The Astrophysical Journal, 685: L125–L128, 2008 October 1

PRESENT-DAY STAR FORMATION AT HIGH GALACTIC ALTITUDE: THE TIDAL ENCOUNTER PARADIGM

R. de la Fuente Marcos and C. de la Fuente Marcos
Suffolk University Madrid Campus, C/ Viña 3, E-28003 Madrid, Spain; raul@galaxy.suffolk.es
Received 2008 April 6; accepted 2008 August 21; published 2008 September 5

ABSTRACT

The Galaxy harbors a population of high Galactic altitude clouds (HGACs) which are, in some cases, similar to those in the disk. About 3% of open clusters younger than 100 Myr are located at least 200 pc away from the disk; in the outer Galaxy, some embedded clusters are found at 500 pc. But, by what mechanism could star clusters form far from the regions in which the usual driving forces of triggered star formation can act efficiently? In this Letter we investigate whether passing preexisting star clusters can induce tidal forces able to trigger star formation in HGACs. The interaction is studied using the impulse approximation and results are compared with available evidence. Our analytical estimate indicates that this mechanism is able to induce star formation if passing clusters are massive enough, i.e., globular clusters. The expected number of interactions appears to be consistent with the observed star formation rate at high Galactic altitude.

Subject headings: Galaxy: halo — Galaxy: structure — stars: formation

1. INTRODUCTION

In the Galactic disk, clusters of young stars are invariably associated with giant molecular clouds (GMCs). The disk includes more than 90% of all known young open clusters and even a larger fraction of GMCs. Therefore, if field stars are born in some type of cluster and clusters are formed out of clouds, recent star formation is mainly expected to occur within the disk. Furthermore, the vast majority of GMCs appear linked to the spiral structure of our Galaxy. The large-scale shock front induced by a spiral arm is widely regarded as the dominant, primary triggering mechanism in the disk. There is, however, a growing body of observational evidence indicating that high Galactic altitude star formation, even if working at a slower rate, is happening now. But, far from the regions in which the usual driving forces of triggered star formation can act efficiently, by what mechanism could star clusters form out of high Galactic altitude clouds (HGACs)? In an attempt to answer this question, supernova-triggered star formation (e.g., Williams et al. 1977) was suggested. Unfortunately, this requires another primary mechanism in order to form the first generation of massive stars eventually exploding as supernovae. With this limitation in mind, Martos et al. (1999) developed a novel primary mechanism capable of inducing star formation hundreds of parsecs away from the Galactic plane out of the sheets of gas ejected by a spiral density wave.

In this Letter we investigate the effect of star clusters passing through the interstellar medium in order to explore the tidal encounter paradigm as a feasible mechanism to trigger star formation far from the disk. The primary mechanism described here is an alternative to that of Martos et al. (1999) and it may work concurrently with it. This Letter is organized as follows: In § 2 we present some available observational evidence for recent star formation in the Milky Way halo. In § 3 we describe the proposed mechanism and provide a quantitative analysis of its efficiency. The impact of this mechanism is discussed in § 4.

2. STAR FORMATION AT HIGH GALACTIC ALTITUDE: OBSERVATIONAL EVIDENCE

In the following we summarize some available observational evidence for recent (and ongoing) star formation far from the plane. In order to restrict the analysis to the high Galactic altitude constituents, we consider objects with $z = d \sin b$ (d and b are the heliocentric distance and the Galactic latitude, respectively, of the object) such as $|z| \geq 200$ pc. We neglect runaway OB stars as they were likely born within the disk.

2.1. *High Galactic Altitude Gas Clouds*

Typical GMCs have masses in the range (1–2) $\times$ 10^5 $M_\odot$, diameters of ~45 pc, and internal velocity dispersions of ~2 km s^{-1}. They are found along the Galactic equator with a small vertical scale height of 75 pc (e.g., see Magnani et al. 2000 and references therein). Molecular clouds located off the Galactic plane can be classified in two different categories: low-mass, transient clouds (e.g., Malhotra 1994; Ford et al. 2008) and larger clouds with properties similar to those in the solar circle (Digel et al. 1994; Brand et al. 2001). As an example, clouds 1 and 2 in Digel et al. (1994) have FWHM velocity widths of 2.8 and 2.2 km s^{-1} and virial masses of 60 and 21 ($\times$ 10^3 $M_\odot$). Some clouds in Brand et al. (2001) have slightly lower velocity dispersions and larger masses. On the other hand, the fraction of HGACs could be as high as 10.5% (Dutra & Bica 2002). These clouds may be primordial but they could also form in Heiles-type shells-supershells (Heiles 1979) or by the supernova-driven Galactic fountain mechanism (Bregman 1980).

2.2. *Embedded Star Clusters in the Outer Galaxy*

IRAS has identified a number of star-forming GMCs in the far outer regions of the Galaxy (Snell et al. 2002), several with $z > 200$ pc. In their study, they conclude that star formation in the far outer Galaxy is comparable to that observed in the inner Galaxy although only three clouds are found to be more massive than 2 $\times$ 10^4 $M_\odot$. In their samples, the most extreme candidate appears to be 2MASXW 2351325+671510 at z = 564 pc but two others are located above 400 pc. IRAS 02395+6244 has a mass of 1950 $M_\odot$, diameter of 8.6 pc, heliocentric distance of 8.8 kpc, population of about 84 stars, and z = 429 pc; at about the same altitude we find IRAS 02421+6233 with a diameter of 5.7 pc, distance of 8.9 kpc, and population of 80 stars. Some of these embedded clusters appear in complexes, which suggests that the original cloud out of which they formed may have been more massive. Another example is Sh 2-128, an H II and star formation region located at 9.4 kpc from the Sun, in Cepheus (Bohigas & Tapia 2003). At $z = 550$ pc, the main ionizing source of Sh 2-128 is an O7 star near its core. CG 12 is also found at $z > 200$ pc (Getman et al. 2008).

2.3. *Young High Galactic Altitude Open Clusters*

The *Open Cluster Database* (WEBDA; Mermilliod & Paunzen 2003) is a compilation of data on open clusters. The latest update (2008 August; Paunzen & Mermilliod 2008) includes 1747 open clusters, with ages and distances for 1005 objects (57%). The subset with $|z| \geq 200$ pc includes 128 objects; i.e., 12.7% can be considered high-altitude objects. However, if we restrict the analysis to clusters younger than 100 Myr we find 418 objects, 12 of them (2.9%) being at high Galactic altitude. The difference appears to be statistically significant and, assuming that the number of clusters in a given age range is a measure of the star formation activity at that epoch, it may indicate that star formation away from the disk was more important in the past. Alternatively, it may be another manifestation of the age-velocity relation for stars (e.g., Freeman & Bland-Hawthorn 2002): the same mechanisms heating up the disk may also affect low-mass star clusters.

Some of the objects in the high-altitude, young cluster group are quite unusual. The most remarkable is Berkeley 93, a faint ~100 Myr old small open cluster located at $z = 0.7$ kpc (Saurer et al. 1994). It harbors a variable carbon star and it is the optically most prominent part of a distant stellar aggregate located within a dust cloud. Its time of flight from the disk is, however, ~30 Myr and it may have formed in the disk. Nevertheless, its orbit (or that of its parent cloud) is unusually inclined as a result of the Galactic warp or, perhaps, a tidal interaction with another object. However, NGC 1624 ($z =$ 275 pc, 4 Myr) and IC 1590 ($z = -320$ pc, 3.5 Myr) are likely genuine high-Galactic-altitude-born clusters.

2.4. *Massive B-Type Stars*

Massive B-type stars are routinely found, in small numbers, well above the Galactic plane, 0.5–2 kpc (Ramspeck et al. 2001). Objects with a main-sequence lifetime too short to reach their current location assuming an acceptable (100–400 km s^{-1}) velocity vertical to the Galactic plane could be young stars born at high Galactic altitude. Ramspeck et al. (2001) found two prospective candidates in SB 357 and HS 1914+7139 with times of flight from the disk more than twice their age. However, the most extreme example of an archetypical halo formation candidate is PHL 346, a β-Cepheid variable. Located at a distance of 7.4 kpc with $z = -6.3 \pm 2$ kpc, this young halo star does not appear to be member of a cluster (Lynn et al. 2002) but its time of flight is more than 3 times its evolutionary time. Lynn et al. (2004) found another halo formation candidate, PG 1209+263. Martin (2006) has studied a sample of young massive stars, potential candidates to have formed in situ in the Galactic halo. This author concludes that although no star in his sample unambiguously shows the characteristics of a young massive star formed in situ, HD 233622 and HD 237840 may be main-sequence stars formed at high Galactic altitude.

3. THEORETICAL ANALYSIS

Let us assume that a cluster of mass M_s and radius r_s is moving in the Galactic halo with speed v_s. The encounter of such object with a HGAC of mass $M_{\rm HGAC}$ and radius $r_{\rm HGAC}$ can be treated analytically as the interaction takes place at high speed. The speed of the cluster is much higher than the characteristic speed of the HGAC. In order to calculate the response of a HGAC to a star cluster that passes by it, we use the impulse approximation (see, e.g., Binney & Tremaine 2008). In this approximation, the density distribution in the HGAC is unchanged during the encounter and both the cluster and the center of the HGAC travel at nearly uniform velocity throughout the encounter. If, at the instant of closest approach, their centers are separated by distance $r_{\rm min}$ and have relative speed v_s, then the effective duration of the event can be estimated as $t_{\rm encounter} \approx \max\,(r_s,\ r_{\rm HGAC},\ r_{\rm min})/v_s$. For the values pointed out above and typical HGACs, this duration is <0.5 Myr, which is shorter than the expected timescale to observe the first supernovae in a recently triggered star-forming region. Besides, the duration of the encounter is short compared to the crossing time within each system (~2 Myr for a globular cluster and ~5 Myr for HGACs). The clouds that can be affected by the star cluster cannot be of arbitrary size: they must not be gravitationally unstable before the encounter. This constrains effectively the upper limit for the mass of the cloud (see below). In the impulse approximation, the relative speed is much higher than the internal velocity dispersion in the HGAC. Assuming that during the encounter the cluster does not penetrate inside the mean radius of the HGAC, we focus our attention on the perturbed cloud and study how its structure is changed by the passage of the cluster. In this approximation, the potential energy of the perturbed HGAC does not change during the encounter. Therefore, the change in the internal energy of the HGAC is just the change in the internal kinetic energy. This change is necessarily positive. After the encounter, the HGAC is no longer in virial equilibrium and the passage of the cluster triggers a period of readjustment to a new equilibrium. This process alters the internal kinetic energy of the system more than the actual encounter. If both $r_s/r_{\rm min}$ and $r_{\rm HGAC}/r_{\rm min}$ are small and $r_s \ll r_{\rm min}$ (Binney & Tremaine 2008), we can obtain an expression for the velocity impulse imparted to the gas: $\Delta\boldsymbol{v}(\boldsymbol{x}) = (2GM_s/r_{\rm min}^2 v_s)(-x, y, 0)$, where x, y are the coordinates of a point in the cloud with respect to its center and we have neglected second-order terms (distant-tide approximation; Binney & Tremaine 2008). Encounters for which both the distant-tide and impulse approximations are valid are called tidal shocks. The velocity increment tends to deform the HGAC into an ellipsoid whose long axis lies in the direction of the cluster's point of closest approach. The encounter will effect no net change in the structure of the central region of the HGAC. The maximum value of this impulse is

$$\Delta v = \frac{2GM_s}{r_{\rm min} v_s}, \tag{1}$$

where $r_{\rm min} > 5\bar{r}_{\rm HGAC}$ (Aguilar & White 1985) and $\bar{r}_{\rm HGAC}$ is the cloud's median radius. If we measure mass in solar masses, speed in km s^{-1}, and $r_{\rm min}$ in pc, the expression yields

$$\Delta v = 8.60 \times 10^{-3} \left(\frac{M_s}{1\ M_\odot}\right)\left(\frac{\rm km\ s^{-1}}{v_s}\right)\left(\frac{1\ \rm pc}{r_{\rm min}}\right). \tag{2}$$

For an assumed $r_{\rm min} = 100$ pc, equation (2) gives $\Delta v > 1$ km s^{-1} only if $M_s > 2 \times 10^6\ M_\odot$. Massive globular clusters may easily induce velocity impulses of several km s^{-1}. Results from equation (2) and $r_{\rm min} = 100$ pc are displayed in Figure 1. The

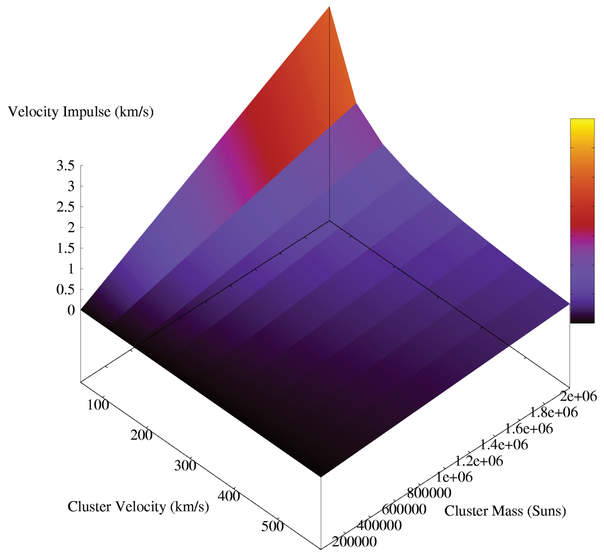

FIG. 1.—Velocity impulse from eq. (2) for $r_{\min} = 100$ pc.

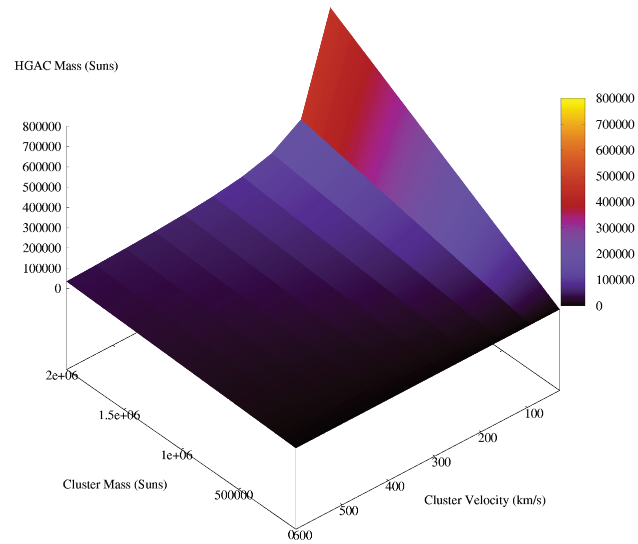

FIG. 2.—Maximum value of the mass of a HGAC (eq. [3]) in which star formation can be triggered by the mechanism described here.

induced impulse is larger than the typical sound speed in a HGAC ($C_s \sim 1$ km s^{-1}, assuming $T \sim 100$ K, $\gamma = 5/3$) even for relatively large minimum separations if the cluster is very massive ($M_s > 10^6\ M_{\odot}$). If we assume that the tidal encounter mostly increases the internal modes of the cloud, i.e., supersonic turbulence, enhanced turbulence leads to a density increase that stimulates star formation (see Mac Low & Klessen 2004 for details). If we assume that the target cloud is just below the Jeans limit, $r_{\rm HGAC} = 3GM_{\rm HGAC}/4\pi^2 C_s^2$ (this may well be the case in § 2.1). To trigger collapse, one needs $\Delta v > C_s$ and using equation (1) we obtain an upper limit to the mass of a cloud in which star formation can be triggered by this mechanism:

$$M_{\rm HGAC} < \frac{16\pi^2}{15}\ \frac{C_s}{v_s}\ M_s. \tag{3}$$

The upper limit from this equation appears in Figure 2 for an assumed typical globular cluster speed of 200 km s^{-1} (Alfaro et al. 2001). We also neglect the case of encounters under the catastrophic regime (Binney & Tremaine 2008) in which the impact parameter is such that a single encounter can disrupt the cloud, aborting any possible subsequent star formation.

4. DISCUSSION AND CONCLUSIONS

This Letter studies the possibility of tidally induced star formation events at high Galactic altitude. The paradigm described focuses on a relatively distant tidal encounter of a cluster with a HGAC. The effects of globular clusters passing through the disk of a galaxy were first studied by Wallin et al. (1996), deriving the velocity and gas density perturbations induced by the passage of a cluster. Their results show that triggered star formation can occur in the disk because the interaction is able to increase the value of Toomre's parameter, inducing gravitational instability. Their mechanism works well for a cluster crossing exactly normal to the disk but an impact even at a slight angle will lead to vertical motions destroying the assumption of an infinitely thin disk, central to their argument. The paradigm described here does not invoke Toomre's criterion, but Jeans' criterion under the distant-tide and impulse approximations and its applicability to high Galactic altitude star formation is more relevant as HGACs are quite separated and the infinitely thin disk approximation is unlikely to be valid. Star formation at high Galactic altitude appears to be rather common, so is it the proposed mechanism able to explain the observed level of star formation at high altitude? In order to estimate its efficiency we follow an approximate method to calculate the frequency of interactions. Let us assume that star clusters pass through the disk following elliptical orbits of semimajor axis a, eccentricity e, and inclination i. The number of tidal interactions experienced by a cluster during each orbit around the Galactic center is the volume enclosed by the collision cross section traveling in an elliptical orbit multiplied by the number of HGACs per unit volume in the disk. To calculate the perimeter of the ellipse we use Ramanujan's first approximation (Ramanujan 1962). This approximation gives an error <0.5% even if $e = 0.9999$. The number of interactions per orbit and cluster is

$$T = \pi\ \frac{a}{h}\left(\frac{r_{\min}}{R_d}\right)^2 N_{\rm HGAC} E(e) f(e, i), \tag{4}$$

where

$$E(e) = 3\left(1 + \sqrt{1 - e^2}\right) - \sqrt{\left(3 + \sqrt{1 - e^2}\right)\left(1 + 3\sqrt{1 - e^2}\right)},$$

h is the height scale of the disk (~1.2 kpc; Ford et al. 2008), R_d is its radius (~35 kpc; Kalberla & Dedes 2008), $N_{\rm HGAC}$ is the number of available clouds (10^4), and $f(e, i)$ accounts for the fraction of the orbit that is within the disklike structure hosting the HGACs. The actual evaluation of this factor is not trivial as it depends on both i and e. Globular clusters appear to be organized in streams so multiple clusters may share very similar orbital parameters and probabilistic arguments suggest that most of the observed globular clusters are now at apogalacticon. The value of this factor should be in the range 0.1 for an almost polar and very eccentric orbit to 1 for a low-inclination, fully embedded disk orbit. Results from equation (4) without the $f(e, i)$ factor appear in Figure 3. If we multiply

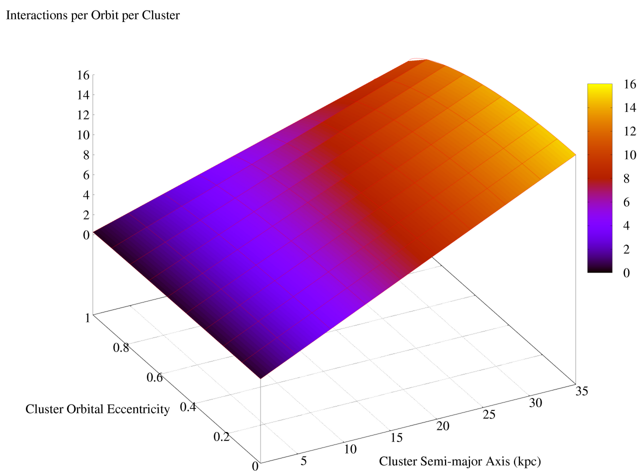

FIG. 3.—Number of interactions per orbit and cluster given by eq. (4) assuming an impact parameter of 100 pc and 10^4 HGACs. The factor $f(e, i)$ is not included.

by the number of orbits (∼40) assuming an age of 10 Gyr for the Galactic disk, by the number of clusters (∼50; 53 known globular clusters have Galactocentric distances >8.5 kpc),[1] and by an average value of 0.3 for f we obtain about 3×10^3 star formation events at high Galactic altitude over the life of the Milky Way disk. A predicted rate of 3 events per 10 Myr could account for the few tens of embedded clusters currently observed at high Galactic altitude as supernova-driven star formation (within complexes) may also be at work after the first generation of stars evolves.

Although effective and perhaps dominant at high Galactic altitude, the mechanism described here can be regarded as an extreme mode of star formation as it requires a significant population of massive clusters. On the other hand and given its geometric nature, its effects can be revealed by velocity gradients in high Galactic altitude star-forming regions and also by studying the orientation of the semimajor axis of embedded clusters, presumably formed by this mechanism, with respect to the Galactic plane. For example, in the case of Sh 2-128 the angle is ∼60° (Bohigas & Tapia 2003). As pointed out in § 2.3, the proportion of high-altitude open clusters is significantly smaller for younger ages but younger clusters are easier to identify at longer distances due to their massive stars. Therefore, the higher proportion of high-altitude open clusters older than 100 Myr appears to suggest an also higher rate of star formation at high Galactic altitude in the past. Alternatively, it may be the signature of enhanced present-day mortality for high-altitude young clusters or the effect of disk heating mechanisms (Freeman & Bland-Hawthorn 2002) on the older sample. Globular clusters are not following simple orbits around the Galactic bulge but streamlike dynamical paths (e.g., Lynden-Bell & Lynden-Bell 1995). Several objects may share the same stream and newly born high-altitude clusters (and clouds) may suffer a whole sequence of encounters over a relatively short timescale that may contribute to their early demise. On the other hand, the apparent scarcity of young massive stars born at high Galactic altitude and pointed out in § 2.4, if real, may suggest that the stellar initial mass function (IMF) far from the Galactic plane could be deficient in massive stars. If true, it may adversely affect detectability of young open clusters at high Galactic latitude for the reasons pointed out above. An undermassive IMF could be, however, the result of poor statistical sampling due to the intrinsically slow star formation rate at high Galactic altitude: molecular clouds are smaller and less dense.

[1] See M. Castellani 2008, *A Galactic Globular Clusters Database* (http://venus.mporzio.astro.it/~marco/gc/).

The authors would like to express their thanks to the referee for his/her very useful reports. In preparation of this Letter, we made use of the NASA Astrophysics Data System and the astro-ph e-print server.

REFERENCES

Aguilar, L. A., & White, S. D. M. 1985, ApJ, 295, 374
Alfaro, E. J., et al. 2001, A&A, 370, L45
Binney, J., & Tremaine, S. 2008, Galactic Dynamics (2nd ed.; Princeton: Princeton Univ. Press)
Bohigas, J., & Tapia, M. 2003, AJ, 126, 1861
Brand, J., Wouterloot, J. G. A., Rudolph, A. L., & de Geus, E. J. 2001, A&A, 377, 644
Bregman, J. N. 1980, ApJ, 236, 577
Digel, S., de Geus, E., & Thaddeus, P. 1994, ApJ, 422, 92
Dutra, C., & Bica, E. 2002, A&A, 383, 631
Ford, A. H., et al. 2008, ApJ, in press (arXiv:0807.3550)
Freeman, K., & Bland-Hawthorn, J. 2002, ARA&A, 40, 487
Getman, K. V., et al. 2008, ApJ, 673, 331
Heiles, C. 1979, ApJ, 229, 533
Kalberla, P. M. W., & Dedes, L. 2008, A&A, 487, 951
Lynden-Bell, D., & Lynden-Bell, R. M. 1995, MNRAS, 275, 429
Lynn, B. B., et al. 2002, MNRAS, 336, 1287
———. 2004, MNRAS, 349, 821
Mac Low, M.-M., & Klessen, R. S. 2004, Rev. Mod. Phys., 76, 125
Magnani, L., et al. 2000, ApJ, 535, 167
Malhotra, S. 1994, ApJ, 437, 194
Martin, J. C. 2006, AJ, 131, 3047
Martos, M., Allen, C., Franco, J., & Kurtz, S. 1999, ApJ, 526, L89
Mermilliod, J.-C., & Paunzen, E. 2003, A&A, 410, 511
Paunzen, E., & Mermilliod, J.-C. 2008, Open Cluster Database, http://www.univie.ac.at/webda
Ramanujan, S. 1962, Ramanujan's Collected Works (New York: Chelsea)
Ramspeck, M., Heber, U., & Moehler, S. 2001, A&A, 378, 907
Saurer, W., et al. 1994, AJ, 107, 2101
Snell, R. L., Carpenter, J. M., & Heyer, M. H. 2002, ApJ, 578, 229
Wallin, J. F., Higdon, J. L., & Staveley-Smith, L. 1996, ApJ, 459, 555
Williams, P. M., et al. 1977, MNRAS, 180, 709