

Future Directions in Ground-Based Gamma-Ray Astronomy

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Abstract. With the recent successes of gamma-ray astronomy an obvious question is raised: where is this field going next? At present we have a network of similar air Cerenkov telescope arrays throughout the world and a large water detector in the USA. Here we try to identify which practical paths exist to newer, more sensitive instruments and what these might hold for the future.

1. Introduction

In any field of observational science the paths to progress can be broadly allocated to two classes of activity:

- Using existing instrumentation and methods on a significantly larger scale than before.
- Finding a technological breakthrough which provides a significant enhancement in sensitivity or the ease of constructing instruments.

There are various examples of these in the history of observational astronomy. The obvious development for the first category is the production of ever larger mirrors for use in optical astronomy throughout its history. An example of the second class is the development of the CCD detector, which rapidly replaced photographic plates providing an increase in quantum efficiency, overall sensitivity, and ease of image analysis in the late 20th century.

In the following we point to ways in which it seems conceptually straightforward to make improvements by changing scale for either the air cerenkov experiments or particle detector arrays. We also provide some consideration of what might be the most important technological development - without a discussion of how difficult these might be to achieve in practice (!).

2. Directions

The history of ground-based gamma-ray astronomy is not very long compared to other fields of astronomy. As such, it is really still in a discovery stage at present, but most likely headed into more of a survey stage in the next generation. The initial idea of looking for cerenkov light from air showers produced by gamma-rays stems from the 1960s[1] inspired by previous theoretical work, but the first clear ground-based detection of a source, the Crab Nebula, was made in 1989[2] using the single dish Whipple telescope. Since then the development of arrays of dishes, first demonstrated by HEGRA[3], has proven to provide significant improvements to sensitivity. In a similar manner the detection of

sources by directly observing particles from showers proved fruitless until Milagro[4] used a large water pool to provide a low enough energy threshold to successfully detect the Crab.

We might reasonably ask which directions are possible with these techniques to try to improve sensitivity. A peculiar aspect of gamma-ray astronomy is that many of the sources display significant transitory behavior, on the timescales as short as hours or minutes. As such it makes a lot of sense to look at as large a region of the sky as possible at any one time, so that transient sources can be discovered. A large field of view of is highly desirable because it also provides for serendipitous discovery of new classes of sources. Below Table 1 suggests some future ways in which things can possibly scale upward in the future for the air cerenkov telescopes and the particle arrays.

Table 1: Possible future scaling of techniques	Air Cerenkov	Future	Particle Arrays	Future
Energy Threshold (GeV)	~100	<50	~2000	<200
FOV (sq. degrees)	~12	~100?	~5000	~5000
Livetime	~8%	10%?	95%	>95%
γ -ray ang. res. (degrees)	0.1	0.05?	1	<0.4
Collection Area (m ²)	10 ⁵	10 ⁶	10 ⁴	10 ⁵
γ -ray energy resolution	~20%	15%	~75%	40%
Hadronic rejection	>99.9%	>99.95%	~90%	~90%

Table 1 illustrates the key attributes of the two techniques. The air Cerenkov has very large effective collecting area, exceedingly good hadronic rejection, good angular resolution but relatively small field of view. The particle arrays have a large field of view, but as pointed out in this meeting, an energy threshold which is a significant function of angle away from the zenith[5]. We can briefly discuss how some of the big gains described in this table might be achieved:

- Energy threshold: Bigger mirrors for air Cerenkov, higher altitude for both particle arrays and air Cerenkov.
- Field of View: Bigger field of view optics for air Cerenkov, possible through Cassegrain optics[6], This may also require cameras with large numbers (>10,000) of pixels.
- Collection Area: More telescopes for air Cerenkov, bigger detector volume for particle arrays.

From this simple list we can identify some straightforward ways in which we can improve sensitivity. The obvious thing for any technique is to simply make things bigger. This can be achieved in the air cerenkov arrays by making a large array of telescopes - significantly larger than the cerenkov light pool on the ground. This idea has been discussed as the HE-ASTRO concept[7]. For the particle arrays, HAWC[8] is a proposed new water pool experiment which is essentially a larger and improved version of MILAGRO. A second obvious next step for either technique is to build the instruments at a higher elevation than present experiments. This reduces the effective energy threshold for gamma-ray detection. The improvement of field-of-view for the air-cerenkov telescopes can be approached in an interesting way once a large array telescopes is built. The proposers of HE-ASTRO have pointed out

that there can be a range of operating configurations for an array. The extremes would be to point all the telescopes at one source for maximum sensitivity or point all the telescopes in different parts of the sky to cover a much larger solid angle with lower sensitivity.

3. Sensitivity Improvements

A key metric of any future instrument is the expected improvement in sensitivity over existing detectors. Since the number of objects with a given gamma-ray luminosity falls very quickly with increasing luminosity, improved sensitivity is crucial to provide a large sample of sources. Table 2 provides an outline of how the sensitivity of observations of the Crab Nebula has improved with the new arrays, and how it might be expected to improve in the future with larger instruments.

Table 2: Sensitivity of γ-ray Detection	Sensitivity on the Crab Nebula
Whipple 10m	$5\sigma/\sqrt{\text{hour}}$
Milagro	$\sim 8\sigma/\sqrt{\text{year}}$ (wide angle)
VERITAS-4, etc	$23\sigma/\sqrt{\text{hour}}$
HAWC	$7\sigma/\sqrt{\text{hour}}$
HE-ASTRO (wide sky view)	$23\sigma/\sqrt{\text{hour}}$ (wide angle)
HE-ASTRO	$166\sigma/\sqrt{\text{hour}}$

The improvement in sensitivity for the air cerenkov telescopes for the present arrays has jumped by around a factor of ~ 5 for the Crab above the levels of the Whipple 10m. (This means something like $\sim \times 25$ less observing time is required to see the same sources at high energies.) A similar jump by a factor of 5 might be expected in the future for a large array like HE-ASTRO. This array will be capable of detecting the Crab at 5σ in ~ 3 seconds!

4. Technological Improvements

As mentioned in the introduction another significant impact on the future directions can arise from a technological breakthrough. These are notoriously difficult to predict, however it seems the single most important technology which could have a large impact on ground-based gamma ray astronomy would be the improvement of detector quantum efficiency. This would enable more light to be collected from a given-sized dish and consequently lower detection energy threshold and generally improve photo-detection statistics. Unlike optical astronomy, where the detectors already have close to $\sim 90\%$ quantum efficiency, both the air cerenkov detectors and the water pools use transmission thin-film photocathode technology which has a quantum efficiency near $\sim 25\%$. Sufficiently fast detectors with areas of $\sim 10\text{cm}^2$, low enough dark current, and high quantum efficiency ($>50\%$) could have a major effect on this field. There are various research groups involved in trying to develop such devices, but a single identifiable breakthrough still seems elusive.

5. Conclusions

Predicting the future is always an imperfect process. However, ground based gamma-ray astronomy seems to be entering a new phase after the initial discoveries made ~ 15 years ago. We are passing into a time of serendipitous discoveries which will start to become more like a discipline of mainstream astronomy in the future. The TeV energy range provides a unique window into the non-thermal universe and might very well have a serious impact on our understanding of broader aspects of physics. It is probably true that as this discipline matures it will evolve from the mostly PI-type

experiments we see in the present era into more "facility" type instruments in the future. The future will probably be driven by how successful we are at forming larger collaborations almost as much as it might be by simple economics. A likely future gamma-ray facility would have the following drivers and attributes:

- In principle collection area can be increased ad infinitum. The collection area of present air-cerenkov arrays is defined by the light pool size of $\sim 10^5 \text{ m}^2$. Future arrays will probably be $> 1 \text{ km}^2$.
- Higher altitudes help air-cerenkov and particle arrays. Future detectors will probably be $> 3000 \text{ m}$.
- Coverage of the full sky is highly desirable. This means probably at least one major facility in the northern and one in the southern hemisphere.
- A method for all-sky monitoring at $< 0.1 \text{ Crab}$ level seems highly desirable. Possibly by co-locating a particle-array type detector with an air-cerenkov array, or using a large array of telescopes in wide angle mode.
- The interest in this science is growing at present - we need to get our world-wide act together.

References

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