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GAIA AND THE EVOLUTION OF YOUNG STARS

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Abstract. Some of the main problems concerning the evolution of low mass ($M \leq 1.5 M_{\odot}$) stars from the formation to the main sequence phase are summarized. The unique potentiality of *Gaia* in shedding light on the hidden parameters, which govern these phases of stellar evolution, are pointed out. *Gaia* will also be able to monitor the evolution of young massive brown dwarfs in the phase of deuterium burning.

Key words: stars: evolution, HR diagram, T Tauri-type – Galaxy: star-forming regions, Gould Belt

1. QUESTIONS ON STAR FORMATION

One of the present aims of study of the galactic star forming regions (SFRs) is to understand the process of star formation in different environments. Attention of researchers is focused on the attempt to derive the ages and star formation history, the masses and the initial mass function, as well as global information on the *temporal* (what is the duration of the "active" phase of star formation in a cloud, what is the star formation efficiency) and *spatial* behaviors, including the dynamics inside and outside of the SFRs. The exhaustive results obtainable from *Gaia* will shed light on the details and modalities of star formation in the whole Galaxy.

2. PROBLEMS POSED BY THE THEORY: MASSES AND AGES OF YOUNG STARS

The main techniques adopted today for deriving information on the ages and masses of stars in SFRs are straightforward: the observers have to obtain the intrinsic parameters of stars, namely, the luminosity and $T_{\rm eff}$, what is a non trivial problem, due to either the presence of the disk (which may alter colors of the objects) and/or to high extinction in the SFR, which must be taken into account for each star separately. Then the objects are placed in the theoretical HR diagram, and the masses and ages of stars are read out from one or more sets of theoretical isochrones.

While I do not discuss at all the uncertainty inherent this derivation – including, of course, the uncertainty in the distance – I point out here the less obvious uncertainties due to the theoretical modeling. This latter is mainly linked to a basic problem still open in stellar astrophysics, the treatment of superadiabatic convection, which affects $T_{\rm eff}$ of giant stars. The Mixing Length Theory (MLT) (Böhm-Vitense 1958) is mostly used to describe stellar convection, in spite of its shortcomings (see the reviews by Canuto & Christensen Dalsgaard 1997 and Mazzitelli 1999). The MLT adopts a phenomenological description of convection based on the hypothesis that the convective energy is carried by convective elements of a unique size, that at the end dissolve into their surroundings. Although the MLT fluxes are *much smaller* than the experimental ones (Castaing et al. 1989), the model is used by adjusting the *scale length.* The MLT scale length is assumed to be proportional to the pressure scale heigth, $\Lambda = \alpha H_p$, which is then fixed by the requirement that some basic $T_{\rm eff}$ is reproduced. The main way this has generally been done till recently has been to *export* the value of α fitting the Sun to other stars. Of course there is no guarantee that this procedure is meaningful (see e.g. the discussion in Canuto & Mazzitelli 1992). Another way it is customary to proceed is to derive the value of α which provides a satisfactory fit of the stars under consideration. This can be done, for instance, for the evolved stars in clusters: these stars define generally a monoparametric sequence (an isochrone), almost coincident with the evolutionary tracks: in fact, the high dependence of the main sequence evolutionary time on the mass, and much shorter post-main sequence evolution conspire into having a very small range of masses defining the giant branch in a cluster. Once the main sequence is fitted by adjusting the distance modulus (and choosing the reddening consistent with observations), it is possible to reproduce the giant branch by adjusting α. Be careful that in this way *we lose predictive power*, i.e., the location of giants *cannot* be used then as a constraint for the distance or the age of the cluster.

There are many examples in the literature which disregard this point. In fact, some researchers choose the value of α so that the red giant location agrees with their models. After that, generally forgetting how the fit was obtained, either the same researchers or others interested in comparisons with observations, reverse the problem and use the giant location as an argument in favour of the quality of these theoretical models or of the chosen distance.

Concerning the pre-MS evolution, this equivocal approach is impossible: the young stars in the SFRs evolve mainly by thermal contraction along their Hayashi tracks, so that *all* the masses are present, and for each of them the treatment of overadiabatic convection is critical. The isochrones for the small masses ($M \leq 1 M_{\odot}$) run almost parallel to the main sequence, starting from the deuterium burning phase which probably represents the starting point for the evolution in the visible (Palla & Stahler 1993). Unless we have binaries from which we can derive independently the masses, the mass calibration relies simply on the predictive power of our convection model. *

In recent years, for computing pre-MS evolution we have made large use of the so-called "Full Spectrum Turbulence" (FST) convective model (Canuto & Mazzitelli 1991), which has an advantage of providing convective fluxes in good agreement with the experiments, and tests a different scale-length, namely, the distance of the convective layer from the closer boundary of convection. For a full description see, e.g., Mazzitelli (1999). Two main sets of models have been available by D'Antona & Mazzitelli (1994, 1997). In spite of being less "tunable", also the FST model somewhat depends on details of the description, especially for the low mass, low $T_{\rm eff}$ case, where non-grey model atmospheres are needed (D'Antona 1999). Progress in future years could lead to improvements of the theoretical situation, but by now the uncertainties are depicted in Fig. 1, where we compare three different sets of tracks and isochrones used to determine mass and age of the full dot representing a typical T Tauri star. The uncertainty, by a factor close to two for the mass, and by a factor of three for the age, is certainly the proof that work is badly

* A further complication occurs at $T_{\rm eff} \leq 4500$ K, where convection penetrates into the optical atmosphere: in this case, also due to the growing importance of molecular opacities, a non-grey atmospheric integration is necessary for deriving correctly the $T_{\rm eff}$ location of the evolutionary track, and this integration must also include a proper treatment of overadiabatic convection – see D'Antona 1999).

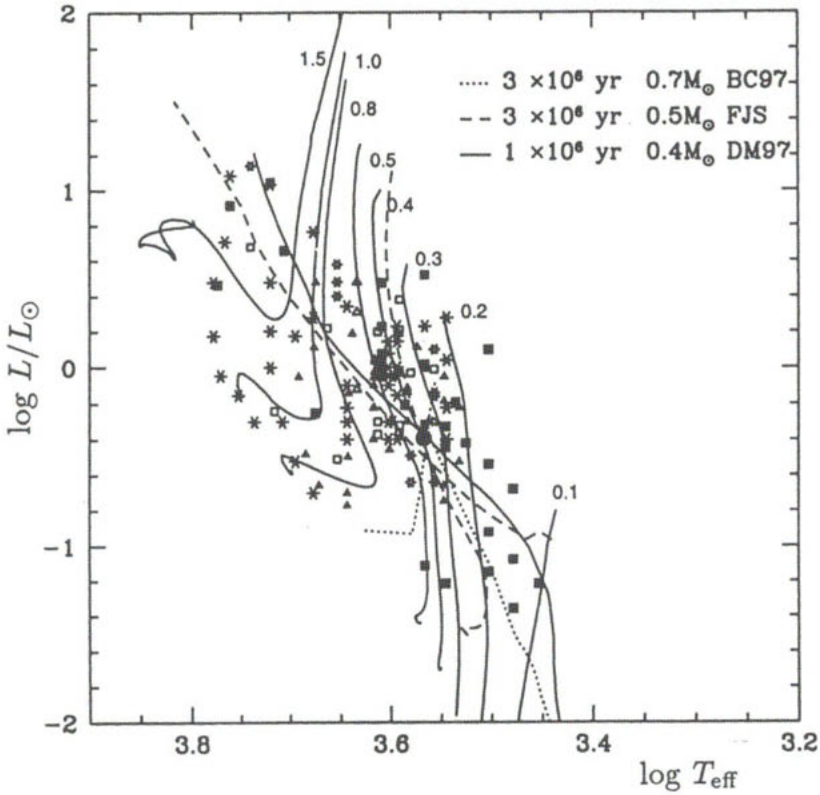

Fig. 1. Location of T Tauri stars taken from several observational sources are shown by different symbols. The pre-main-sequence (hereafter, pre-MS) evolutionary tracks by D'Antona & Mazzitelli (1997, DM97) for the labelled masses from 1.5 to 0.1 $M_\odot$ are shown as continuous lines. Notice that some of the presumed T Tauri stars lie on the main sequence (!); probably, their distance determination is wrong. To determine age and mass of the star, represented by the full big dot, we can use the DM97 set of isochrones, getting 0.4 $M_\odot$ and $\sim 10^6$ yr, or the Swenson et al. (1994) isochrones and tracks (FJS, dashed) obtaining 0.5 $M_\odot$ and $\sim 2 \times 10^6$ yr, or the Chabrier & Baraffe (1997) isochrones (BC97) obtaining 0.4 $M_\odot$ and 3×10^6 yr. Most of these differences are due to different treatment of convection employed in these three studies.

needed in this field, as well as observational constraints by binary observations.

3. THE STATUS OF OUR UNDERSTANDING OF LITHIUM PRE-MAIN-SEQUENCE DEPLETION

Low mass ($M \leq 1.5 M_{\odot}$) pre-MS stars contract, while being fully convective, from the phase of deuterium burning at which they probably start their optical life. Their core temperature increases, till it rises to $\sim 3 \times 10^6$ K at which the ^{7}Li + p $\rightarrow$ 2^{4}He reaction is activated. If the star if still convective at the layers in which this reaction is efficient, the lithium depletion is seen at its surface. This produces the well known pattern of lithium abundance versus $T_{\rm eff}$(or mass, which declines with $T_{\rm eff}$) in the young open clusters (see Fig. 2 for the Pleiades). The smaller the mass, the longer it preserves temperatures sufficient to deplete lithium at the bottom of the convective envelope. Unfortunately, just because the main phase of depletion occurs at the border between the radiative core and the convective envelope, it is dramatically dependent on details of the stellar model.

Maybe my personal point of view is too extreme, but we should admit that, after 35 years of observational and theoretical work, our knowledge on how lithium is destroyed in stars is still very primitive. In particular, we still lack a basic understanding of how much lithium the Sun has depleted during its pre-MS lifetime. In older times (Bodenheimer 1965, but also D'Antona & Mazzitelli 1984) the models provided a very small depletion in the solar pre-MS, at most by a factor of two consistent with observations of young open clusters. Therefore, since the solar system abundance is $\log N(\mathrm{Li}) \approx 3.3$ in the scale

$$\log N(\mathrm{Li}) = 12 + \log \frac{N(\mathrm{Li})}{N(\mathrm{H})},$$

the main depletion to the present solar photospheric value $\log N(\mathrm{Li}) \simeq 1.1$ should have taken place during the main sequence. The most credited view of lithium depletion today is linked to the angular momentum (hereafter, AM) evolution of the star: the external layers are braked by stellar wind AM losses, while the core still rotates fastly. AM transfer from the core to the envelope, and the associated chemical mixing would produce the "long term" depletion mechanism (e.g. Pinsonneault et al. 1990). This view relies on pre-MS models which do not deplete much during the pre-MS stage. Unfortunately, the most modern models (including updated equation of state, opacities and the FST convection model) are able to deplete the solar lithium *completely* during the pre-MS phase (Ventura et al. 1998). MLT

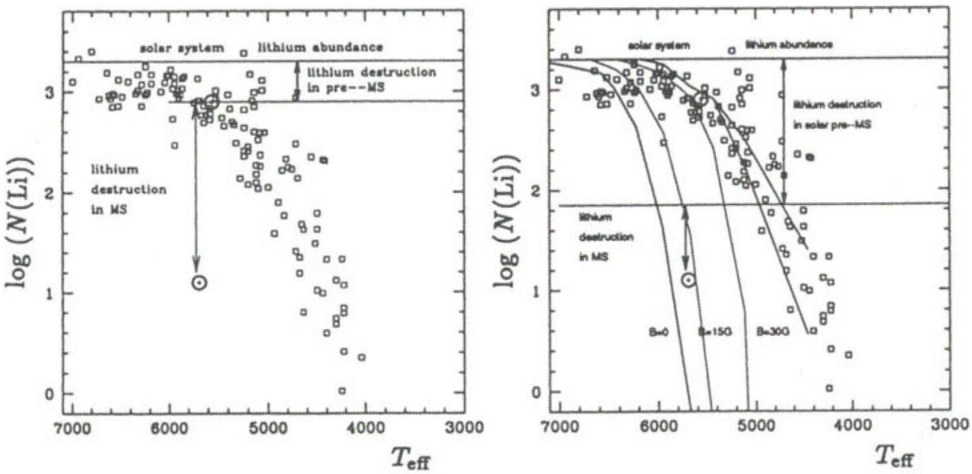

Fig. 2. The open squares represent the lithium versus $T_{\rm eff}$ abundances in the Pleiades open cluster. On the left: the "simple minded" view of lithium depletion in a star of $1M_{\odot}$, assuming that pre-MS depletion for the Sun has been the same as for the $1M_{\odot}$star in the Pleiades and that the present solar abundance (log N(Li) $\simeq$ 1.1) is reached through the "slow" main sequence depletion mechanisms. On the right, the curves show the pre-MS lithium depletion in the models including an approximate treatment of the influence of the dynamo magnetic field on the convective structure (Ventura et al. 1998). A different view for the solar lithium depletion is shown in which pre-MS burning is much more efficient than the main sequence depletion mechanisms.

models deplete somewhat less (Ventura et al. 1998), but certainly much more than what the Pleiades and other open clusters indicate (Martín 1997). Thus we have to forget the "simple minded" picture described in the left part of Fig. 2, in which it is assumed that the pre-MS depletion for the Sun has been the same as for the $1M_{\odot}$ in the Pleiades, and that the present value of lithium in the solar photosphere has been reached through the "slow" depletion mechanisms.

Another point in favour of a more complicated picture for pre-MS lithium depletion relies on the fact that standard models predict a very strong dependence on the *metallicity* of the stars under consideration. This is certainly found when comparing solar-type stars with population II objects, or the Pleiades with the Hyades (but in the latter case the age could be a side effect), but is not directly confirmed by recent comparisons between young open clusters of different metallicities.

In the right part of Fig. 2 I present a different possible interpetation of lithium depletion. The curves represent the pre-MS lithium depletion in the models by Ventura et al. (1998), including updated physics and the FST convection description: in these models the "standard" depletion curve is the leftmost one, in which the Sun would have depleted even more than observed. The other curves in the figure show the depletion obtained when an approximate treatment of the influence of the dynamo magnetic field on the convective structure is taken into account. Notice that the dynamo action should be linked to the stellar rotation rate, and to its evolution, another important parameter in the pre-MS evolution. We can reconstruct the Pleiades depletion curve by introducing this new parameter. A possible interpretation of the solar lithium depletion is shown: at the end of the solar pre-MS stage, lithium is reduced to $\log N(\mathrm{Li}) \simeq 1.9$, and the "slow" mechanisms acting on the main sequence reduce it to the present solar value. In this interpretation, of course, any other value between the Pleiades and the present solar value is possible for the lithium pre-MS depletion. Notice that the schemes for the "slow" main sequence depletion mechanism rely on the solar calibration: a mechanism is required to reproduce the solar lithium abundance at the solar age. Since, in fact, *we have no clear idea* about the true solar pre–MS depletion, it is uncertain how much lithium must be destroyed during the following main-sequence lifetime.

T Tauri stars generally show no lithium depletion, consistently with theoretical models which attribute to them central temperature smaller than what is needed for lithium burning. Apart from a few open clusters of very small age (e.g. Randich et al. 1995, see for a list Randich 1997), we do not know much *directly* about the pre-MS lithium depletion: a large sample of stars of known age between the T Tauri phase and the main sequence of α Per ($\sim$ 50–60 Myr) would give the observational database necessary to finally answer this long-standing problem.

4. STELLAR POPULATION AROUND THE SFRs

So, what do we need to improve our understanding of the star forming region? First of all we need better modeling: there are 10 years before *Gaia* will possibly come, and improvements in the modeling of convection and of stellar atmospheres, as well as on construction of the rotating models and their evolution, including the dynamo magnetic field, are planned by some research groups.

At the same time we also need better *observational constraints*: in this field much will be gained by the detection and study of pre-MS binaries (e.g. Covino et al. 1999).

Then we focus our attention on a less straightforward "bonus" of *Gaia*. This satellite will allow to map the ages and age distribution *inside* the SFRs defined by the presence of gas and dust. In addition, close to the SFR, there are regions which are no longer active sites of star formation, but which possibly were active in past. If we measure distances to these stars, we can derive their ages – probably still quite young ages – from their position in the HR diagram. A further advantage is that close to the SFRs the extinction will be low, allowing to look for intrinsically fainter and less massive objects.

Recent years have seen an enormous progress in the study of young stars, thanks also to the recognition that X–ray emission is directly linked to youth: the first discovery was via the satellite Einstein (Walter et al. 1988): plenty of objects as young as the T Tauri can be identified by their soft X-ray emission (while they lack the characteristic emission line strength, chromospheric activity and large infrared excess of classical T Tauri stars). Then the *Rosat* All Sky Survey (RASS) identified a large number of X-ray luminous stars, not only towards or inside the main SFRs (Orion, Taurus, Lupus, Chamaeleon – see Alcalá et al. 1995, 1996, Wichmann et al. 1996) but also *around* them, within several degrees. As the X-ray activity in late-type stars decreases fastly with age (Micela et al. 1990), the X-ray emission selects preferentially young stars, although not necessary pre-main-sequence stars. This finding led to a debate on the true age and origin of this "sparse" population of young stars (Sterzik et al. 1995, Feigelson 1996, Briceño et al. 1997; see for a summary Caillault et al. 1998).

At last, it is becoming clear that these young stars are not uniformily distributed, but seem to be a part of the *Gould Belt* or *disk*, together with most of the nearby SFRs (Sterzik et al. 1998, Guillot et al. 1998). In particular, Guillot et al. (1998) reach this conclusion by examining the cross-correlation between the Tycho catalogue and the sources detected in the RASS, showing that the asymmetry found in the young star distribution can be understood as a *disk-like* arrangement of stars having an inclination of $\sim$20 deg to the galactic

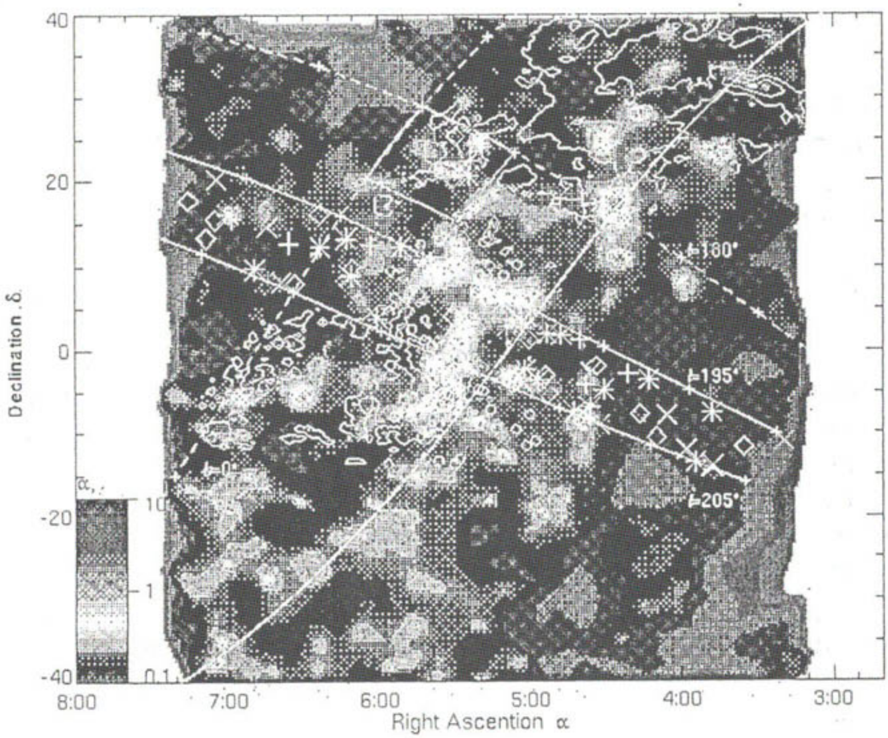

Fig. 3. The galactic plane is the dashed line. The contours of molecular clouds in Orion and Taurus–Auriga are shown, together with the grey-coded space densities of the RASS sources. In the strip between $\ell = 195$ deg and $\ell = 205$ deg, candidates have also been observed for lithium. The lithium-rich sources (crosses) cluster preferentially in the Gould Belt (represented by the continuous line), while the lithium-poor ($\times$) and the no-lithium sources (diamonds) are preferentially far from it (from Sterzik et al. 1998).

plane, just like the Gould Belt, the structure defined by Gould (1879) and based on the distribution of bright stars and OB associations. Another example of the path leading to the association of the RASS sources with the Gould Belt structure is shown in Fig. 3: the distribution of candidate young stars in Orion and Taurus-Auriga is clustered *below the galactic plane* (Sterzik et al. 1998), while towards Lupus the candidate young stars cluster *above* it (Wichmann et al. 1996). The inclination of the Gould Belt is consistent with these distributions.

As the distance of the Gould Belt inner rim spans from $\sim$ 140 pc for ρ Oph to $\sim$ 450 pc for the Orion complex, reaching $V = 20$ mag in the regions of low extinction will allow to study the whole range of low mass stars, down to the massive brown dwarfs which are relatively luminous and long-lived in the pre-main-sequence deuterium burning phase. Notice that these brown dwarfs will be the only ones directly seen by *Gaia*, but they will allow a direct derivation of the IMF from stars to brown dwarfs without need to extrapolate it.

If *Gaia* will determine the distances of the possible Gould Belt population and their kinematics, we will obtain first of all information on the modalities of star formation *in space* (does the main formation occurs in the giant molecular clouds or is the formation in "cloudlets" globally more important?) and *in time* (we will have the age distribution of stars in and outside the present SFRs). This will also produce global information on the initial mass function, and the results will allow us to check our modeling for convection from solar-type stars down to the very low mass stars and young brown dwarfs.

Further, as the Gould Belt stars outside the SFRs may not be as young as the stars in SFRs, they are likely to populate the whole phase between the T Tauri (up to a few million years old) to the hydrogen ignition (several tens of million years, corresponding to the age of the youngest studied open clusters). We have noticed that this evolutionary phase *is the fundamental stage in the evolution of low-mass stars, during which the "hidden" parameters, as rotation, angular momentum evolution and magnetic fields play their most important role.* Summarizing, for this phase we have:

(1) the main rotational evolution of the star: the objects accelerate (or not) from the T Tauri relatively slow rotation rate to the possibly high rotation rates of the stars in young clusters like α Per. The transfer of angular momentum through the star and the role of the protostellar disk are theoretically nicely described (e.g. Bouvier 1994) but need observational counterparts;

(2) planet formation and disk evolution: we need information on the lifetime of disks and on the possible role of planets in the rotational history;

(3) pre-MS lithium depletion, which is still very obscure, as we have seen in the previous section. This problem bears consequences on the understanding of many others, which go from stellar structure to constraining the Big Bang model by observing the primor-

dial abundances of light elements. Monitoring directly the phases of lithium depletion in a large number of stars, with different rotation periods, masses and disks, will finally shed light on this problem too;

(4) the transition from the Hayashi convective track to the "radiative" track which approaches the main sequence. How does the magnetic structure (a dynamo associated to the deep convective zones is responsible for the X-ray emission) change, and how is this reflected in the angular momentum evolution?

Gaia seems the only tool to help observationally in exploring these fundamental problems of stellar evolution. Whatever study we can do in the Gould Belt, it will be useful only in part, if we do not know accurate distances o stars.

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