Star formation in the Local Group

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Summary: We have undertaken a systematic study of pre-main sequence (PMS) stars spanning a wide range of masses (0.5 – 4 $M_\odot$), metallicities (0.1 – 1 Z_\odot) and ages (0.5 – 30 Myr). We have used the HST to identify and characterise a large sample of PMS objects in several star-forming regions in the Magellanic Clouds, namely 30 Dor, the SN1987A field and NGC1850 in the LMC and NGC 346 and NGC 602 in the SMC, and have compared them to PMS stars in similar regions in the Milky Way, such as NGC 3603 and Trumpler 14. Thanks to a novel method that we have developed to combine broad-band (V, I) photometry with narrow-band H\alpha imaging, we have determined the physical parameters (temperature, luminosity, age, mass and mass accretion rate) of more than 3000 bona-fide PMS stars still undergoing active mass accretion. This is presently the largest and most homogeneous sample of PMS objects with known physical properties and it includes not only very young objects, but also PMS stars older than 10 – 20 Myr that are approaching the main sequence (MS). We find that the mass accretion rate scales roughly with the square root of the age, with the mass of the star to the power of 1.5, and with the inverse of the cube root of the metallicity. The mass accretion for stars of the same mass and age is thus systematically higher in the Magellanic Clouds than in the Milky Way. These results are bound to have important implications for, and constraints on our understanding of the star formation process.

In the current star formation paradigm (e.g. Lynden-Bell & Pringle 1974; Bertout 1989), low-mass stars grow in mass over time through accretion of matter from a circumstellar disc. A reliable measurement of the rate of mass accretion onto PMS stars is of paramount importance for understanding the evolution of both the stars and their discs (Calvet et al. 2000). Of particular interest is determining how the mass accretion rate varies with time as a star approaches the MS, how it depends on the mass of the forming star and how it is affected by the chemical composition and density of the parent molecular clouds or by the proximity of massive stars.

Ground-based spectroscopic studies of nearby young star-forming regions (e.g. Taurus, Auriga, Ophiuchus; e.g. Sicilia–Aguilar et al. 2006) show that the mass accretion rate appears to decrease steadily with time, from about $10^{-8} M_\odot$ yr$^{-1}$ at ages of ~1 Myr for stars of about 0.5 $M_\odot$ to less than $10^{-9} M_\odot$ yr$^{-1}$ for the same star at ages of ~10 Myr (e.g. Muzerolle et al. 2000; Sicilia-Aguilar et al. 2005; 2006; 2010). At face value this is in line with the expected evolution of viscous discs (Hartmann et al. 1998), but the scatter of the data exceeds 2 dex at any given age (see also Fig. 3). Such a scatter can 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 very 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. 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, including temperature, luminosity, age, mass and mass accretion rate. This is the largest and most homogeneous sample of PMS objects with known physical properties.

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 (see 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. 2010b, 2011a, 2011b, 2011c, 2013a; Spezzi et al. 2012) and the accuracy of the H\alpha continuum and L(H\alpha) derived in this way has been independently confirmed by spectroscopic measurements (Barentsen et al. 2011).
Figure 1. Run of the $V - H\alpha$ colour as a function of $V - I$ in a field around SN1987A 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 (the lines are not the same in the three panels due to differences between the HST cameras). When $H\alpha$ emission is present in PMS stars, this results in a greater than average value of $V - H\alpha$. We conservatively take as PMS objects all stars with $V - H\alpha$ colour departing from the template line more than four times their photometric uncertainty (thick red dots). We have identified in this way $\sim 3,400$ PMS stars in the three galaxies.

This method allows us to identify all objects with considerable excess emission ($W_{eq} > 10$ Å), 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 properties 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.

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 obvious correlation between the projected spatial distribution of young and old PMS stars and that the younger population is systematically more concentrated whereas older PMS stars are further out, away from the centre of current star formation, regardless of whether we select stars with $H\alpha$ excess or with near infrared excess (De Marchi et al. 2013b). We find this separation in all environments that we have studied, in the Magellanic Clouds as well as in the Milky Way. These findings confirm that the stars with excess that in the CMD appear close to the MS are not just young objects simply affected by veiling, cold accretion or with a disc at high inclination that scatters preferentially the blue light towards us. Veiling, cold accretion and scattering can indeed move some of the objects across the CMD, but definitely they cannot move them across the sky! Therefore, there underlying difference between these populations must be their age.

A fundamental parameter that we can derive with this method is the mass accretion rate, $M_{acc}$. 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 $M_{acc}$ 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 range of masses that we cover.

A multivariate linear regression fit to the distribution of $M_{acc}$ as a function of age $t$ and mass $m$, allowed by the size of our sample, gives $\log M_{acc} \approx -0.5 \times \log t + 1.5 \times \log m + C$, where $C$ is a function of the environment. Since within the uncertainties the dependence of $M_{acc}$ on mass and age as given above applies equally well to both Magellanic clouds and to the starburst clusters that we have studied in the Milky Way, we can reveal systematic differences in the properties of $M_{acc}$ between these environments by studying the variations of the parameter $C$. In practice, $C$ corresponds to the mass accretion rate of an object with $t = 1$ yr and $m = 1 M_\odot$. 
star of given mass and age is systematically higher in the SMC than in the LMC, than in the Galaxy. 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 $L_{\text{acc}}$. Thus, the difference is real, showing that the accretion process depends not only on age and mass but also metallicity. Clearly these effects must be understood in detail, as they can have tremendous implications for the formation of stars and planets in environments of low metallicity, such as in the early Universe.

Even though we have already extended the sample of PMS stars with a measured mass accretion rate by an order of magnitude in number and to lower metallicities, our finding that accretion is more efficient at low metallicity is still preliminary, being dominated by the PMS populations of NGC 346 and 30 Dor. To guarantee considerable progress in this field, we have just completed with the HST an $H\alpha$ survey of nine star-forming regions in the Milky Way and Magellanic clouds, covering a wide range of ages, chemical compositions and stellar densities. Combining our own observations with the extensive coverage of the Tarantula nebula just completed with the HST (Sabbi et al. 2013), we have secured a sample of more than 20,000 PMS stars and will spend the next year to accurately measure their age, mass and mass accretion rate. By increasing the current sample by almost two orders of magnitude, this investigation will make it possible for the first time to study in detail and with high statistical significance how metallicity, age and the environment regulate the stellar mass growth and the star formation process in general.

A comparison of the accretion rates in the various regions that we have studied so far suggest that $C$ scales with the cube root of the metallicity, $C \propto Z^{-1/3}$, because the mass accretion rate for a star of given mass and age is systematically higher in the SMC than in the LMC, than in the Galaxy. 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 $L_{\text{acc}}$. Thus, the difference is real, showing that the accretion process depends not only on age and mass but also metallicity. Clearly these effects must be understood in detail, as they can have tremendous implications for the formation of stars and planets in environments of low metallicity, such as in the early Universe.

In the longer term, this research will make use of the multi-object spectroscopy ability of NIRSpec on board JWST to obtain medium resolution spectra of a representative sample of these objects. Although current multi-object spectrographs at large ground based observatories in principle have the sensitivity needed to obtain spectra of PMS stars in the Magellanic clouds, atmospheric seeing makes these studies possible only for the most massive among them, namely Herbig Ae objects (e.g. Kalari et al. 2014). These stars evolve very quickly through the PMS
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 discs from Hartmann et al. (1998). Our measurements are systematically higher than those models, and the effect remains even when we consider separately stars of different masses (right panel, see legends for mass values). All four mass groups show the same decline of $M_{\text{acc}}$ with age ($\alpha \approx -0.5$, thick dashed lines), but $M_{\text{acc}}$ is higher for more massive stars (see value of intercept $Q$ at 1Myr). Although our method will inevitably miss some stars with weak $H\alpha$ excess emission, the upper envelopes of the distribution (thin dashed lines) appear to be fully consistent with the slope of the best fit.

phase and do not allow us to probe the progression of star formation on scales of several 10 Myr as lower-mass objects do. With NIRSpec we will obtain spectra of individual PMS stars down to $\sim 0.5 M_\odot$ and study in detail their physical properties. This will in turn allow us to completely validate and optimise our photometric approach and to extend it with NIRCam to even more distant or obscured star forming regions in the Local Group. These studies are very much needed if we want to interpret star formation in a cosmological context.

References