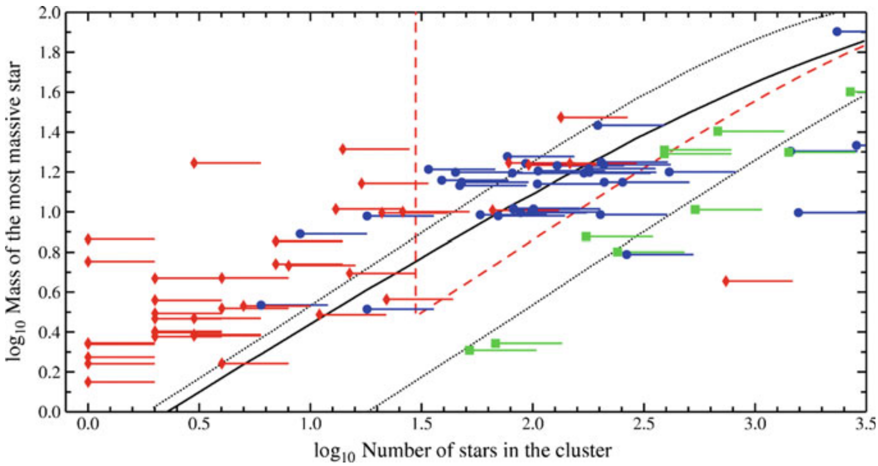

Fig. 7.4 Data on the maximum stellar mass as a function of cluster membership number (see Maschberger and Clarke 2008 for the data sources). The *solid line* is the median value based on random sampling of an untruncated IMF and the *dotted lines* the 1/6th and 5/6th quantiles of the same distribution. Note the fact that the membership numbers suffer from poorly-determined incompleteness (a notional factor of two one-sided errorbar is added to each point). Note also that the location of the points in the diagram depend on whether the data is selected by most massive star or by cluster (see text). Figure from Maschberger and Clarke (2008)

discrepant part of the diagram is that at low mass (low N) where, contrary to the IGIMF theory in the form usually proposed, the observational data is actually too *high* relative to the centiles for random drawing. We will return to the fact that massive stars are apparently to be found in surprisingly sparse clusters when we come to assess the birthplace of the solar system. It is however worth stressing that the values of N in the plot are lower limits since they have been obtained (see Testi et al. 1997, 1998) from deep near-infrared imaging of apparently isolated, but relatively distant, Herbig Ae/Be stars. These values are thus likely to suffer from ill-quantified incompleteness.

The only regime for which the observational data is arguably too low compared with the centiles is for massive clusters ($>10^3\,M_\odot$) where maximum stellar masses of around $30-40\,M_\odot$ are a little low compared with the model (Weidner et al. 2010). In this regime, however, there is a further uncertainty: the lifetime of stars of this age is short (a few Myr). Given the uncertainties in measuring the ages of clusters at these youngest ages, it is then hard to find a sample of clusters that are sufficiently young that one can be sure that the most massive members have not already exploded as supernovae.

Finally, it might be argued that trying to answer this question using only one star per cluster (the most massive) is wasteful of statistical information and requires an unacceptably large ensemble of clusters in order to measure subtle effects. Alternatively, one can search for truncation of the IMF within an individual cluster: see Koen (2006) and Maschberger and Kroupa (2009) for statistical tests that are sensitive to the extremes of the distribution and are hence suitable for detecting evidence of truncation. Nevertheless it should be stressed that however good the statistical tools employed, the significance of the answer also relies on robust mass determinations for massive stars. These are not generally available, particularly in the absence of spectroscopic data (see Burkholder et al. 1997; Massey 2002; Weidner and Vink 2010).

7.3 Imprint of Cluster Birthplace on Discs

The 'proplyds' in the ONC present a vivid demonstration of how the properties of circumstellar discs may be modified in a rich cluster environment. 'Proplyds' are young stars with associated ionisation fronts that are significantly offset with respect to their parent stars (and also, with respect to their protoplanetary discs, which are detected in silhouette against the bright nebular background emission, O'Dell et al. 1993; Bally et al. 2000). This ionised emission is well accounted for by the interaction between ionising radiation from the O6 star (Θ_1C) in the cluster core and a neutral wind that is photoevaporated from the disc by the softer (non-ionising) ultraviolet flux of Θ_1C. Theoretical photoevaporation models (Johnstone et al. 1998) predict disc mass-loss rates that are similar to those inferred from radio free-free emission (Churchwell et al. 1987): these rates are high, being a few times $10^{-7}\,M_\odot\,yr^{-1}$ and imply that a circumstellar disc with the mass of the 'minimum mass solar nebula' (i.e. the mass of hydrogen that would—at solar abundances—have originally accompanied the solid components of the planets in the solar system) would be photoevaporated in a mere 0.1 Myr. Since this timescale is $<10\,\%$ of the age of the ONC, there is little doubt that the cluster environment (specifically the presence of a strong ultraviolet source) must have a major impact on planet formation. Indeed, the short timescale associated with photoevaporation in the ONC suggests that we are witnessing a brief episode at a privileged epoch. In fact this is backed up by the observed paucity of proplyds in other regions (Stapelfeldt et al. 1997; Stecklum et al. 1998; Balog et al. 2006).

On the other hand, it is worth emphasising that the strong effect of Θ_1C is pretty localised, with the high photoevaporion rates cited above being restricted to the inner ~ 0.3 pc of the cluster. Fatuzzo and Adams (2008) have conducted population synthesis studies in which they examine the global impact of photoevaporation by massive stars in clusters, given observationally motivated assumptions about the mass spectrum and stellar content of clusters. Their conclusion (based on the assumption that the field population is derived from the loose clusters seen in star-forming regions) is that the overall impact on discs (and hence on potential planet formation) is rather modest: only about 25 % of stars in the solar neighbourhood would have suffered a 'significant' disc mass-loss (i.e. photoevaporation down to $\sim$30 au) over a 10 Myr timescale.

Another potential environmental effect in dense clusters (such as the ONC) is the stripping of discs by dynamical encounters. It is well-known that stellar fly-bys cause discs to be stripped down to a fraction of the closest encounter distance, this fraction depending on the mutual orbital inclination, mass ratios and velocities of the stars (see Clarke and Pringle 1993; Moeckel and Bally 2006; Pfalzner et al. 2006; Olczak et al. 2006). Scally and Clarke (2001) undertook N-body calculations of the evolution of the ONC, keeping track of the closest encounter distance for every star. Although a few stars in the dense central regions pass within $\sim$ 100 au of each other (with consequently severe consequences for their planet forming discs), the bulk of stars in the ONC do *not* undergo such close encounters (see Fig. 7.5 and de Juan Ovelar et al. 2012). Encounters are more significant in the case of massive stars (Moeckel and Bally 2006; Pfalzner et al. 2006) since these are dynamically segregated to the central, densest regions; nevertheless there are probably other effects (associated with the strong winds driven by ionising radiation from massive stars; Hollenbach et al. 1994) which are also important in limiting disc lifetimes in this case.

7.4 The Birth Environment of the Sun

The properties of the solar system place a number of constraints on the environment in which its planetary system was born and has evolved: for further background, the reader is directed to the excellent review of this subject by Adams (2010).

One important constraint is the fact that—unusually among exoplanetary systems—the solar system is very dynamically cold, with its planetary orbits

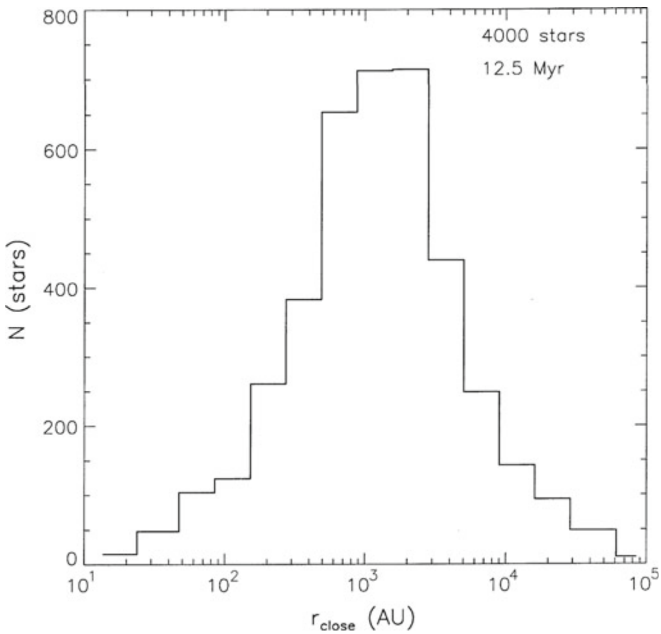

Fig. 7.5 A histogram of the closest encounter distance recorded per star during 12.5 Myr of N-body evolution of a cluster that is initiated with properties similar to the observed ONC. A small fraction of the stars in the cluster will have have encounters within 100 au during the typical lifetime of circumstellar discs. Figure from Scally and Clarke (2001)

being nearly circular and virtually co-planar. This is a property that argues for a rather isolated environment. On the other hand, meteoritic samples contain elements that are daughter products of short-lived radio nuclides (e.g. ^{60}Fe, ^{26}Al; see McKeegan and Davis 2003; Wasserburg et al. 2006; Wadhwa et al. 2007; Gounelle and Meynet 2012); the necessity of condensing these nuclides into grains within their half-lives implies that the primordial solar nebula was rather close to the site of a supernova: this argues generically for a clustered environment. We will quantify the above remarks in order to place limits on the likely range of conditions that are suitable birth environments for the Sun.

Turning first to the constraints offered by the low inclinations and eccentricities of the solar planetary system, large suites of Monte Carlo simulations (e.g. Adams and Laughlin 2001; Heggie and Rasio 1996; Malmberg and Davies 2009) have been used to investigate the types of encounters that are required in order to induce a significant (e.g. factor two) change in these quantities. The results of these calculations imply that the Sun cannot have undergone any encounters with pericentre less than about ~ 200 au. If we combine this result with analyses of close encounter distances in simulations of the ONC (Scally and Clarke 2001) we find that this condition is not particularly constraining: around 90 % of stars in the ONC would not have had such a close encounter.

On the other hand, we can turn the question around and enquire what are the features in the solar system which *can* be explained by encounters. For example, we can enquire how close a stellar fly-by is required in order for this effect to account for the observed drop-off in the density of Kuiper belt objects at 50 au (Allen et al. 2007). The answer to this question (closest approach of $\sim 200-300$ au) is uncomfortably close to the limit obtained above. This suggests that the outer limit of the Kuiper belt should not be explained in these terms because it then requires some orbital contrivance in order to achieve this without 'heating' the planetary orbits excessively. Alternatively, it has been suggested that an encounter is required in order to lift or scatter Sedna into its current orbit (Kenyon and Bromley 2004; Morbidelli and Levison 2004; Brasser et al. 2006): the required encounter distance for this to work is in the range 400–800 au, which fits in better with the constraints on planetary orbits. Encounter distances in this range are comfortably provided by moderately-dense clusters (e.g. 25 % of stars in the ONC have suffered encounters in this range).

Turning now to the constraints provided by radionuclides, we consider the argument first put forward by Cameron and Truran (1977) which invoked a nearby supernova in order to explain the over-abundance of decay products of ^{60}Fe in meteoritic samples. The inferred high value of the ^{60}Fe to ^{56}Fe ratio within meteoritic material (compared with its value in the ISM) requires that the mass of the supernova progenitor is $\sim 25\,M_\odot$ and that the supernova explodes within about 0.2 pc of the Sun (this latter being required in order that the protosolar nebula acquires a sufficient complement of ^{60}Fe). However, the supernova cannot have exploded within about 0.1 pc of the Sun because of the consequent damage to the primordial nebula via blast wave stripping.

There are a variety of environments that can provide a supernova in the near vicinity without inflicting excessive blast wave stripping: for example, the ONC provides a suitable environment. Adams (2010) argues that the requirement of a $25\,M_\odot$ progenitor requires a rather populous birth environment, using the expectation value of the maximum stellar mass as a function of cluster N in order to place a lower limit on N of 10^3-10^4. However, this may be unnecessarily stringent, since empirical data (see Fig. 7.4) suggests that stars of $\sim 25\,M_\odot$ *may* occur in much smaller-N systems.

Putting all this together, the best evidence that the Sun was born in a cluster is the radionuclide data, since this requires that a supernova occurred within 0.2 pc of the young Sun. We have argued that although this is compatible with the Sun being formed in a populous cluster, it does not necessarily require this, since there is observational evidence for suitably massive stars in relatively small-N groupings. It does however place an obvious requirement on the stellar density, since it requires interstellar separations of order 0.2 pc; this is met over most of the ONC, for example (Hillenbrand and Hartmann 1998). It is also met in 25 % of the star-forming regions whose surface densities were compiled by Bressert et al. (2010), although this estimate relies on uncertain de-projection factors. Finally, there appear to be no observed stellar birth environments that are *too* dense to be compatible with the birthplace of the solar system. Even though *some* of the stars in the core of the ONC undergo encounters which are too close to leave the planetary system dynamically cold, there are plenty of stars—even in the central regions—that do not encounter another star within 1000 au.

Since these lectures were delivered, the claimed high inferred value of the initial ^{60}Fe to ^{56}Fe ratio in meteorites has been challenged by the recent measurements of Tang and Dauphas (2012). These authors infer a value that is compatible with that in the ISM and therefore argue against contamination of the primordial solar nebula by the products of a supernova explosion. On the other hand, the high initial ratio of ^{26}Al to ^{27}Al that have been inferred in meteoritic data still requires the proximity of a massive star (in this case a Wolf-Rayet star). In this revised picture, the agent of contamination is via winds rather than an explosive event: a massive star ($>30 M_{\odot}$) is still required however. The requirements on the Sun's natal cluster environment is thus not much modified from those discussed above.

7.5 Summary

In this concluding chapter we first examined attempts to match the results of simulations to modelling specific young clusters and associations. We then turned to a discussion of the ways in which birth in a clustered environment may shape stellar properties. We focussed in particular on the possible relationship between cluster membership number, N, and the maximum stellar mass in a cluster, as well as the extent to which protoplanetary discs are likely to be disrupted by dynamical and feedback effects within a cluster environment. We concluded with a discussion of whether the solar system bears evidence of birth in a cluster environment. Although the paradigm of supernova contamination of the protoplanetary disc is not borne out by recent meteoritic analyses, there is still evidence for the Sun's formation in the vicinity of a massive star. This is the strongest evidence for the Sun's formation in a cluster. However the apparent occurence of suitably massive stars in rather small-N clusters means that the constraints on the properties of the Sun's natal cluster are rather weak.

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