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Star Formation as Seen by Low Mass Stars

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Abstract

Using the Hubble Space Telescope (HST) we have characterised and compared the physical properties of a large sample of pre-main sequence (PMS) stars spanning a wide range of masses ($0.5 - 4\,\mathrm{M}_\odot$), metallicities ($0.1 - 1\,\mathrm{Z}_\odot$) and ages ($0.5-30\,\mathrm{Myr}$). This is presently the largest and most homogeneous sample of PMS objects with known physical properties. The main results of this ongoing study are briefly summarised here.

Keywords: star formation - solar mass stars - Magellanic clouds - Milky Way - photometry.

With a group of European colleagues, whose names are listed in the Acknowledgments, we have undertaken a systematic study of the star formation process in the Milky Way and Magellanic Clouds (MCs), with special emphasis on moderate mass stars, say 0.5 to 4 $M_\odot$. Our motivations are: i) Stars in this range account for most of the star formation in a galaxy, e.g. more than 65% for a Salpeter initial mass function (IMF); ii) Low mass stars can form in small parent clouds as well as in big ones; iii) As a consequence, low mass stars are forming near massive stars as well as in isolated groups. On the other hand, when considering distant galaxies we can probe their star formation rates only by considering the phenomena induced by the presence of massive stars, such as bright HII regions, supernova explosions, unresolved, bright stellar clusters. However, using massive star diagnostics to measure the overall star formation rates is valid if and only if we are confident to be able to extrapolate correctly from what we see coming from a bunch of massive stars to the total amount of mass that is forming the bulk of stars, i.e. the low mass stars. In other words, we need to understand how the formation of moderate mass stars works as a function of the environmental conditions and how it relates to the massive star formation.

Ground-based spectroscopic studies of nearby young star-forming regions (e.g. Taurus, Auriga, Ophiuchus) show that the mass accretion rate appears to decrease steadily with time, from about $10^{-8}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ at ages of $\sim 1\,\mathrm{Myr}$ to $\sim 10^{-9}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ at $\sim 10\,\mathrm{Myr}$. At face value this is in line with the expected evolution of viscous discs, but the scatter of the data exceeds 2 dex at any given age (see also Fig. 3). Such a scatter may be explained in part by the wide mass range covered by the observations, but the true limitation is the paucity of available measurements. Indeed, all the results so far obtained are based on the mass accretion rates of a few hundred stars, located in nearby regions, covering a limited range of ages and no appreciable range of metallicity.

Using the HST, we have started a study of the PMS phase is a number of star forming regions in the local group. Among others, these include NGC 3603 in the Milky Way, 30 Doradus and surrounding regions in the Large Magellanic Cloud, and NGC 346 and NGC 602 in the Small Magellanic Cloud. Thanks to a novel method that we have developed to combine broad-band (V, I) photometry with narrowband $H\alpha$ imaging (De Marchi et al. 2010), we have identified more than 3 000 bona-fide PMS stars still undergoing mass accretion (Fig. 1). We have determined their physical parameters, i.e. temperature, luminosity, age, mass and mass accretion rate. This is presently the largest and most homogeneous sample of PMS objects with known physical properties.

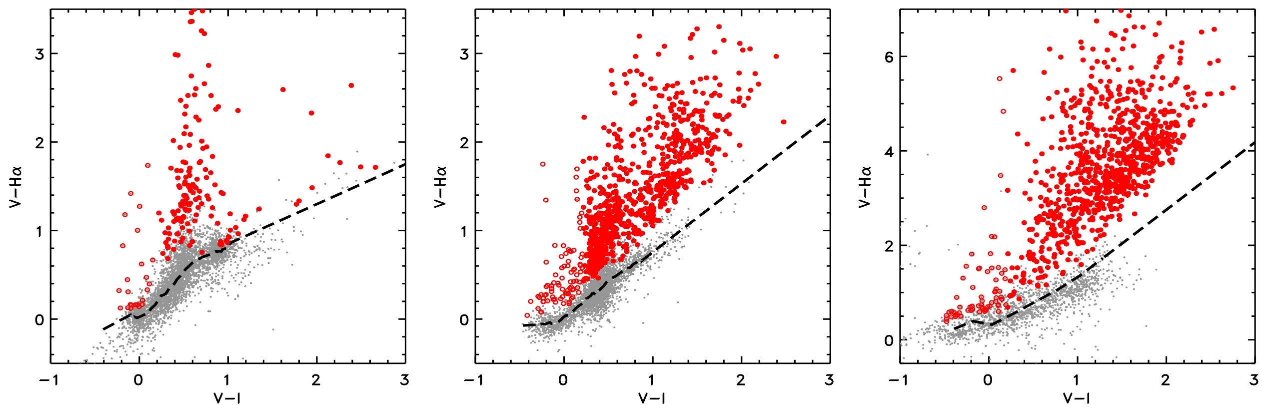

Figure 1: The $V - H\alpha$ colour as a function of $V - I$ in fields around SN 1987A in the LMC (left; De Marchi et al. 2010), in the cluster NGC 346 in the SMC (middle; De Marchi et al. 2011a) and in NGC 3603 in the Galaxy (right; Beccari et al. 2010). All colours are corrected for extinction. Stars with small photometric errors (small dots in light gray) define the reference template for normal stars (i.e. with no $H\alpha$ emission), shown here as a dashed line. Strong $H\alpha$ emission results in a greater than average value of $V - H\alpha$. We have identified in this way $\sim 3\,400$ PMS stars in the three galaxies.

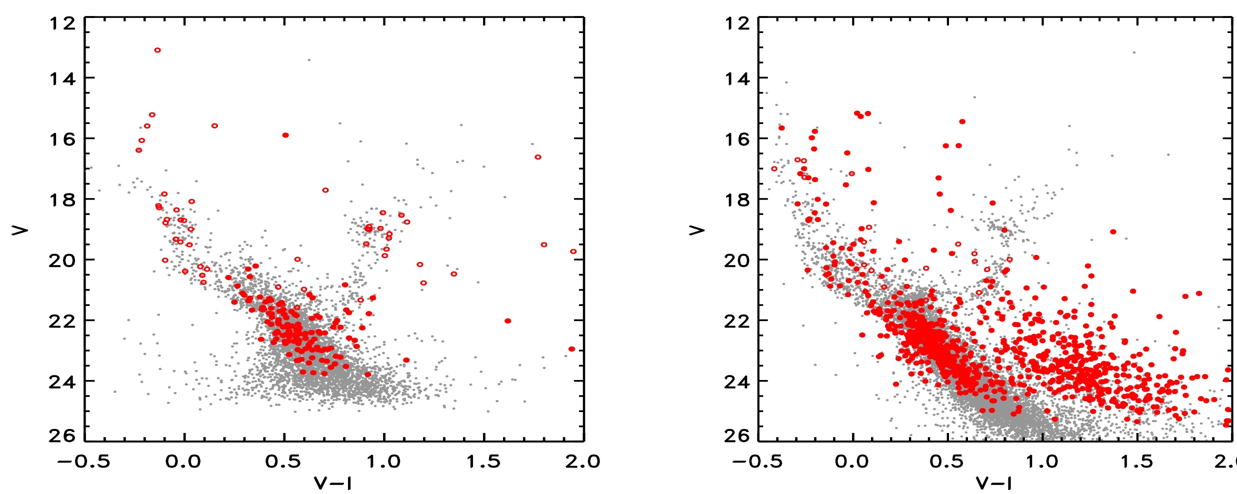

Figure 2: Colour–magnitude diagrams for the fields around SN 1987A (left) and around NGC 346 (right). Stars with significant $H\alpha$ excess are highlighted. Whilst some are still very young, and as such still very distant from the MS, many are older objects already approaching the MS, and as such would not be distinguishable from normal MS stars using standard broad-band photometry alone. By detecting all stars with an $H\alpha$ excess, we can easily identify and study multiple stellar populations in any given region.

The virtue of this new method is that it derives the luminosity of the photospheric continuum of a star inside the specific $H\alpha$ band simply by interpolation from the average $V - H\alpha$ colour of stars with the same $V - I$ index (Fig. 1), the majority of which have no emission.

Equipped with the knowledge of the continuum level in the $H\alpha$ band, we can easily determine the $H\alpha$ luminosity, $L_{H\alpha}$, of each star. The method and its applications are fully explained in a series of papers (De Marchi et al. 2010; 2011a, 2011b; Spezzi et al. 2012) and the accuracy of the $H\alpha$ continuum and $L_{H\alpha}$ derived in this way is independently confirmed by spectroscopic measurements (Barentsen et al. 2011). This method allows us to identify all objects with an excess emission, including relatively "mature" PMS stars, already close to the MS (see Fig. 2), that broad-band photometry alone could not distinguish from normal MS stars. Thus, we can (1) identify different generations of stars within the same region, (2) derive their physical propertiest through comparison to evolutionary tracks for the appropriate metallicity, and (3) study their spatial distribution to establish the relationship to massive stars and nebular gas.

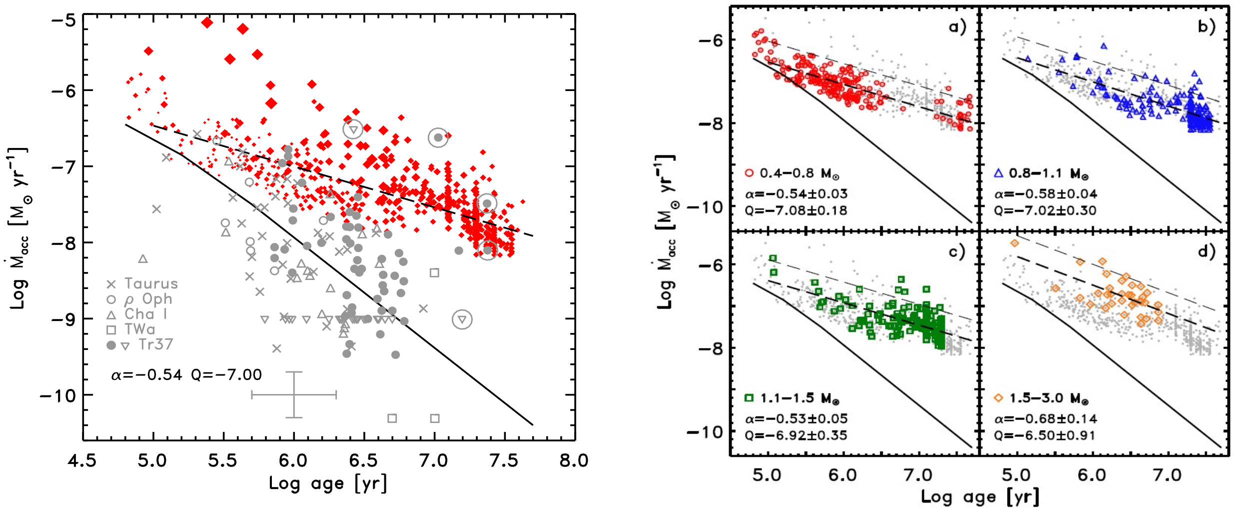

Figure 3: The left panel shows the mass accretion rate as a function of stellar age for PMS stars in NGC 346 (diamonds) compared with that of Galactic T Tauri stars (see legend) from the work of Sicilia–Aguilar et al. (2006; the large cross indicates the uncertainties as quoted in that paper). The solid line shows the evolution for current models of viscous disc evolution from Hartmann et al. (1998). Our measurements are systematically higher than the models, and the effect remains when we consider separately stars of different masses (right panel, see legends for mass values). All four mass groups show the same decline of $\dot{M}_{\rm acc}$ with age ($\alpha \simeq -0.6$, thick dashed lines), but $\dot{M}_{\rm acc}$ is higher for more massive stars (see value of intercept Q at 1 Myr).

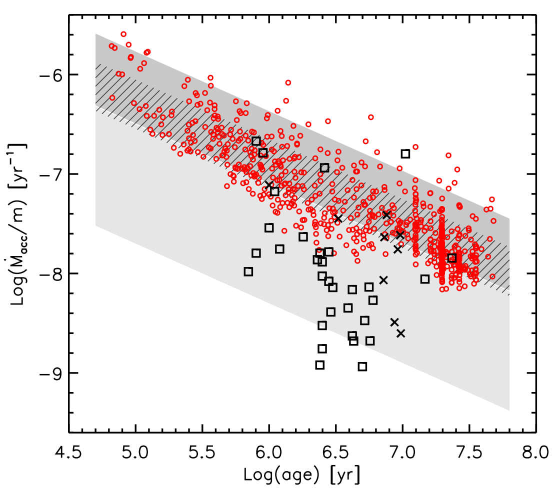

Figure 4: Run of $\dot{M}_{\rm acc}/m$ as a function of age for the PMS objects in NGC 346 (circles) and for Galactic stars in Taurus (crosses) and in Trumpler 37 (squares). The hatched band show the best fit ($\pm 1\,\sigma$) to the NGC 346 data, the dark-shaded band is the fit to the PMS stars in the 30 Dor region (De Marchi et al. 2011c) and the light-shaded band is the fit to the Galactic stars. We note that the value of $\dot{M}_{\rm acc}$ in the Galaxy is systematically lower than in the MCs at all masses and ages.

All regions that we studied exhibit multiple recent episodes of star formation, indicating that star formation has proceeded over a long time, even though our age resolution cannot discriminate between an extended episode or short and frequent bursts. We also find that there is no correlation between the projected spatial distribution of young and old PMS stars and that the younger population is systematically more concentrated.

A fundamental parameter that we can derive with this method is the mass accretion rate, $\dot{M}_{acc}$. Since the energy released by the accretion process goes towards ionising and heating the circumstellar gas, the accretion luminosity L_{acc} can be derived from $L_{H\alpha}$. With the mass and radius of each PMS star determined from the evolutionary tracks, the value of $\dot{M}_{acc}$ can be obtained from the free-fall equation.

We find that older PMS stars have typically lower mass accretion rates (see Fig. 3) and this suggests an evolutionary effect (assuming that the initial conditions are the same at all times). However, the effects of temporal evolution are partly masked by the considerable scatter around the best fit due to the wide range of masses that we cover.

A multivariate linear regression fit to the distribution of $\dot{M}_{\rm acc}$ as a function of age (t) and mass (m), allowed by the size of our sample, gives $\log \dot{M}_{\rm acc} \simeq -0.6 \times \log t + \log m + C$, where C is a function of the metallicity Z and is approximately proportional to $Z^{-1/3}$ (Fig. 5).

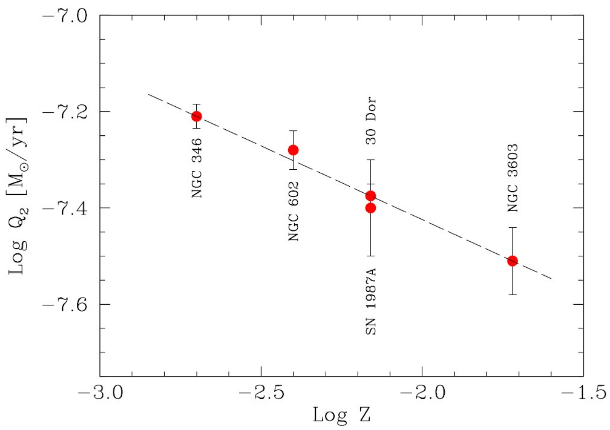

Figure 5: The average mass accretion rates for stars of 1 $M_\odot$ and age 2 Myrs for clusters in the SMC (NGC 346, NGC 602), LMC (30 Dor, SN 1987A field) and the MW (NGC 3603) as a function of their average metallicities. It appears that the accretion rates are a monotonically decreasing function of the metallicity, i.e $\dot{M} \propto Z^{-1/3}$.

In terms of this relationship, the systematic offset of Galactic PMS stars relative to stars in the Magellanic Clouds is as large as factor of six (see Fig. 4).

While our method will inevitably miss some PMS stars with weak $H\alpha$ excess emission, it is very unlikely that ground-based searches of nearby star-forming regions have missed PMS stars with strong L_{acc}. Thus, the difference is real, showing that the accretion process depends not only on age and mass, but also on metallicity (see Fig. 5).

Other important results of our studies are:

• In each region we find evidence for several episodes of star formation, with typical time separation of 10 Myrs.

• Younger generations are spatially more concentrated.

• There are large mass function variations across star formation regions, in that we see stellar groups that are rich of young low mass stars but lack any massive stars, and, viceversa, there are isolated massive stars with no low mass stars associated to them.

• These findings suggest that the processes of star formation be appreciably different for high- and low-mass stars.

Actually it is possible that a large number of low-mass stars are forming in regions where massive stars cannot be produced and, therefore, they remain unnoticed. For certain low surface density galaxies this might be the predominant mode of star formation, which would imply that their total mass based on their luminosity can be severely underestimated and that their evolution not be correctly understood.

Acknowledgement

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DISCUSSION

MANAMI SASAKI: In order to increase the statistics for metal abundance dependencies would it be possible to study stellar populations in M 31 od M 33?

NINO PANAGIA: I wish it was possible but, unfortunately, at present the angular resolution of the available telescopes, even HST, is not good enough to resolve solar mass objects in star forming regions at the distance of M 31 or M 33. In the future the combination of very large telescopes, say >30 m and adaptive optics should eventually do the miracle.

JIM BEALL: Would you expect the same relationship between accretion rates and abundances in massive stars?

NINO PANAGIA: The pre-main-sequence evolution of massive stars is so fast that it is hard to catch one of them while it is still accreting from their parent envelope. Therefore, I don't have an observational answer to your question. From a theoretical point of view, one would need a detailed knowledge of what determines the accretion process under conditions appropriate for massive stars. And, unfortunately, I don't have that, either.