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The non-thermal emission from colliding wind binaries

J.M. Pittard

School of Physics and Astronomy, The University of Leeds, Leeds, LS17 0HA, UK
e-mail: `jmp@ast.leeds.ac.uk`

Abstract. Binary systems containing two massive stars each with a strong wind create a region of high temperature plasma where the winds collide and at which particles can be accelerated to relativisitic energies. I briefly summarize the hydrodynamics of this collision, and recent observations of the non-thermal emission, including at γ-ray energies. I then discuss existing theoretical work on the non-thermal emission, and conclude with possible future developments.

Key words. shock waves – stars: binaries: general – stars: early-type – stars: mass loss – stars: winds, outflows – radio continuum: stars

1. Introduction

Massive stars of O-type or Wolf-Rayet (WR) type couple high mass-loss rates (of $\sim 10^{-7}$ to a few times 10^{-5} $M_{\odot}\,yr^{-1}$) with fast velocities (typically $\sim$ 1000 – 3000 $km\,s^{-1}$). Such winds are hypersonic, and their collision results in strong shocks either side of a wind-wind collision region (WCR), the position of which is determined by the momentum flux of the winds. The shocks convert the wind kinetic energy into thermal energy, resulting in postshock temperatures of $\sim 10^{7} - 10^{8}$ K. The large range in wind and binary properties means that, in turn, the properties of colliding wind systems can be very diverse (see e.g. Table 2 in Pittard et al. 2005).

In systems where the stars are close together (typically having orbital periods of a couple of days to a few tens of days, depending on the wind densities) the shocks are collisional and cooling of the postshock gas is significant. The WCR will also display a large degree of aberration and downstream curvature due to the strong coriolis forces. The radiation field of each star may also exert a powerful influence on the wind of the other star.

In contrast, systems where the orbital period is longer may have collisionless shocks. These are then naturals site for particle acceleration (see Pittard & Dougherty 2006, for a detailed review). The hot shocked gas may only cool adiabatically as it flows downstream, and orbital and radiation-field-induced effects on the dynamics and geometry of the WCR are also much smaller.

Particularly interesting are systems with (highly) eccentric orbits since the changing separation of the stars is useful as a probe of the physics which takes place. Colliding wind systems are also helpful as simpler, less complicated, analogues of the multiple wind-wind collisions which occur throughout the volume of clusters of massive stars.

Send offprint requests to: J.M. Pittard

The properties of the WCR are best studied using hydrodynamical codes. A noteable early study was made by Stevens, Blondin & Pollock (1992). This work was the first to self-consistently include cooling, and it focussed on the dynamical instabilities of, and X-ray emission from, the WCR. More recent works have examined particular aspects of the physics of such systems, including the influence of the companion star's radiation field (Stevens & Pollock 1994; Gayley et al. 1997), the effects of thermal conduction (Myasnikov & Zhekov 1998), electron-ion temperature non-equilibrium (Zhekov & Skinner 2000), and non-equilibrium ionization (Zhekov 2007). The effect of clumps within the stellar winds on a WCR near the radiative and adiabatic limits has been investigated by Walder (1998) and Pittard (2007), respectively. Three dimensional models are now allowing orbital effects to be explored (Lemaster et al. 2007; Okazaki et al. 2008; Parkin & Pittard 2008; Parkin et al. 2009).

The current state-of-the-art is a 3D model which includes gravitational and line-driving forces and cooling of the shocked plasma (Pittard 2009a). Fig. 1 displays cuts through the orbital plane of the density in 2 different systems, with identical stellar parameters, but with orbital periods of 3 days (left) and 10 days (right). In the shorter period system the winds collide (at 730 $\mathrm{km\,s^{-1}}$ between the stars) before they have had much opportunity to accelerate, and the WCR is highly radiative. Moreover, there is considerable inhibition of the winds' acceleration caused by the oppositely directed radiation field of the companion star. In contrast, when the orbital period is increased to 10 days there is more room for the winds to accelerate and radiative inhibition is reduced, leading to much higher pre-shock speeds (1630 $\mathrm{km\,s^{-1}}$ between the stars). This results in significantly higher (lower) post-shock temperatures (densities), and a largely adiabatic WCR. The aberration and downstream curvature of the WCR due to coriolis forces are also lessened due to the higher wind speeds and reduced orbital velocities.

2. Particle acceleration in colliding wind binaries

Direct evidence for non-thermal emission from a colliding wind binary was presented by Williams et al. (1997). Radio images overlaid on UKIRT shift-and-add IR images of WR 147 revealed that when the southern (thermal) radio source was aligned with the southern (WR) star, the northern (non-thermal) radio source was found to lie just south of the northern (O) star, in a position consistent with the point of ram-pressure balance between the winds. Clearly the WCR contains both a population of non-thermal electrons and a significant magnetic field. Further support for this picture has been provided by direct imaging of the WCR in WR 146 and WR 140 (Dougherty, Williams & Pollacco 2000; Dougherty et al. 2005).

The non-thermal radio emission from the WCR escapes easily from WR 146 and WR 147, which are both very wide and likely have orbits with periods of thousands of years, but has a much harder job escaping from WR 140, due to its much tighter, highly eccentric, orbit of 7.94 yr period where the stellar separation varies between $\approx 1.5 - 28$ AU. The radio emission shows dramatic, phase-repeatable, modulations, at least part of which can be expected to be caused by variable circumstellar extinction to the source of the non-thermal emission as the O star orbits in and out of the radio photosphere in the dense WR wind. Of course, there may also be changes in the intrinsic emission. More recently, this system has been imaged with the VLBA, yielding a full orbit definition, including, most importantly, the inclination of the system (Dougherty et al. 2005). While this study has helped to provide some of the best modelling constraints of any system, relatively little is known about the wind of the O star, and the wind momentum ratio of the system remains ill-constrained.

Whereas non-thermal emission is now detected from a significant population of CWBs (O+O systems, as well as WR+O's), there had until recently been many false dawns concerning the detection of γ-ray emis-

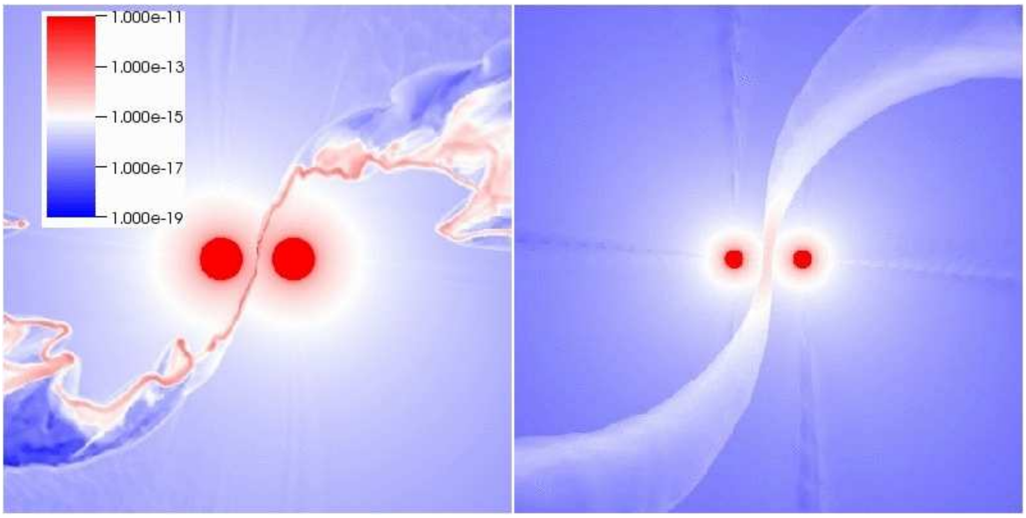

Fig. 1. The density distribution in the orbital plane of hydrodynamic models of the wind-wind collision in short period O6V+O6V binaries. Left: The orbital period is 3 days, the winds collide at relatively low speeds, and the WCR is highly radiative and is strongly distorted by the orbital motion of the stars. Right: The orbital period is increased to 10 days, the winds collide at higher speeds, and the WCR is largely adiabatic. In both panels the colour scale is logarithmic, spanning 10^{-19} g cm^{-3} (blue) to 10^{-11} g cm^{-3} (red). The left panel has sides of length 240 R$_\odot$, while the right panel has sides of length 570 R$_\odot$. Full details of these calculations, including 3D isosurface figures, can be found in Pittard (2009a).

sion from CWBs. However, in the last few years, definitive evidence for non-thermal X-ray and γ-ray emission from CWBs has finally been presented. The clear detection of MeV γ-ray emission from η Carinae with the INTEGRAL satellite was presented by Leyder, Walter & Rauw (2008). This followed an earlier claim of non-thermal emission with the BeppoSAX satellite (Viotti et al. 2004), though the new INTEGRAL observations have revealed that some of the emission is in fact from other nearby sources. Further reports of non-thermal emission from η Carinae come from a recent Suzaku observation (Sekiguchi et al. 2009). At GeV energies, η Carinae has been associated with an AGILE source (Tavani et al. 2009), and is on the FERMI bright source list (Abdo et al. 2009). Upper limits have also been placed on the MeV emission from WR 140, WR 146, and WR 147 (De Becker et al. 2007), while upper limits on the TeV emission from WR 146, and WR 147 have been reported by Aliu et al. (2008).

Many possibilities exist for the acceleration of non-thermal particles in CWBs. Typically it is assumed that diffusive shock acceleration (DSA) is the dominant process, though reconnection and turbulent processes are other possibilities. Each mechanism differs in its efficiency, and in the properties of the non-thermal particles which it produces, such as their spectral index. A detailed discussion of the many possibilities can be found in Pittard & Dougherty (2006).

3. Models of the non-thermal emission

3.1. Early models

The first models of the non-thermal radio emission from CWBs were very simple. The observed flux ($S_\nu^{\rm obs}$) was assumed to be a combination of the free-free flux from the spherically symmetric winds ($S_\nu^{\rm ff}$), plus the flux from a point-like non-thermal source located at the stagnation point of the winds ($S_\nu^{\rm nt}$), the latter being attenuated by free-free absorption (opacity $\tau_\nu^{\rm ff}$) through the surrounding winds:

$$S_\nu^{\rm obs} = S_\nu^{\rm ff} + S_\nu^{\rm nt}\,{\rm e}^{-\tau_\nu^{\rm ff}}. \qquad (1)$$

This approach allows simple solutions to the radiative transfer equation to be obtained (e.g. Williams et al. 1990; Chapman et al. 1999). Unsurprisingly, such simple models fail to reproduce the spectral variation of the emission with orbital phase. Williams et al. (1990) proposed that more complicated models should account for the low-opacity "hole" in the dense WR wind created by the O-star's wind. However, White & Becker (1995) pointed out that in the case of WR 140, even the O-star's wind has significant opacity. Together, these works demonstrated the need for more realistic models which account for the spatial extent of the emission and absorption from the circumbinary envelope and the WCR. More realistc models should also account for the effects of various cooling mechanisms (e.g. inverse Compton, adiabatic, etc.) on the non-thermal electron distribution, and also additional absorption mechanims (e.g. the Razin effect).

In many ways early models of the γ-ray emission were even more rudimentary. With no firm detections at γ-ray energies, theoreticians were reduced to estimating the inverse Compton (IC) luminosity, $L_{\rm ic}$, by the following simple formula:

$$L_{\rm ic} = \frac{U_{\rm ph}}{U_{\rm B}} L_{\rm sync}, \qquad (2)$$

where $L_{\rm sync}$ is the synchrotron luminosity, and $U_{\rm ph}$ and $U_{\rm B}$ are the photon and magnetic field energy densities, respectively. A major problem with this approach is that the predicted value of $L_{\rm ic}$ is highly sensitive to the assumed magnetic field ($B = \sqrt{8\pi U_{\rm B}}$). Varying B results in a wide range of predictions for $L_{\rm ic}$, as shown in Benaglia & Romero (2003). Even today, very few massive stars have had the strength of their magnetic field determined. And even when information on the strength of the surface magnetic field is available, one cannot necessarily extrapolate to obtain the magnetic field in the WCR, since there are the possibilities of large-scale magnetic reconnection within the WCR on the one hand, and magnetic field amplification by non-linear DSA on the other. A final problem is that *observed* rather than *intrinsic* values have been used for $L_{\rm sync}$ in the above formula. This may be of little consequence in the wider systems where the attenuation of non-thermal emission through the circumstellar envelope surrounding the stars may be negligible, but for a given set of parameters, $L_{\rm ic}$ could be underestimated in closer systems.

3.2. Recent developments

While there are many problems and uncertainties associated with the early modelling work of the non-thermal radio and γ-ray emission from CWBs, these simple models nevertheless paved the way for the more sophisticated modelling which has since followed, as now described.

3.2.1. Models of the radio emission

Major improvements in the modelling of the radio emission were undertaken by Dougherty et al. (2003), where the assumptions of a point-like source of non-thermal emission, and a spherically symmetric, single temperature, surrounding envelope, were removed. Instead, models of the thermal and non-thermal radio emission were based on 2D, axisymmetric, hydrodynamical simulations. This allowed a more accurate description of the density and temperature structure of the system, thus allowing sight-lines to the observer to pass through regions of both high and low opacity. The assumption of a point-source of non-thermal emission was also removed, though the emission was treated in a phenonmenological way. Accelerated electrons were assumed to be present within the WCR, with an energy density ($U_{\rm rel,e}$) proportional to the local thermal energy density ($U_{\rm th}$) i.e. $U_{\rm rel,e} = \zeta_{\rm rel,e} U_{\rm th}$. The magnetic field energy density was specified in a similar manner: $U_{\rm B} = \zeta_{\rm B} U_{\rm th}$. The non-thermal electrons were further assumed to have a power-law distribution, $N(\gamma)d\gamma = C\gamma^{-p}d\gamma$, where γ is the Lorentz factor, C is proportional to $\zeta_{\rm rel,e}$, and it was assumed that $p = 2$ (suitable for test particle DSA, with strong shocks and an adiabatic index equal to $5/3$).

Despite a number of further assumptions, this work nevertheless provided a great deal of new insight into the phenomenon of radio emission from colliding wind binaries. An immediate benefit was the realization of the potential importance of the Razin effect in attenuating the low frequency synchrotron emission within the WCR. Several key scaling relationships were also established. For instance, the total synchrotron emission from the entire WCR in adiabatic systems was found to scale as $D^{-1/2}\nu^{-1/2}$, where D is the separation of the stars (for comparison, the X-ray emission in the optically thin, adiabatic limit, scales as D^{-1}). This work also highlighted the importance of IC cooling, which was noted to be important even in wide systems. Indeed, the neglect of IC cooling of the non-thermal electrons in this model resulted in the overestimation of the high frequency synchrotron flux in a model of WR 147.

The IC cooling of the downstream non-thermal electron distribution was addressed in a follow-up paper (Pittard et al. 2006), where it was discovered that non-thermal electrons located near the contact discontinuity of the WCR suffer the greatest amount of IC cooling, thus leading to a dearth of emission (see Fig. 2). Not suprisingly, this improvement led to a significantly better fit between models and observations of WR 147. It also broke the previously identified relationship between the total synchrotron luminosity and the stellar separation noted by Dougherty et al. (2003). Instead, the *intrinsic* luminosity was now observed to *decline* with stellar separation as IC cooling became increasingly strong. The effect of the stellar separation on the *thermal* radio flux was also explored, and it was discovered that the *thermal* radio emission from the WCR scales as D^{-1}, in an identical way to the thermal X-ray emission. Pittard et al. (2006) pointed out that since this emission is optically thin in systems with an adiabatic WCR, it can mimic a synchrotron component, so that one should rather cautiously interpret data with a spectral index $-0.1 \lesssim \alpha \lesssim 0.5$. In shorter period systems with a radiative WCR, the thermal emission from the WCR is optically thick, and can dominate the total radio flux from the system, exceeding the combined flux from identically typed single stars by over an order of magnitude (Pittard 2009b).

3.2.2. Models of the non-thermal X-ray and γ-ray emission

In recent years there has been a revival of interest in non-thermal X-ray and γ-ray emission from colliding wind binaries, as the dramatic sensitivity gains achieved by space-based satellites and ground-based arrays of Cerenkov telescopes have raised the tantalizing prospect of the first detections. This, in turn, has led to new theoretical predictions. Amongst the first was a work by Bednarek (2005), who calculated the expected γ-ray emission from WR20a, a rare WR+WR binary. The short orbital period of this system means that the optical depth to electron-positron pair creation is high enough to initiate electromagnetic cascades. Particle acceleration by magnetic reconnection and DSA was considered, and it was concluded that detectable neutrino fluxes should be produced. Due to this system's high optical depth to TeV photons, it cannot be directly responsible for nearby TeV emission (Aharonian et al. 2007), which more likely is the result of acceleration processes within the collective wind of the nearby cluster Westerlund 2.

A two-zone model for the non-thermal emission was presented by Reimer, Pohl & Reimer (2006). In this model, particles are accelerated in an inner zone where their spatial diffusion exceeds their motion due to advection with the background fluid. Relevant gain and loss mechanisms are considered in the computation of their energy distribution. Particles leave this region once the timescale for their diffusion exceeds their advection timescale. The particles are then assumed to move into an outer advection region where they suffer further losses as they flow downstream.

The anisotropic nature of the IC process is considered in the calculation of the expected

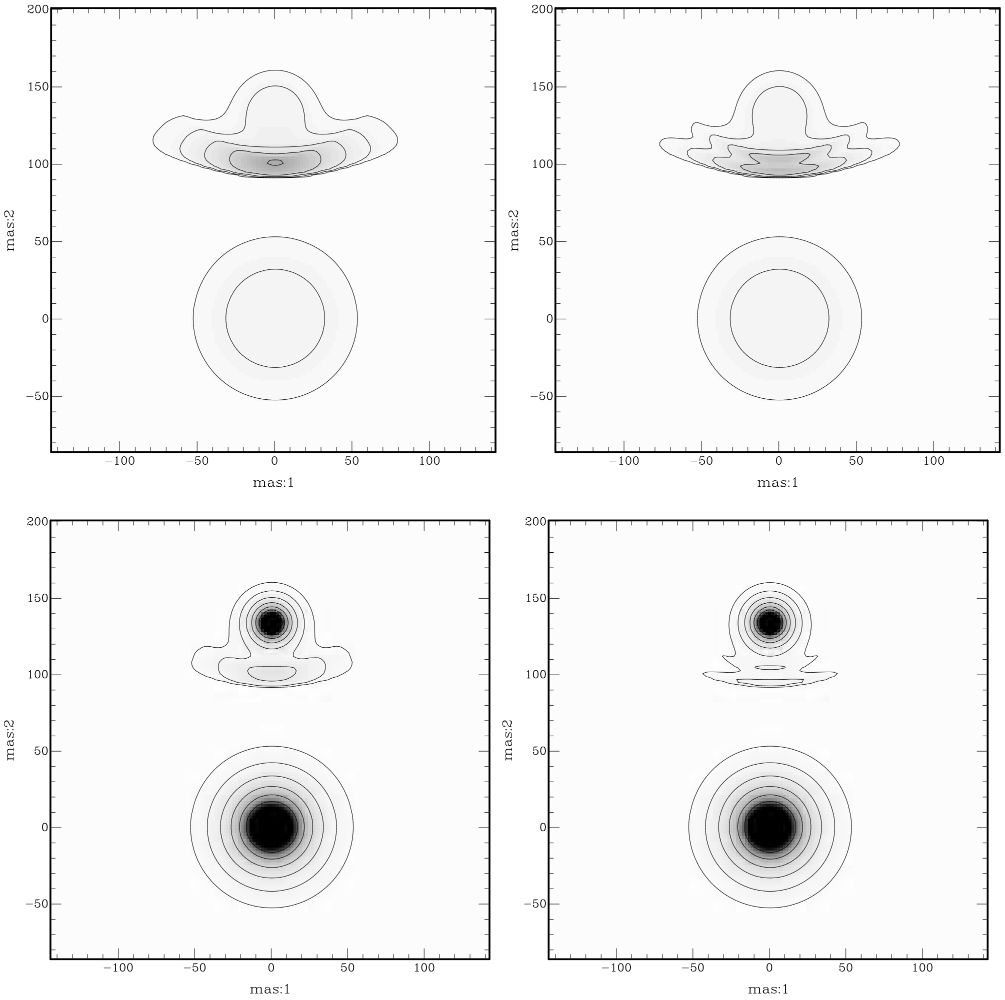

Fig. 2. The impact of IC cooling on the intensity distribution of a CWB model (see Pittard et al. 2006, for details), for a viewing angle of 0° and at 1.6 GHz (top) and 22 GHz (bottom). The images on the left do not include IC cooling, while those on the right do. Each image has the same intensity scale and contours.

flux, though the weaker of the two stellar radiation fields is ignored. Reimer et al. (2006) conclude that GLAST/Fermi should easily detect WR 140, though they expect that the large variation in the energy density of the stellar radiation fields resulting from the high orbital eccentricity is likely to obscure the effect of the change in the IC flux with viewing angle due to anisotropic scattering. In a more recent paper, Reimer & Reimer (2009) demonstrate that it is possible to constrain the orbital inclination of colliding wind systems through the property of their nonisotropic IC emission.

A complementary model of the X-ray and γ-ray emission from WR 140 was presented by Pittard & Dougherty (2006). This work built on the phenomenological model developed previously by Dougherty et al. (2003) and Pittard et al. (2006) to explore the non-thermal radio emission. Here the energy spectrum is assumed rather than calculated, but the model benefits from a more realistic description of the density and temperature distribution within the system. Fits to the thermal X-ray emission also place constraints on some of the key parameters (e.g. mass-loss rates). While an isotropic treatment of the IC emission is adopted, Pittard & Dougherty (2006) find that other uncertainities, such as the particle acceleration efficiency and the spectral index of their energy distribution (both of which unfortunately remain ill-constrained from fits to radio data), have at least as much influence on the predicted flux as the angle-dependence of the IC emission.

A spectral energy distribution from one of the WR 140 models presented in Pittard & Dougherty (2006) is shown in Fig. 3. The nature of the low frequency turndown in the radio spectrum (free-free absorption through the surrounding stellar winds, or the Razin effect) has a large influence on the predicted γ-ray emission. In addition, the index of the non-thermal electron energy distribution was ill-constrained, with a harder index (e.g. $p \approx 1.4$) required when the radio turndown was fitted through free-free absorption. Such indices can result from the shock re-acceleration process, whereby the non-thermal particles pass through a sequence of shocks (Pope & Melrose 1994), or from 2nd order Fermi acceleration. Either of these processes may be significant in CWBs, since the clumpy nature of the winds means that the WCR is likely to be highly turbulent, with weak shocks distributed throughout it (Pittard 2007). In contrast, a softer particle distribution ($p \approx 2$) could be obtained if the radio turndown was fitted through the Razin effect, though this approach required a worryingly high efficiency for electron acceleration.

The degeneracy which exists between the models in the radio is broken at MeV-TeV energies. Future γ-ray detections which determine the γ-ray flux and spectral index, will therefore also distinguish the nature of the low-frequency turndown, the acceleration efficiency of the non-thermal electrons, and the strength of the magnetic field. Fits to the radio spectra of WR 140 are continuing at other phases around its orbit. Preliminary results indicate that there is significant evolution of key parameters in the model (such as the acceleration efficiency and magnetic field).

4. Conclusions

Predictions for the non-thermal emission from CWBs, in both the radio and γ-ray domains, have improved in recent years as the underlying models have become more sophisticated. This progress is in turn being driven by corresponding advances on the observational front. In the past, investigations of the physics of high Mach number shocks and cosmic ray acceleration have concentrated on SNRs, because of their brightness and spatial information, which CWBs cannot match. Nevertheless, CWBs are important because they provide access to higher mass densities, radiation backgrounds, and magnetic field energy densities than found for supernova remnants, thus enabling studies in previously unexploited regimes. This fact, plus recent observational detections of non-thermal emission at hard X-ray and γ-ray energies from CWBs, has resulted in CWBs gaining popularity in the community. Future high energy observational prospects with Fermi and CTA, etc., look very good. An exciting future is also expected in the radio regime, with EVLA, e-Merlin, and SKA.

Future theoretical work should combine the best features of the different modelling efforts to date. For instance, adding a calculation of the non-thermal particle energy spectra and anisotropic IC to the hydrodynamical based models of Pittard & Dougherty (2006). A more distant goal would be to incorporate the effects of particle acceleration on the underlying thermal plasma, since DSA, when present, appears to be very efficient at placing energy into the non-thermal particle distribution.

5. DISCUSSION

MASAHIRO TSUJIMOTO: We observed η Car with Suzaku for the hard X-rays from 10 keV to 50 keV. The data were taken at two

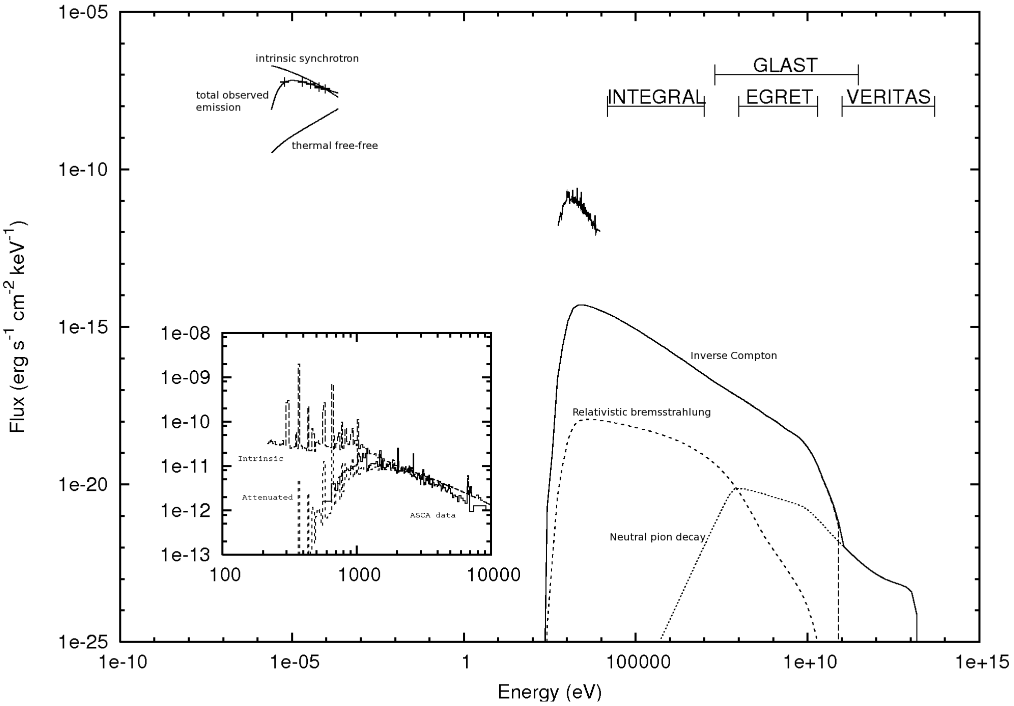

Fig. 3. The radio and non-thermal UV, X-ray and γ-ray emission calculated from model B in Pittard & Dougherty (2006), together with the observed radio and X-ray flux (both at orbital phase 0.837). The model IC (long dash), relativistic bremsstrahlung (short dash), and neutral pion decay (dotted) emission components are shown, along with the total emission (solid). See Pittard & Dougherty (2006) for more details.

apastron epochs. We could not discriminate between non-thermal and thermal models. So, for the hard X-rays from η Car I think the thermal interpretation still remains. Now, do you think that these two possibilities can be discriminated by a different behaviour at the eclipse?

JULIAN PITTARD: Non-thermal X-rays, if from inverse Compton scattering, will respond to the rapid change in angle of the observer relative to the stars, as well as the change in the separation between the stars. The hard thermal X-rays, on the other hand, are likely to be relatively insensitive to changes in the circumstellar absorption, and thus should instead only be influenced by the effect of the changing orbital separation on the thermal properties of the wind-wind collision region. So in principle one may expect to see different behaviour from thermal and non-thermal X-rays.

GIORA SHAVIV: How do you treat the shock when the wind is clumpy?

JULIAN PITTARD: So far we assume that the winds are smooth. If the winds are clumpy, the behaviour of the system will depend on the properties of the clumps. If they have a high density contrast with respect to the interclump material, and are large, individual clumps may penetrate completely through the wind-wind collision region and then suffer high ablation directly by the high speed companion wind. However, more typically I expect most clumps to be destroyed within the wind-wind collision region (Pittard 2007). The main effect then is to make the collision region highly turbulent, which may affect the non-thermal emission.

WOLFGANG KUNDT: Can you convince me that boosting charges to high energies ($E >> mv^2/2$) via colliding winds, at speed v, does not violate the second law? In application to η Car, I have argued that there is a neutron star in the (triple) system (alternative 11, in "Astrophysics, A New Approach", Springer, 2005).

JULIAN PITTARD: There is a huge amount of evidence for particle acceleration at shocks. With regard to η Car, a neutron star in this system would really mix things up!

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