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Non-thermal X-ray and Gamma-ray Emission from the Colliding Wind Binary WR140

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Abstract: WR 140 is the archetype long-period colliding wind binary (CWB) system, and is well known for dramatic variations in its synchrotron emission during its 7.9-yr, highly eccentric orbit. This emission is thought to arise from relativistic electrons accelerated at the global shocks bounding the wind-collision region (WCR). The presence of non-thermal electrons and ions should also give rise to X-ray and γ-ray emission from several separate mechanisms, including inverse-Compton cooling, relativistic bremsstrahlung, and pion decay. We describe new calculations of this emission and make some preliminary predictions for the new generation of gamma-ray observatories. We determine that WR 140 will likely require several Megaseconds of observation before detection with INTEGRAL, but should be a reasonably strong source for GLAST.

1 Introduction

CWB systems are an important laboratory for investigating the underlying physics of particle acceleration since they provide access to higher mass, radiation and magnetic field energy densities than in supernova remnants, which have been widely used for such work. High-resolution observations (e.g., Williams et al. 1997; Dougherty et al. 2000, 2005) show that the particle acceleration site is where the massive stellar winds collide - the WCR. In addition to synchrotron radio emission, these non-thermal particles should give rise to X-ray and γ-ray emission from several separate mechanisms, including inverse-Compton (IC) cooling, relativistic bremsstrahlung, and pion decay, though definitive evidence for such emission does not yet exist. The advent of new and forthcoming observatories (INTEGRAL, GLAST and VERITAS) will dramatically improve the chance of detecting these systems, and in this paper we make new predictions for the expected flux from WR 140.

Previous predictions of the IC emission have been based on the assumption that the ratio of the luminosity from IC scattering to the synchrotron luminosity is equal to the ratio of the photon energy density, $U_{\rm ph}$, to the magnetic field energy density, $U_{\rm B}$:

$$\frac{L_{\rm ic}}{L_{\rm sync}} = \frac{U_{\rm ph}}{U_{\rm B}}. \tag{1}$$

However, the use of this equation is rather unsatisfactory for a number of reasons. For example, $L_{\rm sync}$ is typically set to the *observed* synchrotron luminosity, whereas free-free absorption by

the extended wind envelopes can be significant (see Pittard et al. 2005). In such cases the intrinsic synchrotron luminosity, and thus the non-thermal X-ray and γ-ray luminosity, will be underestimated. The predictive power of Eq. 1 is also greatly undermined by the fact that the magnetic field strength in the WCR of CWB systems is generally not known with any certainty. Since $U_{\mathrm{B}} \propto B^2$, small changes in the estimated value of B can lead to large changes in L_{ic} (see Fig. 3 in Benaglia & Romero 2003).

A more robust estimate of the IC emission from CWB systems can be acquired from model fits to radio data, where the population and spatial distribution of non-thermal electrons is determined (see Dougherty et al. 2003 and Pittard et al. 2005). A key improvement in these papers over earlier modelling of the radio emission from CWB systems is the use of a hydrodynamical model to describe the stellar winds and WCR. The free-free emission and absorption coefficients are determined from the local temperature and density values on the hydrodynamic grid. Particle acceleration at the shocks bounding the WCR creates a population of non-thermal particles with a power-law energy distribution (i.e. $n(\gamma) \propto \gamma^{-p}$, where γ is the Lorentz factor) - as these advect downstream IC cooling modifies the energy distribution of non-thermal electrons. Since the population of non-thermal particles is not determined from first principles, their energy density is normalized to some fraction ($\zeta_{\mathrm{rel,e}}$ and $\zeta_{\mathrm{rel,i}}$ for the electrons and ions, respectively) of the thermal energy density (U_{th}) at the shocks. For the non-thermal electrons, IC cooling reduces this fraction below $\zeta_{\mathrm{rel,e}}$ in the downstream flow. Similarly, the magnetic field energy density is normalized by setting $U_{\mathrm{B}} = \zeta_{\mathrm{B}} U_{\mathrm{th}}$. When modelling specific systems, ζ_{B} and $\zeta_{\mathrm{rel,e}}$ are chosen to best match the observed radio emission. Predictions for the IC and relativistic bremsstrahlung emission then follow since these arise from the same non-thermal relativistic electrons which are responsible for the synchrotron radio emission.

2   The High Energy Non-Thermal Emission

In our current calculations we assume that IC scattering is isotropic and takes place in the Thomson regime. Since the average photon energy of an early-type star, $h\nu_* \sim 10$ eV, Lorentz factors of order $10 - 10^4$ are sufficient to produce IC X-ray and γ-ray radiation. The resulting emission has a spectral shape which is identical to the synchrotron emission at radio frequencies. Bremsstrahlung radiation at γ-ray energies is emitted from relativistic electrons since photons of comparable energy to that of the emitting particle can be produced. Finally, it is possible to obtain γ-ray emission from hadronic collisions involving non-thermal ions, through the decay of neutral pions, e.g., $p+p \rightarrow \pi^0 + X$, $\pi^0 \rightarrow \gamma + \gamma$. The pion decay process yields information on the population of non-thermal nucleons, in contrast to the IC and bremsstrahlung processes where the emission is dependent on the population of non-thermal electrons. We conservatively set the energy density ratio of non-thermal ions to electrons, $\zeta_{\mathrm{rel,i}}/\zeta_{\mathrm{rel,e}}$, to 20. Further background to the calculations can be found in Pittard & Dougherty (2006).

3   Models of WR 140

We apply our model to WR 140, the archetype of long-period CWB systems. It consists of a WC7 star and an O4-5 star in a highly elliptical orbit ($e \approx 0.88$), and in the context of the present paper is most noteable for its possible association with an EGRET source, lying on the outskirts of the positional error box of 3EG J2022+4317 (Romero et al. 1999). We adopt the orbital parameters and mass-loss rates determined by Dougherty et al. (2005), but allow the mass-loss rate of the O star (and thus the wind momentum ratio η) to vary, as this
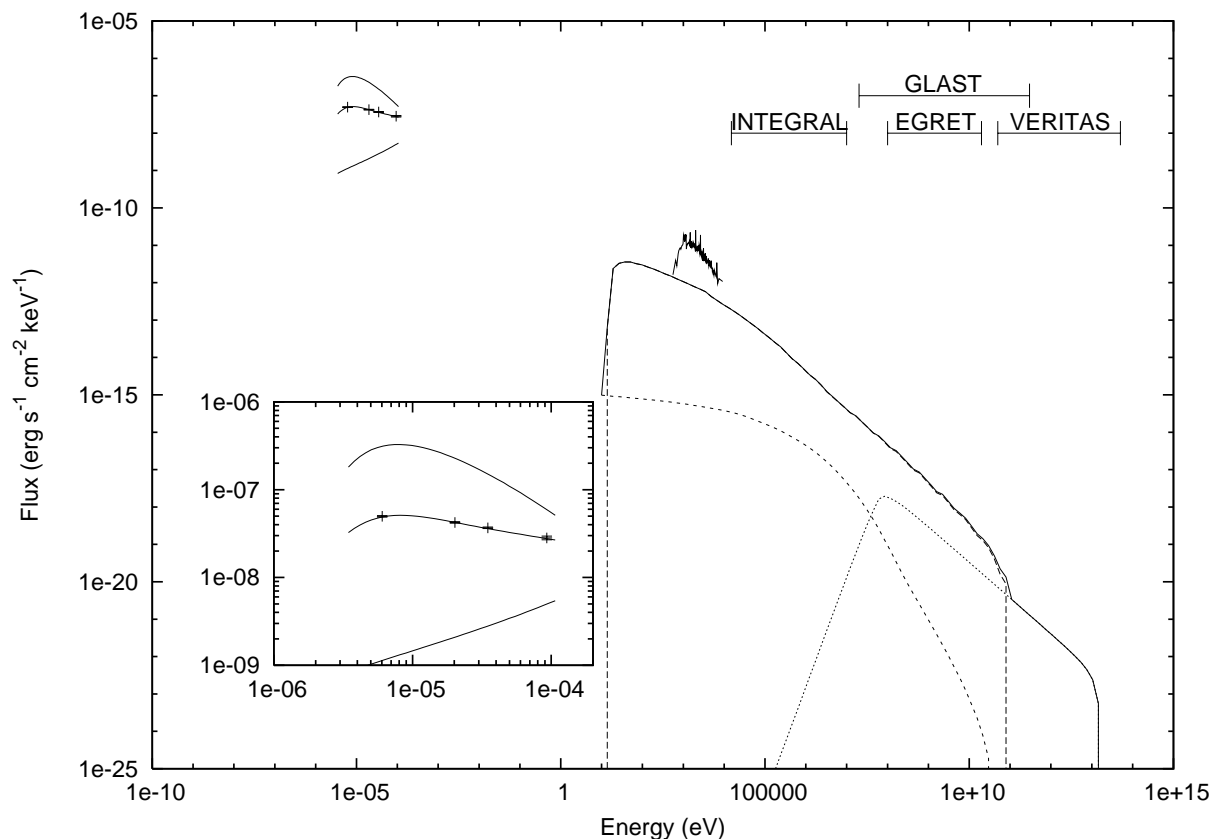
Figure 1: The radio, and non-thermal UV, X-ray and γ-ray emission calculated from our model of WR 140 at $\phi = 0.9$, together with the observed radio and X-ray flux. The model radio data that we show indicate the thermal free-free flux (displayed below the data points), the *intrinsic* synchrotron flux (displayed above the data points), and the total observed emission. This region is expanded in the inset. The IC (long dash), relativistic bremsstrahlung (short dash), and pion decay (dotted) emission are shown as separate components, and their sum is also displayed (solid). No absorption has been included in the calculation of the high-energy emission. We also show the observed X-ray spectrum obtained at $\phi = 0.84$ with *ASCA* (dataset 27022010, observed on 1999-10-22). It is reassuring that the IC flux predicted from our model is less than the observed X-ray flux.

parameter is not well determined. The system distance is assumed to be 1.85 kpc. Further details on the modelling can be found in Pittard & Dougherty (2006) and Dougherty et al. (these proceedings).

Given the wealth of observational data which now exists for WR 140, we have concentrated on obtaining a reasonable spectral fit to the radio data at a specific orbital phase, namely $\phi = 0.9$. Fig. 1 shows the resulting fit where it is clear that the intrinsic synchrotron emission suffers significant free-free absorption by the extended circumbinary envelope. A key point is that the large ratio between the intrinsic and observed synchrotron emission implies that the IC luminosity predicted using Eq. 1 will be substantially underestimated.

The high energy emission resulting from the radio fit is also shown in Fig. 1. The IC emission dominates for photon energies less than 50 GeV, while the emission from pion decay reaches energies up to 15 TeV. The relativistic bremsstrahlung emission is a minor contributor to the total non-thermal flux, and does not dominate at any energy. A gradual steepening of the IC spectrum occurs between $10^2 - 10^6$ eV. The lack of a clearly defined spectral break reflects the

fact that the break frequency is spatially dependent, and so is smoothed out once the flux is integerated over the entire WCR (Pittard et al. 2005).

The total photon flux in the 100 MeV - 20 GeV EGRET band from our model is 3×10^{-8} ph s^{-1} cm^{-2}, which is an order of magnitude below the flux detected from 3EG J2022+4317 during the December 1992 observation at $\phi = 0.97$. The different phases prevent a direct comparison, but we expect that the IC emission will increase between $\phi = 0.9 - 0.97$ as the stellar separation more than halves. Considering the limitations of the present model, this level of agreement is satisfactory. We predict a photon flux in the 15 keV-10 MeV sensitivity range of the IBIS instrument onboard INTEGRAL of 1.4×10^{-4} ph s^{-1} cm^{-2}, which is likely to require an exposure time greater than 3 Msec for a 5σ detection. The predicted 20 MeV-300 GeV photon flux is 1.4×10^{-7} ph s^{-1} cm^{-2}, and thus WR 140 should be fairly easily detected by GLAST. Our flux predictions are approximately 7 times lower than those made by Benaglia & Romero (2003) - this is partly due to the greater distance which we assume for WR 140.

4   Conclusions

We have presented predictions of the high energy non-thermal flux from WR 140. We find that a long observation will be required for detection of WR 140 with INTEGRAL, but it should be a reasonably strong source in the GLAST energy band. The current neglect of two-photon pair production prevents us from making predictions for the flux in the sensitivity range of VERITAS, a Cherenkov air shower telescope array. However, we expect that this absorption mechanism will significantly attenuate the emission in the TeV range and suggest that other CWB systems which are wider and less distant (e.g., WR 146 and WR 147) may be better targets at these energies. Improved high energy data will drive the development of theoretical models which include anisotropic IC emission and two-photon pair production, and will allow a much more detailed comparison between observations and predictions.

Acknowledgements

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