The Origin of the Galactic Cosmic Radiation

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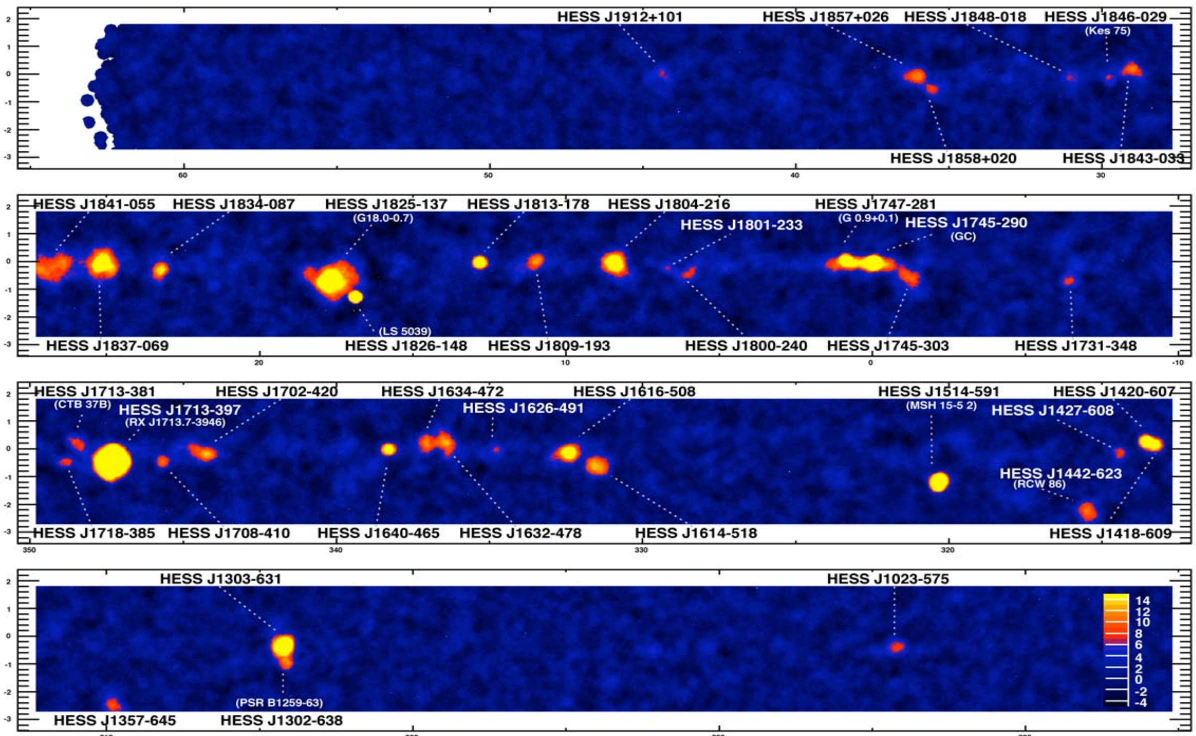

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The above figure shows the HESS TeV gamma-ray survey of the Galactic plane. Thirty-nine sources of TeV gamma rays are detected in the Galactic plane, including supernova remnants, pulsar wind nebulae, X-ray binary systems, molecular clouds, and unidentified sources. Credit the HESS collaboration.

Questions for the Next Decade

The key questions that we believe can be answered in the next decade are:

- What are the sources of the Galactic cosmic rays (from a few GeV to 10^{17} eV)?
- How do these Galactic accelerators work?
- What is the origin of the knee in the cosmic-ray spectrum?
- At what energy is the transition from Galactic to extragalactic cosmic rays?
- What is the source of the TeV excess in the Galactic diffuse emission?
- Is there a nearby (<10's of parsecs) source of cosmic rays?

In the following pages we discuss the current status and technological advances that are necessary to answer these questions.

Abstract

Traditionally, the study of cosmic ray origins has been through indirect methods – measuring the elemental and isotopic composition (where possible) as a function of energy at relatively low energies. In the past decade powerful direct techniques have been developed – imaging atmospheric Cherenkov telescopes and large field-of-view extensive air shower arrays, that have for the first time allowed us to detect and study the sources of high-energy particles. The technology now exists to build upon these recent successes and construct a new generation of instruments with roughly an order of magnitude improved sensitivity. We believe that the completion of these projects will allow us to answer this century old problem of the origin of the Galactic cosmic rays.

Introduction

The origin of the cosmic particle background has been a mystery since its discovery by Victor Hess in 1912. While Victor Hess solved one question: what is the origin of the ionizing radiation in the Earth's atmosphere? He left us with a much more difficult one: what is the origin of the non-thermal ionizing radiation that fills the Galaxy and the Universe? This radiation is composed of nuclei, from protons to uranium, electrons and positrons. While the cosmic-ray flux is low, the energy density in cosmic rays ($\sim$1 eV cm^{-3}) is comparable to that of starlight ($\sim$0.6 eV cm^{-3}) and Galactic magnetic fields ($\sim$0.2 eV cm^{-3}). Thus, cosmic rays are an energetically important component of the interstellar medium. Since they are charged particles they couple to the magnetic fields, generating turbulence in these fields. Thus, the cosmic rays play a role in generating the turbulence that drives their diffusion through the Galaxy.

The flux of hadronic cosmic rays as a function of energy has been measured from $\sim$1 GeV up to 10^{20} eV. The differential cosmic-ray spectral index is $\alpha = -2.7$ up to an energy of about 5×10^{15} eV (the knee) where it steepens to $\alpha = -3.1$. Near $10^{17.5}$eV there has been some evidence of spectral steepening (the 2^{nd} knee), and at roughly $10^{18.5}$ eV the spectrum becomes harder before undergoing a sharp suppression near 4×10^{19} eV[1, 2] (presumably due to interactions of the high-energy protons with the cosmic microwave background radiation [3, 4]). The nuclear composition of the cosmic radiation is a function of energy and has been directly measured up to about 100 TeV. At low energies the composition is predominantly light (protons) and gets heavier for energies approaching and surpassing the knee. At roughly 10^{17} eV the composition is consistent with a purely heavy composition (iron), but then undergoes a transition to a light (proton) composition between $10^{17.5}$eV and 10^{18}eV. The above suggests that there are at least two components to the observed cosmic rays: a Galactic component that dominates below $10^{17.5}$eV and an extragalactic component that dominates at higher energies. While the cause of the knee in the cosmic-ray spectrum is uncertain, several hypotheses have been proposed, from an increase in the diffusive losses from the Galaxy to the existence of a second class of Galactic cosmic-ray accelerator, to the transition to extragalactic cosmic-ray sources.

For many years it has been noted that the energy loss rate of cosmic rays, 10^{41} ergs s^{-1}, is roughly 10% of the kinetic energy released in supernovae explosions in our Galaxy. Thus, supernovae (SN) have been a strong candidate for the source of the Galactic cosmic rays (GCRs). Additional (circumstantial) evidence is provided by the presence of strong shocks in SN. Diffusive shock acceleration (DSA) theory predicts power-law spectra with index α=-2.1. The difference between the observed spectrum, $\alpha = -2.7$, and the acceleration spectrum is believed to be due to an energy dependent loss rate from the Galaxy. Measurements of the ratio of secondary to primary cosmic rays (for example boron to carbon), imply that the path length (measured as grams of material traversed before escape from the Galaxy) of cosmic rays decreases with increasing energy as $E^{-0.6}$.

Based upon the lifetime of the strong shocks in SN (roughly 10,000 years) the maximum energy attainable by a particle in such an environment is given by $E_{max} \sim 100 Z B_{-6}$ TeV [5], where Z is the charge of the nucleus and B_{-6} is the magnetic field at the shock in μGauss). Thus, if SN are responsible for the acceleration of GCRs, they cannot explain the most energetic such particles (>few PeV for Fe nuclei). It has been proposed that SN exploding into a Wolf-Rayet wind or non-linear amplification of a magnetic field in young SNR shocks could result in particle acceleration up to an energy $E_{max} \sim 10^{17} Z$ eV. Furthermore, while gamma rays have been observed from SN, the existence of high-energy electrons in the same environments (leading to gamma-ray production via the inverse Compton mechanism) has complicated the picture. Proof of hadronic acceleration requires detailed knowledge of the acceleration environment (magnetic fields and electron densities) and measurements to higher energies to separate the two components. We await definitive proof that supernovae are the sources of the hadronic GCRs.

Because the Galaxy is filled with a magnetic field, the directions of charged particles are quickly randomized and the cosmic rays arriving at Earth are nearly isotropic. It is only at the highest energies (above $\sim 10^{19}$ eV), where the sources are believed to be extragalactic, that one may expect a correlation between the arrival direction of charged cosmic rays and their acceleration sites [6]. At lower energies, one must look for sources of gamma rays, which are byproducts of cosmic-ray production, to identify the sources of the GCRs.

In the past decade, ground-based TeV gamma-ray telescopes have been operated with sufficient sensitivity to begin to understand the sources of Galactic cosmic rays. Arrays of imaging atmospheric Cherenkov telescopes (IACTs), such as HESS and VERITAS, have discovered 48 Galactic sources of TeV gamma rays. Sensitive extensive air shower (EAS) arrays with a wide field-of-view, such as Milagro, have detected the diffuse gamma radiation from the Galaxy at energies near 10 TeV and discovered an anomalous component to the local cosmic rays. Despite this impressive progress there has been no unequivocal evidence for the direct detection of the acceleration sites of hadronic cosmic rays. The next generation of instruments promises an order of magnitude or greater improvement in sensitivity. These instruments will be able to discover the sources of the Galactic cosmic rays and provide deep insight into the acceleration of hadrons and leptons in these sources.

Recent Advances and Future Requirements

There have been several important discoveries during the past decade with the current generation of ground-based gamma-ray telescopes. We list those most relevant to understanding the origin of cosmic rays here and discuss several of them in detail.

- The discovery of many types of particle accelerators in the Galaxy (cover figure). All of them are believed to accelerate particles at shocks (first order Fermi acceleration).
- The first TeV gamma ray images of particle acceleration sites and the ability to correlate the TeV emission with emission at other wavelengths (in particular X-ray measurements), Figure 1.
- Measurement of the Galactic diffuse emission at 10 TeV showing a large excess over predictions of GALPROP, Figure 2.
- Discovery of small-scale anisotropies in the local hadronic cosmic rays, Figure 3.

The first large IACT array, HESS, has made a sensitive survey of the Galaxy from the southern hemisphere. The results of this survey have profoundly changed the field of TeV gamma-ray astronomy. A composite view of the complete survey is shown in the cover figure. There are now 48 known Galactic sources of very-high-energy gamma rays [7], including supernova remnants, pulsar wind nebulae, X-ray binaries, molecular clouds, and the most numerous TeV source class – the unidentified sources. These sources have spectral indices ranging from α=-1.9 to α=-3.1, with a median value of about α=-2.3. Despite the discovery of $\sim$10 TeV emitting supernova remnants, the unambiguous detection of proton acceleration has proven difficult. Because the acceleration of hadronic cosmic rays in a SNR shock occurs early, one should look for gamma-ray emission from young SNRs. To date gamma rays have been detected from 3 such remnants: RX J1713.7-3946, RX J0852.0-4622 (Vela Junior), Cassiopeia A, SN1006, and RCW86. In the cases of RX J1713.7-3946 and RX J0852.0-4622, TeV images have been obtained (see Figure 1) and the TeV emission is well correlated with the X-ray emission – as expected for emission produced via inverse Compton scattering. However, both sources show hard spectra α=-2.1 and large fluxes (above 10 TeV they are more powerful than the Crab Nebula), implying low magnetic fields, which may contradict the recent finding of variability of the non-thermal X-ray emission from RX J1713.7-3946 on timescales of about a year. In reality it is more likely that these sources are accelerating both electrons and hadrons (protons and heavier nuclei).

To disentangle the leptonic (electrons) from hadronic emission in the Galactic sources requires understanding of their environment via multiwavelenth observations. Simultaneous radio, X-ray, and gamma-ray observations can be used to restrict the leptonic component

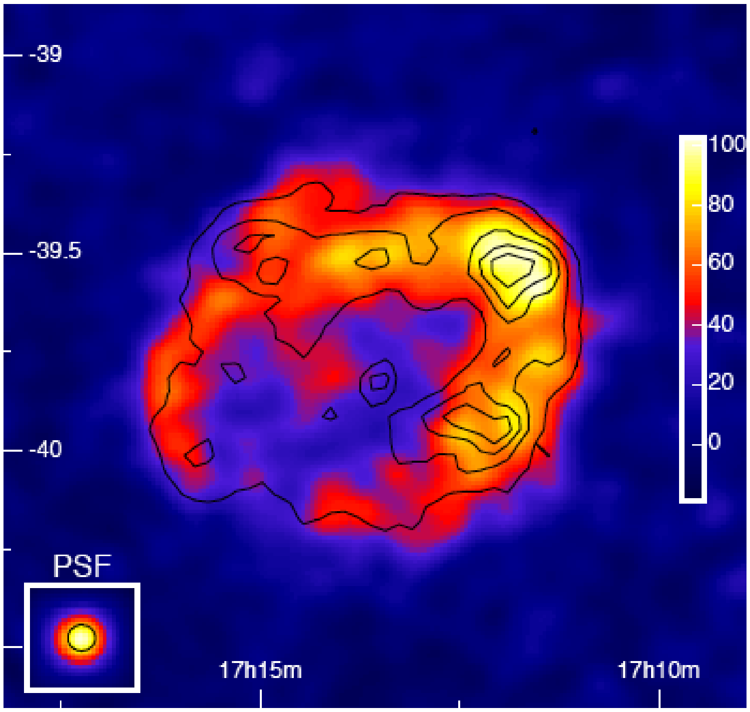

Figure 1: A TeV image of supernova remnant RX J1713.7-3946 from the HESS telescope. The color scale is in excess counts. The X-ray emission (ASCA 1-3 keV data) from the remnant is shown with the contour lines. [8]

and the magnetic field, while spectral measurements at the highest energies (>100 TeV) can unambiguously point to hadronic accelerators due to the very fast electron energy losses at these energies. Such high-energy measurements are also required to find a second source of GCRs, responsible for accelerating particles from energies near the knee all the way up to 10^{18} eV.

Requirements for future instruments: (a) ∼10x improved sensitivity to detect, image, & measure spectra of many more (100's) Galactic sources in a variety of environments, **(b)** extended energy reach to ∼200 TeV with at least 30% energy resolution to measure the endpoint spectra of many Galactic sources and detect the sources of the GCRs beyond the knee (sensitivity of $\sim 10^{-12}$ ergs cm^{-2} s^{-1} at 100 TeV, which is ∼Crab flux at at that energy).

The diffuse gamma radiation from our Galaxy is due to the interaction of cosmic ray protons and nuclei with interstellar gas, via the decay of neutral pions, and the interaction of high-energy electrons with the gas and the radiation fields (radio, microwave, infrared, optical, and UV). To correctly predict the spectral and spatial distribution of this emission one must know the distribution of radiation and matter in the Galaxy as well as the flux and spectrum of the cosmic rays (both hadronic and leptonic) within the Galaxy. Therefore, if the distribution of matter and radiation is known through other measurements, knowledge of the diffuse emission allows one to measure the cosmic-ray flux and spectrum throughout the Galaxy. This information can be used to determine the regions within the Galaxy where particle acceleration has recently occurred.

The EGRET instrument detected the Galactic diffuse emission between 30 MeV and 10 GeV. At energies above 1 GeV the observed flux exceeds the model predictions of a conventional model based on local CR measurements [9]. The possible explanations of this excess are many, including the annihilation of supersymmetric particles and a hard electron spectrum within the Galaxy. A specific model of GALPROP [10] was developed (the "opti-

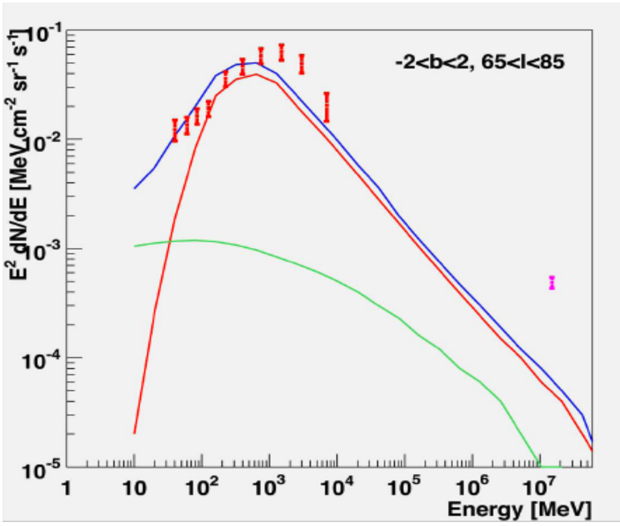

Figure 2: Milagro observations (pink data point) of diffuse gamma-ray flux in the Cygnus Region of the Galaxy [11]. These observations show a significant excess (8x) over GALPROP predictions of the conventional model. The contribution from the inverse Compton component is shown in green and the pion component in red (total in blue). The EGRET data are shown in red. Outside of the Cygnus Region (Galactic longitude 30° - 65°) the flux at 10 TeV is 4.7x that predicted by the conventional model.

mized" model) to match this excess. This model predicts a substantially larger contribution from the IC component at high energies – at 10 TeV the IC component dominates over the pion component. Recent measurements of the diffuse emission at 10 TeV by Milagro [11] indicate an excess over the conventional GALPROP model (Figure 2). When compared to the optimized GALPROP model it is found that the measurements are consistent with the model between Galactic longitudes of 30° and 65° and exceed the model prediction by a factor of ∼2.1 in the Cygnus Region (Galactic longitude 65°-85°). HESS also measured diffuse emission from the Galactic Center Ridge and found an excess over predictions based upon the gas density in the region and the cosmic-ray spectrum and flux measured at earth. These measurements are indications that the regions contain cosmic-ray acceleration sites.

The Fermi Large Area Telescope (LAT) is now providing additional data at GeV energies and the situation regarding the GeV excess is evolving. In any case the TeV excess, whether it is simply within the Cygnus Region or evident across the Galaxy, requires explanation. Several observations will be critical to determine the origin the of the TeV excess. First, the reality of the excess must be established – this requires a cross calibration between the ground-based gamma-ray instruments and the space-based instruments, this should be accomplished by Fermi and the current generation of IACTs. Second, the energy spectrum at TeV energies must be measured in a spatially resolved map. The current observations suffer from relatively low statistical significance, which limit the size of the spatial bins that can be examined, and poor energy resolution.

Requirements for future instruments: **(a)** The ability to measure low emissivity sources (wide angle and high duty cycle), **(b)** ability to measure the energy spectrum of the diffuse emission at TeV energies in relatively small angular bins (∼5°). This requires roughly 10x improved sensitivity over current wide-field instruments, **(c)** the TeV measurements should be extended to higher energies, preferably above 50 TeV.

These capabilities will allow for detailed comparison with the GeV emission to determine the contribution from cosmic-ray sources and to unambiguously measure the pion component of the diffuse emission. (At 10 TeV it is possible for the IC component to dominate the emission process. However, at higher energies the Klein-Nishina affect limits the IC contribution, and the high-energy electrons cannot travel far from their origin.)

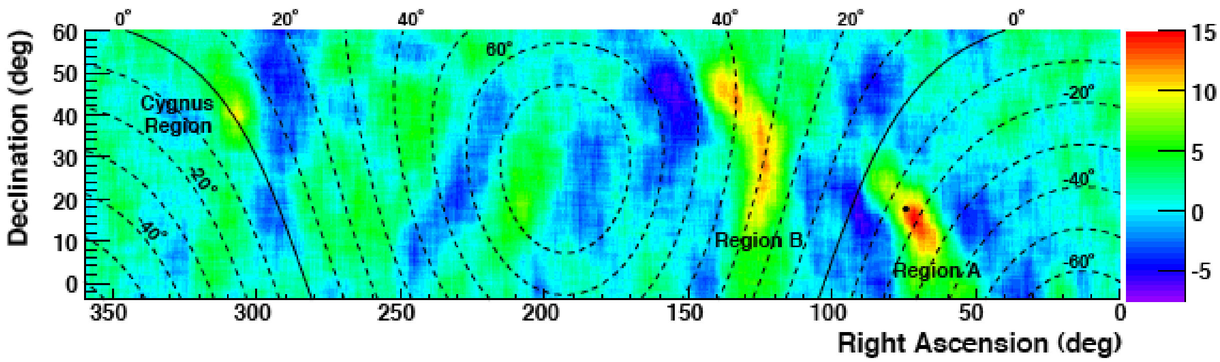

Figure 3: The small-scale anisotropy of the hadronic cosmic rays at energies near 10 TeV. The color scale is statistical significance in standard deviations. Note the analysis has been performed to be insensitive to the large-scale anisotropy (which is roughly one order of magnitude larger).

The Larmor radius of a 10 TeV proton in a magnetic field of 1 μGauss is 0.01pc. Anisotropy of the GCRs is driven by the source distribution and by scattering in a turbulent magnetic field. Large-scale anisotropies have been observed for decades and the amplitude of the anisotropy increases with increasing energy as one would expect. More recently, a small-scale anisotropy has been observed in the cosmic rays, see Figure 3 [12]. The Milagro detector, with the ability to distinguish gamma rays from hadronic cosmic rays, has shown that this anisotropy is due primarily to hadronic cosmic rays. The amplitude of the anisotropies (Regions A and B in the Figure 3) are roughly 5×10^{-4} of the cosmic-ray flux. Despite the relatively poor energy resolution of Milagro, it has been shown that the spectrum of the anisotropy is harder than the background cosmic-ray spectrum. The origin of these anisotropies is difficult to understand [13] and though the anisotropy is coincident with the heliotail such a local phenomenon is ruled out by the required size and power of the acceleration region [14]. At a minimum, the source must be relatively nearby and the magnetic field configuration between the source and the Earth should be highly organized [13]. Understanding these anisotropies should be a high priority as they are post likely due to a relatively local source of cosmic rays ($\sim$10's of parsecs).

Requirements for future instruments: (a) wide angle with 24-hour coverage **(b)** improved energy resolution $\sim$30% over current wide field instruments, and **(b)** improved background rejection capability that is independent of energy.

These improvements will enable a measurement of (or stringent limit on) the gamma-ray contribution to the excesses and a good determination of the energy spectrum of the anisotropy.

Larger Context and Conclusions

The solution to the problem of the origin of the Galactic cosmic rays will naturally lead to an understanding of particle acceleration at the end-points of stellar evolution (supernovae, pulsar wind nebulae, and X-ray binary systems). The study of high-energy gamma rays has natural ties to other wavelengths where non-thermal radiation is produced in these same objects. In fact, it is only with multi-wavelength data (especially in the radio and X-ray bands) that the source environments will be understood sufficiently that one can unravel the acceleration processes at work in each source. In the context of neutrino astronomy and the recently emerged ultra-high-energy cosmic ray astronomy, the connection is a close one. The acceleration sites of hadronic cosmic rays are also sites of neutrino production. Once these objects are understood, the expected neutrino fluxes can be calculated and the model predictions can be tested against observations with the IceCube detector. At the highest energies it is important to understand the energy spectrum of the GCR to correctly characterize the energy spectrum of the extragalactic component of the cosmic rays. Any interpretation of the spectrum of the extragalactic cosmic rays, such as source distribution and evolution, is dependent upon the subtraction of the contribution from the Galactic cosmic rays. Therefore, a detailed understanding of the endpoint of the GCR spectrum is of utmost importance to the understanding of the sources of the ultra-high-energy cosmic rays.

The past decade has seen an enormous advance in our knowledge of Galactic cosmic rays and we are on the verge of understanding their origin. To solve this problem will require a combined approach – pointed instruments to detect many faint Galactic sources and compare the TeV morphology to radio and X-ray images and all-sky instruments to detect the highest energy gamma rays from the Galactic sources and map the diffuse emission at TeV to 100 TeV energies. Both types of future instruments must have at least one order of magnitude improved sensitivity over current instruments. Any future all-sky instrument must also have improved energy resolution ($\Delta E/E \sim$30-40%). Within the U.S. there are such instruments being planned – the AGIS (Advanced Gamma-Ray Imaging System) Observatory would cover 1 km^2 with an array of imaging air Cherenkov telescopes and the HAWC (High Altitude Water Cherenkov) Observatory is an all-sky instrument similar to Milagro located at a higher altitude (4100 m) with roughly 5x the physical area. Both instruments will have roughly an order of magnitude greater sensitivity than the current generation of instruments. Such a suite of ground-based instruments operating in the 100 GeV to 100 TeV energy band, will be capable of determining the sources of the Galactic cosmic rays.

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