Probing the Universe with cosmic rays using high performance computing

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I REPORT ON THE RESEARCH ACTIVITIES OF the South African Centre for High Performance Computing carried out at the Unit for Space Physics at North-West University, Potchefstroom, during 2007/8. Background is given on the aims of the centre and the first three flagship projects that were selected in 2006 for computational-intensive tasks. The project in Computational Space Physics and Astrophysics, called 'Cosmic rays and us: From birth to death', is described in detail, and a summary given of research highlights so far.

Introduction

This article provides information concerning the new initiatives and developments in high performance computing in South Africa, in particular the establishment of the Centre for High Performance Computing (CHPC) in 2007, and the flagship research projects that followed. Most of this review is devoted to research activities of and results arising from the project on Computational Space Physics and Astrophysics, carried out at the Unit for Space Physics at North-West University in Potchefstroom during 2007/8.

Centre for High Performance Computing

The CHPC is an initiative of the Department of Science and Technology (DST), managed by the Meraka Institute of the South African CSIR. It was inaugurated on 22 May 2007 by the minister of science and technology, Mosibudi Mangena. The research objectives of the CHPC are to provide high-end computing resources and expertise for computational research in South Africa. The Cape Town facility fosters research that addresses grand challenges, with the aim to promote computational research alongside experimental and theoretical studies across the academic disciplines, functioning as a national research, training and service centre. The CHPC's mandate is to support world-class research, and skills and development training.

The first phase of computer procurement and integration was completed in May 2007, and the research operations officially started on 1 June 2007. The specifications and technical details on the IBM computer cluster involved can be viewed by visiting www.chpc.ac.za/infrastructure.html. The second phase of cluster expansion is due towards the end of 2008.

Flagship projects

Three research grants for flagship projects were awarded at the beginning of 2007 by the CHPC to the following: 1) the University of Cape Town with Bruce Hewitson and Frank Shillington as team leaders. This initiative is based upon two complementary sub-projects focused on multi-model seasonal climate forecasts and the coupling of ocean and atmosphere. The two themes share the common application of dynamical modelling of the components of the climate system. 2) The University of Limpopo with Phuti Ngoepe as team leader. This project focuses on the use of computational modelling to enhance the economics, energy and power density of high-power rechargeable batteries. 3) North-West University (NWU) with Marius Potgieter as team leader. This project, within the Unit for Space Physics (USP), is the main subject of this article.

All of these projects are conducted in collaboration with the CHPC. The centre provides financial support and computational resources to the scientists, while researchers assist in the career development of the centre's research officers and students through the inclusion of the latter in their research programmes. Further calls for additional flagship project proposals were announced in the second half of 2007 and were allocated during 2008 (for an updated list, see www.chpc.ac.za/research/flagships.php).

The Unit for Space Physics

The Unit for Space Physics at the NWU has been in existence under various names since the beginning of the space exploration era that began with the launch of Sputnik on 4 October 1957. It was established during the International Geophysical Year in 1957. Various aspects of space physics have been investigated over the years. Several experiments have been carried out at Potchefstroom and nearby, as well as further afield in southern Africa and in the Antarctic. Experimental research on astronomical sources of gamma rays began in the mid-1980s. Locally designed gamma-ray telescopes were used to investigate the limits of physics, focusing on astrophysical objects such as neutron stars, pulsars and supernovae. Currently, the USP is a partner in an international group based in Europe, building a world-class gamma-ray telescope in Namibia, called the HESS project (www.mpi-hd.mpg.de/hfm/HESS/). The USP has also been involved in radio astronomy since 1990, collaborating with the Hartebeesthoek Radio Astronomy Observatory west of Pretoria. Regions where star formation is taking place are studied by means of maser radiation that is characteristic of such phenomena.

With the development of more powerful computers, the emphasis of a large part of the research done in the USP has shifted to the numerical modelling of universal processes in space physics (particularly heliospace physics) and in astrophysics. Such theoretical and computational studies can be very cost-effective and provide ideal training for postgraduate students seeking rewarding careers after completing their studies.

The research activities of the USP have three main components: 1) Experimental research, which is funded partially by the South African National Antarctic Programme (SANAP) of the National Research Foundation (NRF). Cosmic ray monitors are operated continuously at Potchefstroom, Hermanus, Tsumeb and at the South African research base in Antarctica (SANAE). This research relates to aspects of space weather, discussed below. 2) Theoretical and numerical modelling; this focuses on heliospheric physics as the part of space physics dealing with the influence of the Sun, as a star, on our immediate galactic environment, including studies of solar activity cycles and magnetic field, the solar wind and its effect on the Earth's magnetic field, ionosphere and atmosphere. Numerical models have been developed that simulate charged-particle acceleration, transport and modulation in the galaxy, in the interstellar medium and in the heliosphere, including Jovian electron transport. Theoretical work has been conducted on aspects of the solar magnetic field, diffusion and turbulence theory. 3) Experimental and modelling research in astrophysics; this focuses on gamma-ray astronomy, radio and optical astronomy, star formation, and cosmic ray sources.

Computational space physics and astrophysics

Scientific background

We use cosmic rays as probes to study the features and properties of the space

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Computational space physics and astrophysics at the USP

Members of the Unit for Space Physics involved with this project are Okkie de Jager, Adri Burger and Stefan Ferreira; postdoctoral fellows Ingo Büsching and Christo Venter; computer expert Mathew Holleran; Ph.D. students Rex Manuel, Mathew Holleran, Donald Ngobeni and Sibusiso Nkosi; and M.Sc. students Rendani Nndanganeni, Edwin Magidimisha, Du Toit Strauss and Michael Vorster.

Research and bursaries are financed mainly by statutory organizations such as the NRF, the Department of Science and Technology, and now the CHPC. Collaboration agreements between the USP and foreign research groups involved in the Voyager[1] and Pioneer missions of the American Space Agency NASA as well as the Ulysses[2,3] and SOHO missions of the European Space Agency (ESA) give the group access to the latest unpublished data and discoveries. An active post-doctoral programme is in place.

surrounding the Sun, and far beyond. These particles are highly energetic, fully-ionized elemental nuclei that arise mostly from the enormous explosions of huge unstable stars, called supernovae, in our galaxy, the Milky Way. They have kinetic energies ranging from about 1 MeV to as high as 10^{21} eV, the latter probably originating from outside our galaxy. The majority of these particles are protons, with substantially fewer helium and other nuclei. Antiprotons, electrons and positrons also occur. These nuclei and other sub-atomic particles move through the galactic medium, following the galactic magnetic field lines into the local interstellar medium, before they interact with the Sun's environment. This conceals the exact location of the cosmic ray sources, as seen from Earth.

Cosmic rays were discovered during 1911–13 by the Austrian scientist Victor Hess. Before his discovery, scientists had been puzzled by the fact that the air in electroscopes became ionized, regardless of how thoroughly the containers were electrically insulated. They attributed the phenomenon to ground-emitted radioactivity. In 1910, Theodore Wulf measured ionization at the bottom and top of the Eiffel Tower (about 300 m apart), and found that there was considerably more ionization at the top than would be expected from atmospheric attenuation of ground-emitted radiation, but his findings were generally rejected. Before making his historic balloon flights, Hess calculated the height at which ground radiation should cease to induce ionization, this being about 500 m, and designed instruments that would be resistant to large temperature and pressure changes. He then made ten historic balloon ascents, two in 1911, seven in 1912, and one in 1913, five of them at night, and found that ionization increased rapidly with altitude. His conclusion was that radiation of very high penetrating power enters the Earth's atmosphere from space, and is being attenuated by the constituents of air.

After making a flight during an almost total eclipse of the Sun on April 12, 1912, he further concluded that since ionization did not diminish during the eclipse, the Sun was not the main source of this radiation. His theory about 'rays from space' did not receive general acceptance at the time, but stimulated research after World War I, supporting and confirming his postulates. The newly discovered radiation was dubbed 'cosmic' by Robert Millikan in 1925. Hess received the Nobel prize for this accomplishment in 1936 (together with Carl Anderson, who discovered positrons: see www.mpi-hd.mpg.de/hfm/HESS/public/hessbio.html, and nobelprize.org/nobel_prizes/physics/laureates/1936/hess-bio.html).

Astrophysicists now have models of how cosmic rays can be produced over such an enormous energy range, but still have no definitive proof, so that cosmic rays remain an active research field at the forefronts of space science and astrophysics. A remarkable feature is that a natural upper limit to the cosmic-ray spectrum has not yet been confirmed. Cosmic rays appear at energies as high as is measurable today, which is technologically very difficult and expensive, because of the very low number of cosmic ray particles arriving at the Earth with these higher energies. About one particle per square metre per second may reach the Earth at 100 GeV, whereas only about one particle per square metre per year arrives at 10^{15} eV. This number drops to one particle per square kilometre per year[4] at 10^{19} eV. Ground-based imaging air Cherenkov telescopes such as used in the HESS project have made important contributions in recent years to high-energy gamma-ray[5,6] and cosmic-ray observations. Improved sensitivity is a key requirement in extending their role in the discovery of the origin of cosmic rays.

Space physicists attribute the bulk of galactic cosmic rays ($E < 10^{16}$ eV) to supernovae. When their ejected matter expands at supersonic velocities (these are extreme speeds at very high temperature), they propagate huge shock-waves into the surrounding galactic and interstellar medium, accelerating nuclei to speeds that make them cosmic rays. Cosmic ray flux is a maximum at a few GeV. The solar modulation of cosmic rays reduces the flux significantly below this range, so that we cannot reliably measure the local interstellar spectra for the various cosmic ray species below a few GeV.

The Sun is an active star, creating charged particles of its own, following an 11-year cycle. These energetic particles have much less energy than cosmic rays. They occur sporadically, especially during maximum solar activity, and have a characteristic energy limit. The largest solar events are called coronal mass ejections. This ejected matter is transported by the solar wind at a high velocity (average of 450 km s^{-1}) towards and past the Earth, causing distortion of the Earth's magnetic field, creating electromagnetic disturbances (magnetic storms) that affect radio, satellite, other forms of wireless communication, and electricity supply networks. These phenomena are features of what is called *space weather.* The activity of the Sun changes with time, the 11-year cycle being the best known. A 22-year cycle is also evident, arising from the solar magnetic field reversing its polarity every 10 to 12 years. This creates a charge-sign dependence[7,8] in cosmic rays because of the gradient and curvatures in the global heliospheric magnetic field.

The theme of this flagship project is 'Cosmic rays and us: from birth to death'. Because cosmic rays can be harmful to life, they need to be studied in detail, from their cosmic origin to their detection on Earth by a large number of balloon experiments, as well as using satellites and spacecraft. The flagship project, through three main programmes, studies the origin of cosmic rays, their propagation in the galactic and interstellar medium, to where they encounter the heliosphere, and eventually reach our planet.

The local interstellar conditions through which the heliosphere moves can change dramatically over thousands of years. These very long-term changes in our interstellar and heliospheric environment are a feature of *space climate.* Since life on Earth has taken millions of years to evolve, space climate is an important issue and must have played a role. This aspect will be discussed briefly in the last section of this paper.

Fortunately for us, there are three important natural protection barriers against galactic cosmic rays. They are:

1. The heliosphere[9]: This is the huge space surrounding the solar system which is dominated by the activity of the Sun. The Sun creates a solar wind which carries with it a turbulent magnetic field

that deflects cosmic rays, because they are charged particles. The diameter of the heliosphere is at least 500 astronomical units (one AU is the average distance between the Sun and the Earth, *c.* 149.5 million km). Two Voyager spacecraft are already exploring the outer heliosphere. Voyager 1 is at *c.*110 AU and Voyager 2 at *c.* 87 AU, moving in the nose direction (opposite end to the trailing tail) of the heliosphere, about 60° apart in heliolatitude.[1,10]

2. The Earth's magnetic field[9]: The Earth has a magnetic field in its own vicinity that is much stronger than the solar magnetic field in the Earth's locality, and it serves as an effective barrier against cosmic rays. This protection is greatest at the Earth's magnetic equator. The consequence is that the closer one lives to the magnetic poles of the Earth, the worse is the protection from cosmic rays. Without this magnetic field, life on Earth would probably have evolved differently (cosmic radiation can damage DNA, the repository of an organism's genetic information).
3. The Earth's atmosphere[9]: The denser the atmosphere, the fewer cosmic rays can reach the Earth's surface. There is better protection at sea level, compared with living at higher altitudes.

If humans are to occupy a sustainable base on the Moon, effective protection against cosmic and solar particle events will have to be installed, as our natural satellite has no protective atmosphere or adequately strong magnetic field. The same precautions will be necessary if travelling to Mars over periods of several months to set up a long-term base there. Advanced knowledge of a fundamental as well as a practical nature of the propagation and modulation processes of cosmic rays in the interstellar medium, the heliospheric and interplanetary medium and through the Earth's magnetosphere and atmosphere is therefore crucially important.

Purpose and aims of the project

The project focuses on the computational modelling of heliospace physics, interstellar physics and astrophysics, using numerical codes that have been developed in the USP over the years. It aims to design, construct, link and expand numerical models in order to simulate the transport and acceleration of cosmic rays, from their creation in the galaxy to their arrival at Earth. The acceleration of these particles as a result of astrophysical shocks in supernova remnants, their propagation in the galaxy and the transport in our local turbulent astrosphere need to be computed for this purpose. Emphasis is on particle propagation, the study of the formation of the physical structure and geometry of supernova remnants and the heliosphere, stellar and solar wind flow, magnetic fields and more. These simulations are used to test different theories, and to explain recent observations and measurements from various spacecraft near and far from the Earth, and using large telescopes such as employed by the HESS collaboration in Namibia. The end results will be applicable to studies of the influence of cosmic rays, space weather and space climate on the environment of the Earth, to long-duration missions to Mars, and to working environments on the Moon and the planet. It has indeed become possible with the establishment of the CHPC facility to embark on ambitious projects on numerical modelling of the nature described here over the longer term, some of which are described below.

Heliospheric modelling

The solar wind. The solar corona, like the Earth's atmosphere, is captured by the Sun's gravity. Although the Sun's gravitational field is very strong, the topmost 'atmospheric' layers easily escape at temperatures of millions of degrees Celsius. This coronal, plasmatic flow of particles away from the Sun has been named the *solar wind.* It fills and shapes the vast region of space surrounding the Sun to form the heliosphere. The Earth's magnetosphere is also shaped and significantly affected by the solar wind.

Two solar wind speed regimes have been observed by the Ulysses mission.[3] They are: the fast solar wind, where the observed speed is typically *c.* 800 km s^{-1} with fluctuations of *c.* 10%. The areas emitting the fast solar wind can be associated with visually darker areas in light images of the Sun, for example, in the emission of the Fe XII line (see http://sohowww.estec.esa.nl). During low solar activity the polar region of each hemisphere is covered by 'coronal holes', which can extend to the heliographic equator and beyond. The slow solar wind has typical speeds that vary around *c.* 450 km s^{-1}. The slow wind is significantly more variable than the fast. Closed magnetic fields are observed near the heliospheric equator, above the solar streamer belt.

Figure 1 is a contour plot of the global solar wind velocity inside the heliosphere, in the meridional heliocentric plane. It is based on the results of a sophisticated hydrodynamic model[11] of the heliosphere.

Heliospheric structural geometry. The solar wind blows away from the Sun into the interstellar medium (the rarefied hydrogen and helium gas that permeates the galaxy). The point where the solar wind is no longer sufficient to push back the interstellar medium is known as the heliopause, and is often considered to be the outer 'boundary' of the solar system. The distance to the heliopause depends on the velocity of the solar wind and the local density of the interstellar medium, and by computation using sophisticated models[12] is found to be far outside the orbit of Pluto.

The space between the Sun and nearby stars is filled with interstellar plasmas, magnetic fields, energetic-but-neutral particles, and charged particles. The Sun moves through the interstellar medium (ISM) with a velocity of *c.* 25 km s^{-1} so that

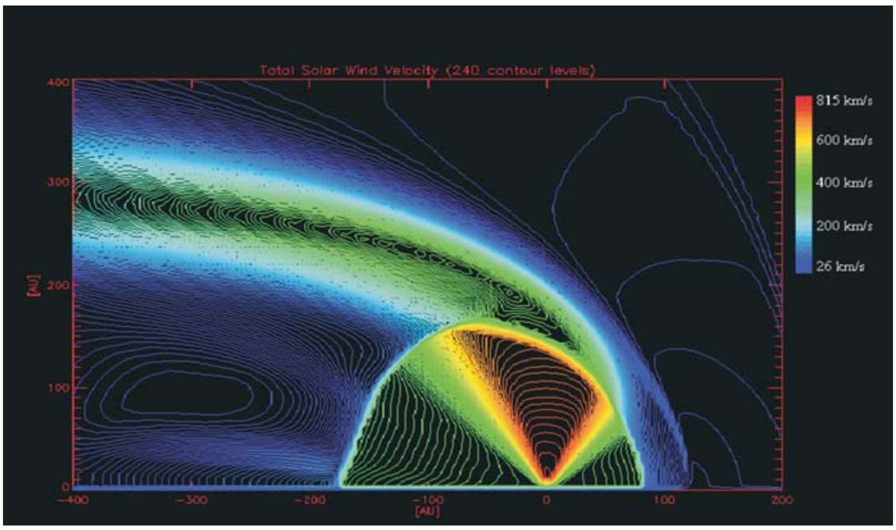

Fig. 1. A contour plot of the solar wind velocity inside the heliosphere. The Sun is in the middle at 0 AU, with a side-view of the heliosphere. This shows that the solar wind has a velocity profile that changes from an average of 450 km s^{-1} in the equatorial plane (horizontal axis) to about 850 km s^{-1} in the heliospheric poles (red contour lines), typical of solar minimum activity. The oval-shaped boundary in the inner region is the termination shock of the solar wind. The heliopause, where the light blue lines end, is the outer boundary of the heliosphere (adapted from Snyman[11]).

an asymmetric heliospheric interface is formed. The solar wind prevents the interstellar medium from flowing into the heliosphere. From a particle astronomy point of view, the heliosphere is considered to be a small but typical astrosphere. The extent of an astrosphere depends on the ram pressure of the stellar wind, compared to the total pressure of the ISM. In this context, the heliosphere extends over at least 500 AU in its equatorial plane and at least 250 AU in the polar plane. Because it is moving through the ISM, the heliosphere is asymmetrical with respect to the Sun, with the tail much more extended than the nose region, this being the direction in which it is moving.

The main constituents of the heliosphere are shown in Fig. 2, based on hydrodynamic computational models.[13] These constituents are the termination shock (TS), the heliopause (HP), and a bow shock (BS), with the region between the TS and BS defined as the heliosheath.[14] The BS shock is expected to be rather weak. The inner heliosheath is defined as the region between the TS and the HP. The HP separates the solar wind and ISM so that it may be considered the outer boundary of the heliosphere. A prediction of magnetohydrodynamic and hydrodynamic modelling is that the solar wind creates a TS where it goes from supersonic (400–800 km s^{-1}) to subsonic speeds at distances between 85 and 105 AU.[13,15] As predicted, Voyager 1 encountered the TS in December 2004 at a distance of *c.* 94 AU from the Sun, at a heliolatitude of *c.* 30° N. This observation[1,16] is of considerable importance and quite an accomplishment for this 30-year-long mission.

Anomalous cosmic rays in the heliosphere. Anomalous cosmic rays (ACRs)[17] were discovered in the early 1970s, with energies of 10–100 MeV/nucleon (nuc). What made them 'anomalous' was their much flatter spectral shape compared with galactic cosmic rays in this energy range. They have a composition consisting of hydrogen, helium, nitrogen, oxygen, neon and argon. They enter the heliosphere as neutral particles that become ionized inside the heliosphere. The interstellar particles are picked up by the solar wind immediately upon ionization, and acquire energies of about 1 keV/nuc. To become ACRs, these pick-up ions must be accelerated by four orders of magnitude. The principal acceleration mechanism to accomplish this remarkable feat has been considered to be diffusive shock acceleration, through which these particles gain energy by multiple crossings of the solar wind TS. However, at the location of the TS observed by the Voyager 1 spacecraft, no direct modulation evidence of the diffusive acceleration of the ACRs was found. This has been interpreted to mean that the ACR source[1] is not in the shock region local to V1. Although the higher energy ACRs seem unaffected by the TS, low-energy ions (*c.* 3 MeV/nucleon) are clearly accelerated, confirming that acceleration does indeed occur at the TS.

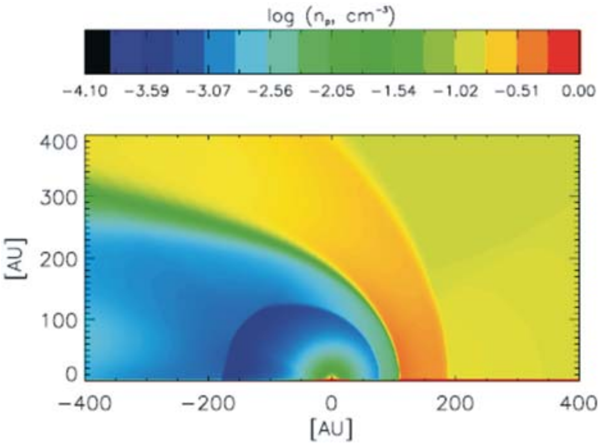

Fig. 2. The hydrodynamically computed heliosphere[13] in the meridional plane, with the Sun at 0 AU. The system is moving from left to right through the interstellar medium. It illustrates the main features of the heliosphere: the termination shock front (surface of the inner dark blue oval), the heliopause (where the light blue region ends), the bow shock (where the orange-brown regions end) and then the interstellar medium (the yellow-green part). Proton density as particles per cubic centimetre is shown in the top panel. The heliosphere is asymmetrically shaped (along the horizontal axis) caused by the movement through the local interstellar medium and is elongated toward the polar regions (vertical axis). The heliopause is the outer boundary of the heliosphere.

Using the computational facilities at the CHPC, it was recently shown[18] that by considering diffusive shock acceleration at the TS, as well as adiabatic heating and stochastic acceleration beyond the TS, the ACRs may get accelerated up to the HP and may thus escape the heliosphere to be the dominant low energy (<50–100 MeV) component in the local interstellar medium, obscuring the value of the galactic cosmic ray spectra at these energies for several particle species inside the heliosphere (see Fig. 3). This field of research, with the focus on the outer heliosphere, is currently actively pursued, with several challenges and issues to be clarified.[8]

Galactic cosmic ray modelling

The discovery of direct evidence for the acceleration of high energy cosmic ray particles in supernova remnants in our galaxy has underlined the need to compute the cosmic ray particle distribution in the Milky Way. Supernovae, as sources of galactic cosmic rays, change with time and location in space, resulting in a range of possible cosmic ray spectra at a given

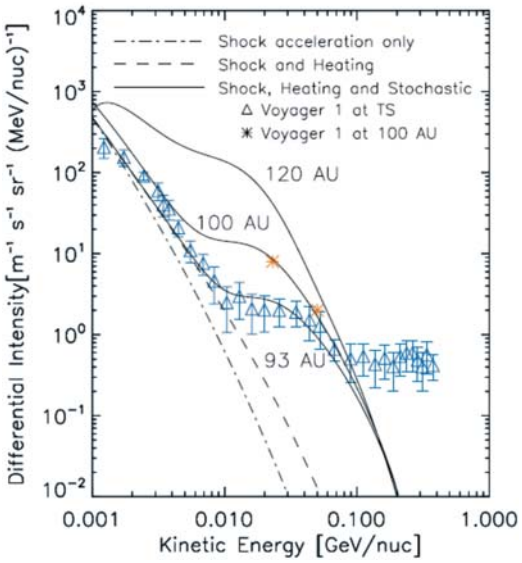

Fig. 3. Computed spectra[18] for singly ionized anomalous He at the termination shock (93 AU) for three acceleration scenarios: (1) diffusive shock acceleration only (dashed-dotted line), (2) diffusive shock acceleration and adiabatic heating (dashed line), and (3) shock acceleration, heating in the inner heliosheath and acceleration of a stochastic nature (solid lines). The last scenario is shown at the shock (bottom solid line), at 100 AU and at 120 AU (top solid line). For comparison, the recorded Voyager 1 spectra from 16 to 23 January 2005 at the observed termination shock are shown as triangles. Also shown by the asterisk symbols are Voyager 1 observations at 100 AU (http://voycrs. gsfc.nasa.gov).

location in the galaxy. Supernovae are found most commonly within the galactic spiral arms, so that it can be expected that a significant difference in cosmic ray intensity may occur inside and outside the spiral arms, as the Sun makes its very long journey around the galactic centre. The variability of the local interstellar cosmic ray proton spectrum during the motion of the Sun around the centre of the Milky Way, has been investigated.[19] The proton density was computed in our galaxy for a time span of 10 Myr, assuming that the cosmic rays originate in 130 001 supernovae events that cluster in the spiral arms as shown in Fig. 4. The averaged cosmic ray flux outside a spiral arm was found to be about 50% of that inside a spiral arm, with spatial and temporal variations inside the arms.

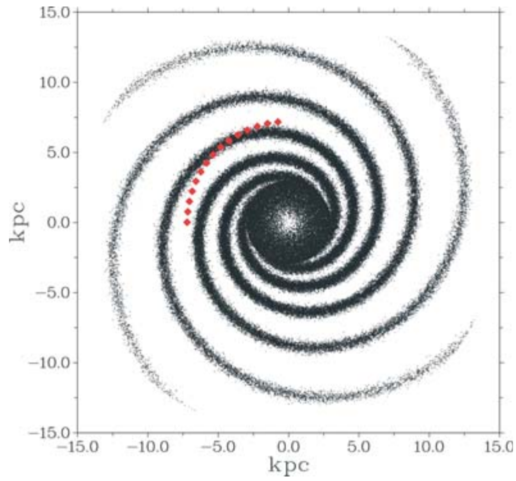

Fig. 4. The variability of the proton cosmic ray flux on the Sun's way around the galactic centre.[19] The computer cluster at the CHPC was used for this computationally intensive modelling. It was done for a time-span of 10 Myr, assuming that the cosmic rays originate in 130 001 supernova events, which concentrate in the spiral arms as shown in the figure to the left. The Sun's trajectory in and out of a spiral arm is shown as red dots.

Computational astrophysics

The explosion of a massive star as a supernova will result in an expanding supernova remnant (SNR) with a speed typically in the range 10^8–10^9 cm s^{-1}, depending on both the ejection energy and ejecta mass. Using the CHPC facility extensively, it has been possible to show how different parameters may influence the evolution of an SNR in a uniform and non-uniform ISM.[20] The time evolution of SNRs was computed using a hydrodynamic model including a kinematic calculation of the interstellar magnetic field. As the SNR moves into a medium of higher density, a reflection wave is found to be created at the interface between the two media. This wave is driven back toward the centre. As this wave moves inward, it also drags some of the ISM field lines with it, and heats the inside of the SNR, resulting in higher temperatures in this region. When an SNR explodes in a medium of high density and this blast wave propagates into a medium with a lower density, then a cavity is blown away, changing the geometry of the high density region. Pulsar wind nebulae have been modelled to understand their geometry and interaction with SNRs. The modelling of these structures plays an important role in understanding measurements obtained by the HESS telescope in Namibia. Also of importance is the diffusive acceleration of cosmic rays at astrophysical shocks, as they occur in SNRs. Valuable information about the different particle spectra can be obtained, and by entering this into a galactic propagation code, much can be learned about the local interstellar spectra of species such as electrons, positrons, protons and anti-protons.

Figure 5 depicts the evolution of the interaction of a typical SNR in our galaxy with a close-by medium of increased density over a simulated period of 6000 years. The density scale is given on the left. The SNR is expanding from an interstellar medium with a density of 10^{-24} g cm^{-3} (left side of figure) to a medium with a higher density of 10^{-23} g cm^{-3} (right side of figure).

The pulsed and unpulsed gamma-ray radiation from a population of millisecond pulsars (MSPs) in the globular cluster 47 Tucanae was modelled[5,6] using the CHPC. The pulsed radiation from each of a population of 70 MSPs was calculated iteratively using an MSP model, and these individual spectra were added to obtain a cluster-pulsed gamma-ray spectrum (Fig. 6). The idea of predicting cumulative gamma-ray fluxes was generalized, and consequential cosmic ray fluxes from a globular cluster were used in these predictions to constrain the underlying MSP models in a way that is independent of individual (unknown) MSP geometries.

Space climate

The solar system can be considered an archive for storing changes of the local interstellar medium over eons, with the Earth as a special archive to us, because it could contain important clues as to how and why we live, as well as explain our climate and the way that it has developed, correlating with the information locked

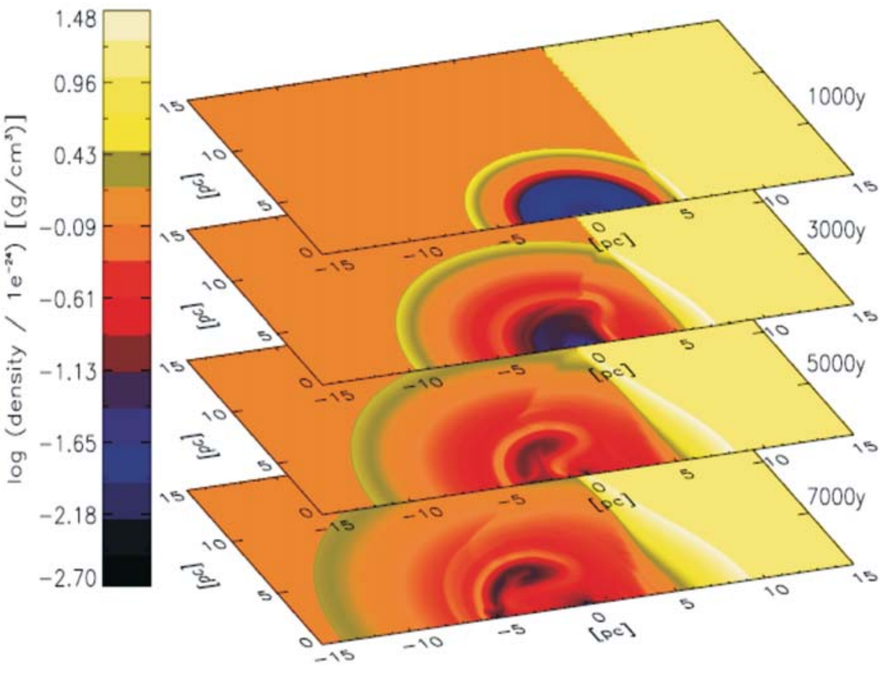

Fig. 5. Depicted here is the evolution of the interaction of a typical supernova remnant (SNR) in our galaxy, with a close-by medium of increased density over a simulated period of 6000 years. The density scale is given on the left-hand axis. The SNR is expanding from an interstellar medium with density of 10^{-24} g cm^{-3} (left side of figure) to a medium with a higher density of 10^{-23} g cm^{-3} (right side of figure). Computations were performed on the CHPC cluster.[20]

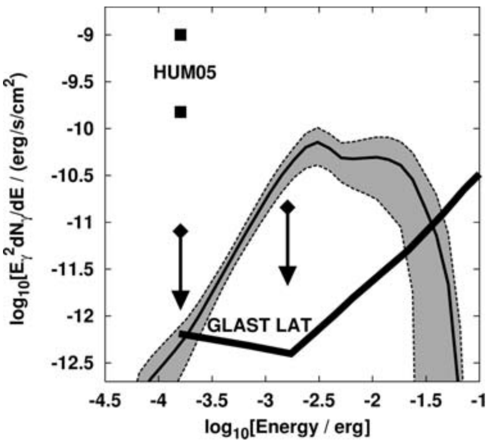

Fig. 6. The average differential-pulsed gamma-ray spectrum (solid line) for an ensemble of millisecond pulsars (MSPs) in the globular cluster 47 Tucanae, with 2 sigma-error bands (shaded band between dashed lines) with smoothed high-energy tails.[5,6] The average cumulative spectrum was calculated using 10^6 cumulative spectra, with each of these calculated by adding 100 randomly selected single MSP spectra. This type of computation can only be done on a high performance computer.

into ice cores, ice sheets, ocean sediments, tree rings, and so on. The terrestrial archives, however, have multiple input variables that arise from complex geological and climatological processes, making this information difficult to view in isolation from the solar-terrestrial and galactic-terrestrial factors.

The best archives, in the form of large data sets, are provided by the ^{14}C and ^{10}Be isotopes that are found on Earth. The ^{14}C is produced in the atmosphere by the interaction of cosmic rays with ^{14}N, whereas ^{10}Be is a spallation product from nitrogen and oxygen. Because of their relatively large mean global production rates and their conveniently long half-lives, they can be examined in the various terrestrial archives. The geochemical behaviour of ^{10}Be and ^{14}C differs, however. After production, ^{10}Be oxidizes to products that become attached to aerosols, and is removed from the atmosphere within 1–2 years, mainly by wet precipitation. Carbon-14 is oxidized to $^{14}CO_2$ and enters the carbon cycle, where it is rapidly exchanged between the atmosphere, biosphere, and the oceans.

As a consequence, the analysis of these nuclides in their respective archives provides information not only on the production history but also on atmospheric transport and mixing processes before being stored in their respective depositories. Cosmogenic radionuclides in terrestrial archives are useful tools[21] for reconstruction of the long-term history of cosmic rays, including solar cycle variations. The ^{10}Be records are used to deduce changes in solar activity, as well as variations in the geomagnetic dipole moment. This can be extended way back into the past, allowing estimations of the galactic cosmic ray fluxes at Earth's orbit. This, in turn, allows a reconstruction of the structure of the heliospheric magnetic shield, as it was in the past, and affords hints on the history of the interstellar environmental changes.

Researchers who are convinced that a cosmic ray link[22] to the terrestrial climate exists, have speculated that the ice ages on Earth might have been triggered by the encounters of the Sun and heliosphere with the galactic environment.[23] Computations performed at the CHPC indicate that the galactic cosmic ray flux reaching the heliosphere may vary by up to a factor of 4 as the heliosphere moves through the galactic spiral arms, where a large number of supernovae may occur.[19] Such a variation should cause a measurable effect on space climate inside the heliosphere, in the solar system and consequently on Earth's climate. Further study, by computational modelling in particular, is obviously required. See the review by Scherer and colleagues[9] for more detailed information on this topic, and for an extensive review on aspects of space climate. They concluded that to determine the spectra and total flux of the cosmic rays, it is necessary to know the number and strength of the sources and their distribution in the galaxy, in space and time.

In view of the apparent lack of *in situ* data (such as the local interstellar spectra), more sophisticated modelling is required, as well as *in situ* observations of the local interstellar and galactic medium. All these effects should be taken into account when interpreting cosmogenic data. Empirical evidence for an influence of 'space weather and climate' on planetary environments, especially on the terrestrial climate, exists for many time scales, from decades up to a billion years. It makes sense to distinguish between solar-terrestrial and interstellar-terrestrial relations, that is, to distinguish between an internal solar and external interstellar trigger for influence on Earth and its environment.

In contrast to solar forcing, cosmic ray forcing operates, in principle, on all time scales. In both cases the processes relevant to an influence on climate are unclear. Nonetheless, the evidence for cosmic ray forcing is increasing, as is the understanding of its physical principles. Cosmic rays, despite their negligible energy when compared with solar irradiance, are the main source of ionization in the troposphere. The detailed chain of processes connecting variable cosmic ray flux with terrestrial climate (that is, via cloud formation) has still to be identified. Given the potentially massive changes in the structure of the heliosphere along its path around the galactic centre, it is likely that not only galactic but also anomalous cosmic rays are mediators of the interstellar-terrestrial relations. The investigation of this problem has only recently started. The complexity of the topic evidently needs an interdisciplinary approach, which alone has great potential for directing research to new frontiers.

Advantages of using the CHPC

The availability of the CHPC has contributed significantly to increased computational research output from the USP during the past two years. A single MSP calculation takes about 5 hours on a fast desktop PC, so that computations for a population of 70 MSPs will normally require about two weeks. In contrast, on the CHPC cluster, it takes a single day. Investigation of the distributions of primary cosmic rays in and outside galactic spiral arms has been shortened by several months, with faster publication of final results and conclusions. Furthermore, the CHPC allows the opportunity to contemplate more ambitious projects that were previously considered to be impossible to do in this country. This is not only for the benefit of the USP but also for all scientists who need computational-intensive support in South Africa.

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