Comments on Inferences of Star Formation Histories and Birthlines

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ABSTRACT

Palla & Stahler have recently argued that star formation in Taurus and other nearby molecular clouds extends over a period of at least 10 Myr, implying quasi-static cloud evolution and star formation. Their conclusions contradict other recent results indicating that molecular clouds are transient objects and star formation proceeds rapidly. The Palla & Stahler picture implies that most molecular clouds should have extremely low rates of star formation, and that in such inactive stages the stellar initial mass function should be strongly skewed toward producing stars with masses $\gtrsim 1M_\odot$; neither prediction is supported by observations. I show that the Palla & Stahler conclusions for Taurus depend almost entirely on a small number of stars with masses $\gtrsim 1M_\odot$; the lower-mass stars show no evidence for such an extended period of star formation. I further show that most of the stars apparently older than 10 Myr in the direction of Taurus are probably foreground non-members. I also present birthline calculations which support the idea that the ages of the stars with masses $\gtrsim 1M_\odot$ have been systematically overestimated because “birthline” age corrections have been underestimated; such birthlines would eliminate the need to postulate skewed initial mass functions. The simplest and most robust explanation of current observations characterizing the vast majority of young stars in molecular clouds is that cloud and star formation is rapid and dynamic.

Subject headings: stars: formation, pre-main sequence

1. Introduction

Several authors have recently suggested that the old quasi-static models of low-mass star formation (e.g., Shu, Adams, & Lizano 1987) are inadequate, and that star formation is a rapid and dynamic process (Ballesteros-Paredes, Hartmann, & Vazquez-Semadeni 1999 =BHV99; Elmegreen 2000; Pringle, Allen, & Lubow 2001; Hartmann, Bergin, & Ballesteros-Paredes 2001 =HBB01). Key constraints in the observational case for the timescale of star formation are the ages of the stellar populations in star-forming regions. Using the mean ages of populations, HBB argued that nearby molecular clouds form rapidly, form stars rapidly, and disperse rapidly (within a few Myr).
In contrast, Palla & Stahler (2000 = PS00; 2002, = PS02), using some of the same stellar data as HBB01, claimed to find evidence for recent “accelerating” star formation in molecular clouds, preceded by very extended periods of time with low star formation rates. Palla & Stahler argue that the inferred extended periods of low star formation are consistent with the old models of quasi-static, slow star formation. PS02 also take issue with several points I made concerning age distributions in a previous paper (Hartmann 2001a = Paper I).

In the following, I attempt to frame the issues in a clear and systematic way, focusing on the recent analysis of the Taurus molecular cloud complex by PS02, but drawing some broader conclusions as well. I show that much of the apparent evidence for an extended period of star formation in Taurus is due to the stars with masses \( \gtrsim 1 \text{M}_\odot \), not the lower-mass stars which dominate the population. I present evidence that the stars with ages \( \gtrsim 10 \text{ Myr} \) are strongly contaminated by foreground non-members. I further argue that the ages of the younger \( \gtrsim 1 \text{M}_\odot \) stars have been systematically overestimated by underestimating the “birthline” correction to their ages; theoretical calculations of birthlines for cold disk accretion are presented to support this hypothesis. My conjecture that birthlines need to be revised avoids the necessity of assuming that the stellar initial mass function varies strongly with age, a position for which there is no clear observational evidence. I conclude that the observations are not consistent with the picture presented by PS00 and PS02, and the star formation is rapid and dynamic, as illustrated by the age distribution of the great majority of the low-mass stars.

2. Implications of the PS00/02 picture

Figure 1 shows the stellar age distribution in Taurus-Auriga inferred by PS02, derived from data downloaded from their website (http://www.arcetri.astro.it/~palla/taurus/table). I have binned the stellar distribution in units of 2 Myr in order to display some of the apparently older stars; these older objects are in the table of PS02, but are not shown in the PS00/PS02 papers, in which the data are binned in 1 Myr increments from 0 to 10 Myr. Note that I have changed the age of HBC 412 (Herbig & Bell 1988 catalog) from the 20.4 Myr to 4 Myr (see Table 1); the former apparently was a typographic error in the PS02 table, given the reported effective temperature and luminosity.

Figure 1 seems to indicate a recent rise or burst of star formation, preceded by a very long period of relatively little activity, with no statistically significant additional peak in the star formation rate. The distributions of stellar ages in other regions found by PS00 are qualitatively similar to that shown in Figure 1. The eight star-forming regions with molecular gas studied in PS00 – Taurus, Lupus, Chamaeleon I, II, \( \rho \) Ophiuchus, IC 348, the Orion Nebula Cluster, and NGC 2264 – all show the same behavior. Of these eight regions, PS00 found that six of them exhibit peaks in their star formation rates over the last 1 Myr; the other two regions peaked 1-2 Myr ago. Even Upper Scorpius, which has no significant associated molecular gas, exhibited a strong peak in its star formation rate only 2-3 Myr ago.
If these results are taken at face value, one must ask: what is so special about the last 1-2 Myr? Why should star forming regions separated by hundreds of pc (NGC 2264 is at a distance of about 800 pc) form most of their stars at the same time, if their overall lifetimes are $\sim 10$ Myr? More broadly, Figures 1-5 of PS00, like Figure 1 of this paper, appear to show that all the star forming regions have spent most of the last 10 Myr forming stars at an extremely low rate. So where are these inactive regions? The clear implication of the star formation histories found by PS00 is that more than half of all molecular cloud complexes should be forming very few stars, much lower than the typical efficiencies seen in star-forming regions. HBB01 considered studies of nearby clouds and found only one plausible example out of nine of low or absent star formation, the Coalsack; PS02 point out another nearby cloud, Cha III, which appears to harbor little star formation. But, according to the PS00/PS02 scenario, most star-forming clouds should be inactive, not the small fraction found so far.

Conversely, suppose one adopts the view of HBB01, Elmegreen 2000, and Pringle et al. (2001), in which molecular cloud and star formation episodes are concurrent, and last only a very few Myr. Then there is no need to explain why all the molecular cloud regions peaked in their star formation rates over the last 1-2 Myr; that is simply the characteristic timescale for star and cloud formation. In the rapid formation picture, star formation events are not coordinated over hundreds of pc; the present epoch is not special in any way.

The basic implication of the PS00/02 scenario is that most nearby molecular clouds of substantial mass ($10^4 - 10^5 M_\odot$, i.e., from Taurus-like clouds to those similar to Orion) should spend most of their lives in a very inactive state of star formation, with no obvious increase in star formation rates toward the present (“acceleration” in the language of PS00/PS02). As current observations contradict this prediction, the PS00/02 interpretation is suspect.

A clue to the nature of the problem is given in Figure 1, where I have singled out stars with effective temperatures $\geq 4350$ K, corresponding to stars of spectral types $\sim$ K5 and earlier (and roughly at masses of $1M_\odot$ and larger for stars on convective tracks, according to the PS02 tracks). As shown in Figure 1, these hotter and generally more massive stars show a distinctly different apparent age distribution than that exhibited by the cooler, lower-mass stars, and dominate the extended tail of the distribution to larger ages. Again, taking the PS02 results at face value, one would have to conclude that the hotter, higher-mass stars formed with a qualitatively different age distribution than the lower-mass stars in Taurus; the hotter stars formed first, with little apparent acceleration to the present. This seems very unlikely; why should $\nabla 1M_\odot$ stars form so differently in time than $< 1M_\odot$ stars?

In the next two sections I consider two factors which could reduce or eliminate the discrepancy between the age distributions of low- and higher-mass stars, following the discussion of Paper I; contamination by non-members and errors in isochrones.
Associating classical T Tauri stars (CTTS) with their natal molecular clouds is usually straightforward; these objects, actively accreting from circumstellar disks, and exhibiting strong line and continuum excess emission, are distinctive and relatively rare. Identifying weak-emission T Tauri stars (WTTS) which belong to a cloud is much more difficult, because the most easily-applied indicators — chromospheric H$\alpha$ emission and coronal X-ray emission — do not decay rapidly with age between 1-100 Myr in low-mass stars (Briceño et al. 1997). As star formation has continued in the solar neighborhood for the last 100 Myr (for example, the Pleiades, α Per, and IC 2602/2391 clusters; Stauffer et al. 1997), these older stars will form a dispersed population, some of which will lie in front of Taurus. Since parallaxes are not available for most of these stars (e.g., Bertout, Robichon, & Arenou 1999), assuming that these foreground objects are members of Taurus, and therefore assigning the cloud distance to them (140 pc; Kenyon et al. 1994), will result in an overestimate of the stellar luminosity and an underestimate of the stellar age. In turn, an underestimated age will make it appear more likely that such a star is a real Taurus member. Given the relatively flat age distribution of the hotter stars in Figure 1, one must consider the possibility of foreground contamination seriously.

Detection of Li I 6707 Å absorption has come to play a crucial role in identifying WTTS. Li can be depleted due to fusion at central stellar temperatures $\sim 3 \times 10^6$ K; however, the timescale over which this depletion occurs exhibits considerable sensitivity to stellar mass. Stars with masses $\sim 0.5M_\odot$ remain completely convective for most or all of their pre-main sequence evolution; evolutionary models predict that depletion should begin at ages $\sim 10 - 20$ Myr, and proceed rapidly. On the other hand, stars with masses $\gtrsim 0.9M_\odot$ develop radiative cores, which limits mixing to the core and thus strongly retards the depletion of Li. Thus, the utility of Li as an indicator of pre-main sequence stars, and the age limit it provides, depends strongly on the mass in question.

Figure 2 shows Li equivalent widths as a function of effective temperature for differing samples. The solid dots are young T Tauri stars, while the solid segmented curve denotes the upper envelope of Li equivalent widths for Pleiades members, which have an age of roughly 100 Myr. While there is strong depletion at low effective temperatures in the pre-main sequence phase, there is much less pre-main sequence depletion in the hotter stars, for the reasons noted in the preceding paragraph. The dotted segmented curve shows the upper envelope for stars in the IC 2391/2602 open clusters, which are estimated to have ages of $\sim 30 - 50$ Myr (see discussion in Randich et al. 1997).

Figure 2 shows that the detection of Li in a star cooler than about 4200 K is a clear indication of pre-main sequence status. However, detection of Li at higher effective temperatures is not enough; the equivalent width must be larger than that of the upper envelope of IC 2391/2602 to make it probable that a star is younger than 30-50 Myr. Failure to recognize this led to the claimed discovery of large numbers of new WTTS associated with Taurus and other regions (e.g., Wichmann et al. 1996); more careful followup showed that a large fraction of these stars had Li abundances consistent with Pleiades age, if not older (Briceño et al. 1997; Neuhäuser et al. 1997;
Figure 2 also shows Li equivalent widths, where available, for the apparently older, hotter Taurus stars (also summarized in Table 1). There are 11 stars with ages > 10 Myr; of these, 8 have Li measurements available. Of these 8, 5 stars have Li equivalent widths at or below the IC cluster line (RXJ0405.7, RXJ0406.7, HBC 388, HBC 392, RXJ0441.8), suggesting that they are \( \gtrsim 30 - 50 \) Myr old and thus are unlikely members of Taurus. These stars are hatched in Figure 1. One other star (RXJ0423.7) is just slightly above the IC cluster line. Thus, at least half, and possibly as many as \( \sim 80\% \), of the population with apparent ages of 10-25 Myr in Figure 1 probably have ages in excess of 30 Myr and thus are likely older, foreground, stars which are not members of Taurus. Furthermore, as many of these objects are probably foreground systems, their true ages are should be older than indicated in Figure 1 because of the overestimate in distance (e.g., Briceño et al. 1997). These conclusions are consistent with deep imaging which has provided no evidence for a population of older pre-main sequence objects among the lower-mass stars (Briceño et al. 1998, 1999); main-sequence low-mass stars will be much fainter and thus drop out of current surveys.

Sometimes association with a cloud is argued on the basis of radial velocities or proper motions. Motions alone do not provide a reliable criterion, as stars younger than about 100 Myr exhibit relatively small velocity dispersions about the local standard of rest. For example, consider several stars studied by Walter et al. (1988) that exhibit Li equivalent widths below the Pleiades boundary. The stars HBC 352, 354, 355, 372, 388, and 392, and SAO 76411A, have a mean radial velocity and dispersion of 15.3 ± 3.5 km s\(^{-1}\); this is near the Taurus mean velocity, and the dispersion, is not much larger than that of the obvious members (Hartmann et al. 1986).

A useful test for contamination would be to have equivalent measurements for a field off molecular gas; the difference between cloud and non-cloud regions should provide some indication of the population not associated with cloud material. The study by Neuhäuser et al. (1997) of RASS sources in a region south of Taurus is of interest in this connection, because it covers a comparable area to Taurus but off the molecular cloud, and has a comparable X-ray detection limit. Neuhäuser et al. (1997) report nine K stars in this southern region with Li equivalent widths comparable to or larger than those of IC 2391/2602; moreover, Neuhäuser et al. report that most of these stars have radial velocities consistent with Taurus. As this region extends much further away from the galactic plane than Taurus, it is reasonable to suppose that these results underestimate the number of relatively young field stars in the direction of Taurus that are not associated with molecular gas. These results support the contention that most of the stars with ages \( \gtrsim 10 \) Myr in Figure 1 and Table 1 are not true members of the present Taurus clouds.

It should be emphasized that PS00/02 do not consider stars with apparent ages larger than 10 Myr in their detailed analysis, even though they are claimed to be vetted members of Taurus in their table of 153 objects. This age limitation seems to avoid most of the obvious Taurus membership problems. However, the situation is less clear for other, more distant clusters at lower galactic latitudes studied by PS00, such as the Orion Nebula Cluster and NGC 2264, where Li
measurements are generally not available, and foreground contamination is much more likely. The possibility of non-members in samples needs to be considered more carefully when assessing the PS00 results for these more distant regions.

4. Isochrones and birthlines

Restricting attention to Taurus stars with ages $\leq 10$ Myr, as in PS02, and assuming non-members are not present, a problem still remains with the PS02 results; the distribution of ages among the stars with $T(\text{eff}) \geq 4350$ K is dramatically different from the age distribution of the cooler stars. A two-sided Kolmogorov-Smirnov test (Press et al. 1986) on the unbinned age data shows that the two samples have a probability of only $\sim 1.5 \times 10^{-3}$ of being drawn from the same underlying distribution. Moreover, this pattern – in which $\sim 1 - 2M_\odot$ stars appear to be considerably older than the $< 1M_\odot$ stars – is seen repeatedly in many regions, such as the Orion Nebula Cluster (Hillenbrand 1997) and in Upper Scorpius, IC 348, and NGC 2264 (Hartmann 1999; see PS00 results).

Thus, the PS00/02 age distributions imply that star forming regions pass through an extended phase in time during which $1 - 2M_\odot$ stars were produced at a far greater rate than the lower mass stars. As shown in Figure 1, the implication of the PS02 results is that for the first $\sim 5$ Myr, Taurus formed stars with a ratio of $\gtrsim 1M_\odot$ stars to $< 1M_\odot$ stars that was roughly an order of magnitude higher than it is today. Similar results apply to the other regions studied by PS00. I am unaware of any evidence for such extremely non-standard IMFs (see Kroupa 2002 for a review). Again, the observations indicate that the PS00/02 results must be treated with skepticism.

This raises an obvious question: are the isochrones in error? And if so, does the problem lie mostly with the higher-mass or lower-mass stars? Baraffe et al. (2002) provide a recent discussion of the difficulties involved in calculating evolutionary tracks. Here I summarize some basic issues, following along the lines of the discussion in Paper I and also in Hartmann (2001b).

The age of a pre-main sequence star (the elapsed time after the end of protostellar accretion) can be approximated by the relation

$$t \simeq \eta GM^2/RL \ - \ \eta_0 GM^2/(R_0 L_0),$$

where $M$, $R$, and $L$ are the stellar mass, radius, and luminosity, respectively, $\eta$ is a coefficient of order unity which depends upon the internal structure of the star (see, e.g., Hartmann 1998; Paper I), and subscript zero indicates quantities at the end of protostellar accretion. The initial stellar radius and luminosity $R_0$ and $L_0$ correspond to the “birth” position of the star, and the loci of such points for stars of differing mass has been called the “birthline” (Stahler 1983, 1988).

Since the stellar luminosity can be determined reasonably well for most objects if the distance is known, and the radius can be inferred from the luminosity and effective temperature with reasonable accuracy, the main uncertainty in the first term of equation (1) has long been the stellar mass. In
the past, it was necessary to estimate masses from theoretical evolutionary tracks, which included substantial uncertainties in stellar photospheric boundary conditions and treatment of convection (see the discussion in Baraffe et al. 2002). The mass uncertainty, and thus the age uncertainty, was greatest for lower-mass stars; the radiative tracks for the higher-mass stars calculated by different groups with differing assumptions were in better general agreement.

A recent development of great importance is the direct determination of T Tauri masses from the measurement of Keplerian rotation in their circumstellar disks, using mm-wave observations of CO emission (Dutrey, Guilloteau, & Simon 1994; Guilloteau & Dutrey 1998; Simon, Guilloteau, & Dutrey 2000). For several Taurus stars, Simon et al. (2000) find internal errors of less than 10% in the mass, with the overall uncertainty dominated by the uncertainty in the distance. Moreover, the quantity $L/M^2$ is independent of distance in the Simon et al. (2000) analysis; for several of their program objects, Simon et al. estimate errors of $< 10\%$ in this quantity. This means that the remaining error in the first term of equation (1) is mostly in the radius $R$, which is directly proportional to the distance. Typical estimates of this error for Taurus CTTS are on the order of 15% (Paper I; Simon et al. 2002). Moreover, although most of the stars studied are lower-mass objects, one, LkCa 15, is a K5 star with $T(\text{eff}) = 4350$ K. Simon et al. (2000) show that the masses estimated from the evolutionary tracks of PS00/02 (from Palla & Stahler 1999 = PS99) and Baraffe et al. (1998) are in good agreement with the observations. Thus it seems very unlikely that errors in the first term of equation (1) can account for the discrepancy in age distributions shown in Figure 1.

The other major uncertainty in pre-main sequence ages arises from considering the initial position in the HR diagram from which pre-main sequence contraction proceeds, represented by the second term of equation (1). Stahler (1983, 1988) showed that the process of protostellar accretion was likely to terminate with the star having a finite, relatively small radius, after which typical pre-main sequence evolutionary tracks apply. The birthline limits on stellar radii and luminosities are in part the result of the very temperature-sensitive fusion of deuterium in the stellar interior, which prevents contraction below the “deuterium main sequence” until most of the deuterium has been burned. The latest version of these calculations is given by PS99, and is employed in PS00 and PS02.

Figure 3 shows the Taurus HR diagram, using the data in the PS02 table. I have superimposed isochrones from Baraffe et al. (1998), which are similar to those employed by PS99/00/02. The dotted curve shows the PS99/00/02 birthline; it lies well above the 1 Myr isochrone. Therefore, the PS99/00/02 birthline has little effect on the inferred ages of most of the stars with masses $\gtrsim 1M_\odot$.

However, the birthline calculations of Hartmann, Cassen, & Kenyon (1997; HCK97) yielded different results. To illustrate this in greater detail, I have recalculated two birthline tracks of HCK97 for accretion rates of $10^{-5}M_\odot\text{yr}^{-1}$ and $2 \times 10^{-6}M_\odot\text{yr}^{-1}$, assuming the cold accretion limit ($\alpha = 0$ in the HCK parameterization; see also Siess, Forestini, & Bertout 1997, 1999). I have also revised the calculations to use a fit to the Baraffe et al. (1998) evolutionary tracks for the
stellar luminosity as a function of mass and radius, and have extended the calculations in mass until radiative cores form, at which point the evolution cannot be followed further using the simple polytropic model of HCK97.

As shown in Figure 3, the revised “HCK” birthline for a protostellar accretion rate of $10^{-5} \text{M}_\odot \text{yr}^{-1}$ is somewhat lower than the PS99/00/02 birthline (which also assumes the same accretion rate). However, the birthline for $\dot{M} = 2 \times 10^{-6} \text{M}_\odot \text{yr}^{-1}$ is markedly lower, crossing the 1 Myr isochrone at $T(\text{eff}) \sim 4000$ K. (The results differ only slightly from those shown in HCK97 for the same parameters.) These tracks imply significantly larger birthline corrections to the ages in equation (1) than implied by the PS99 birthline.

As already mentioned, the simple polytropic approximation used by HCK97 is limited to completely convective stars, and thus cannot be extended directly to higher mass stars with radiative cores. However, the trajectories of the HCK tracks strongly suggest that a continuation of the calculation to higher effective temperatures and masses would result in much lower birthlines, and therefore considerably lower ages, than in the PS99/00/02 analyses.

The difference between the PS99 and HCK97 calculations appears to lie in the differing boundary conditions assumed (see the discussion in HCK97). The PS99 birthlines have been calculated assuming spherical accretion, which is implausible given the angular momenta of protostellar cloud cores; much if not most of the stellar mass must initially fall in to a disk, and then be accreted from the disk. The HCK97 calculations explicitly assume that protostellar accretion is from the circumstellar disk, either through narrow boundary layers or magnetospheric accretion shocks covering small areas, as in T Tauri stars; the latter assumption is consistent with observations suggesting magnetospheric accretion in some protostellar objects (Muzerolle, Hartmann, & Calvet 1998; Folha & Emerson 1998, 2001). Thus, in the HCK97 case, accretion affects only a small fraction of the stellar surface; most of the star is free to radiate into space. This extra energy loss in comparison with the PS99 calculations causes the star to fuse deuterium faster to replenish the extra energy radiated into space; in turn, the faster reduction of deuterium means that the star contracts below the deuterium main sequence sooner, i.e. at a lower mass. The results are dependent upon the mass accretion rate; at higher accretion rates, the fused deuterium is replenished faster, and so the depletion of deuterium occurs at a higher stellar luminosity (higher mass) (see HCK97 for a more detailed discussion).

It is worth noting that the PS99 calculations of the birthline, like those of HCK97 (and Figure 3), assume a deuterium to hydrogen ratio of $D/H = 2.5 \times 10^{-5}$, whereas recent measurements of this ratio in the local interstellar medium yield values $D/H \sim 1.5 \times 10^{-5}$ (Moos et al. 2002). This would lower birthline positions in the HR diagram even further. Stahler’s (1988) calculations for an accretion rate of $\dot{M} = 10^{-5}$ indicated that the birthline radius of a $1 \text{M}_\odot$ star would be reduced from about $5 \text{R}_\odot$ to about $3 \text{R}_\odot$ by reducing the deuterium abundance from $2.5 \times 10^{-5}$ to $1.3 \times 10^{-5}$. Even assuming that the deuterium abundance is not reduced, and within the context of the assumption of spherical accretion, Stahler (1988) showed significant differences in birthline positions for varying
accretion rates.

As emphasized by HCK97, birthline theory does not preclude stars from lying above the birthline; the initial conditions of the quasistatic protostellar core onto which accretion occurs result from hydrodynamical collapse, which is beyond the scope of the calculations (e.g., Bodenheimer et al. 2000). Deuterium fusion simply prevents the initial core from lying below far below the birthline, but does not prevent objects from starting above the birthline; such stars will simply contract rapidly until they reach the birthline and deuterium fusion begins. Furthermore, as shown in Figure 3, if accretion rates vary, stars of the same final mass will have different birthlines. Given that T Tauri stars exhibit a wide range of disk accretion rates among objects of roughly the same age and mass (Gullbring et al. 1998), it is reasonable to expect similar variations in disk accretion rates for protostellar objects. HCK97 also showed that birthlines can differ significantly even at a single accretion rate for differing initial protostellar core masses and radii. Finally, accretion onto protostars is likely to be time-variable (Henriksen, André, & Bontemps 1997) if not episodic; the effects of such variable accretion have not been quantified but might well add additional variability to birthline positions. Thus, it is far more likely that young stars start their quasi-static contraction after protostellar accretion on a range of birthlines, or over a birth region, rather than along a single locus in the HR diagram.

Qualitatively, one would expect that even if deuterium fusion provides a “floor” in the HR diagram, below which very young low-mass stars cannot be found, this limitation is less likely to apply for higher-mass objects. Deuterium fusion can only prevent contraction when it provides a source of energy comparable to that lost from the stellar surface by radiation; in higher-mass, higher-luminosity stars, deuterium fusion cannot match the stellar radiative losses for a long period of time. In addition, once a pre-main sequence star develops a radiative core, mixing of freshly-accreted deuterium from the surface, where it is accreted, into the core, where it can be fused, will be slowed. Thus, it is qualitatively reasonable to assume that the birthlines or birth regions of stars with masses \(<1\,M_\odot\) can be more tightly linked to deuterium fusion independent of initial conditions and accretion rates, while the birthline for higher-mass stars will be less controlled by deuterium fusion and therefore be more sensitive to mass accretion rates and initial conditions. This is demonstrated by the convergence of the two HCK tracks in Figure 3 near 0.5\,M_\odot and their divergence at 1\,M_\odot; similar behavior, though less dramatic, is also shown in the calculations of Stahler (1988).

In summary, I conjecture (as in Paper I) that the discrepancy in age distributions between hotter and cooler stars shown in Figure 1, and the similar behavior found in other star-forming regions, is due to lower, variable birthline positions of the hotter, more massive stars than assumed by PS02. This hypothesis should be tested by more sophisticated evolutionary calculations extending to higher masses, exploring a variety of initial conditions, and following the effects of time-dependent accretion rates. Better empirical constraints on protostellar masses, radii, and accretion rates also are needed. However, apart from these theoretical considerations, in the absence of evidence for such highly-skewed stellar IMFs in star-forming regions, the PS00/02 results must
be viewed with considerable skepticism.

As an aside, if my “birth region” conjecture is correct, the ages of Herbig Ae/Be stars have been systematically underestimated. Moreover, the age estimates would be much more uncertain in absolute terms than those of the lower-mass T Tauri stars, due to variations in birthline positions. More investigation of this conjecture is needed, as it has important implications for efforts to understand the evolutionary timescales of circumstellar disks.

5. Discussion

5.1. Extended and “accelerating” star formation in time

The scarcity of significant molecular cloud complexes with extremely low star formation rates, and the lack of evidence for strongly variable IMFs, with a strong enhancement of \( \gtrsim 1 \text{M}_\odot \) stars relative to \( \lesssim 1 \text{M}_\odot \) stars, casts considerable doubt on the PS00/02 reconstruction of star formation histories. In the case of Taurus, removing older stars with strong Li depletion, and setting aside \( \gtrsim 1 \text{M}_\odot \) stars because of birthline uncertainties, the evidence for an extended period of star formation almost completely disappears. In any event, as emphasized by HBB01, the vast majority of stars in Taurus have been formed over only a few Myr.

Among the stars older than 10 Myr, one (LkCa 19) shows no evidence of Li depletion; two others (HBC 351 and RXJ0423.7) show modest depletion, and another (HN Tau) is a classical T Tauri star, thus suggesting that all four systems are indeed relatively young. However, this does not mean automatically that the rest of the Taurus cloud was present, forming no stars for > 10 Myr, while these stars were formed. It is possible that the molecular material associated with the formation of these few stars formed earlier than Taurus, and has already dispersed. The region south of Taurus, discussed in §3, shows that that a few relatively young stars unconnected with present molecular material are to be expected. Further examples of this possibility are the \( \eta \) Cha and TW Hya associations (Mamajek, Lawson, & Feigelson 1999; Kastner et al. 1997; Webb et al. 1999) which are \( \sim 10 \) Myr-old groups of stars not associated with molecular gas, at distances from the Sun of \( \sim 100 \) and 50 pc, respectively. Understanding the star formation epoch in Taurus and other regions should rest more heavily on the properties of the great majority of stars rather than the interpretation of a very small number of outlying objects.

Because star-forming regions have finite lifetimes, all such regions must experience “acceleration” in their star formation rates (from zero to a finite value). The physical significance of this depends upon the precise timescale involved. I showed in Paper I that observational errors were likely to have a significant effect on estimates of the star formation rates over modest age ranges. Moreover, I showed that estimates of the likely random or quasi-random errors due to distance uncertainties, binary companions, extinction errors, etc. are generally logarithmic in nature. Therefore, linear age binning such as that of Figure 1 has the disadvantage that the errors are
larger on the high age end than on the low age end. Furthermore, if the binning is too coarse, there will be a pile-up of stars in the first age bin. As shown in Figure 2 of Paper I, these effects can cause a spurious impression of acceleration in the star formation rate toward the present time.

Paper I showed that the age distribution of most of the Taurus stars is consistent with a modest age spread of \( \sim 4 \text{ Myr} \); the present results do nothing to change this conclusion. Inferring the variation of star formation rate with time at a more detailed level than this requires a better understanding of observational errors than presently available.

PS02 disagree with these conclusions of Paper I, arguing that if observational errors were responsible for their results, they would expect as many stars to appear too young as those which appear too old. Their argument depends upon the mistaken assumption that all the errors in question are random. As shown in the previous sections, inclusion of non-members and incorrect birthline placement can result in systematic errors, overestimating the star formation rates at earlier times.

### 5.2. Dynamic vs. quasi-static molecular clouds

Star formation in Taurus is strongly confined to narrow bands or filaments which extend over a sizable fraction of the total cloud extent (Hartmann 2002, and references therein; PS02). As discussed in Hartmann (2002), these large-scale filamentary structures suggest that the dominant driving is by large-scale turbulent motions, as observed in some numerical simulations (e.g., Klessen & Burkert 2000, 2001; Mac Low & Ossenkopf 2000; Ballesteros-Paredes & Mac Low 2002). PS02 argue instead that the filaments are produced by “global, quasi-static contraction of the parent cloud material”. But it is unclear how the supersonically-turbulent molecular gas in Taurus can quasi-statically contract, let alone why such quasi-static contraction would produce filaments. PS02 argue that the rough match between self-gravity and turbulent motions supports their notion of quasi-static cloud evolution; but as shown by Ballesteros-Paredes, Vazquez-Semadeni, and Scalo (1999; also HBB), numerical simulations frequently show similar cloud gravitational and kinetic energies even though these clouds are never in virial equilibrium. Moreover, as discussed in Hartmann (2002), there is evidence for departures from equilibrium in the dense Taurus filaments, in that supersonic motions are observed, and the filament line densities may exceed the gravitational stability limit.

PS02 argue that if the rapid star formation picture were correct, with rapid dissipation of turbulence and fragmentation in collisionally produced shells or filaments, then star formation would have to be nearly 100% efficient. This argument is only true if turbulence can be ignored and star formation occurs over an extended period. Star formation occurs in regions where the turbulence has dissipated, which occurs rapidly (Stone, Ostriker, & Gammie 1998; Mac Low et al. 1998; Padoan & Nordlund 1999; Mac Low 1999). Simulations show intense localized star formation surrounded by extended volumes of non-star-forming, highly turbulent gas (Padoan & Nordlund 1999; Ostriker, Stone, & Gammie 2001; Klessen et al. 2000; Klessen & Burkert 2000,
If the remaining cloud is then rapidly dispersed by the energy input of stars, as argued by HBB01, the star formation efficiency will be low.

6. Conclusions

The star formation histories of Taurus and other regions derived by PS02 and PS00 imply that most molecular clouds should experience an extended period of very low star formation, with a strong enhancement in the number of $\gtrsim 1M_\odot$ stars relative to stars with masses $< 1M_\odot$. Current observational evidence contradicts these predictions, rendering the conclusions of PS02 and PS00 suspect. I have shown that in the specific case of Taurus, the PS02 inferences of extended periods of star formation depend almost exclusively on results for stars of masses $\gtrsim 1M_\odot$. Significant foreground contamination in Taurus by older non-members is present in these more massive stars at ages $\gtrsim 10$ Myr, and this is likely to a bigger problem for analyses of more distant regions. Even restricting the sample to stars younger than about 10 Myr, I have shown that the age distribution derived by PS02 for the $\gtrsim 1M_\odot$ stars differs significantly from that of the lower-mass stars. I conjecture that this is due to overestimating the ages of the higher-mass stars due to birthline effects; variations in birthline positions for the more massive stars dominate the apparent ages and age spread. I offer theoretical support for this conjecture. In addition, there is an observational test; if the PS02 interpretation and birthlines are correct, there must be a significant fraction of all star-forming regions with highly variable initial mass functions, in the sense of a vastly reduced relative population of low mass stars. Current studies yield no evidence for this proposition, which favors my birthline/birth region conjecture.

The results for stars with masses $\lesssim 1M_\odot$ in Taurus, which constitute the vast majority of the young stellar population, and are the least affected by non-member contamination and birthline effects, demonstrate that star formation has commenced rapidly, as argued in HBB01. This behavior is consistent with recent numerical simulations of the interstellar medium and molecular cloud formation and evolution which show that cloud and star formation is a dynamic process.

I am grateful to Cesar Briceño and Kevin Luhman for help with making figures and providing other information. This work was supported in part by NASA grant NAG5-9670.

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Fig. 1.— Distribution of stellar ages in Taurus from PS02, with hatching indicating hotter stars (effective temperatures $\geq 4350$ K) and stars known to have Li abundances lower than that of main sequence stars in the young open clusters IC 2391 and IC 2602 (see text)
Fig. 2.— Li I 6707 Å equivalent widths for T Tauri stars (filled dots) and “older” Taurus stars from Table 1 (open circles). The upper envelope of observed equivalent widths for the Pleiades (solid segmented curve) and the IC 2391/2602 clusters (dotted segmented curve) are shown for reference.
Fig. 3.— HR diagram for Taurus objects from PS02, with 1, 10, and 100 Myr isochrones from Baraffe et al. (1998). Birthlines are shown for PS02 (dotted curve) and for calculations of HCK at two differing accretion rates, $10^{-5} M_\odot$ yr$^{-1}$ and $2 \times 10^{-6} M_\odot$ yr$^{-1}$, modified for fits to the Baraffe et al. (1998) tracks (see text).
Table 1. Taurus stars from PS02, ages > 6 Myr

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<th>N</th>
<th>Name</th>
<th>Type</th>
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<th>L/L⊙</th>
<th>Age (Myr)</th>
<th>W(Li) (Å)</th>
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aHBC numbers from the catalog of Herbig & Bell (1998)

bW = WTTS, C = CTTS

cThe age of HBC 412 is estimated at 4 Myr (see text)