Stacked Analysis of Galactic Wolf-Rayet Stars

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Abstract

Wolf-Rayet (WR) stars are massive evolved stars undergoing advanced nuclear burning in their cores and possess strong stellar winds. WR stars – and in particular WR binary systems – are also predicted to be potential emitters of γ rays. Although details of the high-energy emission mechanisms are not well-understood, a majority of the emission is likely due to strong shocks produced by the colliding winds of WR binary systems. The shocked winds accelerate cosmic rays via diffusive shock acceleration, which subsequently produce X rays and γ rays through inverse Compton processes, as well as producing neutral pions that quickly decay into γ-ray photons. To date, only one WR system (WR11) has been detected in both X rays and γ rays, and typically the WR γ-ray emission is expected to be below the detection threshold of the Fermi-LAT. We conduct the first comprehensive analysis of the entire population of Galactic WR stars, including both isolated and binary systems. Since the γ-ray emission from any one of these systems is expected to be faint, we employ a stacking technique.

Wolf-Rayet Stars

Hot, Massive, Luminous

Figure 1: WR 136. In red is the nebula formed by shocks from the hot, fast WR winds.

- Hot: >20,000 K
- Massive: >25 Msolar
- Powerful: Mass Ejection: 10-5 - 10-6 Msolar Wind speeds: 1,000 - 2,500 km/s
- Identified by their broad line emission in He, C, N

Data Sample: Wolf-Rayet Catalog

- Our sample comes initially from the Wolf Rayet Catalogue[a] [1]
  - Galactic Wolf Rayets: Total size 667, last update Aug. 2020
  - Spectral type known for all WRs
  - Other info provided for some WRs includes distances, binary status, photometric magnitudes.
- $\sim$ 11 years Fermi-LAT data in the energy range 1-800 GeV
- Remove sources spatially coincident with known 4FGL-DR2 sources (50 total, half are unknown/unassociated)

[a]http://pacrowther.staff.shef.ac.uk/WRcat/

Wolf-Rayet Emission Mechanisms

Gamma-ray (γ-ray) emission can be produced in WRs through interactions of the powerful shocked winds with either the interstellar medium (ISM) or the winds of a companion in the case of binaries. These interactions produce π^0 that decay into γ-rays as well as $\pi^{\pm}$ that decay to leptons which can then produce γ rays through inverse Compton scattering [2, 3, 4, 5].

Single WR: The powerful shocked winds of the WRs interact with the ISM, producing γ-ray emission [5, 4]:

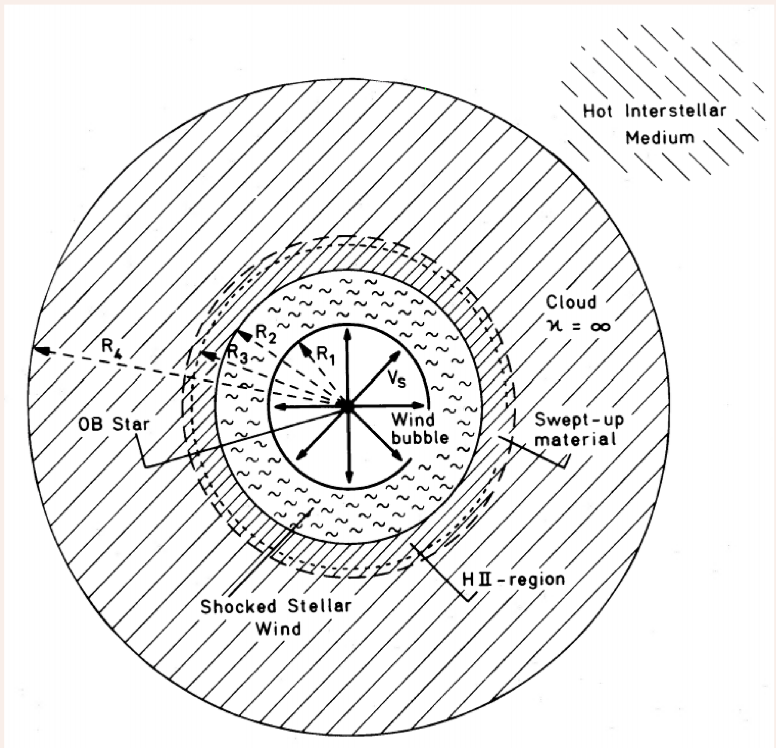

Figure 2: Diagram of the shocked wind-ISM interaction of a massive star from [6].

WR binaries: Many WR (estimates are about 30%-50%) of WRs are part of binary/multiple stars systems. For WRs as part of binary systems, the shocked winds of the WR+companion collide to produce γ-ray emission at the contact discontinuity [2, 3].

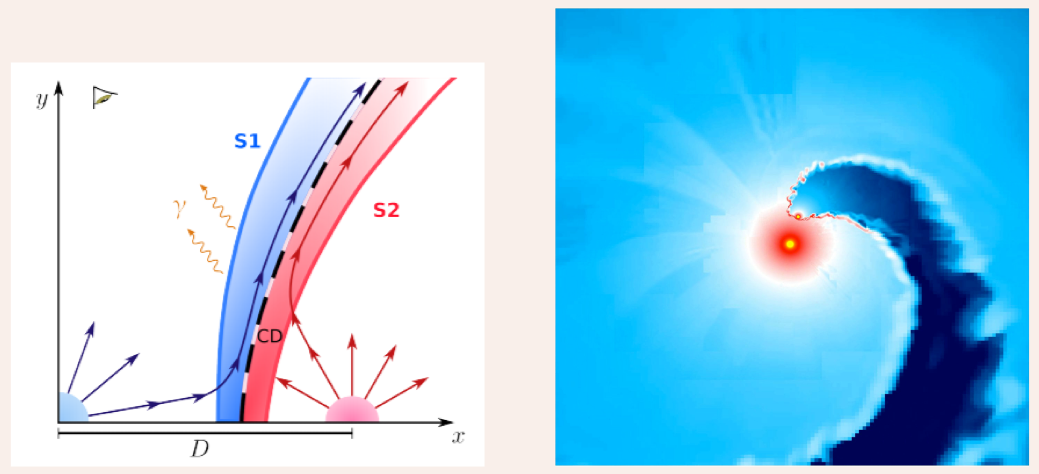

Figure 3: Left: Illustration of the wind collision in a colliding wind binary (CWB) system from [3]. Right: Snapshot of hydrodynamic simulation of the colliding winds of WR 22 (centered) and the companion O star from [7]

With few exceptions (see e.g. γ^2-Velorum [8]) the emission from WRs is expected to fall below the Fermi-LAT sensitivity threshold [5, 4]. This motivates the use of a stacking technique that allows us to characterize the average emission properties of the faint source population.

Preliminary Results

- We assume a power-law emission spectrum for each source and construct a 2-D test statistic ($TS = -2\log(L_0/L)$).
- The additive nature of the TS allows us to combine these profiles and characterize the average emission properties of the source population
- For our sample of WRs (excl. resolved sources) we find:
  Flux: 5.6×10^{-11} ph cm^{-2} s^{-1}
  Photon index: 2.5
  TS: 61.4

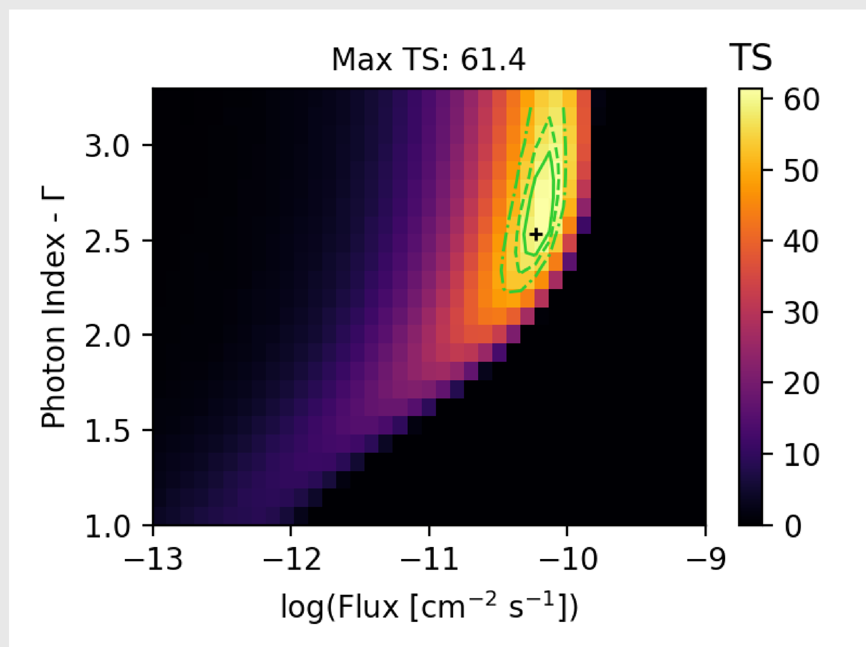

Figure 4: Bi-dimensional TS profile for the sample of unresolved WRs

The resulting energy flux ($\sim 3 \times 10^{-13}$ ergs cm^{-2} s^{-1}) is consistent CWB emission models (see e.g. [9] and [10])

Further Analysis

Theoretically Motivated Selections

Theoretical a priori selections of WR subsamples will allow us to better search for γ-ray emission and understand the relations between the emission and the WR properties. Some examples include:

- Single vs binary/multiple star systems
- Radio detected WRs
- Selections based on distance, wind speed, kinetic energy, etc.

Validation Tests

- To test the robustness of our method we perform our analysis on a representative distribution of fields in the Galactic plane where there are no WRs. A non-detection with this test sample indicates that we are effectively modelling the diffuse backgrounds.
- We also perform the analysis in Galactic star-forming regions where there are no known WRs, which will help us discriminate γ-ray contributions due to the WRs from that due to star-formation.

Conclusions

- The stacking analysis method will allow us to conduct a comprehensive search for faint emission from WR below the Fermi-LAT sensitivity.
- This will allow us to test and/or develop theoretical models of γ-ray emission from these sources.
- We will be able also to explore correlations with different WR properties (wind speed, mass, distance etc.) to better understand their relation to the emission mechanisms.

References

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