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A New Lower Limit to the Galactic Centre's Magnetic Field

Roland M. Crocker

*Max-Planck-Institut für Kernphysik,
P.O. Box 103980 Heidelberg, Germany*

Abstract. The amplitude of the magnetic field surrounding the Galactic Centre (GC) on large scales (> 100 pc) has been uncertain by two orders of magnitude for several decades: different analyses report fields as weak as $\sim 6 \mu\text{G}$ on the one hand and ~ 1 mG on the other. Here I report on our recent work (Crocker et al. 2010) which shows that the field on 400 pc scales has a firm lower limit of about $50 \mu\text{G}$. To obtain this result we compiled existing (mostly single dish) radio data to construct the spectrum of the GC region on these size scales. This spectrum is a broken power law with a down-break (most conservatively) attributable to a transition from bremsstrahlung to synchrotron cooling of the in-situ cosmic-ray electron population. The lower limit on the magnetic field arises through the consideration that the synchrotron-emitting electrons should not produce too much γ -ray emission given existing constraints from the EGRET instrument.

There has long been controversy regarding the strength of the Galactic centre's ambient, large-scale magnetic field. On a scale of ~ 100 pc, fields of $\sim 1000 \mu\text{G}$ have been inferred from observations of the mysterious non-thermal radio filaments (Yusef-Zadeh & Morris 1987; Morris & Yusef-Zadeh 1989; Morris 2007). Alternatively, the assumption of pressure equilibrium between the various phases of the Galactic Centre interstellar medium (including turbulent molecular gas; the contested (Revnivtsev et al. 2009) "very hot" plasma; and the magnetic field) suggests fields of $\sim 100 \mu\text{G}$ (Spergel & Blitz 1992). Finally, radio observations at 74 MHz and 330 MHz (LaRosa et al. 2005) reveal a diffuse region of non-thermal radio emission ('DNS') covering the GC (out to $\sim \pm 3^\circ$ or $\sim \pm 420$ pc from the GC along the Galactic plane). Invoking the equipartition condition, a field of only $6 \mu\text{G}$ is inferred (LaRosa et al. 2005) from these observations, typical for the Galaxy-at-large (for extremal parameter values the field might reach $100 \mu\text{G}$).

To probe this radio structure at higher frequencies, we assembled archival total-intensity, single-dish flux density data at 1.4, 2.4, 2.7, and 10 GHz (Reich et al. 1990, 1984; Duncan et al. 1995; Handa et al. 1987). These data were processed to remove the pollution due to line-of-sight synchrotron emission in the Galactic plane both behind and in front of the GC (measured in 408 MHz all-sky Galactic synchrotron background observations (Haslam et al. 1982)) and to remove the flux density attributable to discrete sources in the field (via spatial wavenumber filtering).

After this processing a distinct, non-thermal, radio structure is revealed in all radio maps up to 10 GHz. However, the structure's 74 MHz–10 GHz spectrum is not described by a pure power-law: this provides a poor fit with a minimum χ^2 of 4.9 per degree of freedom ($dof = 4$), excluded at a confidence level of 3.4σ .

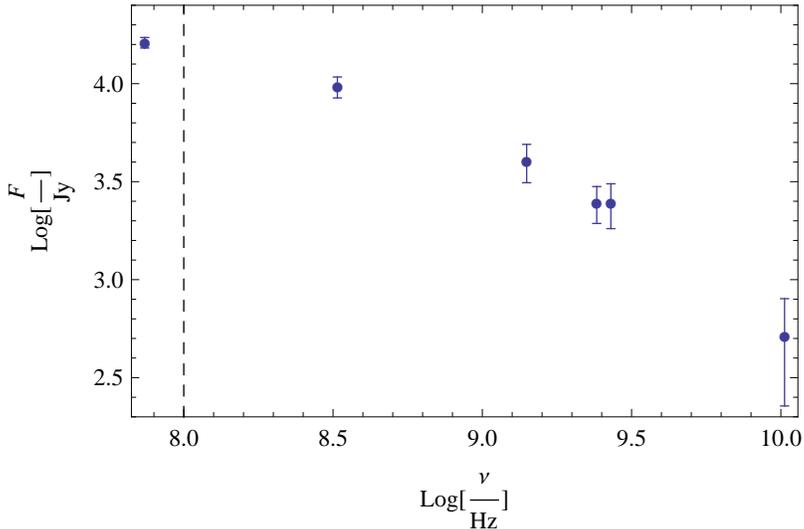


Figure 1. DNS radio spectrum. The DNS is described by an ellipse, centred on the GC, of 3° semi-major axis and 1° semi-minor axis (LaRosa et al. 2005). The vertical dashed line divides the 74 MHz datum (which receives no contribution from the Galactic plane background/foreground) from the other data (which do). The break is just above \sim GHz.

On the other hand, fitting separate power laws to, respectively, the background-subtracted lower three and upper three radio data, we find that these extrapolations intersect at ~ 1.7 GHz with a spectral down-break of ~ 0.6 . 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.

Given these data, we may place a lower limit on the ambient magnetic field as we now explain. The logic of this is the following: for any given B , given the detection of the break, one then knows n_H (since the synchrotron cooling rate is a function of magnetic field, B , and bremsstrahlung a function of n_H , the break frequency is a function of both parameters). Moreover, a certain synchrotron luminosity is observed, so for any given B , the ambient cosmic ray electron population is also known. Thus, for any given B , one knows the n_H value and the relativistic electron population (for the region where the synchrotron emission is occurring) and one can therefore predict the amount of bremsstrahlung emission from this population. (Inverse Compton emission and cooling processes with ambient light (Porter et al. 2006) are also taken into account in our modelling, as is ionization cooling). As one ‘dials down’ the ambient B field, so many ambient cosmic rays electrons are eventually required (to maintain the observed synchrotron luminosity) that they produce too much bremsstrahlung (and IC) emission to obey the 300 MeV γ -ray flux upper limit from the region measured by EGRET (Hunter et al. 1997). This consideration rules out field amplitudes $< 50 \mu\text{G}$. (We eagerly await results from the Fermi Gamma-ray Space Telescope (Awood et al. 2009) on the GC region.)

From our modelling we find that the cosmic ray electron population must be considerably sub-equipartition with respect to the other GC ISM phases explaining why the magnetic field estimate arrived at assuming equipartition (LaRosa et al. 2005) is too low. In contrast, at $\sim 100 \mu\text{G}$ the magnetic field reaches equipartition (at $\sim 300 \text{ eV cm}^{-3}$) with the putative (and contested Revnivtsev et al. (2009)) ‘very hot’ ($\sim 8 \text{ keV}$) phase of the X-ray-emitting plasma supposedly detected throughout the central few degrees along the Galactic plane (Koyama et al. 1989). The energy density of the gas turbulence kinetic energy for the derived n_H is also within a factor of a few of equipartition with these other phases for magnetic field amplitudes up to $\sim 100 \mu\text{G}$. Thus, as originally speculated by Spergel and Blitz (Spergel & Blitz 1992), the GC ISM thus seems to be characterised by near pressure equilibrium between a number of its phases (including the 8 keV plasma – if it is real), mirroring the situation for the Galactic disk (albeit at much higher pressure).

Also noteworthy is a number of interesting parallels between the GC situation and that apparently pertaining within the inner regions of starburst galaxies. In starburst environments, Thompson et al. (Thompson et al. 2006) contend that equipartition magnetic field values significantly underestimate real field amplitudes which are, instead, supposed to be high enough to be in (or close to) hydrostatic equilibrium with the self-gravity of the gaseous disk of the starburst. Finally, Thompson et al. (Thompson et al. 2006) also speculate that radio emission from starbursts is dominated by secondary electrons created in collisions between cosmic ray ions and gas (rather than directly-accelerated electrons).

It is noteworthy, then, that a $\sim 100 \mu\text{G}$ field is precisely in the range required to establish hydrostatic equilibrium in the GC (given the total and gaseous surface densities inferred from the data presented in (Ferrière et al. 2007)). Moreover, a situation wherein a magnetic field provides significant pressure support against gravity may lead to the development of the Parker instability (Parker 1966) and exactly this is suggested by mm-wave observations (Fukui et al. 2006) of molecular filaments of several hundred parsec length within $\sim 1 \text{ kpc}$ of the GC. These observations independently suggest a $\sim 100 \mu\text{G}$ field.

Finally, the diffuse, $\sim \text{TeV}$ γ -ray glow from the vicinity of the GC (Aharonian et al. 2006) is most likely 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 $> 300 \mu\text{G}$, 100% of the radio emission from the region defined by $|l| < 0.8^\circ$ and $|b| < 0.3^\circ$ – the region over which HESS detects diffuse $\sim \text{TeV}$ emission – could be attributed to secondary electrons). Taken altogether, these facts paint the Galactic centre as akin to a weak starburst with a magnetic field of $\sim 100 \mu\text{G}$.

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