# Proposal of CTA Science Cases

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# Topics and people of the proposals

## Galactic Sources

Galactic Center: Christopher van Eldik & Daniil Nekrassov

Galactic diffuse emission: Sabrina Casanova, Kathrin Egberts & Andrew Taylor

Microquasars/Binaries: Valentí Bosch-Ramon, Dmitry Khangulyan & Anja Szostek

SNR: Matthieu Renaud & Omar Tibolla

Clouds: Stefano Gabici

Unidentified Sources: Karl Kosack & Gerd Pühlhofer

## Extragalactic Sources

AGN, Blazars: Frank Rieger, Dmitry Khangulyan & Martin Raue

Clusters: Wilfried Domainko

## Others

Cosmic rays, Composition: Andrew Taylor, Rolf Buehler & Kathrin Egberts

# Galactic Centre Observations with CTA

Christopher van Eldik and Daniil Nekrassov

## 1 The Galactic Centre in VHE $\gamma$-rays

The detection of very-high-energy (VHE) $\gamma$-rays from the direction of the Galactic Centre (GC) by several Cherenkov instruments [1, 2, 3, 4] has established the existence of particle acceleration to multi-TeV energies within the central few pc of our galaxy. VHE $\gamma$-rays, produced in interactions of these energetic particles with ambient material, magnetic fields, or low-energy photons, are an excellent tool to trace the particle accelerators, to learn about the particles' leptonic or hadronic nature, and are a key ingredient to study particle diffusion from the sites of acceleration into a highly turbulent environment.

The H.E.S.S. experiment delivers the at date most sensitive VHE $\gamma$-ray images of the GC region [5]. The data reveal the existence of three discrete VHE $\gamma$-ray sources and the presence of diffuse VHE $\gamma$-ray emission correlated with dense molecular clouds.
The strongest source, HESS J1745-290, is within 7" coincident with Sgr A$^*$ [6]. However, source confusion near the GC make a solid identification difficult, given the – compared to X-ray satellites or infrared observatories – moderate angular resolution of current Cherenkov telescopes. Recently, however, by improving on the systematic and statical errors of the centroid of HESS J1745-290, Sgr A East could effectively be excluded as the dominant $\gamma$-ray source in this region [10]. Besides Sgr A$^*$, the PWN G359.95-0.04 remains a prime candidate for the $\gamma$-ray emission [8]. Limits on a possible contribution to the $\gamma$-ray signal of HESS J1745-290 from the annihilation of Dark Matter particles accumulated at the GC are discussed in [6].

The strikingly good correlation of diffuse $\gamma$-ray emission with the density of molecular clouds within ±150 pc around the GC favours a scenario whereby cosmic rays interact with the clouds' material and produce $\gamma$-rays via production and decay of neutral pions. The differential $\gamma$-ray flux is stronger and harder than expected from just "passive" illumination of the clouds by Galactic cosmic rays, suggesting one or more nearby particle accelerators to be present. In a first approach the observed $\gamma$-ray morphology can be explained by cosmic rays diffusing away from an accelerator near the GC into the surroundings. Adapting a diffusion coefficient of $D = O(10^{30})$ cm$^2$s$^{-1}$, the lack of VHE $\gamma$-ray emission beyond 150 pc in this model points to an accelerator age of not more than $10^4$ years [5]. Recent simulations have, however, indicated that the $\gamma$-ray emission might be better explained by inter-cloud acceleration of these cosmic rays via the Fermi-II process [9]. A leptonic origin of the $\gamma$-rays is also not fully ruled out, but would require a number of not yet detected sources (e.g. PWNe) correlated with the molecular cloud density.

## 2 The Role of CTA

Despite the exciting progress in recent years, a robust understanding of the GC VHE $\gamma$-ray sky needs a more refined data set than currently available. Significant progress in the identification of the VHE sources and the physics processes involved requires an instrument with better sensitivity, wider energy coverage, and, possibly, improved angular resolution. Probing the GC region with CTA will answer many of the open questions within a reasonable amount of observing time.

For the following order-of-magnitude estimations we assume a CTA sensitivity of O(1 mCrab), 4 orders of magnitude energy coverage (10 GeV – 100 TeV), and an angular resolution of 0.02° per event.

## 2.1 Angular resolution

One way of identifying HESS J1745-290 is to search for plausible candidate counterparts within the error circle of the emission centroid. Since the GC is a densely packed region, naively, a good angular resolution $\theta$ is important. Since the statistical error of the centroid position scales like $\theta/sqrt(N_\gamma)$, and therefore linearly with sensitivity, a factor of 50 improvement over H.E.S.S. (6.4" per axis for 73 hours of exposure, [10]) is expected. On the other hand, the systematic pointing error of the H.E.S.S. telescopes is about 5" per axis [10], probably close to the limit of what can be achieved with future instruments. In the special case of HESS J1745-290, subtracting the underlying (asymmetric) diffuse emission imposes additional systematic uncertainties, which for H.E.S.S. are of the order of 1". As a consequence, improved angular resolution is not of much help what regards a measurement of HESS J1745-290's position.

On the other hand, the superior angular resolution of CTA would help in understanding the properties of the diffuse emission. It would allow to probe the region with a few pc binning and test the $\gamma$-ray-cloud correlation in much more detail than currently possible. In this way one might also get a handle on the possible existence of electron accelerators along the Galactic Plane, which might or might not be responsible for the observed $\gamma$-ray emission in parts or in total.

## 2.2 Sensitivity

An unambigous proof that the VHE $\gamma$-ray emission from HESS J1745-290 is associated with Sgr A$^*$ would be the observation of correlated $\gamma$-ray/X-ray (or infrared) variability. Simultaneous H.E.S.S./Chandra observations during a major (factor of 9 flux increase) X-ray flare of 1.7 ks duration have so far resulted in an upper limit on a flaring component in the VHE $\gamma$-ray flux of 100% of its quiescent level (99% CL) [7]. With the assumed CTA sensitivity similar X-ray flare events would test a level as low as 10% of the quiescent state $\gamma$-ray flux.

To test models of cosmic ray/electron propagation through the central region of the galaxy and study the penetration of molecular clouds by cosmic rays, energy spectra have to be provided of the diffuse $\gamma$-ray emission in small regions of a few 10 pc × a few 10 pc only. With these, energy-dependent diffusion processes could be studied in great detail. For a simple power-law fit, the statistical error on the spectral index scales linearly with sensitivity. Therefore, a spectrum measured by CTA in a $0.1^\circ \times 0.1^\circ$ portion of the sky (in the H.E.S.S. energy range) will reach comparable statistical accuracy in the spectral index as H.E.S.S. in a $1^\circ \times 1^\circ$ sky area (e.g. $\Delta\Gamma_{stat} = 0.07$ for 50 hours of observations of the GC diffuse emission [5]).

### 2.3 Energy coverage

The energy spectrum of HESS J1745-290 covers an energy range of 160 GeV – 30 TeV and is well fitted by a straight powerlaw [6]. For the most likely counterparts of the VHE emission, Sgr A$^*$ and G359.95-0.04, emission models fitting the combined spectral energy distributions have been presented by various authors (e.g. [8], [11], among others). While most models can satisfactorily fit the H.E.S.S. data points, they do substantially differ at energies $< 100$ GeV. CTA energy coverage down to 10 GeV would immediately rule out some of the models, and therefore help to identify the source of the $\gamma$-rays and the underlying physical acceleration and radiation processes.

## 3 Observational requirements

A compared to H.E.S.S. by a factor of 10 enhanced sensitivity and an energy coverage down to 10 GeV are probably the most important requirements to CTA what regards Galactic Centre observations. Superior angular resolution compared to H.E.S.S. (at least by a factor of 5) allows for more detailed morphological studies of the diffuse emission. Simultaneous flare observations with X-ray or infrared observatories are of importance to establish or reject the idea of an association of HESS J1745-290 with the particle distribution from Sgr A$^*$ responsible for X-ray/infrared flares.

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# Galactic diffuse sources

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## 1 Sources of cosmic rays and Galactic diffuse sources

The main motivation for studying the angular and spectral features of diffuse $\gamma$ ray emission from the Galactic disk is that it can provide the density and energy spectra of cosmic rays (CRs) in different locations of the Galaxy, and therefore it helps in solving the longstanding problem concerning the origin of cosmic rays. The direct observation of cosmic rays from these candidate injection sites is not possible since CRs diffuse into the Galactic magnetic fields, and the contribution from individual sources merge into the "sea" of background cosmic rays, losing the information on the original acceleration locations and spectra. However, before diffusing into the magnetic fields, the newly injected cosmic rays scatter off the local gas and produce $\gamma$-ray emission, which can significantly differ from the the diffuse emission contributed by the "sea" CRs because of the hardness of the young spectrum, not yet steepened by diffusion. The extension of such diffuse sources does not generally exceed a few hundreds parsecs, the scale at which the spectra of freshly injected CRs can significantly differ from the spectrum of the CR "sea". These diffuse sources are often correlated with dense molecular clouds which act as target of the local enhanced CR injection spectrum which, due to the stochastic nature of the CR source events, varies not only in location, but also in time. On the other hand the $\gamma$-rays emitted in the Galactic disk by "sea" CRs, particles which have already diffused and have a softened spectrum, contain the information on the propagation processes the cosmic rays undergo and provide important inputs concerning the rate of CR acceleration and can help in solving the question whether the knee is a feature of CR sources or it is due to a space dependence of CR diffusion. This large scale emission is correlated mainly with the distribution of Galactic atomic and molecular hydrogen and, to lesser extent, to the ionized hydrogen component.

## 2 Observational goals

The detection strategies to pursue in order to solve the longstanding question of the origin of cosmic rays are:

1) to image the spectrum and the spatial distribution of the Galactic diffuse emission

2) to measure the highest possible energies

3) to compare images, spectra of $\gamma$-ray emission with those from other wavelengths (eg. radio + X-ray + lower energy gammas + possibly neutrinos)

4) to estimate the level of diffuse emission due to unresolved sources

1) The analysis of the spectral and spatial distribution of the Galactic diffuse emission can be broken down into two sections; **global studies** of the entire distribution of gamma ray emission on the sky, leading to information on the large scale distribution and bulk properties of CR sources, and studies of **local gamma ray sources**, leading to information on the location and nature of specific CR sources. HESS detection of hard spectrum $\gamma$-ray emission from the Galactic Center region proves that high sensitivity air Cherenkov detectors are able to beautifully image the diffuse emission on small scales [1]. Milagro achieved the first measurements of TeV diffuse emission from two extended regions of the Galactic Plane, the Cygnus Region and the Milagro inner Galaxy [2, 3]. The emission from the Cygnus Region is most probably produced by particles scattering off gas located at about 1 kpc from the Sun, as suggested by the small spread in velocity in the CO maps at these longitudes. Since this region has an angular extension of about 20 degrees, it must be about 300 parsecs, small enough for young accelerators to strongly influence the $\gamma$ emission. The Milagro inner Galaxy is instead a much larger diffuse source. The $\gamma$-rays from this region are emitted in very different regions of the Galactic disk and the emission shows the features of averaging along the line of sight. Although the small latitude extent of Milagro measurements seem to suggest a hadronic origin of the emission for both the Cygnus region and the inner Galaxy, Milagro observations are difficult to interpret since no spectral information is available and moreover a strong contribution from unresolved sources cannot be excluded. A more satisfactory interpretation of the emission could be obtained by measuring the spectral

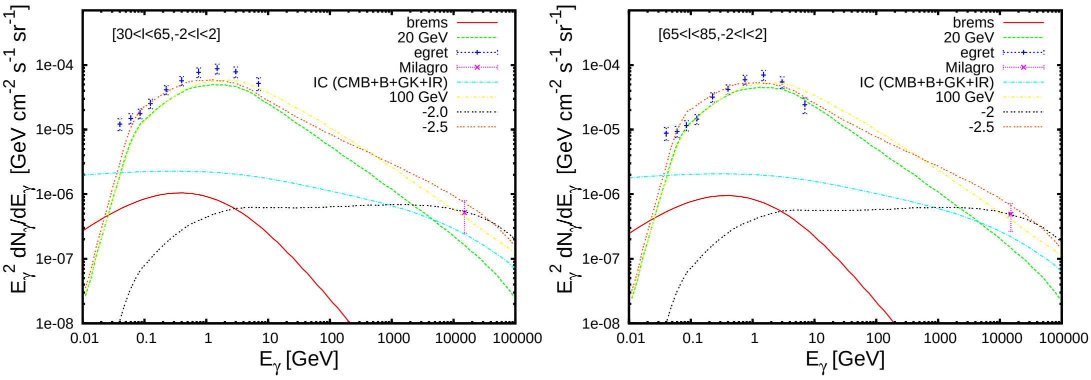

Figure 1: EGRET and Milagro data and flux predictions from hadronic and leptonic processes for Milagro inner Galaxy and for the Cygnus region are shown. The electron spectral slope is assumed to be -2.15. The proton spectrum is either a power law with an exponential cutoff with slope -2.5 or -2.0 or a hard power law with slope -2.1 below 20 GeV or 100 GeV which steepens to -2.75 for higher energy due to diffusive losses . The electron density equal to 0.075 $\frac{eV}{cm}^3$, whereas the proton density is 1 $\frac{eV}{cm}^3$, and the average column density is $22\,10^{22}\,cm^{-2}$.

slope of the emission. In Fig.1 and Fig.2 the diffuse emission from Milagro inner Galaxy and from the Cygnus region measured by EGRET and Milagro are shown together with model predictions for different electron and proton spectra. The contributions from pion decay for diverse proton spectra, from electron bremsstrahlung and inverse Compton scattering off microwave, optical and infrared radiation fields are shown. The electron and proton energy densities, as well as the gas column density are free parameters in such calculations. Also, the lepton spectrum and the radiation fields are highly uncertain. However, measurements done with a differential sensitivity of about $5\,10^{-13}\,cm^{-2}\,s^{-1}\,GeV^{-1}\,sr^{-1}$ (= 5 Crab/sr) at 1 TeV for extended sources could provide some clues concerning the feature of cosmic ray propagation (see Fig.1).

2) Broad band observations of diffuse $\gamma$-ray sources are crucial in order to have a complete picture of the CR density and energy spectra in the Galaxy. The observations of 100 TeV gamma rays emitted by CRs with energies close to the knee at $10^3$ are of special importance, as the spectral break might be due to the spectrum of cosmic ray sources, the escape of the cosmic rays from the Galaxy, a combination of the two effects, or even a single nearby source. At TeV and multi-TeV energies, the two dominant $\gamma$-ray production channels are hadronic, via CR proton collisions with ambient gas (pion production) and leptonic, through CR electrons up-scattering ambient radiation (inverse Compton scattering). Due to competing leptonic mechanisms, which are generally more efficient in emitting $\gamma$-rays, it is very difficult to probe the acceleration of hadrons within Galactic sources. The highest energy observations are key to distinguishing $\gamma$-rays produced by electrons from those produced by hadrons. There are in fact observational differences in the TeV $\gamma$-ray spectrum from electron accelerators and proton accelerators accessible to CTA. Electrons lose their energy more quickly than protons through synchrotron emission and are therefore more difficult to accelerate to the highest energies, close to the knee energy. Also, at tens of TeVs the evaluation of the electron IC contribution to the $\gamma$-emission, which is general difficult because electrons produce $\gamma$s through scattering off anisotropic radiation fields, is dominated by the scattering off the isotropic microwave background photons. Finally, the cross section for inverse Compton (IC) scattering decreases at higher energies, resulting in a break in the gamma-ray spectrum at energies around 50-100 TeV. Gamma rays from hadronic cascades in the accelerating region, on the other hand, follow the power law spectrum of the particles initiating the cascades up to the highest energies.

3) To pinpoint the sources of cosmic rays it is crucial to compare high spatial resolution $\gamma$-ray maps and atomic and molecular line observations tracing the matter density of the ISM. Regions of enhanced or unusual gamma ray emission, which cannot be explained on the basis of an interaction between higher matter density or particular ISM conditions and a constant steady CR flux, point to local variations in the flux or spectrum of the CRs. The comparison of images and spectra of $\gamma$-ray emission with X-ray is crucial to understand the lepton spectrum.

4) A major difficulty when measuring diffuse emission is to identify the truly diffuse $\gamma$-ray emission from the contribution of weak unresolved sources. For instance, many extended sources observed by EGRET and HESS, which are still unidentified and have diverse gamma ray spectra, may possibly be explained as dense molecular clouds illuminated by either the CR sea (passive clouds) or as young accelerators close to dense molecular clouds, and their total contribution might be a significant component of the detected excess in the diffuse emission measured at GeV and TeV energies by EGRET and Milagro, respectively. Source confusion

will be an issue for AGILE and GLAST, which could resolve passive clouds if the cloud parameter $\frac{M_5}{d^2} > 0.1$ for energies below 1 GeV, and $\frac{M_5}{d^2} > 10$ at higher energies. Here, $M_5$ is the mass of the cloud divided by $10^5$ solar masses and $d$ is the distance of the cloud in kilo-parsecs from the detector. Population studies of the HESS source population show that CTA will be able to resolve 10 times more sources than HESS, and this will help in constraining the amount of diffuse emission due to unresolved sources [5]. CTA could also help in disentangling the diffuse emission measured by future survey detectors such as HAWC.

## 3 Diffuse neutrino flux

For hadronic models, in which the origin of the GeV-multi TeV diffuse $\gamma$-ray flux originates from the cosmic ray proton population, a corresponding large scale diffuse $\nu$-flux is produced as a by-product. Interestingly, as demonstrated from a simple convolution of the produced $\nu$-flux with the effective detection area for the upcoming $\mathrm{km}^3$ $\nu$ telescope KM3NeT, this diffuse $\nu$-flux is found to be one of the few promissing detectable sources [4]. However, of crucial importance in these calculations is how high in energy the Galactic proton flux goes before their acceleration mechanism turns off.For this reason, measurements by CTA in the highest energy (100 TeV) end hold the promise of shedding light on the cutoff energy of the large scale diffuse $\gamma$-ray emission, and hence provide invaluable insight for these diffuse $\nu$-flux calculations.

## 4 Technical requirements for CTA

- good sensitivity for extended sources on a large energy range between 100 GeV up to 100 TeV
- field of view between 5 and 8 degrees
- good angular resolution at the level of 0.01 degrees, comparable to the angular resolution of the atomic and molecular line observational data (the angular resolution of the NANTEN2 survey is 0.070 degrees)
- good energy resolution

## 5 Analysis Issues

The main difficulty in any analysis of diffuse emission is the determination of the dominant background of hadronic cosmic rays. The background of large emission regions cannot be modelled from spatially displaced regions without any $\gamma$-ray sources in the same field of view, as is done in standard source analyses of current imaging atmospheric Cherenkov telescopes [6]. In order to avoid dedicated observations of empty fields and the resulting loss of observation time spent on $\gamma$-ray sources, tools were developed to determine the background from events that are not displaced spatially but in image-shape parameter space [7]: In the analysis, cuts on image-shape parameters are applied to reduce the large number of background events in the data set. Instead of discarding all events that do not pass these selection cuts, an interval in the background-dominated part of the image-shape parameter distribution is chosen to estimate the background level. If the shape of the image-shape parameter distribution of the background events is known (i.e. from simulations) the number of background events in the signal region can be deduced. This method allows the analysis of even largely extended emission regions covering the full field of view.

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# CTA Observations of Binary Systems/Microquasars

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# 1 Introduction

Binary systems/Microquasars (BS/MQ) are an important class of TeV sources given the wealth of very high energy (VHE) processes that are expected to occur in them. As it was shown by Khangulyan et al. (2008), several physical processes are to be taken into account to understand VHE emission from BS/MQ. One of these processes is particle acceleration in extreme conditions, which is an important issue to study for astrophysics in general. Another one is the TeV emission mechanism occurring under strongly variable conditions (e.g. orbital motion); this includes the emitting particle nature. Finally, the particle transport/structure of the VHE emitter, which is a result of a combination of MHD, photon-photon absorption/electromagnetic cascading and diffusion, can be studied.

# 2 Why CTA science?

For a deeper study of the mentioned physical processes taking place in BS/MQ, one needs to go beyond the present VHE instrumentation. The relevant timescales in BS/MQ are determined either by cooling or by escape losses, being $\sim 1000$ s (Khangulyan et al. 2008), and a proper study of the source would require at least a 5 $\sigma$ detection for $\sim$ one hour exposures. Therefore, given the fluxes of this kind of sources (Aharonian et al. 2005a, 2005b, 2006; Albert et al. 2006, 2007), none of the operating VHE instruments (e.g. HESS, MAGIC), nor the forthcoming updated versions of them (HESS II and MAGIC II), can provide with the required data quality in the mentioned timescales. Also, at $\sim$ 10–100 GeV, CTA can sample the radiation at sub-orbital timescales in BS/MQ, which is not possible for GLAST.

As shown below, CTA fulfills the conditions that are needed for a detailed and comprehensive approach to these processes. Different configurations will allow to investigate different physical processes in detail. We list these processes and the instrumental requirements in the following Section.

# 3 Observational requirements

A configuration with good sensitivity in the range 10–100 TeV will allow us to probe the next physical properties: acceleration rate, strength of the magnetic field, intrinsic orbital/short timescale variability of the accelerator/emitter, and the emitting particle nature. This will be possible since the opacity and orbital dependence of photon-photon absorption, and the angular IC dependence, sources of extrinsic variability, are smaller in this energy range. In addition, the spectrum of the emission is expected to be different depending on whether the emitting particles are protons or electrons.

For good sensitivities below 0.1 TeV, unlike GLAST, CTA will probe time-scales shorter than the orbital period. *Low energy* transient activity and the orbital evolution of the emission will be

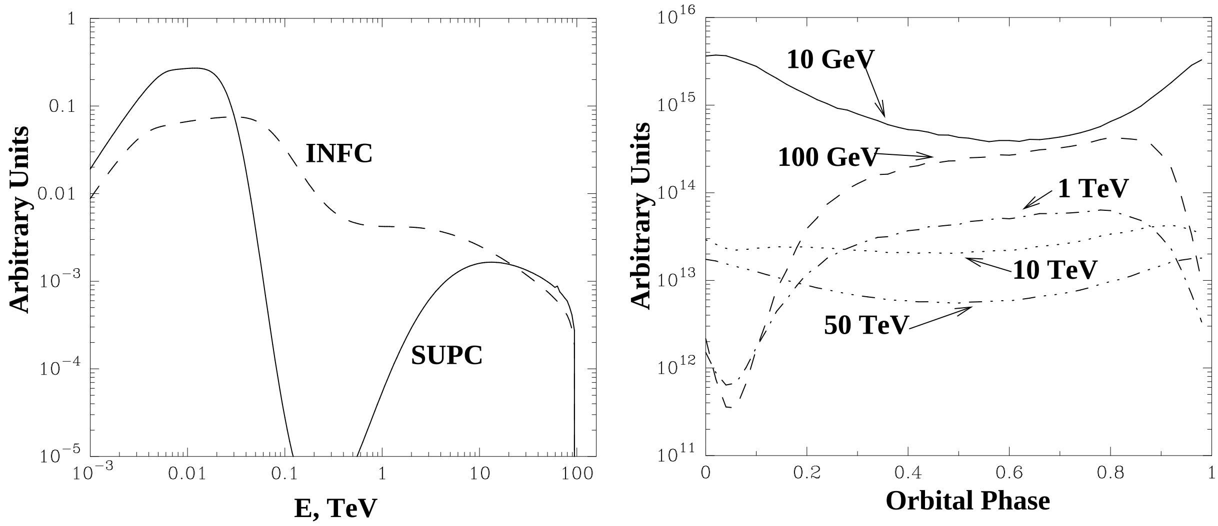

Figure 1: LEFT: Computed VHE spectral energy distribution for two different orbital phases of LS 5039: superior conjuction (SUPC; phase 0.06) and inferior conjunction (INFC; phase 0.72) of the compact object. RIGHT: Computed orbital lightcurves for different energies: $E = 0.01$, 0.1, 1, 10, 50 TeV.

probed. This, in combination with higher energy data, will give very strong constraints on the stellar environment magnetic field and the occurrence of electromagnetic cascading at the key energies.

For good sensitivities between 0.1–10 TeV, high quality data will be obtained allowing accurate orbital variability and spectral modeling. This will permit the extraction of information about the impact of the orbital motion, particle propagation and photon-photon absorption/electromagnetic cascading in the emission. An example of the importance of good spectral sampling along the orbit is given in Figure 1 (left panel), where the computed spectral energy distributions for the emission produced in two different orbital phases are shown. This figure illustrates the strong variations of the radiation properties along the orbit. Intrinsic orbital/short time-scale variability can be better used to extract information when combining data from 0.1–10 TeV and above 10 TeV. In addition, data below 0.1 TeV and 0.1–10 TeV will strengthen the constraints on the conditions for the electromagnetic cascading occurrence, giving also important information on the location of the emitter. An example of the importance of having multiwavelength lightcurves at VHE is exemplified in the right panel of the figure, where lightcurves at 10 GeV, 100 GeV, 10 TeV and 50 TeV show important differences that may used to constrain the emitter properties.

Concerning the energy resolution, relatively "smooth" power-laws are expected in BS/MQ. In general, BS/MQ observations do not have particular energy resolution requirements except when very soft slopes at few 10 GeV occur due to absorption, although this should not be critical.

The angular resolution, of about 1 arcminute, does not allow to resolve the compact systems ($\leq$ AU) harboring the TeV emitter, which implies that one should not worry about this issue. It is worthy noting nevertheless that the improvement of a factor of few that CTA represents with respect to previous instruments, and the jump in sensitivity (whatever the configuration one may adopt), will significantly increase in any case the chances to detect very high-energy emission from the termination regions of BS/MQ outflows, expected to be produced at sub-pc and pc scales, i.e. at angular distances of few arcminutes.

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# Supernova remnants: Perspectives with CTA

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# 1 Introduction

Since the first speculation of Baade & Zwicky in 1934, the question of the supernova remnants (SNRs) being the main sources of the galactic cosmic-rays (CRs) up to the knee (~ 3 PeV) and beyond is not yet settled, in spite of several decades of important observational and theoretical investigations [11, for a recent review]. The broadband spectrum of such sources, from radio to very-high energy (VHE; > 100 GeV) domains, is the signature of particles accelerated at the shock fronts and radiating photons through several channels (synchrotron, non-thermal bremsstralhung, inverse-Compton and $\pi^0$ decay). Therefore, it represents by far our best access to the acceleration processes in SNRs [17]. Thanks to the current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) such as H.E.S.S., three SNRs (RX J1713.7-3946, RX J0852-4622 and RCW 86) have recently been confirmed as VHE sources [3, 10, 14, 9, 15, 16] exhibiting a shell-type morphology. However, the nature of the VHE emission is still a matter of intense debate [18, 20, 19, 21]. On one hand, the correlation between X-ray and TeV emission supports the leptonic scenario but implies a spatially-averaged magnetic field of the order of 10 $\mu$G. This value seems uncomfortably low in comparison with the theoretical prediction of magnetic field amplication associated with the efficient production of cosmic rays by (non-linear) diffusive shock acceleration (DSA) [2, 22]. Magnetic fields of the order of a few 100 $\mu$G have been derived from the measured thinness of the X-ray filaments in several young SNRs [4] in case these filaments effectively reflect the synchrotron losses of high-energy electrons in strong (amplified) B-fields [5, for an alternative explanation]. On the other hand, the lack of correlation between the tracers of the ambient matter and the TeV emission together with the constraints on the local density derived from the absence (or the faint level) of thermal X-ray emission prevent from drawing firm conclusions in favor of an hadronic origin in these three shell-type SNRs. Besides the debate on the nature of the VHE emission, several other important questions related to the acceleration mechanisms remain open; for instance, the maximal energy that particles can reach throughout the SNR evolution is still unclear even though some recent works have provided with new insights in this regard [13, and references therein]. Therefore, the high acceleration efficiencies, amplified magnetic fields, and large shock modifications predicted by the non-linear DSA theory need to be confronted to the observations of several shell-type SNRs, from radio to VHE domains, all together.

# 2 Why CTA science?

Although current VHE observations have shown that multi-TeV particles are being accelerated in the above-mentionned SNRs at their respective evolutionnary stages, they could not allow us to clearly state that these SNRs are those responsible for the bulk of Galactic CRs because, first, there is no *direct* observational evidence that protons indeed are being efficiently accelerated. Second, even in this case, the maximal energy these protons (and nuclei) have been able to reach in these three SNRs before starting to escape (theoretically thought to be at the beginning of the Sedov-Taylor phase [6]) may not be that currently measured through the VHE spectrum. For instance, the observed cutoff in the spectrum of RX J1713.7-3946 lies at ~ 100 TeV (in terms of particle energy) [14], *i.e.* more than a decade below the knee of the CR spectrum. One would then need to detect several SNRs in the act of accelerating particles up to 3 PeV and beyond. The first point arises from a combined lack of angular resolution and sensitivity of the current generation of IACTs, as shown in Figure 1 (left). The second point is entirely due to a lack of sensitivity (Figure 1, right) which limits the detection of many more SNRs and especially the remnants of historical Galactic SNe (*e.g.* SN 1006, Kepler, Tycho) whose external parameters (age, distance, circumstellar/interstellar medium) are known or at least better constrained.

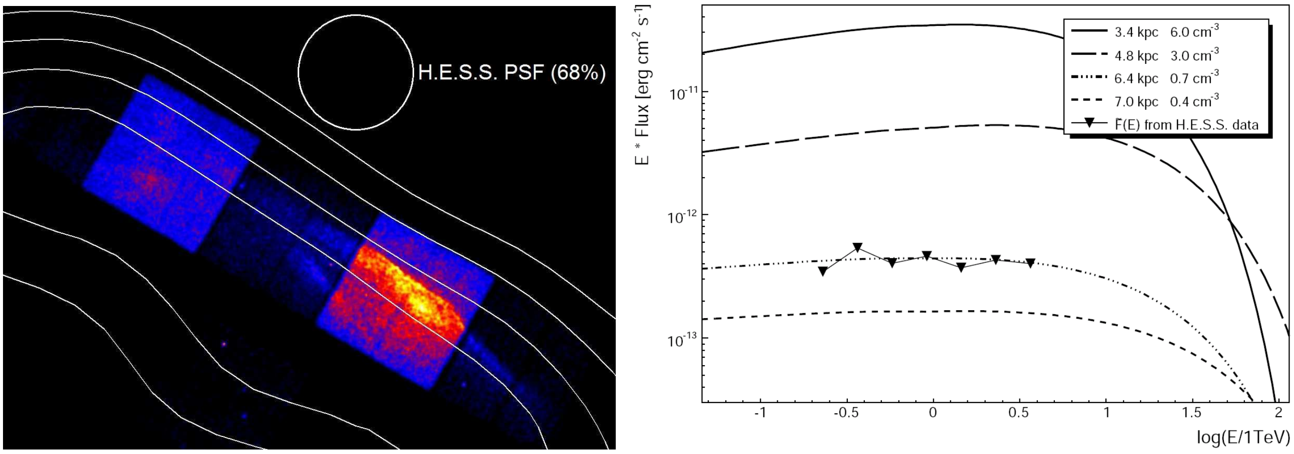

Figure 1: Left: Chandra image of RX J0852-4622 with the H.E.S.S. contours superimposed. The H.E.S.S. PSF is also shown by the white circle. Right: Kepler spectrum as predicted by [12] together with the H.E.S.S. constraints [23]. One can clearly see that an instrument 10 times more sensitive will easily detect Kepler's SNR, even in the less favorable case (larger distance and smaller density) and will bring important constraints in the cutoff region. The same also holds for SN 1006 and Tycho SNRs.

# 3 Observational requirements

- **Field of view:** RX J1713.7-3946, RX J0852-4622 and RCW 86 are extended sources, at the degree scales. Thanks to its large field of view ( ~ 5°), H.E.S.S. has been able to image these three shell-type SNRs. Therefore, in order to study their morphology in more detail, CTA should have a field of view at least similar to that of H.E.S.S..

- **Sensitivity:** One of the most important observational requirements for shell-type SNRs is the sensitivity. By improving the sensitivity of the current IACTs by a factor of 10 between ~ 50 GeV and > 100 TeV, CTA should easily detect other SNRs such as the remnants of the historical SNe SN 1006 and Kepler, according to detailed non-linear DSA models [8, 12]. So far, only upper limits have been derived from the H.E.S.S. observations of these two SNRs [7, 23].

- **Angular resolution:** A factor of 10 in sensitivity should be accompanied by a significant improvement of the angular resolution. Current simulations show that a PSF of the order of five times better than that of H.E.S.S. could be reached (*i.e.* ~ 1 arcmin). As mentionned before, the nature of the VHE emission is tightly linked to that of the X-ray filaments. If the strong magnetic field is efficiently damped downstream at the ~ 0.1 pc scale [5], all of the accelerated electrons responsible for the VHE emission might not feel the same B-field and a pure leptonic scenario might still explain the broad-band spectrum of the VHE SNRs. Such damping scale would correspond to 1 arcmin at a distance of ~ 350 pc, *i.e.* of the order of that of RX J0852-4622.

- **Energy coverage:** Covering the energy range between ~ 50 GeV (where *GLAST* will probably suffer from a lack of sensitivity) and > 100 TeV with a ~ mCrab sensitivity will allow us to determine with CTA the spectra of shell-type SNRs accurately. Such measurements could reveal the concavity predicted by the non-linear DSA theory. Moreover, CTA will have a better sensitivity than H.E.S.S.-II and *GLAST* at ~ 50 GeV and will not suffer from systematical effects while combining the results from these two different instruments. At high energies (*i.e.* 100 TeV and above), CTA will be the unique instrument to measure the spectrum of young SNRs in the cutoff region.

- **Relation with other observatories:** Shell-type SNRs are sources of interest for the upcomming instruments in the radio (SKA, LOFAR) and soft/hard X-ray (*Simbol-X*, *NEXT*) domains. The former will be able to study the morphology of the radio emission (filamentary structure?) and to measure the concavity in the synchrotron spectra [1]. The latter will allow us to study in great details the morphology of the filaments beyond 10 keV for the first time. Together with these observatories and *GLAST* (covering the range between 20 MeV and ~ 50 GeV), CTA should shed further light on these important Galactic sources.

## 4 Response of CTA

In addition to an optimal gamma-hadron separation over a broad energy range, simulations focusing on the final angular resolution of several CTA configurations are highly desirable, especially in the case of extended (at the degree scales) and potentially weak sources, such as previously unknown SNRs and Superbubbles (SBs). In Table 1 are listed the performance parameters desirable for the different classes of shell-type SNRs discussed before.

Table 1: Performance parameters desirable for studying different classes of shell-type SNRs. 1 cross: good, 2 crosses: improvements welcome, 3 crosses: key parameter.

| | ~ 50 GeV concavity? | > 100 TeV cutoff | S ~ 1 mCrab population studies | PSF ~ 1′ fine morphology | FOV ≥ 5° source extent |
|---|---|---|---|---|---|
| Known VHE SNRs | XX | XX | XX | XXX | XXX |
| Young SNRs | X | XXX | XXX | XX | X |
| Other known SNRs | X | X | XXX | X | XX |
| Others (*e.g.* SBs) | X | XX | XXX | X | XXX |

Below, we summarize the key aspects of the CTA scientific case regarding shell-type SNRs:

- **Population studies**: thanks to its higher sensitivity, CTA will be the only experiment able to perform population studies of the VHE shell-type SNRs, increasing the number of known SNRs (potentially seven so far: RX J1713.7-3946, RX J0852-4622, RCW 86, CTB 37A, CTB 37B, IC 443 and Cas A) and allowing us to study these objects at different stages of their evolution.
- **Youngest SNRs**: thanks to its higher sensitivity and to its large energy range, CTA will be the only experiment able to easily detect in the VHE domain the youngest SNRs that are now entering in the Sedov phase, such as Tycho (if CTA is located in the Northern hemisphere), Kepler and SN 1006 SNRs (if CTA is located in the Southern hemisphere). Moreover, CTA will offer the unique opportunity to study the spectra of these sources up to the cut-off region at ≥ 100 TeV, crucial to determine the maximal energy the accelerated particles can reach in such young sources.
- **Non-linear DSA theory**: thanks to its large effective area and its improved angular resolution, CTA will be able to constraint the non-linear DSA theories through the expected concavity in the spectra of the brightest VHE SNRs (RX J1713.7-3946 and RX J0852-4622) and a detailed spectro-imaging study of the morphology of the VHE emission.

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# Molecular clouds: Perspectives with CTA

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The diffuse gamma ray emission from the Galacic disk is due to the decay of neutral pions produced during interactions between cosmic rays (CR) and interstellar matter. If, as a zeroth-order approximation, we assume that CRs are homogeneously distributed throughout the Galaxy, then the level of the gamma ray emission observed from a given direction is simply proportional to the gas column density. For this reason the gamma ray emission from directions intersecting dense regions, such as molecular clouds (MC), is expected to be enhanced [10, 2].

The gamma ray emission from a molecular cloud can be further enhanced if the cloud is located close to a source of CRs [3, 5]. In this case, CRs escaping from the accelerator can reach the cloud and produce there gamma rays. This component adds to the gamma ray emission from background CRs. A similar enhancement is expected if a CR accelerator is located inside a cloud [3].

Molecular clouds are generally referred to as *passive* if they are embedded in the Galactic CR background or as *active* if they are located close to CR sources [2]. The $\pi^0$ decay gamma ray flux and spectrum from a passive cloud depends only on the cloud mass and on the CR intensity and spectrum at the cloud location. Since the mass of a cloud can be measured from CO observations, passive clouds can be used as probes of the CR intensity at different location in the Galaxy. On the other hand, active clouds can reveal the presence and location of nearby CR accelerators, and thus their detection is important in connection with the problem of the origin of Galactic CRs. It is important to stress that, in the conventional scenario in which CRs are accelerated in the expanding shock wave of supernova remnants (SNR) or stellar winds, a correlation between CR sources and molecular clouds is indeed expected [12, 4].

Molecular clouds are extended objects with apparent size up to degree scale or more. They are characterized by a very irregular density profile, with dense sub-parsec scale cores. Imaging Atmospheric Cherenkov Telescopes are ideal instruments to study molecular clouds, since they can easily accommodate extended objects within their large field of view (5° or more) and study their morphology thanks to the good angular resolution of few arcminutes.

The capabilities of Cherenkov telescopes arrays in studying molecular clouds are demonstrated by the detections by H.E.S.S. of TeV gamma rays from molecular clouds located in regions of the Galaxy that exhibit an enhancement in the background CR density [7, 9]. Moreover, the gamma ray emission detected by MAGIC and VERITAS from the direction of the supernova remnant IC 443, is likely to be related to the presence of a dense molecular cloud [11, 14, 13]. This suggests that a next generation instrument like CTA, with better sensitivity and extended energy coverage will have a major impact on the field.

# CTA science and observational requirements

In this section we discuss briefly the potential of a telescope with a reference sensitivity of $10^{-14}$ TeV/cm$^2$/s at 1 TeV and angular resolution of $\sim 0.1°$. This sensitivity is roughly an order of magnitude better than the sensitivity of H.E.S.S.at the same energy.

We first consider the case of a passive cloud with mass $10^5 M_5$ solar masses and typical density $\sim 100$ cm$^{-3}$ located at a distance $d_{kpc}$ kpc. Such a cloud will appear as a very extended gamma ray source, with angular size $\vartheta \approx 1^\circ M_5^{1/3}/d_{kpc}$, requiring a large instrument field of view of several degrees or more. CTA will detect such clouds up to a distance of $\approx 2\ \delta\ M_5^{2/3}$ kpc, where $\delta$ represents the ratio between the CR intensity at the cloud location and the local one. Thus, CTA will detect passive clouds if they are located within a few kpc from the Sun or virtually everywhere in the Galaxy if clouds are located in regions where the value of $\delta$ significantly exceed 1. The detection of such clouds will allow to study possible deviations of the CR intensity throughout the Galaxy, an issue which is strictly connected to the fundamental problem of the CR injection and propagation in the interstellar medium.

Another issue concerns the diffusive penetration of CRs into molecular clouds. If the (unknown) diffusion coefficient inside a cloud is significantly smaller compared to the average Galactic one, then low energy CRs are excluded from the cloud, the gamma ray emission from the cloud is suppressed and its gamma ray spectrum appears harder than the CR spectrum. Both this effects are more pronounced in the densest central region of the cloud. With this respect, an angular resolution of the order of 1 arcmin will allow to resolve the inner part of the cloud and measure the degree of penetration of CRs into the cloud and thus put constraints on the diffusion coefficient [6].

The gamma ray flux from a molecular cloud is expected to be enhanced if the cloud is located close to a source of CRs. In the context of the SNR origin of CRs, it has been shown that clouds with a relatively small mass of $10^4$ solar masses located within $\approx$ 100 pc from a SNR and within few kpc from the Sun are expected to emit TeV photons at a flux level which is within the capabilities of currently operating telescopes [5]. For this reason, it has been suggested that at least some of the TeV unidentified sources detected by H.E.S.S.[8] and MILAGRO [1] might be in fact active clouds [5]. With CTA, the number of such sources is expected to increase dramatically (both more distant and less massive clouds will be detected) allowing to test the standard scenario for CR origin. Moreover, such a study will possibly allow to constrain the diffusion properties of CRs in the Galaxy, since the expected number of detectable active clouds depends on the value of the diffusion coefficient.

Another remarkable aspect of the problem is that Galactic CR sources are expected to accelerate particles at least up to PeV energies, namely, up to the position of the knee in the CR spectrum. Due to propagation effects, PeV particles escaping from the CR source reach the cloud first, and produce there gamma rays with a very hard spectrum peaking at an energy of $\approx$ 100 TeV. Thus, an array optimized to observe photons with energies up to hundreds of TeV, an energy region almost unexplored by currently operational telescopes, will have the chance to detect such sources and indirectly reveal the presence of a CR PeVatron [5].

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# CTA Unidentified Source Population

K. Kosack, G. Pühlhofer

## 1 Introduction

Though the science case for (re)observing *known* Galactic astrophysical objects with CTA is clear—we will be able to better understand the processes involved and make substantial model constraints—these results depend on being told what to look at by longer-wavelength instruments (e.g. in the GeV gamma-ray, X-ray, and radio wavebands). However, since CTA will have significantly better sensitivity than current VHE gamma-ray instruments, it will detect previously unknown sources and consideration must be placed on optimizing the array for making such discoveries. The only way to have an unbiased estimate of the Galactic source population that is accelerating *hadronic* cosmic rays is via gamma-ray surveys along the galactic plane. VHE observations are probing the highest energies currently accessible and are the most successful in discriminating sources which are above the Galactic diffuse emission. The HESS VHE Galactic Plane Survey has proven the capability of identifying both previously known and unknown astrophysical objects that are injecting high-energy particles into the Galaxy. Furthermore, more sensitive surveys of the Galactic plane will allow us to extend the VHE logN-logS distribution to fainter fluxes. This is required to separate individual sources from the diffuse galactic emission (see separate proposal), a typical technique used e.g. in X-ray astronomy (e.g. Colafrancesco & Giommi 2006), and allows for the testing of model predictions for source populations.

It is important to note that most of the Galactic sources in the HESS catalog are (or began as) unidentified sources—roughly 40% remain with unclear lower-energy counterparts to date Aharonian et al. (2005c, 2006, 2008, 2005b). These objects were predominantly discovered as part of the on-going HESS survey of the inner Galaxy, via scan-based observations where the target position was not known a priori. One explanation for such *unidentified VHE gamma-ray emitters* is simply that sufficient multi-wavelength data are not available to make a positive identification in longer wavelengths. Indeed, several unidentified VHE sources have recently been revealed to be "conventional" gamma-ray sources, such as a previously undiscovered supernova-remnants (e.g. Tian et al. 2008), or pulsar-wind-nebula candidates (e.g. Aharonian et al. 2007, 2005a). This clearly demonstrates the power of VHE observations for discovering new VHE sources. Instead of the traditional mode of observation, where radio, X-ray, and GeV gamma-ray instruments discover a source and VHE instruments follow, it may be possible that with more sensitive instruments many high-energy sources can be discovered first by CTA. A second explanation for the sources which remain unidentified is that there exists another type of VHE emitter which emits more strongly in the VHE band than in any other. Such a scenario may occur for example in some high-energy proton models, and even may be predicted for such an exotic phenomenon as a gamma-ray burst remnant Atoyan et al. (2006). In this case we may place considerable constraints on theoretical models of VHE gamma-ray production.

Finally, there is currently evidence for roughly 20 new sources in the Galactic Plane survey that are just below the detection threshold for HESS ($5\sigma$ after trials-factor correction). A large fraction of these *hot-spots* are likely real VHE sources that simply have too little exposure. As the sensitivity to weak sources increases, we expect the number of detected sources to approximately follow that shown in Figure 1. Assuming that most of these sources will be PWN or SNRs, this will allow detailed statistical studies of these types of objects, which is currently limited by low statistics.

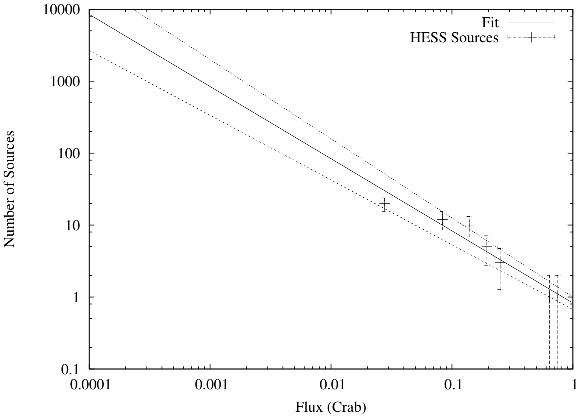

Figure 1: Differential logN-logS distribution of published HESS sources with a fit for extrapolation. This is a conservative estimate, not including unpublished or "hot-spot" sources, which would tend to make the slope steeper.

## 2 CTA Requirements

The unidentified sources in the HESS catalog share the following characteristics: **Extended emission** (non-point-like, $\sim 0.2°$ extension), **low flux** ($< 10\%$Crab), **Hard spectrum** ($\Gamma \sim 2.1$), and **located on galactic plane**.

**Sensitivity** Since the unidentified sources have so far relatively weak fluxes, currently at or near the detection threshold for the HESS Galactic plane survey, a higher-sensitivity instrument will allow more such sources to be detected (see Figure 1). The question of CTA sensitivity in this case is specifically for *extended* sources, which means that no increase in sensitivity can be achieved via increased angular resolution, and therefore *gamma/hadron separation* is the limiting factor that will need to be optimized.

A rough numerical argument based on HESS is as follows: we would need at least $10\sigma$ significance for a target to get reasonable statistics for a spectrum and minimal morphology studies (e.g. to get its extent assuming a 2D Gaussian shape). The HESS Scan data-set currently has roughly 20 "hot-spots"—possible sources which do not yet cross the trials-factor-corrected significance threshold to be considered confirmed discoveries. Assuming that these are all real sources, one can estimate the amount of time needed to both confirm and study them with reasonable statistics.

Given that the HESS Galactic Plane Survey, which has been underway for approximately 5 years, currently has (optimistically) 25 hours of exposure time at most positions directly along the galactic plane, and that the "hot-spots" currently are seen at a $\sim 5\sigma$ significance level, we can estimate the time needed to reach significance $S$, $\tau(S) = \left(\frac{S}{S_0/\sqrt{\tau_0}}\right)^2 \xrightarrow[\tau_0=25]{S_0=5} S^2$. Therefore, HESS would require 100 additional hours along the galactic plane to study and identify these sources, which with an estimated scan efficiency of 5 hours/year (limited by the finite observation time and field of view, both of which should be similar for CTA), this could take over 10 more years of scan observations.

With a 5x extended-source sensitivity increase, this requires 25x less observation time, or less than a year to detect and study the (at least) 20 new sources predicted by HESS.

**Energy Range** Given the generally hard-spectra of the current sources, the energy range covered by HESS is sufficient (100 GeV–10 TeV) for detecting such objects, and is the main recommendation of this proposal. However, source population studies will of course benefit from a wider energy range.

**Field-of-View** Discovering sources which are so far unidentified by other instruments obviously benefits from a large field-of-view and scan-based observations, since no target information is available.

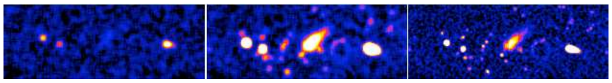

Figure 2: Comparison of CTA sensitivity and angular resolution to that of HESS (from toy-model simulation by G. Hermann et al.) *Left:* HESS angular resolution (0.1°) and sensitivity, *Center:* 10x HESS sensitivity with same angular resolution (not all sources are resolvable), *Right:* 10x HESS sensitivity with 0.05° resolution.

**Angular Resolution** Though increased angular resolution has only limited benefit for extended-source sensitivity, it is nevertheless crucial for identifying sources. From the current distribution of hot-spots in the HESS survey, we can estimate source confusion is not yet the limiting factor for resolving new sources with CTA-like sensitivity. Though it has been a problem for at least some of the unidentified sources, and will increase with sensitivity, we do not expect such a dense population of sources that we will not be able to identify a major fraction of them.

High angular resolution will be primarily beneficial for morphology studies, Since these objects are extended, studying their morphology is important for initially characterizing their origin and for comparisons with follow-up observations by longer-wavelength instruments, which are generally higher-resolution than current ACTs. As current HESS resolution of $\sim 0.1 - 0.07°$ at high energies is insufficient, one would ideally want a resolution of at least 0.04° to disentangle the emission from the brighter unidentified sources (see the proposal *High precision observations of unidentified sources with CTA*, G. Pühlhofer and K. Kosack). Since angular resolution is related to the telescope multiplicity, a more densely-packed array would be favored here, however detailed simulations will need to be made to optimize the resolution at 1 TeV.

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# CTA AGN proposal: Testing particle acceleration close to the supermassive black hole horizon in M87

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## 1 Introduction

HESS observations of the giant elliptical radio galaxy M87 (distance d$\sim$16 Mpc, black hole mass $M_{\rm BH} \simeq [2-3] \times 10^9 M_\odot$) in 2005 have led to the discovery of fast TeV variability (observed doubling time scale of $t_{\rm var} \sim [1-2]$ days) and a hard power law (TeV photon index $\Gamma \sim 2.2$) VHE $\gamma$-ray spectrum extending beyond 10 TeV (Aharonian et al. 200; see also the recent MAGIC results presented in Albert et al. 2008). Being a non-blazar (jet inclination $i \gtrsim 20°$, only modest Doppler beaming $D \sim 2$) and a highly underluminous ($L_{\rm bol} \lesssim 10^{-5} L_{\rm Edd}$) AGN source, these VHE characteristics prove difficult to account for within conventional acceleration and emission (e.g., leptonic synchrotron self-Compton [SSC], proton synchrotron, external Compton starlight) scenarios. The HESS results have thus triggered a number of new and interesting developments in particle acceleration and emission theory (e.g., Neronov & Aharonian 2007; Rieger & Aharonian 2008), where the TeV $\gamma$-ray production site is considered to be located in the vicinity of the central supermassive black hole (typically at a few Schwarzschild radii $r_s \simeq [6-9] \times 10^{14}$ cm). It is a natural consequence in these models that the minimum variability timescale should always be larger than a few Schwarzschild light crossing times $r_s/c \simeq (0.2-0.4)$ d and that the TeV spectra should exhibit a clear break (due to internal $\gamma\gamma$ absorption and maximum energy constraints) well below 50 TeV. Both, falsification or verification of these pulsar-type scenarios by future high-sensitivity observations with CTA will be highly relevant for a fundamental progress in our understanding of the central engine in AGNs: in the former case new jet physics beyond current developments would be demanded, in the latter case a strong link between jet formation, particle acceleration and disk physics would be established.

## 2 Why CTA science?

CTA will be uniquely suited for this task. With its low TeV $\gamma$- ray flux ($\sim 1-2\%$ Crab in its frequent low state and $\sim 10-15\%$ in its historic high state) M87 is already probing the sensitivity limit of current IACT instruments ($\sim 1\%$ Crab at 1 TeV for HESS, MAGIC II and VERITAS). The anticipated one-order-of magnitude better sensitivity (milliCrab) and larger collecting area of CTA will be crucial for studying the variability of M87 independent of its active source stage and to achieve the required photon statistics needed for both spectral (evolution of TeV photon index, break energy above 10 TeV) and short-time (potentially intraday) variability analysis. On the other hand, the non-blazar source M87 will be an ideal CTA target for such a kind of science given its modest Doppler beaming (little confusion by the usual SSC contribution), its underluminosity (required to avoid internal absorption) and its nearness (negligible external EBL absorption up to 30 TeV).

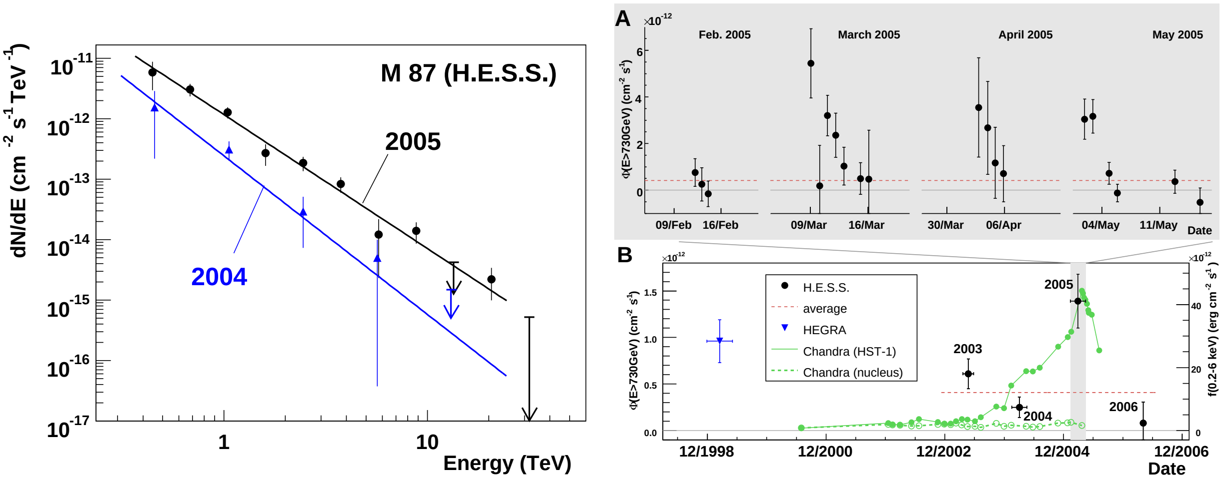

Figure 1: LEFT: The differential very high energy (VHE) spectra of M87 from HESS observations during the 2004 low and the 2005 bright state, ranging from $\sim$ 400 GeV to $\sim$ 10 TeV. Limited event statistics did not allow to derive a spectrum during the 2006 low state. The indicated fits give power law photon indices of $\Gamma = 2.62 \pm 035$ (2004 data) and $\Gamma = 2.22 \pm 0.15$ (2005 data). No variation in spectral shape is found within errors. One Crab unit at 1 TeV corresponds to a flux of $\simeq 3 \times 10^{-11}$ s$^{-1}$ cm$^{-2}$. RIGHT: HESS gamma-ray flux above 730 GeV as a function of time during the 2005 high state (top), with evidence for a $\sim$ 2 d doubling time scale in March. See Aharonian et al. (2006) for more details.

## 3 Observational requirements

The proposed science case will require the following CTA specifications: milliCrab sensitivity, effective collecting area of $\sim 10^6$m$^2$, energy range up to 100 TeV. (While the improved 1' angular resolution will be less instructive, it could help excluding knot A (1 kpc) as potential VHE $\gamma$-ray production site).

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# Clusters of galaxies with CTA

Domainko Wilfried

## 1 Introduction, science cases

Clusters of galaxies would represent a completely new type of gamma-ray source and would probe non-thermal activity on the largest spatial scales and longest time spans in the universe. However, up to now no galaxy cluster has firmly been established as a gamma-ray emitter. Various scenarios for gamma-ray emission are expected in clusters.

**Galaxy clusters as storehouses of hadronic cosmic rays:** Clusters of galaxies act as storehouses of hadronic cosmic rays for the entire age of the universe: it has been recognized that such particles with energies of up to $\sim 10^{15}$ eV have diffusion times in the cluster volume and in typical cluster magnetic fields of a few $\mu$G which are longer than the age of the universe [12], [1]. Hence, clusters keep memory of the entire non-thermal activity which happened in the cluster volume. There are several sources of cosmic rays possible in galaxy clusters. Particles can be accelerated in large-scale shock waves generated by hierarchical structure formation and cluster galaxies can inject relativistic particles in the cluster volume by supernova driven galactic winds and AGN activity. Hadronic cosmic rays can produce gamma rays through inelastic collisions between the cosmic rays protons and nuclei of the thermal X-ray emitting Intra-Cluster Medium (ICM) and subsequent $\pi^0$ decay ([5], [12]). Gamma-ray emission produced by the hadronic channel is expected to originate predominantly from the central region of the cluster where relative high density target material is located. Therefore detection of gamma-ray emission which traces the distribution of the thermal ICM would offer direct evidence for hadronic cosmic rays outside our own Galaxy. The intensity of the radiation is linked to the sum of the energetics of all non-thermal processes which populated the cluster volume with hadronic cosmic rays. Thus this will be a measure for the entire non-thermal activity over the Hubble time.

**Feedback of radio galaxies in clusters:** In some clusters feedback of AGN outbursts in form of radio emitting lobes which form bubbles in the thermal ICM can be seen (e.g. [2]). The energetic of such outbursts can even exceed $10^{61}$ ergs and influence the evolution of the entire cluster [10]. The dominant pressure component which is responsible for expanding the observed bubbles is up to date not known but can either be relativistic electrons, cosmic ray hadrons or magnetic fields (see e.g. [6]). For the case of cluster scale outbursts it was argued that cosmic ray protons are the main contribution to the energy content of the bubbles [8]. Very high energy protons will then leave observable signatures in form of gamma rays due to inelastic collisions with thermal nuclei of the ICM and $\pi^0$ decay. Therefore gamma-ray observations can be powerful tools to probe proton dominance of AGN blown bubbles in clusters.

**Accretion shocks:** Clusters grow either by merging with galaxy groups and sub-clusters or by accretion of surrounding cold intergalactic medium. In the latter process a high Mach number accretion shock forms around the galaxy cluster. Particle acceleration is efficient in such strong shocks and it is expected that accretion shocks can easily accelerate particles to the very-high energy range (e.g. [9]). Cosmic ray electrons can then up-scatter CMB photons to gamma-ray energies in inverse Compton processes [7]. No accretion shock has been observed in any wave band so far. The observations of accretion shocks will give deep insight in the growth of the largest structures in the universe.

## 2 Why CTA science

Theoretical predictions for the gamma ray luminosity of galaxy clusters are quite uncertain and are mainly constrained by the fraction of energy in the non-thermal component with respect to the thermal ICM and by the spectrum of the cosmic rays (e.g. [3], [11]). In general it seems that predictions lie below the sensitivity of current instruments. Therefore a lower sensitivity limit is the most important feature for the detection of clusters. Hence, CTA is the most appropriate instrument since improved sensitivity is one key advantage of CTA in comparison with currently operating instruments and GLAST. In the following predictions for two different clusters which represent two different science cases are presented and the impact of CTA observations on the science topics will be discussed. As sensitivity of CTA in 10 hours at 1 TeV of $5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ for sources with extension of 0.1° and of $5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ for source extension of 1° is assumed:
**Coma cluster – clusters as storehouses of hadronic cosmic rays:** The Coma cluster is a very massive ($M_{\mathrm{tot}} \sim 10^{15}$ $M_\odot$) nearby ($D \sim 100$ Mpc) galaxy cluster. The gamma-ray luminosity of the Coma cluster depends on the amount of energy in cosmic ray protons which is usually given as a fraction of the energy in the thermal ICM. Model predictions give for the energy in relativistic protons a fraction of about 10 % of the thermal energy of the ICM. Assuming a hard spectrum with a spectral index of -2 and further assuming that the distribution of hadronic cosmic rays follow the gas density the Coma cluster with a source extension of 1° can be detected with CTA within 10 hours if the energy in relativistic protons is 5% of the thermal energy (see also [4]). Consequently, for nearby, massive clusters moderate model predictions for the fraction of energy in hadronic cosmic rays are in the reach of CTA.
**Hydra A – cluster scale AGN outbursts:** Hydra A is a galaxy cluster at a distance of $\sim 220$ Mpc which harbors a cluster scale AGN outburst. From the PdV work done on the ICM by bubbles inflated by the AGN the total energetics of the outburst can be estimated to $\sim 10^{61}$ ergs (see [8] for more details). Assuming that this energy is predominantly in form of cosmic ray protons the gamma-ray flux of this object should be larger than $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ for a source extension of 0.1° at 1 TeV [8]. Therefore with the sensitivity of CTA the hypothesis of proton dominance can either be confirmed or rejected for cluster scale AGN outbursts.

## 3 Observational requirements

**Observing mode** The most appropriate observing mode for these targets is a deep exposure with all telescopes pointing at the cluster position to detect the faintest accessible sources. Surveys are not expected to result in any serendipitous discoveries since the location on the sky of all prominent galaxy clusters are known from observations in other wave bands.
**Relation with other observatories:** Accretion shocks are an important science topic for CTA. These large scale shocks are also key science drivers for upcoming low frequency radio instruments such as LOFAR (http://www.lofar.org/), LWA (http://lwa.unm.edu/) and SKA (http://www.skatelescope.org/). Observations in these different wavelength bands will allow to

study the growth of the largest structures of the universe in great detail where CTA traces the inverse Compton emission of the electrons accelerated in the shocks and the next generation of radio observatories observes the synchrotron radiation of the leptonic cosmic rays.

## 4 Response of CTA

Clusters are expected to be faint gamma-ray sources with hard spectra. A deep sensitivity level in the energy range of 100 GeV – 1 TeV is highly desirable for cluster observation. This can be achieved by CTA if it contains a large number of $\sim$ 12 Meter class telescopes. Clusters of galaxies are furthermore expected to be extended gamma-ray sources. Therefore a low level of background events is highly desirable for this kind of observations. The CTA configuration should be constructed for optimal gamma - hadron separation to be best suited for galaxy cluster observations.

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# CTA- Heavy Nuclei Cosmic Ray Flux Measurement

Andrew Taylor, Rolf Buehler, and Kathrin Egberts

Abbreviations: Cosmic Ray (CR); Extended Air Shower (EAS); Direct Cherenkov (DC); Ultra Heavy Cosmic Rays (UHCRs)

## The Point

Using the CTA instrument can tell us about the iron group nuclei ($Z$ >24) CR flux up to energies a factor 20 larger than HESS. The HESS measurements enabled spectrum measurement of iron group up to 100 TeV in energy, though with only low statistics (∼16 events) for the highest data point shown in Fig. 1. Though only sub-"knee" energies are realistically achievable with this method, such measurements would constitute the most accurate CR composition measurements for at least the next ten years. It would allow the CR nuclei flux gap to be closed (see Fig. 1), leading to the possibility of constraining the hadronic models used in CR shower models. Furthermore, competitive composition measurements including lighter nuclei ($Z$ <24) and UHCRs ($Z$ >28), which were not possible with HESS, are also possible for the CTA, if detector criteria specified later in the document are satisfied.

## Present Status and Future Detection of Heavy Nuclei CR Flux Below "Knee" (5 PeV)

| Balloon Detector | Shower Detector |
|---|---|
| RUNJOB | EAS-TOP |
| JACEE | KASCADE |
| ATIC | TIBET |
| TRACER | |

Of these two detection methods, balloon experiments are preferable for composition measurements since they measure the primaries directly and therefore carry no hadronic model uncertainties. However both methods have their limitations.
**Balloon measurement limitations**: These are sporadically sent up (eg. TRACER, with 2 flights so far: 2003 + 2006)- their measurements are limited by small exposure (∼50 $\mathrm{m}^2$ sr days). The possibility of reaching energies around the knee with direct measurements of protons to iron on balloons is unlikely to occur without significant increases in the payload and flight duration capabilities of high altitude balloons.
**CR Shower detector measurement limitations**: Poor discernment of CR composition (use electron and muon shower information to infer the primary composition). This is a result of the analysis being heavily hadronic model dependent since the particles detected are the low energy products of high energy CR showers. The two most up-to-date measurements of the heavy nuclei CR flux come from TRACER and KASCADE, both shown in Fig.1.

Future measurements in the next 10 years will come from: subsequent TRACER and ATIC balloon flights, TIBET and KASCADE CR shower detectors (thouigh KASCADE's lower energy measurements will cease next year). TRICE (S. Swordy), a proposed detector for only DC light measurement, may be constructed.

However, balloon flights have gone as high in energy as they can feasibly go. Contrary to balloon measurements, the CR shower detector measurements have large exposures, with the results instead being limited by the large hadronic model uncertainties.

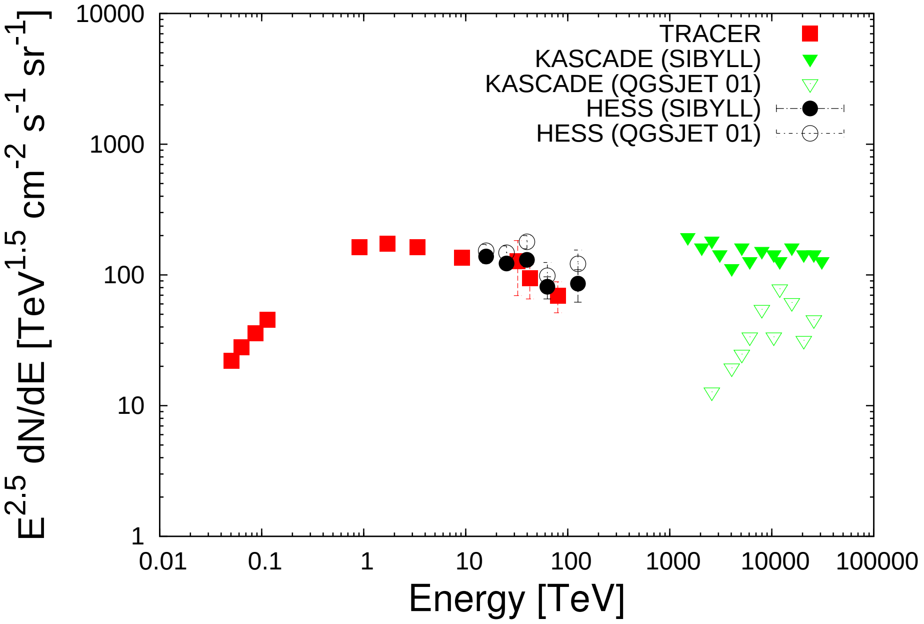

Figure 1: Energy Spectra from TRACER (solid squares) compared with the air shower measurements by KASCADE (solid triangles: for the QGSJET01 and SIBYLL hadronic interaction models). The TRACER spectra are for oxygen and for iron, but for the "CNO-group" and the "Fe-group" for KASCADE [2].

## Importance of Heavy Nuclei CR Physics at the "Knee"

The "knee" feature in the CR spectrum is presently associated with a maximum energy of the Galactic CR sources. This interpretation leads to the expectation that separate "sub-knees" should be exhibited as the cut-off of the different CR nuclei species occur in the CR spectrum. However, as yet, only tentative evidence for a change in CR composition at the "knee" has actually been reported [1]. Furthermore, with the primary particle interactions having a much smaller dependence on hadronic interaction models than the CR shower measurements, measuring the heavy nuclei CR fluxes in the PeV energy range provides the possibility to constrain these hadronic models through a simple comparison with CR shower measurements.

## Physics of DC Light

In order to understand the requirements for CTA, we will here outline the relevant key properties of DC light emission:

- The DC light originates from the charged primary CR particle. This DC-emission is produced higher in the atmosphere and hence with a emission smaller angle than the subsequent Cherenkov emission from secondary shower particles. This characteristic allows IACTs to distinguish the DC-light from the much brighter shower light. Additional separation can be gained by the fact that the DC-light lags the shower light by typically 4 ns ($c\Delta t = \Delta x(n^{-1} - \beta) = \Delta x(\gamma_{\rm min}^{-2} - \gamma^{-2}) = \Delta x\ \theta^2$).
- The refractive index of the atmosphere and the particle's Lorentz factor describes the DC-light emission physics. Writing the refractive index as $(1 + \delta)$, the minimum Lorentz factor required for Cherenkov production is $\gamma_{\rm min} = (2\delta)^{-1/2}$ and the Cherenkov emission angle is $\theta = (\gamma_{\rm min}^{-2} - \gamma^{-2})^{1/2}$. For typical DC production heights of 25 km, $\delta = 3 \times 10^{-6}$, giving $\gamma_{\rm min}$=380 and $\theta = 2.6 \times 10^{-3}$ rad.
- The DC-light reaches the ground at as a well defined cone of ~100 m radius (ie. of the order of DC emission height multiplied by the emission angle, $\Delta x\ \theta$).
- The amount of DC light produced increases with $Z^2(\gamma_{\rm min}^{-2}$-$\gamma^{-2})$, ie. $Z^2\ \theta^2$, making this detection ideally suited for determining the heavy nuclei fraction of CRs. However, the DC-light yield unfortunately also depends strongly on the emission height, which limited the charge resolution of the HESS analysis.

## Requirements of CTA for CR Composition Analysis

For increasing the energy range of the iron spectrum measurement above a PeV:

- Cover a wide physical area with many telescopes with a wide field of view. Assuming 40 telescopes with a field of view of 8° each would yield a detection aperture increase of a factor $\sim$20 with respect to HESS. This allows to expand the HESS measurements to energies $\sim$1 PeV with comparable statistics.
- At higher energies the DC-light gets increasingly harder to distinguish from the shower light (since the intensity of the latter increases linearly with energy). To measure DC-light events above $\sim$500 TeV additional separation power between the two is needed. This can be achieved by sampling the photon arrival times in steps of $\sim$2 ns, since the DC-light typically lags the shower light by $\sim$4 ns.

To enable composition measurements - improve the charge resolution - one needs to constrain the emission height of the DC-light. To achieve this several proposed methods exist [4, 3]. These methods however require a shower reconstruction accuracy of $\sim$0.025° for the direction and 5 m for the core distance. Due to the large fluctuations that exist in hadronic showers, this can only be achieved by including the DC-light information in the shower reconstruction [4]. This means that the angular position of the DC-light in the cameras, or the distribution of DC-light on the ground, need to be accurately sampled. For this CTA requires:

- Pixels of small angular size ($\sim$0.02°)
- Close spacing of the telescopes ($\sim$50 m)

For quantitative statements about the level of improvement in the charge resolution Monte Carlo studies are needed. However, as a rough estimate, a resolution of around 5% for the iron group nuclei (as discussed in [3]) is possible. An additional very interesting possibility is to expand composition measurements to UHCRs. Because of their high charge they are ideally suited for the DC-light technique. Flux measurement in this region presently only reach energies of $\sim$30 GeV, showing that the flux of these UHCR is three orders of magnitude below the iron flux. With CTA these flux levels could be measured around $\sim$10 TeV. One technical problem of this measurement is to avoid saturation of the photomultiplier due to the high DC-light yield (approx. $10^5$ photons m$^{-2}$ for $Z$=30).

## CR Composition Measurements Through Other Techniques with CTA

Other information from the shower images can also be used to obtain a handle on the CR composition. Examples of such CR shower parameters are the height of the shower maximum, the lateral arriving photon distribution on the ground, and the width the shower image. However a quantitative statement about the composition sensitivity of such methods requires further consideration, though will invariably contain hadronic model dependence.

Electron CR flux measurements, which have already been acheived up to 4 TeV energies by HESS [6], will be extended up to and beyond 10 TeV in energy with CTA, an energy range presently (and in the near future) inaccessible to balloon and satellite experiments and below the range probable by air shower detectors [5]. Along with this, a reduction of the errors in low energy measurements can be expected.

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