Are Supernovae Responsible for the Gamma Ray Spectrum from the Galactic Center?

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Abstract

We discuss the supernova remnants distribution as a function of the galactic longitude and compare their positions to that of the detected TeV gamma ray sources. A large fraction of these sources either coincide or a close by known supernova remnants. If we look within 10° of the Galactic center most identified sources are combinations of supernova remnants with giant molecular clouds. The diffuse gamma ray flux from the direction of the Galactic center is much smaller.

Keywords: supernova remnants - cosmic rays acceleration - TeV gamma rays.

1 Introduction

I will start this write-up the same way as I started the talk: with the answer to the question, which is **I do not know.** What I will write about is what we know about different types of supernova remnants (SNR) from which TeV γ rays are detected and what theoretical research says about the way these γ rays are produced in them.

The main reason we are interested in supernova remnants is they are supposed to be the sources of galactic cosmic rays, which are accelerated at the supernova shocks. The outer regions of the expanding supernova initially move with high velocity, approximately 0.1c. The expansion velocity is supersonic and a shock is formed in front of the remnant. The shock collects the interstellar matter that it meets during the expansion. Once the shock radius is close to 1 pc, when the remnant is about 1,000 years old, the amount of the swept-up material becomes too much and the remnants velocity decreases.

This is the time when cosmic rays are accelerated at the shock front. The magnetic field at the shock front is significantly higher than that of the interstellar medium and only a small fraction O(few %) of the kinetic energy of the remnant can supply all galactic cosmic rays (Ginzburg & Syrovatskii, 1964).

2 Supernova Remnants

The latest supernova remnant catalog that I am familiar with is that of D.A. Green (Green 2009). It contains 274 supernova remnants studied in radio and gives their location, power at 1 Ghz, and spectral indexes. Ten of these SNR have longitude less than 10° from the Galac-

tic Center. All of them are closer than 1.5^o from the Galactic plane. The directions of all 274 these supernova remnants are shown in Fig. 1 where the ones from supernovae after 1,000 AD (and the Galactic center) are indicated. One can easily see that most of the remnants are very close to the Galactic plane and a few are more than 5° away from it. One can also see that the supernova remnants density is much higher in the inner 60° of the Galaxy.
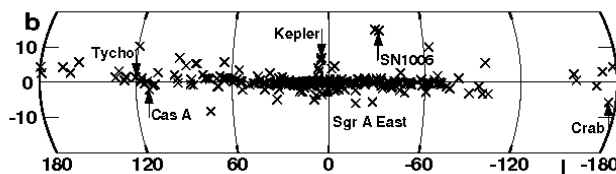
Figure 1: Locations of the supernova remnants in D.A. Green catalog.

The question if these SNR are the sources of cosmic rays and of high energy γ-rays becomes very reasonable. To approach this question we will have a look at the galactic sources of high energy γ-rays, the TeVCat of the University of Chicago (*http://TeVCat.uchicago.edu*). This catalog contains 145 gamma ray sources that have been discovered by the atmospheric Cherenkov gamma ray telescopes. These devices consist of several mirror telescopes that observe the Cherenkov light emitted by the cascade developing after the high energy gamma rays interact with atmosphere. The shape of the image of the cascade is enough to differentiate between atmospheric γ-ray cascades and cascades from the interactions of cosmic ray

protons and nuclei in the atmosphere. When the cascade is observed by more than one telescope the angular resolution is a small fraction of a degree. The threshold energy for these devices depends on the size of the mirrors and is often of $O(100 \text{ GeV})$. The three major TeV gamma ray atmospheric telescopes are, in order of their completion, HESS (Hinton et al, 2004), VERITAS (Hanna et al., 2008), and MAGIC (Boria Tridon et al., 2010). HESS and VERITAS have each four 12 m. telescopes and MAGIC has two 17 m. telescopes. The average detection threshold for 12 m. telescopes is between 100 and 200 GeV while the 17 m. telescopes can come down to 60 GeV. TeVCat has identified 64 galactic sources listed by different types in Table 1.

Table 1: Galactic TeV gamma ray sources

| Pulsar wind nebulae	31
Shell supernova remnants	12
X-ray binaries	3
Gamma ray binaries	1
Massive stars	3
SNR/Molecular clouds	8
Globular clusters	1
Unidentified	5

It is not obvious that the different distribution of the TeV gamma ray sources within 10° of the Galactic Center is important. Out of the ten sources four are SNR with close by molecular cloud, three are unidentified (which includes the Galactic center and the Galactic center ridge), one is pulsar wind nebula. There is also one Shell SNR and one globular cluster. Since all of these objects are at the approximately the same distance from us we expect the gamma ray fluxes from them to correspond to the overall luminosity of the sources. The number of the detected gamma rays will also correspond to the threshold energy for detection.

The exact threshold energy for detection by the TeV air Cherenkov telescopes depends on the size of the telescope mirrors and on the positions of the source and the telescope. To demonstrate this we show in Fig. 2 the galactic plane and the sources in equatorial coordinates. The telescopes are sensitive to source elevation down to 30° but the lower the source is the higher the energy threshold. The HESS telescope is in Namibia at 23 degrees South, VERITAS is in Arizona, U.S.A. at 31 degrees North, and Magic is at 29 degrees North. All of them can observe most of the Galactic plane, but the location of HESS is the best one for observations of the Galactic center. This is the reason it was constructed in Namibia.
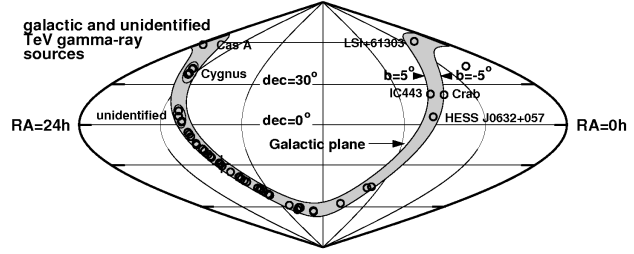
Figure 2: The vicinity of the Galactic plane and the galactic sources of TeV gamma rays in equatorial coordinates.

Figure 3 shows the galactic sources of TeV gamma rays (circles) overlayed on the supernova remnants. The sources from the first Fermi/LAT catalog (Abdo et al (2010)) are shown with triangles. If we had a look at the later Fermi/LAT catalogs we would find many more galactic sources the coincide with supernova remnants. One should not forget that Fermi/LAT is sensitive to γ-rays of energy 0.1 to 100 GeV and the average spectral slope of the gamma ray sources is about 2.5. This means that are 30,000 more gamma rays above 100 MeV than are gamma rays above 100 GeV. This number varies, of course, from source to source depending on the spectral index of the source.
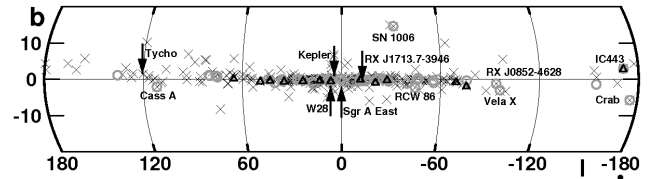
Figure 3: The position of the galactic TeV gamma ray sources (circles) are overlayed on top of the supernova remnants from the Green's catalog. The triangles show the the Fermi/LAT gamma ray sources from its first catalog (Abdo et al (2010)).

2.1 Pulsar wind nebulae

Pulsar wind nebulae are formed by the highly relativistic MHD winds expelled by the rotating neutron stars. Such objects can accelerate all kinds of charged particles, from electrons to heavy nuclei if there is a proper injection mechanism close to the neutron star. The best studied PWN is that of the Crab. The gamma ray fluxes from different sources are often given in Crab units that describe the ratio of their emission to that of the Crab. Its gamma ray energy spectrum is best described by the synchrotron self Compton model that is based only on electron acceleration. Electrons emitted by the source suffer from synchrotron energy loss to photons. These photons than go through inverse Compton interactions

with the accelerated electrons that pushes them to TeV energies.

It is not expected that such sources can produce very high energy gamma rays when the inverse Compton cross section decreases in the Klein-Nishina regime. The studies of most TeV pulsar wind nebulae, however, agree better with leptonic models than with cosmic ray interaction models. The same is true for many other TeV gamma ray sources such as Geminga and Vela X.

2.2   Shell supernova remnants

Shell supernova remnants sources are the typical supernova remnants as we imagine them. The shock wave from supernova explosion heats up the interstellar material as it propagates through it. When we observe such a remnants we see mostly its outer edge that is brighter than the inside of the remnant. In optical astronomy this effect is called *limb brightening*. The observations also indicate higher magnetic fields at the limbs of the remnants. A very good introduction to the processes in the remnant is given in (Reynolds, 1998) where the author deals only with electron acceleration. The acceleration of protons and heavier nuclei is discussed by (Caprioli, Amato & Blasi, 2010). In order to understand the limb brightening one has to assume that there is electron acceleration at the edge of the remnants where the electrons have synchrotron energy loss in the higher magnetic field.

The shell supernova TeV gamma ray sources in TeV-Cat include IC443, SN1006, CassiopeiaÃ, and Tycho.

2.3   SNR/Molecular clouds

This type of sources includes supernova remnants that have massive molecular clouds nearby. Very often the TeV gamma ray sources do not point at the center of the remnant, rather at the molecular cloud itself or at the side of the remnant that is close to the cloud.
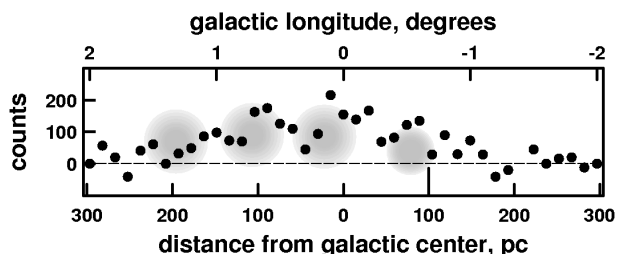
Figure 4: Positions of the molecular clouds and the number of TeV gamma rays observed by the HESS experiment (Aharonian et al, 2006).

Most of these sources were first observed by the HESS experiment and carry its name. An extremely interesting analysis was performed by HESS after its observation of the Galactic center ridge (Aharonian et al, 2006).

This analysis is illustrated in Fig. 4. HESS saw that the number of TeV gamma rays coming from the vicinity of the Galactic center has gaps, i.e. there would be hundreds of gamma rays coming from certain direction, then almost no gamma rays, then again hundreds of gamma rays. The exact directions of the locations that produced hundreds of gamma rays coincided with the positions of several giant molecular clouds containing $2\text{-}4\times10^7$ $M_\odot$. At the 8.5 kpc distance of the Galactic center 0.2^o longitudinal difference corresponds to a distance of 30 pc.

The analysis concluded with the idea that cosmic rays were accelerated in the Galactic center (maybe at Sagittarius A EAST) many years ago and started diffusing away from it. When they diffuse into one of the huge molecular clouds they interact with the matter there, generate neutral mesons that decay into gamma rays. These cosmic rays were able to diffuse at distances up to 100 pc but have not yet reached the molecular cloud at a distance of 200 pc. This leads to an estimate of the time of the supernova remnant acceleration episode of 10^4 years ago. An acceleration episode could be similar to the movement of a small molecular cloud to the black hole Sgr A* in the galactic center that is being observed now (Gillesen et al, 2013). The absorption of large amount of matter by the black hole can easily create a shock and thus accelerate cosmic rays for a relatively short time.

There are now analyses of different gamma ray sources that require the existence of molecular clouds nearby. A very interesting one is that of (Torres, Rodriguez Marrero & deCea del Pozo, 2010) of the supernova remnant IC443. The gamma ray emission of this source is known from the 1990's when it was detected by EGRET. It was observed by the TeV Cherenkov telescopes MAGIC and VERITAS at a slightly different (0.4^o) direction. The direction of the same source from Agile and Fermi/LAT are consistent with this of EGRET. The authors of this analysis identify two (or maybe three) different sources: IC443 as seen by the TeV telescopes and a molecular cloud in front of it that is observed in the GeV energy range. It is also possible that another, relatively small molecular cloud also emits gamma rays. The existence of different sources solves the problem with the different spectral indices in the GeV and the TeV gamma ray emission.

3   Other Possible Ideas

An old paper (Berezinsky et al, 1993) looks at the possibility that there would be a strong diffuse radiation from the central region of the Galaxy. The paper uses a matter density study (Bloemen, 1989) that determined that

the matter density in the inner 300 pc of the Galactic plane within $b < |2|^o$ is 38 nucleons cm$_{-3}$. The matter density strongly decreases to reach less than 1 per cm^3 at distances greater than 6 kpc. Assuming that the matter distribution in the Galaxy is symmetric (which it is not) the paper used the data of Bloemen to calculate the column density in different directions. The highest column density for latitude less than 2° around the galactic center reached 8×10^{22} cm^{-2}. Using this mapping the paper provides the ratio between the γ-ray flux and cosmic ray flux as a function of the galactic longitude.

In the vicinity of the Galactic center and for energies less than 10 TeV this ratio is still less than 10^{-4}. It is easy the explain that: a column density of 8×10^{22} cm^{-2} is slightly more than 0.1 g/cm^2 when the proton interaction length is about 50 g/cm^2. This means that only 0.6% of the galactic cosmic rays interact and generate gamma rays that we will see coming from the direction of the galactic center. In all other directions the diffuse gamma ray flux is smaller.

I refer to this paper because it attempted to calculate in an easy way the diffuse gamma ray flux. The contemporary attempts to do this are much more sophisticated and involve measurements and subtraction of all known gamma ray sources. The Fermi bubbles were discovered in this way (Su, Slatyer & Finkbeiner, 2010). The bubbles cover an area much larger than the Galactic center region and are still discussions of the origin of the gamma ray emission from them. One example of the Fermi/LAT studies of the diffuse gamma ray radiation in the Galaxy is in (Ackermann et al, 2012) where the small and large scale anisotropy is studied and the existence of unknown gamma rays sources is discussed. In other papers the diffuse radiation is searched for for possible dark matter signatures.

4   Discussion and Conclusions

The gamma ray energy spectra from the detected gamma ray sources are very often compared to leptonic and hadronic models models of gamma ray production. Some of the sources, typically the pulsar wind nebulae, fit better the leptonic models, where electrons accelerated at the source have inverse Compton collisions with synchrotron photons emitted by the same electrons in propagation of the magnetic fields around the source. Even if these so called SSC models fit much better the gamma ray emission in a wide energy range, there are still problems that are hard to solve. The main problem (for me) is that it is difficult to imagine a mechanism that only injects electrons and not charged nuclei in the acceleration site. One possible answer is that both electrons and cosmic rays are accelerated but the matter density around the source is very low and the

cosmic rays do not interact to produce neutral mesons and gamma rays. Electrons, on the other hand, emit synchrotron radiation in their propagation in magnetic fields and these low energy photons are the target for inverse Compton interactions.

There are, of course, several sources that fit better the hadronic interaction models and this is true for more of the combinations of supernova remnants and molecular clouds. The proof of π^0 origin of the gamma rays in a source is the decrease of the flux at energies lower than 70 MeV, one half of the π^0 mass. This however does not happen if there is a significant contribution to the gamma ray flux from bremsstrahlung. This is one of the reasons that for most of the gamma ray sources the hadronic origin is suspected, but not proven. The suspicion is usually because of the existence of large matter density around or in front of the source.
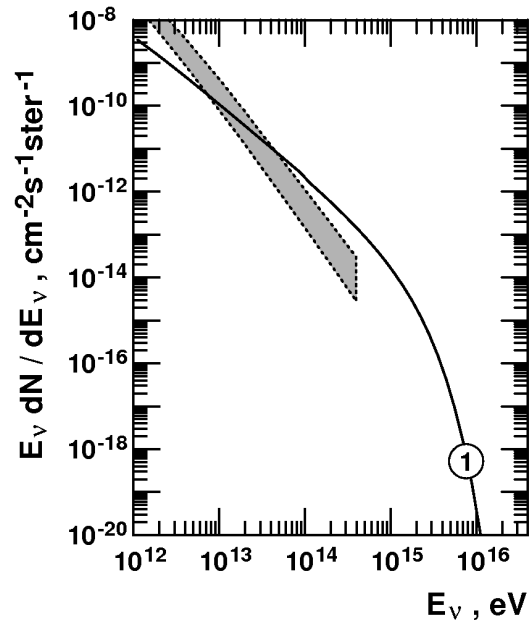
Figure 5: The neutrino flux that corresponds to the gamma ray flux of IC 443. No neutrinos attributed to this sources have been observed yet.

The only way we can be certain that the gamma ray generating process is hadronic is if we observe also neutrinos from the same object. Gamma ray and neutrino productions are closely related as shown in Eq. 1 that gives the shape of the gamma ray and neutrino fluxes as a function of the same astrophysical parameters.

$$\frac{dN_{\gamma(\nu)}}{dE_{\gamma(\nu)}} = \frac{dN_{CR}}{dE_{CR}} f_A \frac{\sigma_{inel}}{m_N} [\rho R] C_\nu \frac{2 Z_{N\pi^0(\pi^\pm)}}{\gamma + 1} \quad (1)$$

The term f_A accounts for the differences between proton-proton and nuclei interactions and the term C_ν, that is less than 1, accounts for the different kinematics

of gamma ray and neutrino production. The gamma ray flux is higher than that of neutrinos.

The big problem is the tiny neutrino interaction cross section that requires huge detectors similar to the 1 km^3 IceCube detector at the South Pole. In some cases the low neutrino cross section is an advantage as all neutrinos generated by a source will not be absorbed and will be visible by the neutrino telescopes.

Acknowledgement

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DISCUSSION

CARLOTTA PITTORI: Is there any possible correlation between your viewgraph of the Galactic center with the idea of an episode of cosmic ray acceleration 10^6 years ago and the 511 KeV integral map shown by Ubertini?

TODOR STANEV: As Piero Ubertini said himself it is a matter of electron and positron density in the annihilation site. There is, of course, also the problem of their diffusion. How far these particles would go away from the acceleration site in a million years and how big the annihilation area would be? The HESS analysis of the Galactic ridge discusses the diffusion in a location where we expect very irregular and strong magnetic fields and thus fast diffusion.