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The birth of stars in star forming regions and in Globular Clusters

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Abstract. Understanding the physics of star formation is one of the most challenging tasks of modern astrophysics. Beside the well known and documented problems associated to the interpretation of the observed color-magnitude diagrams of star forming regions, other problems arose in the way of interpreting the recent observational evidence of Globular Clusters stars, that indicates that the assumption that these constitute a simple stellar population, sharing the same age and chemical composition, needs severe revision. We discuss the difficulty towards the comprehension of the way with which stars form, that is limited by the partial unreliability of theoretical tracks and isochrones describing the Pre Main Sequence stage. Some possible solutions of the existence of multiple populations in Globular Clusters, indicating more than a single star formation episode, are also discussed.

Key words. Stars: evolution — Stars: rotation — Stars: pre-main sequence — Globular Clusters: general

1. Introduction

Studies focused on understanding the star formation process show that the way with which stars form is rather complex; this is confirmed both for newly born objects in star forming regions in the Galaxy, and for more compact structures like Globular Clusters (GC), that have been traditionally interpreted as being a simple stellar population.

Observations of young stellar systems prove to be an essential tool for these studies. The advent of HST made it possible to extend the galactic surveys to systems external to the Milky Way. Gilmozzi et al. (1994) studied a population of Pre Main Sequence (PMS) objects in NGC 1850 (LMC), followed by two investigations by Romaniello et al. (2004) and Romaniello et al. (2006), that identified, respectively, a group of PMS stars in the SN1987A field and in the 30 Doradus region. The importance of these pioneering studies was that they evidentiated some differences in the distribution of mass and age between systems formed in the Galaxy and in the Magellanic Clouds, thus suggesting that the physics of the star formation depends in some way on the environment where stars form. Other systems external the Milky Way have been discovered in the last decade, allowing very detailed analysis aimed to understand the star formation hystory of the populations investigated (see, e.g., the recent work by Cignoni et al. (2009) on NGC 602, in the SMC).

The investigations focused on the physics of star formation have been traditionally ded-

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icated to the star forming regions, but in the last decades the interest of researchers also encompass more closed environments, such as the Globular Clusters: despite these latter have been traditionally identified as simple stellar populations, made up of objects born at the same time, and thus with the same chemical composition, there is a convincing observational evidence, both from the spectroscopic (Kraft, 1994) and the photometric (Piotto et al., 2007) side, that more generations of stars are present, in particular in the most massive GCs.

In this contribution we describe the problems currently affecting the use of theoretical stellar models to understand the distribution of mass and age in young stellar associations, outlining the main discrepancies between theory and observations that limit the possibility of using the stellar tracks and isochrones to shed light on the process of star formation. We trace the status of the studies focused on the physics of stellar rotation, which is the key ingredient often invoked to explain the afore mentioned discrepancies.

Finally, we focus of the debate, still open, on the possibility that in GCs multiple stellar generations exist, and describe the hypothesis, still to be confirmed, that further stellar populations may form in GCs from the gas ejected by rapidly-evolving stars belonging to the first generation, according to the so called "self enrichment" scenario scheme (Cottrell & Da Costa , 1981). The two most common hypothesis, i.e. that the polluting stars are massive rotating objects (Decressin et al. , 2007), or intermediate mass stars the evolve along their Asymptotic Giant Branch (AGB) phase (Ventura et al. , 2001), are described and commented.

2. Understanding the star formation history in star forming regions

2.1. The uncertainties in PMS modelling

The interpretation of photometric results of stars belonging to young systems are normally based on the comparison between theoretical and observed stellar locii. Sets of individual tracks are used to assign the masses, whereas the isochrones allow to infer the age distribution.

Unfortunately, the path followed by the PMS tracks is extremely sensitive to the way with which convection is modelled, the tracks becoming hotter when a more efficient convective mechanism is adopted (see, e.g., Montalban et al. (2004)). We may quote the result by Landin et al. (2006), that, in an attempt of interpreting the population of the Orion Nebula, found the results to be strongly dependent on the free parameter (α) entering the Mixing Length Theory (MLT) prescription to evaluate the temperature gradient with regions unstable to convection.

A very exhaustive analysis concerning the uncertainties of PMS modelling was presented by Hillenbrand & White (2004), who compared a set of $\sim$ 150 PMS objects with known masses with those assigned theoretically on the basis of tracks presented by different research groups. The result was that while for masses in the range $M > 1.2M_{\odot}$ the agreement is reasonable, meaningful discrepancies emerged for lower-mass objects, the theoretical masses being sistematically lower than the true values. This investigation showed that the ages attributed to various stellar systems vary according to the tracks adopted, and that, even when adopting a single set, age differences are found to depend on the range of masses investigated: older ages are assigned when bluer objects (hence more massive) are considered.

These results indicate that a full understanding of the PMS evolution of stars is far from being completely understood, the main problem being that the theoretical tracks of the less massive models are indeed too hot, thus indicating that a less efficient convective model should be adopted to describe this evolutionary phase for these masses.

2.2. The lithium depletion

An indipendent indicator of the reliability of the PMS theoretical evolution is the depletion of the surface lithium initially present within the star. Lithium is an extremely volatile element, and is thus easily destroyed at the bottom of the convective envelope, as soon as the temperature exceeds $\sim 2 \times 10^6$K. Together with deuterium, it is the only species undergoing proton capture during the PMS phase.

This nuclear burning is a natural explanation of the Lithium vs. effective temperature pattern observed in even the youngest open clusters (Soderblom et al. , 1993), for which a major contribution during the following main sequence phase (MS) can be ruled out. The lowest masses possess a deeper convective envelope, and are thus more suitable to lithium destruction compared to their more massive counterparts: this is the reason why cooler objects show a smaller surface lithium content. When the theoretical expectations are compared with the data, a clear difficulty arises: models in which convection is modelled with the same efficiency required to fit the Sun deplete too much lithium, the discrepancy with the observations increasing for the lowest masses (D'Antona & Montalban , 2003). These results have been recently confirmed by more detailed investigations, where many different mixtures have been considered in the evaluation of the opacity in the interior (Sestito et al., 2006).

These findings, in agreement with the results outlined precedently, confirm that a less efficient convective model is required, and suggest that some key-ingredient is still missing in the input physics adopted to simulate the evolution of the young, PMS objects.

Based on the fact that some of these stars are observed to rotate very fast, the interest of modellists was recently focused on the effects of rotation. We describe the most recent development on this topic in the next section.

3. Rotating stars

Rotation is known to produce a structural effect on the star, by reducing the effective gravity by means of the centrifugal acceleration. A full investigation of the effects of rotation must also include the mixing induced by the redistribution of the internal angular momentum, that splits into a diffusive and an advective component (Zahn , 1992).

On the observational side the massive stars are those where the physics of rotation can be tested more efficiently, because they are known to rotate fast, and undergo strong mass loss, by which they pollute the interstellar medium. Meynet & Maeder (2000) presented a first investigation focused on solar metallicity stars, that showed that stars initially rotating as rigid body tend to develop already during the main sequence phase a gradient in the angular velocity, triggered by angular momentum losses from the surface. The development of a meridional circulation velocity field tends to smooth out these gradients, and renders more uniform the angular velocity profile.

The development of an internal gradient of angular momentum, with the consequent effects on mixing, is shown by Meynet & Maeder (2002) to be enhanced in lower metallicity models, for two reasons:

1. Low metallicity stars suffer a smaller mass loss, thus reducing the overall angular momentum losses, and keeping a higher internal angular velocity profile.
2. The meridional circulation velocity U(r) is proportional to the Gratton-Opik term, which is $\sim (E_\Omega + E_\gamma)$ (Zahn , 1992), where $E_\Omega \sim -\Omega^2/2\pi G\rho$. At low metallicities, the structure evolves at higher densities, which reduces U(r), and thus the internal redistribution of angular momentum determined by the meridional circulation itself.

Both effects determine a much steeper gradient of angular velocity inside low metallicity models, that is expected to favour a strong mixing in the interiors.

Meynet & Maeder (2002) showed that during the core He-burning phase outwards mixing of carbon produced by 3α reactions and inwards mixing of protons from the outer layers favour proton capture reactions by carbon nuclei to occur, with the consequent production of great amounts of nitrogen, that renders these stars the most efficient producers of primary nitrogen. This effect is seen to increase for smaller Z, until the metallicity becomes so small that the stars evolve at almost constant angular momentum: in this latter case the expansion of the structure following hydrogen exhaustion in the core is associated to a general spin-down, so that only a modest mixing takes place, and less nitrogen is produced (Ekström et al. , 2008).

Rotating models reproduce qualitatively and quantitatively the (N/O) and (C/O) vs (O/H) patterns observed in metal poor stars in the Galaxy (see e.g. Israelian et al. (2004), Spite et al. (2005), Spite et al. (2006)), allowing for the first time to explain the extremely high N/O ratios detected at small metallicities.

Despite these promising results, the reliability of these models, particularly for what concerns the efficiency of the internal mixing associated to the angular velocity gradient, is still from being confirmed. A recent analysis by Suijs et al. (2008) showed that the development of such a gradient is expected to be associated to the presence of magnetic torques which, in turn, would favour strong angular momentum losses. Results from full evolutionary models indicate that when these effects are considered the angular momentum drops by almost two orders of magnitude, which would dramatically modify the picture above discussed.

4. Multiple populations in Globular Clusters

The popular idea that GC stars are a single stellar population, whose objects share the same age and chemical composition, was challenged by many spectroscopic and photomteric analysis that evidentiated many anomalous patterns, in contrast with the homogeneity expected on the basis of the above hypothesis.

1. Spectroscopic analysis of GC stars, extended down to Turn-Off and SGB luminosities, outlined star-to-star differences in the surface abundances of the light elements (up to Alluminum). The finding, common to the totality of the GCs observed, that Sodium is anticorrelated to Oxygen, and Magnesium is anticorrelated to Alluminum (Carretta et al. , 2006), suggests the presence of material nuclearly processed via multiple proton capture reactions.
2. Piotto et al. (2007) discovered three main sequences in the massive GC NGC 2808, that can be interpreted only by assuming the presence of three group of stars, differing in the helium content.

The fact that some stars showing the anomalous surface chemistry belong to the MS and the SGB rules out the possibility that these features are due to some in situ mechanism, such as a sort of extra-mixing enriching the outer envelope with material that had been nuclearly processed in previous evolutionary phases, and confirms that this chemical composition was the same as the gas from which these stars formed. According to the self-enrichment scenario scheme (Cottrell & Da Costa , 1981), the stars showing up the chemical anomalies were born in an environment that was contaminated by the matter lost by an early generation of rapidly evolving stars, the main candidates being either massive, rapidly rotating stars, or intermediate mass stars during the AGB phase.

According to the first hypothesis, the pollution of the interstellar medium would take place during the main sequence phase of massive, rotating stars, when the high angular momentum favours angular velocities close to break-up, so that the mass lost could be ejected into the interstellar medium via the formation of a decretion disk (Decressin et al. , 2007). The enhanced mixing favoured by the internal angular momentum gradient would enrich the external envelope with nuclearly processed matter, that would show the signature of proton captures. For this mechanism to work it is essential that strong angular momentum losses make rotation to slow down, so that during the following core helium burning phase mass is lost via high velocity winds, that are ejected out of the cluster. This hypothesis is supported by the oxygen and sodium abundances observed, although it is hardly consistent with the large alluminum abundances detected, and particularly with the distribution of helium, that is observed only at discrete values, and not with a continuous distribution predicted by the scenario (Renzini , 2008).

The AGB hypothesis seems to match better the observational evidence. This idea was initially disregarded, because even models of the most massive among the intermediate masses were unable to achieve oxygen depletion in the outer convective zone (Fenner et al. , 2004), but was later reconsidered when Ventura & D'Antona (2005) showed that when convection is modelled efficiently, massive AGBs reach extremely hot temperatures at the bottom of their external mantle, and undergo strong Hot Bottom Burning (HBB) (Blöecker & Schoenberner , 1991), with the activation of practically all the proton capture channels. The observed anticorrelations are naturally achieved, and these results also provide a natural explanation for the existence of multiple main sequences, as one of the most robust predictions concerning the yields of this class of objects is that they are expected to be helium rich.

5. Conclusions

The process of star formation is one of the most complex phenomena of extreme interest in modern Astrophysics. The advent of HST provided a unique opportunity of identifying young associations even out of the Galaxy, thus opening the way for an investigation of the star formation properties in other galaxies, and how these are influenced by the environment.

Theoretical tracks and isochrones are essential tools to shed light on the physics of star formation, as they allow to determine masses and age distribution of any stellar sample in a young association. Unfortunately, the PMS stellar models are extremely dependent on the way with which convection is modelled in the outer region, so that different masses and ages are assigned to the observed objects, when using different tracks. The comparison between stars with known masses and theoretical predictions indicate that the present generation of PMS models, calibrated on the evolution of the Sun, are characterized by a convective description which is too efficient; this problem is further enhanced by noting that the extent of the discrepancy varies with mass, and is maximized for the coolest objects.

The idea that rotation may play a role pushed researchers to build rotating stellar models, that are more generally invoked to explain the high nitrogen content of many metal poor stars. The way that stars form in more closed environments, such as Globular Clusters, is also far from being completely understood. The spectroscopic and photometric analysis of most of the GCs examined evidentiated that the standard paradigma of a simle stellar population must be abandoned, and suggested that at least one further episode of star formation must have occurred, with the new stars that form in an environment polluted by the winds of rapidly evolving objects of the first generation, that are probably the intermediate mass stars.

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