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Star formation history and dynamical evolution of the solar neighbourhood

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Abstract. Based on cosmological re-simulations we have shown that the impact of satellite galaxies has a minor effect on the thin disc heating. In contrast satellite galaxies can generate long-lived warps of the outer disc and they can advance or delay bar formation significantly.

Keywords. methods: n-body simulations, Galaxy: disk, Galaxy: evolution, galaxies: interactions

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We investigated the statistical impact of satellite galaxies on the Galactic disc of the Milky Way by high-resolution re-simulations ($N_{\rm d,b,h,sat} = 10, 0.5, 4, 0.05$ million particles for disc, bulge, DM halo, and each satellite, resp.) of cosmological simulations. We selected all (∼100) satellites of the Aquarius A2 ... F2 (Springel *et al.* (2008)) and the Via Lactea II (Diemand *et al.* (2008)) cosmological dark matter only simulations of Milky Way-like host halos at redshift $z = 0$ with $M > 10^8 M_\odot$, which are coming closer than 25 kpc to the host galaxy in the subsequent 2 Gyr (see left panel of Fig. 1). The seven full simulations provide the basis to analyse the secular evolution of the disc in terms of thickening, warping and bar formation. Only satellites above $10^9 M_\odot$ significantly affect the overall disc structure.

1. Disc heating

In Moetazedian & Just (2016) we have shown that the thin disc heating by satellites contribute only 10% to the observed rate in the solar neighbourhood at $R = 8$ kpc (right panels of Fig. 1). The delay of 0.5 Gyr compensates for a potentially reduced interaction in the initial phase of the simulations. The specific heating rate is independent of R for $R > 4$ kpc.

2. Vertical wiggles and warp

The strongest effect of interacting satellite galaxies are vertical oscillations and the formation of a warp in the outer disc. For a detailed analysis of the warp and wiggle dynamics, we have extended the Aquarius F2 re-simulation Aq-F2 with the most massive satellite ($M = 5.9 \cdot 10^{10} M_\odot$) up to 6 Gyr. We have analysed the vertical pertubations in terms of the Fourier decomposition of the mean vertical elevation $\langle z\rangle(R, \varphi)$ and the mean vertical velocity $\langle V_z\rangle(R, \varphi)$.

The top left panel of Fig. 2 shows a time series of the vertical disc distortion in terms of the mean vertical velocity $\langle V_z\rangle$. The structure is dominated by $m = 1$ perturbations (tilted rings or warp). The top right panel shows the amplitude at the positive x-axis and reveals that the wiggles in the inner disc are quickly winding-up and moving outwards

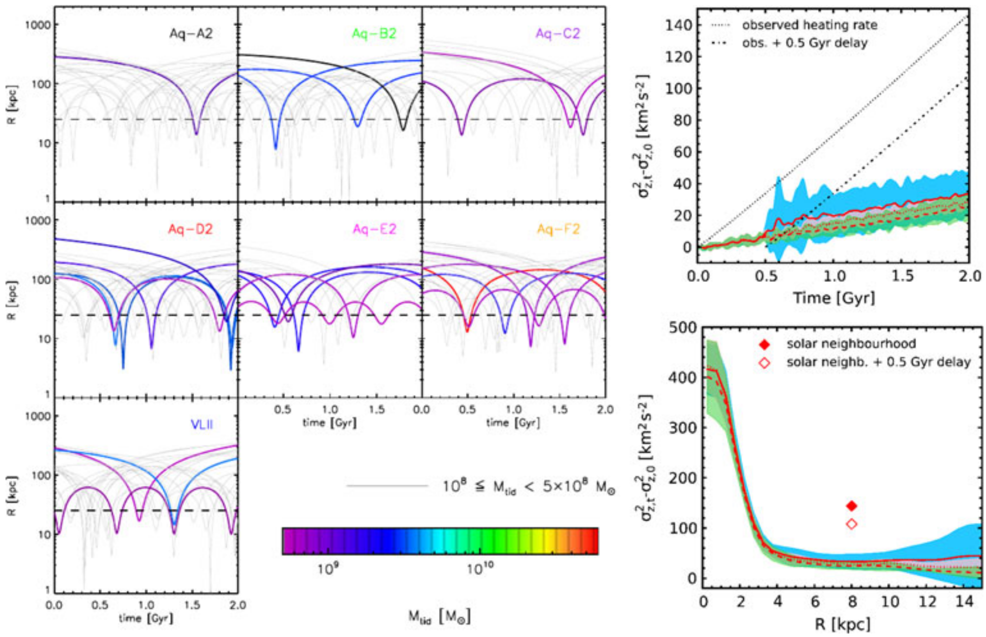

Figure 1. Left: Satellite orbits (high mass satellites colour-coded) labelled according to their parent cosmolgical simulation Aq-A2 ... Aq-F2 and VLII. Right: Mean (specific) heating rate and rms scatter of the 7 simulations with satellites (full red line, blue area) compared to the isolated numerical heating (dashed red line, green area); growing vertical velocity dispersion at $R = 8$ kpc as function of time (top) and after 2 Gyr as function of radius (bottom). Dotted black lines and red squares show the observed heating rate in the solar neighbourhood.

supporting the outer warp. The first pericentre passage excites a resonant perturbation over the whole radial range with $R > 7$ kpc (bottom left panel).

The outer warp is established after 1 Gyr and counter-rotating (the phase is shown in the middle right panel and the pattern speed in the middle bottom panel of Fig. 2); its amplitude is enhanced additionally by the second encounter at $t \sim 2$ Gyr. The warp is long-lived with an amplitude of ∼1 kpc over a couple of Gyr (bottom right panel of Fig. 2), whereas some groups of star reach a distance up to $z \sim 3$ kpc.

In conclusion we find that the dominant feature of a LMC (or heavy Sgr dwarf) -like encounter is a long-lived warp, which is slowly counter rotating. Multiple approaches can, dependent on the phase of the disc crossing relative to the warp orientation, enhance or diminish the warp perturbation.

3. Bar formation

In a galaxy with a cuspy bulge there exists an inner Lindblad resonance for all pattern speeds, which suppresses the formation of a bar in a razor-thin disc. With a set of tailored N-body simulations we have shown in Polyachenko, Berczik & Just (2016) that the finite thickness of the disc is responsible for the observed bar instability, because the inner Lindblad resonance is smeared out. In Moetazedian *et al.* (2017) we have used the same initial conditions for the Milky Way–like galaxy as in Polyachenko, Berczik & Just (2016) ($N_{\rm d,b,h} = 6, 1.5, 9.25$ million particles for disc, bulge and DM halo, resp.) to investigate the impact of a satellite galaxy interactions on bar formation. The isolated galaxy (run B-0, 'B' stands for the simulation code, the TREE code 'Bonsai', '0' for the number of satellites included) forms a bar out of random noise

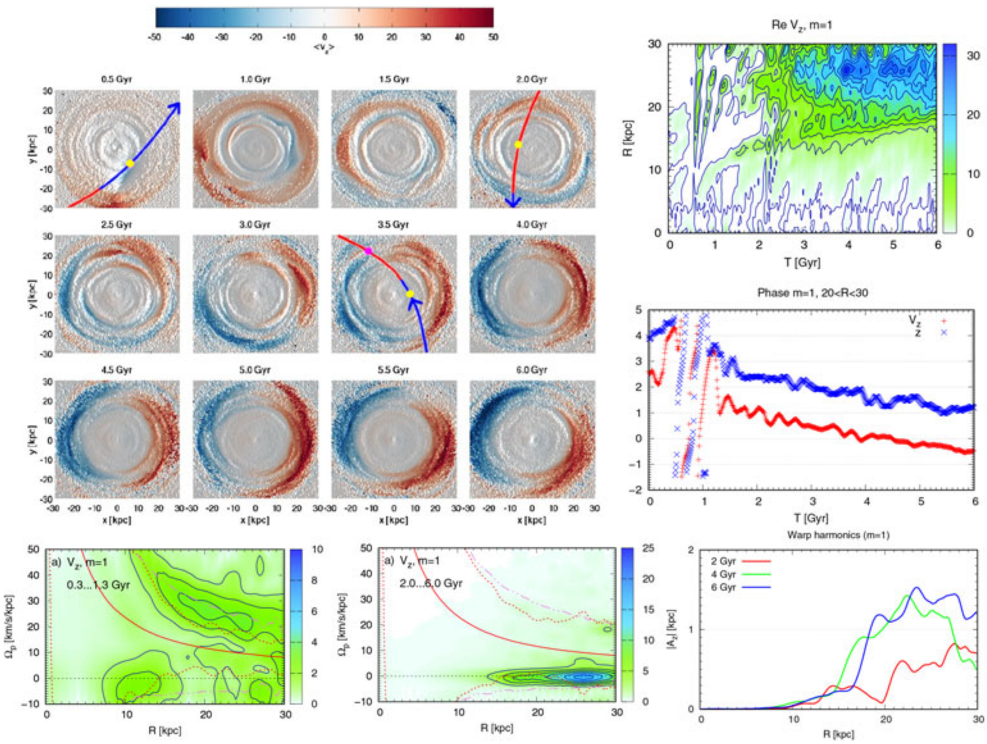

Figure 2. Top left: Mean vertical disc velocity $\langle V_z \rangle$ in km/s with projected satellite orbit (red: above, blue: below the plane, yellow dots: pericentre passages). **Top right:** Amplitude of the mean vertical warp velocity as function of time (real part: amplitude in km/s at positive x-axis) including phase information. **Middle right:** Azimuthal phase in radians of the warp in $\langle V_z \rangle$ and $\langle z \rangle$. **Bottom:** Pattern speeds Ω_p of $m = 1$ modes excited at first pericentre passage (**left**) and long-lived warp (**middle**); pink dash-dotted lines show the resonances $\Omega_\mathrm{p} = \Omega \pm \nu$ with vertical oscillation frequency ν including the force of the disc, and red dotted lines show the epicyclic resonances $\Omega_\mathrm{p} = \Omega \pm \kappa$ with epicyclic frequency κ (Ω is the corotation frequency of the disc). **Bottom right:** Amplitude of the mean vertical elevation $\langle z \rangle$ of the long-lived warp at different times.

with growth rate Ω_I =3/Gyr and a pattern speed of Ω_P =49 km/s/kpc. The initial conditions of the satellites were taken from the Aquarius D2 simulation rescaled to the smaller halo mass (B-23, B-4, B-1 including all 23 satellites with $M > 10^8 M_\odot$, the 4 with $M > 10^9 M_\odot$, and the only the one with largest tidal impact on the disc, resp.) In the simulations B-1m, B-4m with same satellite masses the orbits were not rescaled leading to delayed peri-centre passages. In B-1-500Myr and B-1-110Myr the orbits were shifted by -500 Myr and +110 Myr to test the sensitivity on the impact timing with bar orientation.

We find that the bar properties in terms of growth rate, pattern speed and saturation is independent on the impact of the satellites. Only satellites with mass larger than $10^9 M_\odot$ show a measurable impact. The bar is prone to satellite perturbations only in a critical amplitude regime of 0.2-1%. If the pericentre passage happens in this critical phase the bar formation is advanced, if it is in phase with the radial velocity perturbation of the bar (B-1, B-4, B-23), or delayed (B-1m, B-4m, B-1-110Myr), if out of phase, by up to 600 Myr (see Fig. 3). No effect is observed for the case B-1-500Myr, where the impact happens too early.

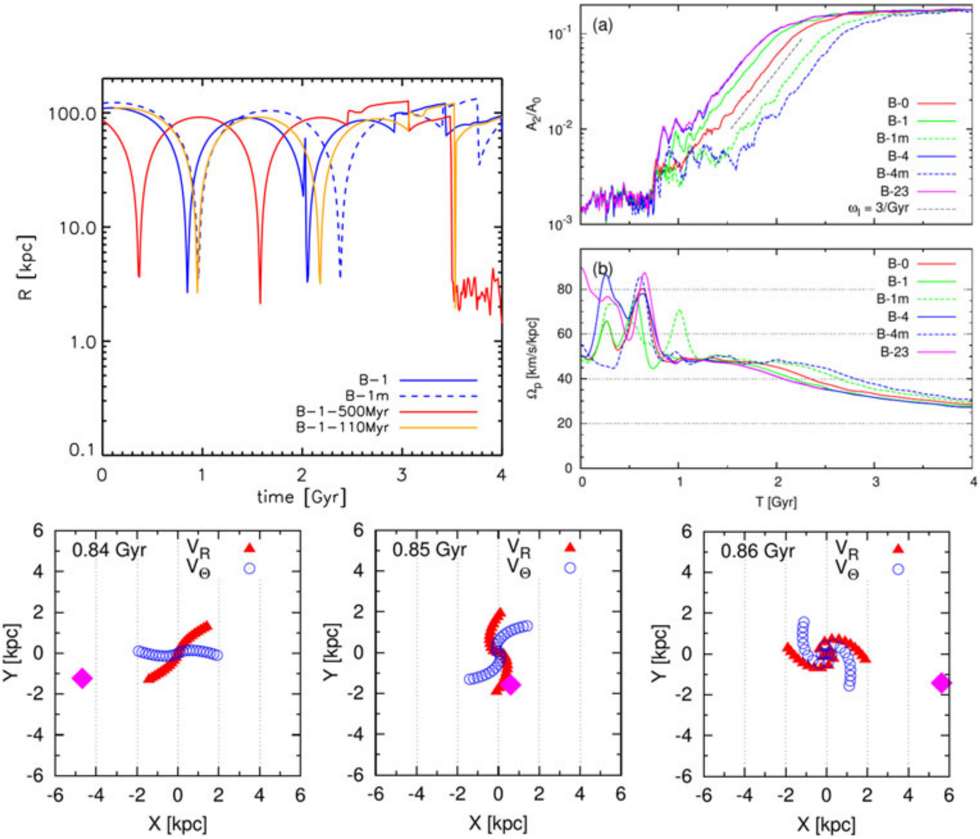

Figure 3. Top left: Timing of first pericentre passage for the different simulations. Top and middle right: Amplitude and pattern speed of the bar (formation advanced for B-1, B-4 and B-23, delayed for B-1m and B-4m). Bottom: Satellite B-1 (pink square) in phase with radial velocity perturbation of bar instability at first impact.

Acknowledgements

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