
Einstein@Home
World Year of Physics 2005
14:26:38
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Total credit: 272724
Host credit: 77995
Team: Einstein@Penn State
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Gravitational Waves
on Home Computers

The Einstein@Home project makes it possible for anyone to search for gravitational waves on their own PC, laptop or smartphone and thus become scientific explorer themselves. **Bruce Allen**, Director at the **Max Planck Institute for Gravitational Physics** in Hannover, is the founder of this citizen science project. The software is now also used to track down pulsars in big data. Researchers from the Max Planck Institute for Radio Astronomy in Bonn are also involved in this search.

TEXT **THOMAS BÜHRKE**

The discovery of a gravitational wave on September 14, 2015 with the LIGO detectors in the US is regarded as a scientific sensation and confirmed one of the final predictions of Albert Einstein's general theory of relativity. Scientists from the Max Planck Institute for Gravitational Physics in Golm and Hannover were significantly involved in the discovery (MaxPlanckResearch 1/2016, p. 78 ff.).

The first gravitational wave ever detected was unexpectedly strong. Its signal was even visible to the naked eye in the data stream that was continuously analyzed by the Hannover-based Atlas supercomputer. The first person to recognize the signal was a researcher from the Max Planck Institute. Yet matters could have turned out differently. Since the beginning of the LIGO measurements, scientists have been searching for weak periodic gravitational waves that are likely to be emitted by rapidly rotating neutron stars. Atlas is the world's largest cluster for data analysis, yet in undertaking this task, even it would be stretched to its limits.

The designers of gravitational wave detectors were aware of this problem right from the start, so two of them came up with an idea. Bruce Allen remembers distinctly: "It was August 19, 1999." He had met his colleague Stuart Anderson for a meal at the California Institute of Technology (Caltech). Allen had read an article in the Los Angeles Times about the SETI@home project. The search for signals from extraterrestrial intelligence in the data from large radio telescopes presented researchers with the same problems as those confronted by Allen and his colleagues: how can they find the periodic signals in the vast data chaos?

A NETWORK WITH ENORMOUS COMPUTING CAPACITY

SETI@home is based on a decentralized analysis of data that is distributed to thousands of private computers. It works like this: a person logs in with a home computer and then receives the software, which analyzes data whenever the screen saver starts. The results are automatically returned. In this way, the search for signals is distributed throughout a network with massive computing capacity. From the very beginning, SETI@home was extremely popular. However, the search for aliens has so far been in vain.

"I discussed with Stuart the possibility of searching the gravitational

Screen savers with a purpose: The Einstein@Home program automatically searches for rapidly rotating neutron stars in the data from gravitational wave detectors, gamma satellites and radio telescopes.

Left A satellite dish surrounded by nature: The Arecibo radio telescope in Puerto Rico has a diameter of 305 meters and listens for pulsar signals. Einstein@Home can detect them, thus transforming home PCs, smartphones and tablets into valuable tools for science.

Right page An idea that started in the cafeteria: In 1999, Bruce Allen, Director at the Max Planck Institute for Gravitational Physics in Hannover, discussed with a colleague the possibility of having the data from gravitational wave detectors scanned. The result of this discussion was Einstein@Home, a program in which hundreds of thousands of people worldwide have so far participated. Allen is standing next to the Atlas cluster, which plays a central role in the network.

wave data of the two LIGO instruments in the same way," says Bruce Allen. "But then the thought occurred to us that, while everyone is interested in aliens, who really cares about gravitational waves?" As a result, the idea died, at least temporarily. Yet, four years later, it was revived. Allen received a call from a SETI@home pioneer who was looking for a way to take part in the upcoming 2005 International Einstein Year.

Immediately thereafter, Allen remembered the conversation in the Caltech cafeteria and he suddenly saw a chance to realize the idea he had discussed at that time. He promptly applied to the National Science Foundation for a grant of two million dollars over three years that would involve the University of Berkeley and the Max Planck Institute. But this relatively small amount was not approved. It was now June 2004 and the Einstein Year was fast approaching.

Without further ado, Bruce Allen and his coworkers decided to develop the necessary software on their own. The project received its finishing touches through David Anderson, from the University of Berkeley, who had already written the software for SETI@home. "We transferred the software to our own project, which led to great advances in its realization," said Allen. Scientists were thus able to complete an initial version by February 2005, which they presented at a press conference held at the annual meeting of the American Association for the Advancement of Science.

The media was enthusiastic about the project. It was christened Einstein@Home and customized for the Einstein Year. The news spread quickly: according to Allen, within a few days, 20,000 participants had registered. This, in turn, attracted the attention of the National Science Foundation to the project, which now offered financial support with little administrative ado.

The Max Planck Institute for Gravitational Physics, where Allen was appointed Director in 2007, was a part of Einstein@Home from the very beginning. To date, several hundred thousand people throughout the world have participated in the project, with more constantly joining in, so that now 40,000 amateur researchers are actively involved – sometimes with several devices simultaneously.

SIGNALS ARE CHOPPED UP INTO SMALL PARCELS

There are around 100 other projects in which data is viewed by means of distributed computing. The spectrum extends from the development of drugs for combating malaria and molecular simulations of proteins all the way to the search for the greatest known prime number. Einstein@Home is one of the largest of these endeavors. It has now reached a total computing power of 1.7 petaflops per second, which is 1.7 billion calculation steps. This computer network is one of the 60 most powerful supercomputers worldwide.

"The Atlas cluster plays a central role in this network," says Bruce Allen. It prepares the signals received by the LIGO detectors and chops them into small packages. They are chosen so that each participating computer re-

Photo: NAIC-Arecibo Observatory

Photo: Frank Vinken

ceives no more than one megabyte of data per hour. Atlas requires only 1 percent of its output for this administrative activity. Data from the PCs and laptops are then sent back to Atlas and prepared for scientists, for example in the form of diagrams. If a promising point in the data stream is reported, Atlas examines it in detail.

Despite years of research, the search for gravitational waves remained unsuccessful. While this was somewhat frustrating, resourceful researchers were able to draw astrophysical conclusions from this very absence of a signal. The conclusions were reached concerning neutron stars – the remains of exploded suns with a size of around 20 kilometers.

These neutron stars have extreme properties. The matter in them is so strongly compressed that a teaspoon of it on Earth would weigh as much as a million long-distance trains. They also rotate very rapidly about their own axis. This creates excellent conditions for the emission of gravitational waves, where the frequency of such a wave would correspond to the rotational frequency of the body. But neutron stars emit these space-time waves only if they're not perfectly symmetrical.

Yet neutron stars are among the most spherical bodies in the universe, making them poor transmitters. The fact that no periodic signal has been received from them up to now says something about their symmetry. The intensity of a gravitational wave received on Earth decreases with the increasing distance of the neutron star. Moreover, LIGO detectors are most sensitive in the frequency range from several dozen to several hundred hertz. As a result, only statistical statements can be made about the shape of neutron stars.

Accordingly, there are no neutron stars with a rotational frequency of 100 hertz or more within a radius of about 1,000 light-years for which the surface differs by more than 10 centimeters from a perfect sphere. This is truly a very remarkable result. "In the electromagnetic wave range, we have already detected several thousand neutron stars – of a total of perhaps 100 million that exist in our Milky Way," says Maria Alessandra Papa from the Max Planck Institute in Hannover. "In the future, gravitational wave astronomy will offer a whole new way to gather more information about these unseen denizens of our universe."

BUNDLED RADIO WAVES SWEEP THE EARTH LIKE SEARCH LIGHTS

These findings are of great importance to astrophysicists. Nevertheless, the enthusiasm of even the biggest Einstein@Home enthusiast will begin to wane if no signal is caught over the years. This was a matter of deep concern to Bruce Allen, which is why he was seeking other areas of application. He found one in late 2007 after listening to a lecture by a radio astronomer on the search for pulsars.

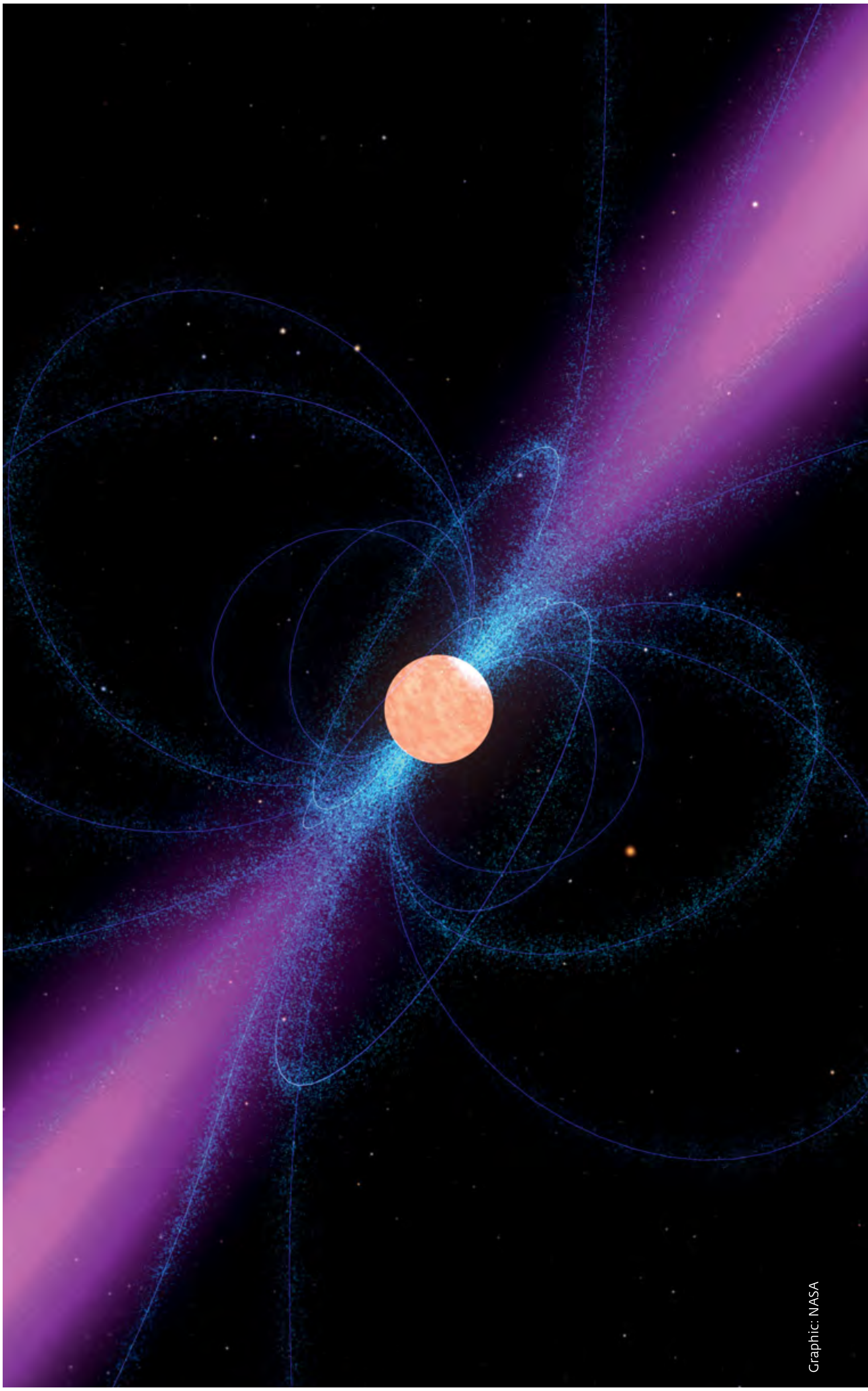
Hidden behind these objects are neutron stars, which emit two bundles of radio waves in opposite directions along the magnetic field axis into space. If the axis of rotation and the magnetic field axis are inclined toward one another, then the two bundles of radio waves pass through space like the searchlights of a lighthouse. If they happen to traverse the Earth, telescopes would receive a periodic signal with the rotation frequency of the pulsar.

Bruce Allen immediately realized that Einstein@Home could be applied to this area. Particularly for double systems in which a neutron star and a companion orbit one another, Einstein@Home could make a significant contribution to the discovery of such systems. "With their analytical methods, radio astronomers can find only pairs for which the orbital period is longer than an hour," says Allen. "We should also be able to track tighter pairs down to an orbital period of ten minutes."

Even though the analysis of the measurement data of radio telescopes is similar to that used in gravitational wave detectors, this expansion still required considerable effort. Doctoral student Benjamin Knispel found the endeavor to be especially fascinating and devoted himself to it. The subject matter even became his doctoral thesis. "The software had to be significantly modified," recalls Knispel. "The data from radio telescopes differs in many aspects from that detected by the LIGO detectors."

The biggest challenge is that physicists don't know whether a pulsar signal was actually hidden in the data record in question. And if it was, they don't know at what frequency. A further difficulty arises in the case of a pulsar in a double system. If it is moving toward us in its course, the pulses arrive in shorter intervals, while if it is moving away from us, the pulse sequence slows down. The pulse frequency therefore changes periodically with the orbital period of the pulsar.

"This blind search for signals of which the parameters are not known at all is very complex," explains Knispel. "We want to make the optimal use of our limited computing capacity, just as if a person wanted to win the biggest profit in a casino from a certain stake." Einstein@Home is ideal for these blind searches, because it is particularly efficient to analyze small data packages



Graphic: NASA

Left page A cosmic lighthouse: The strong magnetic field of a neutron star creates bundles of radiation at its poles in the form of two cones that, with a bit of luck, will traverse the Earth and reveal a pulsar – an object that blinks rhythmically.

Right A look at the data: Maria Alessandra Papa from the Max Planck Institute in Hannover coordinates the search for a continuous signal from gravitational waves, such as those that neutron stars should produce. In the future, the researcher hopes to learn more about a large, invisible population of these objects that has thus far been invisible.

Photo: T. Damm/Max Planck Institute for Gravitational Physics

with a high level of data processing power. Because of the many decentralized private computers, the computing power is obtained almost for free.

THE SUCCESSFUL SEARCH FOR UNKNOWN BEEPERS

Since March 2009, Einstein@Home is also searching for radio pulsars. The data is provided by the PALFA project (Pulsar Surveys with the Arecibo L-Feed Array) that is being carried out by the Arecibo Observatory through its 305-meter antenna. It took only about a year until the first discovery. The PCs of two participants had discovered a conspicuous signal in the same data set.

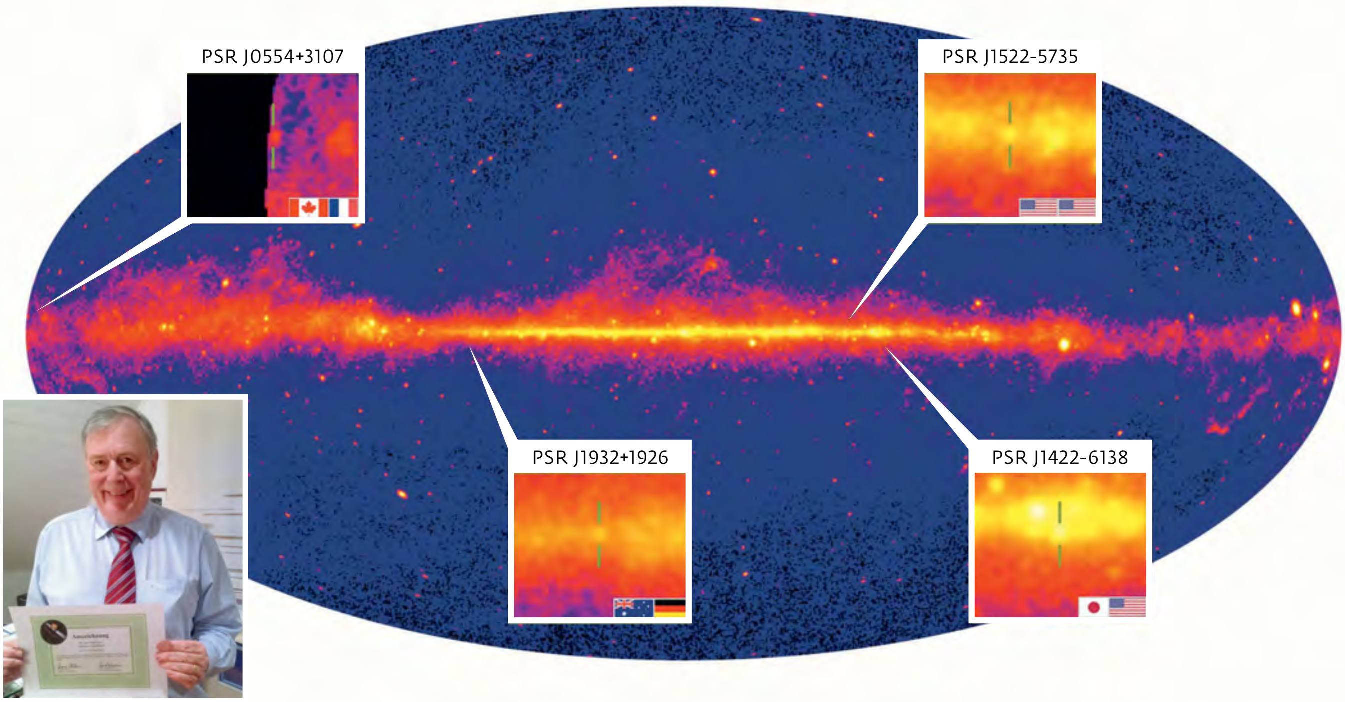
A subsequent analysis with Atlas confirmed the find. Then the professionals took over. In July 2010, astronomers searched for the previously unknown beeper with the radio telescope in Green Bank (USA). They were successful in their search: it was a pulsar that spins around its axis 41 times per second. Astronomers directed further radio telescopes at the newly discovered heavenly body, including the Effelsberg 100-meter antenna of the Max Planck Institute for Radio Astronomy. These observations have shown that the pulsar is a loner located about 17,000 light-years away from Earth, and that it has a magnetic field around 20 billion times stronger than that of Earth.

To date, Einstein@Home has led to the discovery of a total of 55 radio pulsars, including some rare specimens, such as an object 25,000 light-years away named PSR J1913 + 1102. This is a pair consisting of a pulsar and a neutron star; the two revolve around one another with a five-hour orbital period. However, the neutron star can't be detected as a pulsar – probably because its radio wave emissions don't traverse the Earth.

"With a total of 2.88 solar masses, we now have a new record for the total mass of a system composed of two neutron stars," says Paulo Freire from the Max Planck Institute for Radio Astronomy in Bonn, who is extensively involved in Einstein@Home. These rare double neutron stars are unique labs for testing relativity theory in strong gravitational fields – a special area of the group headed by Michael Kramer, Director at the Institute.

Most of the currently 2,500 known radio pulsars that have been identified in space are isolated and rotate as single stars. Only 255 of them are located in double systems, and only a handful orbit around another neutron star. This is where Einstein@Home hit the bull's eye.

However, the success story doesn't end here. Since August 2011, the Einstein@Home computers have also been rummaging through data from the Fermi space telescope. This telescope detects cosmic gamma radiation, which is of a significantly higher energy level than radio waves or visible light. The detection of pulsars in this manner is an enormous challenge because the



The joy of discovery: Hans-Peter Tobler of Rellingen is one of those lucky amateur astronomers whose computers identified the signals from the first four gamma pulsars. In the background is an image of the Milky Way showing the positions of the pulsars. The flags in the enlargements refer to the nationalities of Einstein@Home users who participated in the discovery.

gamma radiation received is extremely weak: on average, Fermi detects only about 10 gamma photons per day from a typical pulsar! It therefore takes years of data collection to detect a pulsating signal – in the absence of prior knowledge as to pulse frequency and phase, meaning the positions of the pulses in the data stream.

This intricate analysis problem is precisely where Einstein@Home demonstrates its strength. First the software had to once again be rewritten and made more efficient, but the effort was immediately rewarded: within a year, the participants had detected more than a dozen pulsars in the Fermi data, and since then, further discoveries have been achieved exclusively with Einstein@Home.

Astrophysicists recently published a catalog of 13 newly discovered gamma pulsars. Using only a single home PC, the search would have taken more than 1,000 years. Einstein@Home was able to accomplish this within a year, although only a part of the project's performance capacity was utilized. A total of one-third of all such discovered objects has been due to the use of the decentralized computers.

AMATEUR ASTRONOMERS DETECT FOUR GAMMA PULSARS

The new data is of great importance for research because it isn't yet clear just how pulsars generate radiation. Gamma radiation and radio waves are probably generated in different areas above the surface, which is why information about the various radiation types can give us an overall picture of these fascinating celestial bodies.

Successful amateur researchers who participate in Einstein@Home are informed by e-mail, receive a certificate and are specifically acknowledged in the scientific publication pertaining to their work. Hans-Peter Tobler from Rellingen, something of an old hand at these matters, is one of them. He was already participating in SETI@home and immediately signed up in the beginning stages of Einstein@Home. Just about four years ago, he received the news that he was one of the discoverers of the first four gamma pulsars.

"Of course I was delighted and at first could hardly believe it when Bruce Allen got in touch with me," he recalls. "The certificate, which came later, has been framed and given a place on my desk," says the former economist, who has had a deep love for astronomy since youth.

Einstein@Home can look back on an impressive history of discovery, even if its actual intention – the detection of gravitational waves – hasn't yet been realized. And Allen isn't all that optimistic about the future. "Over the past few years, more and more people have switched from laptops and PCs to tablets and smartphones, which are

Photo: Knispel/Pletsch/AEI/NASA/DOE/Fermi LAT Collaboration/Hans-Peter Tobler devices that have been designed to maximize battery time." In other words, idle times with screen savers are a thing of the past. But the Max Planck researchers have come up with a new idea.

Since July 2013, they have been offering the software for Android smartphones and tablets. In order to preserve battery life, minimize load times and avoid using up download quotas, the software calculates only when the device is connected to a WLAN network and the battery charge is above 90 percent. Currently about 4,000 active participants are registered – which is encouraging. "I hope that we will finally find the first gravitational wave signal in the data of the improved LIGO detectors," says Allen. This would mean that, for the first time, amateurs would have been involved in a discovery worthy of a Nobel Prize. ◂

TO THE POINT

- **The project for distributed computing called Einstein@Home has been underway since 2005. The project has enabled tens of thousands of participants throughout the world to search the data provided by the LIGO detectors for signals from gravitational waves.**
- **Since 2009, an extension of the software has made it possible to search data from radio telescopes, and since 2011 it has also been possible to search for pulsars in gamma ray satellite data. This has facilitated the discovery of 55 radio pulsars and 19 gamma pulsars.**
- **Since 2013 it has also been possible to search with Android smartphones and tablets.**

GLOSSARY

Gravitational waves: Curves in space-time produced by the accelerated motion of celestial bodies. Gravitational waves move through space at the speed of light and were first detected on September 14, 2015.

LIGO: This observatory consists of two detectors, each of which has laser arms with a length of four kilometers. The detectors are located in Hanford (Washington, USA) and Livingston (Louisiana, USA). After an upgrade, the sensitivity of the detectors was significantly increased. As a result, the observatory has been operating under the name Advanced LIGO since 2015.

Distributed computing: A combination of independent computers that work as a single system and analyze large amounts of data. The Atlas supercomputer coordinates the independent computers that participate in Einstein@Home.