We have discovered a 716-Hz eclipsing binary radio pulsar in the globular cluster Terzan 5 using the Green Bank Telescope. It is the fastest-spinning neutron star ever found, breaking the 23-year-old record held by the 642-Hz pulsar B1937+21. The difficulty in detecting this pulsar, due to its very low flux density and high eclipse fraction (∼40% of the orbit), suggests that even faster-spinning neutron stars exist. If the pulsar has a mass less than 2 M⊙, then its radius is constrained by the spin rate to be < 16 km. The short period of this pulsar also constrains models that suggest gravitational radiation, through an r-mode instability, limits the maximum spin frequency of neutron stars.

While the majority of neutron stars are observed to rotate slower than a few times a second, those in binary systems can reach spin rates of hundreds of times a second through the transfer of angular momentum from their companion star \[ \text{[1][2]} \]. Some of these neutron stars, termed millisecond pulsars, are persistent radio sources whose emission is modulated at the star’s spin...
frequency. Determining the maximum achievable rotation rate of a neutron star is important for a variety of astrophysical problems, ranging from understanding the behaviour of matter at supra-nuclear densities, to estimating the importance of neutron stars as gravitational wave sources for current and upcoming gravitational wave detectors. For over 23 years, the 642-Hz pulsar B1937+21, the first millisecond pulsar ever found, has been the fastest-spinning neutron star known (3). It has been argued that faster ones are exceedingly rare, if they exist at all (4).

Per unit mass, globular clusters have many more millisecond pulsars than the Galactic disk. This is due to the extremely high stellar densities in their cores ($10^4 - 10^6$ pc$^{-3}$), which promote the creation of binary systems (5) where a neutron star is spun-up (or “recycled”) to rotate hundreds of times a second (6, 7). We have searched the massive and dense globular cluster Terzan 5 for millisecond pulsars using the National Radio Astronomy Observatory’s (6) 100-m Green Bank Telescope (GBT). Our searches have thus far uncovered 30 millisecond pulsars in Terzan 5 (7), in addition to the three previously known pulsars in this cluster (8, 9, 10). The discovery of 21 pulsars in Terzan 5 was presented in (11). Following that paper, an additional nine pulsars have been found in searches of our monitoring observations. These will be reported elsewhere. Terzan 5 has the largest known population of millisecond pulsars of any globular cluster, roughly one quarter of the entire population of globular cluster millisecond pulsars, and the five fastest rotating pulsars in the Galactic globular cluster system (7). Among the newest discoveries in Terzan 5 is PSR J1748−2446ad, a 716-Hz eclipsing binary millisecond pulsar, which is the fastest-spinning neutron star ever found.

**Observations and data analysis.** We discovered PSR J1748−2446ad in 10 November 2004 observations of Terzan 5 and confirmed it in 8 January 2005 observations using the Pulsar Spigot backend (72) on the GBT. All observations employed the Spigot with 600 MHz of usable bandwidth centered at 1950 MHz, 768 spectral channels, and 81.92-µs sampling. Observations were generally 6–7 hours in length and taken at roughly monthly intervals starting June 2004.
In addition, there was a more closely spaced set of observations in early May 2005.

The discovery observation showed that the pulsar is part of a binary system and is eclipsed by its companion; both of these properties restricted our ability to detect the pulsar in our monitoring sessions. Nonetheless, we have now detected the pulsar in at least 18 out of the 30 multi-hour observations taken thus far (see Fig 1 for pulse profile). We have derived a reliable orbital ephemeris (see Tab 1) by initially modelling the pulse phase delays of a few good detections with a simple sine function and then refining the model by fitting pulse times of arrival to a simple Keplerian orbital model, with arbitrary pulse phase offsets between observing epochs. This ephemeris allowed us to detect the pulsar in many observations where it was not initially identified through a periodicity search.

The pulsar is in a highly circular 26-hr orbit with a \( \geq 0.14 \, M_\odot \) companion, and is eclipsed for \( \sim 40\% \) of its orbit at 2 GHz. Such a large eclipse fraction, corresponding to an eclipse region with physical size \( \sim 5-6 \, R_\odot \) is extremely rare for such a relatively wide orbit (separation between the pulsar and companion of \( \sim 4-5 \, R_\odot \)). The companion may be a bloated main-sequence star, possibly still filling its Roche Lobe, as has been suggested for PSR J1740–5340, a 35-hr binary millisecond pulsar with a \( \geq 0.21 \, M_\odot \) companion and \( \sim 40\% \) eclipse fraction at 1.4 GHz (73). The eclipse properties are also similar to those of PSR J1748–2446A, a 1.8-hr binary with a 0.089 \( M_\odot \) minimum mass companion, also located in Terzan 5 (8). Like PSR J1740–5340 and PSR J1748–2446A, there is evidence that the eclipse duration of PSR J1748–2446ad is variable, and sometimes lasts longer than 40% of the orbit. On at least two epochs when our ephemeris predicts the pulsar should have been visible for several hours, it was not detected at all. The pulse signal-to-noise is too low to measure dispersion measure variations on short timescales. Future observations should allow a phase-coherent timing solution to be derived, which will provide a precise position and observed spin frequency derivative \( \dot{\nu} \). Until then, we have provided an upper limit on \( |\dot{\nu}| \) (Tab 1).
We have verified that this signal is not harmonically related to any of the other known pulsars in Terzan 5. We have also carefully investigated the possibility that our searches have identified the second harmonic of a new 358-Hz pulsar. When we fold the data at 358 Hz, there are two identical peaks (within the resolution and RMS noise level of the Spigot data) separated by 180° in pulse phase. This is what we expect to see if the pulsar signal is folded at half its intrinsic spin frequency, and strongly suggests that 716 Hz is the true spin frequency of the pulsar. The results of folding the data at other harmonically related spin frequencies are also consistent with the pulsar having a true frequency of 716 Hz. There is also evidence (Fig 1) for a weak, but statistically significant interpulse (extra structure in addition to the main pulse peak) when the data are folded at 716 Hz. This interpulse, if real, is further evidence that the spin frequency is 716 Hz.

Lastly, we have simultaneously observed the pulsar using the GASP coherent dedispersion pulsar machine ([14][15], which records only $\sim 1/6$ the bandwidth achievable with Spigot but which removes all dispersive smearing due to the ionized interstellar medium, resulting in significantly sharper (i.e. narrower) pulse profiles ([16]). When the GASP data are folded at 358 Hz, two peaks, consistent in shape with each other to within the RMS of the noise, are seen separated by 180° in pulse phase, again indicating that 358 Hz is half the true spin frequency. We conclude that PSR J1748−2446ad is indeed a 716-Hz pulsar.

**Implications and discussion.** The equation of state of matter at supra-nuclear densities, and thus the mass-radius relation for neutron stars, is unknown. If a star is rotating too rapidly for a given radius, centrifugal forces will cause it to shed mass. Lattimer & Prakash ([17]) derive the following equation which, independent of the true equation of state, gives the maximum spin frequency for a neutron star with a non-rotating radius $R$ and mass $M$ (assuming this is not close to the maximum mass allowed by the equation of state): $\nu_{\text{max}} = 1045(M/M_\odot)^{1/2}(10\text{km}/R)^{3/2} \text{Hz}$. Using this, and assuming a mass less than 2 $M_\odot$ (which accommodates all measured neutron star
masses (17) we find an upper limit of 16 km on PSR J1748–2446ad’s radius. We note that this constraint applies specifically to PSR J1748–2446ad and that slower-spinning pulsars could have larger radii. Recently, Li & Steiner (18) have derived a radius range of 11.5–13.6 km for a 1.4 M⊙ neutron star, based on terrestrial laboratory measurements of nuclear matter. For a 1.4 M⊙ neutron star, we find an upper limit of 14.4 km, which is in agreement with their result. These radius constraints are more robust than those obtained through observations of neutron star thermal emission, which is faint, difficult to measure, and whose characterization depends on uncertain atmosphere models (19). Although in principle a radius measurement could constrain the unknown equation of state of dense matter, PSR J1748–2446ad does not rule out any particular existing models, since the pulsar mass is unknown. It is unlikely that a mass measurement will be achievable through timing of the pulsar, as the orbit is too circular to measure the relativistic advance of the periastron, which would likely be contaminated by classical effects as well. However, once a timing position is available, optical spectroscopy may allow determination of the mass ratio, as has been done in the case of PSR J1740–5340 in the globular cluster NGC 6397 (20). The feasibility of such a measurement will depend on the pulsar not being located in the dense and optically crowded core of the cluster. Fortunately, as PSR J1748–2446ad has a dispersion measure which is ∼ 3 units lower than the ∼ 239 pc cm⁻³ average dispersion measure of the cluster pulsars, it is likely to be located outside of the core.

Although there are selection effects, especially at radio wavelengths, against finding fast, binary pulsars (21), we have maintained excellent sensitivity to these through the use of advanced search techniques (22) and data with high time and frequency resolution. For example, these searches blindly detect the 596-Hz binary pulsar PSR J1748–2446O (P orb ∼ 6 hrs) at its second and fourth harmonic, which is equivalent to detecting a highly accelerating 1192-Hz pulsar and its second harmonic. While these searches are clearly sensitive to pulsars faster than 716 Hz, we note that obscuration of the pulsar signal by material blown off the companion by the pulsar
wind may play an important role in reducing the chances of detecting such systems \(^{23}\). Of the five fastest known millisecond pulsars (including the two found in the Galactic plane; see Tab 2), four are eclipsing, and the fifth, PSR B1937+21, is unusual because, unlike \(\sim 80\%\) of Galactic plane millisecond pulsars, it has no binary companion. Since rotational energy loss is inversely proportional to the cube of the spin period \(\dot{E} = 4\pi^2 I \dot{P} / P^3\), where \(\dot{E}\) is the spin-down luminosity and \(\dot{P}\) is the period derivative), it is plausible that a large fraction of the fastest binary pulsars are evading detection because their powerful winds are ablating their companions. Some of the ablated material remains in the vicinity of the system and obscures radio pulsations, particularly at lower radio frequencies. Although we have no detections of the pulsar at other frequencies, several other eclipsing pulsars are observed to have longer eclipse durations at lower radio frequencies \(^{24}\). If this is also the case for PSR J1748–2446ad, then the unusually high observing frequency used here (2 GHz, while most globular cluster surveys have been conducted at 1.4 GHz or lower) was likely crucial in detecting this pulsar. PSR J1748–2446ad is too weak (the flux density at 1950 MHz is \(\sim 0.08\) mJy) to be detectable by the vast majority of Galactic plane surveys and its high eclipse fraction compounds this problem. This suggests that other even faster-spinning pulsars exist, but will require deeper surveys (perhaps at higher observing frequencies to mitigate obscuration of the pulsar signal by intra-binary material) and more concentrated efforts to be detected. In effect, the isolated nature and very large luminosity of PSR B1937+21 make it a unique object, rather than a representative member of the millisecond pulsar population.

Low-mass X-ray binaries (LMXBs) with neutron star members are the likely progenitors of the radio millisecond pulsars. As the spin-up time for a neutron star to reach \(> 1000\) Hz rotation via the accretion of matter in an LMXB is much shorter than the typical LMXB lifetime, one might naively expect many millisecond pulsars to be rotating at sub-millisecond periods. However, given the observed lack of pulsars spinning this fast, gravitational radiation has been
proposed as a limiting mechanism, as it could be responsible for carrying away rotational kinetic energy from the star, thus spinning it down. Specifically, gravitational waves may be acting either through an accretion-induced mass quadrupole on the crust (25), a large toroidal magnetic field (26), or an r-mode (Rossby wave) instability in the stellar core (27,28).

PSR J1748–2446ad provides interesting constraints on the r-mode possibility. These oscillations are believed to be present in all rotating neutron stars (29,30). Due to gravitational radiation emission, the r-modes become unstable and grow exponentially. The amplitude of the mode continues to grow as angular momentum is radiated away, and the star spins down. However, it is unclear whether the driving of these modes by gravitational waves can overcome viscous damping in the star. Damping depends on the core temperature of the star and its spin rate, as well as several other factors including the thickness of the neutron star crust and how it couples to the core. For a given core temperature, it is possible to derive a critical spin frequency above which the proposed mode is unstable and will cause the star to spin down rapidly. It has been predicted that the critical frequency is \(< 700 \text{ Hz}\) for a wide range of core temperature \(10^7 – 10^{10} \text{ K}\) and a realistic model of the neutron star crust (28). Our discovery of a 716-Hz pulsar indicates that if the r-mode instability limits neutron star spin-up, then either it must become important only at more rapid spin rates or better modelling of the neutron star crust is required.

The observed spin frequencies of LMXBs are all less than 620 Hz. The biases that exist at radio wavelengths against finding much faster pulsars do not exist for LMXBs, as X-rays
do not suffer from the dispersive effects of the interstellar medium and are less obscured by intra-binary material. This suggests that faster-spinning neutron stars in LMXBs should be detectable if they exist. However, transient coherent pulsations are only observed in seven sources, and there may be unidentified sources of bias in the population that are preventing faster pulsations from being detected. Chakrabarty et al. 2003 (4) performed a Bayesian statistical analysis on the spin frequencies of 11 nuclear-powered millisecond pulsars, those for which the spin frequency is known from the detection of burst oscillations, and concluded that the sample is consistent (at the 95% confidence level) with a cutoff $\nu_{\text{max}} = 760$ Hz. More recent work by the same authors (31), which added 2 pulsars to the sample, has revised this limit to 730 Hz. Based on this, they conclude that something, possibly gravitational radiation, is limiting the spin frequency of neutron stars. If their statistically derived upper limit is realistic (and therefore some mechanism is limiting neutron star spin-up), then the 716-Hz pulsar presented here is likely an extremely rare object. However, we note that their Bayesian calculation is very sensitive to the neutron star with the slowest spin frequency included in the analysis. In addition, the assumption made by these authors that the pulsar spin rates are uniform in frequency (at least over some range $\nu_{\text{low}}$ to $\nu_{\text{high}}$) would likely not apply to the Terzan 5 pulsars, whose spin period distribution is clearly not uniform (11), even accounting for the observational bias against detecting the fastest pulsars. Hence, a recalculation of the maximum spin cutoff using the Terzan 5 sample of pulsars and the same statistical analysis would not be appropriate, although the existence of PSR J1748−2446ad already implies that the cutoff must be higher.

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34. We thank Robert Ferdman and Paul Demorest for help with GASP observations, and acknowledge their work, along with Donald Backer, David Nice, R. Ramachandran, and Joeri van Leeuwen in creating the GASP instrument. We also thank Lars Bildsten, Phil Arras and Jim Lattimer for very useful discussions. JWTH is an NSERC PGS-D fellow and is grateful to the Canada Foundation for Innovation for funding the computing resources used to make this discovery and to Paul Mercure for helping to maintain them. IHS holds an NSERC UFA and is supported by a Discovery grant and UBC start-up funds. VMK is a Canada Research Chair and is supported by an NSERC Discovery Grant and Steacie Fellowship Supplement, by the FQRNT and CIAR. FC thanks the US NSF for support. GASP is funded by an NSERC RTI-1 grant to IHS and by US NSF grants to Donald Backer and David Nice.
| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| **Rotational Parameters**  |                                            |
| Pulse period $P$ (s)       | 0.00139595482(6)                           |
| Period derivative $|\dot{P}|$ (s/s) | $\leq 6 \times 10^{-19}$                   |
| Pulse frequency $\nu$ (Hz) | 716.35556(3)                               |
| Frequency derivative $|\dot{\nu}|$ (Hz/s) | $\leq 3 \times 10^{-13}$                   |
| Epoch (MJD)                | 53500                                      |
| **Orbital Parameters**     |                                            |
| Orbital period $P_{orb}$ (days) | 1.09443034(6)                           |
| Projected semi-major axis $a$ (lt-s) | 1.10280(6)                               |
| Time of ascending node $T_{ASC}$ (MJD) | 53318.995689(12)                         |
| Eccentricity $e$           | $< 0.0001$                                  |
| **Derived Quantities**     |                                            |
| Companion minimum mass $M_{2,min}$ (M$_{\odot}$) | 0.14                                      |
| Dispersion measure DM (pc cm$^{-3}$) | 235.6(1)                                  |
| Flux density at 1950 MHz $S_{1950}$ (mJy) | 0.08(2)                                   |
| Characteristic age $\tau_c$ (years) | $\geq 2.5 \times 10^7$                     |
| Surface magnetic field $B_{surf}$ (G) | $\leq 1.1 \times 10^9$                    |
| Spin-down luminosity $\dot{E}$ (erg/s) | $\leq 1.3 \times 10^{37}$                 |

Table 1: Measured and derived parameters of PSR J1748$-$2446ad. All measured spin and orbital parameters were determined using the TEMPO software package (32), using arbitrary phase offsets between observing epochs. Given the currently sparsely sampled data, it is impossible to phase connect separate observations. For this reason, we provide only an upper limit on the magnitude of the spin frequency derivative of the pulsar, which incorporates the maximum possible acceleration due to the gravitational potential of Terzan 5 assuming a position close to the cluster center. Likewise, we can currently only place limits on the derived characteristic age, surface magnetic field and spin-down luminosity. The minimum companion mass is derived assuming a pulsar mass of 1.4 M$_{\odot}$. The dispersion measure was determined by measuring pulse arrival time delays in the different frequency channels across the 600-MHz observing bandwidth.
| Pulsar     | Spin Frequency (Hz) | $P_b$ (days) | $M_{2,\text{min}}$ (M$_\odot$) | Eclipse Fraction | Location       |
|------------|---------------------|--------------|-------------------------------|------------------|----------------|
| J1748−2446ad | 716.358             | 1.0944       | 0.14                          | 0.4              | Terzan 5       |
| B1937+21   | 641.931             | isolated     |                               |                  | Galaxy         |
| B1957+20   | 622.123             | 0.3819       | 0.021                         | 0.1              | Galaxy         |
| J1748−2446O | 596.435             | 0.2595       | 0.035                         | 0.05             | Terzan 5       |
| J1748−2446P | 578.496             | 0.3626       | 0.37                          | 0.4              | Terzan 5       |
| J1843−1113 | 541.812             | isolated     |                               |                  | Galaxy         |
| J0034−0534 | 532.714             | 1.5892       | 0.14                          | 0                | Galaxy         |
| J1748−2446Y | 488.243             | 1.17         | 0.14                          | 0                | Terzan 5       |
| J1748−2446V | 482.507             | 0.5036       | 0.12                          | 0                | Terzan 5       |
| B0021−72J  | 476.048             | 0.1206       | 0.020                         | 0.1*             | 47 Tucanae     |

Table 2: The ten fastest-spinning known radio pulsars. Data compiled from the ATNF pulsar database (33). *B0021−72J is eclipsed only at radio frequencies <1 GHz.
Figure 1: Master PSR J1748−2446ad pulse profile from the combination of eight GBT Pulsar Spigot observations at 2 GHz with particularly good detections of the pulsar. The cumulative integration time is $\sim 54$ hrs. There are 32 phase bins across the profile, and the y-axis plots flux in arbitrary units. The one sigma error bar on the flux is shown in the lower left-hand corner. The effective time resolution of the data, $\sim 300 \mu s$, which accounts for pulse smearing due to channelisation of the dispersed data and finite time sampling, is indicated by the horizontal bar. A weak, but statistically significant interpulse is seen at a phase of $\sim 0.75$. 