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A strong magnetic field around the supermassive black hole at the centre of the Galaxy

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Earth's nearest candidate supermassive black hole lies at the centre of the Milky Way[1]. Its electromagnetic emission is thought to be powered by radiatively inefficient accretion of gas from its environment[2], which is a standard mode of energy supply for most galactic nuclei. X-ray measurements have already resolved a tenuous hot gas component from which the black hole can be fed[3]. The magnetization of the gas, however, which is a crucial parameter determining the structure of the accretion flow, remains unknown. Strong magnetic fields can influence the dynamics of accretion, remove angular momentum from the infalling gas[4], expel matter through relativistic jets[5] and lead to synchrotron emission such as that previously observed[6–8]. Here we report multi-frequency radio measurements of a newly discovered pulsar close to the Galactic Centre[9–12] and show that the pulsar's unusually large Faraday rotation (the rotation of the plane of polarization of the emission in the presence of an external magnetic field) indicates that there is a dynamically important magnetic field near the black hole. If this field is accreted down to the event horizon it provides enough magnetic flux to explain the observed emission—from radio to X-ray wavelengths—from the black hole.

Linearly polarized radio waves that pass through a magnetized medium experience Faraday rotation. The resulting rotation of the polarization vector is given by $\Delta\phi = \mathrm{RM}\lambda^2$, where the rotation measure, $\mathrm{RM} = e^3/\left(2\pi m_e^2 c^4\right)\int B(s)n(s)\mathrm{d}s$, depends on the line-of-sight magnetic field, B; the free-electron density, n; the path length, s; the electron charge, e, and mass, m_e; and the speed of light, c. The radio emission associated with the Galactic Centre black hole, Sagittarius A* (Sgr A*), has $\mathrm{RM} = -5\times10^5\,\mathrm{rad\,m^{-2}}$, which is the highest known RM of any source in the Galaxy, and is believed to be due to a column of hot, magnetized gas from the accretion flow onto the black hole[13,14].

The radio emission from Sgr A*, however, probes only the innermost scales of accretion. For most accretion models[14], the term $B(r)n(r)$ decays much faster than r^{-1}, where r is the radial distance from the black hole. Consequently, the Faraday rotation imprinted onto the radio emission from Sgr A*, which has to pass through the entire column of accreting gas, is dominated by the smallest scales. To measure the magnetization of the accretion flow on the outermost scales, other polarized radio sources, such as pulsars, are needed. A pulsar closely orbiting Sgr A* would also be an unparalleled tool for testing the space-time structure around the black hole[15]. Despite predictions that there are more than a thousand pulsars in the central parsec of the Galaxy[16], there has been a surprising lack of detections[17], potentially owing to severe interstellar dispersion and scattering in the inner Galaxy[18].

Recently, the NASA Swift X-ray Telescope detected a bright X-ray flare[9] near Sgr A* (projected offset of $\sim3'' = 0.12$ pc (ref. 19) at a Galactic Centre distance of $d = 8.3$ kpc). Subsequent X-ray observations by the NASA NuSTAR telescope resulted in the detection of pulsations with a period of 3.76 s (ref. 10). This behaviour is indicative of a magnetar, a highly magnetized pulsar, in outburst. During radio follow-up observations at the MPIfR Effelsberg Radio Observatory on 28 April 2013, the first weak detection of pulsations, with spin parameters matching those reported by NuSTAR, was made. Since then, the pulsar, PSR J1745–2900, has been consistently detected at Effelsberg, at the Paris Observatory-Nançay Radio Astronomy Facility, at the NRAO Karl G. Jansky Very Large Array (VLA), tentatively at The University of Manchester Jodrell Bank Observatory (Fig. 1) and with the CSIRO Australia Telescope Compact Array[12]. Measurements of the delay in the arrival times of pulses at lower frequencies (2.5 GHz) with respect to those at higher frequencies (8.35 GHz) yield an integrated column density of free electrons, the dispersion measure, of $\mathrm{DM} = 1{,}778 \pm 3\,\mathrm{cm^{-3}\,pc}$, which is the highest value measured for any known pulsar. This is consistent with a source located within <10 pc of the Galactic Centre, in the framework of the NE2001 free-electron density model of the Galaxy[20]. Including this source, only four radio-emitting magnetars are known[21] in the Milky Way, making a chance alignment unlikely. If we consider a uniform source distribution occupying a cylinder of radius 10 kpc and height 1 kpc, then the fraction of sources present within an angular distance of $\sim3''$ around Sgr A* is $\sim3\times10^{-9}$. Given the current population of radio pulsars ($\sim$2,000) and radio magnetars, the numbers present within the same region by chance will be $\sim6\times10^{-6}$ and $\sim1\times10^{-8}$, respectively.

The emission from the pulsar is highly linearly polarized[12,22] (Fig. 2). Using the RM synthesis method[23] and measuring the Faraday rotation in three frequency bands and at three different telescope sites, we derive a RM of $(-6.696 \pm 0.005)\times10^4\,\mathrm{rad\,m^{-2}}$ (Fig. 3). This measurement is consistent with that reported elsewhere[12]. The RM is the largest measured for any Galactic object other than Sgr A*[13,14], and is more than an order of magnitude larger than all the other RMs measured to within tens of parsecs of Sgr A*[24]. The RM is also more than what can be optimistically expected as foreground[25]. This constrains the magnetized plasma causing the Faraday rotation (the Faraday screen) to be within some ten parsecs from the Galactic Centre.

A frequently used estimate of the magnetic field is $B \geq \mathrm{RM}/0.81\mathrm{DM}\,\mu\mathrm{G}$, which gives $B \geq 50\,\mu\mathrm{G}$ (ref. 12). However, this is not a stringent limit, because DM and RM are dominated by very different scales. Hence, the extra information about the gas in the central 10 pc must be used for a more robust estimate of the magnetic field.

Two ionized gas phases in the Galactic Centre interstellar medium towards the line of sight of the pulsar could be associated with the Faraday screen: a warm component from the northern arm of the gas streamer Sgr A West[26], which passes behind Sgr A*, and a diffuse hot component seen in the X-ray emission[3] with $T = 2.2\times10^7$ K. The warm gas in the northern arm has a width of >0.1 pc, electron densities of $\sim10^5\,\mathrm{cm^{-3}}$ measured from radio recombination lines[26], and a magnetic field of ~2 mG (ref. 27). The inferred RM and DM values for

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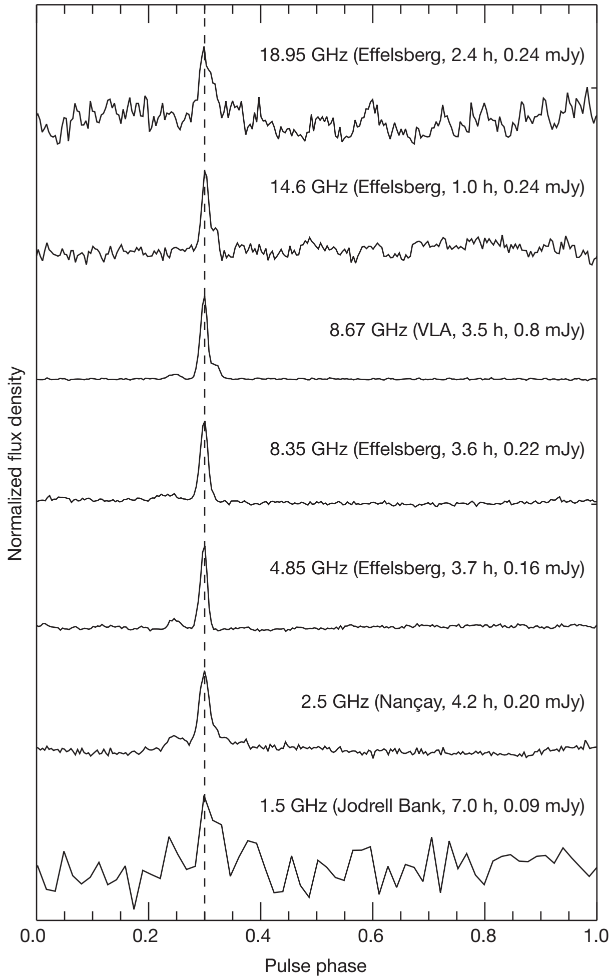

Figure 1 | Average pulse profiles of PSR J1745–2900 at each of the radio frequencies where detections have been made. All observations have been centred on the X-ray position measured with NASA's Chandra X-ray Observatory[19]. The telescope used, the total observation time required to generate the profile and the average flux density are indicated in brackets after the frequency label. In each case, the profile has been down-sampled from the original sampling interval to 256 phase bins (64 for the Jodrell Bank data), and the peak flux density has been normalized to unity. The profiles have been aligned on the peak of the main pulse detected. By measuring accurate pulse arrival times, we have constructed a coherent timing solution, that is, a model that tracks every single rotation of the pulsar. Between modified Julian dates 56414 and 56426, this model has given a value for the spin period of $P = 3.76354676(2)$ s and a value for the time derivative of the period (spin-down) of $\dot{P} = 6.82(3) \times 10^{-12}$; uncertainties in the last digit, given in brackets, are derived from the 1σ error of the timing model fit. Absolute timing from 1.5 to 8.35 GHz has established that the main pulse in each profile is indeed aligned at each frequency.

a source in or behind the northern arm are $\mathrm{RM} \approx 2 \times 10^7\,\mathrm{rad\,m^{-2}}$ (for an ordered magnetic field) and $\mathrm{DM} \approx 10^4\,\mathrm{pc\,cm^{-3}}$. The measured DM and RM values therefore place the pulsar and the screen in front of the northern arm[26].

Consequently, the Faraday screen must be associated with the hot gas component, for which no magnetic field estimates yet exist. The density in the hot gas shows a radial fall-off as a function of r. At 0.4 pc (10″) we find that $n \approx 26\,\mathrm{cm^{-3}}$, whereas at 0.06 pc (1.5″) it can be inferred that $n \lesssim 160\,\mathrm{cm^{-3}}$, using the optically thin thermal plasma model[3]. Farther away, on the 40-pc scale[28] (17′), the density has decreased to 0.1–$0.5\,\mathrm{cm^{-3}}$ and we can roughly describe the density within the central parsecs with a profile of the form $n(r) \approx 26\,\mathrm{cm^{-3}}(r/0.4\,\mathrm{pc})^{-1}$. The contribution of this hot gas component to DM is of order $10^2\,\mathrm{cm^{-3}}$ pc. This is consistent with the modest increase in DM with respect to the hitherto closest known pulsars to the Galactic Centre.

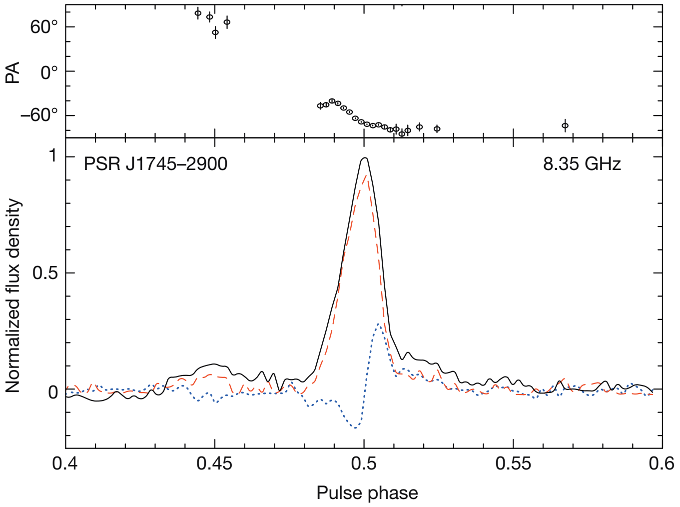

Figure 2 | Pulse profile of PSR J1745–2900 at 8.35 GHz. After correcting for the Faraday rotation of $(-6.696 \pm 0.005) \times 10^4\,\mathrm{rad\,m^{-2}}$, we can measure the intrinsic polarization across the pulse profile, together with the polarization position angle (PA). The degree of linear polarization (red dashed line) is nearly 100%, and a significant amount (~15%) of circular polarization (blue dotted line) is also detected. A consistent 'S'-shaped PA swing is measured at each frequency.

For a simple one-zone Faraday screen, where $\mathrm{RM} \propto B(r)n(r)r$, we have $\mathrm{RM} = 8.1 \times 10^5 B(r)n(r)r\,\mathrm{rad\,m^{-2}}$, where $B(r)$ is in units of Gauss, $n(r)$ is expressed in units of $\mathrm{cm^{-3}}$ and r is expressed in parsecs. Using the density prescription above with an r^{-1} scaling, we find that $B \gtrsim 8[\mathrm{RM}/(66{,}960\,\mathrm{m^{-2}})][n_0/(26\,\mathrm{cm^{-3}})]^{-1}$ mG. This is a lower limit, because possible turbulent field components or field reversals reduce RM. We note again that this RM value is indeed dominated by the smallest distance scale, that is, by the gas on scales of the de-projected distance, $r > 0.12$ pc, of the pulsar from Sgr A*.

This B value is higher than the magnetic field in the northern arm and is also higher than the equipartition field in the hot phase at this scale. To bring thermal and magnetic energy into equipartition, the gas density at $r \approx 0.12$ pc would need to increase by a factor of three, to $260\,\mathrm{cm^{-3}}$, yielding $B \approx 2.6$ mG. If there were many field reversals within the Faraday screen, the magnetic field would be driven to values much greater than the equipartition field, suggesting that a relatively ordered magnetic field is pervading the hot gas close to the supermassive black hole.

Because Sgr A* accretes from this magnetized hot phase, density and magnetic field will further increase at smaller radii. Emission models of Sgr A* require magnetic fields of about 30–100 G to explain the synchrotron radiation from near the event horizon[6–8]. Hence, if the gas falls from 3×10^5 Schwarzschild radii (0.12 pc) down to a few Schwarzschild radii, a simple $B \propto r^{-1}$ scaling would be enough to provide a magnetic field of several hundred gauss. This is well within the range of most accretion models, where equipartition between magnetic, kinetic and gravitational energy in the accreting gas is assumed[14,29].

The field at large radius in the accretion flow onto Sgr A* is therefore sufficient to provide the necessary field at small radius, via simple accretion. Moreover, the availability of ordered magnetic fields would make the proposed formation of a jet-like outflow in Sgr A*[30] viable. Super-equipartition magnetic fields could also suppress accretion and help to explain the low accretion rate of Sgr A*.

At its projected distance, PSR J1745–2900 could move (owing to orbital motion) through the hot gas surrounding Sgr A* at several milliarcseconds per year and reveal RM variations as well as proper motion. Continued pulsar polarimetry and very-long-baseline interferometry astrometry can readily measure these effects. Also, given that magnetars constitute only a small fraction of the pulsar population and the excess DM towards the Galactic Centre is not too large, we expect

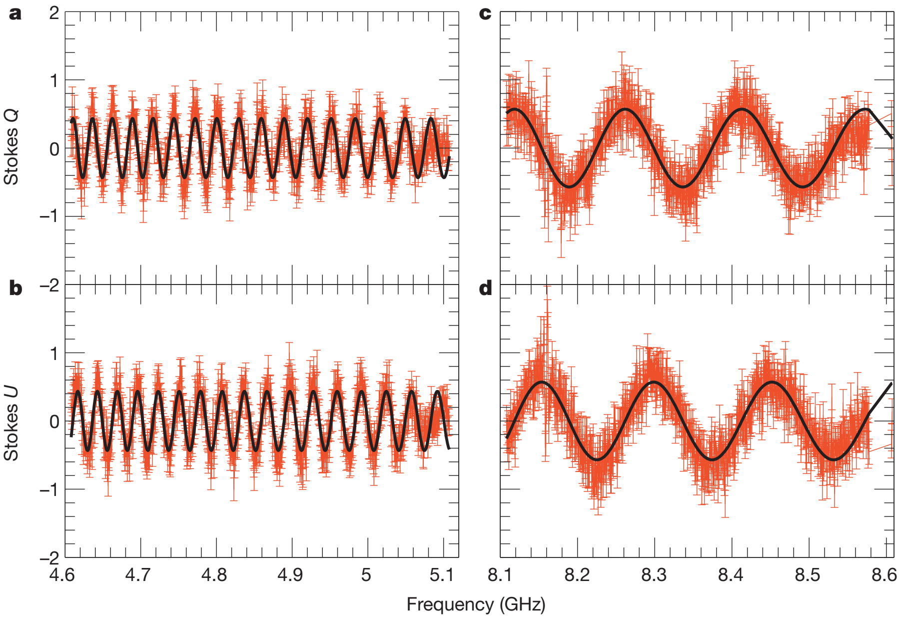

Figure 3 | RM synthesis analysis for the radio polarization of PSR J1745–2900. The red points, with 1σ error bars given by the off-pulse, baseline root mean squared value of the polarization profile, show the observed polarized flux density in the Stokes parameters Q and U. We note that polarization measurements were not possible at all frequencies, owing to hardware limitations. RM is measured by a two-step method. First we perform the Fourier transformation of the polarization intensity to get the RM Faraday spectrum, the peak of which is used to find a rough estimate of RM. Using this initial value, we then perform a least-squares fit to the Q and U curves to find RM and its error. The black curves are the model values based on the best-fit RM. The sinusoidal variation in Q and U due to Faraday rotation is seen across the frequency bands centred at 4.85 GHz (**a** and **b**) and 8.35 GHz (**c** and **d**). At 2.5 GHz (not shown), the variation is so severe that this signature is more easily seen in the RM spectrum. The RM values derived for each frequency band are independently consistent: at 2.5 GHz, $\mathrm{RM} = (-6.70 \pm 0.01) \times 10^4\ \mathrm{rad\ m^{-2}}$; at 4.85 GHz, $\mathrm{RM} = (-6.694 \pm 0.006) \times 10^4\ \mathrm{rad\ m^{-2}}$; and at 8.35 GHz, $\mathrm{RM} = (-6.68 \pm 0.04) \times 10^4\ \mathrm{rad\ m^{-2}}$. RM has also been measured with the VLA at 8.67 GHz, giving $(-6.70 \pm 0.04) \times 10^4\ \mathrm{rad\ m^{-2}}$. The combined and appropriately weighted average is $(-6.696 \pm 0.005) \times 10^4\ \mathrm{rad\ m^{-2}}$.

there to be additional observable radio pulsars in the same region. Such pulsars could be used to map out the accretion region around the black hole in more detail, and even to test its space-time properties.

Online Content Any additional Methods, Extended Data display items and Source Data are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Author Contributions R.P.E.: initial detections, observations performed at Effelsberg and data processing; H.F.: observational and theoretical background and paper

formulation; R.K.: observational technical assistance and pulsar timing; K.J.L.: polarization and RM measurements; D.J.C.: pulsar timing solution; E.F.K.: flux density calculations, observational assistance and observations at Jodrell Bank; G.D.: observations at Nançay; D.H.F.M.S.: observational background and RM interpretation; L.G.S.: observational background and data processing and analysis; M.K.: observational background and RM interpretation; B.K.: technical observational assistance at Effelsberg; C.B.: observations at Jodrell Bank; G.C.B.: observations at the VLA and RM interpretation; A.B.: observations at the VLA; I.C.: observations at Nançay; A.T.D.: observations at the VLA; P.B.D.: observations at the VLA; P.C.C.F.: observational background and pulsar timing; A.K.: technical observational assistance at Effelsberg; A.G.L.: observations at Jodrell Bank and help with initial detections; A.N.: observational background and RM interpretation; B.S.: observations at Jodrell Bank; N.W.: theoretical background and orbital characteristics.

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