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Pulsar Discovery by Global Volunteer Computing

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Einstein@Home aggregates the computer power of hundreds of thousands of volunteers from 192 countries to "mine" large data sets. It has now found a 40.8 Hz isolated pulsar in radio survey data from the Arecibo Observatory taken in February 2007. Additional timing observations indicate that this pulsar is likely a disrupted recycled pulsar. PSR J2007+2722's pulse profile is remarkably wide with emission over almost the entire spin period; the pulsar likely has closely aligned magnetic and spin axes. The massive computing power provided by volunteers should enable many more such discoveries.

Einstein@Home (*1*) (E@H) is a volunteer distributed computing project (*2*). Members of the public "sign up" their home or office computers ("hosts"), which automatically download "workunits" from the servers, carry out analyses when idle, and return results. These are automatically validated by comparison with results for the *same* workunit, produced by a different volunteer's host. More than 250,000 individuals have contributed; each week about 100,000 different computers download work. The aggregate computational power (0.25 PFlop/s) is on par with the largest supercomputers. E@H's primary goal is to detect gravitational waves from rapidly-spinning neutron stars in data from LIGO and VIRGO (*1*).

Since 2009, about 35% of E@H compute cycles have also been used to search for pulsars in radio data from the PALFA project (see SOM) at the 305 m Arecibo Telescope. Data disks are sent to Cornell University's Center for Advanced Computing, where data are archived. For E@H, data are transferred to Hannover, de-dispersed for 628 different dispersion measures (DM $\in$ [0, 1002.4] pc cm^{-3}), and resampled at 128 μs. Hosts receive workunits containing time series for four DM values for one beam. Each is 2MB in size, covering 268.435456 s. A host demodulates each time series (in the time domain) for 6661 different circular orbital templates with periods greater than 11 minutes (our Galaxy has even shorter period binaries). The grid of templates is spaced so that for pulsar spin-frequencies below 400 Hz, less than

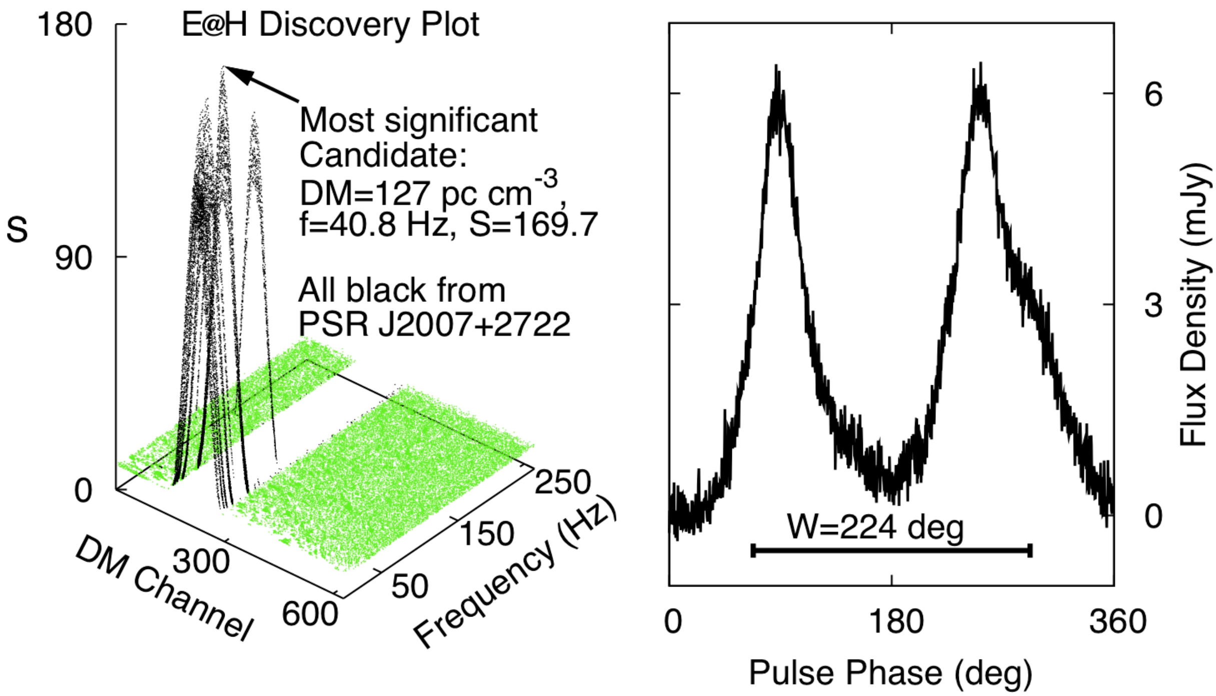

Figure 1: **(Left)** significance $\mathcal{S}$ as a function of DM and spin frequency (all E@H results for the discovery beam). **(Right)** the pulse profile at 1.5 GHz (GBT). The bar illustrates the extent of the pulse.

20% of signal-to-noise ratio is lost. Fourier algorithms sum up to 16 harmonics. A total of 1.85% of the power spectrum is removed to eliminate well-known sources of radio frequency interference. A significance ($\mathcal{S} = -\log_{10} p$, with p the false-alarm probability in Gaussian noise) is calculated at each grid-point. After ~ 2 CPU-hours, the host uploads the 100 most significant candidates to the server.

When all workunits for a given beam are complete, the results are post-processed on servers at Hannover. Candidates with $\mathcal{S} > 15$ are identified by eye, then optimized with PRESTO (see SOM). To date E@H has searched 27,000 of 68,000 observed beams. It has re-detected 120 pulsars, most in the past four months, because code and algorithm optimizations sped-up the search by a factor ~ 7.

On 11 July, the 24-ms PSR J2007+2722 was discovered with a significance of $\mathcal{S} = 169.7$

(Fig. 1). The pulsar was later re-detected in another PALFA survey observation. Follow-up observations were done by the Green Bank Telescope (GBT, USA), the Lovell Telescope at Jodrell Bank Observatory (UK), the radio telescope at Effelsberg (Germany), the Westerbork Synthesis Radio Telescope (WRST, Netherlands), and Arecibo. The period-averaged flux density is 2.1 mJy at 1.5 GHz. Gridding observations using Arecibo and WSRT unambiguously associate the pulsar with a source in an archival VLA C-array observation, having 1.2 mJy flux density at 4.86 GHz, at RA $20^{\mathrm{h}}07^{\mathrm{m}}15^{\mathrm{s}}.77$ Dec $27°22'47''.7$ (J2000) with uncertainty $\lesssim 1''$. The pulsar is not in a supernova remnant or globular cluster and has no counterpart in X-ray or gamma-ray point-source catalogs. The DM of 127 pc cm^{-3} implies a distance of 5.3 kpc (*3*). The full pulse width between the outer half-maxima is $W \approx 224°$. The wide pulse and initial polarization observations indicate that the pulsar likely has nearly aligned magnetic and spin axes.

The pulsar's barycentric spin frequency (*4*) is $40.820677620(6)$ Hz at MJD 55399.0. With the VLA position, the 2010 data give limits $|\dot{f}| < 3\times10^{-14}\mathrm{s}^{-2}$, magnetic field $B < 2.1\times10^{10}$ G, and spin-down age >21 Myr. These limits and lack of a companion mean that J2007+2722 is likely the fastest-spinning disrupted recycled pulsar yet found (*5*). However we cannot rule out it having been born with low B (*6*). Either way, PSR J2007+2722 is a rare, isolated low-B pulsar which contributes to our understanding of pulsar evolution.

This result demonstrates the capability of "consumer" computational power for realizing discoveries in astronomy and other data-driven science.

We thank Einstein@Home volunteers, who made this discovery possible. The computers of Chris and Helen Colvin (Ames, Iowa, USA) and Daniel Gebhardt (Universität Mainz, Musikinformatik, Germany) identified J2007+2722 with the highest significance. This work was supported by CFI, CIFAR, FQRNT, MPG, NAIC, NRAO, NSERC, NSF and STFC; see the Supporting Online Material for details.

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Supporting Online Material for "Pulsar Discovery by Global Volunteer Computing"

Materials and Methods

The observations use a seven feed-horn, dual-polarization radio camera at 1.4 GHz (ALFA) (*1*). Autocorrelation spectrometers sum polarizations and generate spectra over 100 MHz of bandwidth with 256 channels every 64 μs. Data are independently searched for isolated pulsars in three independent pipelines: (1) the Einstein@home pipeline described in this paper, searching for isolated or binary pulsars with orbits longer than 11 minutes, (2) a pipeline at Cornell University's Center for Advanced Computing, and (3) a pipeline using the PRESTO (*2*) package operating at several Pulsar ALFA (PALFA) Consortium member sites, searching for isolated or binary pulsars with orbits longer than $\sim$1h.

Timing data were collected from the GBT, Arecibo, Jodrell Bank, and Effelsberg over a total of 18 days. Pulse times of arrival were calculated using standard procedures and analyzed using the tempo software package (*3*). The timing analysis used the JPL DE405 solar system ephemeris, and times of arrival were referred to local observatory clock standards.

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