A lower limit of 50 microgauss for the magnetic field near the Galactic Centre

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The amplitude of the magnetic field near the Galactic Centre has been uncertain by two orders of magnitude for several decades. On a scale of ~100 parsecs (pc), fields of ~1,000 microgauss (μG; refs 1–3) have been reported, implying a magnetic energy density more than 10,000 times stronger than typical for the Galaxy. Alternatively, the assumption of pressure equilibrium between the various phases of the Galactic Centre interstellar medium (including turbulent molecular gas, the contested[4] 'very hot' plasma, and the magnetic field) suggests fields of ~100 μG over ~400 pc size scales[5]. Finally, assuming equipartition, fields of only ~6 μG have been inferred from radio observations[6] for 400 pc scales. Here we report a compilation of previous data that reveals a downward break in the region's non-thermal radio spectrum (attributable to a transition from bremsstrahlung to synchrotron cooling of the *in situ* cosmic-ray electron population). We show that the spectral break requires that the Galactic Centre field be at least ~50 μG on 400 pc scales, lest the synchrotron-emitting electrons produce too much γ-ray emission, given other existing constraints[7]. Other considerations support a field of 100 μG, implying that over 10% of the Galaxy's magnetic energy is contained in only ≲ 0.05% of its volume.

Pinning down the large-scale magnetic field of the Galactic Centre—which provides our closest view of a galactic nucleus—within the uncertainty (greater than two orders of magnitude) implied by existing, rival analyses has long been of interest. A 1,000 μG field would have substantial ramifications for the region's dynamics, including limiting the diffusion distances of relativistic particles (thereby excluding scenarios where the diffuse, ~TeV γ-ray glow of the Galactic Centre[8] is ultimately explained as due to a single, astrophysical accelerator[9]). It would also generate a large enough magnetic drag to enhance the spiralling-in rate of giant molecular gas clouds towards the Galactic Centre[3], limiting the lifetime of these to ~100 million years, implying 'starbursts' on the same timescale. On the other hand, the formation of individual stars might be inhibited (or the stellar initial mass function biased) by the tendency of a strong magnetic field to support gas against gravitational collapse.

Radio observations at 74 MHz and 330 MHz (ref. 6) reveal a diffuse (but distinct) region of non-thermal radio emission covering the Galactic Centre (out to about ±3° or about ±420 pc from the Galactic Centre along the Galactic plane). Invoking the 'equipartition' condition (minimizing the total energy in magnetic field and relativistic electrons), a field of only 6 μG is inferred[6], typical for the Galaxy at large, climbing to 11 μG over the inner ~±0.8° (for extremal parameter values, the field might reach 100 μG).

To probe this radio structure at higher frequencies, we have assembled total-intensity, single-dish flux density data at 1.4, 2.4, 2.7 and 10 GHz (refs 10–13). These data are polluted by line-of-sight synchrotron emission in the Galactic plane (both behind and in front of the Galactic Centre) and the flux density contributed by discrete sources; we used a combination of low-pass (spatial wavenumber) filtering to remove the latter and all-sky Galactic synchrotron background observations to remove the former (see Supplementary Information). After this processing, a distinct, non-thermal, radio structure is revealed in all radio maps up to 10 GHz (Fig. 1). However, the structure's spectrum from 74 MHz to 10 GHz is not described by a pure power law: attempting to fit such a power law to the cleaned data we find a minimum χ^2 of 4.9 per degree of freedom (d.f. = 4), excluded at a confidence level of 3.4σ (see below).

In fact, fitting separate power laws to the background-subtracted lower three (1.4–2.7 GHz) and upper three (2.4–10 GHz) radio data, we find that these extrapolations intersect at ~1.7 GHz with a down-break of ~0.6 in spectral index. This is close to the canonical break of 1/2 produced by a steady-state synchrotron-radiating electron population that transitions (with increasing energy) from bremsstrahlung-cooled to synchrotron-cooled. As the synchrotron cooling rate is a function of magnetic field, B, and bremsstrahlung a function of ambient hydrogen number density, n_H, the break frequency is a function of both parameters. Observation of a spectral break then determines acceptable pairs of B and n_H for the environment of the synchrotron-emitting electrons.

We have modelled the cooled electron distribution and resulting synchrotron emission as a function of B, n_H and spectral index at injection of the electron population. We have accounted for losses due to inverse Compton emission following collisions with ambient light[14], ionization, bremsstrahlung and synchrotron emission.
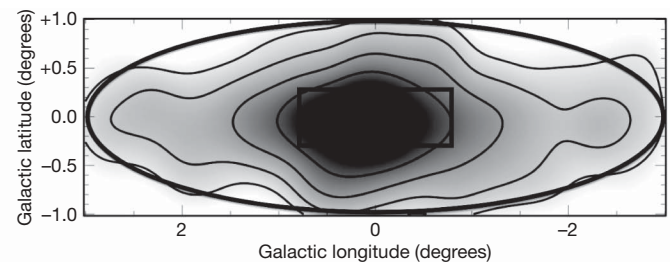
Figure 1 | Total intensity image of the region at 10 GHz. Radio map[13] convolved to a resolution of 1.2° × 1.2° with contours at 10, 20, 40, 80, 160 and 240 Jy per beam. (Native resolution and convolved images at $v \geq 1.4$ GHz are available in the Supplementary Information.) There is a striking constancy in the appearance of the radio structure from 74 MHz to at least 10 GHz (the large ellipse traces the diffuse, non-thermal radio emission region first identified at 74 and 330 MHz; ref. 6). The small rectangle delineates the region from which the HESS collaboration determines a diffuse ~TeV γ-ray intensity[8].

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The results of our fitting procedure are displayed in Figs 2 and 3. A very important constraint is proffered by γ-ray data covering the non-thermal emission region: bremsstrahlung and inverse Compton emission will inescapably be generated by the electrons responsible for the observed radio emission (the energies of electrons synchrotron-radiating at ~GHz and bremsstrahlung-radiating at $\gtrsim 100$ MeV are very similar). This must not surpass the 300 MeV γ-ray flux from the region measured by EGRET[7] (Fig. 2b). This consideration rules out field amplitudes $\lesssim 50\,\mu G$.
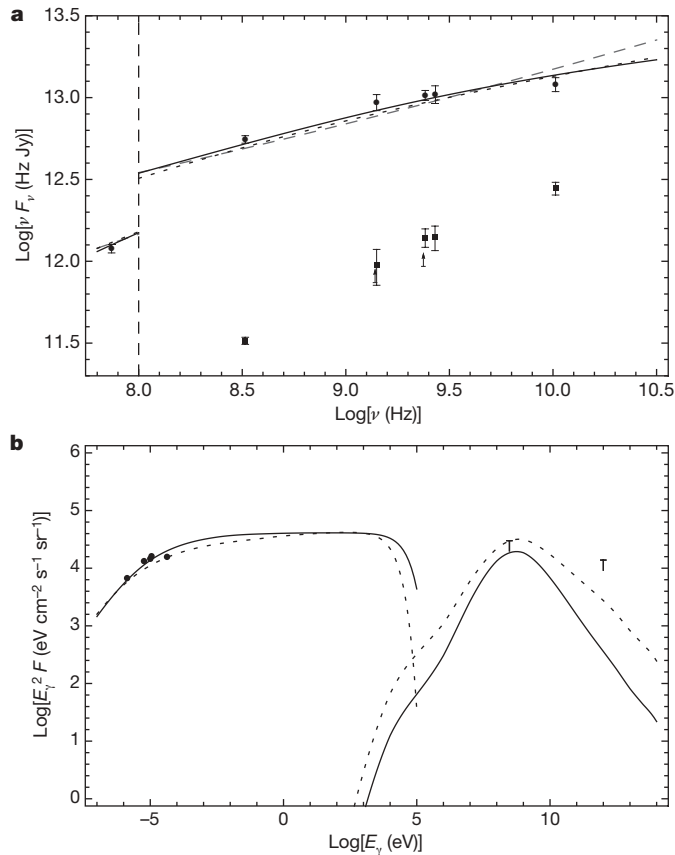
**Figure 2 | Spectrum of the region: data and models. a,** Radio spectrum; **b,** broadband spectrum. **a,** Circles, flux density of the radio structure after removal of flux from sources with sizes <1.2°. The vertical line divides the 74 MHz datum (that receives no contribution from Galactic plane synchrotron background/foreground) from all the other data (that do)—hence the discontinuity in the model curves at 100 MHz. Squares, discrete source flux densities (measured directly by the VLA at 330 MHz (ref. 6) and otherwise obtained through the Fourier technique described in Supplementary Information). Arrows, discrete source lower limits obtained from ATCA. Error bars, 68% confidence intervals. Curves, the best-fit flux density, F_ν, due to synchrotron emission from a cooled electron distribution plus Galactic plane synchrotron for the case of 100 μG fields (solid line) and 30 μG fields (dotted line; the break in the radio synchrotron curve mirrors a corresponding break in the distribution of radiating electrons; we assume the electrons are injected with a power law in momentum[22]). Dashed line, the best-fit null hypothesis case of a pure power-law signal plus Galactic plane synchrotron. **b,** Models for flux, F, as a function of photon energy, E_γ, for a magnetic field of 100 μG (solid lines) and 30 μG (dashed lines). The injected electron spectrum is assumed to follow a power law up to ~100TeV. (Note that the cut-off energy is only weakly constrained; our conclusions are not sensitive to the exact cut-off energy, however, given that radio observations guarantee the existence of ~GeV electrons whose bremsstrahlung emission we can compare against the EGRET intensity datum.) The lower-energy curves are synchrotron emission. The higher are bremsstrahlung plus inverse Compton emission from the same electrons responsible for the synchrotron (a figure showing the individual bremsstrahlung and inverse Compton contributions is shown in Supplementary Information). The upper limits are due to observations by EGRET[7] at 300 MeV and HESS[8] at 1 TeV.

In the context of diffuse, ~GeV emission around the Galactic Centre, we await results from the Fermi Gamma-ray Space Telescope[15], whose sensitivity (more than an order of magnitude better than EGRET's) promises, at worst, an increased lower limit to the large-scale magnetic field or, more optimistically, a measurement of this field (in concert with radio observations). For now, we emphasise that it is a novel analysis—not new data—that has allowed the new constraint on the Galactic Centre magnetic field.

Figure 4 shows the energy densities of various Galactic Centre interstellar medium phases. For acceptable field amplitudes, the cosmic-ray electron population is considerably sub-equipartition with respect to the other Galactic Centre interstellar medium phases (even after accounting for filling factor effects), in particular, the magnetic field, explaining why the magnetic field estimate arrived at assuming equipartition[6] is too low. We have also calculated the maximum possible energy density in the Galactic Centre cosmic-ray proton population, given the EGRET γ-ray constraints. Note that at ~100 μG the magnetic field reaches equipartition (at ~300 eV cm^{-3}) with the putative 'very hot' (~8 keV) phase of the X-ray-emitting plasma supposedly detected throughout the central few degrees along the Galactic plane[16]. Moreover, the energy density of the gas turbulence kinetic energy for the derived n_H is within a factor of a few of equipartition with these other phases up to magnetic field amplitudes of ~100 μG.

This situation—implying near pressure equilibrium between a number of Galactic Centre interstellar medium phases (including the plasma)—mirrors that of the Galactic disk, albeit at much higher pressure. Such considerations led to the prediction[5] that the real amplitude of the Galactic Centre's magnetic field lies close to ~100 μG. Very recently, however, observations have shown[4] that the X-ray emission from a region around Galactic longitude $l = 0.08°$ and latitude $b = 1.42°$ (taken to be typical of the so-called X-ray Ridge) is due to unresolved point sources, implying that the very hot X-ray plasma is illusory. This casts the pressure equilibrium argument[5] into some doubt. Note, however, that our magnetic field lower limit holds irrespective of whether the 8 keV plasma is real or not.

There are a number of intriguing parallels between the situation described above and the situation apparently pertaining within the inner regions of starburst galaxies. These independently support the idea that the field is in fact close to 100 μG. In starburst environments, it is contended[17], equipartition magnetic field values obtained from radio observations significantly underestimate the real field. Fields are actually sufficiently high to be in hydrostatic equilibrium with the self-gravity
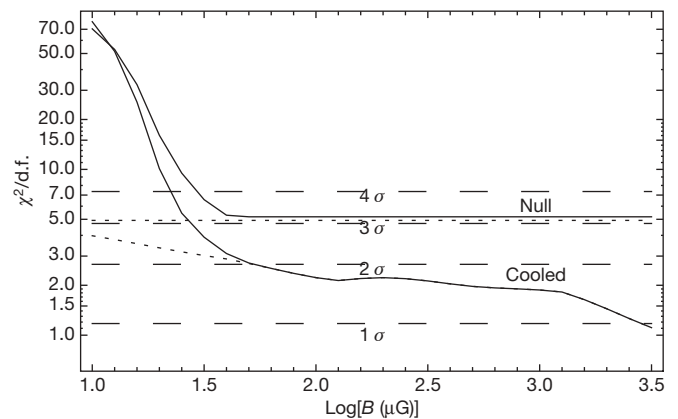
Figure 3 | Plot of the χ^2 per degree of freedom as a function of magnetic field amplitude. Curves, model for a cooled primary electron model (with 3 degrees of freedom, d.f.; 'cooled') and the null hypothesis of a pure power-law electron distribution (with 4 d.f.; 'Null'). The solid curves are constrained by the requirement that the γ-ray emission from the synchrotron-radiating electron population be less than the upper limit obtained from EGRET data[7] (dotted curves are not so constrained). The horizontal dashed lines mark the 1,2,3,4σ confidence limits for a model with 3 d.f. and do not apply to the null hypothesis (which only achieves a best fit acceptable at the ~3.4σ level).
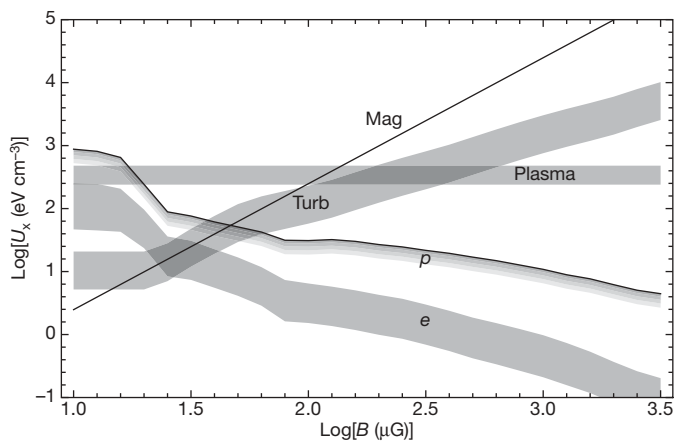
Figure 4 | Energy density, U_{X}, in phase 'X' of the Galactic Centre interstellar medium as a function of magnetic field. Bands show 68% confidence limits (except for p). Mag, magnetic field. Plasma, the disputed[4] X-ray emitting 8 keV plasma (with a density[23] 0.03–0.06 cm^{-3}). Turb, turbulent motions of the local gas (assuming it is at the best-fit n_{H} and has a velocity dispersion in the range 15–30 km s^{-1} typical for Galactic Centre molecular clouds[24]; note that, as the n_{H} required to fit the radio spectrum increases with B, the turbulent energy density is an increasing function of B). e, Cosmic ray electrons. p, a conservative upper bound on the cosmic ray proton energy density inferred from the 300 MeV γ-ray upper limit (a putative proton population, colliding with ambient gas at the best-fit n_{H}, would produce γ-rays mostly via neutral meson decay). The electron and proton energy densities take into account the filling factor of gas at the given value of n_{H} (ref. 25; we take the filling factor of gas within 1σ around the best-fit n_{H} value); this is a correction upwards to the values of U_e and U_p by an amount 100–1,000. Without this correction, one would have $U_e \approx U_{mag}$ at ~10 μG in agreement with the estimate derived assuming equipartion[6]. A factor of 2 uncertainty[26] in the hydrogen mass of the region is also accounted for in determining the electron and proton energy densities.

of the gaseous disk of the starburst. Such strong fields (together with high gas densities) guarantee that the relativistic particle population dumps all its energy before being transported out of the system. This calorimetric limit[18] may explain[17] why even very luminous starbursting galaxies fall on the far-infrared/radio-continuum correlation[19]. Circumstantial evidence also suggests that radio emission from starbursts is dominated by secondary electrons created in collisions between cosmic-ray ions and gas[17] (rather than directly accelerated electrons).

It is noteworthy, then, that the 60 μm and 1.4 GHz emission from the radio emission region place it within scatter of the far-infrared/radio-continuum correlation[19]. Furthermore, in the Galactic Centre a field of ~100 μG is precisely in the range required to establish hydrostatic equilibrium (given the total and gaseous surface densities). A situation wherein a magnetic field provides significant pressure support against gravity may lead to the development of the Parker instability[20], and exactly this is suggested by millimetre-wave observations[21] of molecular filaments of several hundred parsec length within ~1 kpc of the Galactic Centre. These observations independently suggest a ~100 μG field. Finally, the diffuse, ~TeV γ-ray glow from the vicinity of the Galactic Centre[8] is most probably explained by cosmic-ray impacts with gas. Unavoidably, such collisions would also produce copious secondary electrons, which could then contribute significantly to the region's synchrotron radio emission (for fields $\gtrsim$ 300 μG, 100% of the radio emission from the rectangular region shown in Fig. 1 could be attributed to secondary electrons). Taken altogether, these facts paint a picture of the Galactic Centre as akin to a weak starburst with a magnetic field of ~100 μG.

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Author Contributions R.M.C. led the work and performed the main analysis. D.I.J. performed the analysis of radio data, including development of the Fourier-based technique for background and foreground removal, was responsible for original radio observations, and provided critical scientific discussion. F.M. provided input on theoretical and statistical problems, and critical discussion of scientific interpretation. J.O. supervised the analysis of archival radio data and the taking of original radio data, and provided input on statistics. R.J.P. provided input on thermal and relevant non-thermal processes and critical discussion of scientific interpretation. R.J.P. and R.M.C. provided supervision of D.I.J. as doctoral candidate. All authors discussed the results and commented on the manuscript.

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