RECENT STAR FORMATION IN THE LEADING ARM OF THE MAGELLANIC STREAM

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ABSTRACT

Strongly interacting galaxies undergo a short-lived but dramatic phase of evolution characterized by enhanced star formation, tidal tails, bridges, and other morphological peculiarities. The nearest example of a pair of interacting galaxies is the Magellanic Clouds, whose dynamical interaction produced the gaseous features known as the Magellanic Stream trailing the pair's orbit about the Galaxy, the bridge between the Clouds, and the leading arm (LA), a wide and irregular feature leading the orbit. Young, newly formed stars in the bridge are known to exist, giving witness to the recent interaction between the Clouds. However, the interaction of the Clouds with the Milky Way (MW) is less well understood. In particular, the LA must have a tidal origin; however, no purely gravitational model is able to reproduce its morphology and kinematics. A hydrodynamical interaction with the gaseous hot halo and disk of the Galaxy is plausible as suggested by some models and supporting neutral hydrogen (H I) observations. Here we show for the first time that young, recently formed stars exist in the LA, indicating that the interaction between the Clouds and our Galaxy is strong enough to trigger star formation in certain regions of the LA—regions in the outskirts of the MW disk ($R \sim 18$ kpc), far away from the Clouds and the bridge.

Key words: galaxies: interactions – Galaxy: general – Magellanic Clouds – stars: early-type

Online-only material: color figures

1. INTRODUCTION

The Magellanic Clouds (MCs) offer a unique opportunity to study galaxy interactions in unprecedented detail due to their proximity to the Milky Way (MW). Thus, detailed mapping of their gaseous content, the three-dimensional (3D) kinematics of their stellar content, and the chemical-abundance makeup of these components are readily available for the Clouds. The most obvious features of their interaction are the H I structures known as the $\sim 200°$ long Magellanic Stream (MS), the bridge, and the leading arm (LA; Nidever et al. 2010). The recent work on the modeling of the Clouds' interaction by Diaz & Bekki (2012) makes a compelling case for the tidal model, where the MS, bridge, and LA are made primarily of material pulled out from the Small Magellanic Cloud during two close encounters between the two Clouds. The first encounter took place ~ 2 Gyr ago, and the second ~ 200 Myr ago. This work used the most recent absolute proper-motion determinations for the Clouds: one *Hubble Space Telescope* (*HST*) based (Kallivayalil et al. 2006), the other ground-based (Vieira et al. 2010). Both determinations imply exactly two encounters between the Clouds to reproduce the MS, LA, and bridge. As for their motion relative to the MW, *HST* measurements (Kallivayalil et al. 2006, 2013) favor the scenario where the MCs are on the first passage about the MW, with the MS and LA determined solely by the tidal interaction between the Clouds. The ground-based proper-motion measurement allows for two pericentric passages of the Clouds about the MW in the past 2.5 Gyr, and thus some tidal influence of the Galaxy in the formation of the MS, LA, and bridge is expected. The main drawback of the tidal models is that, while they produce a LA, they all fail to reproduce

the observed multi-branches morphology of the LA, and its kinematics. A model by Diaz & Bekki (2011) that also includes a hydrodynamical interaction of the LA with the diffuse, hot gaseous halo of the MW better reproduces the kinematics along the LA, but not its morphology. The LA has a complex structure, possibly made up of as many as four substructures according to For et al. (2013) and Venzmer et al. (2012), situated above and below the Galactic plane and encompassing $\sim 60°$ in width. It has been argued that there is a strong drag exerted by the MW gaseous disk on the H I substructures in the LA (McClure-Griffiths et al. 2008; Venzmer et al. 2012). This is implied by the head–tail velocity structure of the H I clouds in the LA, as well as the velocity gradient seen in a given LA substructure/arm (Venzmer et al. 2012). Thus it would be enlightening to search for newly formed stars in the LA, an expected result of the hydrodynamical interaction between the MS gas and the MW gaseous disk and halo. We also note that the most recent (~ 200 Myr ago) encounter between the two Clouds, which created the bridge, is abundantly accompanied by recent star formation, a fact well known since the work by Irwin et al. (1990) and subsequent follow up by, e.g., Demers & Battinelli (1998).

In a recent study, Casetti-Dinescu et al. (2012) listed 567 OB-type star candidates in a ~ 7900 deg^2 area encompassing the periphery of the Clouds, the bridge, the LA, and part of the MS. The photometric and proper-motion selection was aimed at finding hot (earlier than B5) and distant stars. Also, the proper-motion selection was aimed at selecting stars with motions consistent with membership in the Magellanic system. In the LA region, three stellar overdensities were found comprising a total of 45 candidates. This is a lower limit of such candidates,
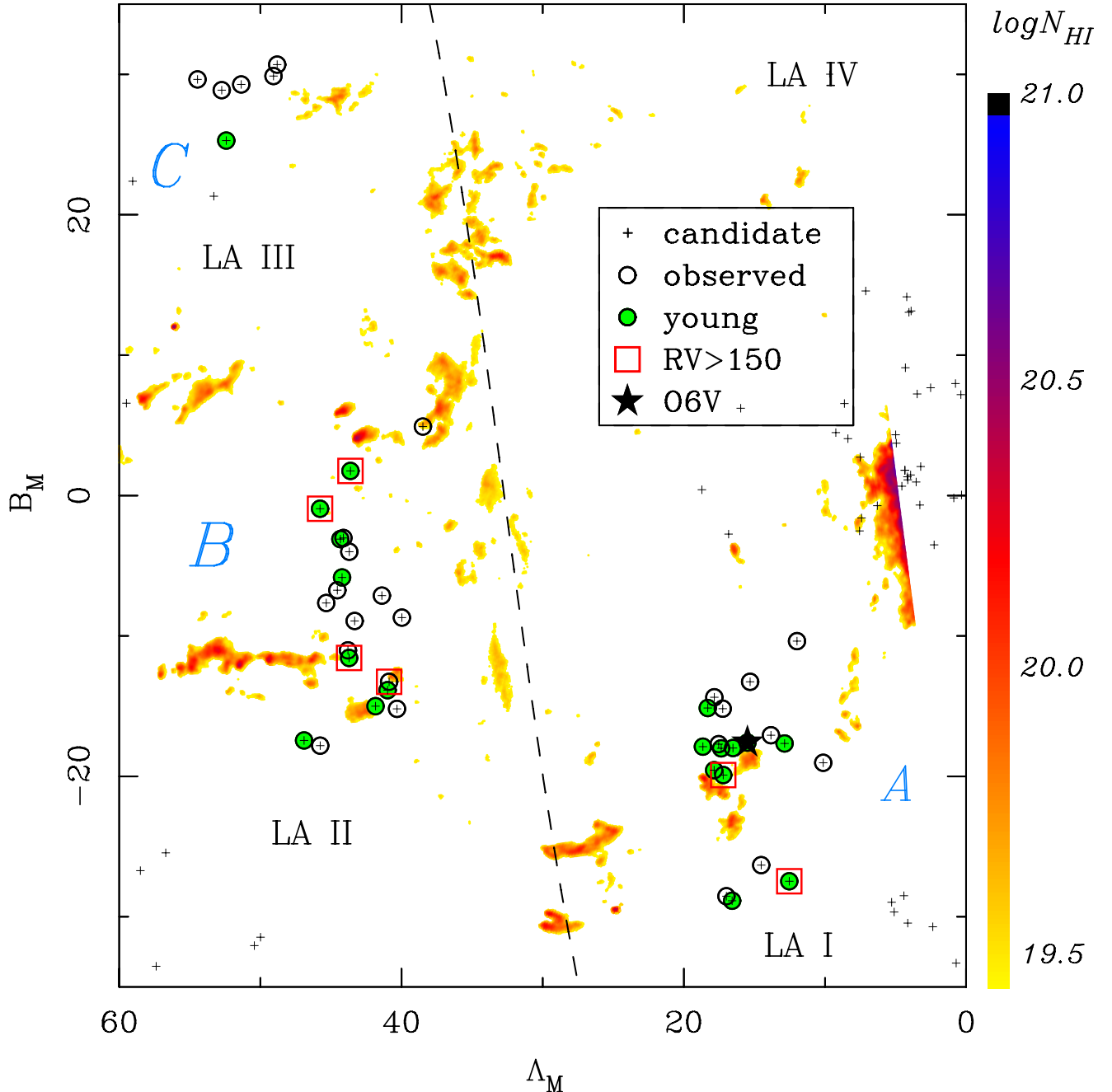
Figure 1. Spatial distribution in Magellanic coordinates of our OB candidates (crosses). The background color map shows the H I density distribution for $150 \leqslant RV_{LSR} \leqslant 400$ km s^{-1}, with the main LA branches (Venzmer et al. 2012) indicated. The 42 OB candidates observed spectroscopically are shown with circles. Filled green symbols indicate the young stars, while symbols highlighted with red squares indicate stars with radial velocity RV > 150 km s^{-1}. The black star symbol represents the most massive, young star in our sample (sp. type O6V). Our three regions of interest (A, B, and C) are also labeled. The dashed line represents the Galactic plane.

(A color version of this figure is available in the online journal.)

since the study is incomplete area-wise (Casetti-Dinescu et al. 2012). Here, we have spectroscopically observed 42 of the 45 candidates. Their spatial distribution is shown in Figure 1. Also shown is the H I distribution from the GASS survey (McClure-Griffiths et al. 2009; Kalberla et al. 2010) for which we have restricted the velocity with respect to the local standard of rest (LSR), to be $150 \leqslant V_{LSR} \leqslant 400$ km s^{-1}. We label the three candidate overdensities as A at $(\Lambda_M, B_M) \sim (15°, -22°)$, B at $(\Lambda_M, B_M) \sim (42°, -8°)$, and C at $(\Lambda_M, B_M) \sim (52°, 28°)$. In what follows, we describe the spectroscopic observations and the results.

2. OBSERVATIONS

Intermediate-resolution spectra were obtained with the IMACS spectrograph on the 6.5 m Baade telescope at Las Campanas Observatory. The setup gave a resolution of 1.3 Å($R \approx$ 3500) in the range 3650–5230 Å. The 1200 l/mm grating at the $f/4$ camera was employed at first order, with a blaze angle of 17° and a 0″.75-wide slit, for a resulting resolution of 1.3 Å($R \approx$ 3500) in the range 3650–5230 Å. The average seeing during observations was 0″.7, and the resulting spectral signal-to-noise ratio was higher than 50 for all the targets. Cross-correlation

techniques (Tonry & Davis 1979) as implemented in the IRAF *fxcor* task were used to measure heliocentric radial velocities (RVs). In the absence of prior knowledge concerning the exact temperature and gravity of the targets, the synthetic spectrum (Munari et al. 2005) of a main-sequence B-type star was adopted as the template.[7] The final uncertainty, taking into account the relevant sources of errors, are estimated to be between 3 and 14 km s^{-1}, typically $\approx$5 km s^{-1} for most of the targets. The spectra are also fitted with standard routines (Bergeron et al. 1992; Saffer et al. 1994; Napiwotzki et al. 1999) to derive the temperature, gravity, surface helium abundance, and, in some cases, rotational velocity.[8] At these colors, our major sources of contamination are foreground subdwarf O and B stars (sdBs) and white dwarfs. Close binaries are extremely common among sdB's (Maxted et al. 2001), and hence RVs alone are not conclusive for assessing the membership of our targets in the LA. To distinguish main-sequence stars from sdBs, besides the surface gravity, we can also use the surface helium abundance because the atmosphere of sdB's in the temperature range $T_{\rm eff} > 11,500$ K is depleted of helium by a factor between 10 and 100 due to gravitational settling (Baschek 1975; Moni Bidin et al. 2012). Rotational velocity is also indicative, as fast rotators are common among early-type main-sequence stars, but not among sdB's (Geier & Heber 2012).

3. RESULTS

Of the 42 candidates observed, we find 19 young, massive stars, together with 22 foreground sdB and white dwarf stars, and 1 uncertain object. The density of young stars in regions A and B is higher than in C, at a significance of 2.6σ in A, for instance, after correcting for areal incompleteness.

We adopt RV = 150 km s^{-1} as the lower limit for kinematical membership in the LA based on H I velocities in the LA (e.g., Venzmer et al. 2012). Note that in this region of the sky, heliocentric and LSR RVs differ by a very small amount (at most 14 km s^{-1} in region C). We find a total of six stars with RV > 150 km s^{-1}: four in region B, two in region A, and none in region C (Figure 1). These are listed in Table 1, along with one other star of interest.

Remarkably, of the six stars with RV > 150 km s^{-1}, five are young, massive objects, as inferred from $T_{\rm eff}$, log g and helium abundance. Three of these stars are also fast rotators. The RV average and dispersion of these five stars is 201 $\pm$ 15 km s^{-1} and 33 km s^{-1}, respectively. Even more remarkably, we find one candidate star to be a very hot, main-sequence star with spectral-type O6V (Table 1), and thus a massive ($\sim$40 $M_{\odot}$), short-lived (1–2 Myr) star at a heliocentric distance of $\sim$40 kpc. In Figure 1, we highlight the 19 young stars, the 6 stars with RV > 150 km s^{-1}, and the 1 O6V-type star. We plot the RVs as a function of surface gravity, color-coded by effective temperature, in Figure 2, and highlight the fast rotators. As a guide, we also indicate the mean RV of the thin+thick disk populations and its $\pm 2\sigma$ standard-deviation range as derived from the Besancon galactic model (Robin et al. 2003). The group of stars with RV > 150 km s^{-1} and log $g \leqslant 4$ stands out in this plot.
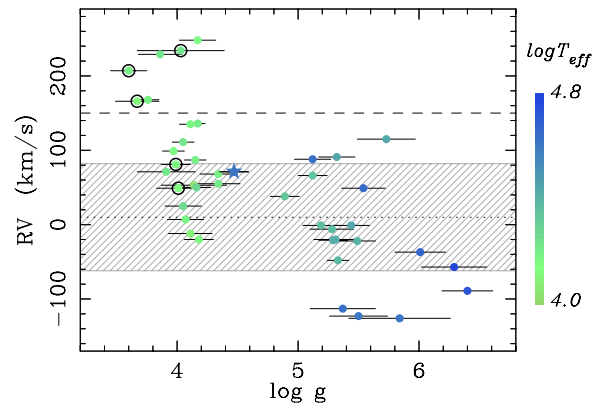

Figure 2. Kinematic and spectral properties of our OB candidates. Heliocentric radial velocity as a function of surface gravity for 42 observed stars. Each symbols' color represents the effective temperature as indicated. The mean and $\pm 2\sigma$ standard deviations for the Galactic thin+thick disk (Robin et al. 2003) are indicated with a hatched area. The horizontal line at 150 km s^{-1} shows the limit for LA RV-member candidates. Fast rotators ($v \sin i > 100$ km s^{-1}) are highlighted with a black circle. Note the group of six stars with velocities in excess of 150 km s^{-1} and log g smaller than $\sim$4.2 dex. Five of these are classified as massive, young stars, and only one as an sdB, primarily on account of its low He abundance (see Table 1). Note also the hot, relatively low log g star at RV $\sim$ 70 km s^{-1} (star symbol). This is the earliest spectral-type star found with this surface gravity, and thus is classified as O6V, a massive, young star located at $\sim$40 kpc from the Sun.

(A color version of this figure is available in the online journal.)

A possible non-LA origin for the young stars must be considered, i.e., that these are runaway stars. Such stars are believed to originate in star-forming regions of the Galactic disk as massive binaries that are disrupted by either a supernova or by a three- or four-body dynamical interaction, probably within a young star cluster (e.g., Bromley et al. 2009). In principle, all of our 19 young stars could be suspected of having such an origin. However, the five young B-type stars with RV > 150 km s^{-1} do not fit such a scenario, since their RV dispersion of 33 km s^{-1} is too low compared to that of runaway stars, $\sim$130 km s^{-1} (Bromley et al. 2009). To obtain such a low velocity dispersion, the ejection mechanism would have to be directionally coherent, which is highly unlikely. For the remaining young stars, it is difficult to distinguish, on an individual basis, between a runaway star and an LA member. This is because the RV is compatible with both the kinematics of a runaway star and the orbital motion of a binary star in the LA. Massive young stars are known to form predominantly in binary and multiple systems (Sana et al. 2012), thus it is likely that our single-epoch RVs are affected. Given these two stochastic effects on RVs—contamination by runaway stars and binary orbital motion—it is remarkable that we have found five young stars exhibiting a dispersion of only 30 km s^{-1} and a mean RV compatible with LA kinematics. Considering also the areal incompleteness (Casetti-Dinescu et al. 2012), what we have discovered is probably the "tip of the iceberg."

Absolute magnitudes and ages have been derived for all the young stars based on isochrones in the log $g - T_{\rm eff}$ plane (Bressan et al. 2012). In Figure 3, we plot the distance modulus versus age for these stars. Stars with RV > 150 km s^{-1} are once again highlighted. As a guide, the gray band indicates the kinematical distance (21 kpc) with uncertainty, derived for a high velocity cloud in the LA by McClure-Griffiths et al. (2008) that crosses the Galactic disk. Clearly, this kinematic distance is within the range of our stellar distances. A number of more nearby stars

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[7] A mismatch between the parameters of the template and object spectra enhances the uncertainties but does not affect the results, especially for hot stars (Moni Bidin et al. 2011).

[8] Rotational velocities were not fitted for, but rather used as an input parameter. By using different inputs, the one that gave the lowest χ^2 was adopted as the value of the $v \sin i$. These values should be regarded as indicative, with errors $\sim$30 km s^{-1}.

Table 1
Spectral Parameters for Stars of Interest

ID	SPM ID	l	b	RV	$v \sin i$	T_{eff}	$\log g$	$\log \frac{N_{\mathrm{He}}}{N_{\mathrm{H}}}$	Sp. Type
		(°)		(km s^{-1})		(K)	(dex)		
B02	2880084481	275.3	10.5	168 ± 4	0	16000 ± 400	3.76 ± 0.09	$[-1]$	B4III
B03	2890097375	277.7	13.1	229 ± 5	0	17500 ± 1100	3.86 ± 0.18	-1.60 ± 0.18	B3IV
B14	2310104323	288.8	12.2	207 ± 5	300	15800 ± 700	3.60 ± 0.15	$[-1]$	B4/5III
B15	2310425880	290.8	9.6	248 ± 5	0	14800 ± 700	4.17 ± 0.15	-2.10 ± 0.33	sdB
A15	0400042068	300.7	-11.8	166 ± 6	280	13400 ± 600	3.67 ± 0.18	$[-1]$	B7III
A19	0420365194	309.4	-14.1	234 ± 6	260	17200 ± 1900	4.03 ± 0.36	-1.58 ± 0.42	B3IV
A08	0390226948	298.8	-13.9	71 ± 11	0	43700 ± 1200	4.47 ± 0.12	-1.20 ± 0.39	O6V

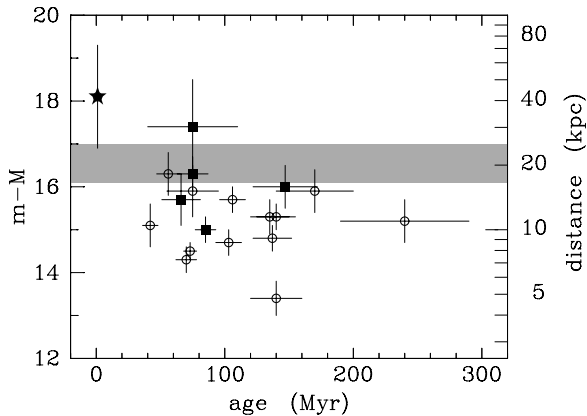**Note.** The [] indicate an adopted rather than fitted value.

Figure 3. Distances and ages for the young stars. Distance moduli vs. ages are shown for our 19 massive, young stars. The stars with RV > 150 km s^{-1} are shown with filled squares. The star symbol indicates the O6V star. The gray band represents the kinematical distance of one high velocity cloud member of the LA (McClure-Griffiths et al. 2008); the width of the band corresponds to a 20% error in the distance.

are also present in this young sample, and they may be more readily explained as having originated in the disk.

Finally, we discuss the notable O6V star (Table 1). Its origin in the MW disk is doubtful, since it is too young (1–2 Myr) to have traveled at a reasonable speed to a Galactocentric distance of ∼39 kpc. To demonstrate this, we calculate its orbit using a three-component Galactic potential model and find that its last disk crossing occurred over 500 Myr ago. Even allowing for uncertainties in the distance, the shortest time since the last disk crossing in the orbit is 385 Myr. Therefore, this star could not have been born in the Galactic disk. Another possibility is that it was born in the LMC and was subsequently ejected, but this would require a velocity of the order of 10^4 km s^{-1} for such a young star to reach its current position. This being an unrealistic value, the only viable possibility is that it was born in situ, far away from both the Galactic disk and the LMC.

These observations establish that conditions were met for recent star formation in the LA material located in the outskirts of the Galactic disk ($R \sim 18$ kpc), most likely as a consequence of the interaction between the Galactic disk and portions of the LA. We note that the most distant H I structure associated with the MW disk is a spiral arm at $R = 18$–24 kpc (McClure-Griffiths et al. 2004), while stellar samples indicate shorter distances for the "edge" of the disk of ∼14 kpc (e.g., Minniti et al. 2011).

Our findings cast new light on the interaction of the Clouds with the MW, perhaps making a first infall scenario less likely. Whether or not this is the case remains to be established by more complex models, and in light of the lower velocity of the Clouds

as indicated by the Vieira et al. (2010), Costa et al. (2009), and the Kallivayalil et al. (2013) studies compared to the first *HST* study by Kallivayalil et al. (2006).

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