Non-thermal processes in the bow shocks of hyper-velocity stars

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Resumen / Las llamadas "estrellas fugitivas" se mueven con velocidades supersónicas respecto al medio que las rodea, generando a su paso ondas de choque en el gas interestelar. Estos objetos han sido mayoritariamente estudiados mediante la emisión infrarroja y las líneas espectrales ópticas producidas por el choque delantero. Sin embargo, los choques de propagación también pueden acelerar partículas relativistas y producir emisión no térmica a diferentes frecuencias. Esta radiación ha sido investigada en los choques reversos de estrellas fugitivas "normales", con velocidades $\lesssim 100$ km s^{-1}. En este trabajo expandimos la investigación al caso de estrellas de hiper-velocidad que alcanzan velocidades de miles de km s^{-1}. Analizamos su potencial como aceleradores de partículas y como fuentes de radiación no térmica. En particular, mostramos que los procesos no térmicos son relevantes en ambos choques, el reverso y el delantero. Calculamos su emisión multifrecuencia y evaluamos su detectabilidad en función de distintos parámetros, como el tipo espectral de la estrella, la velocidad espacial, y la densidad del medio.

Abstract / Runaway stars move at supersonic speed with respect to their surrounding medium. Such stars generate bow shocks in the interstellar gas as they propagate. These bow shocks are usually studied by means of the infrared radiation and the optical emission lines produced by the forward shock. However, bow shocks can also accelerate particles up to relativistic energies, which in turn produce broadband non-thermal emission. This radiation has been investigated in the reverse shocks of runaway stars with velocities of $\lesssim 100$ km s^{-1}. In this work, we expand the research to the case of hyper-velocity stars with speeds reaching thousands of km s^{-1}. We analyze their potential as particle accelerators and non-thermal radiation sources. In particular, we show that non-thermal processes are relevant in both the reverse and forward shocks. We estimate the broadband spectra and assess their detectability as a function of different parameters such as their spectral type, spatial velocity, and the medium density.

Keywords / radiation mechanisms: non-thermal — shock waves — acceleration of particles

1. Introduction

Massive stars launch supersonic winds that interact with the interstellar medium (ISM) generating two shock fronts: a forward shock (FS) and a reverse shock (RS). The FS propagates through the ISM, sweeping-up and heating the surrounding gas and dust, then creating a thin, dense shell. The RS propagates through the stellar wind, compressing and heating it. This generates cavities known as wind-blown stellar bubbles (e.g. Arthur, 2007, and references therein).

When massive stars have a supersonic velocity with respect to the ISM, the geometry of the bubble becomes bow-shaped instead of spherical (van Buren & McCray, 1988); this structure is referred as a bow shock (BS; see Fig. 1). The heated dust and gas emit mostly infrared (IR) and optical radiation (Peri et al., 2012; Kobulnicky et al., 2016). BSs can also accelerate particles by diffusive shock acceleration up to relativistic energies. These particles then produce non-thermal (NT) radiation. Synchrotron emission has been detected at radio frequencies in one system by Benaglia et al. (2010), and two *Fermi* sources have been associated with stellar bow shocks by Sánchez-Ayaso et al. (2018). Moreover, theoretical models predict NT radiation across the whole electromagnetic spectrum (del Valle & Romero, 2012; del Palacio et al., 2018; del Valle & Pohl, 2018).

In this work, we investigate the NT radiation produced in the BSs of a sub-type of runaway stars, called hyper-velocity stars (HVSs). HVSs are those with peculiar velocities of hundreds to thousands of km s^{-1} (Brown, 2015). The Hills mechanism (Hills, 1988) is the most promising process to explain their origin in view of the ejection velocities and rates it predicts. This mechanism consists of a 3-body exchange between a stellar binary and a supermassive black hole, which tidally disrupts the binary. Hundreds of HVSs have been observed (Marchetti et al., 2019). Furthermore, theoretical models even predict the existence of semi-relativistic stars (SRSs), with peculiar velocities up to 60 000 km s^{-1} in the case of B-type stars (Guillochon & Loeb, 2015).

We intend to investigate the emission from bow shocks of HVSs in various contexts. Here we present the results corresponding to two of these scenarios: a typical massive HVS and a putative SRS, both propagating in the Galactic disk.

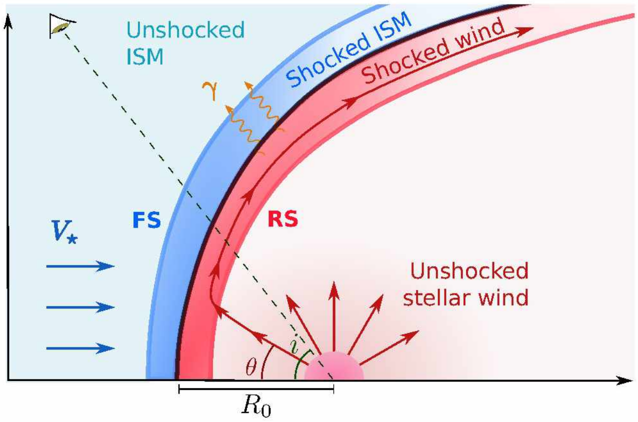

Figure 1: Sketch of a bow shock produced by a massive runaway star. Adapted from del Palacio et al. (2018). Reproduced with permission ©ESO.

2. Model

The BS is formed by the collision of the stellar wind with the ISM, which acts as a planar wind in the star's reference frame. The two shocked fluids in the FS and the RS are separated by a contact discontinuity as shown in Fig. 1. Diffusive shock acceleration can operate in the presence of strong adiabatic shock waves. In Sec. 3 we verify that this condition is fulfilled in both the RS and the FS for the HVSs and SRSs considered in this work.

The characteristic spatial scale of the system is given by the distance R_0 from the star to the stagnation point, located where the wind and ISM ram pressures balance each other. If $R_0 \gg R_\star$, the stellar wind reaches its terminal speed v_∞ and R_0 is given by (Wilkin, 1996)

$$R_0 = \sqrt{\frac{\dot{M}_\mathrm{w} v_\infty}{4\pi \rho_\mathrm{ISM} V_\star^2}}, \tag{1}$$

where ρ_ISM is the ISM the density.

We assume that the BS reaches a steady state, since we do not expect significant changes in the ambient conditions on short timescales and we neglect the effects of turbulence in the BS. The shocked gas flows downstream from the BS apex, dragging away the relativistic particles accelerated in the RS and FS. Particle acceleration and electromagnetic emission are most relevant within a region near the BS apex of characteristic length R_0 (del Valle & Romero, 2012). We thus consider the emitter as homogeneous and stationary and apply a one-zone approximation for each shock. We determine hydrodynamical magnitudes employing a semianalytical approach. We rely on the assumption that the fluid behaves like an ideal gas with adiabatic coefficient $\gamma_\mathrm{ad} = 5/3$, and we apply the Rankine-Hugoniot jump conditions for strong shocks. We set the magnetic field by the condition that the magnetic pressure in the shock is 0.1 of the thermal pressure of the shocked plasma.

We adopt an energy distribution of the injected particles $Q(E) = Q_0 E^{-p} \exp(E/E_\mathrm{cut})$, where p is the spectral index and E_cut is the cut-off energy. We assume $p = 2$, consistent with diffusive shock acceleration in a strong non-relativistic shock, and obtain E_cut by equating the acceleration timescale with the minimum between the cooling and escape timescales. Finally, the normalization constant Q_0 is set by the condition $\int E Q(E)\,\mathrm{d}E = L_\mathrm{NT}$, being L_NT the power injected into NT particles. For the RS and the FS this power is

$$L_\mathrm{NT}^\mathrm{RS} = f_\mathrm{NT}\, L_\mathrm{w} = f_\mathrm{NT}\, 0.5\, \dot{M}_\mathrm{w}\, v_\mathrm{w}^2, \tag{2}$$

$$L_\mathrm{NT}^\mathrm{FS} = f_\mathrm{NT}\, L_\mathrm{ISM} = f_\mathrm{NT}\, 0.5\, \pi\, \rho_\mathrm{ISM}\, R_0^2\, V_\star^3, \tag{3}$$

where $f_\mathrm{NT} \approx 0.05$ is the fraction of the wind (ISM) kinetic power injected into relativistic particles in the RS (FS). In turn, we assume that a fraction of 5% of this power goes into relativistic electrons and the remaining into relativistic protons.

The accelerated particles interact with local matter, radiation and magnetic fields producing NT radiation. Electrons cool mainly via synchrotron emission and inverse Compton interactions (IC) with IR radiation from the dust and ultraviolet (UV) photons from the star. Moreover, NT particles can also escape from the emission region via convection and diffusion. The corresponding timescales for these processes are given in del Palacio et al. (2018), together with the solution of the transport equation for relativistic particles. The emitted spectrum is unaffected by absorption processes, which are negligible since $R_0 \gg R_\star$.

We apply our model to two different scenarios representing an HVS or a SRS moving in the Galactic disk. We specify the adopted parameters for each scenario in Table 1.

Table 1: Parameters of the systems modeled, an hyper-velocity star (HVS) and a semi-relativistic star (SRS). The values of v_w and $\dot{M}_\mathrm{w}$ are taken from Krtička (2014) and Kobulnicky et al. (2019), and $R_\star$ and $T_\star$ from Harmanec (1988).

Parameter	Symbol	HVS	SRS
Spectral type		B1	B2
Peculiar velocity	$V_\star$ [km s^{-1}]	1000	60 000
Wind velocity	v_w [km s^{-1}]	1200	1000
Wind mass-loss rate	$\dot{M}_\mathrm{w}$ [M$_\odot$ yr^{-1}]	10^{-9}	10^{-10}
Stellar radius	$R_\star$ [R$_\odot$]	4.8	4
Stellar temperature	$T_\star$ [kK]	25	20
Ambient density	n_a [cm^{-3}]	10	10

3. Results

We first characterize the conditions in the RS and the FS. A shock is adiabatic if the gas radiative cooling time is longer than its convection time (Stevens et al., 1992). For the parameters given in Table 1, both the RS and the FS are adiabatic. Thus, particles are accelerated in both shocks. Moreover, we find that protons are rapidly removed from the acceleration region by convection, so we only focus on leptonic emission in what follows.

3.1. Hyper-velocity star

In this scenario we consider an HVS crossing the Galactic disk. We consider a favorable yet viable case of a B-type star with $V_\star = 1000$ km s^{-1}. The feasibility of this

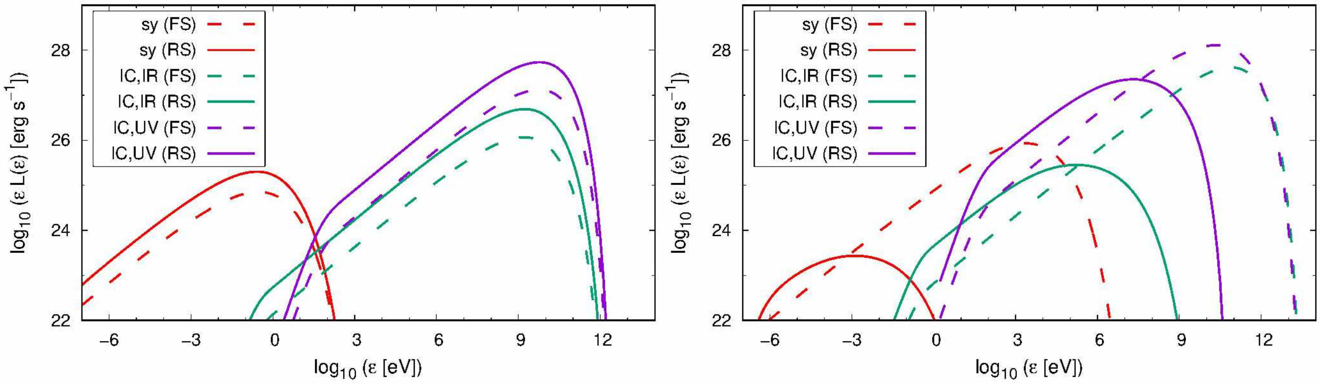

Figure 2: *Left panel:* SED for an HVS. *Right panel:* SED for a SRS. Solid (dashed) lines are the emission components of the RS (FS).

scenario is supported by the detection of B-type runaway stars with $V_\star > 1000\ \mathrm{km\,s^{-1}}$ by Marchetti et al. (2019).

Convection losses are dominant for relativistic electrons in both shocks, although synchrotron and IC with the stellar UV photons are also efficient processes at energies $E_\mathrm{e} \gtrsim 1$ GeV. Considering also diffusion effects, the electron distribution slightly softens in this range. The electrons reach energies of $E_\mathrm{cut} \approx 100$ GeV.

In Fig. 2 we show the spectral energy distribution (SED). The SED is governed by synchrotron radio emission and IC X-ray and γ-ray emission with the stellar UV photons. The RS is ~ 4 times more luminous than the FS.

3.2. Semi-relativistic star

In this scenario we consider a SRS crossing the Galactic disk. Even though their existence is still hypothetical, SRSs are promising NT emitters, as $L_\mathrm{NT}^\mathrm{FS} \propto V_\star^3$. We focus on B2 stars as they have lifetimes of tens of Myr and can therefore arrive from nearby galaxies such as the Magellanic Clouds, M31 or even M82. Considering $V_\star \sim 60\,000\ \mathrm{km\,s^{-1}}$, Doppler boosting effects are negligible, and the dynamical BS model proposed is still valid.

This system presents some interesting characteristics given that the high value of $V_\star$ leads to a small value of R_0 (Eq. 1). On the one hand, IC cooling with the stellar UV photons in the Thomson regime becomes very efficient and dominates the cooling of electrons in the RS with energies $E_\mathrm{e} > 100$ MeV; this significantly softens their energy spectrum and leads to a small value of $E_\mathrm{cut} \approx 5$ GeV.

On the other hand, a very different behavior occurs for electrons in the FS. Particle acceleration is really efficient and electrons reach very high energies ($E_\mathrm{cut} \approx 5$ TeV). Thus, IC radiation from the FS with stellar photons dominates the SED for $\epsilon \gtrsim 1$ GeV. The reason is that the luminosity injected by the FS increases with $V_\star$; therefore, for $V_\star > v_\mathrm{w}$, the emission from the FS becomes higher than the emission from the RS.

4. Conclusions

We modeled the NT emission in the BSs of HVSs, particularly a feasible HVS and a putative SRS. Our preliminary results suggest that NT radiative processes are relevant in both the RS and the FS, being this the biggest difference with BSs formed in typical runaways stars. Moreover, cosmic-ray acceleration becomes very efficient in the BS of SRSs, and electrons can reach very high energies ($\gtrsim 10^{12}$ eV). We note that the IR, optical and UV emission from these objects should be completely dominated by thermal radiation from the BS and the star. Nonetheless, the predictions presented in this work could guide future observational campaigns in the radio, X-ray and γ-ray domains.

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