Inhomogeneous stellar winds in gamma-ray binaries

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Abstract

We study the interaction between pulsar and stellar winds in gamma-ray-emitting binaries in the presence of an inhomogeneous stellar wind. In such systems, the acceleration of particles likely occurs at the region of collision between the two winds, which is typically assumed to be smooth. However, the early-type stars that are thought to be present in some gamma-ray binaries appear to have clumpy winds. During the two-wind interaction, these clumps arrive at the acceleration region, reshape the interaction structure, and subsequently impact the related non-thermal emission. Depending on the adopted stellar wind parameters, the clumps can produce observable fluctuations in the X-ray and very-high-energy bands. Semi-analytical calculations of the dynamical evolution and non-thermal emission allow the study of both the orbit-modulated large-scale variability and clump-induced small-scale variability of such systems.

CD Distortion By Clumps

In a high-mass gamma-ray binary harbouring a young pulsar, the contact discontinuity (CD) formed by the collision of the stellar and pulsar winds can be reshaped by clump–pulsar wind interactions. Single interactions have been studied elsewhere with RHD simulations (Paredes-Fortuny 2015) to compute the non-thermal emission (de la Cita 2017), but full HD codes are very computationally demanding to model the collective effect of multiple events. In this work, stellar wind inhomogeneity is introduced by spherical clumps generated by Monte Carlo from a mass distribution $\propto M^{-2}$. The shape of the initially smooth CD is found by equating the wind ram pressures (Cantó et al. 1996) and tilting it by an angle accounting for orbital Coriolis effects. Large enough clumps will penetrate the pulsar wind termination shock (Bosch-Ramon 2013), expand, and distort the CD structure (see Fig. 1). Beyond the CD, the dynamic evolution of the clumps is described by a semi-analytical hydrodynamical model (Barkov et al. 2012).

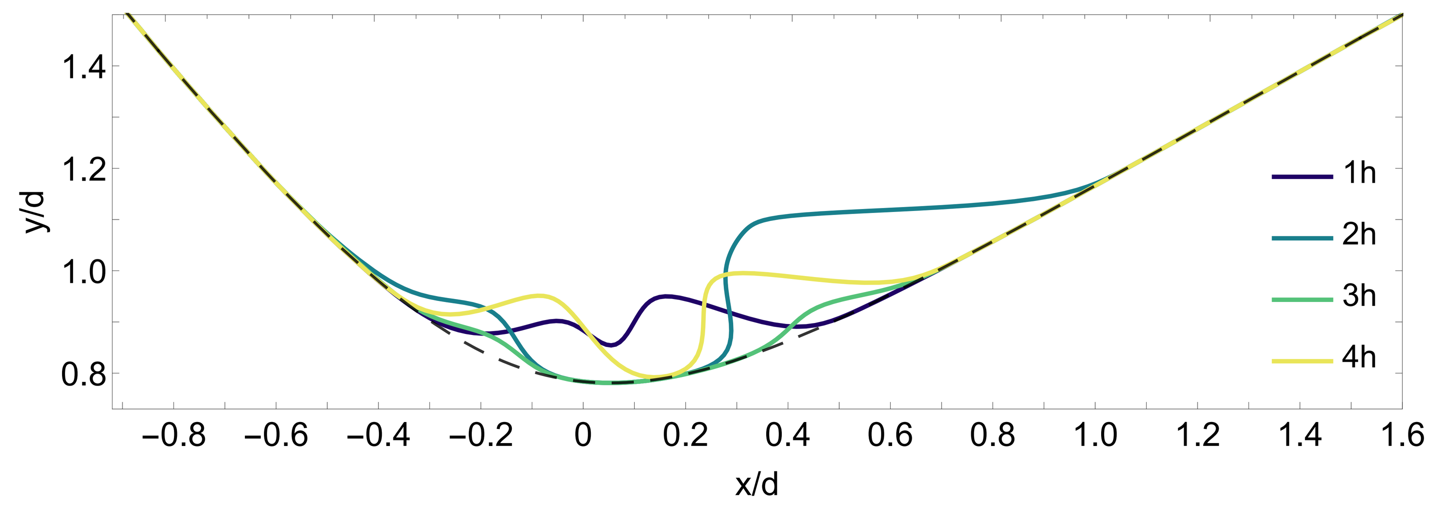

Figure 1: 2D snapshots of the CD at 1 hr intervals and for a smooth stellar wind (dashed line). The simulated region extends up to 1.5 times the orbital distance d from the star at an intermediate orbital phase.

Clump Effect On Emission

The disturbed CD is treated as a multi-zone emitting region, and the non-thermal emission is modelled assuming synchrotron and inverse Compton (IC) scattering losses for two extreme cooling regimes. The energy distribution of rapidly cooling particles is directly determined by the injected energy distribution (power law of index 2 and exponential cut-off) and radiative losses (saturation regime). When escape dominates, it is the total energy density stored in the shock region that determines the particle distribution (adiabatic regime). In Fig. 2, we compare the SEDs for the smooth and distorted CDs for two values of the magnetic-to-plasma energy density ratio η_B (magnetic-to-stellar photon energy density ratios: $\eta_* = 10^{-2}\eta_B$). Larger changes are observed in the adiabatic regime, which is directly affected by changes in the size (thickness) of the emitting region besides changes in the magnetic and photon fields. However, we expect the radiative regime to be more realistic overall. For a moderate η_B value (right), this part of the spectrum is dominated by IC losses. Only for a strongly magnetized pulsar wind (left), lower-energy X-rays are characterized by synchrotron emission.

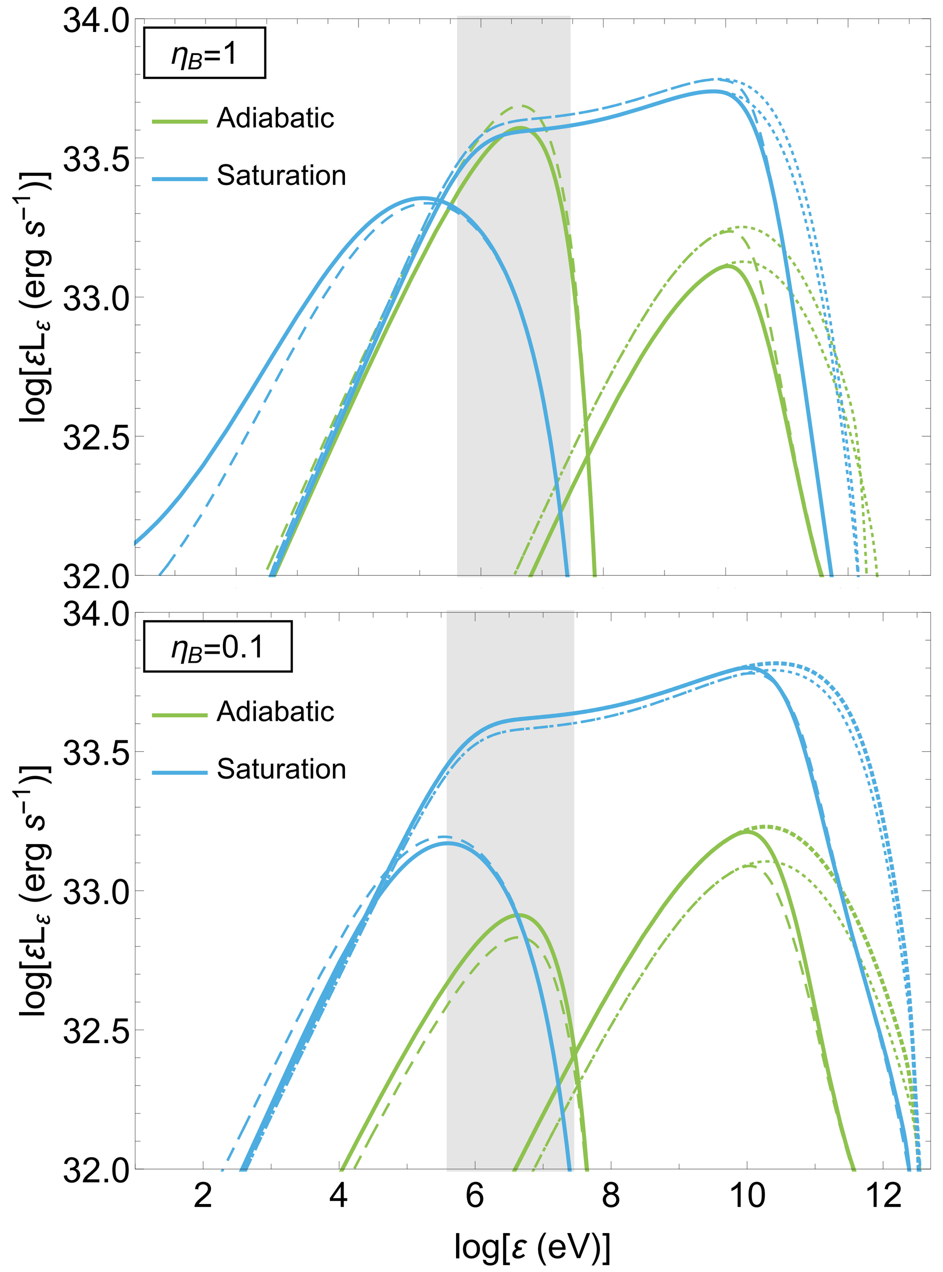

Figure 2: X-ray to TeV SEDs for the smooth stellar wind case (dashed) and the clumpy snapshot at 2 hr shown in Fig. 1 (solid) for the two regimes for two η_B values. The unabsorbed spectra (dotted) are also shown. The shaded area marks the transition from the adiabatic to the radiative regime for IC.

Clump-induced Variability

Stellar wind clumps can be an origin of short-scale variability in gamma-ray binaries, as captured by the light curves in Fig. 3, which exhibit some fluctuations in the flux of approximately 10–20%. The flux basically scales linearly with the inclination toward the line-of-sight direction, whose role is more evident in orbital-scale variability. Fluctuations in the adiabatic regime are mainly associated with reductions and increments in the total emitting volume. Therefore, this regime generally better captures the primary geometric effects, especially those related to emission from the outer parts of the CD. Fluctuations in the fully radiative regime mostly originate from enhancements in the magnetic field due to local changes in the emitter–pulsar distance and IC/gamma-ray absorption angular effects in the HE and VHE. The enhancement in synchrotron versus IC emissivity per particle results in a peak of approximately a factor of 2 in the X-rays in the saturation regime.

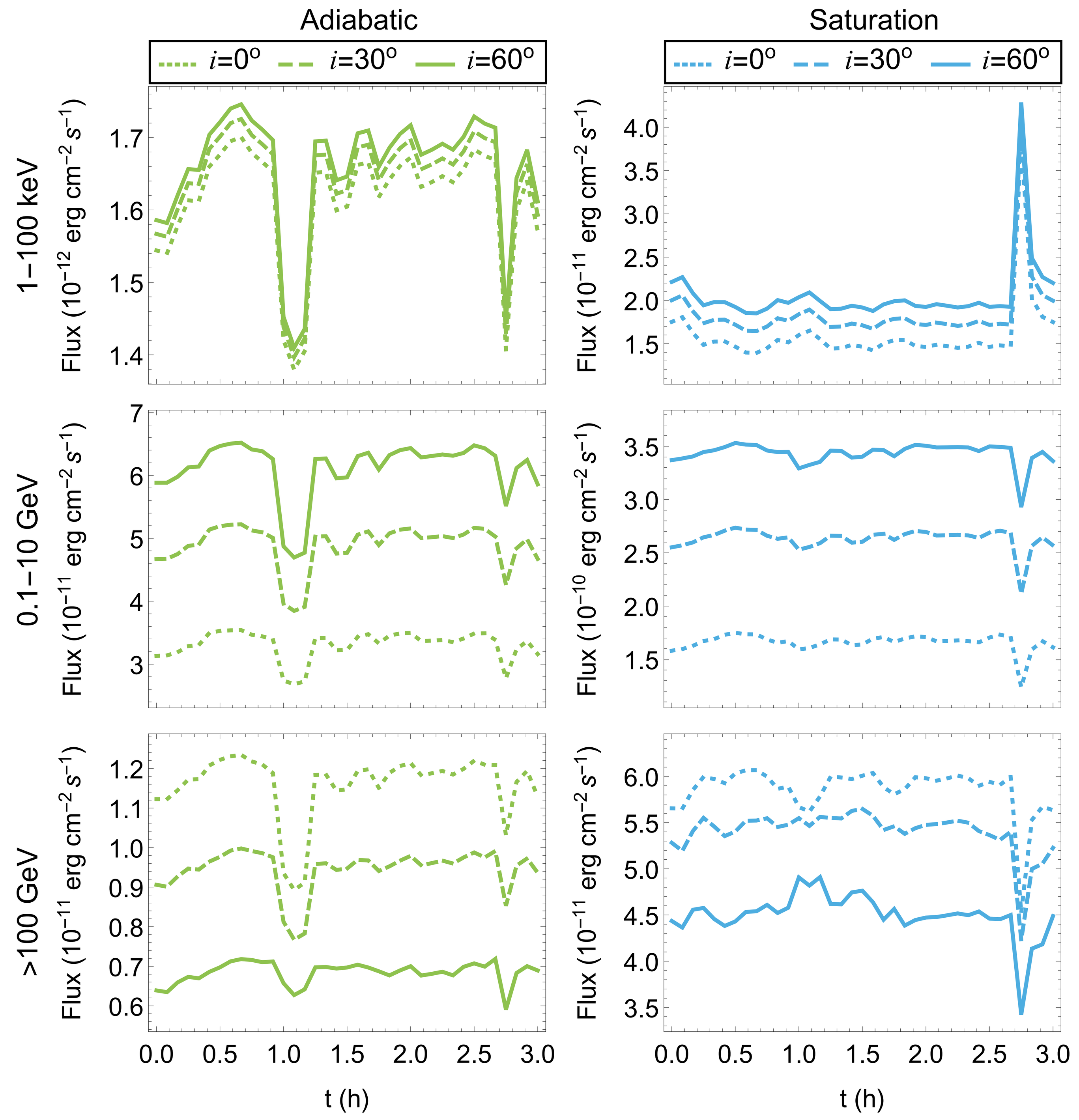

Figure 3: Light curves over a period of 3 hr for different inclinations i at X-rays (1–100 keV; synchrotron), HE (0.1–10 GeV; IC), and VHE gamma rays (> 100 GeV; IC) for $\eta_B = 0.1$.

System Parameters

Stellar luminosity	L_*	10^{39} erg s^{-1}
Star temperature	T_*	4×10^4 K
Stellar radius	R_*	$10.5\,R_\odot$
Stellar mass-loss rate	$\dot{M}$	$10^{-7}\,M_\odot$ yr^{-1}
Stellar-wind velocity	u_w	2×10^8 cm s^{-1}
Pulsar spin-down power	P_{sd}	3×10^{36} erg s^{-1}
Pulsar-wind Lorentz factor	Γ_w	10^5
Periodicity	P	3.91 days
Eccentricity	e	0.35
Semi-major axis	α	2.1×10^{12} cm
Filling factor	f	0.1
Distance to source	D	3 kpc

Discussion

A moderately clumpy stellar wind may introduce slight fluctuations in the luminosity, while highly clumpy winds may lead to luminosity increases of approximately a factor of few, mainly for the lower-energy adiabatic regions of the particle distribution. Even for an almost smooth stellar wind the effect of clumps should not be entirely overlooked as interactions of the shocked pulsar wind with large clumps can still occur. Although infrequent, such interactions can significantly perturb the emitting region leading to observable flux variations. Our simple semi-analytical approach allows us to quickly but robustly estimate the effects of stellar winds with different degrees of inhomogeneity and model the highly diverse population of gamma-ray binaries. Application of our model is limited though to regions close to the pulsar where the shocked flow is still subsonic. Beyond this region, a more complex model is necessary to account for the complicated hydrodynamics and orbital effects.

References

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