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SLOW VS. RAPID STAR FORMATION - A REVIEW OF RECENT DISCUSSIONS OF THE AMBIPOLAR DIFFUSION PICTURE

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Abstract

A discussion of the recently emerged challenges to the model of quasi static star formation, focused on the review article "Remarks on Rapid vs. Slow Star Formation" by Javier Ballesteros-Peredes and Lee Hartmann (Ballesteros-Paredes & Hartmann 2006), including discussion of some other articles on key topics considered. The main objective of Ballesteros-Paredes & Hartmann (2006) is to promote a picture of rapid and dynamic cloud and star formation rather than slow, quasi-static formation in magnetically supported clouds. To provide a background for these debates, a brief overview is given of the current theories of the interstellar medium, molecular clouds and star formation processes, including (but not limited to) an introduction to the concepts of Ambipolar Diffusion, the Stellar Birthline and to methods for identification of low mass protostars and determination of their age and mass.

Subject headings:

1. INTRODUCTION

The question of how molecular clouds and dense cores are formed has been a matter of intense debate in recent years. The hitherto accepted view of long-lived clouds slowly growing magnetically supercritical through the process of Ambipolar Diffusion and field line reconnection before collapsing and forming dense cores, giving the clouds a life time of 10 Myr before the onset of star formation, has recently been challenged by a combination of observations, modeling and theoretical considerations that suggests a very short life time of the clouds before the onset of star formation, leaving a smaller importance of magnetism and hence Ambipolar Diffusion than so far believed. Clouds in the cold component of the ISM (see sec. 2.1 for more detail) are, in the classic picture, believed to locally condense into molecular clouds that are then compressed by the traveling shock waves of the spiral arms of the Galaxy (or, to be precise, the shock front travels in the inter-arm regions). This compression leads to the formation of the molecular clouds that host the formation of stars. It has until recently been generally believed that this formation would start at a time $\sim 10^7$ years after the initial shock, based on the distance between the shock front (indicated in other galaxies by dust lanes and a sharp peak of HI emission (e.g. Mouschovias et al. 2006)), the spiral arm regions of massive star formation activity and the rotational speeds of stars in those galaxies. It is, in the classical model, believed that the MCs spend a small part of this time in a state of rapidly decaying turbulence (e.g. Mouschovias et al. 2006), after which the big clouds, supported against gravitational collapse by Magneto Hydro Dynamic waves and the pressure of the magnetic field, settle into quiescence. During most of the clouds' life times, regions inside them slowly grow denser through the mechanism of Ambipolar Diffusion (AD) and finally reach supercriticality, allowing inside-out collapse into protostars (see sec. 2.2 for more detail). As most of the surrounding cloud has fallen into the star and the remains blown away by the growing emission from the protostar, it enters the Pre-Main Sequence phase, in which it will be observable as first a Classic and then a weak-lined T Tauri star. During this phase, the star undergoes contraction until finally the onset of hydrogen fusion stabilizes it at the Zero-Age Main Sequence (ZAMS) of the HR diagram. The sections 2.1 and 2.2 are devoted to a more detailed description of the established views on ISM and star formation processes, respectively.

However, recent observations of the Galaxy, combined with numerical models and theoretical considerations, have led to the suggestion of a radically different picture of the pre-collapse phases, in which the role of AD is reduced heavily, taken over primarily by dynamical effects. These arguments include statistical arguments about the ratio of Molecular Clouds (MCs) with and without ongoing or recently ended star formation; Numerical modeling of the Magneto-Hydrodynamics (MHD) of molecular clouds and the enveloping atomic gas, quantitative considerations on the densities required for cloud formation and core collapse, and more. Ballesteros-Paredes & Hartmann (2006) gives a review of the different observations and models supporting this picture and discusses some of the questions and arguments raised by others during the discussion. It is the main scope of this paper to summarize, review and discuss this article, along with mention of some of the articles forming its basis and some of the articles challenging its views. Section 3 is dedicated to this purpose.

2. THE INTERSTELLAR MEDIUM, MOLECULAR CLOUDS AND YOUNG STARS

In the following, I will give a brief overview of the interstellar medium and the mechanisms that lead to its collapsing into dense clouds and eventually new stars with an emphasis on the parts relevant to the later discussion.

2.1. *The Interstellar Medium*[1]

The ISM is made up of different components, or phases, distinguished by their temperature, density, ionization and chemical constitution, which are, as we shall see,

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[1] Where nothing else is mentioned, the information in this subsection is from Cox (2005).

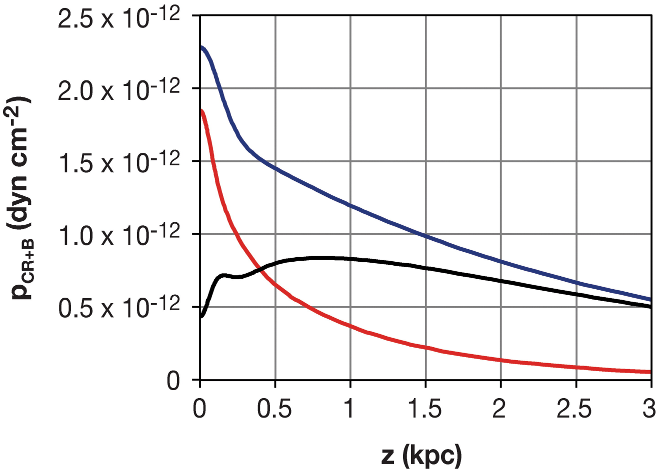
tightly interwoven. The medium consists of a cold phase ($10K, > 10cm^{-3}$) of HI, called the cold HI or the diffuse clouds, a warm intercloud medium ($1000-10.000K, 0.1-1cm^{-3}$) consisting of both neutral and ionized Hydrogen (HI and HII, respectively), and a hot, superdiluted element with temperatures of 10^5 or 10^6 K and a density below 0.01 cm^{-3}. The latter has not been given much importance in earlier work, where it was often neglected in two-phase models, in which only the pressure gradients, mass exchange etc between the cold and warm component were considered. However; recent better observations and mounting evidence, including discrepancies between the expected and measured pressure gradients in the Galactic mid-plane, has led to more accurate and surprising models of a three-phase medium, in which the hot, dilute component plays a key role.

The hot component has shown to fill out much of the interstellar space, not only far above and below the disk, but also in mid-plane and near-mid-plane areas. This has, in summary, led to a picture of a foam-like structure in which the warm HI is arranged in thick sheets surrounding bubbles and cavities of hot gas. Within these sheets are substructures in the shapes of sheets and filaments of cold, dense gas of low volume filling factor[2]. As the distance $|z|$ from the plane grows, the relative abundances of the colder components drop off much more rapidly than the hot component which is totally dominant in vast areas off the galactic plane, and extending to much larger distances than previously thought.

A reason why the large extend of the hot component has not been previously foreseen is the fact that the mass of the hot component would result in a significantly higher pressure than is observed in the mid-plane. When synchrotron emissivity of the high-$|z|$ areas have revealed a larger abundance of hot, dilute ionized hydrogen (see fig. 1 for an example) but no correspondin mid-plane thermal pressure, it has triggered a number of speculations on the mechanisms that counteract this thermal pressure. The solution seems to be the pressure exerted by the magnetic field of the Galaxy, resisting the gravitational pull without raising the thermal pressure.

This has led to a picture of an ISM with very complicated magnetohydrodynamic properties to account for all the observed phenomena that include tunnels and cavities, lack of mid-plane thermal pressure etc. Cox suggests a structure of tubes made up of magnetic field lines, forming a felt-like structure that supports itself in a way similar to how the mechanical stiffness of straws keep the haystack airy and tall despite the gravitational pull.

The properties of the interstellar magnetic field are not well known, though, which leads us to a very central point to this paper. In much the same way as the magnetic pressure of the hot ISM component supports it against the pull of self gravity, the interstellar magnetic field also to some extend counteracts the self gravity of dense molecular clouds. The crucial point is, how much? Most molecular clouds (and, of course, especially the GMCs) span several Jeans lengths. Does that mean they are (quasi-)static, supported by magnetic pressure, or does that mean they are dynamic objects, undergoing relatively rapid collapse along with turbulence and other dynamical effects? In the works of e.g. (Palla & Stahler 2000) or (Mouschovias et al. 2006), the GMCs are believed to be more or less static, whereas e.g. Ballesteros-Paredes & Hartmann (2006) or Hartmann et al. (2001) subscribe to the idea that they are highly dynamic, with magnetic pressure playing only a marginal role.



Cox, DP. 2005
Annu. Rev. Astron. Astrophys. 43: 337–85

Fig. 1.— Comparison between cosmic ray and magnetic pressure inferred from ISM weight distribution (red) and synchrotron emission (blue); the difference between the two shown in black. It is clear that from $z \sim 1 - 1.5kpc$, the hotnonthermal pressure is dominant. Figure taken from Cox (2005).

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2.2. *Clouds to Stars*[3]

The formation of molecular clouds and the onset of star formation within these is the main topic of the debate of (Ballesteros-Paredes & Hartmann 2006); a heated debate that has yet to reach conclusion. In this subsection, I describe the established view which is represented in e.g. Stahler & Palla (2004), Palla & Stahler (2000), Tassis & Mouschovias (2004) or Mouschovias et al. (2006).

2.2.1. *GMCs and Dense Cores*

In this picture, the GMCs are condensing from the warmer HI clouds, when these get sufficiently dense and/or grow sufficiently large so that the column density reaches a value where it protects the inner parts of the clouds from stellar photoionization, and at the same time cools the dust of the cloud. This dust plays an important role in the recombination of the neutral atomic hydrogen into H_2 gas by providing a surface on which hydrogen atoms stick and move around, significantly raising the probability of interaction with other atoms. However, if these dust grains get too hot, the evaporation time of a Hydrogen atom will be only a small fraction of the time required to scan the surface of the dust grain, rendering the recombination processes extremely inefficient (Hartmann et al. 2001).

The condensation and/or compression of molecular clouds is especially common in the interarm shock fronts

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[2] The filling factor is partly determined by the morphology of the gas clouds, which makes it important to the life time, stability and star forming potential of molecular clouds too, since a low filling factor of a dense material could imply a filamentary or "fractal" structure, rendering the cloud more susceptible to high-energy photons that dissociate the cloud material and can ultimately disperse a cloud (Hartmann et al. 2001)

[3] Unless otherwise mentioned, the information in this subsection is from (Stahler & Palla 2004)

of the Galaxy. These pressure waves induce a certain level of turbulence in the clouds, but this turbulence rapidly decays (this is uncontroversial, see Hartmann et al. (2001) or Mouschovias et al. (2006)), after which the cloud in the established view settles into a state in which the magnetic field pressure and thermal pressure balance the pull of self gravity, having the overall contraction of the cloud (Palla & Stahler 2000) and the formation of dense cores evolve slowly and quasistatically.

There is an empirical, roughly linear relation between cloud size and velocity dispersions within the clouds. while the cloud is still turbulent and/or riddled by MHD waves, these are all large scale disturbances, having a decreasing effect on smaller scales, until the velocity dispersion at a certain scale,

$$L_{therm} = 0.1pc\left(\frac{T}{10K}\right)$$

is the same as the ambient thermal speed. This is also, roughly, the scale of the dense cores, from which the individual stars are later formed. In summary, the MHD waves of the large cloud complexes keep the cloud from undergoing a monolithic, large scale collapse, whereas it still permits the fragmentation of the cloud and contraction into dense cores (Stahler & Palla 2004, p. 289).

2.2.2. *Ambipolar diffusion, collapse and accretion*

In the view of Stahler & Palla (2004), the clouds spend the main part of their existence in this quasistatic state, in which the cores slowly condense through the mechanism of ambipolar diffusion, which I shall present briefly here.

If we consider a self gravitating cloud of roughly the core scale length with a reasonably strong magnetic field, the gas will be gravitationally pulled towards the center. However, the gas in the cloud will be at least partly ionized and have a significant abundance of electrically charged particles, which gyrate rapidly around the field lines, colliding with the neutral particles and thus creating a frictional drag significantly slowing down the inward motion of the latter. Besides, at jeans length scales, $\sim L_j$, the thermal pressure also plays a nonnegligible role. At sufficiently low ionization - and at the low temperatures of the GMCs, the ionization is low - this drag is not enough to completely counteract the gravitational pull of the neutral component, which slowly and gradually moves inwards across the magnetic field lines, resulting in a loss of magnetic flux. As the density and gravitational pull increases, the charged component is also dragged inwards, bending the field lines and eventually resulting in field line reconnection (e.g. Stahler & Palla 2004, fig. 10.10), yielding a further loss of magnetic flux.

With lowered magnetic flux, the critical mass M_{crit} of the system decreases until it is exceeded by the actual mass of the system, which becomes *supercritical* and unstable to gravitational collapse (Stahler & Palla 2004, p. 282).

Once the core has reached supercriticality, it undergoes an inside-out collapse, in which the inner parts collapse, removing the thermal pressure supporting the surrounding layer, which will then enter free-fall and remove support of the next layer etc. It is important to note, though, that while each layer falls (almost) freely, the core in its entirety does not collapse at free fall speed (Mouschovias et al. 2006), since the onset of infall is confined to propagate outwards in the cloud at the sound speed of the cloud gas. The shock energy of the collision between the protostar and the accreting material is transformed into thermal energy in the young star and finally disposed of as electromagnetic radiation. In early stages of this phase, the radiation is insignificant compared to the infall energy, but as the mass of the star grows and the density of the infalling cloud material decreases, at some point the energy emission will begin to dominate the decreasing infall, and the star enters the *Pre-Main Sequence* (PMS) phase. In the meantime, temperature has also risen enough that appreciable deuterium burning, at least for heavier protostars, is going on.

Observationally, the accreting matter and the surrounding cloud strongly extincts the visible light of protostars, which are only seen in infrared and longer wavelengths. Since it is not possible to determine their effective temperatures from their spectra, these objects cannot be placed on the HR diagram.

2.2.3. *The Stellar Birthline & TTau stars*

The discussion in Ballesteros-Paredes & Hartmann (2006) focuses on the conditions for star formation to ensue, and thus the evolution of dense cores to stars has little connection to this discussion. However, for a complete picture of interstellar dust and gas evolving into stars, I shall give it a short treatment here.

In associations of young PMS stars, a certain trend is observed: practically all the stars lie above the main sequence in the HR diagram, which is not odd, since they are less dense and thus have a larger surface area and luminosity than at the later Main Sequence stage. However, a bit more surprising at first glance, is the fact that there also seems to be an upper bound to the stars, as can be seen in e.g. (Stahler & Palla 2004, fig. 16.2). From this upper boundary, the protostars seem to set out and migrate towards the ZAMS, downwards for dwarfs, to the left and even slightly upwards for giants (see sec. 2.2.4 for more detail). Therefore, this line looks like a birth place for young stars, and hence has gotten the name the *Stellar Birthline*.

The birthline can be understood as a manifestation in the HR diagram of the typical properties of young stars of a group or association at the time they become optically visible. This happens, once the main infall of material has ended and the energy outflow of the star dispersed the surrounding cloud enough to make it transparent to visible light, from which time the star becomes a PMS Star. These properties are dependent on factors such as accretion rate, cloud density, typical mass of dense cores etc. and hence is not uniquely defined but rather an observational trend for each association.

During the entire protostar phase, the stars are heated by the gravitational energy released by the collapse and dispose of this energy by thermal radiation. However, during the infall time, the mass and thermal energy of the star is continuously increased by the infall. At the time the main infall has ended and the star enters the Pre Main Sequence phase, it is no longer supplied by infall. As its deuterium-burning and stored thermal energy is emitted, the star slowly contracts, the smaller radius resulting in a slowly decreasing luminosity of the star, seen as a downward movement in the HR diagram along the so called Hayashi tracks[4]. Meanwhile, as the core of the star grows denser, nuclear reactions start to take place, finally resulting in the onset of hydrogen fusion, at which time the contraction ends and the star enters the Zero Age Main Sequence (ZAMS). see sec 2.2.4 for more a more detailed treatment of these nuclear reactions.

During the contraction phase, stars of mass $M_\star < 2M_\odot$ show a continuum spectrum with some additional features, including strong excess X-ray emission which led to their discovery in the first place. Stars of this class are called T Tauri stars after the prototype star T Tau, and the class includes two types: one with strong optical emission lines in Hα and H- and K-band emission lines of Ca II, called *Classical TTau Stars* or CTTSs, and one lacking these strong emission lines, named *Weak-lined T Tauri Stars* or WTTSs.

Although there is often a significant overlap in age of the populations of CTTSs and WTTSs, recent analysis of emission lines and spatial distribution of the Taurus-Auriga association (Bertout et al. 2007) has established that the data are consistent with an evolutionary process, in which the emission lines of the CTTS are due to the accreting matter of the circumstellar disk hitting the star. At the end of accretion, the CTTS becomes a WTTS, consistent with a larger spatial spread in the populations of WTTSs than that of CTTSs, possibly even suggesting that they are two different populations - a conclusion similar to what has been drawn for the Lupus PMS association by Makarov (2007).

A few things should be noted here. First, for low mass stars, the infall time and contraction are fairly slow, and thus the birthline is not a sharp line. Rather, the embedded clusters and TTau associations are to be seen as extremes of a continuous development. Second, the transition from protostar to PMS is continuous; there is no sharp line on which the infall ends, and the properties of the star such as temperature and radius, which are dominantly determined by internal structure and insensitive to infall, do not change at this point. The birthline is simply the point in the HR diagram at which a PMS star has protostellar radius, before the Hayashi contraction can significantly change this picture.

To theoretically construct the birthline, one must include both PMS and Protostar theory. One starts out with a series of modele stars of different mass or, equivalently, position on ZAMS. The four stellar structure equations must then be solved for each stellar mass $M_\star$. As a boundary condition, the radius $R_\star(M_\star)$ is adopted from protostellar theory and imposed on the equations, and so the luminosity and effective temperature can be found for each star.

Since the birth line marks the transition between the protostellar and PMS phases, it line obviously depends on protostar physics including geometry, infall rates etc. For example; a slower infall rate would give the protostar more time to radiate its thermal energy and hence the radius to decrease. So, in a naive picture, a lower infall rate could significantly affect the thinckness and shape of the birth line. Typical infall rates adopted from the dynamics of inside-out collapse lie in the range of $10^{-6} - 10^{-5} M_\odot/yr$, the different resulting birthlines in the naive picture shown in (Stahler & Palla 2004, fig. 16.2), right panel. However, the cosmological abundance of deuterium in the protostar has a thermostatic effect constraining the radius, making the mass/radius shift induced by different infall rates significantly smaller than would be expected without considering deuterium fusion, offering a possible explanation to why the birthline of a given association seems surprisingly narrow and well defined - see also sec. 2.2.4 for more detail.

2.2.4. *Nucleosynthesis*

From some point during the protostellar phase and through the PMS untill hydrogen fusion starts, different other nuclear reactions play a role - albeit of varying importance - in the evolution of the young star. When, and which reactions, depends on the interior temperature of the star, which again is determined by the mass and infall rate of the protostar. The interior temperature of the star can be calculated by:

$$T_c = 7.5 \times 10^6 K \left(\frac{M_\star}{1M_\odot}\right)\left(\frac{R_\star}{1R_\odot}\right)^{-1}$$

Knowing the rate of contraction, this equation makes it possible to follow the central star temperature during contraction. If applied to the time of the birthline for varying masses, one finds that in a range from 0.4 to 1.5 $M_\odot$, the temperature stays within a factor two of 1×10^6K. This is the ignition temperature of deuterium fusion:

$$^2H +^1 H \rightarrow^3 H + \gamma$$

A reaction that, once it has been started, acts as a thermostat: if the star has a bit of mass added to it, the resulting higher pressure and temperature will ignite deuterium burning, which in turn makes the radius swell and thus lowers the temperature, effectively keeping it around the ignition level. As long as the protostar is in its convective phase, the deuterium burning can go on because of the internal mixing and supply of fresh fuel; however, eventually the star becomes radiatively stable, the fuel in the core is fused, but not in the rest of the star. Thus, the PMS star inherits a Deuterium abundance lower than the cosmologically determined interstellar mean. If a protostar has any significant deuterium-induced luminosity L_D, its subsequent PMS star will have a luminosity $L_\star$ close to L_D, lower mass PMS stars will initially have no deuterium generated luminosity, but the following contraction will raise the interior temperature enough that deuterium will eventually ignite fusion, so that $L_\star$ climbs to L_D. In any case, once this level is reached, the stellar radius is kept at a constant while deuterium burns; helping stabilize the radius around roughly the birthline value while the deuterium burns and the cloud disperses, helping limit the width of the birthline as mentioned above in 2.2.3.

As the deuterium depletes, the star starts contracting again, until the interior of the star reaches the ignition

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[4] This is only true for low mass stars ($< 2M_\odot$). For higher mass stars, the evolution of the interior of the star is much faster, and for sufficiently high mass, hydrogen fusion ensues even before the dispersal of the core, resulting in an intersection of ZAMS and the birthline for sufficiently high masses. The evolution of high and intermediate mass stars is more complicated and less well observed due to the much shorter life times, and will not be treated here.

limit of another important reaction, Lithium Burning, in which Lithium fuses with protons to form Helium:

$$^7Li + ^1H \rightarrow ^4He + ^4He$$

Curiously, most of the Interstellar Helium has been formed in the reverse process, by highly energetic cosmic ray α-particles colliding in interstellar clouds. Since Lithium is also strongly absorbant and hence easily observable, the abundance of Lithium is a very helpful indicator of the age of PMS stars.

After further contraction, the star eventually reaches an internal temperature of $T_c \sim 10^7 K$, at which hydrogen fusion is ignitited. As hydrogen fusion grows in strength, the heat outflow slows down the contraction that initially ignited it, causing the star to asymptotically reach thermal equilibrium as the radius settles at the ZAMS value.

The basic reaction is th following:

$$4^1H \rightarrow ^4H + 2e^+ + 2\nu$$

although this is overly simplified; the four protons are brought together through either the CNO bicycle or one of the two PP chains, the processes dominant in massive and low-mass stars, respectively.

As an aside, objects below the critical mass of $M_c = 0.075 M_\odot$ never reach internal temperatures high enough to spark hydrogen fusion. They do burn deuterium, and during contraction their temperature may even rise enough to spark transient hydrogen burning, but it ceases again, and while the object *still* shrinks, the temperature drops off during the later part of the contraction. With no sustainable burning, the only pressure to counteract gravity is the electron degeneracy pressure, the same pressure that keeps a white dwarf from collapsing. The object becomes a Brown Dwarf, eventually dropping off to zero luminosity and zero density.

2.3. *Determination of Age and Mass of Low-Mass TTau Stars*

Observationally, determining the ages and masses of TTau type stars is done by means of theoretical models for the evolution tracks, as the ones used to derive the birth line. Such a set of theoretical evolutionary tracks are then evaluated (with observationally obtained boundary conditions) at different times, the poits of which are connected on isochrones crossing the evolutionary track. The observed stars are then placed in the HR diagram superimposed on the tracks and isochrones, and the ages and masses can be estimated by interpolating (Palla & Stahler 2000, e.g,).

A number of possible errors are present in this method. Contamination from foreground stars that are mistaken for cluster members can lead to errors in the age spread and average error estimates (Ballesteros-Paredes & Hartmann 2006), as can unresolved binaries, which for each star gives an overestimation of luminosity by a factor of 2 (Hughes et al. 1994). See figure 2 for an example of the determination of aage and mass for PMS stars (Palla & Stahler 2000)

3. A NEW VIEW: RAPID, DYNAMIC STAR FORMATION

Now let us return to the formation and contraction of molecular clouds and dense cores eventually leading to the collapse and protostar formation. As presented earlier, the established view is that the galactic shock fronts compress molecular clouds that then settle into quiescence for the time span $\sim 10^7$ yrs required for ambipolar diffusion to finally let the dense cores reach supercriticality and collapse. For this to happen, the cloud must be supported against monolithic collapse while the supporting mechanism still lets dense cores contract and collapse. The mechanism is, in this view, the magnetohydrodynamic Alfvén waves, since there is a broad aggreement that magnetic and mechanic turbulence decays too rapidly to support the cloud for its entire life span. the life times of clouds are mostly derived from extragalactic observations of the typical scale of interarm regions, which are interpreted as a measure of the time span from initial cloud compression to core collapse and star formation.

However, as earlier mentioned, this view has been challenged by a compound of observations, numerical models and other arguments in recent years, of which some are described in Ballesteros-Paredes & Hartmann (2006). Instead, the authors advocate a view, in which cloud formation and core condensation are rapid, dynamical and mainly turbulence-driven events, taking place essentially at the same time and within a relatively short time span; formation, collapse and dispersal are believed to all take place within a few Myr (Hartmann et al. 2001), arguing that surveys show that there are not enough molecular clouds without star formation to be consistent with the long life time of molecular clouds, and instead advocating that the interarm distances reflect a cycle of star formation and dispersal rather than one single collapse time. Hartmann et al. (2001) even report that turbulence can play the role of Alfvén waves by supporting the cloud against monolithic collapse while still allowing contraction at the smaller scales of dense cores. Although Ballesteros-Paredes & Hartmann (2006) is the main focus here, it is very well supplemented by Hartmann et al. (2001), in that the former points out some observational problems with the classical picture, but builds on the results of Hartmann et al. (2001), the main focus of which is to suggest a coherent alternative. It will therefore get some attention in this section, too, along with a few additional arguments from the litereature.

3.1. *Observational Arguments*

3.1.1. *Cloud Statistics*

The most important observational argument against quasistatic star formation is the survey of CO clouds in the Galaxy by Dame et al. (2001) showing a very low ratio of the observed numbers of starless to star forming clouds in the solar neighbourhood, which is inconsistent with the AD theory of long life times of molecular clouds. Age spreads within clusters and associations are of the order $\sim 10^6$ yrs. Hence, the time of star formation can only be a small fraction, of the cloud life span, if we are to adopt the quasistatic picture. Ballesteros-Paredes & Hartmann have, for investigation, adopted the value of $\tau_{SF}/\tau_{MC} \sim 0.1$, with τ_{SF} and τ_{MC} being the characteristic time spans of star formation and molecular cloud life time, respectively. Age spreads up to an order of magnitude larger than the above mentioned have been assumed earlier, but more recent studies have pointed out

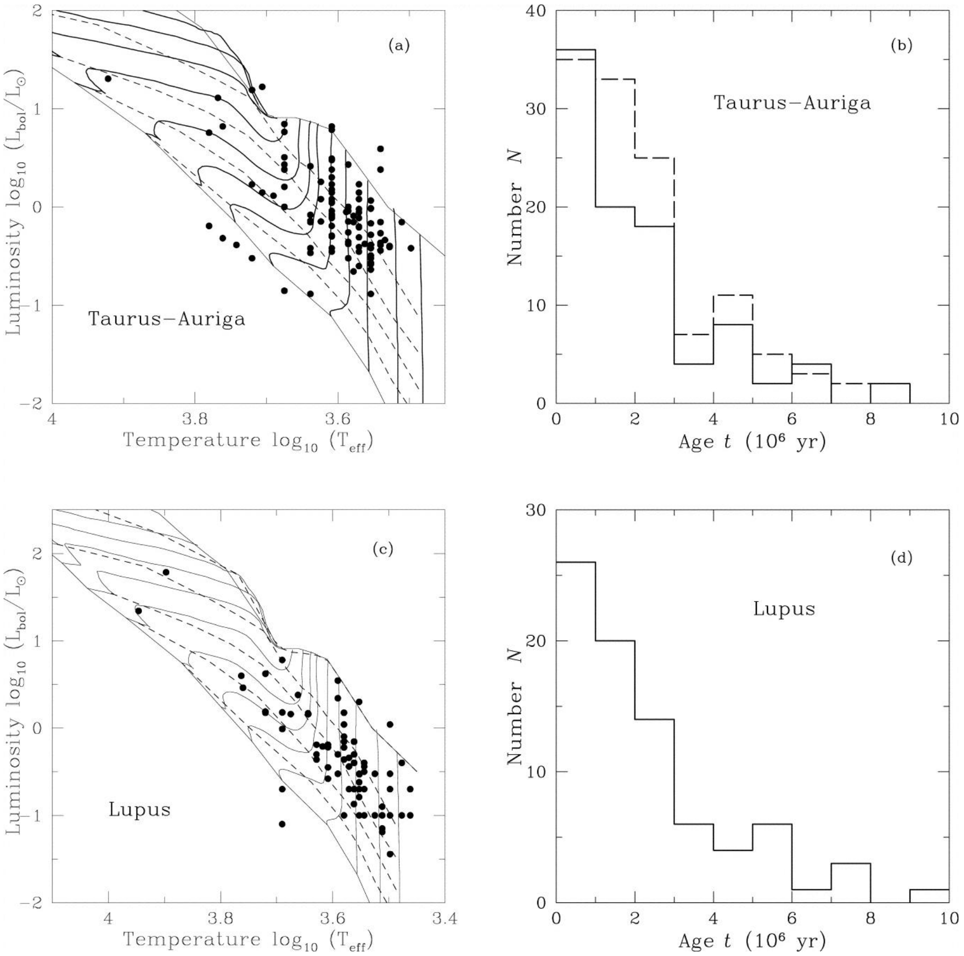

Fig. 2.— Determination of the ages and masses of the young low-mass star associations of Taurus-Auriga and Lupus, the cloud complexes also treated by Bertout et al. (2007) and Makarov (2007), respectively. The dashed columns in the upper right panel are an earlier age estimate. The dashed curves in the left panels are isochrones, the full line curves are theoretical evolutionary tracks(Palla & Stahler 2000).

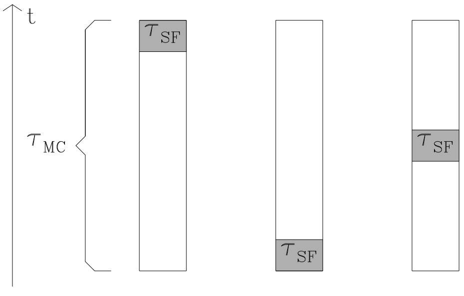

Fig. 3.— Figure from Ballesteros-Paredes & Hartmann (2006) illustrating the problem of long life times of molecular clouds compared to length of the star forming epoch. The time of star formation, τ_{SF}, can essentially be placed in three different ways relative to the overall life span of the cloud. None of the three configurations are consistent with observations, as explained in the text.

that these are most likely due to spatially and temporally separated star forming events, e.g. (Makarov 2007) or (Bertout et al. 2007).

The statistical problem of a short star forming epoch in the long life span of the molecular cloud is illustrated in fig. 3, taken from Ballesteros-Paredes & Hartmann (2006). Essentially, the epoch of star formation can fall in the beginning, in the middle or in the end of the cloud life span. If, as is suggested in (Mouschovias et al. 2006), it takes place at the end of the MC life span, the ratio of the numbers of clouds without vs. with stars should be 10 to 1 with the time ratios adopted (a motivation for this is given in Ballesteros-Paredes & Hartmann (2006)), where it is in fact 7 to 14, and this is even an upper limit of the number of non star forming regions, since a number of them have not been searched in depth for star formation.

Another possible case would be that τ_{SF} would be in the beginning of the MC life time, but if so, there should be a significant number of clouds with stars associated of ages $\sim$ 10 Myr, which has not been observed - this is in fact the so-called Post T tauri problem that triggered the ideas of rapid star formation in the first place. Besides, in this case, the long time needed for ambipolar diffusion before the onset of star formation is not present, and a major motivation for the long cloud life disappears. In addition, a reason for the sudden cessation of star formation would be needed, since the usual suspect - cloud dispersal - is ruled out by definition.

The third option would be to put τ_{SF} in the middle, but this would still need a reason for star cessation, and in general, star clusters and associations aged $\sim$ 5 Myr contain no molecular gas.

Ballesteros-Paredes & Hartmann then proceed to analyze a sample of MCs to further investigate the claim of Tassis & Mouschovias (2004), that MCs of low column density contrast are missed observationally, which would mean that surveys would be biased against slowly evolving cores. Ballesteros-Paredes & Hartmann state that this is not the case; every observed molecular cloud shows appreciable substructure, even in a worst case scenario, where the lower limit of molecular CO gas is measured (that is, there could be more CO out there, condensed as dust grains etc, but the data of the specific data set provide a lower limit). This implies that the formation of substructure within a MC is a rapid process, as also numerically suggested by Hartmann et al. (2001), lending further credibility to the rapid star formation scenario by removing one of the motivations for assuming slow ambipolar diffusion.

Another important question dealt with is the time required for atomic hydrogen to combine into H_2; a time scale that has traditionally been assumed long, but which is shown to very uncertain, and in the models of Hartmann et al. (2001), rapid H_2 condensation should be expected, since the dust temperature (see 2) is low in post-shock cold atomic clouds. Rapid condensation could allow the cloud to be formed on time scales lower than those on which turbulence effects die out, removing the need for strong Alfvén waves to support the cloud and yet allowing the cloud to evolve dynamically.

3.1.2. *Cloud Dispersal*

According to (Ballesteros-Paredes & Hartmann 2006), (Hartmann et al. 2001) and citations therein, molecular clouds are expected to end their lifes practically immediately after the arrival of massive stars. In the B star association Scorpius-Centaurus, for instance, no molecular gas is found, but there are large HI shells around the three major subconcentrations in the association, interpreted as the result of the cloud being disrupted by stellar winds and/or supernovae, putting an abrupt end to star formation in the region, securing the low efficiency in star formation of the cloud that is another of the main issues the Ambipolar Diffusion theory was meant to address. Furthermore, in Hartmann et al. (2001), it is suggested that this ejected matter can recondense by ramming into other nearby molecular regions and trigger new generations of star formation. The authors include a possible explanation to how large, short-lived cloud complexes can coordinate star formation in multiple locations at apparent supersonic speed, as illustrated in figure 4 taken from the article. The left panel shows the simplest picture, in which the gas dispersed by the stellar winds and/or SN energy from the central young star association expands isotropically, becoming self-gravitating and finally spark formation of new protostars. The density in the swept up area can be very uniform, and so star formation can be coordinated over very large scales, even though the cloud life time is short. However, this picture is not realistic, since the ISM is not uniform, so "bubbles" inside it generally do not have simple bubble morphology, and most likely the bubble structure wil rapidly break down due to interaction with this inhomogenous gas, as shown in the middle panel. Besides, as shown on the right, star formation events are from simulations predicted to take place at the intersections between bubble fragments, whose relative velocity will compress the gas at collision. Hartmann et al. (2001). Single supernovae could strip a close association almost entirely of molecular gas, and so as soon as a few massive stars are formed in the region, the rapid dispersal of the cloud seems almost enevitable, and even the stellar winds of low mass stars seem to be able to disperse an enveloping cloud.

3.1.3. *Starless Cores*

Just like the quasistatic model predicts a high rate of starless to starforming clouds, it also predicts a high relative number of starless, subcritical cores that - due to being quasistatic - would show a regular morphology. The rapid core formation picture, on the other hand, would show very few starless cores with a more irregular morphology. The authors point out various difficulties about the statistics of these counts that make them highly uncertain, whereas new searches are mentioned, in which a number of cores show irregular, transient features, suggesting a short and turbulent rather than stable and quasistatic life time for the cores.

Also the MHD properties of the cores are discussed. It has been suggested Mouschovias et al. (2006) that the molecular clouds and their cores initially are only slightly subcritical, thus adressing the statistical problem of few starless molecular clouds by dramatically lowering the time needed for ampipolar diffusion to let the core collapse by up to an order of magnitude. However, as is argued in (Ballesteros-Paredes & Hartmann 2006), this would make for an overall near-critical cloud which would easily be locally perturbed into supercriticality in shorter time spans than needed for AD. These perturbed, supercritical cores would quickly dominate the cloud and most likely disrupt the subcritical condensations.

3.1.4. *Spiral Arms*

Finally, Ballesteros-Paredes & Hartmann (2006) adress the argument of interarm distances as an indicator for molecular cloud life times. The main problem is that it asumes that the clouds stay largely unchanged and definitely unbroken for a time span of $\sim$ 10 Myr, a time span where even the morphology of the clouds has to be roughly maintained, which seems unlikely, as the galactic shock front is likely to set off at least some star formation almost immediately, which will then quickly disrupt the cloud and create supercritical zones elsewhere and hence trigger new star formation, until finally the cloud gets diffused enough that star formation wears off. Thus, the arm-interarm pattern is, in this picture, consistent with slowly decaying cycles of star formation rather than one single generation as believed in the quasistellar picture.

3.2. *Numerical Modeling*

Where Ballesteros-Paredes & Hartmann (2006) mainly points out discrepancies between observations and the AD picture, Hartmann et al. (2001) presents a numerical and observational analysis that point towards a more coherent picture of the interstellar medium and its transformation into stars. This paper has met some criticism, mainly by Tassis & Mouschovias, which a large part of Ballesteros-Paredes & Hartmann (2006) is dedicated to adressing. A thorough treatment of Hartmann

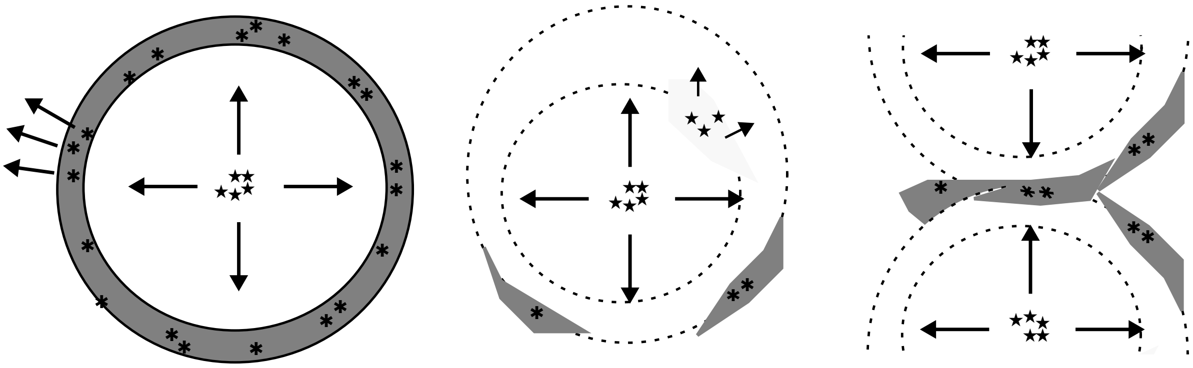

Fig. 4.— Illustration of large-scale triggered star formation, as explained in the text.

et al. (2001) is outside the scope of this paper, but I shall mention a few of its more interesting resuls here:

- The conditions for atomic gas to become molecular and the conditions for turbulence-induced gravitational instability in terms of column density, turbulence and magnetic field strength, are roughly equal with collapse times of ~ 1 Myr, corresponding well to the measured ages and age spreads of young stallar groups.

- As mentioned previously, the expansion and collision of superbubbles can coordinate star formation in young clouds in time scales very small compared to the cloud complex size and sound speed.

- In addition, the turbulent triggering makes the star and cloud formation depend on the same trigger mechanism, whereas local triggering requires very long life times for the stars.

- In a realistic cloud, turbulence can counteract monolithic collapse of the cloud and still permit core collapse in much the same way as the Alfvén Waves of AD theory.

- Clouds are formed mainly at kinks or bends of the Galactic magnetic field, in which atomic gas is accumulated until column densities are reach that allow for rapid recombination of H atoms and core condensing.

- Most of the cloud accretion is in the atomic state, the gas only gets molecular at a very late stage. Large accumulation langths of the atomic gas give a higher mass-to-flux-ratio and can ensure supercriticality already at the time the cloud becomes molecular.

4. CONCLUSION AND DISCUSSION

Adopting the picture of Ballesteros-Paredes & Hartmann and others, data and models suggest that dynamic ISM events play a very large role for the formation of stars, with magnetic pressure and turbulence left only a minor, higher order role to play. Turbulent events can make molecular clouds form rapidly, and since the same condition and time scales apply to apply to the formation of dense cores, these form practically simultaneously with the cloud itself. At most a few Myr after the star formation epoch begins, the stellar winds and supernova output disperses the cloud, which is blown away to recompress when meeting the clouds of more quiescent nearby regions, triggering new generations of star formation, until eventually the large scale depletion of molecular gas and dust causes star formation in the region to die out. The cloud or the cores are at no time in equilibrium, and there are significant pressure gradients withing the clouds. Large scale fluctuations can not only disturb, but also trigger the formation of cores.

It seems clear that more observation is needed to settle the discussion at hand. Both sides seem to have absolutely valid arguments, and the evidence is not conclusive. However, the picture of rapid, dynamical star formation seems to be more appealing; not only does it suggest a theory of the transformation of molecular clouds into stars, it also presents a coherent picture of the process of cloud formation and contraction based on larger scale considerations on the ISM. The authors have taken a path of suggesting a model coherent on a wide range of scales from a wide range of arguments, finding likely replacement mechanisms for the ones of the AD picture.

The proponents of the quasistatic AD model, on the other hand, seem to confine themselves to defending a view that has merit, but does not seem more consistent with data than the dynamic view, and that does little in order to suggest coherence with the overall notions of the ISM.

In any case, it is going to be interesting to follow the development in the field in the years to come, when new observational and modeling work can hopefully tip the balance more clearly in favor of one of the models more clearly and convincingly than is that case today.

REFERENCES

Ballesteros-Paredes, J., & Hartmann, L. 2006, Revista Mexicana de Astronomía y Astrofísica, 123

Bertout, C., et al. 2007, Astronomy and Astrophysics, 473,

Cox, D. P. 2005, Annual Review of Astronomy and Astrophysics, 337

Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, The Astrophysical Journal, 547, 792

Hartmann, L., et al. 2001, ApJ

Hughes, J., et al. 1994, Astronomical Journal, 108, 1071

Makarov, V. V. 2007, The Astrophysical Journal, 658, 480

Mouschovias, T. C., Tassis, K., & Kuntz, M. W. 2006, ApJ, 1043

Palla, F., & Stahler, S. W. 2000, The Astrophysical Journal, 540, 255

Stahler, S. W., & Palla, F. 2004, The Formation of Stars (Wiley-VCH)

Tassis, K., & Mouschovias, T. C. 2004, ApJ