The Maximum Mass of Star Clusters

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1 A Maximum from Size-of-Sample Effects or Physics?

If an universal untruncated cluster initial mass function (CIMF) of the form $N(M)\,dM = C\,M^{-2}\,dM$ is assumed, the mass of the most massive star cluster in a galaxy ($M_{\text{max}}$) is the result of the size-of-sample (SoS) effect. This implies a dependence of $M_{\text{max}}$ on the total number of clusters ($N$). For a power-law index of -2, the constant $C = M_{\text{max}}$ and $N$ follows from integrating the CIMF from $M_{\text{min}}$ to $M_{\text{max}}$, resulting in $N = M_{\text{max}}/M_{\text{min}}$. Since the cluster luminosity function (CLF) is also a power-law distribution, with a comparable index, a similar relation holds for the luminosity of the brightest cluster in a galaxy ($L_{\text{max}}$) and $N$, which has been observed \cite{13, 11}. An attempt to compare $M_{\text{max}}$ in a sample of galaxies with the star formation rate (SFR) has shown a similar relation \cite{12}. However, finding the most massive cluster in a galaxy is not trivial, since star clusters fade rapidly due to stellar evolution. For example, a 1 Gyr old cluster of $10^6 M_\odot$ has about the same luminosity as a 4 Myr old cluster of $10^4 M_\odot$. The SoS effect also implies that $M_{\text{max}}$ within a cluster population increases with equal logarithmic intervals of age. This is because the number of clusters formed in logarithmic age intervals increases (assuming a constant cluster formation rate). This effect has been observed in the SMC and LMC \cite{10}. The observations of this increase argues for a $M_{\text{max}}$ (in the LMC and SMC) that is determined by sampling statistics, or a physical upper limit that is higher than the $M_{\text{max}}$ following from statistics.

Based on the maximum pressure ($P_{\text{int}}$) inside molecular clouds, it has been suggested that a physical maximum mass ($M_{\text{phys}}^{\text{max}}$) should exist, which scales as $M_{\text{phys}}^{\text{max}} \propto P_{\text{int}}^{1/2}$ \cite{6}. The ISM pressure in a galaxy scales approximately as the square of the column density of molecular gas ($\Sigma^2$), and when assuming that $P_{\text{int}}$ is determined by the ISM pressure (i.e. pressure equilibrium), then $M_{\text{phys}}^{\text{max}} \propto \Sigma$. Since the star formation rate (SFR) scales in another way with $\Sigma$, namely $\text{SFR} \propto \Sigma^{1.4}$, and since $M_{\text{phys}}^{\text{max}}$ is independent of the size of the galaxy ($A$), for a certain minimum $A$ and SFR a $\Sigma_{\text{crit}}$ should exist where $M_{\text{max}} = M_{\text{phys}}^{\text{max}}$. For galaxies where $\Sigma > \Sigma_{\text{crit}}$, $M_{\text{phys}}^{\text{max}}$ is lower than the $M_{\text{max}}$ determined by sampling statistics. To observe signatures of the presence of $M_{\text{phys}}^{\text{max}}$, one should look in big galaxies where $\Sigma$ (or the SFR) is high.
2 The Size-of-Sample Effect in M51

A good candidate galaxy, which is big and has a high SFR, is M51. We used the 1052 star clusters identified by [2] to study the SoS relation of $M_{\text{max}}$ with log(age). In Fig. 1 we show a comparison between the clusters in the LMC (left), the SMC (middle) and M51 (right). In the top panel we compare the age-mass diagrams, where we have overplotted the predicted SoS increase of $M_{\text{max}}$ with log(age) as dashed lines, based on a power-law CIMF with index -2. As was shown by [10], $M_{\text{max}}$ in the LMC and SMC follows this prediction quite well. In M51, however, there is a lack of old ($\sim 10^8$ yr), massive ($\sim 10^6 M_\odot$) clusters. In the bottom panels we show the luminosity (magnitude) vs. log(age). The SoS relation for $M_{\text{max}}$ is converted to $L_{\text{max}}$ using the GALEV SSP models [1] and is almost a horizontal line. Fading lines, scaled to the brightest clusters at young ages, are shown as full lines. The brightest cluster vs. log(age) in M51 follow this fading line of a $5 \times 10^5 M_\odot$ cluster quite well, similar to what was found for the “Antennae” galaxies (for a $10^6 M_\odot$ cluster) [15]. This suggests that the cluster mass function in M51 and the “Antennae” galaxies is truncated around $\sim 0.5-1.0 \times 10^6 M_\odot$.

3 The Integrated Star Cluster Luminosity Function

Since the age determination from broad-band colours has limitations, we want to have an independent check of the truncated mass function scenario, without relying on age determination. Therefore, we model for two scenarios the integrated cluster luminosity function (CLF) of a population which has formed with a constant cluster formation rate (CFR): 1.) $M_{\text{max}}$ is determined by SoS effects and increases with log(age) and 2.) $M_{\text{max}} = M_{\text{max}}^{\text{phys}}$ is constant.
with log(age). The CLF in case 1.) is a power-law distribution, with an index similar to the underlying mass function. This has been observed for various spiral galaxies and the LMC and SMC [7, 11]. The resulting CLF of scenario 2.) is better described by a double power-law distribution, for which the location of the break is determined by $M_{\text{phys}}^{\text{max}}$. On the bright side of the CLF the index is smaller than $-2$ (i.e. steeper), and on the faint side it is $\simeq -2$. The steeper bright side is because a truncation in the mass function will be spread out over a range of luminosities due to the age spread in the population and fading of clusters in time (e.g. young clusters with $M_{\text{phys}}^{\text{max}}$ are brighter than old clusters with $M_{\text{phys}}^{\text{max}}$). Tentative evidence for a double power-law CLF was observed for NGC 6946 and M51 [7].

Recently, the Hubble Heritage project released new HST/ACS data of M51, covering the entire disc with 6 pointings. We used this dataset and selected clusters based on the size. All sources found with SExtractor ($\sim 70 000$), were compared to (extended) cluster profiles convolved with the camera PSF. Around 6 000 sources, above a conservative completeness limit, were found to be more extended than the instrumental PSF. The resulting CLF of this sample shows a pronounced double power-law behaviour and is very similar to what was found from the models (see Fig. 2).

Several predictions from the CLF model are found back in the observations: 1.) The power-law index on the bright side ($-\alpha_2$) increases when going to bluer filters. This is because clusters fade more rapidly in the bluer filters, which spreads out the luminosity of $M_{\text{phys}}^{\text{max}}$ over a larger range of magnitudes; 2.) The break in the CLF shifts to brighter luminosities when going to redder filters. This is because the majority of the clusters with the break luminosity is red (see [7] for details). The best agreement between data and model, taking into account cluster disruption and extinction, is for $M_{\text{phys}}^{\text{max}} = 5 \times 10^5 M_\odot$. A similar double power-law CLF was observed for the “Antennae” clusters [14], although with a break 1.4 mag brighter, implying that $M_{\text{phys}}^{\text{max}}(\text{Antennae}) = 4 \times M_{\text{phys}}^{\text{max}}(M51) \simeq 2 \times 10^6 M_\odot$. We note that a direct comparison between the CLF of “Antennae” clusters and the one following from our model is dangerous because of the non-constant CFR in the “Antennae” galaxies. Nevertheless, the observed break in the CLF is an independent confirmation of the truncated mass function scenario, confirming the results from the SoS comparison of Sect. 2.
4 The Environmental Dependency of $M_{\text{max}}^{\text{phys}}$

The difference between $M_{\text{max}}$ in the “Antennae” galaxies and in M51 and the recently discovered super-massive star clusters [3] (also Bastian in these proceedings), suggest an environmental dependent $M_{\text{max}}^{\text{phys}}$. We looked for variations of the bend location within M51 at different galactocentric radii ($R$). If $M_{\text{max}} \propto \Sigma$, and $\Sigma \propto \exp(-R/R_h)$, then $M_{\text{max}} \propto \exp(-R/R_h)$, with $R_h$ the disc scale length of molecular gas. We found a correlation, since in three radial bins with $R/\text{kpc} = [1.5, 4.5, 7]$ we find the bend at $M_V = [-8.6, -8.5, -7.7]$ [9]. Although the errors in the fit are large ($\pm 0.2 \text{mag}$), the decreasing $M_{\text{max}}^{\text{phys}}$ with $R$ is a third argument supporting the truncated mass function scenario in M51.

5 Final Thoughts

Our observations of a truncation of the integrated mass function does not necessarily imply that a truncation is visible in the CIMF, since there $N$ is much lower. Therefore, the observations of an untruncated CIMF in M51 [4] and the “Antennae” galaxies [15] are not in disagreement with what we discuss here. In addition, the scaling of $L_{\text{max}}$ with $N$ is expected to be determined by the SoS effect, since the brightest cluster is generally young ($< 10 \text{ Myr}$). The number of clusters in a young sample is too small to sample the mass function up to $M_{\text{max}}^{\text{phys}}$.

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