Clumping in Hot Star Winds
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VHE gamma-rays from Westerlund 2 and implications for the inferred energetics

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The H.E.S.S. collaboration recently reported the discovery of VHE γ-ray emission coincident with the young stellar cluster Westerlund 2. This system is known to host a population of hot, massive stars, and, most particularly, the WR binary WR 20a. Particle acceleration to TeV energies in Westerlund 2 can be accomplished in several alternative scenarios, therefore we only discuss energetic constraints based on the total available kinetic energy in the system, the actual mass loss rates of respective cluster members, and implied gamma-ray production from processes such as inverse Compton scattering or neutral pion decay. From the inferred gamma-ray luminosity of the order of 10^{35}erg/s, implications for the efficiency of converting available kinetic energy into non-thermal radiation associated with stellar winds in the Westerlund 2 cluster are discussed under consideration of either the presence or absence of wind clumping.

1 The stellar cluster Westerlund 2 in the HII region RCW 49

The prominent giant HII region RCW 49 is characterized by still ongoing massive star formation (Whitney et al. 2004). The regions surrounding the central stellar cluster Westerlund 2 appear evacuated by stellar winds and radiation, and dust is distributed in fine filaments, knots, pillars, bubbles, and bow shocks throughout the rest of the HII complex (Churchwell et al. 2004, Conti & Crowther 2004). Radio continuum observations revealed two wind-blown shells in the core of RCW 49 (Whiteoak & Uchida 2004), surrounding the central region of Westerlund 2, and the prominent Wolf-Rayet star WR 20b. There is an ongoing controversy over the distance to Westerlund 2, and consequently about the association of WR 20a with Westerlund 2, as will be discussed later. The stellar cluster contains an extraordinary ensemble of hot and massive stars, at least a dozen early-type O-stars, and two remarkable WR stars. One of them, WR 20a was only recently established to be a binary (Rauw et al. 2004, Bonanos et al. 2004) by presenting solutions for a circular orbit with a period of 3.675, and 3.686 days, respectively. Based on the orbital period, the minimum masses were found to be $(83 \pm 5)\,\mathrm{M}_\odot$ and $(82 \pm 5)\,\mathrm{M}_\odot$ for the binary components (Rauw et al. (2005)). At that time, WR 20a was classified as the most massive of all confidently measured binary systems in our Galaxy. Synchrotron emission has not yet been detected from the WR 20a system, presumably because of free-free-absorption in the optically thick stellar winds along the line of sight. Although WR 20a has been detected in X-rays (Belloni & Mereghetti 1994), the non-thermal and thermal components of the X-ray emission remain currently indistinguishable. Detectable VHE gamma-radiation from the WR 20a binary system was only predicted in a pair cascade model (Bednarek 2005), although detailed modeling of the WR 20a system in other scenarios (e.g. as of Reimer et al. (2006) when produced either by optically-thin inverse Compton scattering of relativistic electrons with the dense photospheric stellar radiation fields in the wind-wind collision zone or in neutral pion decays, with the mesons produced by inelastic interactions of relativistic nucleons with the wind material) is still pending. In VHE γ-rays, photon-photon absorption would modulate (and diminish) the observable flux from a close binary system such as WR 20a.

2 H.E.S.S. observations towards Westerlund 2

The H.E.S.S. (High Energy Stereoscopic System) collaboration observed the Westerlund 2 region between March and July 2006, and obtained 14 h (12.9

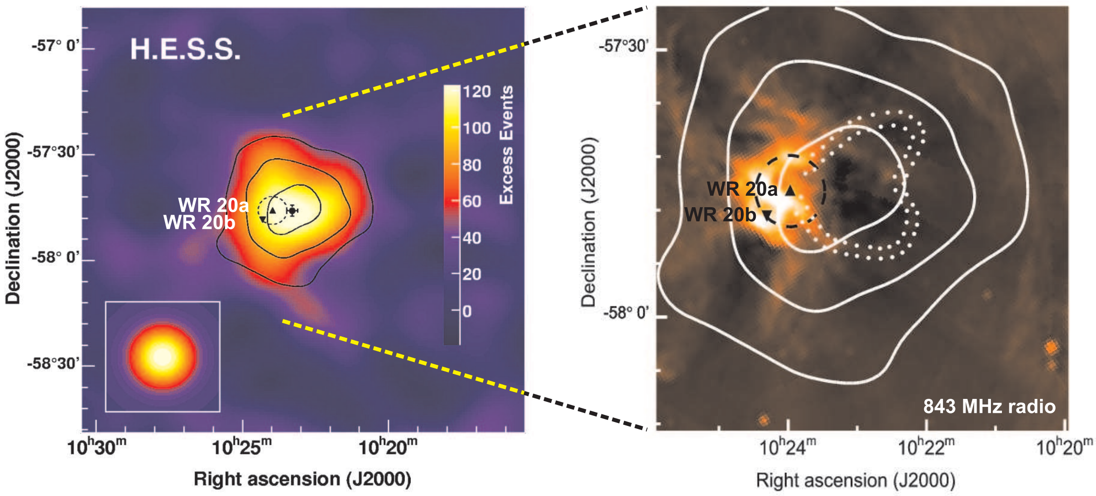

Figure 1: Left: H.E.S.S. gamma-ray sky map of the Westerlund 2 region, smoothed to reduce the effect of statistical fluctuations. The inlay in the lower left corner shows how a point-like source would have been seen by H.E.S.S. The WR stars WR 20a and WR 20b are marked as triangles, and the stellar cluster Westerlund 2 is represented by a dashed circle. Right: Significance contours of the gamma-ray source HESS J1023–575 (corresponding 5, 7 and 9σ), overlaid on a radio image from the Molonglo Observatory Synthesis Telescope. The wind-blown bubble around WR 20a, and the blister to the west of are seen as depressions in the radio continuum. The *blister* is indicated by white dots, and appears to be compatible in direction and location with HESS J1023–575.

h live time) of data, incorporating targeted observations of WR 20a and data from the ongoing H.E.S.S. Galactic plane survey. The data were obtained under zenith angles in the range between 36° and 53°, resulting in an energy threshold of 380 GeV for the analysis. A point source analysis on the nominal position of WR 20a resulted in a clear signal with a significance of 6.8σ, and further investigations revealed an *extended* excess with a peak significance exceeding 9σ. The center of the excess was derived by fitting the two-dimensional point spread function of the instrument folded with a Gaussian to the uncorrelated excess map: $\alpha_{2000} = 10^{\rm h}23^{\rm m}18^{\rm s} \pm 12^{\rm s}$, δ_{2000} = -57°45'50" ± 1'30". The systematic error in the source location is 20" in both coordinates. The source is clearly extended beyond the appearance of a point-like source for the H.E.S.S. instrument (Fig. 1), and a fit of a Gaussian folded with the PSF gives an rms extension of $0.18° \pm 0.02°$. The differential energy spectrum can be described by a power law $\mathrm{d}N/\mathrm{d}E = \Phi_0 \cdot (E/1\,\mathrm{TeV})^{-\Gamma}$ with a photon index of $\Gamma = 2.53 \pm 0.16_{\rm stat} \pm 0.1_{\rm syst}$ and a normalization at 1 TeV of $\Phi_0 = (4.50 \pm 0.56_{\rm stat} \pm 0.90_{\rm syst}) \times 10^{-12}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The integral flux for the whole excess above the energy threshold of 380 GeV is $(1.3 \pm 0.3) \times 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. No significant flux variability or the characteristic orbital periodicity of WR 20a could be detected in the data set. Full details regarding the discovery of HESS J1023–575 at VHE γ-rays are given in Aharonian et al. (2007).

3 Size constraints and energetics

The detection of extended VHE γ-ray emission towards Westerlund 2 is indicative of the presence of extreme high-energy particle acceleration in this young (~2-3 Myrs; Piatti et al. 1998) star forming region. Following the HEGRA detected source TeV J2032+4130 and its suggested connection to the Cygnus OB2 cluster (Aharonian et al. 2002), HESS J1023–575 and Westerlund 2 is the second but even more prominent association between VHE γ-ray emission and an extraordinary assembly of young, hot and massive stars in our Galaxy. Given that the size of the γ-ray emission does not resemble the nominal size of the stellar cluster as known from radio, infrared to optical, and X-ray energies very well, but stretches further out in the direction of the *blister* (Whiteoak & Uchida 2004), we discuss the implied energetics based on the most simple possible, and accordingly least model-dependent considerations. A central problem for any stringent energetic assessment lies in the still unsettled dispute on the distance to Westerlund 2, when even recent determinations differ apparently by more than a factor of 3 (see Fig. 2): The distance to

Westerlund 2 is uncertain in the range of values between ∼2.2 kpc (Brand & Blitz 1993) and 7.9 kpc (Moffat et al. 1991), and intermediate values of 4.2 kpc were derived from 21 cm absorption line profile measurements (McClure-Griffiths et al. 2001), 5.75 kpc from the distance estimate towards the prominent WR star WR 20a (van der Hucht 2001), and 6.4 kpc from photometric measurements (Carraro & Munari 2004). Recently, Rauw et al. (2007) presented a compelling re-determination of the distance to Westerlund 2 by spectro-photometric measurements of 12 cluster member O-type stars of (8.3±1.6) kpc, a value in very good agreement with the (8.0±1.0) kpc as measured by Rauw et al. (2005) as determined from the light curve of the eclipsing binary WR 20a. We adopt the value of the weighted mean of (8.0±1.4) kpc (Rauw et al. 2007) throughout this manuscript, thereby associating WR 20a as a cluster member of Westerlund 2. Note, however, that Ascenso et al. (2007) and Dame (2007) put forward significantly lower values.

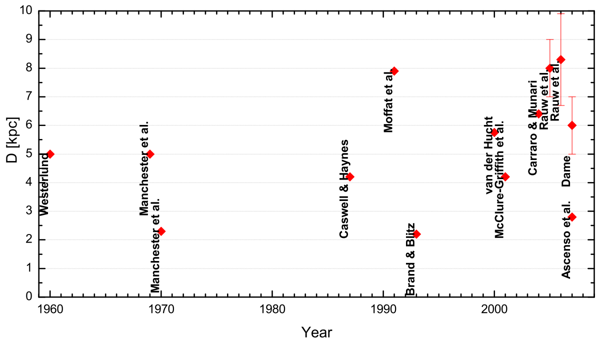

Figure 2: Distance measures for Westerlund 2 and/or WR 20a. The lasting distance ambiguity from different methodological approaches translates into the energetic constraints imposed by the detection of VHE γ-radiation.

With a projected angular size of submilliarcsecond scale, the WR 20a binary system, including its colliding wind zone, would appear as a point source for observations with the H.E.S.S. telescope array. At a distance of 8 kpc, the measured γ-ray source extension is equivalent to a diameter of 28 pc. Unless there are extreme differences in the spatial extent of the particle distributions producing radio, X-ray, and VHE γ-ray emission, scenarios based solely on particle acceleration in the colliding wind zone of WR 20a are unlikely to account for the observed source extent of 0.18° in the VHE γ-rays. Therefore the bulk of the γ-rays cannot energetized to TeV energies close to WR 20a. The apparent size of the VHE photons is however consistent with theoretical predictions of bubbles blown from massive stars into the ISM (Castor et al. 1975).

We estimated the γ-ray luminosity above 380 GeV to $\sim 1.5 \times 10^{35}$erg/s (at 8 kpc), corresponding to 0.2% (smooth wind: $\dot{M} = 2.5{\times}10^{-5} M_\odot/\mathrm{yr}$) or 0.7% (clumped wind: $\dot{M} = 8.5{\times}10^{-6} M_\odot/\mathrm{yr}$) of the total kinetic energy available from the colliding winds of WR 20a, and 0.2% (smooth wind: $\dot{M} = 5.3{\times}10^{-5} M_\odot/\mathrm{yr}$) or 0.7% (clumped wind: $\dot{M} = 1.7{\times}10^{-5} M_\odot/\mathrm{yr}$) of the kinetic energy of WR 20b, respectively. With up to 1.4% of the available E_{kin} in the WR-winds alone, a canonical value of 10% acceleration efficiency, the implied γ-ray production efficiency ($L_{\gamma,\mathrm{VHE}}/L_{\mathrm{particle}}$) is as high as 14% in case of clumped winds, or 4% for the less realistic case of smooth winds. These estimates, however, do not consider additional mass loss from other hot and massive stars present in Westerlund 2, which needs to be included when the H.E.S.S. result is interpreted in terms of collective stellar wind outflows. The energetic constraint is further relaxed when the distance to Westerlund 2 is indeed lower than the 8 kpc assumed, due to the accordingly higher integral γ-ray luminosity, and lower efficiency $L_{\gamma,\mathrm{VHE}}/L_{\mathrm{particle}}$.

In summary, the inferred γ-ray luminosity from the detection of VHE γ-ray emission from Westerlund 2 implies a rather high conversion efficiency when considering the mass loss rates for clumped winds from the two WR stars. This constraint can be relaxed if Westerlund 2 is indeed more closer than 8 kpc, as well as by considering mass loss transfer from the O- and B-stars in the stellar cluster.

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Gull: Models of superbubbles would suggest that the extended structure of Wd2/WR20a might be due to first generation stars that have contributed winds and ejecta. A good test would be a study of Constellation III in the LMC, where a core of remnant stars are surrounded by second generation stars not becoming SNe, see Brohweiler et al. and Kafatos et al.

Owocki: I am confused. You seem to imply that clumping and the implied mass loss rates would relieve the energetics problem of explaining observed TeV γ-ray luminosity, but would not the reduced wind kinetic energy make that problem worse?

O. Reimer: No, that is not what I was trying to say. I just thought that we have to invoke wind clumping in order to treat the energetics correctly. Clumped winds would imply less energy content from the particles whereas the γ-ray luminosity remains unchanged. If we back up to smooth wind, we would ease energetic constraints, but (to my understanding) at the expense of a more realistic description of the situation. Other factors come to play independently of the clumping problem: A lower distance to Wd2 will yield a lower γ-ray emissivity as the one I obtained for a distance of 8 kpc; if we consider not only WR20a – which itself may not account solely for the observed extended γ-ray emission – but also WR20b, and if the hot and massive stars in Wd2 will take their share, we can avoid a crisis concerning the γ-ray efficiency, which is thought to be comfortable only when it is below 10 %.

Romero: Is there any evidence for a high-energy cut-off in the HESS spectrum of Westerlund 2?

O. Reimer: Not on the basis of the HESS data taken so far. A single power law fit to the VHE spectrum is the preferred representation from a threshold energy of 380 GeV up to 20 TeV.

Moffat: Just for clarification: The stars in WR20a are not classical WR stars, rather they are close to solar-hydrogen, main-sequence stars well before any kind of Roche lobe overflow can occur. The strong winds are merely due to the extremely high luminosity of the stars.