STAR FORMATION IN A CROSSING TIME

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ABSTRACT

Observations suggest that star formation occurs in only one or two crossing times for a range of scales spanning a factor of ≈1000. These observations include (1) measurements of embedded cluster ages in comparison with the cloud core dynamical times, (2) measurements of the age difference versus separation for clusters in the Large Magellanic Clouds in comparison with the crossing time versus size correlation for molecular clouds, (3) the hierarchical structure of embedded young clusters, and (4) the high fraction of dense clouds that contain star formation.

Such a short overall timescale for star formation implies that sources of turbulent energy or internal feedback are not required to explain or extend cloud lifetimes and that star and protostar interactions cannot be important for the stellar initial mass function. Stars appear in a cloud as if they freeze out of the gas, preserving the turbulent-driven gas structure in their birth locations. The Galaxy-wide star formation rate avoids the Zuckerman-Evans catastrophe, which has long been a concern for molecular clouds that evolve this quickly, because the multifractal structure of interstellar gas ensures that only a small fraction of the mass is able to form stars. Star formation on large scales operates more slowly than on small scales, but in most cases the whole process is over in only a few dynamical times.

Subject headings: galaxies: evolution — stars: formation

1. INTRODUCTION

The duration of star formation in a region of a particular size is a physical parameter related to the star formation process that has rarely been considered interesting, except perhaps for the notion that star formation lasts sufficiently long in giant molecular clouds (GMCs) that sources of turbulent cloud support and internal feedback are necessary. This concept of inefficient and prolonged star formation goes back to the first galactic surveys when it was realized (Zuckerman & Evans 1974; Zuckerman & Palmer 1974) that the Galactic CO mass and density are too large, and the total star formation rate too small, to have the conversion of gas into stars take place on anything shorter than several tens of crossing times per cloud. Early claims to the longevity of clouds were also based on chemical abundance considerations (Goldreich & Kwan 1974; Field 1978) that supersonic turbulence should dissipate more rapidly. Two types of models arose: those in which turbulence supports a cloud on the large scale but not on the small scale (Bonazzola et al. 1987; Leorat, Passot, & Pouquet 1990; Vazquez-Semadeni & Gazol 1995) and those in which stellar winds continuously drive turbulence to support a cloud (Norman & Silk 1980), possibly with some type of feedback to maintain stability (Franco & Cox 1983; McKee 1989).

A variety of recent observations now suggests a different picture. Star formation appears to go from start to finish in only one or two crossing times on every scale in which it occurs (§ 2). The star formation rate does not just scale with the self-gravity rate, as recognized for a long time, it essentially equals the self-gravity rate. The first hint at such quick star formation came long ago from the observation that a high fraction of clouds contain stars (Beichman et al. 1986) combined with the idea that pre-main-sequence lifetimes are short. As a result, the total cycle of star formation, before and after cloud dispersal, has to be short as well (Elmegreen 1991).

Today the observational picture for rapid star formation is more complete, consisting of direct measurements, such as embedded cluster ages or cluster age differences in comparison to the associated gas turbulent crossing times, and indirect indicators, such as hierarchical structure in embedded stellar groups and the fraction of clouds with embedded stars. Much of these data are well known but have not been viewed together in this fashion and are rarely interpreted as indications that star formation occurs in only one crossing time. The implications of such an interpretation could be important for understanding the processes of star formation.

Here we point out that star formation in a crossing time implies four changes to way we view the physical processes involved: (1) feedback and cloud support from turbulence are not necessary for molecular clouds; (2) protostar interactions have too little time to affect the average stellar initial mass function, which must be determined primarily from a rapid sampling of existing cloud structure rather than from a long time sequence of internal cloud dynamics; (3) the chemical clock inside a molecular cloud is determined by transient, high-density events rather than by slow chemistry at the mean density; and (4) the inefficiency of star formation on a Galactic scale results from an inability of most molecular or CO-emitting gas to form stars at all, and not from any of the previous explanations, which include a delay in the onset of star formation, slow magnetic
diffusion, turbulent cloud support, local inefficiencies in a cloud core, and cloud disruption. This inability to form stars arises simply from the turbulence-driven structure of clouds (Falgarone, Phillips, & Walker 1991): most molecular gas either is at too low a density, in an interclump medium, or is dense, evanescent, and too small to be self-gravitating (Padoan 1995).

2. OBSERVATIONS OF RAPID STAR FORMATION

2.1. Age Difference Versus Size for LMC Clusters

A correlation between the age difference and spatial separation for Cepheid variables in the LMC suggests that star formation lasts for a time that is approximately equal to the dynamical crossing time for a wide range of scales (Elmegreen & Efremov 1996). This implies not only that young star positions are hierarchical, as had been claimed before (Feitzinger & Braunsfurth 1984; Feitzinger & Galinski 1987), but also that the timing for star formation is hierarchical, with many small regions coming and going in the time it takes the larger region surrounding them to finish. A second study using cluster ages and positions in the LMC confirmed this Cepheid result (Efremov & Elmegreen 1998) and illustrated again that the timescale for coherent star formation in a region is always about one turbulent crossing time, scaling approximately with the square root of size.

Figure 1 shows this result by plotting the crossing times inside molecular clouds and subclouds of various sizes $S$ versus these sizes (which are essentially cloud diameters). The crossing time is defined as the half-size (radius) divided by the Gaussian dispersion in internal velocity, $c$. The data is from the literature, as indicated. Superposed on this is the analogous correlation between age separation and distance separation for 244 LMC clusters in the age range 10–100 million years (from Efremov & Elmegreen 1998). The clusters lie on a continuation of the crossing time–size relation for individual clouds, suggesting that in each region in which this cluster hierarchy is observed, the duration of the star formation process is an average of about one crossing time.

Hierarchical clustering in time and space is also shown by cluster pairs, analogous to $h$ and $\gamma$ Persei in our Galaxy. Equal-age pairs have been studied in the LMC by Bhatia & Hatzidimitriou (1988), Kontizas, Xirakaki, & Kontizas (1989), Dieball & Grebel (1998), and Vallenari, Bettoni, & Chiosi (1998) and in the SMC by Hatzidimitriou & Bhatia (1990). Their existence implies that star formation is synchronized in neighboring regions, which means there is only a short time interval available for the complete formation of a cluster and its neighbor.

2.2. Substructure in Embedded Infrared Clusters

A second indication that star formation is extremely rapid is the observation that some embedded IR clusters have subclustering. For example, IC 342 contains eight smaller subclusters inside it with 10–20 stars each (Lada & Lada 1995). Such subclustering would be mixed up by star-star scattering and gravitational tidal interactions if the individual stars had enough time to orbit even once...
through the cloud core. Instead, the cluster seems to have crystallized instantly, preserving the prestellar hierarchical cloud structure in the pattern of young stars. The star formation process is not just beginning in this region either. At the present time, a fraction equal to about 50% of the total cloud mass has already been converted into stars (Lada & Lada 1995). This fraction is comparable to the likely final efficiency for the cluster, so the total star formation process is nearly over.

Other clusters with hierarchical subclustering include NGC 3603 (Eisenhauer et al. 1998), W33 (Beck, Kelly, & Lacy 1998), and NGC 2264 (Piché 1993), which has two levels of hierarchical substructure, i.e., two main clusters with two subclusters in one and three in the other. Elson (1991) found spatial substructure in 18 LMC clusters and suggested it might result from merging subclusters. Strobel (1992) found age substructure in 14 young clusters, and Persi et al. (1997) found both age and positional substructure in G35.20–1.74.

Some of the structure inside a cluster could be the result of triggering (Elmegreen & Lada 1977), but this operates on a crossing time for the outer scale too. For example, the subgroups in OB associations listed by Blaauw (1964), some of which may be triggered by older subgroups, have spatial separations on the order of ~10 pc and age differences on the order of ~3 million years. These numbers fit on the correlation in Figure 1.

2.3. Statistical Considerations

If a high fraction of clouds contains stars and the stellar ages are always young, then the whole star formation process must be rapid. Three new compilations of this statistical measurement point to this conclusion. Fukui et al. (1998) finds that about 1/3 of the clusters in the LMC younger than 10 Myr are associated with CO clouds, while essentially none of the clusters older than this are significantly associated. This implies that the entire cluster formation process, including cloud formation and dispersal, is only around 3 Myr. If the average CO cloud density at the threshold of their detection is in the usual range from $10^2$ to $10^3$ cm$^{-3}$, then 3 Myr is 2–1.5 dynamical times, respectively [we take a dynamical time to be $(Gho)^{-1/2}$].

Jessop & Ward-Thompson (2000) found that the mean prestellar lifetime decreases with increasing density, from about $10^2$ yr at $10^3$ cm$^{-3}$ to $5 \times 10^2$ yr at $3 \times 10^4$ cm$^{-3}$. At $10^3$ cm$^{-3}$, this time is 5 dynamical times, and at $3 \times 10^4$ cm$^{-3}$, it is 1.4 dynamical times.

Myers (2000) confirms the result of Jessop & Ward-Thompson (2000) using different data and finds that the mean waiting time for star formation begins to decrease rapidly with increasing density once the density reaches $\sim 10^4$ cm$^{-3}$. At that density, the mean waiting time is 1 Myr or less, which is less than 2 dynamical times.

3. DIRECT PRE–MAIN-SEQUENCE AGE MEASUREMENTS

The age spread for 80% of the stars in the Orion Trapezium cluster is apparently less than 1 Myr (Prosser et al. 1994). The same is true for L1641 (Hodapp & Deane 1993). The age spread is much shorter for a large number (but not necessarily a large fraction) of stars in NGC 1333 because of the preponderance of jets and Herbig-Haro objects (Bally, Devine, & Reipurth 1996). In NGC 6531 as well, the age spread is immeasurably small (Forbes 1996). These short timescales are all less than a few crossing times in the cloud cores.

In a recent study of the time history of star formation in the trapezium cluster, Palla & Stahler (1999) found that most of the low-mass stars formed in the last ~1 Myr and that the rate increased to this value somewhat gradually before this, perhaps as the associated cloud contracted. A comparison of their Figures 1 and 3, along with their Figure 6, indicates that the low-mass stars mostly formed between $10^2$ and $10^6$ yr ago. The stellar density in the trapezium is now about $10^3 M_\odot$ pc$^{-3}$ (Prosser et al. 1994; McCaughrean & Stauffer 1994), so if the local efficiency of star formation was around 50% to make a nearly bound cluster, then the prior gas density in the core was $\sim 6 \times 10^4$ H$_2$ cm$^{-3}$. This is a reasonable value considering the densities in other Orion cluster-forming regions (Lada 1992). The corresponding dynamical timescale is $(G\rho)^{-1/2} \sim 0.3$ Myr, which is comparable to the isochrone times of the low-mass stars. The increase in the rate of star formation during cloud contraction is what should be expected if this rate always follows the local dynamical rate (Palla & Stahler 1999), because that increases too during cloud contraction.

On larger scales, the age spread in a whole OB association is about 10 Myr (Blaauw 1964), and the prior gas mass ($\sim 2 \times 10^5 M_\odot$) inside a typical radius ($\sim 20$ pc) corresponds to an average density of $\sim 200$ atoms cm$^{-3}$; this gives a similar dynamical time of 6.3 Myr. On even larger scales, the age spread in a star complex like Gould’s Belt is ~40 Myr (Pöppel 1997). These larger regions form inside and downstream from spiral arms in ~500 pc sized cloud complexes that contain $10^7 M_\odot$ (Elmegreen & Elmegreen 1987; Efremov 1995). The average density is $\sim 5$ atoms cm$^{-3}$, so the dynamical time is ~40 Myr. Note that the large-scale star-forming regions contain smaller scale regions inside them and that all of the regions form on a local dynamical time. This means that several smaller regions come and go throughout the larger region during the time the larger region exists (Elmegreen & Efremov 1996).

Evidently, the total duration of star formation in most clouds is only 1–2 dynamical times once star formation begins, and this is true for scales ranging from 1 to $10^3$ pc. The general concept that the star formation time should scale with the dynamical time is not new, but direct observations of the actual timescales have been available only recently.

Some clusters have larger age spreads than the dynamical time, but this could be the result of multiple bursts. Hillenbrand et al. (1993) found that the most massive stars ($80 M_\odot$) in NGC 6611 have a 1 Myr age spread around a mean age of ~2 Myr, which is consistent with the spreads mentioned above, but there are also pre–main-sequence stars in the same region, probably much younger, and a star of 30 $M_\odot$ with an age of 6 Myr. The LMC cluster NGC 1850 has an age spread of 2–10 Myr (Caloi & Cassatella 1998), and NGC 2004 has both evolved low-mass stars and less evolved high-mass stars (Caloi & Cassatella 1995). In NGC 4755, the age spread is 6–7 Myr, based on the simultaneous presence of both high- and low-mass star formation (Sagar & Cannon 1995).

The large age spreads may result from multiple and independent star formation events, perhaps in neighboring cloud cores or triggered regions. A merger event or projec-
tion effects could disguise the initial multiplicity. If this is the case, then the relevant dynamical time for comparison with the age spread should be calculated with the average density of the whole region surrounding the two cores and not the density of each. Thus, the whole region could form in less than a few crossing times, but the currently dense part of the cluster would have too short a crossing time for the mixture. This consideration of the average density surrounding multiple clusters is also necessary to explain the large-scale correlation between duration and size for star-forming regions defined by Cepheids and clusters in the LMC (cf. § 2.1).

A good example of this multiplicity may be the Pleiades cluster, which has the largest reported age spread of any of the well-studied clusters. Features in the luminosity function (Belikov et al. 1998) and synthetic H-R diagrams (Siess et al. 1997) suggest continuous star formation over ~30 Myr for an age of ~100 Myr. However, the Pleiades primordial cloud could have captured stars from a neighboring, older region nearby (e.g., Bhatt 1989). Indeed, the age spread for the Pleiades is comparable to that in whole OB associations or star complexes, and the Pleiades, like most clusters, probably formed in such a region.

4. IMPLICATIONS

The formation of stars in only one or two crossing times implies that cloud lifetimes are short and the observed turbulent energy does not have to be resupplied. Turbulent dissipation times are this short anyway (Stone, Ostriker, & Gammie 1998; MacLow et al. 1998), so the implication is that all clouds proceed directly to star formation on a dissipation time and never require rejuvenation or self-sustaining feedback. Fine-tuning of cloud stability from feedback should be very difficult anyway, since protostellar wind speeds are much larger than cloud escape speeds and the wind energy should just escape through fractal holes and tunnels (see also Henning 1989).

Short timescales also imply that protostars do not have time to orbit inside their cloud cores. For example, Palla & Stahler (1999) noted that the stars in Orion could not have moved very far from their birth sites. Each star essentially stays where its initial clump first became unstable, and it does not move around to interact with other gas or distant protostars (although it may interact with one or two near neighbors). Maps of self-gravitating protostellar clumps by Motte, André, & Neri (1998) and Testi & Sargent (1998) illustrate this point: the protostars in the Ophiuchus and Serpens cores have such small individual angular filling factors that each one would have to orbit many times (the inverse of this filling factor multiplied by the relative gravitational cross section) in the cloud core to interact with each other. This result would seem to rule out models of the initial mass function (IMF) based on clump or protostar interactions, such as those by Price & Podsiałowski (1995), Allen & Bastien (1995), Murray & Lin (1996), Bonnell et al. (1997), Bonnell, Bate, & Zinnecker (1998), and others. Instead, IMF models based on the availability of gas to make stars in an overall fractal network seem preferred (Elmegreen 1997a, 1999).

As a result of this birthsite freeze-out, the youngest star positions should appear fractal, or hierarchical, like the gas in which they form (see reviews in Elmegreen & Efremov 2000; Elmegreen et al. 2000). Larson (1995) and Simon (1997) discussed power-law two-point correlation functions for star fields, but this is not necessarily the same as a fractal distribution and the fields they studied were probably too old (Bate, Clarke, & McCaughrean 1998; Nakajima et al. 1998). Gomez et al. (1993) discussed hierarchical structure in Taurus, which is more to the point. A recent study by Vavrek, Balázs, & Epchtein (2000) finds multifractal structure in field star positions behind clouds.

Short cloud lifetimes have implications for chemistry, too. Most chemical reactions should be occurring at the high density of a turbulent-compressed clump, which may be around $10^5$ cm$^{-3}$ (e.g., Falgarone et al. 1991; Lada, Evans, & Falgarone 1997), rather than the low average density that is observed in studies with poor angular resolution. The formation of some chemical species at elevated temperatures in turbulent shocks has already been noted (Falgarone, Pineau des Forêts, & Roueff 1995; Joulain et al. 1998).

The rapid rate of star formation suggested here for individual clouds does not imply there should be a rapid rate of star formation on a galactic scale, as suggested by Zuckerman & Evans (1974) and Zuckerman & Palmer (1974). Even if star formation proceeds on a dynamical timescale, the actual time depends on the size of the cloud that contains it. This is true even on a galactic scale, where the star formation rate is generally a fixed fraction of the density (i.e., $\epsilon_p$ for “efficiency” $\epsilon$ and density $\rho$) divided by the local orbit time (Elmegreen 1997b; Kennicutt 1998). This galactic rate probably involves the same physical principles that apply to individual complexes, associations, and clusters, all of which form stars at a rate equal to the local $\epsilon_p$ divided by the local dynamical time. There is no catastrophe in the galactic star formation rate if all regions evolve on a dynamical time, because the dynamical time is very long on a galactic scale.

The essential point is that star formation does not occur in every location where the gas is dense; it occurs primarily in self-gravitating cores that comprise only a small fraction of the total cloud mass. Even if most of a cloud is in the form of extremely dense clumps (Falgarone 1989), because of turbulence compression, for example, most of these clumps are generally stable and unable to form stars (e.g., Bertoldi & McKee 1992; Falgarone, Puget, & Péraud 1992). Some gas is probably in a lower density interclump medium too, which is also unable to form stars. Thus, a lot of gas contributes to the total CO emission in our Galaxy, but it does not contribute to star formation.

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