Gamma-ray Emission from Molecular Outflows

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Abstract

Many star-forming galaxies and those hosting active galactic nuclei (AGN) show evidence of massive outflows of material in a variety of phases including ionized, neutral atomic, and molecular outflows. Molecular outflows in particular have been the focus of recent interest as they may be responsible for removing gas from the galaxy, thereby suppressing star formation. As the material is ejected from the core of the galaxies, interactions of accelerated cosmic rays with the interstellar medium can produce high-energy gamma rays. However, the gamma-ray emission from these individual objects is expected to be below the threshold for LAT detection and has yet to be directly observed. In order to search for this faint gamma-ray signal we conduct a stacked analysis of a sample of molecular outflows in the nearby universe using 11 years of Fermi-LAT data and present preliminary evidence of a detection. Confirmed observations of gamma-ray emission from these sources can have significant implications for our understanding of AGN feedback mechanisms and the extragalactic gamma-ray background.

Molecular outflows: Detections and General Properties

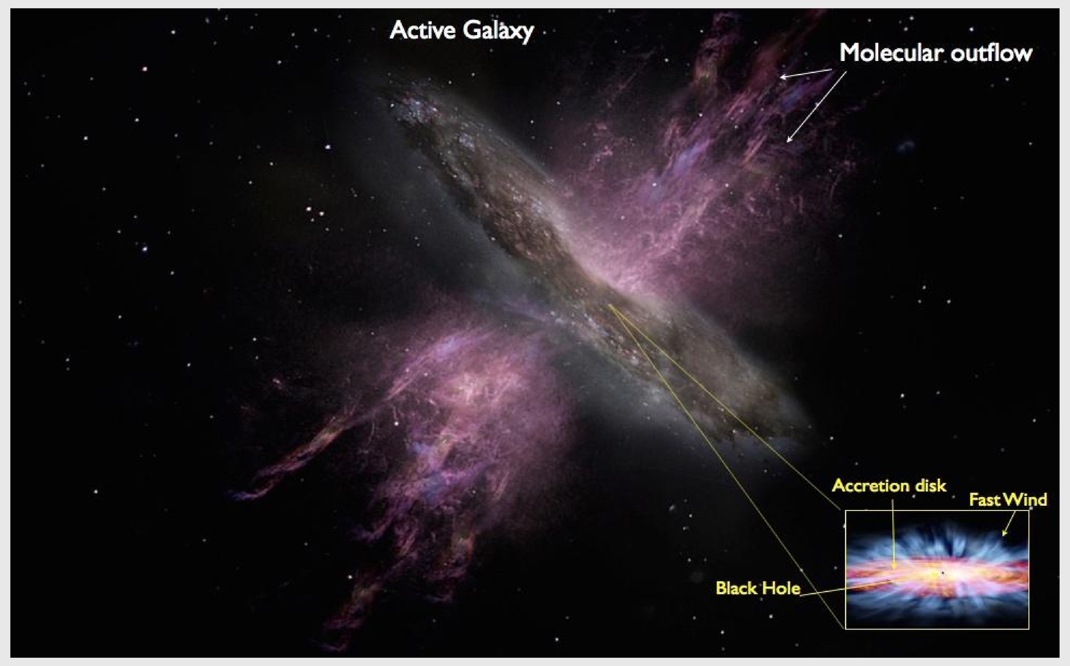

Figure 1: Artist representation of an active galaxy with a powerful molecular outflow. Photo Credit: ESA/ATG medialab/NASA/CXCandNahksTr'Ehn.

Typical Properties

Velocity: V_{out} 100 – 1000s km s^{-1}

Radius: R_{out} 0.1 – 10 kpc

Kinetic Power: $P_k \sim$ few % L_{AGN}

Observed redshifts: $z \sim 0 - 6$

Usually observed by CO emission lines (e.g. ALMA), but other approaches are used also (e.g. OH w/ Herschel).

Outflow Sample

- Original sample is of 45 Outflows from [1], collected from literature and archival ALMA data with $z < 0.2$.
- Remove those spatially coincident with known 4FGL-DR2 sources, blazars, or radio galaxies.
- Remove those with only upper limits on outflow detections.

Benchmark Sample: 29 Molecular Outflows

We use $\sim$ 11 years of Fermi-LAT data with energies in the range 1 – 800 GeV.

Gamma-ray Emission Mechanism

- The central wind (from AGN or star formation) is launched from the galactic nucleus and is shocked at the contact discontinuity [2, 3].
- The shocked wind is then driven into the ambient ISM [2, 3].
- Interaction of the outflowing material and the ISM can produce gamma rays through hadronic (π^0 decay) or leptonic processes [4, 5].
- In principle the outflow driving mechanism can be an energy or momentum conserving process depending on the radiative cooling time of the shocked wind [4].

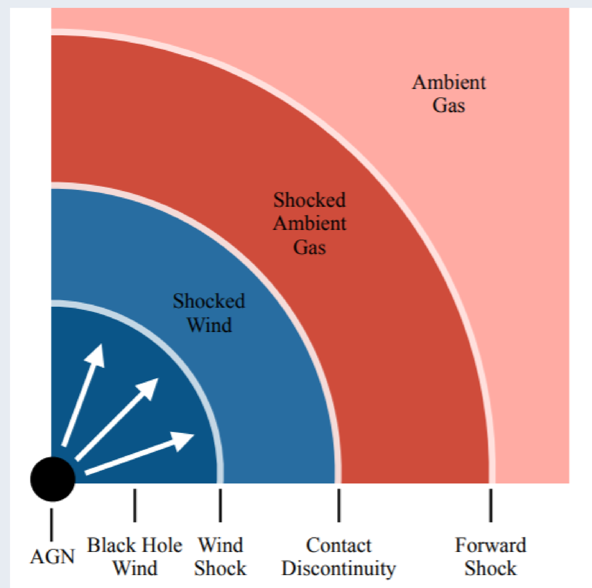

Figure 2: Schematic of an AGN wind, adapted from [2]. The wind is shocked at the wind shock and acts like a piston by driving out the ISM at the contact discontinuity.

Preliminary results

- Since the gamma-ray emission from molecular outflows is expected to be faint we make use of a stacked analysis by creating a two dimensional test statistic (TS) profile for each source and combining them.
- In the stacked analysis we assume a power-law spectrum in order to characterize the average emission properties of the source population.
- For our sample of 29 molecular outflows we find:
  Flux: 1.3×10^{-11} ph cm^{-2} s^{-1}
  Photon index: 1.96
  TS: 22.8.

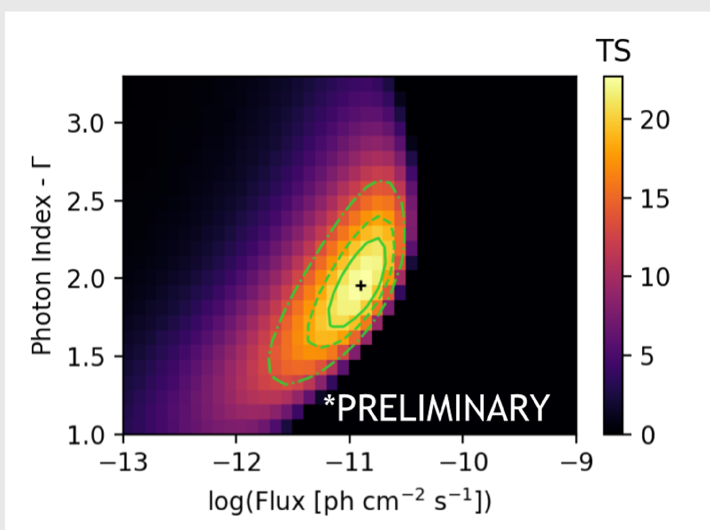

Figure 3: Bi-dimensional TS ($TS = -2\log(L_0/L)$) profile for the sample of 29 molecular outflows.

- To determine the origin of the putative signal we explore relations between the gamma-ray emission and various properties of the galaxy and outflow.
- The gamma-ray luminosity is correlated with the IR luminosity, however the relation for the molecular outflows deviates from the relation found for star-forming galaxies in [6].

$$\log\left(\frac{L_\gamma}{\mathrm{erg\,s^{-1}}}\right) = \beta + \alpha \log\left(\frac{L_{IR}}{10^{10}\,L_\odot}\right)$$

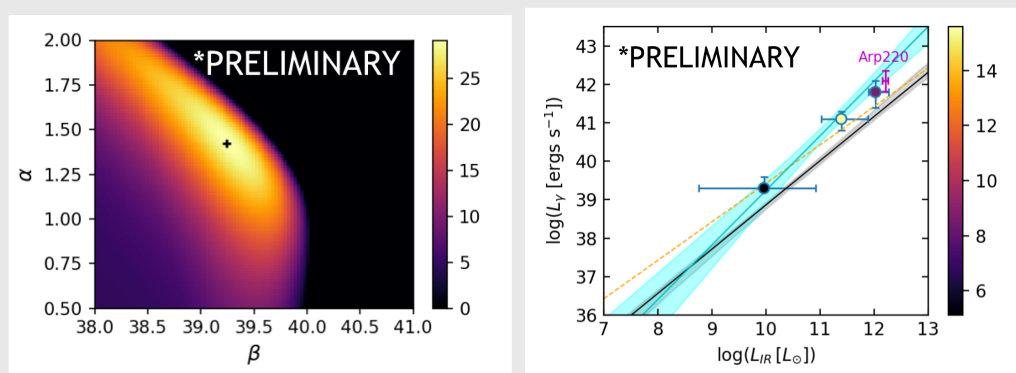

Figure 4: Left: TS profile in the $\alpha - \beta$ plane. Right: $L_\gamma - L_{IR}$ plot for the sample separated into bins of L_{IR}. Colorbar indicates the TS value for each of the three bins. The grey band shows the relation for star forming galaxies found in [6] and dashed orange line shows the calorimetric limit from [7].

Other parameters of interest include L_{AGN}, kinetic power, mass outflow rate, etc.

Control Sample

To verify the sensitivity of our method we compile a control sample of ALMA galaxies with no known molecular outflows and IR luminosities comparable to our benchmark sample.

This will allow us to i) verify that we do not produce a spurious signal in our stacking pipeline and ii) compare the emission properties found for the molecular outflows directly with the emission properties of known star-forming galaxies. We are currently in the process of performing the analysis on the control sample with results anticipated in the near future.

Conclusions

- Molecular outflows are expected to be gamma-ray emitters, however since the emission is predicted to be below the Fermi-LAT sensitivity we employ a stacking analysis.
- The TS for our full sample of 29 molecular outflows is 22.8, giving a $\sim 4.4\sigma$ detection.
- To discriminate the contribution to the gamma-ray emission of the outflow from that of star formation, we look for correlations with various outflow and host galaxy properties (e.g. L_{IR}, L_{AGN}, outflow rate, etc.).
- Comparison of our results with a control sample of galaxies without known molecular outflows will allow us to verify that we do not detect a spurious signal as well as helping to further discriminate from gamma-ray emission due to star-formation.

References

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