HONEST Workshops: Hot Topics in High Energy Astrophysics

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A spatially resolved study of hard X-ray emission in Kepler's SNR: indications of different regimes of particle acceleration

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Synchrotron X-ray emission in young supernova remnants (SNRs) is a powerful diagnostic tool to study the population of high energy electrons accelerated at the shock front.
We performed a spatially resolved spectral analysis of NuSTAR and XMM-Newton observations of the young Kepler's SNR, aiming to study in detail its non-thermal hard X-rays emission.
We selected a set of regions all around the rim of the shell and extracted the corresponding spectra.
The spectra were analyzed by adopting a model of synchrotron radiation in the loss-limited regime,

to constrain the dependence of the cutoff energy of the synchrotron radiation on the shock velocity. We identify two different regimes of particle acceleration, characterized by different Bohm factors. In the north, where the shock interacts with a dense circumstellar medium (CSM), we found a more efficient acceleration than in the south, where the shock velocity is higher and there are no signs of shock interaction with dense CSM.
Our results suggest an enhanced efficiency of the acceleration process in regions where the shock-CSM interaction generates an amplified and turbulent magnetic field.
By combining hard X-ray spectra with radio and $\gamma-$ray observations of Kepler's SNR, we modelled the spectral energy distribution. In the light of our results we propose that the observed $\gamma-$ray emission is mainly hadronic, and originates in the northern part of the shell.

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The supernova remnant SN 1006 as a Galactic particle accelerator

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The origin of cosmic-rays is an open issue of high-energy astrophysics. Supernova remnants are expected to be the main source of Galactic cosmic rays up to energies of about 3 PeV, provided that they transfer a significant fraction of their kinetic energy to the particles (~ 10%). In particular, the loss of such a large fraction of energy is predicted to alter the shock dynamics (shock modification) by enhancing the shock compression ratio above the canonical value of 4. The bilateral supernova remnant SN 1006 is an ideal target to study shock modification because of its evolution in a fairly uniform environment. SN 1006 shows bright synchrotron X-ray emission from ultrarelativistic electrons accelerated at the shock front in its northeastern and southwestern limbs. If efficient hadron acceleration occurs in these regions, we should observe shock modification therein. We performed a spatially resolved spectral analysis of Chandra and XMM-Newton observations of SN 1006 by selecting narrow regions between the shock front and the contact discontinuity and measuring the density of the X-ray emitting plasma. Our results show an increase of the compression ratio from the characteristic value of 4, in thermal limb, up to ~ 7 in nonthermal limbs, i.e. in regions where the ambient magnetic field is almost parallel to the shock velocity. We conclude that an efficient particle acceleration causes shock modification in quasi-parallel shocks in SN 1006. By comparing our results with state-of-the-art models, we find that SN 1006 is trasferring a significant fraction of its kinetic energy to hadrons. The inferred values of compression ratios and cosmic ray slopes are consistent with those expected for modified shocks which is affected by the effects of the postcursor.

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Origin of the very high energy gamma-ray emission from the Crab nebula

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LHAASO has detected gamma-ray emission from the Crab Nebula up to PeV energies. We show here that our recent model for electron acceleration at pulsar wind termination shocks can fit well both the inverse Compton and the synchrotron emission from the Nebula. Integrating individual particle trajectories in a model of the magnetic field and flow pattern near the shock, we find that drift motion on the shock surface maintains either electrons or positrons on Speiser orbits in a ring-shaped region close to the equatorial plane of the pulsar, where they are accelerated up to multi-PeV energies by the first-order Fermi mechanism. We calculate the inverse Compton emission from these electrons, and demonstrate that the observed > TeV gamma-ray emission from the Crab Nebula can be well reproduced for reasonable parameters of the Crab pulsar wind and turbulence levels in the nebula. Comparing to the LHAASO observations of the Crab Nebula, we can place novel constraints on parameters of the Crab pulsar wind that are still poorly known.

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A bright (near) future in the PeVatron era with the ASTRI Mini-Array

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Despite the enormous efforts done in very recent years, both theoretically and experimentally, the basic three questions about the Cosmic Ray (CR) origin remain without clear answers: what are their sources, how are they accelerated, how do they propagate?

Gamma-ray astronomy plays a fundamental role in this field. Both relativistic protons and electrons can emit in the gamma-ray band through different processes but only the detection of hadronic gamma-ray emission can probe CR acceleration. The recent results published by the LHAASO collaboration revealed the existence of several PeV sources. Most of them are likely related to pulsars, well known leptonic factories, and/or their nebulae, PWNe (e.g. the Crab Nebula for all), the only sources where we expect to see electrons accelerated up to PeV energies. Consequently, a gamma-ray detection at these energies still cannot be considered the final proof of hadronic acceleration. Furthermore, the limited angular resolution of LHAASO at TeV scale makes associations uncertain and, thus, more detailed and deeper studies are needed.

In this context, the ASTRI Mini-Array can play a fundamental role. The first three telescopes will be operative by fall 2023 and the full array of nine telescopes in 2025. With its unprecedented sensitivity and angular resolution in the multi-TeV band with respect to the existing IACTs, not only this instrument can extend the gamma-ray spectra of candidate PeVatrons but it can also help to distinguish whether the emission is actually connected with pulsars/PWN systems, shedding light on the nature of the highest energies emission.

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Cosmic and gamma rays from young supernovae

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Supernovae issued from massive star explosion produce collisionless shocks after the breakout. These shocks propagate in the dense circum-stellar wind of the progenitor star. The combination of a high density medium and shock speeds at a fraction of c make these places as potential sites of high energy cosmic ray acceleration because particles can self-drive an efficient magnetic field amplification. Under some favorable circumstances multi PeV cosmic ray energies can be reached within day timescales after the shock breakout. As Cosmic Rays propagate in dense medium they are prone to produce gamma-rays from nuclear interaction. These GeV-TeV gamma-rays if detected would be strong evidences these objects can be the missing Pevatrons. However, the gamma-ray signal detection is hampered by strong gamma-gamma absorption on soft photospheric photons within the first weeks after the explosion. A detailed time-dependent calculation is hence necessary to evaluate their detectability by the Cerenkov Telescope Array. This detectability as well as the multi-wavelength /-messager signatures of different classes of supernovae is the main object of this talk.

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Gamma-ray emission from young supernova remnants in dense environments

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Supernova remnants are known to accelerate cosmic rays from the detection of non-thermal emission of radio waves, X-rays, and gamma rays. The presence of cut-offs in the gamma-ray spectra of several young SNRs led to the idea that the highest energies might only be achieved during the very initial stages of a remnant's evolution. Unfortunately, the gamma-ray luminosity is assumed to peak in the first weeks after the Supernova explosion where strong γγ-absorption attenuates the observable signal. Here, we investigate to which extend the interaction of SNR-shocks with dense structures in the medium around luminous blue variable (LBV) stars can boost the gamma-ray emission months to years after the explosion.

We use the time-dependent acceleration code RATPaC to study the acceleration of cosmic rays in supernovae expanding into dense environments around massive stars. We performed spherically symmetric 1-D simulations in which we simultaneously solve the transport equations for cosmic rays, magnetic turbulence, and the hydrodynamical flow of the thermal plasma in the test-particle limit.

We investigated typical parameters of the circumstellar medium (CSM) in the freely expanding winds around LBV stars and added dense structures that arise from episodes of highly-enhanced mass-loss of the progenitors. The results are compared to calculation of smooth, unstructured winds.

We find that the interactions with the dense structures happens typically after a few months for LBV progenitors. During the interaction stage, the γγ-absorption by photons emitted from the Supernova's photosphere became negligible. The gamma-ray luminosity of the interacting SNRs can surpass the internal/unabsorbed peak-luminosity that arises shortly after the explosion. As a consequence, the observable flux can be considerably higher compared to the signal expected shortly after the explosion where γγ-absorption is important and where most gamma-ray observatories search for

transient signals from these Supernovae. Further, the change of the shock-speed during the shock-shell interaction boosts the achievable maximum energy beyond a PeV, where early interactions yield higher peak-energies.

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Supernova remnant/starformation scenarios: why it is necessary to separate the energy requirement for Galactic cosmic rays from the PeVatron requirement

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Supernova remnants (SNRs) have long been considered to be the dominant source of Galactic cosmic rays, which was then implied to mean that they provided most of the energy to power cosmic rays as well as that they are capable to accelerate protons up to the cosmic-ray knee. The lack of evidence for PeV cosmic rays inside SNRs, as well as theoretical considerations, has made this scenario untenable. At the same time the latest LHAASO and IACTs results suggest that PeVatrons lurk inside starforming regions. Here I will talk about why SNRs should still be considered the main scenario for the explanation of the energy in Galactic cosmic rays, but show that cosmic-ray data allows for a second component of energies between 10-1000 TeV. This second component could be a subset of supernovae/SNRs, re-acceleration inside star forming regions, or pulsars.

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Search for the Galactic accelerators of Cosmic-Rays up to the Knee with the Pevatron Test Statistic

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The recently introduced PeVatron Test Statistic (PTS) method in the framework of Cherenkov Telescope Array (CTA) PeVatrons study offers a new approach to detect spectral signatures of hadronic PeVatrons. The PTS is, for the first time, applied to PeVatron candidate sources' data from gamma-ray observatories to test for the origin of Cosmic Rays (CRs) at energies around and above the knee of the CR spectrum. Public data from gamma-ray observatories are analyzed jointly within hadronic emission models, assuming conservative systematic errors. It is outruled with a high statistical significance of more than 5σ that the two shell type Supernova remnants (SNRs) RX J1713.7−3946 and Vela Jr., as well as the gamma-ray source HESS J1745−290, which is spatially coincident with the dynamical center of the Galaxy, are PeVatrons. These results were previously derived by other means but the analyses confirm the performance and reliability of the PTS. Assuming that the gamma-ray emission from the region which contains the SNR G106.3+2.7 and the Boomerang nebula has a single component, a PeVatron hypothesis can be outruled with a statistical significance of more than 5σ. No statistically significant conclusion with respect to an association to a PeVatron is drawn for the diffuse gamma-ray emission around the Galactic Center (GC), and the two unidentified gamma-ray sources LHAASO J2108+5157 and HESS J1702−420A. However, it is argued that data from the Northern CTA and the Southern Wide-field Gamma-ray Observatory (SWGO) will respectively allow to decide whether these two sources are associated to a PeVatron or not. Based on the straw-man

design sensitivity for SWGO, the experiment is expected to have sufficient point source sensitivity to probe large parts of the relevant parameter space for PeVatrons after 5 years of observations.

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