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LOW SURFACE BRIGHTNESS IMAGING OF THE MAGELLANIC SYSTEM: IMPRINTS OF TIDAL INTERACTIONS BETWEEN THE CLOUDS IN THE STELLAR PERIPHERY

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ABSTRACT

We present deep optical images of the Large and Small Magellanic Clouds (LMC and SMC) using a low cost telephoto lens with a wide field of view to explore stellar substructure in the outskirts of the stellar disk of the LMC (r $<$ 10 degrees from the center). These data have higher resolution than existing star count maps, and highlight the existence of stellar arcs and multiple spiral arms in the northern periphery, with no comparable counterparts in the South. We compare these data to detailed simulations of the LMC disk outskirts, following interactions with its low mass companion, the SMC. We consider interaction in isolation and with the inclusion of the Milky Way tidal field. The simulations are used to assess the origin of the northern structures, including also the low density stellar arc recently identified in the DES data by Mackey et al. (2015) at $\sim$ 15 degrees. We conclude that repeated close interactions with the SMC are primarily responsible for the asymmetric stellar structures seen in the periphery of the LMC. The orientation and density of these arcs can be used to constrain the LMC's interaction history with and impact parameter of the SMC. More generally, we find that such asymmetric structures should be ubiquitous about pairs of dwarfs and can persist for 1-2 Gyr even after the secondary merges entirely with the primary. As such, the lack of a companion around a Magellanic Irregular does not disprove the hypothesis that their asymmetric structures are driven by dwarf-dwarf interactions.

1. INTRODUCTION

The Large and Small Magellanic Clouds (LMC and SMC, respectively) are our closest example of an interacting pair of dwarf galaxies. Evidence of this interaction is clearly illustrated by the existence of the gaseous Magellanic Bridge connecting the Clouds (Kerr 1957; Hindman et al. 1963), and the tail of gas that trails them known as the Magellanic Stream (Mathewson et al. 1974; Putman et al. 2003; Nidever et al. 2010). However, signatures of this interaction history are less clear in their stellar components.

On-going star formation in the LMC is stochastic, giving the dwarf galaxy an irregular appearance in the

disk, extending to at least 9 kpc in radius (van der Mar
2001). This is similarly revealed by the smooth distribu
tion of RR Lyrae stars in the LMC disk (Haschke et al
2012).

Asymmetries in the stellar disk do exist, howeve
the disk appears to be warped (van der Marel & Cio
2001; Olsen & Salyk 2002; Nikolaev et al. 2004) and th
stellar bar of the LMC is geometrically off-center an
warped relative to the disk plane (Subramanian 200
Lah et al. 2005; Koerwer 2009). 3D maps of the LM
created using Cepheids and RR Lyrae illustrate that th
bar is in fact protruding from the disk (Haschke et al
2012; Nikolaev et al. 2004). This can be explained

We present the first results of our panoramic imaging of the Magellanic System and compare these observations with simulations of the LMC disk that include repeated interactions with the SMC, with and without the tidal effects of the MilkyWay.

Используется портативная установка: две CCD- камеры со светосильными объективами Canon: 5 см f/1.4 и 20 см f/2.8;
Фильтры: Luminance filter (4000°A < < 7500°A) и RGB-filters.
Экспозиции 5 мин и 10 мин.

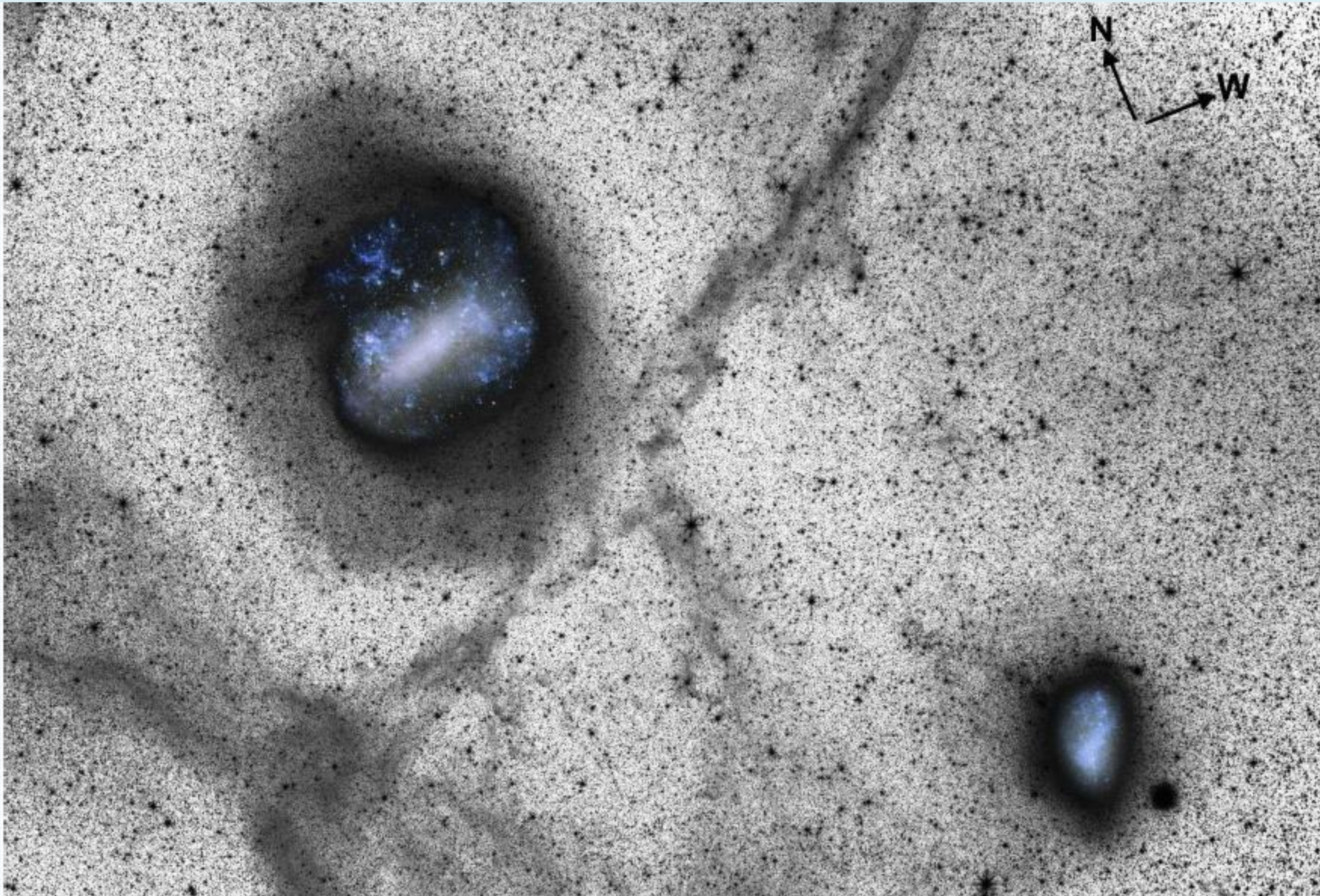


Figure 1. Wide-field Luminance filter image of the Magellanic System (39 x 27 degrees). The LMC is located towards the top left and the SMC is to the bottom right. The Milky Way globular cluster 47 Tuc is visible to the West of the SMC. A tail of stars from the SMC is visible stretching towards the LMC in the East. The outskirts of the LMC disk display pronounced asymmetries. For illustrative purposes, a color inset of the inner regions of the LMC and SMC, made from the color data obtained in our observing run (see Section 2), is inserted as a reference and for comparison with previous studies.

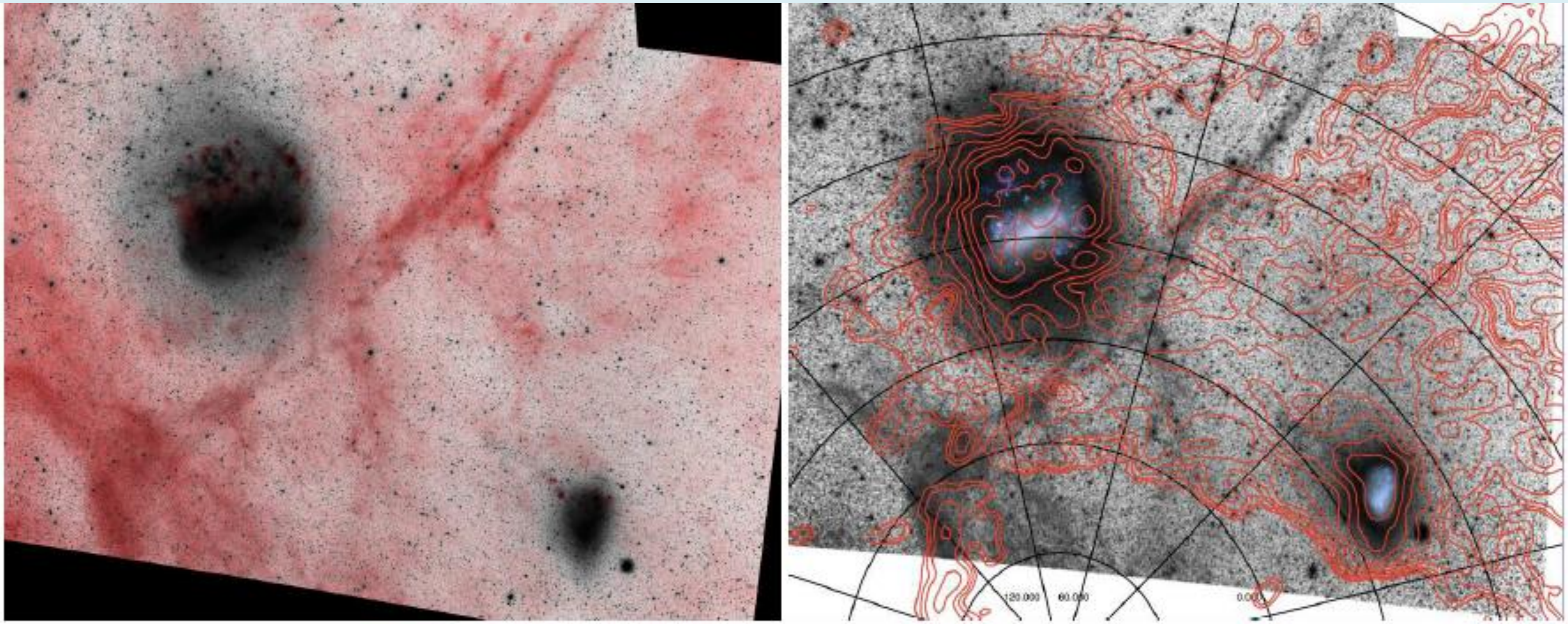
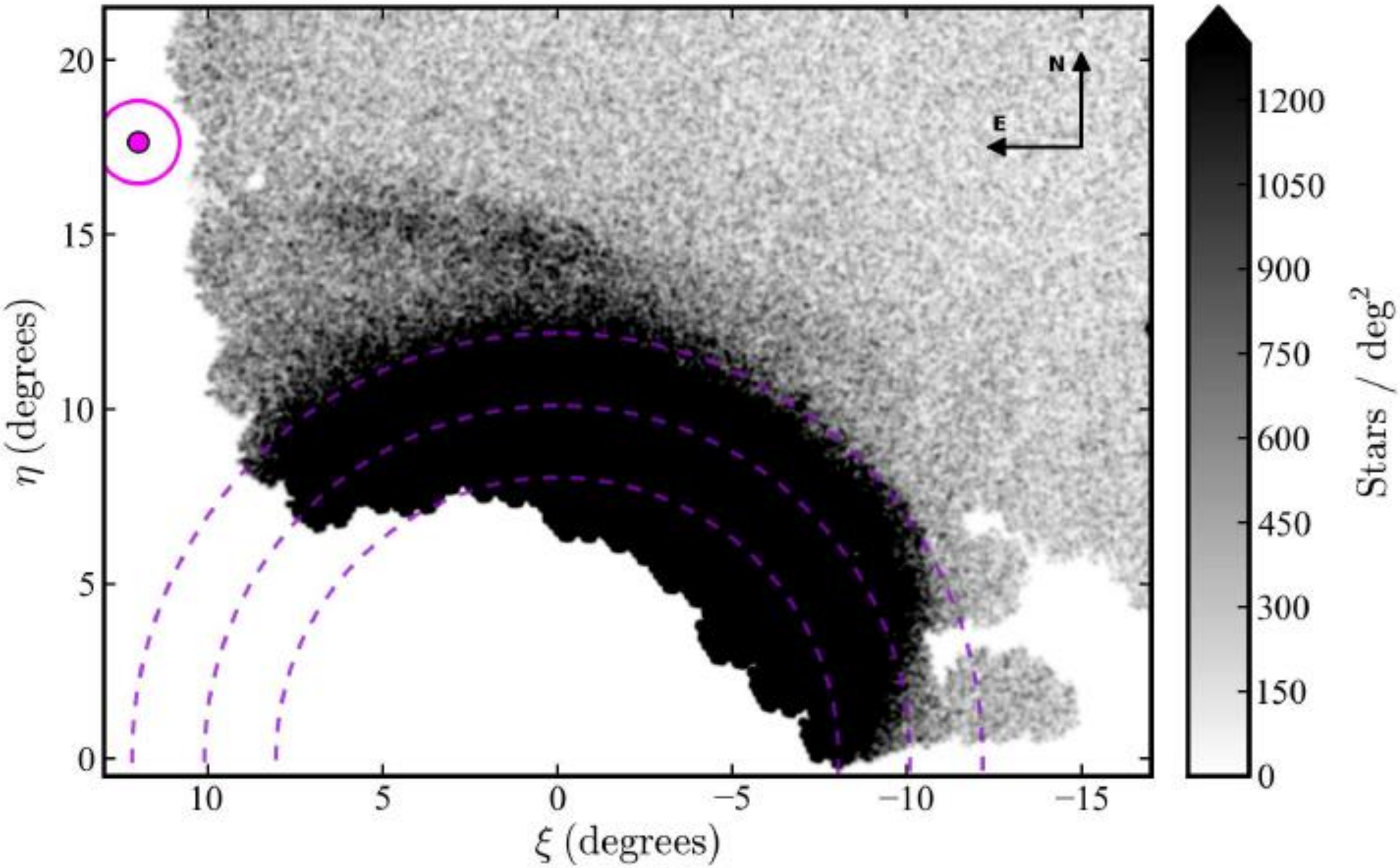


Figure 2. Left: Same as Figure 1 where Galactic cirrus, identified based on far-IR observations by IRAS and DIRBE, is highlighted in red. There is very little cirrus in the outskirts of the LMC disk. Right: Same with HI contours from (Putman et al. 2003) overplotted. Column densities range from 10^{19} to 10^{21} atoms cm^{-2}. There is a sharp drop in gas density in the LMC outskirts towards the North East (top left), which was modeled in Salem et al. (2015) as an effect induced by ram pressure.



Map showing the spatial density of stars consistent with being members of the LMC old main sequence turn-off population.

CTIO 4v
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2.2^0

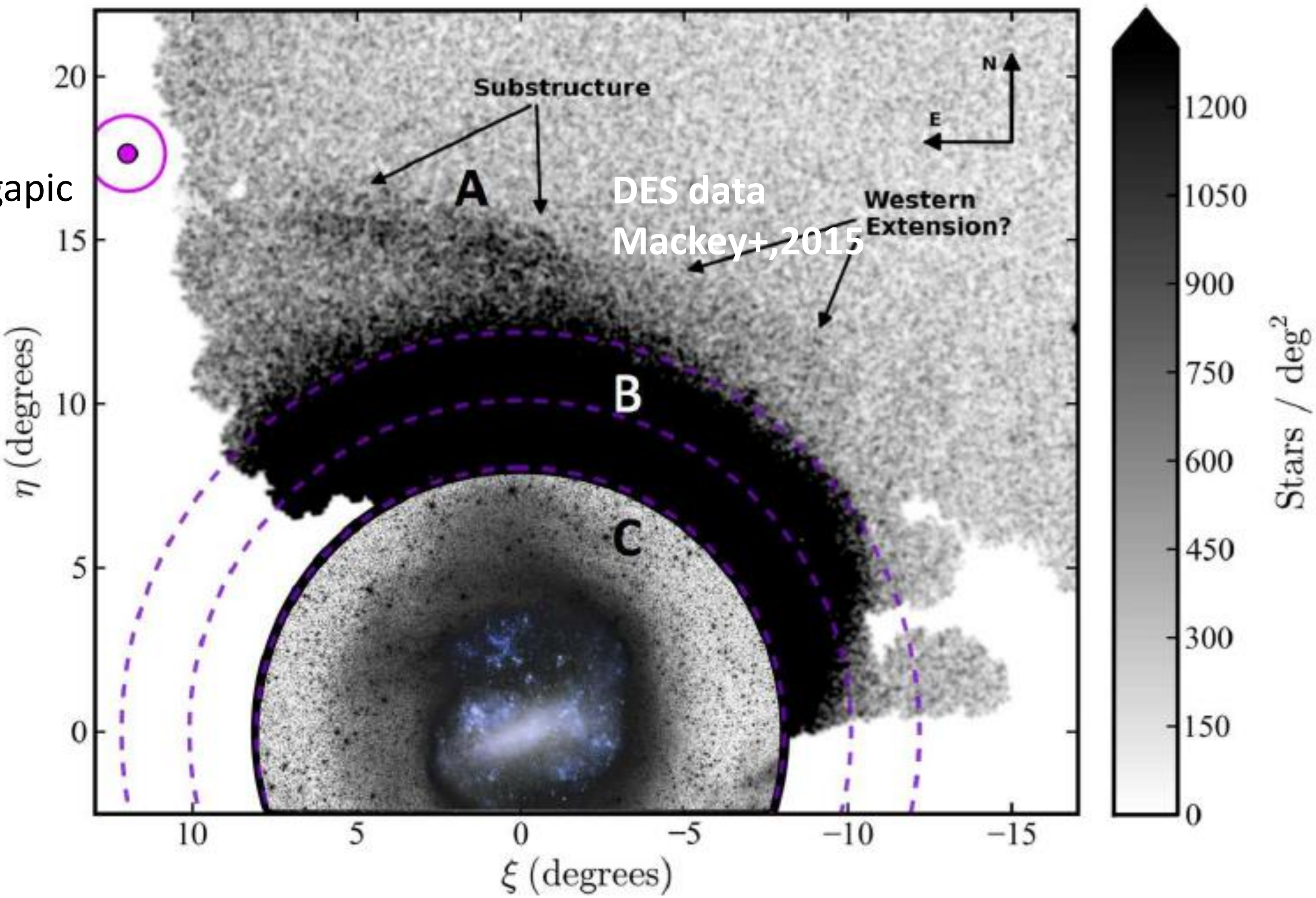

Figure 4. A modified version of Figure 1 from Mackey et al. (2015) showing the spatial density of old main sequence turn-off stars in the LMC. the three purple dashed circles indicate angular separations of 8^o, 10^o and 12^o from the center of the LMC. The stellar stream identified by Mackey et al. (2015) is marked as region A and extends towards the Carina dwarf (magenta point). Our data extends to ∼8 degrees. The substructure we have identified in the LMC is marked as region C. The intermediate region between our data and the DES arc is marked as region B.

LMC: моделирование (без учета Галактики)

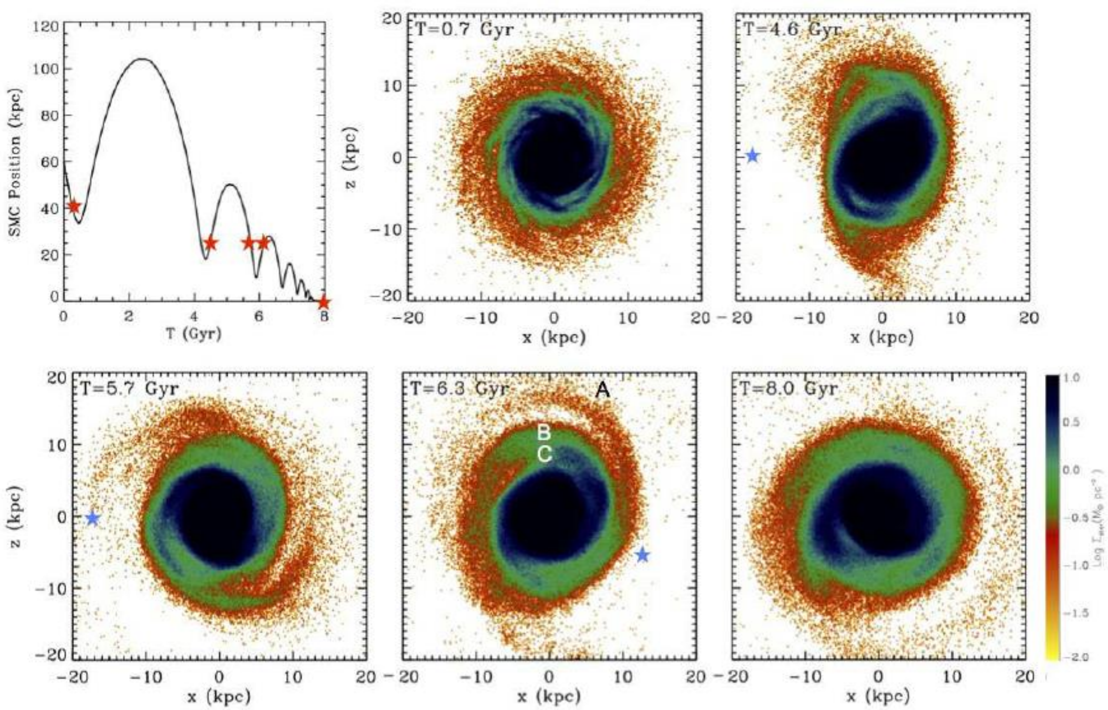

Figure 5. The simulated interaction history of the Large and Small Magellanic Clouds in isolation (i.e. without the Milky Way). The top left panel illustrates the separation between the SMC and LMC as a function of time. The Clouds were likely captured by the Milky Way after 5 or 6 Gyr of evolution as an isolated binary pair. However, here the simulation is followed past that point until the system merges, as would have happened had the Clouds never been captured. Stellar density maps of the LMC disk are plotted at key moments in the interaction history as denoted by red stars in the top left panel. T=0.7 Gyr represents the initial state of the LMC disk as a symmetric exponential disk. At T=4.6, 5.6, and 6.3 Gyr the SMC is roughly 25 kpc from the LMC, as it is today. SMC particles have been omitted from these maps, but the rough location of the SMC is marked by a blue star if it is visible in the field of view. After 6.3 Gyr of evolution the SMC has just passed through the disk of the LMC ($b < 10$ kpc), inducing strong asymmetrical spiral structure and arcs (Region C) that exist as far as 15 kpc from the LMC center (Region A). This structure is similar to that seen in Mackey et al. (2015), illustrating that low density arcs can form at large radii from the LMC center without the influence of the Milky Way tidal field. After 8 Gyr of evolution the system has completely merged, yet asymmetric spiral structure still persist.

Синяя звездочка – положение SMC

Extreme impact parameters are not a necessary to reproduce the broad morphology of the outer stellar discs. While many of the outer stellar structures are transient, the dominant one-armed spiral persists even after the SMC is completely cannibalized at T=8.0 Gyr! A 1:10 Mass ratio is insufficient to destroy the disk of the LMC.

Оптимальная модель с учетом Галактики:

109 лет назад Облака вошли в гало Галактики (масса $1.5 \cdot 10^{12}$ Мс), а в настоящее время только что прошли точку максимального сближения с Галактикой.

Сами Облака максимально сближались ~10^8 лет назад, следствием чего образовался мост между ними..

Главные выводы

- Our data has confirmed the existence of stellar arcs and multiple spiral arms in the northern periphery, with no comparable counterparts in the South. The asymmetry of these structures disfavors a formation scenario driven by global Milky Way tides.
- Outer spiral arms and arcs are found to be transient,

but the dominant one-armed spiral induced by a collision

between dwarfs would persist for 1-2 Gyr even after the

secondary galaxy merges entirely with the primary. As such, the

lack of a companion around a Magellanic Irregular does

not disprove the hypothesis that the structures defining this class of galaxy (one-armed spiral and geometrically off-center bar) are driven by interactions with low mass companions.