

# INAUGURAL LECTURE

of

## Prof Markus Böttcher

### The Violent Universe



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# **The Violent Universe**

**Inaugural Address by Prof. Markus Böttcher  
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## Gamma-Ray Astronomy

The most violent phenomena in the Universe reveal themselves through the emission of gamma-rays. Gamma-rays are a form of electromagnetic radiation, just like visible light. Electromagnetic radiation can be described in terms of its frequency or wavelength, and within the wavelength range of visible light, humans perceive different wavelengths as different colors: Red light having long wavelengths (about 0.7  $\mu\text{m}$ ) and low frequencies, blue light having short wavelengths (about 0.4  $\mu\text{m}$ ) and high frequencies. The spectrum extends beyond the range visible to human eyes both towards higher and lower frequencies. Infrared radiation and radio waves have longer wavelengths (lower frequencies) than visible light. At high frequencies, we reach ultraviolet, X-rays, and finally gamma-rays representing the highest-frequency radiation. As the energy carried by light and other electromagnetic radiation is proportional to its frequency, gamma-rays carry energies more than 1 million times larger than visible light and therefore probe the most violent environments in the Universe.

Gamma-rays from space are absorbed in Earth's atmosphere and do not reach the ground. Gamma-rays with Giga-electronvolt (GeV) energies (about 1 billion times the energy carried by visible light) can be observed using satellites orbiting above the atmosphere. The most recent and most successful such gamma-ray astronomy satellites is the Fermi Gamma-Ray Space Telescope, which was launched into orbit in June of 2008. At even higher energies (over 100 GeV, or more than 100 billion times the energy carried by visible light – referred to as Very High Energy [VHE] gamma-rays), one can use an indirect observing technique to detect astronomical VHE gamma-rays. This technique is based on the fact that gamma-rays of these extreme energies produce showers of secondary particles (primarily electrons and positrons) in the atmosphere, which emit short flashes of Cherenkov light. Specially designed telescopes (called Atmospheric Cherenkov Telescopes) and camera electronics can image these showers, and the images can be analyzed to re-construct the arrival direction and energy of the primary gamma-ray. Three major ACT facilities are currently operating around the world: The Very Energetic Radiation Imaging Telescope Array System (VERITAS) in Arizona, USA; the Major Atmospheric Gamma-ray Imaging Cherenkov Telescope (MAGIC) on the Canary Island of La Palma; and the High Energy Stereoscopic System (H.E.S.S.) near Windhoek, Namibia.

North-West University is a partner in the H.E.S.S. Collaboration, with several researchers in the Centre for Space Research actively involved in the H.E.S.S. observing program as well as theoretical studies of high-energy astrophysics phenomena observed by H.E.S.S. The first phase of H.E.S.S., referred to as H.E.S.S.-I, began science operations in 2002 with an array of four telescopes with mirror diameters of 12 m each. In September 2012, the H.E.S.S. Collaboration inaugurated the largest Cherenkov Telescope in the world with a mirror diameter of 28 m in the centre of the original 4-telescope array. This marks the beginning of the second phase, H.E.S.S.-II.

## The Cherenkov Telescope Array

The current generation of Cherenkov Telescope facilities (VERITAS, MAGIC, H.E.S.S.) have been in operation for about a decade now. Members from all three current facilities have formed a world-wide consortium which is actively developing plans for the construction of the next-generation ground-based gamma-ray observatory, the Cherenkov Telescope Array (CTA). Almost 1200 scientists at 177 institutions in 27 countries all around the world are involved in this project, including 22 scientists from four South African institutions: North-West University, Wits University, the University of the Free State, and the University of Johannesburg. These four institutions have formed a national consortium, the South African Gamma-Ray Astronomy Programme (SA-GAMMA), which is headquartered at NWU and chaired by the author.

The concept of CTA foresees the construction of two arrays, one in the northern and one in the southern hemisphere. The southern array, CTA-South, is envisioned to consist of three sub-arrays: A low-energy array of 4 – 5 very large telescopes (25 – 30 m mirror diameter, similar to the current H.E.S.S.-II telescope); a core array of about 20 mid-sized telescopes (10 – 12 m mirror diameter, similar to the H.E.S.S.-I telescopes), and a very extended (10 km<sup>2</sup> area) high-energy array of relatively small (~ 5 m mirror diameter) telescopes. Scientists from NWU and the University of Namibia have identified an excellent candidate site to host CTA-South in southern Namibia (on the farm Aar near the small town of Aus, between Lüderitz and Keetmanshoop), and proposed this to the CTA Consortium. Alternative sites have been proposed in Argentina and Chile. Based on the expected scientific performance, the CTA Consortium has assigned the proposed site on Aar the highest priority among all candidate sites for CTA-South, and, in its recent general meeting in September 2013, voted to suggest this as its top choice to the CTA Resource Board, which is scheduled to make a final site decision in December 2013.

The Italian Istituto Nazionale di Astrofisica (INAF – National Institute for Astrophysics) has initiated a programme to develop a prototype of the small-size telescopes for CTA, called Astrofisica don Specchi a Tecnologia Replicante Italiana (ASTRI – Astrophysics with Italian replica mirror technology). This will begin with the construction of a mini-array of 5 – 7 small-size telescopes at the site of the future CTA-South, which will later be integrated in the full CTA assembly. NWU and Wits University are partners in this project, and NWU has invested ZAR 3.5 million in the construction of one of the ASTRI mini-array telescope structures.

## Multi-Wavelength Astronomy in Southern Africa

While gamma-rays reveal the most energetic phenomena in the Universe, a true understanding of the processes at work in these sources and their surroundings requires observations at all wavelength ranges, from radio waves all the way to gamma-rays – a concept known as multiwavelength astronomy. Southern Africa is in an extraordinarily fortunate position to have some of the best conditions for ground-based multi-wavelength astronomy and some of the world's best astronomy facilities. These include H.E.S.S.-II as the world's leading ground-based gamma-ray observatory. South Africa has also been chosen as the site for the world's largest radio telescope project ever built: the Square Kilometre Array, an array of radio dishes adding up to a collection area of one square kilometre, spread over all of southern Africa. Also the Hartebeesthoek Radio Astronomy Observatory (HartRAO) is involved in multiwavelength observations of astronomical high-energy sources. These world leading radio and gamma-ray astronomy facilities are complemented by world-class optical telescopes, first and foremost the South African Large Telescope (SALT) near Sutherland, in addition to other optical telescopes

operated by the South African Astronomical Observatory (SAAO) and the Boyden Observatory near Bloemfontein, operated by the University of the Free State. Construction of the CTA in Namibia would complete Southern Africa's position as the world's leading hub for ground-based multi-wavelength astronomy.

### The High-Energy Universe

A surprising variety of objects in the Universe are sources of VHE gamma-rays: Almost 150 sources have so far been detected by ground-based Cherenkov Telescope facilities. This indicates that many objects in the Universe are able to accelerate particles to extreme energies, exceeding the capabilities of the most powerful man-made particle accelerators (such as the Large Hadron Collider [LHC] at CERN) thousand- or even million-fold.

Within our own Galaxy, the Milky Way, many of these sources are associated with the deaths of very massive stars. Stars that have more than 8 times the mass of our sun, will end their lives in powerful explosions called Supernovae. These explosions are triggered when the core of the star runs out of its nuclear fuel that produces the energy that makes stars (like our sun) shine. The core collapses to an extremely compact object, called a neutron star, in which matter is so densely packed that one teaspoon full of this material would weigh about 2 billion tons on Earth! While the core collapses, the outer layers of the star will bounce off the newly-formed neutron star, and explode in a supernova. This explosion produces very strong shocks as the outer layers are flung away from the star, and these shocks are the sites where particles are accelerated to the extreme energies needed to produce gamma-rays. However, also the neutron star itself can produce gamma-rays: In addition to being extremely dense, these collapsed stellar cores also rotate very fast (up to a thousand times per second) and have the strongest magnetic fields of any known object in the Universe. These rapidly rotating, extremely strong magnetic-fields are also accelerating ultra-high-energy particles that produce gamma-rays (along with radiation in all other wavebands of the electromagnetic spectrum), in some cases in a pulsating manner due to the rotation of the star – hence, these objects often reveal themselves as pulsars.

Still within our own Galaxy, gamma-rays have been observed from binary systems in which a normal star (like our sun) and a neutron star or black hole orbit around each other. If the star is close to the compact object (i.e., the neutron star or black hole), material will be sucked off the star, onto the compact object. While approaching the neutron star or black hole, the material heats up to temperatures of typically a few million degrees and begins to radiate X-rays. These binary systems are among the brightest X-ray sources in the sky and are therefore known as X-ray binaries. Only a small percentage of these X-ray binaries are also known to emit gamma-rays.

Beyond our own Galaxy, there are also many extragalactic objects detected in gamma-rays. Even more extreme explosions than supernovae result when a star of more than 25 times the mass of our sun ends its life. In that case, the core is too massive to even become a neutron star, and it collapses straight into a black hole. The rest of the star falls onto the newly-formed black hole. Due to the rotation of the stellar material, it can not fall directly into the black hole, but will form a disk around it (called an accretion disk); material will gradually be sucked into the black hole from the inner edge of the disk. Along with the formation of such a disk, extremely fast beams of matter (called jets, moving with almost the speed of light) are expelled along the rotation axis, and these seem to be the source of gamma-rays they are seen as short (a few seconds to a few minutes) flashes, called gamma-ray bursts (GRBs). For the few seconds to minutes of their duration, these GRBs are the brightest gamma-ray

sources in the sky. On average, about one GRB happens every day somewhere in the observable Universe. There is no way to predict where the next GRB will happen, so in order to find GRBs, one needs to employ telescopes that scan at least a sizeable fraction of the entire sky all the time. Several dedicated GRB monitoring satellite observatories have been launched specifically for this purpose. Since most telescopes have rather small field of views (i.e., they only see a very small portion of the sky), observing GRBs with such telescopes requires that the data from the detection of the GRB is analyzed to pinpoint the location of a GRB on the sky, that this information is relayed to the telescope, and that the telescope re-pointed to the position of the GRB while the burst is still in progress (i.e., all of this needs to happen within a few seconds!). This represents an extreme challenge for observing GRBs with ground-based Cherenkov Telescopes, as they typically need about a minute to re-point to a different position on the sky. So far, GRBs have been detected in gamma-rays up to a few GeV (i.e., with the Fermi Gamma-Ray Space Telescope), but not at higher energies by ground-based Cherenkov Telescopes. It is unclear whether they do really not emit radiation at such high energies (VHE gamma-rays), whether their VHE gamma-ray emission is absorbed along the way to us, or whether the VHE gamma-ray emission has simply already faded away by the time that ground-based Cherenkov Telescopes pointed to the location of the burst.

The most abundant class of objects known to emit very-high-energy gamma-rays are active galactic nuclei (AGN). Probably every galaxy (like our own Milky Way) hosts a supermassive black hole in its centre. The masses of these black holes range from a few million (our Milky Way hosts a black hole of about 4 million solar masses) to several billion solar masses. In the case of our Milky Way, the environment around its central black hole is rather empty, with very little material to accrete onto the black hole. It is therefore a very faint source of high-energy radiation. There are, however, galaxies whose central black holes reside in very dense environments and have plenty of material to fuel very active mass accretion. Just like in the case of GRBs described above, the material will organize itself into an accretion disk that gradually transfers mass through its inner boundary onto the black hole, and long with this disk accretion goes the ejection of jets that move with almost the speed of light. It is believed that it is within these jets that extremely efficient particle acceleration happens, resulting in the production of gamma-rays up to the highest energies.

## Conclusions

Gamma-ray and multi-wavelength astronomy studies the most violent places in the Universe, from exploding massive stars at the end of their lives, to rapidly-feeding supermassive black holes in the centres of galaxies billions of light-years away. Southern Africa is in a privileged position to have excellent conditions for ground-based multiwavelength astronomy – at radio, optical and very-high-energy gamma-ray frequencies. World-class radio, optical, and gamma-ray astronomy facilities are already present in Southern Africa, and the construction of SKA as well as possibly CTA in Southern Africa will solidify Southern Africa's position as the world's leading hub for multiwavelength astronomy.