TOSCA - Topical Overview on Star Cluster Astrophysics

Monday, 28 October 2024 - Thursday, 31 October 2024

Siena, Santa Chiara Lab

Book of Abstracts

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Constraining the Diffusion Coefficient and Cosmic-Ray Acceleration Efficiency using Gamma-ray Emission from the Star-Forming Region RCW 38

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We report a detailed study of gamma-ray emission near the young Milky Way star cluster (0.5 Myr old) in the star-forming region RCW 38. Using 15 years of data from the Fermi-LAT, we find a significant (σ>22) detection coincident with the cluster, producing a total gamma-ray luminosity of L = (2.66±0.92) x 10^34 erg s^-1 adopting a power-law spectral model (Γ=2.34±0.04) in the 0.1-500 GeV band. Using an empirical relationship and Starburst99, we estimate the total wind power to be 7×10^36 erg s^−1. This corresponds to a CR acceleration efficiency of η_CR = 0.4 for a diffusion coefficient consistent with the local interstellar medium of D = 10^28 cm^2 s^−1. Alternatively, the gamma-ray luminosity could also account for a lower acceleration efficiency of 0.1 if the diffusion coefficient in the star-forming region is smaller D = 2.5 x 10^27 cm^2 s^−1. In addition, we perform a Chandra X-ray analysis of the region to compare the hot-gas pressure from the CR pressure and find the former is four orders of magnitude greater, suggesting that the CR pressure is not dynamically important relative to the stellar wind feedback. As RCW 38 is too young for supernovae to have occurred, the high CR acceleration efficiency in RCW 38 demonstrates that stellar winds may be an important source of Galactic cosmic rays.

Contributed posters - Flash Talks / 3

Gamma-ray signatures of particle acceleration at stellar wind termination shocks up to PeV energies

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Young massive stellar clusters have recently brought attention as PeVatrons candidates, to explain the knee of the cosmic ray spectrum and how protons can be accelerated to such energy scale in galactic sources. The new detector LHAASO is the first to probe well the photon detection band >0.1 PeV, that can correspond to multi-PeV hadronic cosmic rays. Thus, it enables the use of its gamma-ray data to constrain the galactic particle acceleration models and parameters, and to identify the contribution from the different categories of galactic accelerators to the observed cosmic ray flux, especially in the PeV domain.

To that extent, we model the escape and the transport of cosmic rays from their accelerator to molecular clouds, where a lot of p-p interactions producing gamma rays occur. We are focusing on the case where the source is a young massive star cluster, hence the particles are accelerated in stellar wind termination shocks before escaping. We try to determine in a semi-analytical approach the parameters needed (distance between cloud and source, time, slope of injection, number of stars, etc) to produce an excess in the gamma-ray flux corresponding to PeV cosmic rays, that could be

detectable by LHAASO. This enables to constrain the subspace of the parameter space for which a detectable excess could exist, and therefore constrains the subset of systems (cluster+cloud) that could produce such an excess. Then, the goal is to find such systems and compare predictions of the models for the gamma-ray flux to LHAASO data in order to determine more precisely different acceleration parameters, such as the wind termination shock efficiency or the injection spectrum in the interstellar medium. Another goal is to try to explain some of the dark PeVatrons seen by LHAASO with systems star cluster+cloud.

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A census of OB stars within 1 kpc and the star formation and core collapse supernova rates of the Milky Way

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O- and B-type stars constitute valuable tools across many areas of astronomy. They are significant sources of stellar feedback, through which they enrich the interstellar medium in new chemical elements, but also contribute to and hinder the emergence of future generations of stars. Being short-lived, they tend to remain near their birth environment, and thereby are vital tracers of the position and motion of the Milky Way spiral arms. Furthermore, they are crucial to study star formation and early evolution, as well as stellar multiplicity.

It is thus important to map out the distribution of OB stars across the Galaxy. Data from Gaia DR3 offers an opportunity to produce an updated census of their population. In this work, we have applied an improved, flexible SED fitting tool to identify and characterize OB stars in the solar neighborhood. With this tool we have identified about 25,000 O- and B-type stars (hotter than 10,000 K) within 1 kpc of the Sun, with a completeness of 90-95 % across all magnitudes. This list of OB stars typically include fainter stars non-included in similar catalogues, and reach higher completeness particularly in the solar neighborhood (< 300 pc).

Several overdensities on this map correspond to well-known regions such as Orion, Sco-Cen, Vela OB2, Cepheus and Circinus, hinting at the presence of OB associations and/or massive star clusters. These overdensities thereby constitute potential sources of stellar feedback, driving particle acceleration in the surrounding medium, and also future targets for detection of gravitational waves. Since we used our census of OB stars to provide a new estimation of the star formation and supernova rates within the local Milky Way, we have confirmed this by determining a rate of about 20 core-collapse supernova explosions per million year within 1 kpc.

Contributed posters - Flash Talks / 5

Protostellar Jets as Particle Accelerators. The case of HH 80-81.

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Massive stars are capable to accelerate particles due to their powerful winds ejected during the main sequence and post-main sequence evolutionary stages. However, recent studies on massive young stellar objects with *Fermi*-LAT have demonstrated that collimated jets, created by the protostars while they are still accreting mass, can produce a significant amount of accelerated particles even though during the pre-main sequence stages.

In this context, we have studied the particle acceleration in IRAS 18162-2048, a massive protostar with ~20 M⊙ that powers the longest collimated jet in our galaxy. The jet is located in a very dense environment, surrounded by a recently reported protostellar cluster with many medium and low-mass protostars. The main knots of the jet (HH 80, HH 81, and HH 80N) have been detected in radio and X-ray wavelengths, emitting non-thermal emission. In this work, we have associated a *Fermi*-LAT 4FGL source with the protostellar jet based on positional arguments.

The study of the high-energy spectrum of the source, spanning from 300 MeV to ~1 GeV, suggests a soft particle distribution consistent with diffusive shock acceleration. We test both leptonic and hadronic models, finding them consistent with the kinetic energy of the outflow jet. We also perform a morphological analysis, finding interesting correlations between the emission and the molecular clouds in the region.

In our poster, we will present the detection of gamma-ray emission originated by a protostar in a star-forming region. The proven capability of massive stellar objects for accelerating particles since their forming stages is an interesting starting point for analyzing cosmic ray production within massive star-forming clusters, as we expect many of these protostars in the densest regions of the active forming clusters.

Contributed posters - Flash Talks / 6

Isolated massive star candidates in nearby star forming galaxies

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The debate on whether star formation of massive stars always occurs clustered or could also happen in isolation is still open. Although small in numbers, massive stars strongly affect the environment around them: they can stop or trigger star formation, reshape the distribution of the gas around them and enrich the ISM due to supernova events or stellar winds. Thus, understanding how frequently high-mass stars can form in isolation in sparse density environments becomes extremely important. So far this has mostly been studied in only three Local Group galaxies: the Milky Way and the Magellanic Clouds. All three galaxies show a fraction of seemingly isolated massive stars that do not appear to be part of even very low-mass clusters nor can be explained as runaways or walkaways.
In order to shed light onto this open question, we are undertaking a systematic survey of other star-forming galaxies in the Local Volume to address this question with better statistics, using high-resolution photometry from two UV-optical Hubble Space Telescope legacy surveys, GULP and LEGUS. In this poster presentation, I will mainly focus on the spiral galaxy NGC 4242 and compare our findings to the Local Group.

Contributed posters - Flash Talks / 8

Creating a Hydrodynamic simulation of Cygnus OB2

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The Cygnus X star-forming region has been of great interest to the high-energy astrophysics community due to the diffuse gamma-ray emission detected by Fermi, HAWC and LHASSO in recent years. At the heart of this region lies the OB association Cygnus OB2, with tens of powerful O stars and 3 Wolf-Rayet stars. It has been argued that efficient stellar wind interactions in the vicinity of massive star clusters create favourable conditions for particle acceleration up to very high energies, which could potentially explain the observed diffuse gamma-ray emission in this region. However the core of Cygnus OB2 is rather extended, which puts into question the appropriateness of simplified spherical models and calls for a more detailed investigation of the wind-wind interaction given the peculiarity of the region.

In this poster, we describe a large-scale hydrodynamic simulation of a massive star cluster whose stellar population mimics that of the Cygnus OB2 association, as a collaborative project between research groups specialising in both particle acceleration theory and winds of massive stars. The main-sequence stars are first simulated during 1.6 Myr, until a quasi-stationary state is reached. At this time, the three Wolf-Rayet stars observed in Cygnus OB2 are added to the simulation, which continues to 2 Myr. Using a high-resolution grid in the centre of the domain, we can resolve the most massive stars individually, which allows us to probe the kinetic structures at small (parsec) scales. We find that, although the cluster excavates a spherical "superbubble"cavity, the stellar population is too loosely distributed to blow a large-scale cluster wind termination shock, and that collective effects from wind-wind interactions are much less efficient than usually assumed. This challenges our understanding of the ultra-high energy emission observed from the region. This work includes detailed treatment of the massive stellar population, incorporating Gaia astrometric data, empirically determined mass loss and terminal wind velocities for the most powerful stars, and stellar evolution. In this poster we will emphasise how these considerations directly affect results of interest to the high-energy astrophysics community.

Particle acceleration and propagation / 9

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X-rays from the Winds of Massive Stars

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Stellar Physics and the Chemical Enrichment of the ISM from Massive Stars

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