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Is the bowshock of the runaway massive star HD 195592 a *Fermi* source?

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ABSTRACT

Context. HD 195592 is an O-type super-giant star, known as a well-established runaway. Recently, a *Fermi* γ-ray source (2FGL J2030.7+4417) with a position compatible with that of HD 195592 has been reported.
Aims. Our goal is to explore the scenario where HD 195592 is the counterpart of the *Fermi* γ-ray source, modeling the non-thermal emission produced in the bowshock of the runaway star.
Methods. We calculated the spectral energy distribution of the radiation produced in the bowshock of HD 195592 and we compared it with *Fermi* observations of the 2FGL J2030.7+4417.
Results. We present relativistic particle losses and the resulting radiation of the bowshock of HD 195592 and show that the latter is compatible with the detected γ-ray emission.
Conclusions. We conclude that the *Fermi* source 2FGL J2030.7+4417 might be produced, under some energetic assumptions, by inverse Compton up-scattering of photons from the heated dust in the bowshock of the runaway star. Therefore, HD 195592 might be the very first object detected belonging to the category of γ-ray emitting runaway massive stars, whose existence has been recently predicted.

Key words. stars: early-type – gamma-rays: general – radiation mechanisms: non-thermal – stars individual: HD 195592

1. Introduction

The star HD 195592 (DB+43 3630) is a massive runaway visible from the northern hemisphere, located at a distance ~1.1 kpc (see Schilbach & Röser 2008). There is strong evidence supporting the hypothesis that HD 195592 is a binary system, with a period of about five days (De Becker et al. 2010) and produces a clearly detected bowshock, as it moves supersonically through the interstellar medium (ISM) as reported by Noriega-Crespo et al. (1997).

Relativistic particles can be accelerated at strong shocks produced by the stellar wind of a massive runaway interacting with the ISM (i.e. bowshocks). These particles can yield non-thermal radiation (Benaglia et al. 2010; del Valle & Romero 2012). Recently, a *Fermi* source, 2FGL J2030.7+4417, that might be associated with HD 195592, has been reported in the *Fermi* Large Area Telescope Second Source Catalog (Nolan et al. 2012, see Fig. 1). In this paper, we apply the model developed by del Valle & Romero (2012) for the non-thermal emission that takes place in the bowshocks of runaway stars to HD 195592. We then compare our theoretical spectral energy distribution (SED) with the measured flux of the *Fermi* source in order to explore the possibility of a physical association of the bowshock associated with HD 195592 (see Peri et al. 2012) with 2FGL J2030.7+4417.

In Sect. 2, we make a census of the relevant information related to HD 195592 with emphasis on previous observational results in different wavebands. Next, in Sect. 3, we discuss the computation of the non-thermal emission and present the best-fit to the 2FGL J2030.7+4417 source. A brief discussion and our conclusions are given in Sect. 4.

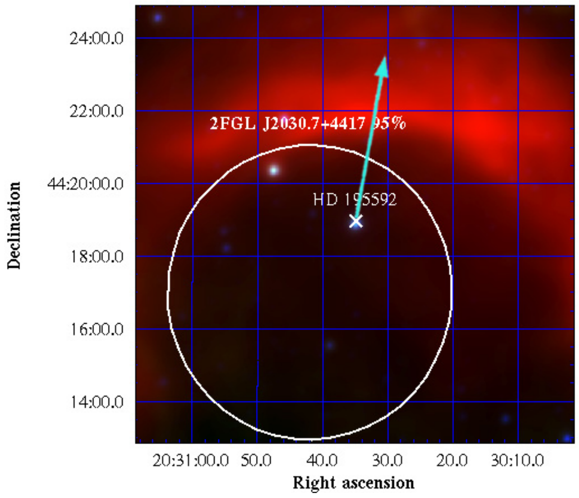

Fig. 1. Wide-field Infrared Survey Explorer (WISE) RGB image at bands W2 (4.6 μm), W3 (12 μm), and W4 (22 μm) of the shocked gas around the runaway star HD 195592; the radiative heating of the swept-up dust produces the IR emission and traces the bowshock. The 95% location-error circle of the gamma-ray source 2FGL J2030.7+4417 is shown (the 99% countour is outside the figure). The probability contours from gamma-ray sources are model-dependent and they must be taken as indicative only.

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2. The stellar system HD 195592

The star HD 195592 is an O9.5Ia-type runaway star that is thought to originate in the open cluster NGC 6913 (Schilbach & Röser 2008). A detailed spectroscopic study revealed that HD 195592 is a binary system with a period of a few days, with a lower-mass early B-type companion (De Becker et al. 2010). Low-amplitude radial velocity variations were detected in every strong absorption line in the blue spectrum of HD 195592. The variations exhibit two time-scales: ~5.063 and ~20 days. The 5.063-day variation is thought to be the period of the binary system associated with HD 195592. For the second time scale, De Becker et al. (2010) give two possible explanations. It may be the signature of an additional star or it may be the signature of intrinsic variability related to the stellar rotation.

Previous radio observations with the Very Large Array (VLA) at 4.85, 8.45, and 14.95 GHz revealed thermal emission with flux densities of a fraction of mJy and a spectral index equal to 0.98 (Scuderi et al. 1998). Adopting a distance of 1.1 kpc (Schilbach & Röser 2008), the integrated radio luminosity in the centimeter-domain is estimated to be 4×10^{28} erg s^{-1}. It should be pointed out that the radio source reported by Scuderi et al. (1998) has an angular size of the order of a few arcseconds and must therefore be associated with the stellar system itself and not with the more extended bowshock. If the bowshock produces radio emission, its flux level should be lower than the thermal contribution from the stellar winds of the O9.5 and B components, since Scuderi et al. (1998) did not report any extended non-thermal emission.

In the soft X-ray domain HD 195592 was never the target of a dedicated observation; however, the survey for point sources in hard X-rays in the Cygnus region (including the position of HD 195592) performed by De Becker et al. (2007) with the INTEGRAL Soft Gamma-Ray Imager (ISGRI) instrument on-board the INTEGRAL satellite allowed the upper limits for undetected point sources to be derived. Even though the background level in hard X-rays is not uniform, depending notably on the vicinity of bright X-ray sources, one could consider upper limits derived in regions of similar background level to be fairly applicable to the position of HD 195592[1]. According to the flux upper-limit values determined by De Becker et al. (2007), and assuming once again a distance of 1.1 kpc, we estimate that our target should not be more luminous than about 7×10^{32} erg s^{-1}, 5×10^{33} erg s^{-1}, and 7×10^{33} erg s^{-1}, respectively, in the 20–60 keV, 60–100 keV, and 100–1000 keV energy bands.

Finally, it might be worth commenting briefly on the potential role of binarity in the production of non-thermal radiation. It is indeed well established that at least some colliding-wind binaries are able to accelerate particles up to relativistic energies and consequently to produce non-thermal radiation (Benaglia & Romero 2003; De Becker 2007; Benaglia 2010). However, the short orbital period in HD 195592 suggests that the stellar separation in the system would not allow relativistic electrons to reach Lorentz factors high enough to produce a significant γ-ray emission as detected by *Fermi*. The particle acceleration process would probably be greatly inhibited by the strong ultraviolet/visible radiation fields from both stars through inverse Compton (IC) scattering, preventing the colliding-winds to emit significantly in the *Fermi* bandpass. In this paper, we will therefore explore the scenario where the γ-rays come from the bowshock produced by the stellar wind interacting with the ISM.

Table 1. Parameters for HD 195592.

Parameter		Value
R_0	Standoff radius	1.73 pc
$\dot{M}_{\rm w}{}^{a}$	Wind mass loss rate	$3.3\times10^{-7}\ M_\odot$ yr^{-1}
α	Particle injection index	2
$V_{\rm w}{}^{a}$	Wind velocity	2.9×10^{8} cm s^{-1}
χ	Subequipartition factor	5×10^{-2}
B	Magnetic field	$\sim2\times10^{-6}$ G
$T_\star{}^{b}$	Star temperature	2.8×10^{4} K
$L_\star{}^{b}$	Star luminosity	$3.1\times10^{5}\ L_\odot$
$T_{\rm IR}$	Dust temperature	~40 K

Notes. $^{(a)}$ Values from Muijres et al. (2012). $^{(b)}$ Values from Martins et al. (2005).

3. Non-thermal emission calculation

For the calculation of the non-thermal radiation we follow the model recently developed by del Valle & Romero (2012). The values for the relevant parameters are given in Table 1.

The collision of the supersonic stellar wind with the interstellar medium produces two shocks (e.g. Wilkin 2000). Relativistic particles are accelerated at the reverse shock that propagates in the opposite direction of the motion of the star, inside the stellar wind. This shock is adiabatic and strong. The particle acceleration mechanism is diffusive first order shock acceleration (e.g. Bell 1978). The interactions of the locally injected relativistic particles with matter, radiation, and magnetic fields in the shocked wind produce non-thermal radiation by a variety of processes (del Valle & Romero 2012).

The acceleration region is assumed to be a small region near the bowshock apex, of scale length $\sim\Delta$, where $\Delta \sim M^{-2}R_0$. Here, M is the Mach number of the shocked wind and R_0 is the so-called standoff radius (e.g. Wilkin 1996). In the case of HD 195592, we adopt $R_0 \sim 1.73$ pc (Peri et al. 2012).

In order to roughly estimate the magnetic field in the flow, we assume that the magnetic energy density is in sub-equipartition with respect to the kinetic energy $L_{\rm T}$ of the wind[2]. Therefore, we adopt the constraint $\chi < 1$. This means

$$\frac{B^2}{8\pi} = \frac{\chi L_{\rm T}}{V_{\rm w} A}, \tag{1}$$

where A is the area of a sphere of radius R_0 and $L_{\rm T}$ is the available power in the system (best fits are provided by $\chi \sim 5\times10^{-2}$).

The kinetic power of the stellar wind is

$$L_{\rm T} \sim \frac{1}{2}\dot{M}_{\rm w}V_{\rm w}^2. \tag{2}$$

For HD 195592, according to the best available data (Table 1), the kinetic power is about $L_{\rm T} \sim 10^{36}$ erg s^{-1}. Our estimate relies on the primary star parameters, even though we are dealing with a binary system. However, the contribution to the total kinetic power coming from the B-type component is expected to amount to only a small fraction of the power from the O super-giant, and would therefore not seriously affect our order of magnitude estimate.

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[1] The upper limits published by De Becker et al. (2007) were determined in a region located closer to the position of the bright X-ray source Cyg X-3 where the background level should be slightly higher than at the position of HD 195592. These values should therefore be considered as conservative. This does not affect their relevance in the context of this discussion.

[2] Otherwise the gas would be mechanically incompressible.

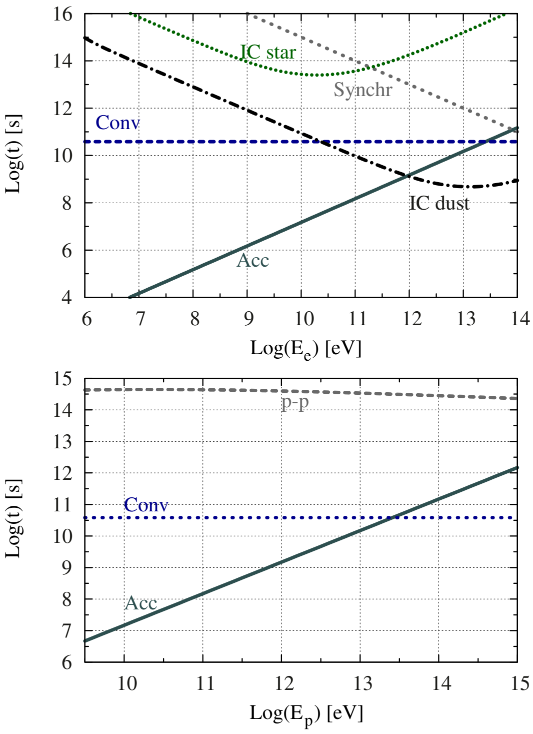

Fig. 2. Acceleration and cooling time scales for electrons and protons for HD 195592. The upper panel is for electrons and the lower panel is for protons.

The power available to accelerate particles in the reverse shock is $L = fL_{\rm T} \sim 2\times10^{34}$ erg s^{-1}, where f is the ratio of the volume of a sphere of radius R_0 and the volume of the acceleration region. Some fraction of this power goes into relativistic particles $L_{\rm rel} = q_{\rm rel}L$. The energetics of the γ-ray source requires $L_{\rm rel} \sim 4\times10^{33}$ erg s^{-1}, so $q_{\rm rel} \sim 0.2$, which seems to be a reasonable value if compared, with supernovae, for instance, which are expected to convert about 20% of their kinetic power into relativistic particles (e.g. Ginzburg & Syrovatskii 1964).

In the calculations of the SED we take into account both hadronic and leptonic content in the relativistic power, $L_{\rm rel} = L_{\rm p} + L_{\rm e}$. We consider $L_{\rm p} = L_{\rm e}$, which means equal efficiency in the acceleration of both types of particles.

A proton-dominated scenario seems to be unlikely in the case of HD 195592. Since the fraction of the relativistic proton energy that goes to neutral pions in each interaction is of ~17% (e.g. Aharonian & Atoyan 2000), in order to obtain the observed γ-ray luminosity, a very high effciency in converting kinetic energy into relativistic particles is necessary. This would require very extended, or perhaps even multiple, acceleration sites in the bowsock. For simplicity, we use the simplest hypothesis: equipartition beteween electrons and protons. This assumption, from the energetic point of view, is also the most conservative.

The electrons lose energy mainly by IC scattering, synchrotron radiation, and relativistic Bremsstrahlung. Protons lose energy through proton-proton inelastic collisions with the shocked wind material. The relativistic particles can escape from the acceleration region convected away by the stellar wind. These non-radiative losses impose the upper limit to the energy of protons. In Fig. 2 we show the cooling rates for both electrons and protons in the acceleration region. The IC scattering of IR photons completely dominates the radiative losses. Little power is radiated as synchrotron radiation, rendering the non-thermal radio and X-ray counterparts quite weak in comparison to the IC γ-ray source.

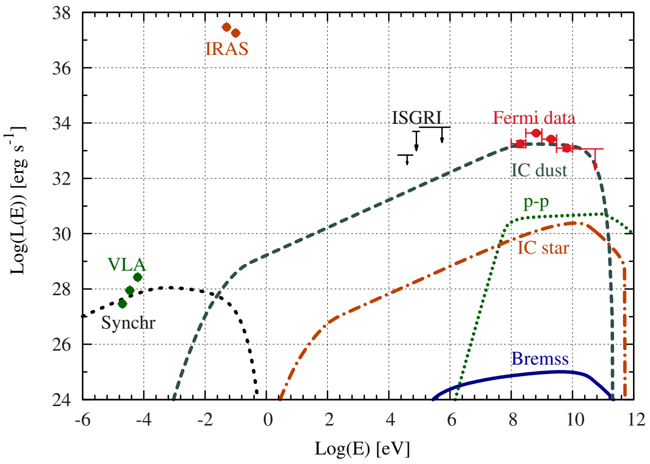

Fig. 3. Computed SED for HD 195592 bowshock at $d \sim 1.1$ kpc and *Fermi* data of 2FGL J2030.7+4417. The hard X-ray upper limits, thermal radio data (VLA) (Scuderi et al. 1998), and the IR-IRAS-emission (Van Buren et al. 1995) are also shown.

As can be seen from Fig. 2, the electrons reach energies of ~0.6 TeV while the protons can reach ~15 TeV. In both cases the Hillas criterion is satisfied, i.e. $E_{\rm max} < 300(\Delta/{\rm cm})(B/{\rm G})$ eV.

To determine the steady-state particle distributions for electrons and protons, we solved the transport equation in steady state (Ginzburg & Syrovatskii 1964). We refer to del Valle & Romero (2012) for the details of calculation. Although most protons are convected away before cooling (see Fig. 2) downstream instabilities can produce some mixing with external gas. We consider that a fraction $f_{\rm p}$ (~10%) of the convected protons interact downstream with the gas, and hence enhance proton-proton contribution. Even if all protons were to cool, the hadronic contribution would remain minor, except at energies above 1 TeV. At the energies of interest in this paper, both the emission from the shocked ISM and the absorption are negligible.

Figure 3 shows the computed SED for the emission produced at the bowshock of HD 195592. *Fermi* data are also shown along with data at other wavelengths. The IR emission from Infrared Astronomical Satellite (IRAS) is produced by the heated dust (Van Buren et al. 1995), as is the WISE emission. Only the γ-ray flux is non-thermal, while at other wavelengths the emission is mainly thermal. In the calculation we have taken into account only the wind of the primary star of the potential binary system, so our estimates can be considered energetically conservative.

The SED derived by our calculation lends support to the scenario where the γ-ray emission from 2FGL J2030.7+4417 could come from the bowshock produced by HD 195592. Our SED is also compatible with the lack of detection of any significant hard X-rays with INTEGRAL at the same position. In addition, the predicted synchrotron radio flux is too low to have been detected by previous radio investigations in the vicinity of HD 195592 where the thermal radio emission dominates.

4. Discussion and conclusions

Massive stars with strong winds have been suspected to be γ-ray sources since the early 1980s (Cassé & Paul 1980; Völk & Forman 1982; Chen & White 1991; White & Chen 1992). Despite some statistical evidence (Montmerle 1979; Romero et al. 1999), conclusive identifications remain elusive to this day. This is not surprising, taking into account the strong non-radiative losses experienced by relativistic particles in the stellar winds (Völk & Forman 1982) and the strong absorption expected close to the massive star (Romero et al. 2010). The best prospect, then, is the detection of high-energy photons wherever strong shocks can re-accelerate electrons and ions far from the star. This is the case of combined effects of massive stars in stellar associations (Torres et al. 2004) and colliding wind binaries (Eichler & Usov 1993; Benaglia & Romero 2003; De Becker 2007). Recent detections of Westerlund 2 (Aharonian et al. 2007) and Eta-Carina (Tavani et al. 2009; Abdo et al. 2010) at TeV and GeV γ rays, respectively, seem to support this picture.

Runaway massive stars offer a unique opportunity to detect GeV-TeV emission from single massive stars. The stagnation point of the wind of these stars is located at sufficient distance to preclude, under the adequate viewing angles, significant γ-ray absorption. The recent detection of non-thermal radio emission from the bowshock of BD +43°3654 by Benaglia et al. (2010) and the non-thermal X-ray emission reported recently from AE Aurigae López-Santiago et al. (2012) confirms the ability of some of these stars to accelerate at least electrons to relativistic energies. The presence of rich infrared photon fields locally generated by the heated dust swept by the shocks guarantees suitable targets for IC interactions that might yield, in some cases, detectable γ-ray fluxes.

The star HD 195592 presents some characteristics (e.g. strong IR field, distant stagnation point caused by the relatively small stellar velocity in a dense medium, absence of any other source in the *Fermi* location error box) that makes it a good candidate for the very first γ-ray emitting bowshock runaway identified so far. A confirmation of the nature of this source would require deep X-ray observations to check whether there is a power-law spectrum as expected from our modeling. The star HD 195592 is therefore a good candidate for additional observations for instance, with ASTRO-H (JAXA – Japan Aerospace Exploration Agency – mission to be launched in 2014, Takahashi et al. 2010) to investigate non-thermal hard X-rays, and with Advanced CCD Imaging Spectrometer (ACIS) on the *Chandra* X-ray Observatory because of its low background and high spatial resolution necessary to spatially disentangle the soft thermal emission from the binary and the expected soft non-thermal X-rays from the bowshock.

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