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REMARKS ON RAPID VS. SLOW STAR FORMATION

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RESUMEN

Discutimos los problemas que presentan algunas estimaciones observacionales que indican tanto tiempos de vida largos para los núcleos densos protoestelares, como grandes dispersiones de las edades de las estrellas asociadas a nubes moleculares. Notamos algunas restricciones observacionales que sugieren que los núcleos densos no tienen tiempos de vida largos antes de colapsar. Para galaxias externas, argumentamos que los anchos de los brazos espirales no implican un proceso de formación estelar largo, ya que la formación de estrellas masivas debe romper las nubes moleculares, mover el material y comprimirlo en otras regiones para producir nuevas regiones de formación estelar. Así, parece inevitable que este proceso cíclico tenga como resultado un período de formación estelar extendido, el cual no representa la longevidad de una nube molecular individual. Argumentamos que la formación estelar rápida indicada observacionalmente es también más fácil de entender teóricamente que el escenario de contracción cuasiestática lenta vía la difusión ambipolar.

ABSTRACT

We discuss problems with some observational estimates indicating long protostellar core lifetimes and large stellar age spreads in molecular clouds. We also point out some additional observational constraints which suggest that protostellar cores do not have long lifetimes before collapsing. For external galaxies, we argue that the widths of spiral arms do not imply a long star-formation process, since the formation of massive stars will disrupt molecular clouds, move material around, compress it in other regions which produce new star-forming clouds. Thus, it seems unavoidable that this cyclical process will result in an extended period of enhanced star formation, which does not represent the survival time of any individual molecular cloud. We argue that the rapid star formation indicated observationally is also easier to understand theoretically than the traditional scenario of slow quasi-static contraction with ambipolar diffusion.

Key Words: **STARS: FORMATION — TURBULENCE**

1. INTRODUCTION

For many years the common picture of (particularly low-mass) star formation was one in which protostellar cores quasi-statically contract over timescales as long as 10 Myr until sufficient magnetic flux has been removed by ambipolar diffusion to permit free-fall collapse (Shu, Adams, & Lizano 1987; Mouschovias 1991). This picture was motivated in part by (a) the apparent need to avoid monolithic collapse of giant molecular clouds, reducing thus the star formation efficiency (i.e., the fraction of a molecular gas mass that is converted into stars); (b) the apparent need to reduce magnetic fluxes to the level necessary to allow local gravitational collapse of magnetically supported clouds (Mestel & Spitzer 1956); and (c) the old idea that all the forces (in the ISM) should be in balance and the medium should have no net acceleration (see e.g., Spitzer 1978, Chap. 11). However, both observational (Jenkins, Jura, & Loewenstein 1983; Bowyer et al. 1995; Jenkins & Tripp 2001; Jenkins 2002; Redfield & Linsky 2004), and numerical (Vázquez-Semadeni et al. 2003; Mac Low et al. 2005; Gazol, Vázquez-Semadeni, & Kim 2005) studies have found that the ISM is not in pressure balance, but exhibits

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strong pressure fluctuations. Equivalently, several studies on smaller scales have suggested that star formation is not a quasistatic process, but generally rapid and dynamic (Lee & Myers 1999; Ballesteros-Paredes, Hartmann, & Vázquez-Semadeni 1999; Elmegreen 2000; Pringle, Allen, & Lubow 2001; Briceño et al. 2001; Hartmann, Ballesteros-Paredes, & Bergin 2001, hereafter HBB). These studies seem to be in better agreement with numerical simulations indicating that cloud cores are more dynamic, have shorter lifetimes, and still a large fraction of them may appear to have equilibrium density profiles (Ballesteros-Paredes, Klessen, & Vázquez-Semadeni 2003) and to be quiescent (Klessen et al. 2005). In response to these and other developments, several theoretical approaches have been made to achieve shorter magnetic flux reduction timescales, either by starting with a more nearly-critical field strength, or by enhancing ambipolar diffusion of magnetic fields through turbulent motions, or both (Ciolek & Basu 2001; Fatuzzo & Adams 2002; Li & Nakamura 2004; Nakamura & Li 2005).

In contrast to these investigations, Tassis & Mouschovias (2004, hereafter TM04) have recently challenged the picture of rapid star formation, arguing that the phase of cloud evolution prior to star formation has been ignored. TM04 argue that by taking this potentially long phase of evolution into account the observations are consistent with the old scenario of slow, magnetically-controlled star formation. Additionally, Mouschovias, Tassis, & Kunz (2006, hereafter MTK06) argue that galactic statistics are biased, and that the widths of spiral arms in external galaxies indicate longer molecular cloud lifetimes.

In this paper we review the observational results that are in disagreement with the view of TM04 and MTK06. In particular, we use the CO data from the survey by Dame, Hartman, & Thaddeus (2001), in order to emphasize that, if clouds were living for many Myr before they form stars, there should be many more clouds without young stars and without internal structure than what is observed in the solar neighborhood (within 1 kpc from the Sun). We also identify problems which contradict other observations often cited for long starless core lifetimes and significant stellar age spreads. We discuss observations of protostellar core structure which by themselves suggest that cores do not last for many free-fall times. We stress that in regions of massive star formation (where most stars form), the destructive effects of massive stars on their environment cannot be ignored when considering lifetimes of molecular clouds. We also review theoretical problems with the scenario of slow star formation, emphasizing the importance of boundary conditions in understanding star formation. Finally, we suggest that the observations of external galaxies are entirely consistent with *cycles* of cloud formation, disruption, and reformation, rather than the lifetimes of single molecular clouds. We conclude that the observational evidence supports the picture of rapid star formation, and that the rapid formation scenario conforms well with recent numerical simulations.

2. STATEMENT OF THE ISSUE

The fundamental question we wish to address is whether star formation is a dynamic, relatively rapid process, or if it proceeds by slow, quasi-static evolution. More precisely, did the parcel of gas which ultimately ended up inside a star experience long stretches of slow, quasi-static evolution in near-equilibrium conditions, or was it always dynamic? This question is important because to the extent that magnetic fields dominate the support of molecular clouds, as originally stated by TM04 and references therein, one would expect slower evolution, addressable by quasi-static, near-equilibrium calculations, but in which the origin of cores is not addressed. Conversely, if this evolution occurs on a very few free-fall timescales, it suggests that magnetic field support is not strong, that the formation of the cores themselves matter, and that dynamic models of star formation are required.

The lifetime of a molecular cloud complex provides an *upper* bound to the timescale over which an individual parcel of gas concentrates into cores and then evolves to collapse, because core formation over areas tens of pc or more distant need not be (and in general will not be) coordinated perfectly in time. Even with this caveat, the lifetimes of molecular clouds in the solar neighborhood prove to be interesting. As HBB pointed out, the average stellar population ages within these clouds are about 1–2 Myr. The free-fall timescale for an isothermal, uniform spherical distribution of gas of density ρ is (Hunter 1962)

$$t_{\rm ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2} , \qquad (1)$$

which applied to molecular gas becomes

$$t_{\rm ff} \sim 3.4 \times n_{100}^{-1/2}\,{\rm Myr}\,, \qquad (2)$$

where n_{100} is the density of molecular hydrogen in units of $100\,{\rm cm}^{-3}$. With a typical *average* volume density of a giant molecular cloud (GMC) in the solar neighborhood of ~ 50 cm^{-3} (e.g., Blitz 1991), it is clear that there must be locally denser regions where the stars are forming to meet the requirement of forming stars within 1-2 Myr; and many observations in a variety of clouds clearly demonstrate that stars form in the much denser regions present. Furthermore, as only a small fraction of substantial molecular clouds in the solar neighborhood do not harbor young stars (HBB), and none of the local GMCs are devoid of star formation (Blitz 1991), these denser regions must form quickly, probably as part of the cloud formation process (e.g., Heitsch et al. 2005; Vázquez-Semadeni et al. 2006; Vázquez-Semadeni et al. 2007; Ballesteros-Paredes et al. 2006, for a review).

It is important to recognize that the age spread in a stellar association is not necessarily a useful constraint for the timescale question posed here. For example, the nearest B association to the Sun, Sco-Cen, has an age spread of $\sim$ 10–15 Myr, but the molecular gas is confined to the adjacent Ophiuchus clouds, with a stellar population having ages of $\sim$ 1 Myr; the older regions are devoid of molecular gas and thus have no continuing star formation (e.g., de Geus 1992). Moreover, stellar energy input through photoioinization, winds, and supernovae can pile up gas in adjacent regions and trigger later star formation (e.g., Elmegreen & Lada 1977), creating an age spread of several Myr or more over a volume of a few to tens of pc, as is seen in regions such as Sco-Cen and Cep OB2 (Patel et al. 1995); but this age spread does *not* represent the timescale of an individual parcel of molecular gas to form stars. Another example is that of Cep OB3, for which Burningham et al. (2005) found some evidence for an age spread, but which lies at the interface between an H II region and a dense molecular cloud, suggesting multiple star forming epochs (e.g., Pozzo et al. 2003). The possible superposition of star-forming gas with previous regions of star formation should be kept in mind when considering observations of distant extragalactic regions with limited spatial resolution (§5).

Molecular clouds in the solar neighborhood are especially useful in addressing the timescale question posed above because the gas becomes molecular at column densities such that self-gravity is important, given pressures in the local interstellar medium (Franco & Cox 1986; Elmegreen 1982). They represent the regions of sufficient density to form stars, and constitute only a fraction of the total gas nearby, with a small volume filling factor. In other regions where most of the gas remains molecular, such as may be the case in the inner molecular ring of the Galaxy, self-gravity need not be important compared with external pressures in all regions containing molecular gas, and the very definition of a molecular cloud is in question.

In summary, the issue we wish to address is how rapidly the matter of stars is assembled. Lifetimes of molecular clouds and ages of associated stars provide upper limits to the local timescales of star formation; the significance of these upper limits needs to be considered carefully depending upon the circumstances.

3. (NEARBY) MOLECULAR CLOUD LIFETIMES

3.1. *Ages of young stars in molecular clouds*

Despite the caveats about ages of stellar associations discussed above, the ages of stars *within* molecular clouds provide the essential observational result which implies rapid star formation. This subject has been treated in detail by HBB, Hartmann (2001), and Hartmann (2003); here we briefly review some issues.

The fundamental starting point of any analysis is the recognition that the median age of stars in nearby molecular clouds is $\sim 1 - 2$ Myr. As Hartmann (2003) pointed out, this means that unless we are observing at a special epoch in the history of local star formation – an unattractive assumption – the median age of star-forming molecular clouds is also 1-2 Myr.

The more complicated issue is how to treat the apparent age spread. As Palla & Stahler (2000) showed, stars apparently older than about 3 Myr in most nearby star-forming regions are quite sparse; that is, they form a small tail on the older end of the distribution (this is implicit in the low median age; if the age spread for most of the stars were much larger, the median age would have to be larger than 1-2 Myr). The small number of stars in this tail of apparently older stars implies a very low star formation rate compared with the present. As Hartmann (2003) pointed out, the Palla-Stahler model implies that the molecular cloud was present for several Myr while making very few stars. Since most molecular clouds are actively forming stars (see following section) at similar rates (Hartmann 2003), the Palla-Stahler model is inconsistent with observations.

A related issue has arisen recently concerning the massive Orion Nebula Cluster (ONC). Slesnick, Hillenbrand, & Carpenter (2004) carried out an infrared spectral survey of stars in the direction of the ONC and found a population of M dwarfs with apparent ages $\sim$ 10 Myr (assuming the same distance as the

ONC). In a related study, Palla et al. (2005) argued that the Li depletion in two objects in the ONC direction was consistent with an age $\sim$ 10 Myr, as indicated by their positions in the HR diagram; thus, as likely members of the cluster, they demonstrate a significant age spread.

The older stars identified by Slesnick et al. (2004) and Palla et al. (2005) raise the following question: what was the Orion Nebula region like 10 Myr ago? Was it really similar to its properties at the present epoch, i.e. a dense concentration of $\gtrsim$ 5000 $M_\odot$ of molecular gas, while forming stars at an extremely low efficiency compared with the current $\sim$ 30% (e.g., Hillenbrand & Hartmann 1998)? The authors are unaware of any comparable molecular region which is not actively forming many stars; but according to the Palla et al. (2005) picture, one would expect them to be common, as the ONC would have to have most of its lifetime in the low-efficiency state.

It seems much more plausible to assume that the gas now in the ONC region was much more dispersed, if it was indeed anywhere nearby at that time. A region of much lower densities and mass presumably would produce stars at much lower rates, consistent with the observations. One might imagine that small molecular clumps formed stars and then dispersed in an early phase of accumulation of the Orion Nebula region.

One must also emphasize that the membership of the older stars in the ONC is far from certain. The HR diagram displayed by Slesnick et al. (2004) suggests a gap between the young and older stars, clearly indicating two separate populations of stars, as would be the case if the older stars were a foreground group. Slesnick et al. discount the idea of a foreground population, but Furesz et al. (in preparation) have found some evidence for a population in the direction of the ONC with radial velocities more consistent with those of the Orion 1a association than with the ONC. In the case of Palla et al. (2005), it is worth noting that their theoretical depletion timescales are considerably shorter than those of Baraffe et al. (1998). As indicated, for example, in Figure 2 of White & Hillenbrand (2005), the Baraffe et al. (1998) calculations would require much older ages than found by Palla et al. (2005) implying that they are a foreground population and thus appear younger in HR diagrams assuming the same distance as the ONC.

In any event, it is clear that the most robust result is the median age, at the peak of the apparent distribution of stellar ages. As the above discussion demonstrates, care must be used in interpreting the tails of the age disitribution.

3.2. *Statistics of local molecular gas*

HBB pointed out that *most* nearby molecular clouds contain young stars, that those stars are at most a few Myr old, while stellar associations older than 5 Myr contain no molecular gas. Thus, star formation *in the solar neighborhood* proceeds very quickly upon molecular cloud formation and the timescales for star formation epochs must not be much more than a few Myr, after which the star-forming gas gets dispersed.

In contrast, TM04 argued that timescales of star formation estimated from age distributions of the stars in molecular clouds ignore a potentially lengthy period of pre-stellar cloud core evolution. However, if there is a long lag time between molecular cloud formation and star formation, as suggested by TM04, then on a statistical basis most nearby molecular clouds should not be forming stars. This is observationally not the case, as already pointed out by HBB. To expand upon our previous discussion, in Table 1 we show the list of nearby molecular clouds (within 1 kpc), according to Dame et al. (1987, see their Table 2). Columns 1 and 2 indicate respectively the name of the cloud, and its distance to the Sun, in pc. In Column 3 we note whether the cloud is currently known to be forming stars. It should be noted that the total young star content of the Cygnus and Aquila Rifts are under initial investigation (R. Gutermuth, personal communication.) The ratio by number of non-star-forming clouds to star-forming clouds is 7 to 14; by mass, 11.3 to 30.5 $\times 10^5 M_\odot$. This is an upper limit to the number or mass of non-star-forming clouds, because we know of no careful search for young stars in clouds A, B, C, the Lindblad Ring, and G317-4. Given the typical ages of young stars in known star-forming clouds of 1-2 Myr (HBB, and references therein), the extreme upper limit for the time between molecular cloud formation and star formation is thus 1 Myr or less. Thus, the argument of TM04 is strongly at variance with the observations.

In an attempt to get around this problem, MTK06 tried a different argument, using the steady-state equation

$$\frac{\tau_{\rm SF}}{\tau_{\rm MC}} = \frac{N_{\rm NS}}{N_{\rm tot}}\,, \tag{3}$$

where $\tau_{\rm SF}$ is called the star-formation timescale, $\tau_{\rm MC}$ is the molecular cloud lifetime, and $N_{\rm NS}$ and $N_{\rm tot}$ are the number of molecular clouds without stars

TABLE 1

MOLECULAR CLOUDS WITHIN 1 KPC FROM THE SUN

Cloud	Distance from Sun [pc]	Star Formation?	Mass [$10^5 M_\odot$]	Ref
Aquila Rift	270	yes	2.7	1,2,4
Cloud A	500	?	0.4	1
Cloud B	300	?	0.4	1
Cloud C	500	?	0.3	1
Vul Rift	400	linked to VulOB1	0.8	1,3
Cyg Rift	700	yes	8.6	1,4
Cyg OB7	800	yes	7.5	1
Lindblad Ring	300	?	1.6	1
−12 km/sec	800	?[a]	8.7	1
Cepheus	450	yes	1.9	1
Taurus	140	yes	0.3	1
Perseus	350	yes	1.3	1
Monoceros	800	yes	2.8	1
Orion	500	yes	3.1	1
Vela	425	yes	0.8	1
Chamaleon	215	yes	0.1	1
Coalsack	175	no	0.04	1
G317-4	170	?	0.03	1
Lupus	170	yes	0.3	1
ρ Oph	165	yes	0.3	1
R CrA	150	yes	0.03	1

[1]Dame et al. 1987.

[2]Straizys et al.(2003).

[3]Fresneau & Monier (1999).

[4]Gutermuth 2006, personal communication.

[a]The "−12 km/sec" cloud is a fuzzy cloud in the second quadrant which may very well be associated to the Gould Belt, which is well known to have stars.

and the total number of molecular clouds, respectively. MTK06 adopt $N_{\rm NS}/N_{\rm tot} \sim 0.1$ from the earlier tabulation of HBB, use $\tau_{\rm SF} = 1$ Myr from Vázquez-Semadeni et al. (2005), and then conclude that $\tau_{\rm MC} \sim 10$ Myr.

Although the numbers $N_{\rm NS}$ and $N_{\rm tot}$ in MTK06's exercise are based on observational surveys (see HBB), this result is actually inconsistent with observations, and with the evolutionary AD-based scheme depicted in Figure 2a of TM04. To explain this problem, we have drawn in Figure 1 a similar figure to that of TM04. In this figure, we adopt the 10 Myr lifetime of MCs inferred by MTK06. In which moment of this 10 Myr lifetime does star formation occur? Judging from TM04's Figure 2a, it should occur at the end of the lifetime of the parental MC (see Figure 1, left panel). But this is inconsistent with the cloud numbers used to infer $\tau_{\rm MC} \sim 10$ Myr above: precisely in this case there should be 9 clouds *without* star formation per each cloud with star formation. In other words, in this case, the observed ratio $N_{\rm NS}/N_{\rm tot}$ should be 0.9, not 0.1.

Another possibility to have a ratio $N_{\rm NS}/N_{\rm tot} \sim 0.1$ as used by MTK06, is if the star formation event occurs at the beginning of the molecular cloud lifetime, since only in this case there are few clouds without star formation. This situation is drawn in the middle panel of Figure 1. But this situation has

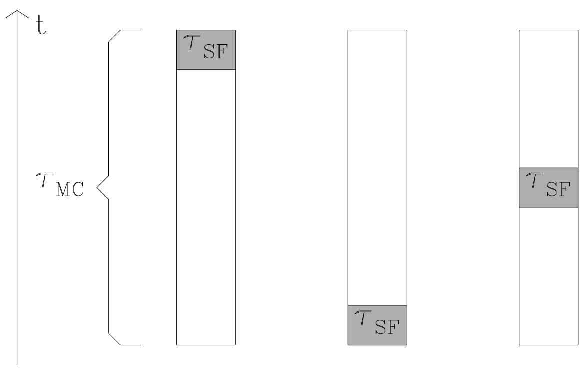

Fig. 1. Three illustrative cases in which the star formation episode $\tau_{\rm SF}$ is a small fraction (1/10th) of the total lifetime of the parental molecular cloud lifetime $\tau_{\rm MC}$, as suggested by TM04 and MTK06. None of them is compatible with observations, as discussed in the text.

one observational and two theoretical problems. In the first case, we notice that there should be 10 Myr-old stars associated to MCs, which is clearly in contradiction with observations, as it is well known for 28 years now (Herbig 1978). This is precisely the so-called post-T Tauri problem that has given origin to the line of thought that star formation should be fast. As for the theoretical problems, where is the (usually quoted as long) timescale needed for ambipolar diffusion to allow inefficient star formation, if the stars are formed right at the same time in which its parental MC is formed? Moreover, why does star formation stop after 1 Myr? (If it goes on, then $N_{\rm NS}/N_{\rm tot} \neq 0.1$, as used by MTK06).

One would be tempted at this point to argue that the situation should fall in the middle of these two extremes (Figure 1, right panel). But this situation is also inconsistent with observations. According to our Table 1 and the discussion above, either by mass, or by number, it is not true that half of the nearby molecular clouds have formed stars while the other half have not. Moreover, as also we have mentioned above, the ages of young stars associated to MCs are 1-2 Myr, while 5 Myr-old stellar associations have no left molecular gas (HBB). Furthermore, as above, what stopped the formation of stars after 1 Myr, in order to keep the ratio $N_{\rm NS}/N_{\rm tot} \neq 0.1$? As a conclusion, the $\tau_{\rm MC} \sim 10$ Myr estimation by MTK06 should to be wrong.

The problem with the MC ages estimated by MTK06 is that the timescale $\tau_{\rm MC}$ is *not* the unknown variable; it is the *known constraint* ($\lesssim$ 3–5 Myr) from which the pre-star formation lifetime of clouds is estimated. We have no clear way to determine lifetimes of non-star-forming molecular clouds independently; they have no stars to provide age estimates. Thus, equation (3) should be used to determine $\tau_{\rm SF}$ from the other quantities, not the other way around. If $N_{\rm NS} \lesssim N_{\rm tot}/3$ (e.g., Table 1), then $\tau_{\rm MC}$ cannot be much longer than the stellar ages $\sim 1-2$ Myr in star-forming molecular clouds. This results in pre-star formation molecular cloud timescales of order 1 Myr or less.

Additionally, the calculation MTK06 makes use of the value $\tau_{\rm SF} \sim 1$ Myr obtained by Vázquez-Semadeni et al. 2005 from numerical simulations. However, those simulations start with an already-formed uniform density molecular cloud, which is unlikely to be a realistic initial condition. Furthermore, by adopting periodic boundary conditions, turbulent numerical simulations by different groups (in particular the Vázquez-Semadeni's quoted above) are unable to address cloud dispersal: mass cannot be lost from the system, and this is the essential process ultimately limiting molecular cloud lifetimes. It is inappropriate to use a simulation to examine an issue which the simulation was never intended to address.

Another argument concerns the structure of molecular clouds. According to TM04 (see their Section 4, Figure 3), molecular clouds spend $\sim$ 10–15 Myr before subcritical cores within them achieve column density contrasts of 2–4, and only in the last few million years dense cores become supercritical and collapse to form stars. They argue that surveys miss a large part of the evolutionary phase of molecular clouds because cores with column density contrasts of 2–4 are undetectable observationally. If this model is applicable, there should be a substantial fraction of local molecular clouds with column density contrasts not larger than 2–4. At issue is whether the lowest-density concentrations in molecular clouds can be detected observationally, as this constitutes the longest phase of ambipolar diffusion.

To address this, we analyze the internal structure (named, the first moments of the column density) of the local molecular clouds (see Table 2). We use ^{12}CO data from Dame et al. (2001) because it is a reasonably homogeneous and complete data set, while it provide us a worst-case estimation of the actual column density: either by depletion into grains, or by optically thick effects, any column density inferred for the carbon monoxide is just a lower-limit value. If even in this limit we found that most of the clouds exhibit column density contrasts larger than 2–4, it will be clear that the argument that cores evolving slowly are missed observationally is not applicable.

TABLE 2

CO COLUMN DENSITY CONTRAST AND VELOCITY DISPERSION OF LOCAL MCS

Cloud	$N_{\rm max}$ [K km sec^{-1}]	$N_{\rm mean}$ [K km sec^{-1}]	$N_{\rm rms}$ [K km sec^{-1}]	$N_{\rm max}/N_{\rm mean}$	$N_{\rm rms}/N_{\rm mean}$	Δv [km sec^{-1}]
Aquila Rift	57.19	9.58	6.34	5.97	0.66	
Cloud A	28.23	6.15	4.86	4.59	0.79	5
Cloud B	27.81	5.74	4.06	4.85	0.71	3.5
Cloud C	34.94	5.88	5.45	5.94	0.93	4
Vul Rift	23.25	5.41	3.35	4.30	0.62	5
Cyg Rift	81.33	12.79	12.19	6.36	0.95	13
Cyg OB7	48.45	7.95	6.17	6.09	0.78	7
Lindblad Ring	33.24	5.08	3.71	6.54	0.73	> 7 (r)
-12 km/sec	56.98	6.12	4.98	9.30	0.81	> 4 (l)
Cepheus	27.49	5.92	4.48	4.65	0.76	4
Taurus	27.51	7.57	4.59	3.63	0.61	3
Perseus OB2 1	65.23	10.81	10.06	6.04	0.93	> 3.5 (r)
Perseus OB2 2	38.6	7.22	4.40	5.29	0.61	3
Monoceros OB1	73.75	11.82	10.24	6.24	0.87	6
Orion A	159.71	12.75	14.16	12.53	1.11	6–7
Orion B	123.23	13.21	15.51	9.33	1.17	5
Monoceros R2	57.85	8.73	6.68	6.63	0.77	4
Vela Sheet	17.14	4.40	2.80	3.90	0.64	> 5 (l)
Chamaleon	20.91	7.54	4.05	2.77	0.54	5
Coalsack	14.35	4.65	2.69	3.09	0.58	5
G317-4	16.41	5.29	3.06	3.19	0.58	3
Lupus	23.28	6.54	4.43	3.56	0.68	4
ρ Oph 1	51.34	8.34	6.83	6.16	0.82	4
ρ Oph 2	22.13	6.96	4.53	3.18	0.65	3.5
R CrA	28.71	6.20	5.19	4.63	0.84	3

Table 2 lists the properties of the local clouds. Column 1 lists the name of the cloud, Columns 2–4 list the maximum, mean and rms CO column density, in K $\cdot$ km sec^{-1}. Columns 5 and 6 list the ratio of maximum-to-mean and rms-to-mean CO column densities[3]. Finally, Column 7 shows the width of the line integrated over the whole cloud, in km sec^{-1}. From this table we note (a) that the typical rms-to-mean column density is 0.75, indicating that the values of the column density oscillate $\sim$ 1.5 times around the mean column density. Thus, it is far from true that column density contrasts of 2–4 are missed in observational surveys; and (b) that the maximum derived ^{12}CO column density is *at least* 2.7 times larger than the mean column density (for Chamaleon), and as large as 12 times (for Orion A), with typical values of the order of $\sim$ 5.4 times the mean column density. This result show what is obvious by looking at maps of any local molecular cloud: that every local molecular cloud exhibits substantial substructure (see, e.g., the maps published by Tapia 1973; Dame & Thaddeus 1985; Dame et al. 1987; Nyman, Bronfman, & Thaddeus 1989; Mizuno et al. 1995; Dame et al. 2001; Onishi et al. 2002; Straižys, Černis, & Bartašiūtė 2003; Wilson et al. 2005, and a long etc.). Thus, even in this worst-case scenario, there are no MCs without large-column density contrasts, as will be the case if MCs spend a large fraction of their lives evolving from subcriticallity

[3]Note that the numbers quoted in Table 2 have been computed by rejecting data below 3σ, with $\sigma = 0.43$ K being the worst rms noise level of the whole Galactic survey (Dame et al. 2001)

to supercriticallity. We emphasize that while there are uncertainties in translating column densities into volume densities, ^{12}CO is usually so optically thick that it strongly underestimates the true variations in column density.

In any event, the timescale of generating substructure within any molecular cloud cannot be longer than the total lifetime of the cloud itself; and as pointed out earlier, this cannot be a long timescale in the solar neighborhood.

3.3. *H_2 formation timescales*

An important question for any model of star formation is how long does it take for a parcel of interstellar atomic gas to become molecular. Traditionally, this timescale has been thought to be large, since the formation of molecular hydrogen in the ISM occurs in timescales given by $t_{\mathrm{H_2 form}} \simeq 10^9 yr/n$, where n is the number density in cm^{-3} (e.g., Jura 1975), meaning that a GMC with mean density of the order of $n \sim 100$ cm^{-3} has spent ~ 10 Myr in the transition from atomic to molecular. This timescale is favored by chemical evolution models at constant density by, e.g., Goldsmith & Li (2005, hereafter GL05). These authors have argued that lifetimes of molecular cloud cores are long, based on detections of small amounts of cold H I in dense cores, and interpreting the H I/H_2 ratios in terms of chemical evolution at constant density in regions shielded from the interstellar radiation field. GL05 found "minimum" lifetimes of 3-20 Myr, much longer than estimated from stellar ages. However, there are substantial uncertainties in the chemical rates and the physical model employed which render these estimates suspect.

As GL05 themselves state in § 6.1 of their paper, "Combining the uncertainties in the various factors, $k'_{\mathrm{H_2}}$ (the rate for forming H_2) may differ from its nominal value by a factor of 5. This directly affects the H_2 formation timescale and the steady state H I density, both of which vary as $1/k'_{\mathrm{H_2}}$". As an example of this, Bergin et al. (2004) used a sticking probability of 1 instead of 0.3 adopted by GL05, making the timescales shorter by a factor of three. As a further illustration of uncertainties, GL05 note that if they had used C^{18}O densities instead of C^{13}O densities, the timescales would be reduced by a factor of two.

Furthermore, the physical model used by GL05 is probably unrealistic. The shock model of Bergin et al. (2004) for molecular cloud formation showed that H_2 formation can be nearly complete before the cloud becomes "molecular" in the sense of having significant CO. This means that much of the evolutionary time in the GL model should be attributed to the atomic phase, not the molecular cloud phase. Moreover, as Glover & Mac Low (2007) have recently shown, supersonic turbulence can enhance the production of molecular hydrogen. In fact, these authors show that the low density regions ($n < 300$ cm^{-3}) of numerical simulations of molecular clouds exhibit more H_2 than the expected amount of H_2 if the gas were in photo-dissociation equilibrium. The physical mechanism is simple: a large fraction of the H_2 found at low densities was actually rapidly formed at higher densities, in gas with $n > 1000$ cm^{-3}, but subsequently transported to low densities by the advection of the turbulent velocity field (Glover & Mac Low 2007).

3.4. *Dispersal*

An important constraint on molecular cloud lifetimes clearly comes into play when massive stars are present. Such stars are very destructive to their natal clouds (see Ballesteros-Paredes et al. 2007, for a review). For example, Leisawitz, Bash, & Thaddeus (1989) found that clusters older than 10 Myr do not have associated with them molecular clouds more massive than a few times 10^3 M$_\odot$. More recently, in the nearest B association, Scorpius-Centaurus, which consists of stars with ages of $\sim$ 5–15 Myr, molecular gas is not present; instead, one can observe large H I shells around the three sub-concentrations –Lower Centaurus-Crux, Upper Centaurus-Lupus, and Upper Scorpius– which are probably the result of the dispersal of association gas by stellar winds and supernovae (de Geus 1992). As de Geus (1992) showed, the action of a single supernova would be sufficient to remove the gas in the 5 Myr-old Upper Scorpius sub-association (Preibisch & Zinnecker 1999), while the molecular gas at the eastern end of the region remains as the Ophiuchus cloud, with young stars (of ages $\sim$ 1 Myr or less) and forming protostars.

As another example, the Cep OB2 association consists of a central 10 Myr-old cluster, NGC 7160, surrounded by a partial ring/bubble of radius $\sim$ 50 pc of molecular and atomic gas (Patel et al. 1995), and with recent star formation within the molecular bubble. As Patel et al. (1995) showed, this extended distribution of gas is consistent with being blown out by stellar winds and supernovae from NGC 7160. On a smaller scale, the $\sim$ 4 Myr-old cluster Trumpler 37, lying near the rim of the bubble, has itself a blown-out region of several pc in radius; the central O7 star has driven out material due to the pressure of the H II region (IC 1396), which has called a halt to star formation within the bubble except in small globules of molecular gas which contain ~ 1 Myr-old stars (Sicilia-Aguilar et al. 2004, 2005).

We also note two other examples of rapid dispersal. The O9.5V star σ Ori has dispersed most of the gas surrounding its low-mass stellar cluster by an age of ~ 2.5 Myr (Sherry, Walter, & Wolk 2004), and in the λ Ori star-forming region, gas has been cleared out and star formation has ceased out to a distance of 20 pc over a timescale of 5-6 Myr (Dolan & Mathieu 2001).

In summary, it is very likely that giant molecular clouds in the solar neighborhood are disrupted by the energy input of their massive stars over timescales of order 5 Myr, or perhaps even less in some cases, explaining why regions of ages $5 - 10$ Myr, such as Scorpius-Centaurus and Orion 1a, are devoid of molecular gas and ongoing star formation. This addresses another "problem" that magnetically-slowed star formation was supposed to solve, specifically, the inefficiency of molecular gas in forming stars. Star formation can be relatively rapid and still result in a low efficiency as long as molecular clouds are dispersed rapidly. It is less clear what happens to low-mass molecular clouds; they may be blown away by their own outflows, or nearby supernovae may also play a role.

4. STARLESS CORES

4.1. *Statistics*

Another question is how long protostellar cores last before collapsing to form stars. The lifetimes for starless cores have been estimated by several authors using, again, steady state:

$$t_{\rm SC} = \frac{N_{\rm SC}}{N_p} t_p \,, \tag{4}$$

where $t_{\rm SC}$, is the lifetime of the starless cores, $N_{\rm SC}$ is the number of starless cores, N_p is the number of protostars or embedded (heavily-extincted) young stars, and t_p is the corresponding lifetime. TM04 argue that t_p is only estimated theoretically, leading to uncertainty in equation (4). However, one can estimate the protostellar lifetime, again assuming an approximate steady state, by using the ratio of protostars or embedded sources to T Tauri stars, and using estimated T Tauri ages. In Taurus, the ratio of protostars (Class I objects) to T Tauri stars is approximately 1:10 (Kenyon et al. 1990, 1994); given an average age in of Taurus stars of roughly 2 Myr (Kenyon & Hartmann 1995; Hartmann 2003), this means that $t_p \sim 2 \times 10^5$ yr. This result is consistent with theoretical expectations for free-fall collapse (e.g., Shu et al. 1987). Thus, t_p is so short that $t_{\rm SC}$ cannot be many millions of years unless $N_{\rm SC}$ is more than an order of magnitude larger than N_p.

As TM04 note, the studies of Lee & Myers (1999) and Jijina, Myers, & Adams (1999) derive estimates of the lifetime of the starless core phase between 0.1 and 0.5 Myr, inconsistent with slow contraction controlled by (substantial) ambipolar diffusion. TM04 in contrast cite results from Ward-Thompson et al. (1994) and Jessop & Ward-Thompson (2000, hereafter JWT00) which suggest lifetimes of order 10^7 yr for lower-density cores. However, the Lee & Myers (1999) and Jijina et al. (1999) core surveys are much more heavily weighted toward nearby regions which have been the subject of much more extensive ground-based optical and infrared studies than the JTW00 study, focused on generally more distant and far fewer well-studied regions, and using only the IRAS point source catalog to find embedded members rather than the often more sensitive near- to mid-infrared ground-based studies. IRAS source counts of the JTW00 regions, at least half of which lie at distances of 300–800 pc, are very likely to be significantly incomplete.

To illustrate the problem, the median 60 μm IRAS fluxes in Taurus are $\sim$ 6 Jy for protostars (Class I) and ~ 1.4 Jy for accreting (Class II) T Tauri stars. Although a lower limit of 0.4 Jy is claimed by JWT00 at 60μm, they detect no source fainter than about 1 Jy at this wavelength. At this limit, about half of the Taurus protostars would have been missed at distances $d \gtrsim 6^{1/2} \times 140$ pc ~ 350 pc; almost all of the T Tauri stars would be undetectable. This estimate assumes that the flux decrease due to distance is the only difficulty, but in fact there are additional problems due to the large beam sizes of IRAS, which lead to increasing source confusion and problems with background subtraction with increasing distance. The result is that IRAS source counts in any but the closest star-forming regions are likely to underestimate stellar source populations by large factors, suggesting that the Lee & Myers (1999) and Jijina et al. (1999) results are more reliable for stellar statistics.

As a specific example, Reach et al. (2004) used the Spitzer Space Telescope to detect 8 embedded sources (Class 0/I) in a small field centered on a single globule in Tr 37; at this distance ($\sim$ 900 pc, Contreras et al. 2002) only one of these sources was detected with IRAS. Young et al. (2004) demonstrated that L1014, a dense core previously thought to be starless, actually shows evidence of an embedded source in higher-sensitivity Spitzer observations, leading them to suggest that traditional estimates of pre-stellar core lifetimes may be overestimated.

Equation (4) assumes that every starless core will end up forming a star(s). However, cores may be disrupted by shocks as well as formed. Numerical simulations of turbulent molecular clouds show a population of cores that do not end up collapsing, but re-dispersing on a fraction of the ambipolar diffusion timescale (e.g., Vázquez-Semadeni et al. 2005; Nakamura & Li 2005). Thus, even if these simulations included ambipolar diffusion, there may not be enough time for AD to operate and allow the core to become supercritical. In this connection it is important to note that the JWT00 cores on the average have considerably less column density and are more extended than the Lee & Myers (1999) and Jijina et al. (1999) cores, and thus may be less likely to eventually collapse than the objects in the latter two surveys.

TM04 suggest that, because of the difficulty of recognizing low-density, slowly-evolving cores, some studies may have undercounted $N_{\rm SC}$ and thus greatly underestimated the lifetimes of starless cores. However, molecular cloud cores must be situated in molecular clouds by definition; and if clouds do not spend a long time before forming stars, cores cannot spend a long time evolving before forming stars.

Given the potential for source count incompleteness in some surveys and the possibility that not all cores will collapse to form stars, it appears that equation (4) provides an upper limit for the lifetime estimate. The much deeper samples that will be obtained using the Spitzer Space Telescope in the near future should strongly reduce source incompleteness (e.g., Young et al. 2004).

4.2. *Core Morphology*

If protostellar cores are really quasi-equilibrium objects, one might expect them to be more regular in shape. Detailed images of cores show that many have extended and not entirely regular or smooth shapes (e.g., Myers et al. 1991; Bacmann et al. 2000; Steinacker et al. 2005), which as Myers et al. (1991) pointed out, suggests problems for equilibrium models. Irregular cores suggest that they are *not* objects which have lasted for several free-fall times, but instead have transient structures, as seen in numerical simulations (Ballesteros-Paredes & Mac Low 2002; Gammie et al. 2003; Li et al. 2004, see Ballesteros-Paredes et al. 2006 for a review).

Another long-standing problem for theories in which magnetic fields strongly constrain core structure is the general finding that cores, irregular as they are, are more nearly prolate than the naturally oblate structure expected for compression along magnetic field lines. This conclusion has been reached by different analyses assuming random distributions on the sky (Myers et al. 1991; Ryden 1996). In the case of Taurus, the strong tendency of the cores to be elongated not randomly but along filaments makes the argument even stronger for more prolate than oblate objects (Hartmann 2002). Curry & Stahler (2001) conducted a careful study of the structure and equilibria of prolate cores embedded in filaments. Although equilibrium solutions can be found, they noted that the structures of the field lines in such solutions were dynamically unstable in laboratory plasmas, and suggested that their prolate states would rapidly transform into lower-energy configurations.

Perhaps an even greater problem is the global nature of gravity in molecular clouds in general and dense filaments in particular. In their solutions, Curry & Stahler (2001) either assumed no external gravitating mass or a vanishing gravitational force at specified distances along the filament, as for example with an infinite chain of equal cores. However, as Burkert & Hartmann (2004) have argued, it is extremely difficult to set up an equilibrium condition for a finite filament of many Jeans masses; even with supporting turbulent motions or rotation or expansion, it is difficult to avoid gravitational collapse somewhere. Equilibrium models of cores ignore the important and unavoidable questions of just how one prevents gravitationally-driven motions arising from large scale mass distributions, motions which can eliminate local equilibria (Burkert & Hartmann 2004).

4.3. *Mass to Flux Ratios*

Ciolek & Basu (2001), TM04, and MTK06 point out that the ambipolar diffusion timescale, and thus the starless core evolutionary timescale in their picture, is not a constant but depends upon the initial mass-to-magnetic flux ratio. If in a region of star formation, one adopts an initial mass-to-flux ratio close to critical, ambipolar diffusion in small subregions can be fast enough that it does not significantly lengthen the timescale of core collapse. Moreover, if the *average* mass-to-flux ratio in a molecular cloud is near critical, assuming variations in this ratio under realistic conditions will yield some supercritical regions as well as subcritical areas; it would seem likely that the supercritical regions would be easier to condense and then faster to collapse than the subcritical regions.

It is also worth emphasizing that, under the assumption of subcriticallity, gravity *cannot* be responsible for assembling the mass of the core, because by definition the magnetic forces are stronger than the opposing gravitational forces; non-gravitational flows must then converge to make the mass concentrations. Given the rapidity with which star formation follows molecular cloud formation in the solar neighborhood, it is not clear that one can consider equilibrium or quasi-equilibrium models for these structures without showing that the flows responsible for forming the cores in the first place do not distort or buffet the core; and especially, that the flows are not gravitationally-driven, which would imply supercriticallity.

Recent numerical simulations of clumps in subcritical boxes have been performed by Vázquez-Semadeni et al. (2005) and Nakamura & Li (2005). Vázquez-Semadeni et al. (2005) found that in subcritical boxes only a minority of moderately-gravitationally bound clumps form, but they are redispersed by the large-scale supersonic turbulence on timescales smaller than the local ambipolar diffusion timescale, suggesting that only a small fraction of cores can be *marginally* affected by ambipolar diffusion to increase their mass-to-flux ratio and eventually collapse.

Nakamura & Li (2005) found that subcritical cores formed in a turbulent medium can have shortened ambipolar diffusion timescales and thus collapse rapidly (see also Fatuzzo & Adams 2002). However, their simulations suggest only a *limited* importance for ambipolar diffusion in the collapse of subcritical cores for the following reasons: (a) their simulations, although initially at Mach 10, are decaying, and thus the flow spends most of the time at low Mach numbers, $\mathcal{M} \sim 2$–3. By simple inspection of column 7 in Table 2, the velocity dispersion reported for nearby molecular clouds is at least 10 times larger than the sound speed (~ 0.2 km sec^{-1} if clouds are nearly isothermal at ~ 10 K). In other words, the simulations by Nakamura & Li (2005) assume a much less violent medium than actual molecular clouds. (b) In a turbulent medium, the timescale for core formation is much shorter than AD-mediated contraction because a core forms in the turbulent crossing time for the larger scale from which it gathers its mass, rather than on the AD-timescale (Li & Nakamura 2004; Nakamura & Li 2005; Vázquez-Semadeni et al. 2005; Ballesteros-Paredes et al. 2007). (c) Nakamura & Li (2005, see also Li & Nakamura 2004) found their best results for marginally subcritical clouds, with mass to flux ratios only 20% smaller than the critical value. Making clouds only slightly subcritical rather than strongly subcritical reduces the ambipolar diffusion timescale by a similar ratio, even without turbulent enhancement. Again, if clouds are close to overall criticality, one wonders whether fluctuations in the flux to mass ratio would result in initially supercritical density enhancements which could collapse without flux loss.

Furthermore, it is far from clear that subcritical boxes are a good representation of global molecular cloud conditions. Bertoldi & McKee (1992) and McKee et al. (1993) suggested that, as a whole, molecular cloud complexes are magnetically supercritical, and Bertoldi & McKee (1992) extended this statement of supercriticality to most clumps. Nakano (1998) argued that cores must also be generally supercritical if they are objects of higher-than-average surface density (which of course is generally expected of cores).

If molecular clouds are, in fact, supercritical, then even if subcritical regions exist within such clouds, there must be even more supercritical regions within the cloud by definition; and one would expect star formation to occur fastest, and thus preferentially, in such especially supercritical regions. Numerical simulations in which the boundary conditions do not demand subcriticallity support Nakano's argument; subcritical regions are low-density, while the highest-density regions tend to be supercritical (see HBB). Slowly-evolving, quasi-static, significantly subcritical cloud cores do not seem to appear in numerical simulations with supersonic turbulence characteristic of molecular clouds (Mach numbers of the order of 10, see, e.g., Mac Low et al. 1998; Stone, Ostriker, & Gammie 1998; Ballesteros-Paredes, Vázquez-Semadeni, & Scalo 1999; Heitsch, Mac Low, & Klessen 2001; Li & Nakamura 2004; Vázquez-Semadeni et al. 2005).

Finally, the traditional picture of slow, quasi-static contraction of initially subcritical molecular cloud cores does not address how such cores are formed in the first place. The numerical simulations, whatever their limitations, illustrate an important point: it does not seem to be straightforward to make and maintain a subcritical, quasi-static cloud core, confined by external pressure, if that external pressure is both anisotropic and time-dependent. It is important to consider the problem of core formation and their maintenance within a supersonic, turbulent medium.

5. SPIRAL ARMS AND STAR FORMATION IN OTHER GALAXIES

TMK06 argue that observations on larger scales than the solar neighborhood need to be considered to understand timescales of star formation. For one thing, they argue that the local census of molecular clouds and star formation is highly biased because most regions are embedded just downstream of the spiral arm shock, due to the difference in rotation and spiral pattern speeds, and that these regions are difficult to observe.

In HBB we limited our direct conclusions to the solar neighborhood within about 1 Kpc for observational completeness reasons (see Table 1 and §2). This constitutes an interarm region in the galaxy (e.g., Taylor & Cordes 1993). However, this does not detract from the fact that the long-lived molecular cloud scenario does not hold locally. Furthermore, simply because more distant, confused regions have not been studied adequately does not automatically mean that they refute the concept of dynamic star formation.

Another argument made by TMK06 is that the external galaxies M51 and M81 show a spatial separation between the dust lanes in spiral arms – which correspond with the peak of the CO emission – and the peak in Hα emission (citing, e.g., Vogel, Kulkarni, & Scoville 1988). Using estimated differences between rotation and pattern speeds, they interpret this as a time lag between the formation of molecular clouds and the formation of stars on the order of 10 Myr.

However, this interpretation demands that the molecular clouds maintain their identity over size scales of 100 pc or more and timescales of $\gtrsim$ 10 Myr. Specifically, this interpretation *assumes* that the molecular gas does not get dispersed by the action of stellar photoionization, winds, and supernovae, and then gets concentrated in other locations to make new clouds which make additional stars. Suppose that a first generation of stars forms within the CO clouds just after passing through the spiral shock. The most massive of these stars will start disrupting their environments as they form H II regions (note: the very process of forming the H II region will shut off *local* star formation; see §2). The expansion of the H II regions, and eventually supernovae, will compress gas to make secondary generations of stars with additional H II regions, etc. –just as observed in nearby regions such as Cep OB2 (§2). Thus the spiral shock wave represents the beginning of the (locally rapid) star formation process by concentrating gas. As time goes on, gas is disrupted (H II regions) and flows make new concentrations which make new generations of stars with associated H II regions. In this dynamic picture, the peak of the H II region emission extends further downstream than the highest concentration of molecular gas because of succeeding phases of expansion and compression, with succeeding local events of star formation, which eventually slow down as gas gets dispersed by stellar energy input and eventually also due to changes in the gravitational potential. The lifetimes of H II regions, if more than 1–2 Myr, can also add to the distance downstream of peak H II emission; the longer H II regions last (this is the timescale of dispersing the local ionized gas), the further downstream they will appear.

It is important to emphasize, as found by Vogel et al. (1988), that in the relevant regions of M51 *most* of the gas is molecular, not atomic; these authors conclude that *most* of the gas is in the interarm region, not in the "arms". This raises the question of just where a molecular "cloud" begins and ends (§2). And it seems inevitable that the giant H II regions must have molecular gas around them –since they formed relatively recently– gas which does not show up in the interferometer maps. It seems quite possible that the CO arms in Vogel et al. (1988), represent the first concentration of gas downstream from the spiral shock, but not the densest clumps which are the true progenitors of the H II regions. Thus, it is far from clear that the observations of spatial displacement between CO spiral arms and H II regions demand a long lifetime of molecular clouds as a physical entity, rather than as a complex region with locally rapid evolution. And in any event, in terms of the issue we have posed here –the evolution timescale of parcels of self-gravitating gas (§2)– the very formation of an H II region implies that *local* star formation timescales are relatively short, independently of whatever is deemed to be a molecular cloud or cloud complex.

6. CONCLUSIONS

The scarcity of (well-studied) molecular clouds without star formation indicates that the time lag between cloud formation and star formation in the solar neighborhood is short. Statistical estimates of pre-stellar core lifetimes in well-characterized star forming regions indicate that the pre-stellar phase is short, which also supports rapid star formation. Age spreads in well-studied and carefully-analyzed star-forming regions are at most a few Myr. Theoretical studies of cloud pressure balance, core formation, and core evolution in turbulent gaseous clouds are consistent with the observational evidence for rapid star formation, possibly because magnetically supercritical or at least critical conditions are generally applicable.

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