The Cluster Birthline and the formation of stellar clusters in M33

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Abstract. We present a new method to analyze the IMF at its high mass end in young stellar clusters, which rely on two integrated observables: the cluster bolometric and H\textalpha luminosity. Using several cluster samples selected in M33 we show that a stochastically sampled universal IMF is in better agreement with the data than a truncated IMF whose maximum stellar mass depends on cluster mass. We also discuss the possibility that a delayed formation of massive stars is taking place in low density star forming regions as an alternative to a strong leakage of ionizing photons from HII regions of young luminous clusters.

1. Introduction

Extragalactic surveys of young stellar clusters in the Local Universe complement Milky Way studies because star formation can be traced in different environments: from spiral arms to interarms, from galaxy centers to galaxy outskirts, from metal poor to metal rich disks, from dwarfs to more massive spirals. Even though the physical scales which can be spatially resolved will never be as small as in galactic surveys, extragalactic studies benefit from the larger database available. Having a statistically meaningful ensemble of clusters is crucial when testing the Initial Mass Function (hereafter IMF), given the fact that the IMF is a probabilistic function describing the distribution in mass of stars at their birth. This is especially true when studying the upper end of the IMF, since massive stars are rare and short lived events. The Milky Way disk is not the ideal laboratory for investigating the birth rate of massive stars due to their paucity and to the high dust extinction along the line of sight which prevent searches over large areas. Signatures of massive stars are used to infer the rate of star formation in galaxies, and hence, even though most of the stellar mass is in small mass stars, it is very important to investigate the upper end of the IMF to correctly draw any conclusion on the star formation rate. M33, a Local Group galaxy, is an ideal candidate for studying the formation of young stellar clusters. Its distance is only 840 kpc, its disk is undisturbed, it has a low inclination (55\textdegree) respect to our line of sight, a low dust content, and a higher star formation rate per unit area compared to other Local Group members such as M31. Using Spitzer data, \cite{Verley2007} have cataloged infrared sources in M33 which span over 4 order of magnitude in luminosity and recovered sources as faint as...
embedded B2-type stars. We shall use the 24 \( \mu m \) Spitzer maps of M33 to select stellar clusters which have an infrared counterpart due to dust in the surrounding interstellar gas, and hence likely to be young cluster candidates.

2. The cluster birthline

![Figure 1](image)

Figure 1. The distribution of the ratio of the bolometric-to-H\( \alpha \) luminosity versus the bolometric luminosity for newly born clusters simulated for the stochastically sampled universal IMF extending up to 120 \( M_\odot \). Vertical dashed lines mark evolutionary sequences, i.e., aging moves clusters upward from the simulated birthline because H\( \alpha \) luminosities fade away more rapidly than bolometric luminosities.

Rather than resolved star counts we shall investigate integrated properties of star clusters which can be used to infer their massive stellar population. Low mass stars determine the stellar cluster mass because the slope of the IMF is steeper than \(-2\). The cluster bolometric luminosity and the ionizing photon rate, as measured by the extinction corrected H\( \alpha \) emission, are instead linked to the massive stellar population. For this reason we shall focus on the last two observables to describe clusters. For individual massive stars, the bolometric and H\( \alpha \) luminosity scale in a rather similar way with stellar mass while for stars less massive than 20 \( M_\odot \) the H\( \alpha \) luminosity drops with stellar mass much more quickly than the bolometric luminosity does. This implies
that when the newly born cluster is small and very massive stars are lacking, we cannot easily infer the cluster mass or the star formation rate in the surrounding region from the observed Hα luminosity. If the stellar cluster is massive enough that the IMF is fully populated up to its high mass end, the ratio between the bolometric and Hα luminosity is constant and it does not depend on the cluster mass. Both the bolometric and the Hα luminosity scale linearly with cluster mass. To pin down the effects of the IMF incompleteness, which set in as the cluster mass gets below a critical value and affect the cluster luminosity, we introduce the concept of cluster birthline (Corbelli et al. 2009). We shall call birthline the region in the log L_{bol} – log L_{bol}/L_{Hα} plane where newborn young stellar cluster lie. We show in Figure 1 the cluster birthline for a stochastically sampled IMF whose slope at its high mass end is the Salpeter one i.e. 2.35. The shape of the cluster birthline does not depend much on the slope of the IMF and on the cluster mass function. Its shape is linked to the dependence of the bolometric luminosity and ionizing flux of individual stars on stellar mass as well as to the mass of the most luminous star that can ever be formed.

The cluster birthline changes if one assumes a cluster-mass dependent IMF instead of a stochastically sampled universal function. Weidner & Kroupa (2006, and references therein) proposed that the maximum possible mass of a star in a cluster decreases systematically with decreasing cluster mass. This implies that no high mass stars can ever be formed in intermediate mass clusters. For a randomly sampled universal IMF they can occasionally be formed. As long as there is enough gas, intermediate mass clusters can make bright “outliers”. In Figure 1 we show also the cluster birthline for the maximum mass case according to the IMF model of Weidner & Kroupa (2006). The cluster birthline in the maximum mass case has higher values of L_{bol}/L_{Hα} ratio over the range of L_{bol} where O- and B-type stars start lacking.

An important property of the cluster birthline is that aging moves the clusters above it. This is because the death of massive stars makes the cluster Hα luminosity fade away more rapidly than the bolometric luminosity does. For a given IMF the cluster birthline is a theoretical lower boundary for the L_{bol}/L_{Hα} ratio. In fact possible leakage or dust absorption of ionizing photons in the HII region increases the value of the observed L_{bol}/L_{Hα} ratio. Hence if clusters with a well determined value of L_{bol} and L_{Hα} lie below a theoretical birthline the assumed model for the upper end of the IMF needs to be revised.

A stochastically sampled universal IMF implies that the cluster mass is highly undetermined when the observed bolometric luminosity is below 10^{40} erg s^{-1}. Results of a numerical simulation shown in Figure 2 emphasize this by showing the wide range of cluster masses corresponding to L_{bol} values below 10^{40} erg s^{-1}. Stochasticity allows for example a 5×10^{39} erg s^{-1} luminous cluster to be made by a single 100 M_⊙ star or by a more massive ensemble of small mass stars distributed according to a fully populated IMF up to about 30 M_⊙.

3. Young stellar clusters in M33

In Figure 3 we compare the observed values of L_{bol}/L_{Hα} ratio for an infrared selected sample of stellar clusters in M33 with the cluster birthline for the maximum mass case and for the case of a universal stochastically sampled IMF. For this last model we plot the expected median values of L_{bol}/L_{Hα} with their relative dispersion. The bolometric luminosity of clusters in the sample has been computed by adding the far and near
Figure 2. Possible values of cluster masses and of the most massive star that forms as a function of the cluster bolometric luminosity. The cluster mass here is computed only counting stars more massive than 1 $M_\odot$. The presence of stars of lower mass will shift log $M_{\odot}$ upward by a constant value which will depend on the IMF lower mass cut-off.

Figure 3. Bolometric to H$\alpha$ luminosity ratio versus bolometric luminosity for the infrared selected sample in M33. Bolometric luminosities have been estimated by adding the emission at various wavelengths and individual extinction corrections have been applied to H$\alpha$ luminosities. Median values of the theoretical cluster birthline for the stochastically sampled universal IMF (filled triangles) and for the maximum mass case (filled dots) are also shown.
UV luminosities to the total infrared luminosity as inferred from the 24 \( \mu \text{m} \) emission (Verley et al. 2009). A term which depends on the H\( \alpha \) luminosity has been added to take into account the contribution of the ionizing part of the spectrum to the bolometric luminosity. We can see that all of the M33 clusters are compatible with the stochastically sampled universal IMF. There is a group of clusters which falls below the birthline relative to the maximum-mass IMF. This finding suggests that a stochastically sampled universal IMF is more appropriate than the maximum-mass case. The bolometric luminosity formula that we have used is valid for young clusters whose unabsorbed light falls mostly in the UV bands, which is the case if stars more massive than 10 \( M_\odot \) are present. In the next subsection we will determine the age and bolometric luminosity of stellar clusters using synthesis model fits to the spectral energy distribution (hereafter SED).

### 3.1. Cluster ages from SED fits

Multiwavelength observations of 32 young star clusters in M33, from UV to the near infrared, has allowed Grossi et al. (2010) to derive stellar cluster properties by fitting synthesis models to the cluster spectral energy distribution. Ages, bolometric luminosities, masses and extinction have been determined from the best fitting single age stellar population burst model with a fully populated IMF. The selected sample is made of isolated compact sources visible both in infrared, optical, and UV images and with a well determined nebular metal abundance. Cluster ages range between 2 and 15 Myr and bolometric luminosities between \( 10^{39} \) and \( 2 \times 10^{41} \text{ erg s}^{-1} \). Relatively low values for the extinction have been found, \( 0.2 < A_v < 1.1 \), in agreement with what suggested by the Balmer line decrement. Since we also measured the H\( \alpha \) emission from the HII region around the cluster, in Figure 4 we compare the data for this sample with the cluster birthline. We expect younger clusters to lie close to the birthline than older cluster and instead we seem to find the opposite trend. Notice that if \( L_{\text{bol}} \) from SED fits were correct for the whole sample, and hence only a couple of clusters have an incomplete IMF, most of the young clusters would be highly underluminous in H\( \alpha \). This means that a high fraction of ionizing photons, sometime very close to 100% of them must have leaked out of the HII region. This is in contrast with previous analysis of the leakage in HII regions of M33 (Hoopes & Walterbos 2000) and with theoretical models.

As discussed in the previous Section, when the cluster bolometric luminosity is below \( 10^{40} \text{ erg sec}^{-1} \) incompleteness of the IMF at the high mass end sets in and should be taken into account. We now compute the bolometric luminosity of the clusters by adding the emission in the various bands, as in Figure 3, and only when this is close to \( 10^{40} \text{ erg sec}^{-1} \) or above it we run SED fits to re-determine \( L_{\text{bol}} \) and the other cluster parameters. Figure 4(b) shows the results. The luminosities predicted by SED model fits using a fully sampled IMF are higher than those derived by the arithmetic sum for low luminosity clusters, as discussed also in Grossi et al. (2010). This discrepancy warns against an indiscriminate use of SED synthesis models if stochastic effects are not taken into account. Detailed SED models which take into account stochasticity will help in the future to confirm this finding. Note that several clusters have now bolometric luminosities below \( 10^{40} \text{ erg sec}^{-1} \) and lie along the birthline: the problem of a strong ionizing photon leakage is alleviated. Bright clusters however are still underluminous in H\( \alpha \), especially the young ones. For the data shown in Figure 4(b) a standard universal IMF which extends up to 120 \( M_\odot \) implies that on average about half of the ionizing photons are leaking out of bright HII regions in our sample. It is worth to mention...
Figure 4. The cluster birthline for the stochastically sampled IMF which extends up to 120 $M_\odot$ (filled triangles) and to 40 $M_\odot$ (dashed line in (b)). Data for infrared selected clusters in M33 are shown in (a) when $L_{bol}$ is determined from SED model fits using a complete IMF up to 120 $M_\odot$. Asterisk symbols are for clusters younger than $3 \times 10^6$ yrs, open squares for clusters with age between $3 \times 10^6$ and $6.3 \times 10^6$ yrs and open circles for older clusters. In panel (b) we compute $L_{bol}$ by adding the emission in the various bands (open star symbols), and only when this is close to $10^{40}$ erg sec$^{-1}$ or above it we show $L_{bol}$ as from SED model fits. Filled dots trace the birthline for the maximum mass case.

that despite the relatively low extinction predicted by the SED models, we expect more light re-emitted in the IR around these clusters than estimated from M33 Spitzer images using simple dust models. This suggests that not only ionizing photons but also continuum UV photons are lacking in these HII regions, and that dust cannot be responsible for the missing ionizing photons. Notice that M33 is a galaxy with a high diffuse fraction of H$\alpha$ and continuum UV (Hoopes & Walterbos 2000, 2003; Thilker et al. 2005) and moreover our selected sources lie in non crowded, low density regions, so leaking might be more pronounced than close to giant molecular clouds on the arms.

Leakage becomes less pronounced if massive stars are missing. In Figure 4(b) we show the birthline for a stochastically sampled IMF which extend only up to 40 $M_\odot$ as well as the birthline relative to the maximum mass case. M33 clusters are compatible with the two stochastically sampled universal IMF while there are a few clusters that lie well below the maximum mass birthline and hence the relative IMF model is less suitable. However, a universal lower mass cut-off to the IMF for our sample does not solve the age problem i.e. that younger clusters lie close to the birthline than older cluster do. This can happen if a delayed formation of massive stars is taking place in the low density regions where the star formation timescale is longer.

3.2. The embedded sample

In order to test a cluster birthline it is important to select newborn clusters over a wide range of luminosities. Cluster ages determined through SED model fits with a fully sampled IMF are reliable if clusters are luminous enough to be on the flat part of the birthline. For the rising part of the birthline, one can hope that infrared selected clusters are young if they are still embedded in molecular gas. Through deep observations of
the CO J=1-0 and J=2-1 line we have 14 young clusters candidates which we use to test the rising part of the birthline. They are dim infrared sources with no or little flux in the UV and we compute $L_{bol}$ by summing the emission in the various bands. Figure 5 shows how well these sources trace the birthline for a stochastically sampled universal IMF.

![Figure 5](image.png)

Figure 5. The cluster birthline for the stochastically sampled IMF (filled triangles) and data for infrared selected clusters in M33 embedded or close to a molecular cloud (open star symbols).

4. Conclusions

We have used the cluster birthline, which is the place in the log $L_{bol} - \log L_{bol}/L_{H\alpha}$ plane where newborn young stellar clusters lie, to test the IMF of individual clusters in the Local Group galaxy M33. Cluster aging or ionizing photon leakage moves the clusters above the birthline. A stochastically sampled universal IMF with a Salpeter slope at its high mass end gives a cluster birthline in agreement with M33 data. Low luminosity clusters, which lie on the rising part of the birthline, are in better agreement with a stochastic universal IMF rather than with truncated IMF models whose maximum stellar mass depends on cluster mass.

Fits to the spectral energy distribution of individual luminous clusters suggest a delayed formation of massive stars i.e. a non instantaneous burst of star formation in low density environments. This helps explaining the unexpected result that older clusters lie closer to the birthline than younger clusters do. The alternative is to invoke
a substantial leakage of ionizing photons in young luminous clusters, in addition to multiple burst models.

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