Astrophysics

Hunting the strongest accelerators in our Galaxy

Petra Huentemeyer

Twelve candidates for the most powerful astrophysical particle accelerators in the Milky Way have been detected. This advance will help to uncover the nature of these exotic objects. **See p.33**

What are the most powerful particle accelerators in our Galaxy, and how many of them are out there? Given what is already known about the Milky Way, it is perhaps surprising to hear that scientists are still not entirely sure. On page 33, the Large High Altitude Air Shower Observatory (LHAASO) Collaboration[1] reports the detection of an unprecedented number of candidates for such accelerators, signalling the advent of a new era in very-high-energy astrophysics.

Interstellar space is pervaded by protons and other atomic nuclei that move at nearly the speed of light. These particles, called cosmic rays, were first detected more than a century ago by the Austrian–American physicist Victor Hess[2]. Hess launched, on balloon flights, devices that allow the ionization rate in the atmosphere to be measured. He found that the ionization rate increases with altitude, and concluded that "radiation of very high penetrating power enters from above into our atmosphere". Scientists later determined that cosmic rays are charged particles[3].

Modern ground-based observatories have found that cosmic rays can reach energies of more than 1 petaelectronvolt (1 PeV is 10^{15} eV). Such energies are about 100 times higher than those achieved in the accelerators of the Large Hadron Collider at CERN, Europe's particle-physics laboratory near Geneva, Switzerland. The astrophysical accelerators that can drive particles to these tremendous energies are dubbed PeVatrons, by analogy with the Tevatron — an accelerator that operated until 2011 at Fermilab near Chicago, Illinois.

It has not been unequivocally confirmed what PeVatrons are, or how many of them reside in our Galaxy. One challenge to finding them is that, because cosmic rays are charged, the tracks on which these particles travel are altered by interstellar magnetic fields. It is therefore impossible to determine where cosmic rays originate. However, there is a way to bypass this problem: tracing the paths of γ-rays.

Cosmic rays can produce γ-rays when they collide with interstellar matter, such as clouds of molecular gas, or interact with interstellar electromagnetic fields close to accelerators. These γ-rays can carry about one-tenth of the energy of their progenitor cosmic rays, and move in a straight line — unaffected by magnetic fields — to a potential observer. Therefore, discovering a location from which γ-rays exceeding 0.1 PeV in energy are emitted is strong evidence for a PeVatron in that region. The current authors used the LHAASO in Sichuan, China (Fig. 1) to identify 12 such locations, approximately doubling the number of PeVatron candidates discovered so far.

In the standard model of cosmic-ray acceleration, the particles are swept up by a fast-moving shock wave in the remnant of a supernova explosion. Magnetic-field inhomogeneities associated with the shock wave result in the particles repeatedly reflecting back and forth across the shock front. This process, known as diffusive shock acceleration, causes the particles to speed up. However, it is not obvious whether the particles remain in the acceleration zone long enough to reach PeV energies. Moreover, until now, only one PeVatron candidate has been potentially associated with a supernova remnant[4,5].

There are other astrophysical objects that could accelerate cosmic rays to PeV energies. In 2016, the High Energy Stereoscopic System (HESS) Collaboration, operating telescopes in Namibia, reported the detection of γ-rays coming from the Galactic Centre[6]. These γ-rays were interpreted as tracers of PeV cosmic rays associated with past activity of the supermassive black hole at the Galactic Centre. Moreover, since 2019, several other telescopes across the globe have measured γ-ray emission at energies approaching or exceeding 0.1 PeV, from locations in our Galaxy that are near highly magnetized, fast-rotating compact stars called pulsars or near star-forming regions[7–12].

None of the previous measurements had the high-energy reach of LHAASO observations. In its final configuration, the LHAASO will have three detector subsystems, known as the Water Cherenkov Detector Array, the Wide Field-of-view Cherenkov Telescope Array and the Kilometer Square Array. In the current paper, the authors identified the 12 PeVatron candidates using data collected in less than a year by the half-completed Kilometer Square Array. Completing the LHAASO and obtaining more data will increase the observation

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Figure 1 | The Large High Altitude Air Shower Observatory (LHAASO) in Sichuan, China. The LHAASO Collaboration[1] has used the LHAASO to detect γ-rays produced by 12 candidates for the strongest astrophysical particle accelerators in our Galaxy.

sensitivity, providing further confidence in the extremely high energies reported for the γ-rays produced by the PeVatron candidates.

For one of these candidates, the authors detected γ-rays with energies as high as 1.4 PeV, coming from the direction of the constellation Cygnus. This finding will catch the attention of many researchers and will surely be examined critically by scientists inside and outside the LHAASO Collaboration. Intriguingly, both the Tibet ASγ Collaboration[12] and the High-Altitude Water Cherenkov (HAWC) Collaboration[13] reported γ-ray emission exceeding 0.1 PeV from this region of the sky. The HAWC researchers studied the surface brightness of the region and connected the emission to the Cygnus OB2 star cluster, where powerful shock waves generated by strong stellar winds might accelerate particles to PeV energies. In the future, the LHAASO Collaboration could carry out similar studies to constrain the maximum power of cosmic-ray acceleration in star clusters.

New telescopes will come online in the next few years, and others are in the planning phase. The Cherenkov Telescope Array[14] is a ground-based observatory that will be run by a multinational consortium at sites in Chile and the Canary Islands, Spain. Another group of astrophysicists plans to build the Southern Wide-field Gamma-ray Observatory[15] in South America. With its large field of view, this instrument would be ideally positioned to survey huge swathes of the Southern Hemisphere's sky, which includes an excellent view of the Galactic Centre. These next-generation instruments will search for signs of PeVatrons and other extreme, possibly unexpected structures to learn more about the nature and transport of matter and energy in the Universe.

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Food

Unearthing hidden hunger in Africa

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A diet containing insufficient micronutrients can harm human health. Maps that pinpoint areas of Africa associated with micronutrient-poor grains now offer a way to target interventions that tackle such deficiencies. **See p.71**

Access to sufficient safe, nutritious food for a healthy diet is a basic human right, and eradicating hunger lies at the heart of the global sustainability agenda. As we move towards the United Nations Food Systems Summit later this year, it is imperative that the debate about global food security shifts from a narrow focus on providing enough calories to consideration of how to provide the right balance of foods needed. A challenge related to this, and one not often placed in the limelight, is the issue of 'hidden hunger', the deficiency of specific micronutrients (minerals and vitamins), which is prevalent in many countries of sub-Saharan Africa. On page 71, Gashu *et al.*[1] present maps of Ethiopia and Malawi that highlight hotspots at greatest risk of human micronutrient deficiency associated with local cereal intake. This information, obtained by measuring the mineral content of cereal grains and the soils in which they were grown, enlarges the range of options available when selecting interventions to enhance human health.

Micronutrient deficiencies negatively affect the growth and development of plants, animals and people alike. Women and children are disproportionally affected[2] as a result of their dietary needs and because of the socio-economic and cultural disadvantages that they can face. If hidden hunger causes health problems during early childhood and an individual's learning ability is impaired[3], this can have lifelong negative consequences. As with all health problems, correct diagnosis is the first step towards an effective remedy. However, by the time health disorders due to micronutrient deficiencies become apparent, the damage has been done, so it is essential to develop methods that can predict where problems will probably occur.

Direct assessment of human micronutrient deficiency requires blood sampling, which is a complex task for large-scale population studies spanning wide geographical areas. Instead, dietary intake of micronutrients is commonly assessed indirectly on the basis of a typical diet and with the use of food-composition tables giving the micronutrient content of foods. However, this approach is confounded by local variability in food quality.

The link between soil micronutrient deficiencies and dietary effects on human health is a subject of growing research interest owing to the possible interconnections between soil, plants, animals and human health. The empirical evidence for this link in the regions most severely affected by micronutrient deficiencies is variable and not well established. Could we predict the likelihood of the existence of hidden hunger on the basis of soil properties? Gashu and colleagues, part of a large team of soil scientists and statisticians, have addressed that question on a national scale across Ethiopia and Malawi. They sampled cereal grains from thousands of farmers' fields, at locations selected to be representative of large geographical areas.

The authors overcame major logistical challenges to carry out this work over huge areas, within the short time frame around harvest time. The grain samples obtained were ground and analysed to determine their concentrations of calcium, iron, selenium and zinc. These are key micronutrients that are often deficient in the human diet.

The cereal crops most commonly consumed in Ethiopia are wheat and teff (*Eragrostis tef*; Fig. 1), a tiny-seeded grain. The authors' study of Ethiopia indicated that wheat and teff could contribute up to one-quarter of the recommended dietary calcium needed. By contrast, they found that maize (corn), the staple cereal in Malawi, could provide only 3% or less of the dietary calcium needed. Maize also provided less than one-quarter of the selenium requirement, half of the iron and three-quarters of the zinc requirement. The mapping exercise revealed a high variability in grain micronutrient concentrations, with an increased risk that this grain intake, if part of a diet lacking diversity, will lead to human micronutrient deficiencies in some regions of the countries studied.