Supernova remnants and molecular clouds

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Laboratoire d'Annecy-le-Vieux de Physique des Particules, Université de Savoie, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France

The search for the origin of galactic cosmic rays cannot be led directly as charged particles scatter on magnetic perturbations inside our Galaxy. Neutral particles such as high or very high energy gamma-rays, produced by interacting high energy charged particles, can be effectively used to search for acceleration sites. Large matter concentrations such as molecular clouds in the vicinity of potential accelerators are very interesting probes for accelerated hadrons. The interest of supernova remnant associated with molecular clouds in order to confirm the standard paradigm of the origin of galactic cosmic-rays is presented here.

1 The standard paradigm of the origin of galactic cosmic rays

The origin of Galactic cosmic rays (CRs) is a long standing question, since their discovery more than 100 years ago in 1912 by Victor Hess. It is commonly believed that supernova remnants (SNRs) are the main particle accelerators in the Galaxy. Diffusive shock acceleration mechanism in the associated strong shock could accelerate particle efficiently up to 10^{15} eV (for a review see e.g. [1]). A conversion efficiency of 10% of the kinetic energy of the Galactic SNRs into CRs can explain the observed flux at Earth (taken to be typical of the Galaxy). Even if the connection between supernovae and cosmic rays has been proposed a short time after the discovery of cosmic rays in 1934 by Baade and Zwicky [2], the definitive confirmation is still missing.

In the last decade, the proof that high energy particles are efficiently accelerated has been brought by very high energy (VHE, E >100 GeV) gamma-ray telescopes. A VHE gamma-ray emission has been detected toward several shell-type SNRs with H.E.S.S., MAGIC and VERITAS. The emission of such non thermal energetic photons can only occur through the interaction of high energy charged particles. It confirms that these objects accelerate particles up to at least 10 TeV [3 4]. However, TeV measurements alone do not allow to disentangle between a hadronic or a leptonic origin of the gamma-rays and thus the confirmation that hadronic cosmic rays are accelerated by SNRs is still missing.

More recently, the high energy gamma-ray space telescopes Fermi-LAT and AGILE have completed the picture of those objects. A GeV gamma-ray emission has been detected towards several shell-type SNRs. Amongst them are two remnants already detected at TeV energies: Tycho [5] and RX J1713.7-3946 [6]. Whereas in the first case the spectral energy distribution clearly favors a hadronic origin, in the latter a leptonic scenario seems preferred. In general, even if the gamma-ray measurements indicate that hadronic gamma-ray seems effectively accelerated inside supernova remnants, it seems difficult to completely confirm that SNRs are responsible for the bulk of cosmic rays. Another pending question concerns the highest energies. Diffusive shock acceleration mechanism predicts that the accelerated particles could reach PeV energies into strong shocks. However, no gamma-ray emission produced by such energetic particles has been detected, leading to the conclusion that either no such energies have been reached, or these particles have already escaped the acceleration site. Given the age of the observed SNRs, the latter hypothesis is expected.

2 Molecular clouds and the origin of cosmic rays

The ingredients for a leptonic gamma-ray emission are naturally present in supernova remnants. A population of accelerated electrons will naturally produce high energy photons through Inverse Compton diffusion on the CMB photons, even without additional photon field target. On the contrary, a gamma-ray emission from a population of hadrons needs a consequent target density to produce a detectable gamma-ray signal. A supernova remnant evolving into a low density medium may not have enough target matter in its surrounding to be observed with current telescopes. The lake of detection of hadronic gamma-ray from some supernova remnant could be thus due to the low density medium surrounding the remnant.

In order to confirm that supernova remnant are efficient hadrons accelerator, a good strategy would be to look at remnants close to a large concentration of matter [7]. Such kind of association are frequent in our Galaxy. Most of the neutral matter is concentrated into dense molecular clouds, in which up to 10^5 solar masses can be confined with densities up to 10^6 particles per cm^3. Such massive clouds frequently host star forming regions with massive stars that gives birth to supernova. This childhood link between supernova remnants and molecular clouds explains why the association is frequently expected [8].

However, the detection of such associations is difficult to assess. The distance to molecular clouds is pretty accurate thanks to radio or millimetric line doppler effect, but is much difficult to evaluate in the case of supernova remnants. To search for physical associations, the presence of 1720 MHz OH masers is a very helpful indicator. This maser is emitted within shocked dense region as the line inversion can occur only through collisional pumping in low temperature clouds [9]. The detection of this maser undoubtedly indicates that a shock wave propagates through the cloud and thus that the cloud is physically associated with the remnant. Over 10% of the known supernova remnants are OH masers emitting, indicating that a physical association is very frequent. These remnants appears to be very promising target to search for a population of accelerated hadrons. A recent study summarized the detection of GeV or TeV gamma-ray emission towards these remnants and showed that a significant fraction of the know interacting remnant are gamma-ray emitters [10]. Around 10% of the know supernova remnants, all showing evidences of interaction with a dense cloud (either OH masers or radio line broadening) emit gamma-rays, whereas another 10% that could be interacting are also emitters.

It should be kept in mind that there are some caveats related to such associations when looking at particle acceleration. First the presence of dense matter slowing down the propagation of the shock wave may have an impact on the acceleration efficiency. Moreover, this maser line is observed when a slow shock propagate through the cloud, meaning that the remnant is already in an advanced stage of its evolution. The particles with the highest energies have very probably escaped the remnant at this stage. These two caveats add to the fact that the morphology of the remnant is most of the time unusual due to the propagation into an inhomogeneous medium. These supernova are thus probably not the best candidates to compare to theoretical models.

3 The gamma-ray picture: from GeV to TeV

In the last five years, this class of gamma-ray source has grown-up very rapidly, mainly thanks to the observations of the GeV instruments Fermi-LAT and Agile. Only a bunch of TeV detections by H.E.S.S., MAGIC or VERITAS were known four years ago: W28, IC443, CTB 37A, W51,

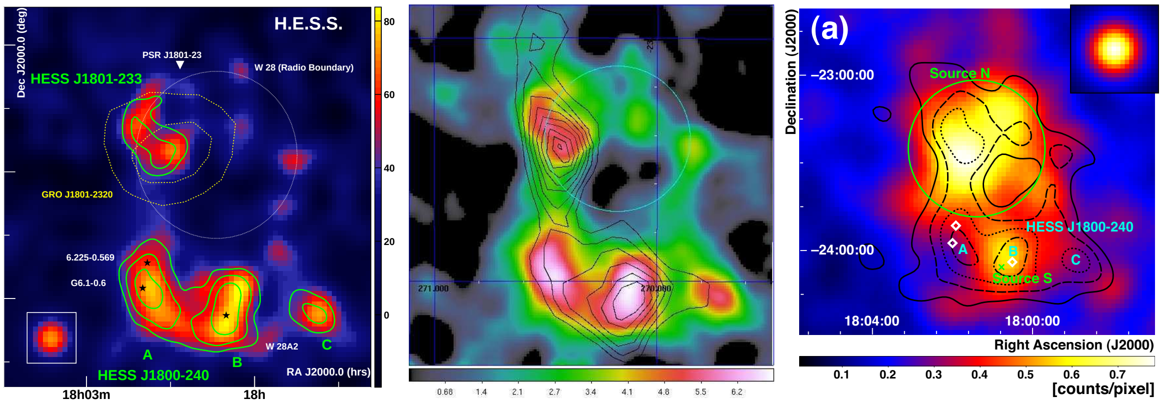

Figure 1: The GeV-TeV picture of the W28 field. The position of the supernova remnant is indicated by a white or green circle. Left: The VHE gamma-ray excess map seen by HESS. Middle: The HE gamma-ray excess contours from Agile in black over-imposed on the H.E.S.S. excess map. Right: The HE gamma-ray excess map from Fermi-LAT with the H.E.S.S. excess contours overlaid as black lines.

G359.1-0.5 [11]. Fermi or Agile have confirmed that these are also emitting in the GeV range. Several other GeV emissions have been detected since then. As well, several other TeV emissions have been discovered toward interacting SNRs.

The brightness of these sources in the GeV range put a strong constraint on the origin of the gamma-ray emission. Even if a leptonic origin of the gamma-ray emission cannot be completely ruled out for all of these gamma-ray emission, a hadronic origin is much more favored by their spectral energy distribution. In most of the case the position of the gamma-ray emission is well correlated with the presence of the molecular clouds, making the hadronic interpretation even more convincing.

3.1 The case of W28

The W28 complex is a well known case of supernova remnant interacting with a molecular cloud. Figure 1 *left* is the VHE gamma-ray excess map of the W28 field observed by HESS [12] . Two sources are detected: at the northeastern boundary of the remnant, HESS J1801-233, and to the South, HESS J1801-240 (possibly divided into three components, A, B and C). The W 28 SNR is interacting along its northern and northeastern boundaries with molecular clouds visible within NANTEN observations in the CO(J=1→0) line. NANTEN observations showed also the presence of a dense molecular cloud coincident with the southern gamma-ray excess. The doppler effect of the CO line showes that this cloud lies also in the vicinity of the remnant, even not being physically associated.

The GeV view of the remnant has been published by Agile [14] and Fermi-LAT [13] in 2010. Figure 1 *middle* represents the HE gamma-ray excess map contours from Agile over imposed on the HESS VHE gamma-ray map. Figure 1 *right* is the HE gamma-ray excess map from Fermi-LAT with the HESS contours over-imposed. The GeV emission appears quite nicely correlated with the TeV emission. Both the northern and the southern TeV excesses have a counterpart at lower energies. The coincidence between these gamma-ray emission and the molecular clouds argues in favor of a hadronic origin of the photons. The spectral energy distribution favors also a hadronic origin.

It should noted that the three hotspots of the southern TeV excess are not all detected at GeV energies. Only one of the hotspots associated with the southern molecular clouds (region A and B on figure 1 *left*) is detected. Moreover, the brightness ratio between the two parts is different in the two energy band. While the northern excess is the fainter in the HESS map, the southern is the fainter in the GeV maps. This different brightness ratio as well as the lake of

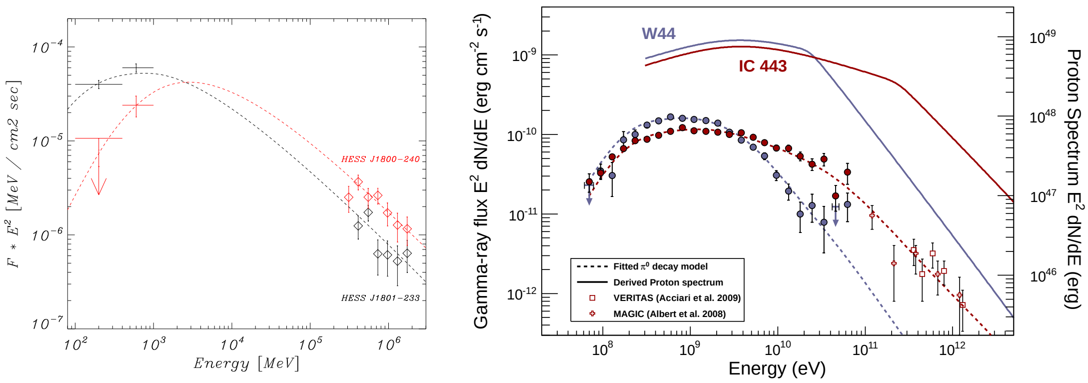

Figure 2: Left: GeV to TeV energy spectral distribution of the gamma-ray emission detected by AGILE and HESS toward the W28 field. The black and red lines correspond respectively to the northern and southern excess. Right: Spectral energy distribution of the SNRs W44 and IC 443. The dashed lines are hadronic model over-imposed on the spectra measured by Fermi-LAT. The solid lines show the hadron spectra corresponding to the gamma-ray model.

detection in the A region can be explain by diffusion effects. W28 is a prototype to test the effect of particle escaping the remnant when they are not anymore confined in the acceleration zone. Only the northern cloud is in the immediate vicinity of the shock, although the southern cloud is more distant and thus particle interacting into this cloud have already escaped the remnant. The propagation effect is visible on figure 2 *left* showing the measurement from Agile combined with the one obtained by HESS and a model of accelerated particle propagation outside the remnant. The spectral energy distribution of the southern source is visible in red. The peak in the distribution is shifted toward the highest energy compared to the blck one describing the northern cloud. It showes that the lowest energy particles did not reached the cloud yet and that they are still confined into the shock.

3.2 The pion decay signature

Recently, the Fermi-LAT collaboration has reported the detection of a pion decay signature in the gamma-ray spectrum of two interacting SNRs: IC 443 and W44 [15]. Figure 2 *right* showes the spectral points obtained by Fermi compared to a hadronic model (dotted lines). The solid lines indicate the original particle energy spectra that produced the modeled gamma-ray spectra. The very precise measurement of these strong GeV gamma-ray sources, combined with an improved data treatment reducing the energy threshold, helped to detect the pion decay spectral feature above a few tens of MeV. Here also a leptonic origin of the gamma-ray cannot be excluded but this scenario cannot easily reproduce the spectra without adding ad hoc features in the electron spectrum.

3.3 Common pictures

The number of detected sources, either at GeV and/or TeV energies, is now larger than ten and several common features appear. All these sources are bright GeV emitters with a spectral index in the GeV index close to 2, whereas in the TeV range, these sources are much fainter with a softer spectral index. This steepening of the spectra implies the presence of a spectral break in between that arrises around a few GeV. These recent detections triggered a lot of attempts to model the gamma-ray emission from those objects. Modeling the case of interacting supernova remnants needs to take into account the diffusion of accelerated particles around the remnant. It has been shown that the spectral break can be reproduced taking into account the finite volume of the cloud and the diffusion of particle within the cloud [16]. The low energy part of the spectra

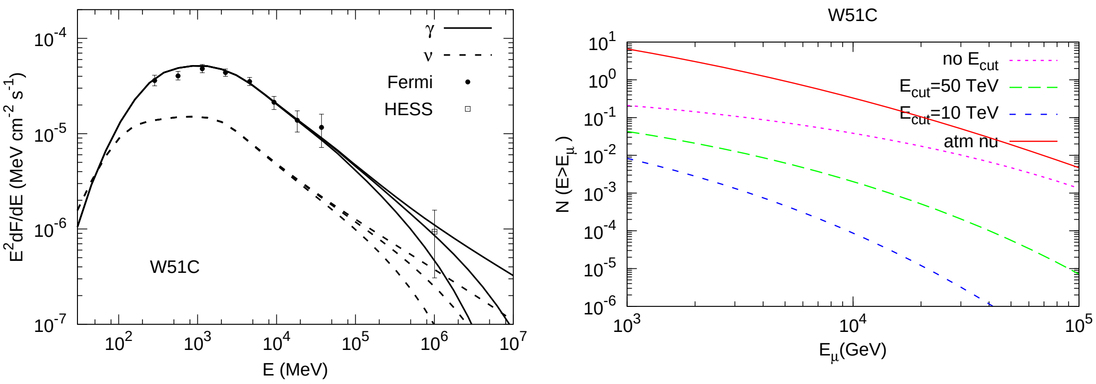

Figure 3: Left: GeV to TeV energy spectral distribution of the emission detected toward the W51 region. The solid lines are hadronic models reproducing the data with three different energy cuts of the particle spectrum considered. The dashed lines correspond to the associated neutrino flux. Right: Integrated neutrino flux as a function of the threshold energy detected by an IceCube-like detector in one year. The dotted and dashed lines corresponds to three particle spectrum cut-offs considered and are compared to the red solid line representing the number of atmospheric neutrinos detected during the same period.

is dominated by still confined particles which follow a spectral shape compatible with diffusive shock acceleration model. At high energy, the particles are not confined in the acceleration zone and are diffusing into the cloud that could extend further than the shock region. This diffusion is responsible for the energy break that arises around a few GeV.

4 Other view angles for interacting SNRs

4.1 Neutrinos

A definitive answer concerning the origin of the detected gamma-rays could come from the detection of associated neutrinos. The gamma-rays are prodiced when π^0 produced in hadronic inelastic interaction decay into photon pairs. These π^0 are produced with associated $\pi^{\pm}$ that decay producing neutrinos. The detection of neutrinos from supernova remnants would thus confirm unambiguously the presence of accelerated hadrons. Unfortunately, the effective area of current neutrino detectors such as Antares, IceCube or the future network Km3Net is too limited to be sensitive to the low neutrinos flux induced by interacting SNRs. Figure 3 left showes the expected neutrino fluxes from the SNR W51C [17]. The neutrino spectrum follows the same shape as the gamma-ray spectrum. The soft gamma-ray spectrum observed in the TeV range for most of the interacting SNRs leads to a soft neutrino spectrum above 1 TeV. Figure 3 right showes the expected number of detected neutrinos in one year. Even in the most favorable case with no energy cut-off below a few tens of TeV, the expected number of neutrinos is less than one per year (of the order of 1 per year for some remnants) with an atmospheric background event number at the same level in the most favorable case.

4.2 Low energy cosmic rays and molecular clouds

Not only the highest energy particles interact within molecular clouds. The lowest energy particles, much more abundant, have also an impact inside the clouds. They are more effective in ionizing the interstellar gas. This induced ionization has an impact on the cloud chemistry and can lead to visible effect. The enhanced ionization rate within interacting molecular clouds could be thus helpful to bring additional indication of the presence of accelerated particle. Recently, several studies has been led towards the known interacting remnants IC 443 [18] and W51C [19]. These millimetric observations pointed at several species which abundance ratio are directly proportional to the ionization rate inside the cloud. They showed that the ionization rate is larger by a factor 100 inside these clouds compared to clouds without accelerator nearby. It confirms that at least low energy particles are freshly accelerated by the SNRs and brings an additional confirmation that the observed gamma-rays from these clouds are originated in higher energy hadronic particle interactions.

5 Summary and perspectives

The class of interacting SNRs is a new field in rapid expansion. In the last five years, a lot of new candidates have been discovered, either at GeV or TeV energies. Individually these detections cannot be attributed undoubtedly to hadron particles interacting within the cloud. However, the accumulation of indications and the improvement in the spectral description of these emissions provide evidence that cosmic rays protons are effectively accelerated by supernova remnants.

Due to the rapidly falling spectra in the TeV band, current VHE observations do not have the same precision level brought in the GeV band by Fermi-LAT. In particular, the question of the highest energies, whether SNRs can accelerate particle up to the knee can be hardly solved with current detectors. The future VHE gamma-ray observatory CTA will bring a factor 10 in sensitivity and around a factor 5 in angular resolution compared to current telescopes. Observations with CTA of interacting SNRs will probably improve the measurement in the TeV range in the same order as Fermi-LAT did in the GeV band. More detections could be expected and the improved sensitivity and resolution will help disentangling between the different scenario.

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