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A model for the non-thermal emission of the very massive colliding-wind binary HD 93129A

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Resumen / Recientemente se logró resolver la región de colisión de vientos del sistema binario HD 93129A, uno de los más masivos de la Galaxia, utilizando interferometría de larga base. En este trabajo desarrollamos un modelo radiativo para la región de colisión de vientos. Nuestro modelo tiene en cuenta la aceleración y evolución de las partículas a medida que se mueven a lo largo de las líneas de fluido, su emisión a través de distintos procesos radiativos, y la atenuación de dicha radiación al propagarse por distintos campos locales. Reproducimos los datos observacionales disponibles en la banda de radio, y analizamos la detectabilidad de la fuente en rayos X duros y rayos γ. También predecimos cómo cambiará la emisión del sistema en los próximos años a medida que las estrellas se acerquen entre sí, y desarrollamos mapas sintéticos a 2.3 GHz y 8.6 GHz que servirán como referencia para interpretar futuras observaciones en estas bandas. De acuerdo a nuestros resultados, la emisión no térmica del sistema se incrementará, por lo que será posible determinar la naturaleza (hadrónica y/o leptónica) de las partículas relativistas emisoras a partir de observaciones a altas energías con instrumentos como *NuSTAR*, *Fermi* y CTA. A su vez, se podrá restringir el valor del campo magnético en la región de colisión de vientos estelares e, indirectamente, en la superficie de estrellas muy masivas.

Abstract / Recently, the wind collision region of the system HD 93129A was resolved for the first time using very large baseline interferometry. This system is one of the most massive known binaries in our Galaxy. In this work we develop a broadband radiative model for the wind collision region. The model takes into account the evolution of accelerated particles streaming along the shocked region, their emission through different radiative processes, and the attenuation of the radiation while it propagates across all local fields. We reproduce the available radio data, and analyze the consequent detectability of the source in hard X/gamma-rays. We predict how the emission from the system will evolve in the forthcoming years when the stars come closer, and we also provide synthetic radio maps that allow to interpret the future observations with very large baseline interferometry in 2.3 GHz and 8.6 GHz. According to our results, the non-thermal emission from this system will enhance in the near future. With instruments such as *NuSTAR*, *Fermi*, and CTA, it will be possible to determine whether the relativistic particle content is hadron or lepton dominated, and other parameters such as the strength of the magnetic field in the wind collision region and, indirectly, the magnetic field in the surface of the very massive stars.

Keywords / stars: winds, outflows — radiation mechanisms: non-thermal — acceleration of particles

1. Introduction

Early-type stars produce powerful stellar winds with mass-loss rates $\dot{M} \sim 10^{-7} - 10^{-5}$ M$_\odot$ yr^{-1} and wind terminal velocities $v_\infty \sim 1000-3000$ km s^{-1}. In massive binary systems, these winds interact with each other; we refer to these as colliding-wind binaries (CWBs). The radio emission from the winds of single massive stars is of thermal origin and has a characteristic spectral index $\alpha \sim 0.6^\star$ (Wright & Barlow, 1975). However, in about 40 massive binaries a non-thermal (NT) component, usually with $\alpha < 0$, has also been reported (De Becker & Raucq, 2013). In a few cases very large baseline interferometry observations resolved the NT emission region and confirmed their association with the winds collision. The detection of NT emission indicates that relativistic particle acceleration is taking place in these systems, probably through first-order diffusive shock acceleration (DSA) in the strong, supersonic shocks produced in the wind-collision region (WCR). The relativistic electrons interact both with the magnetic field and with the stellar UV field, producing low energy synchrotron photons and high-energy (HE) photons through inverse Compton (IC) scattering, respectively (Eichler & Usov, 1993; Benaglia & Romero, 2003; Reitberger et al., 2014).

The system HD 93129A, located at a distance of 2.3 kpc, is among the earliest, hottest, most massive and luminous binaries in the Galaxy. The primary is an O2 If* star, and the secondary is likely an O3.5 V star. The estimated system mass is 200 ± 45 M$_\odot$ (Maíz Apellániz et al., 2008). The angular separation between the components was $D_{\rm proj} = 55$ mas in 2003, 36 mas in 2008, and 27 mas in 2013. The inclination of the orbit is unknown, and therefore only a lower limit of 80 au can be given for the linear separation in 2008

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*The flux density at a frequency ν is $S_\nu \propto \nu^\alpha$.

(see Benaglia et al., 2015a, and references therein). The available data at radio-frequencies (Benaglia et al., 2015b) allow to characterize the injection spectrum of relativistic particles in the WCR. Using this as an input we predict the behavior of the system in the HE domain. Notice that the NT emission from IR to soft X-rays is completely overcome by the thermal emission from the stars and/or the WCR, so the signatures of relativistic particles in the Spectral Energy Distribution (SED) are limited to radio and potentially to γ-rays. In particular, we are interested in determining the orbital phase at which HD 93129A is most suitable for being observed in γ-rays. So far, η-Carinae (Tavani et al., 2009) and WR 11 (Pshirkov, 2015) are the only CWBs observed at HE, and we intend to predict whether HD 93129A is a promising candidate to join the family of γ-ray emitting, massive star binaries.

2. Model

The stellar winds collide forming an interaction region bounded on either side by the termination shocks of the winds. In our model the WCR is treated as a two thin-layer structure, where each shock is adiabatic and has different properties according to the conditions of the respective incoming wind. We consider the winds to be spherical and smooth (i.e., clumping negligible), and that they reach their terminal velocity on scales much smaller than the system scale (i.e., $v_{\rm w}(r) = v_\infty \sim 3000$ km s^{-1} for both stars). We characterize the relevant thermodynamical quantities in either shock with approximated analytical prescriptions. In different locations of the WCR relativistic particles are injected assuming DSA and subject to the constraints provided by radio observations. These particles are followed as they stream along the field lines in a 2D plane, and different line-emitters are distributed to account for a 3D geometry similar to a parabolic cone. Assuming a steady state, i.e., neglecting orbital effects, the fluid lines have azimuthal symmetry, although a 3D dependence arises when computing some emission and absorption processes which depend also on the observer direction. The relativistic particles cool through different processes. The most relevant ones are, for electrons, synchrotron, relativistic Bremsstrahlung, and anisotropic IC, whereas for protons only pp interactions. We take into account Razin-Tsytovich suppression for low-energy synchrotron photons, as well as free-free absorption (FFA) in the stellar wind as the photons propagate towards the observer. Similarly, we calculate the $\gamma-\gamma$ absorption of HE photons in the stellar photon field, though this correction is very small in such a wide system.

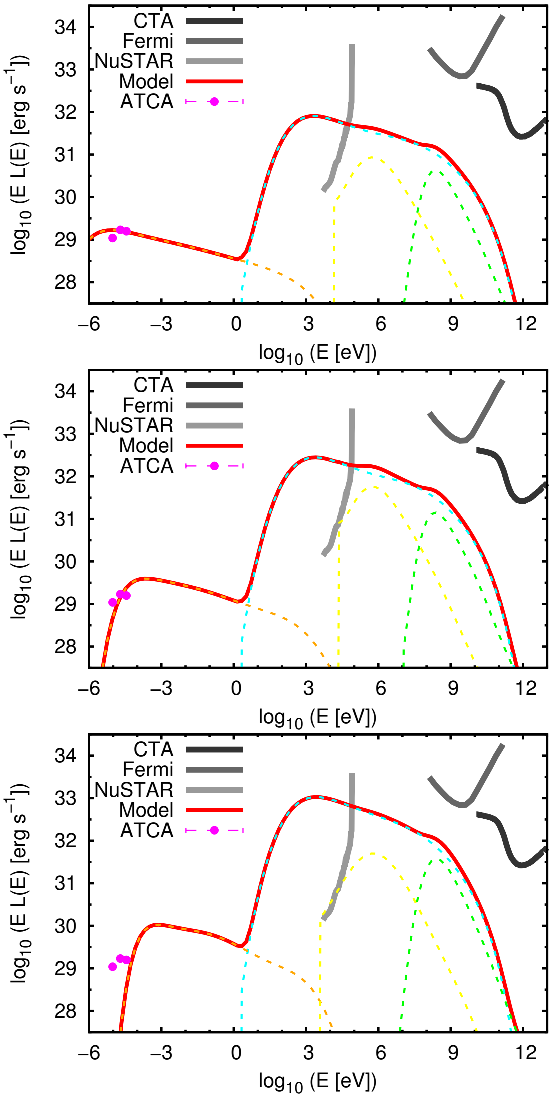

Figure 1: Broadband SEDs for the epoch of radio observations (top), roughly the present epoch (middle), and roughly the periastron passage (bottom). Dashed lines indicate contributions from synchrotron (orange), IC (cyan), relativistic Bremsstrahlung (yellow), and pp (green); the filled red curve is the total emission. We show instrument sensitivity curves for 1-Ms *NuSTAR* (grey), 4-yr *Fermi* (dark grey), and 50-h *CTA* (black).

3. Results

We apply the model described in Sec. 2. fixing the values of several parameters: system inclination $i = 10°$, fraction of injected energy that goes into NT particles equal to 0.3, electrons and protons in equipartition, wind momentum ratio $\eta = 0.5$, stellar mass-loss rate of the primary derived from the radio observations ($\dot{M}_1 = 3 \times 10^{-5} M_\odot$ yr^{-1}, which is a factor ~ 5 larger than the one derived from X-rays), and a magnetic-field strength obtained from fixing $u_{\rm mag}/u_{\rm thermal} = 0.07$. Those parameters are selected in order both to reproduce the 2008 radio observations and also to maximize the possible HE outcome. We calculate the broadband SED for the epoch of observation, when the distance between the two stars was D, and repeat the calculations for closer distances, $D/3$ (roughly the present time), and $D/10$ (roughly the periastron passage). The different SEDs presented in Fig. 1 show that the flux at 2.3 GHz is getting fainter with time due to increased FFA (as photons have to travel through denser regions of the winds), whereas this effect is not so important at

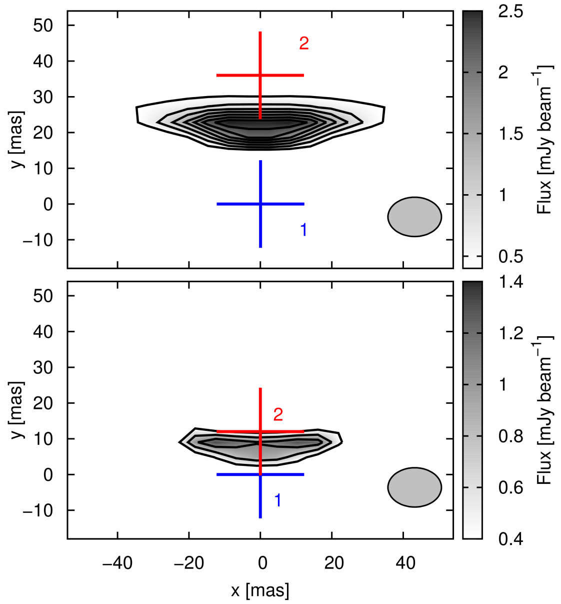

Figure 2: Synthetic radio maps at 2.3 GHz for a binary separation of the epoch of the radio observations (top), and for roughly the present epoch (bottom). The contours start at 0.4 mJy beam^{-1} and increase in 0.3 mJy beam^{-1}.

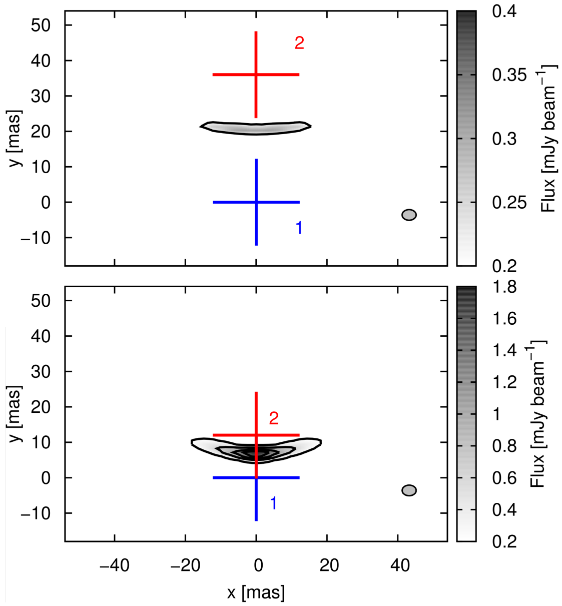

Figure 3: Same as Fig. 2 but at 8.6 GHz. The contours start at 0.2 mJy beam^{-1} and increase in 0.4 mJy beam^{-1}.

8.6 GHz unless the star separation has reached its minimum. The IC luminosity increases as the stars get closer due to the higher energy density of the stellar photon field.

All the information from the spatially resolved radio observations is only partially contained in the SED. Therefore we contrast the outcome of our model with the morphology present in the radio maps. For that purpose we produce synthetic radio maps at two frequencies, 2.3 GHz and 8.6 GHz, for the epoch of observation and the present epoch, shown in Figs. 2 and 3. We can appreciate that the size of the emitting region at 2.3 GHz is comparable to the one seen in the maps of Benaglia et al. (2015b). The maps also show that future observations at 8.6 GHz should be able to track the evolution of the WCR, as it is becoming brighter with time.

4. Conclusions

This work had two main purposes: the first was to show the link between radio- and HE-astronomy, in particular how radio data can be used to make predictions at HE using physical models; the second was to assess future observational campaigns of HD 93129A at radio and HE frequencies. Our model reproduced fairly well the radio observations, and it showed that it is possible to explain the low-energy cutoff in the SED by means of free-free absorption in the stellar winds. However, it required high stellar mass-loss rates (larger than the ones derived from X-rays observations), and a low inclination of the orbit (whereas the preliminary orbital fits favor high inclinations instead). Therefore, such scenario is in tension with the observational data. Another possible explanation for the low-energy cutoff in the SED is a corresponding low-energy cutoff in the electron energy distribution, which will be studied in a future work. Nevertheless, the results presented in this work provide a conclusive insight on how future observations of the system HD 93129A at 1–10 GHz radio frequencies can disentangle the nature of the radio absorption/suppression mechanism. Moreover, observations in the hard X-ray range (10-100 keV) would provide tighter constraints to the electron-to-proton ratio, the magnetic field strength, and the high-energy particle distribution. We predict that this source is not expected to be a strong γ-ray emitter, although it is possible that it will be detectable by *Fermi* and/or CTA during the periastron passage.

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References

Benaglia P., et al., 2015a, A&A, 579, A99
Benaglia P., et al., 2015b, A&A, 579, A99
Benaglia P., Romero G. E., 2003, A&A, 399, 1121
De Becker M., Raucq F., 2013, A&A, 558, A28
Eichler D., Usov V., 1993, ApJ, 402, 271
Maíz Apellániz J., et al., 2008, in RMAASC Vol. 33, The stellar upper mass limit in the solar neighborhood. p. 55
Pshirkov M. S., 2015, ArXiv e-prints
Reitberger K., et al., 2014, ApJ, 789, 87
Tavani M., et al., 2009, ApJL, 698, L142
Wright A. E., Barlow M. J., 1975, MNRAS, 170, 41