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Formation of Stars in Clusters

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Abstract. Models of star formation in clusters and some of their observational constraints are reviewed. The formation of old globular cluster stars required a gas temperature close to the microwave background temperature at a time when cooling rates were low because of a low metallicity. Globular clusters were probably the first clusters that could form with a normal IMF, and therefore the first that could survive until today. This makes their universal presence the result of a selection effect for survival over a Hubble time

Key words. star formation, globular clusters

1. Star Formation Models

There are several models for star formation in clusters but no clear observational evidence that could indicate a preference. One model is that supersonic turbulence fragments a cloud through compression, shocks and intersecting shocks, and these compressed regions are massive enough to exceed their own thermal Jeans mass and also dense enough to have an internal dynamical time scale that is shorter than the compression time. Then they collapse to dense cores before they disperse and the dense cores form single and binary stars (Elmegreen 1993). Numerical simulations show this process well and also get about the right stellar initial mass function (see review in MacLow & Klessen 2003).

Observational support for this model includes the appearance of dense prestellar cores (Whitworth & Ward-Thompson 2001) in regions of star formation that have a mass distribution similar to the IMF (Motte, André, & Neri 1998; Testi & Sargent 1998; Bacmann et al. 2001; Tachihara et al. 2000), suggesting that this stellar distribution is determined in the gas phase. These observations sometimes also show a hierarchical positioning of the cores (Testi, et al. 2000), which is reminiscent of the hierarchical structure of turbulent clouds elsewhere, and a close packing of cores that can only be explained if they grow in mass at constant density rather than collapse to high density at constant mass (Elmegreen & Shadmehri 2003).

A problem with this model is that the observed dense cores are not always strongly self-gravitating, so it is not clear they will form stars. Also, their steep mass function, which is $dn/dM \sim M^{-2.4}$ above 1 $M_\odot$ like the Salpeter mass function, is expected anyway for the densest regions of a perfect fractal, regardless of their state of stability and formation history (Elmegreen 2002). Another problem is that brown dwarfs cannot form at typical cloud pressures because they are much smaller than the thermal Jeans mass. It is not clear if turbulent pressure bursts can decrease the thermal Jeans mass enough to form brown dwarfs (Padoan & Nordlund 2002).

A second model for star formation suggests that turbulence-shocked gas collapses directly to opacity-limited fragments, which are $\sim$ 0.001 $M_\odot$ stable cores that are too optically thick to radiate away any more collapse energy. The cores accrete their surrounding gas until stellar masses are reached. In the model by Shu, et al. (1987), this accretion is stopped by the star itself when it becomes sufficiently bright. In the model by Bate, Bonnell, & Bromm (2003), the accretion stops when the star is ejected from its tight sub-cluster and finds itself without any more gas nearby. The Bate et al. model forms the correct IMF and easily makes brown dwarfs, which are the opacity-limited fragments that get ejected early. It does not get an IMF-like distribution of pre-stellar cores because the IMF is determined entirely by competitive accretion in this model, not by cloud dynamics. It could, however, get an IMF-like distribution of dense objects that resemble the observed dense cores.

A third model of star formation has clumpy structure in clouds formed by thermal instabilities and then star formation inside these clumps triggered by other processes, such as clump collisions (Murray & Lin 1992). The thermal instability in turbulent molecular clouds is not well enough understood to comment on this model. Turbulence models with 2 stable thermal states separated by an unstable state do not actually form clumps by a thermal instability but have gas density and temperature following the turbulent pressure fluctuations (Gazol et al. 2001).

None of these models satisfies all of the observations of star formation in clusters. A hybrid model might have supersonic turbulence make structure with a wide range of masses above and below the stellar mass. The most unstable of these would contract into dense regions that are the observed pre-stellar clumps. These clumps could then either collapse to opacity-limited fragments and accrete the rest of the clump mass over time without competition, or they could contract more slowly into stars via ambipolar diffusion. In either case, the final stellar mass would be proportional to the clump mass and not be determined entirely by competitive accretion. The hybrid scenario does not appear in the models by Bate et al., perhaps because the cloud did not have enough time to evolve to a highly clumped initial condition before gravitational instabilities set in. In their model, most of the collapse occurs in one large, thermalized filament that comes from the first big crash in the convergent part of the initially turbulent motion.

2. Formation of Globular Clusters

There are several models for the formation of globular clusters: (1) they form inside dwarf galaxies that have since dispersed (Coté, West, & Marzke 2002; Yoon & Lee 2002; Bellazzini, Ferraro, & Ibata 2003); (2) they form in subgalactic halos (Nishi & Susa 1999; Cen 2001; Kitayama et al. 2001; Bromm & Clarke 2002), (3) in pieces of the outer regions of galaxies (Harris, Harris, & McLaughlin 1998; Susa & Kitayama 2000; Weil & Pudritz 2001), (4) in the disks of $z > 3$ galaxies (Kravtsov & Gnedin 2003), (5) in gas-rich proto galaxies during mergers (Ashman & Zepf 1992; Beasley et al. 2002), and (6) in radio-jet triggered shells (Krause 2002).

Most of these processes could have formed globular clusters. Once a cluster relaxes internally and gets fully incorporated into the halo of a galaxy, its detailed formation mechanism will become obscure.

3. Star Formation in Globular Clusters

This review is not concerned with the cluster formation process itself but with the formation of stars inside clusters. In this respect, there are several important differences between the epoch of globular cluster (GC) formation at cosmological $z = 3$ to 10 and the present day. When globular clusters formed, the microwave background temperature was higher than it is today by a factor of 3 to 10: $T_{MWB} \sim 10-30$ K. The gas had a lower metallicity, $< Z >\sim -1.6$ (1/40 of solar). There was also a bright non-thermal environment from QSO radiation, a high pressure potential from the protogalaxy ($< P >\sim 10^6$ k_B for $M \sim 10^{11}$ $M_\odot$ inside 20 kpc), and a lower mean magnetic field in the halo than in present-day disks. These differences had several important consequence for star formation, as discussed momentarily.

In other respects, star formation in globular clusters seems very similar to star formation in today's clusters because of the universal presence of turbulence, self-gravity, and some level of thermal cooling. The biggest indication that star formation in GC was not much different than star formation today is that the stellar IMF's are similar (compare Paresce & De Marchi [2000] and Hillenbrand & Carpenter [2000]), although perhaps the mass at the peak of the IMF was larger for GC by a factor of 2 (Chabrier 2003). GC are also similar to today's clusters with respect to stellar density and velocity dispersion (when compared to today's young super star clusters), and neither cluster has dark matter.

The similarity of the basic structure of dense star clusters suggests that the overall processes of star formation are about the same in all environments. For example, supersonic turbulence rapidly fragments the gas which then collapses somehow into stars. This process is usually very fast, taking less than 2 dynamical times. For globular clusters with 2×10^5 M$_\odot$ inside a radius of 5 pc, the average gas density assuming 10% star formation efficiency was 10^5 H cm^{-3}, in which case the dynamical time was ~ 0.25 million years. This means that star formation was over before the most massive stars supernovaed. Thus we can infer that GC will not enrich themselves with their own supernova ejecta (Elmegreen & Efremov 1997).

The similarity in IMF between GC and today's clusters suggests that the thermal Jeans mass is about the same in these two cases. According to some theories, the thermal Jeans mass determines the turnover or "characteristic" mass in the IMF (Larson 1992; Elmegreen 1997). This is the mass where the Salpeter power law at high mass joins the shallower or flat part at low mass. For GC this turnover mass is ~ 0.4 M$_\odot$ (Paresce & De Marchi 2000). In view of the average density of GC clouds, a thermal Jeans mass of 0.4 M$_\odot$ requires a temperature at the time of star formation of

$$T \sim 15\mathrm{K}\left(\frac{M_J}{0.4\ \mathrm{M}_\odot}\right)^{2/3}\left(\frac{n}{10^5\ \mathrm{H}_2\ \mathrm{cm}^{-3}}\right)^{1/3}. \quad (1)$$

This temperature seems reasonable for modern star formation and indeed its value supports this particular IMF theory. However, it is a surprisingly low temperature for GC that formed at $z \sim 3-10$ when T_{MWB} was also $\sim$ 15 K. Apparently *the GC gas had to cool down to about the ambient mircowave temperature* if this IMF theory is correct.

Gas cooling rates at the time of GC formation were far less than they are today for the same density and temperature because of the lower C, O, and dust abundances for near-primordial gas. Cooling at $n \sim 10^5$ cm^{-3} is dominated by dust, CI, and OI, and can bring gas down to $\sim$ 15 K or so, with heating only from H_2 formation (Omukai 2000). Additional heating from QSO light and forming elliptical galaxies would make it hard to reach even this T.

In the second model of star formation mentioned above, where the IMF is determined by competitive accretion onto opacity-limited fragments, the characteristic mass at the turnover point of the IMF scales directly with the opacity-limited mass (according to M. Bate, Joint Study 11, IAU in Sydney, July 2003). This is the stable mass at which the opacity over one radius is so large that the energy input from collapse cannot be radiated away. According to Rees (1976) and Low & Lynden-Bell (1976), the minimum mass is insensitive to the opacity per gram, in which case it would also be insensitive to metallicity. However Masunaga & Inutsuka (1999) find that the minimum mass varies inversely with opacity/gram and suggest this mass is larger in low metallicity clouds, equaling 3.71 $M_\odot$ in clouds with $Z = 0.01 Z_\odot$. Because such a change in characteristic IMF mass is not observed for globular clusters, the role of opacity-limited fragmentation during star formation is unclear.

The IMF is critical for a cluster because it determines whether the cluster can remain self-bound after mass loss from stellar evolution (Portegies Zwart et al, 1998; Joshi, Nave, &

Rasio 2001; Giersz 2001). The binary fraction is important too as binaries eject stars. If GC did not form low mass stars with about the IMF they are observed to have, then their stars would not be bound in a cluster today and they would be very difficult to see. Also, without stars less than a solar mass, there would be no stars that survived a Hubble time. In this sense, GC are the result of a remarkable selection effect: *they are the first non-galactic bound stellar systems (i.e., with no dark matter) that were dense enough to survive galactic tidal forces and that could make low mass stars*. Earlier star formation may have occurred in clusters also, but they could not survive disruption and fading from stellar evolution. The earliest star formation may not have occurred in clusters at all (Abel, Bryan, & Norman 2002).

References

Abel, T., Bryan, G.L., Norman, M.L. 2002, Sci, 295, 93
Ashman, K.M. & Zepf, S.E. 1992, ApJ, 384, 50
Bacmann, A., André, P., & Ward-Thompson, D. et al. 2001, ASP Conf. Vol. 243, From Darkness to Light: Origin and Evolution of Young Stellar Clusters, ed. T. Montmerle & P. André (San Francisco: ASP), p. 113
Bate, I.A., Bonnell, M.R., & Bromm, V. 2003, MNRAS, 339, 577
Beasley, M. A., Baugh, C. M., Forbes, D.A., Sharples, R. M., & Frenk, C. S. 2002, MNRAS, 333, 383
Bellazzini, M., Ferraro, F.R., & Ibata, R. 2003, AJ, 125, 188
Bromm, V. & Clarke, C.J. 2002, ApJ, 566, L1
Cen, R. 2001, ApJ, 560, 592
Chabrier, G. 2003, PASP, 115, 763
Coté, P., West, M.J., & Marzke, R.O. 2002, ApJ, 567, 853
Elmegreen, B.G. 1993, ApJ, 419, L29
Elmegreen, B.G. 1997, ApJ, 486, 944
Elmegreen, B.G. 2002, ApJ, 564, 773
Elmegreen, B.G. & Efremov, Yu. N. 1997, ApJ, 480, 235
Elmegreen, B.G. & Shadmehri, M. 2003, MNRAS, 338, 817
Gazol, A., Vázquez-Semadeni, E., Sánchez-Salcedo, F. J., & Scalo, J. 2001, ApJ, 557, L121
Giersz, M. 2001, MNRAS, 324, 218
Harris, W.E., Harris, G.L.H., & McLaughlin, D.E. 1998, AJ, 115, 1801
Hillenbrand, L.A. & Carpenter, J.M. 2000, ApJ, 540, 236
Joshi, K.J., Nave, C.P., Rasio, F.A. 2001, ApJ, 550, 691
Kitayama, T., Susa, H., Umemura, M., & Ikeuchi, S. 2001, MNRAS, 326, 1353
Krause, M. 2002, A&A, 386, L1
Kravtsov, A.V. & Gnedin, O.Y. 2003, astroph/0305199
Larson, R.B. 1992, MNRAS, 256, 641
Low, C., Lynden-Bell, D. 1976, MNRAS, 176, 367
MacLow, M.-M. & Klessen, R.S. 2003, Reviews of Modern Physics, in press (astroph/0301093)
Masunaga, H. & Inutsuka, S.-I. 1999, ApJ, 510, 822
Motte, F., Andre, P., & Neri, R. 1998, A&A, 336, 150
Murray, S.D. & Lin, D. N. C. 1992, ApJ, 400, 265
Nishi, R. & Susa, H. 1999, ApJ, 523, L103
Omukai, K. 2000, ApJ, 534 , 809
Padoan, P. & Nordlund, A. 2002, ApJ, 576, 870
Paresce, F. & De Marchi, G. 2000, ApJ, 534, 870
Portegies Zwart, S.F., Hut, P., Makino, J., McMillan, S.L.W. 1998, A&A, 337, 363
Rees, M.J. 1976, MNRAS, 176, 483
Shu, F.H., Adams, F.C., & Lizano, S. 1987, ARA&A 25, 23
Susa, H. & Kitayama, T. 2000, MNRAS, 317, 175
Tachihara, K., Mizuno, A., & Fukui, Y. 2000, ApJ, 528, 817
Testi, L., & Sargent, A. I. 1998, ApJ, 508, 91L
Testi, L., Sargent, A.I., Olmi, L., & Onello, J.S. 2000, ApJ, 540, L53
Weil, M.L. & Pudritz, R.E. 2001, ApJ, 556, 164
Whitworth, A. P. & Ward-Thompson, D. 2001, ApJ, 547, 317
Yoon, S.J & Lee, Y.W. 2002, Science 297, 578