Gammapy analysis of the H.E.S.S. observations of the Composite SNR Kes 75

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Eleni Kanellaki

Aristotle University of Thessaloniki

Supervisors

Stefan Ohm, Dmitriy Kostiunin, Robert Daniel Parsons, Annanay Jaitly

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Abstract

The aim of this project is to reanalyze the composite supernova remnant (SNR) Kes 75 using the gammapy software. The results are compared to the H.E.S.S. data and they are consistent, except for the index γ and the spectral energy contribution. The Kes 75 is detected in the VHE range and it harbors a bright pulsar wind nebula (PWN). The TeV source is point-like and its position is compatible with the PWN, but an extension comparable to the SNR shell radius cannot be excluded so that a contribution from the SNR shell is possible.

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1 Introduction

1.1 The cosmic ray energy spectrum

Cosmic rays include particles such as electrons, protons and heavier nuclei. Their sources are yet unknown, but are both galactic and extragalactic in origin. The energy spectrum of cosmic rays, which is how the rate changes with increasing energy, has been constructed by decades of measurements. It is one of the most famous plots of modern physics, exhibiting a remarkable power law in energy, dN/dE $\propto E^{\gamma}$, over many orders of magnitude. This power law has a break in energy at a few PeV, which is referred to as the knee.

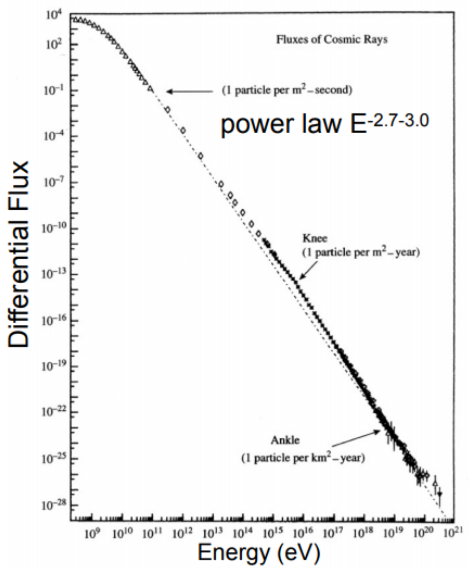

Figure 1: The cosmic ray energy spectrum.[1]

The explanation of the knee is generally believed to be a corner stone in understanding the origin of cosmic rays, providing answers to one of the key questions of astroparticle physics. Understanding the origin of cosmic rays using direct measurements is an impossible task due to the presence of interstellar magnetic fields that deviate the path of the charged particles before they reach Earth. Neutral messengers generated by cosmic ray interactions, such as gamma-rays and neutrinos, are used to determine the origin of cosmic rays.

1.2 Theoretical models for the knee

[2] Proposed explanations in the literature for the knee may be divided into four categories. The first three discuss astrophysical reasons, arguing that the knee is an intrinsic property of the energy spectrum, while in the last class the authors consider new particle physics processes in the atmosphere. In these theories the knee does not exist in the primary energy spectrum, but is only an effect of observing extensive air showers in the atmosphere.

Models in the first category relate the knee to the acceleration process. Models of the second category connect the knee with leakage of cosmic rays from the Galaxy. Interactions of cosmic rays with background particles in the Galaxy are considered as origin for the knee in the third category. Last but not least, the fourth class of theories accounts the air shower development in the atmosphere for the knee.

1.3 Cosmic rays from supernova remnants

[3] Supernova remnants are considered to be the most plausible candidates of cosmic ray sources in the Galaxy, both from the theoretical and the observational points of view. It has been theoretically established that shock waves associated with supernova remnants can accelerate particles from the thermal pool to a non-thermal distribution of energetic particles. The underlying acceleration process, commonly referred to as the diffusive shock acceleration process, produces a power law spectrum of particles with a spectral index close to 2, which is in good agreement with the values inferred from radio observation of supernova remnants. In addition to the radio measurements, observational evidence for the presence of high-energy particles inside supernova remnants is provided by the detection of non-thermal x-rays and TeV gamma-rays from a number of supernova remnants.

1.4 The Composite Supernova Remnant Kes 75

[4] After some massive stars run out of nuclear fuel, then collapse and explode as supernovas, they leave behind dense stellar remnants called "neutron stars". Rapidly rotating and highly magnetized neutron stars produce a lighthouse-like beam of radiation that astronomers detect as pulses as the pulsar's rotation sweeps the beam across the sky.

A team of astronomers has confirmed that the supernova remnant Kes 75, located about 19,000 light years from Earth, contains the youngest known pulsar in the Milky Way Galaxy. The rapid rotation and strong magnetic field of the pulsar have generated a wind of energetic matter and antimatter particles that flow away from the pulsar at near the speed of light. This pulsar wind has created a large, magnetized bubble of high-energy particles called a pulsar wind nebula.

The Chandra data taken in 2000, 2006, 2009 and 2016 show changes in the pulsar wind nebula with time. Between 2000 and 2016, the Chandra observations reveal that the outer edge of the pulsar wind nebula is expanding at a remarkable 1 million meters per second. This high speed may be due to the pulsar wind nebula expanding into a relatively low-density environment. Specifically, astronomers suggest it is expanding into a gaseous bubble blown by radioactive nickel formed in the explosion and ejected as the star exploded. This nickel also powered the supernova light, as it decayed into diffuse iron gas that filled the bubble. If so, this gives astronomers insight into the very heart of the exploding star and the elements it created.

The expansion rate also tells astronomers that Kes 75 exploded about five centuries ago as seen from Earth. Unlike other supernova remnants from this era such as Tycho and Kepler, there is no known evidence from historical records that the explosion that created Kes 75 was observed. Why wasn't Kes 75 seen from Earth? The Chandra observations along with previous ones from other telescopes indicate that the interstellar dust and gas that fill our Galaxy are very dense in the direction of the doomed star. This would have rendered it too dim to be seen from Earth several centuries ago.

The brightness of the pulsar wind nebula has decreased by 10% from 2000 to 2016, mainly concentrated in the northern area, with a 30% decrease in a bright knot. The rapid changes observed in the Kes 75 pulsar wind nebula, as well as its unusual structure, point to the need for more sophisticated models of the evolution of pulsar wind nebulas.

2 Analysis

[5],[6] H.E.S.S. is a system of Imaging Atmospheric Cherenkov Telescopes (IACTs) that investigates cosmic gamma-rays in the energy range from 10s of GeV to 10s of TeV. It is located at an altitude of 1800 m above sea level in the Khomas highland of Namibia, an area well known for its excellent optical quality. The name H.E.S.S. stands for High Energy Stereoscopic System and is also intended to pay homage to Victor Hess, who received the Nobel Prize in 1936 for his discovery of cosmic radiation. The instrument allows scientists to explore gamma-ray sources with intensities at a level of a few thousandths of the flux of the Crab nebula, the brightest steady source of gamma-rays in the sky that is used as a standard candle reference in VHE gamma-ray astronomy.

H.E.S.S. detects Cherenkov light emitted by charged particles in an electromagnetic extensive air shower initiated when a primary photon (gamma-ray) of sufficient energy enters Earth's atmosphere. These air showers are simultaneously observed by several telescopes, under different viewing angles, and these telescopes are combined to a large system to increase the angular resolution and the effective detection area for gamma-rays. The H.E.S.S. array consists of four smaller telescopes with a mirror 12 m in diameter and a fifth much larger with a 28 m mirror in diameter, at the center of the array.

The observations that we used for our analysis are taken by the H.E.S.S.

[7] For the analysis of VHE γ-ray events from H.E.S.S. below we used an open-source Python package for gamma-ray astronomy, called `gammapy`. It is built on `numpy`, `scipy` and `astropy`. Gammapy is used as core library for the Science Analysis tools of the Cherenkov Telescope Array, recommended by the H.E.S.S. collaboration.

We accessed the H.E.S.S. observations and we defined an observation filter to select only the relevant observations. In particular, we selected those observations that were in a sky circle with a radius of 3 degrees around the Kes 75 SNR position. In this way, there were 210 observations selected. We performed a 3D analysis on them and then we took the significance and the excess map. The excess is the just difference between detected gamma-rays and ones expected from background. The significance is calculated according to the equation 17 of Li & Ma. [8]

Figure 2 shows the resulting smoothed excess map centered on the Kes 75 SNR position. On the top of the excess map we plotted the significance contours. A TeV source, HESS J1846-029 is spatially coincident with Kes 75, one of the youngest composite SNRs in the Galaxy, which contains the nebula PSR J1846-0258.

Then, we defined a model to be fitted to the dataset. We performed the fit on the stacked observations and as a result we obtained the parameters that are presented in the Table 1.

Table 1: The parameters after the fitting.

Name	Value	Unit	Error
index	2.5675		0.1915
amplitude	7.281813	$cm^{-2}s^{-1}TeV^{-1}$	1.163×10^{-13}
reference	1.000	TeV	0.000
longitude	281.6	deg	3.713×10^{-3}
latitude	-2.9738	deg	3.705×10^{-3}

So, the source is found to be centered on: RA = 18h46m24.0s and dec = -2°58′25.7″. Figure 3 is a Chandra 2-10 keV image of Kes 75 that shows the x-ray morphology of the composite remnant and two markers are used in order to indicate the pulsar's position. The orange cross indicates the new result that we obtained using the best-fit longitude and latitude of Kes 75 from the Table1 and the blue triangle indicates the result according to the H.E.S.S. Galactic plane survey (HGPS) that was a decade-long observation program carried out by the four smaller Cherenkov telescopes in Namibia from 2004 to 2013.

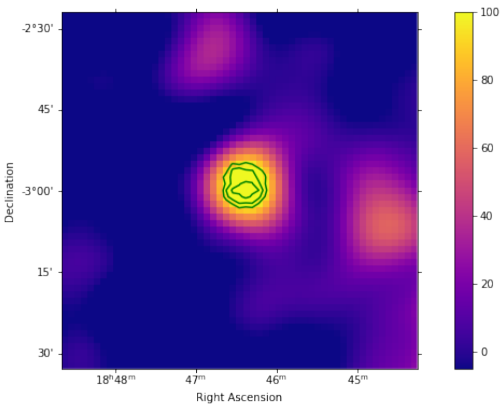

Figure 2: VHE γ-ray excess map, smoothed with a Gaussian of width $\sigma = 0.05°$, centered on the Kes 75 SNR position. Significance contours at 8, 9 and 10 σ obtained with a correlation radius of 0.1° are overlayed in green.

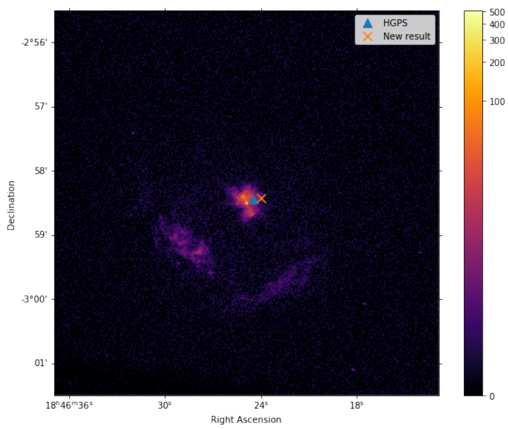

Figure 3: A Chandra 2-10 keV image of Kes 75. The markers indicate the pulsar's best-fit position.

A function was defined, the power law function, using four parameters, the energy E, the reference E_0, the index γ and a differential flux at 1 TeV, the Φ_0. This function returns as a result the:

$$\Phi(E) = \frac{dN}{dE} = \Phi_0 * (\frac{E}{E_0})^{-\gamma}$$

Figure 4 shows the flux points of Kes 75 and the best-fit of these as well as the spectral energy distribution that is expressed by the product of squared energy times the power law function for the values from HGPS, $\Phi_0 = 0.671 \times 10^{-12}$ cm^{-2} s^{-1} TeV^{-1} and $\gamma = 2.41$. The index that we calculated is harder and we notice a discrepancy here.

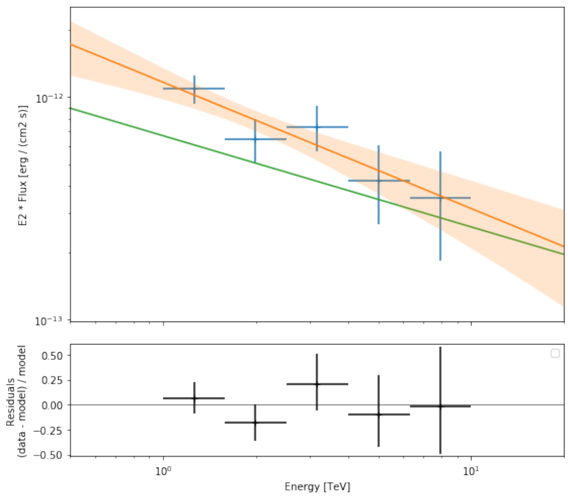

Figure 4: Differential energy spectra of Kes 75.The orange line is the best-fit of the flux points of Kes 75 and the green line is spectral energy contribution for the best-fit index as it was calculated according to the H.E.S.S. Galactic plane survey.

3 Conclusions

- Kes 75 was reanalyzed using the gammapy software.
- The results are consistent with previous analysis.
- Kes 75 is detected in the VHE range.
- The TeV source is point-like and its position is compatible with the pulsar wind nebula, but there is no evidence for a supernova remnant emission.
- The spectrum is well represented by a power-law, but the spectral fit is slightly different comparing to HGPS. This has to be studied in detail.
- The framework for the detailed analysis is set up.

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