CURRENT VIEWS ON LOW-MASS STAR FORMATION
Francesco Palla and Sofia Randich
INAF–Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5, 50125 Firenze, Italy

Abstract
The process that leads to the formation and early evolution of low-mass stars is in a broad sense well understood theoretically and carefully traced observationally. The largest uncertainties in this framework reside in the poorly known initial conditions for the origin and gravitational collapse of dense cores within molecular clouds. In this review, we will discuss the evidence for an accelerated pattern of star formation in clusters and associations, the physical origin of this phenomenon, and the age spread in low-mass star forming regions. On the latter issue, we will show how the observation of lithium depletion in young clusters, such as the Orion Nebula Cluster and the Upper Scorpius association, can provide an independent estimate of their ages and age spreads with important implications on the understanding of the initial conditions and history of star formation.

Key words: Stars: Low mass – Stars: Formation and Evolution – Young Clusters and Associations

1. Introduction
Boldly stated, the formation of low-mass stars (solar and below) is a rather well understood process, both theoretically and observationally. Empirically, circumstantial evidence has been accumulated in the last three decades over the whole e.m. spectrum, from X-rays to the millimeter domain. This progress has led to a paradigm that allows to follow the evolutionary path of a nascent low-mass object from the initial seed, a dense molecular core within more diffuse gas, to the formation of an accreting protostellar core with its attendant outflow, to the final buildup through a circumstellar disk (e.g., Shu et al. 1999). Each step is characterized by a complex array of physical processes that have been theoretically laid out and analyzed in detail with semianalytic techniques or by means of sophisticated numerical simulations. Of course, the extremely wide range of physical scales involved prohibits (or limits substantially) the ability to follow in a single model the fragmentation, collapse and accretion/ejection phase of a low-mass object including all the essential processes. As a result, some fundamental questions are still only partially answered, including the origin of outflows, the mechanisms responsible for mass accretion in disks, etc.

Another important aspect that has emerged from observational studies is that most stars in the Galaxy form in clusters and associations and that the occurrence of isolated objects and small groups represents a rare phenomenon restricted to specific regions, such as Bok globules and bright rimmed clouds. Considering the solar vicinity, the vast majority of the young stellar population within 0.5 kpc from the Sun is contained in a variety of T, R, and OB associations (about 30 known groups), plus 15 embedded clusters of varying richness (e.g., Lada & Lada 2003), and a number of relatively sparse moving groups and associations (e.g., Lepine & Gregorio-Hetem 2003). Thus, in order to discuss the problem of low-mass star formation in a more realistic way, one should be able to answer the basic question of how do stars form in groups, clusters, and associations. Equally important is to consider the relation of the young stars found in these systems to the molecular clouds and cloud complexes that spawn them.

The problem of the origin of low-mass stars is obviously directly linked to the question of what supports a massive cloud against its self-gravity before the production of an interior stellar group: how do individual dense cores, each capable of forming single and binary stars, arise within the magnetized and turbulent medium that characterizes molecular clouds? Considering the main interests of the participants at the Cool Stars meetings, in this review we will focus the attention on these global issues rather than the specific problems related to the formation of a single/binary system. As we will see, there is a lot of fertilization in the field of star formation that can come from studies traditionally carried out by the stellar community.

2. Models of global star formation
Answering the above questions requires a broader understanding that is currently at hand, one that connects the birth of individual stars to the growth and evolution of clouds on a multiparsec scale. A big effort in this respect is represented by a variety of numerical simulations of cloud evolution and star formation based on gravoturbulent (e.g., MacLow & Klessen 2004) or MHD turbulent (e.g., Padoan et al. 2004) models. In simple terms, the picture that emerges from these models is one in which
molecular clouds are formed in large-scale turbulent HI flows and that the intersection of these flows compresses the gas to the point that it collapses, fragmenting simultaneously into stars over a broad front. Star formation is thus considered as a process that occurs promptly in localized regions where turbulence is dissipated in a dynamical timescale (Elmegreen 2000). Then, molecular clouds can sustain star birth only for few million years.

This dynamic picture contrasts sharply with that suggested by, e.g., Palla & Stahler (2002) in which the formation of dense cores is not seen as a random event in the cloud medium, but is supposed to occur in response to some global change in that medium. One such change would be large-scale, gravitational contraction of the parent cloud. This contraction presumably occurs through gradual loss of the mechanical support driven by ambipolar diffusion, i.e. the clouds evolve in a quasi-static fashion (see also Tassis & Mouschovias 2004). The time scale for this process is of order \(\sim 10\) Myr and exceeds that predicted by the dynamic models.

Empirical evidence in favor of the slow mode of star formation comes from the reconstruction of the star formation history in clusters and associations using the classical method of placing stars in the HR diagram to infer isochronal ages. The application of this method to the most conspicuous regions in the solar vicinity with a statistically significant population of young stars has led to the following conclusions (Palla & Stahler 2000). In general, it is found star formation began at modest levels roughly \(1 \times 10^7\) yr in the past and increased rapidly toward the present epoch with an acceleration pattern. This trend is similar in different systems, although the time scale of the acceleration varies from region to region, typically between 1 and \(3 \times 10^6\) yr. The fast acceleration must be followed by a prompt deceleration to limit the global star formation efficiency of each unit to the observed low values (few percent). Evidence for such a steep decline is seen in regions such as Upper Scorpius and \(\lambda\) Ori where the activity reached a peak \(\sim 3 \times 10^6\) yr ago and then dropped essentially to zero owing to the efficient removal of the dense gas by the radiative and mechanical effects of massive stars.

The physical interpretation of this empirical pattern is that the formation and evolution of dense cores and stars therein occurs in response to a global, quasi-static contraction of the parent cloud. Then, the formation of stars is seen as a threshold phenomenon where a minimum column density of molecular gas must be reached for dense core formation which then produce stars on a relatively brief time scale. Although these findings seem to be robust, a number of important effects (incompleteness of the knowledge of both the dense gas and stellar population in each system, uncertainties in PMS tracks and isochrones and in stellar parameters, etc.) should be considered carefully in each case. The limitations of the method have been analyzed by Hartmann (2002, 2003), while additional discussion is provided by Palla (2004). Let me conclude this section by noting that the two models discussed above have a strong similarity, namely the accelerating character of star formation, but depart in an essential respect: in the dynamic mode there is no past activity and star formation occurs in a single major burst, while in the quasi-static mode there is a long history that can be traced back to its beginnings.

3. Age spreads in star forming regions

The presence of a relatively old population in young clusters and associations seems to indicate that molecular clouds can produce stars over extended periods of time. Whether the inferred age spread is real or not is the central question to be answered. Although much information is available from the study of regions of ongoing star formation, a definite answer cannot come from them since they are still actively turning dense gas into stars and we cannot infer how long this process will continue in the future. Thus, active SFRs can only provide a partial estimate of the true age spread. This simple consideration rules out quite a large number of well known complexes, including Taurus-Auriga, Chamaeleon, and \(\rho\) Ophiuchi in which the amount of available gas for future episodes of star formation greatly exceeds that already converted into stars.

In contrast, the ideal laboratories to derive reliable age spreads are represented by two other classes of objects: fully exposed, young clusters and associations (\(t < 10\) Myr), and intermediate-age (\(t \sim 10–30\) Myr) open clusters. In both cases, the key to determine their age and age spread is the use of the lithium depletion history and boundary tests (LDB) as a powerful clock (e.g., Basri et al. 1996). This method is well known to the stellar community for its successful application to a number of older open clusters, such as \(\alpha\) Per, IC 2391, NGC 2547, and the Pleiades, with significant revisions of their ages (e.g., Jeffries 2004). In the remaining part of the section, We will discuss the potential of its application to younger systems.

3.1. The lithium test

The lithium test rests on the ability of young stars to deplete their initial lithium content during the early phases of pre–main-sequence (PMS) contraction. Young, low-mass mass stars (\(M_* < 1 M_\odot\)) begin their PMS phase with the full interstellar supply of lithium since the central regions are too cold to ignite nuclear burning during the protostellar phase. As contraction proceeds, the critical temperature for lithium reactions (\(\sim 2.5 \times 10^6\) K) is reached, and the initial content is readily depleted in fully convective, sub-solar stars (\(M_* < 0.5 M_\odot\)). It has been shown that the physics required to study the depletion history as a function of age has little uncertainty, since it depends only on the stellar mass and radius (e.g. Bildsten et al. 1997). Ac-
correspondingly, fully convective stars in the range 0.2–0.5 $M_\odot$ start to deplete lithium after about 2 Myr, and completely destroy it in approximately $\sim 10$ Myr (e.g., Baraffe et al. 1998). Lower mass stars take much longer to burn lithium, and there is a sharp transition (i.e., the boundary) between fully depleted objects and those with the initial lithium content. The mass at which the boundary occurs reveals the age of the cluster. The predicted region of partial and full lithium depletion is sketched in the HR diagram of Figure 1. Stars more massive than $\sim 0.8 M_\odot$ only burn a small fraction of the interstellar value; on the other hand, fully convective objects ($M < 0.5 M_\odot$) readily consume lithium while contracting toward the ZAMS.

![Figure 1. The region of lithium burning and depletion in the HR diagram. The light shaded area is for a depletion down to 1/10 of the interstellar value, while the darker shading indicates larger depletion. Theoretical tracks are from Palla & Stahler (1999), while the values of lithium depletion are from the models of Siess et al. (2000). The isochrone for 3 Myr is shown by the dashed line.](image)

Returning to the criteria for selecting suitable astronomical objects, the choice of open clusters with ages between 10 and 30 Myr is dictated by at least three reasons. First, by this time the star formation activity is certainly completed. Second, the age spread can be better estimated than for older systems since isochrones at this age do not suffer from crowding. Third, the LDB falls in the stellar regime (between 0.2–0.4 $M_\odot$ for typical distances) and thus can provide strong constraints on their internal structure. So far, the LDB test has been determined in older systems where it falls in the substellar regime. The identification of the best systems to study is not easy, due to an intrinsic paucity of open clusters of the appropriate age in the solar vicinity and an observational bias introduced by the current strong interest on the discovery and characterization of brown dwarfs in older clusters rather than on the accurate measurements of lithium abundances in low-mass stars. However, it is important that a large effort be dedicated to the study of younger clusters and the initial steps in this direction have already been started with the completion of the CFHT Key Project on Young Clusters (Bouvier et al. 2004, in preparation).

The other class of fully exposed, young clusters and associations may be considered at first sight a surprising choice since one would not expect to see any feature related to lithium burning and depletion. However, we will show below that this is not true in general and present the case of two extremely interesting objects, the Orion Nebula Cluster (ONC) and the Upper Scorpius Association (USA).

3.2. Li-depletion in the ONC

The ONC is the best known star forming region in the solar neighborhood. It is close ($d = 450$ pc), away from the Galactic plane ($b \sim -19^\circ$), and it lies in front of a giant molecular cloud, whose total extinction (up to $A_V = 50 - 100$ mag on the close edge) eliminates most of the background confusion. The richness of the stellar cluster ($n_\star \sim 3500$ stars) and density ($\rho_\star \sim 2 \times 10^4$ stars pc$^{-3}$ at the core) make the ONC an ideal, and unique target for the study of the full mass spectrum of young stars from 45 $M_\odot$ to less than $\sim 0.02 M_\odot$ (e.g., Hillenbrand 1997, Slesnick et al. 2004). The reconstruction of the star formation history indicates that the period of most active formation is confined to a few $\times 10^6$ yr, and has recently ended with the dispersal of the remnant molecular gas (Palla & Stahler 2000).

![Figure 2. HR diagram of the older population of low-mass stars of the ONC. The hatched regions have the same meaning as in Fig. 1.](image)

In addition to providing an average age of the ONC, the reconstruction of the pattern of stellar births has re-
revealed another important aspect regarding its age spread: namely, the existence of a small, but statistically significant population of older stars with estimated ages in excess of $\sim 5$ Myr. The distribution in the HR diagram of the low-mass members ($0.2-0.8 \, M_\odot$) is shown in Figure 2. Here, we see that there are more than about 80 stars that fall within the predicted Li-depletion region. Observations of a sample of $\sim 90$ stars (membership probability $>80\%$) with mass $0.4-0.8 \, M_\odot$ and isochronal ages greater than $\sim 1$ Myr have been carried out using FLAMES+Giraffe on ESO-VLT2 and the results are very encouraging (Palla et al. 2004, in preparation). As shown in Figure 3, we find a decrease of the Li-abundance by a factor 5–10 in the coldest ($T \sim 3700$ K) and faintest objects. Comparison with PMS evolutionary models indicates that the observed Li-depletion corresponds to stellar ages greater than $\sim 5$ Myr. These observations will be soon extended to members of mass down to $\sim 0.2 \, M_\odot$ with the goal of probing the full depletion history. Below $\sim 0.2 \, M_\odot$, the LDB would occur at an age $\geq 30$ Myr, well in excess of any realistic estimate of the age spread of the ONC. Note that independent evidence for a population of old stars in this cluster has been presented by Slesnick et al. (2004) in a study of the spectroscopically confirmed brown dwarf population.

We conclude that, despite its evident youth, the ONC is not simply the result of a single burst of star formation. Interestingly, a large number of low-mass stars of the USA (about 70) fall in the critical region where lithium depletion is expected to occur. Their distribution in the HR diagram is shown in Figure 4. For all of them, the Li I $6708$ Å line equivalent widths (EW) have been measured from low resolution spectra (Preibisch et al. 2002). The exciting result is that most of the objects for which substantial Li-depletion is expected indeed show lower values of EW(Li). Unfortunately, because of the poor spectral resolution, Li-abundances could not be reliably measured for comparison with the predictions of stellar models. The

Figure 3. Lithium abundances in stars of the ONC with mass $\simeq 0.4-0.5 \, M_\odot$ (Palla et al. 2004, in preparation).

Figure 4. HR diagram of the low-mass members of the Upper Scorpius Association (from Preibisch et al. 2002). The hatched regions have the same meaning as in Fig. 1.

3.3. Li-depletion in the USA

The Upper Scorpius Association (USA) is the nearest OB association to the Sun ($d=145$ pc) and the youngest of the three subgroups that compose the Scorpius-Centaurus OB2 association. In the recent past, the USA was a site of vigorous star formation activity that has produced a rich group of objects over the full mass spectrum (de Zeeuw et al. 1999 for the high mass and Preibisch & Zinnecker 1999 for the extension to low masses). Owing to the lack of dense molecular clouds in the vicinity (typically, $A_V \lesssim 2$ mag) and of deeply embedded young stellar objects, one can consider that the star formation activity in this region is basically finished, thus allowing a full census of the stellar population in the range $0.1-20 \, M_\odot$ (Preibisch et al. 2002).

Using the isochronal method for gauging stellar ages and hence the star formation history of the USA, Preibisch et al. (2002) find that the bulk of the stellar population is characterized by a rather narrow age distribution, centered at about 5 Myr ago. This property has been interpreted as evidence for a short-lived episode of star formation, perhaps triggered externally by the explosion of a nearby supernova (Preibisch & Zinnecker 1999). However, as in the case of the ONC, the USA displays a significant population of older stars with estimated ages in excess of $\sim 5$ Myr. If true, this finding suggests an alternative scenario to the rapid episode for the history of star formation.
trend of Fig. 5 is quite intriguing since the stars with the lowest EW(Li) are also the least massive objects of the sample for which the LDB is expected to show up. Future high resolution spectroscopic observations should be carried out to obtain accurate abundances and to test these initial results. In the meantime, we can conclude that the history of star formation in the USA seems not to be limited to a major single burst.

![Figure 5. Variation of the Li I 6708 Å equivalent width with age for the low-mass sample of the USA that falls in the Li-depletion region of Fig. 4. Filled circles correspond to stars in the dark region of the HR diagram of Fig. 4, while empty circles are for those in the light grey area.](image)

4. Conclusion

The initial tests on lithium depletion in the low-mass stars of two major systems, Orion and Upper Scorpius, can offer a new way of attacking the fundamental problem of determining the relevant time scale over which stars form in molecular clouds. Although the debate on the rapid vs. slow mode of star formation is still open, the observational support for the presence of an old population in young objects is becoming more compelling. Additional measurements of lithium abundances in other nearby, young clusters and associations can be (and will be) performed soon with existing instrumentation. The hope is that the results will offer not only stronger constraints on stellar interior models, but also more definite answers on the history of low-mass star formation.

Acknowledgements

We are very grateful to Roberto Pallavicini who has generously allocated part of the GTO time on FLAMES for the ONC observations and Ettore Flaccomio for useful discussions. Finally, it is a pleasure to thank the organizers of a very interesting and informative meeting.