Polarized thermal emission from dust in a galaxy at redshift 2.6

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Magnetic fields are fundamental to the evolution of galaxies, playing a key role in the astrophysics of the interstellar medium (ISM) and star formation. Large-scale ordered magnetic (*B*) fields have been mapped in the Milky Way and nearby galaxies[1,2], but it is not known how early in the Universe such structures form[3]. Here we report the detection of linearly polarized thermal emission from dust grains in a strongly lensed, intrinsically luminous galaxy that is forming stars at a rate more than a thousand times that of the Milky Way at redshift 2.6, within 2.5 Gyr of the Big Bang[4,5]. The polarized emission arises from the alignment of dust grains with the local magnetic field[6,7]. The median polarization fraction is of order one per cent, similar to nearby spiral galaxies[8]. Our observations support the presence of a 5 kiloparsec-scale ordered *B*-field with a strength of around 500μG or lower, orientated parallel to the molecular gas disc. This confirms that such structures can be rapidly formed in galaxies, early in cosmic history.

We observed the lensed galaxy 9io9[4] with the Atacama Large Millimeter/Submillimeter Array (ALMA) at a representative frequency of 242 GHz (equivalent to a wavelength of approximately 350 μm in the rest-frame of the galaxy) to record the dust continuum emission averaged over a total bandwidth of 7.5 GHz. The set of *XX*, *YY*, *XY* and *YX* linear polarization parameters recorded in full polarization mode allow measurement of the Stokes parameters Q and U, yielding the total linearly polarized intensity, $PI = \sqrt{Q^2 + U^2}$, and position angle (PA) of polarized emission $\chi = 0.5 \arctan{(U/Q)}$. The root mean squared sensitivity of the observations is $\sigma_I = 47\,\mu\text{Jy beam}^{-1}$ and $\sigma_Q \sim \sigma_U = 9\,\mu\text{Jy beam}^{-1}$. In Figure 1 we present image plane maps of the total intensity I, Stokes Q and U, and polarized intensity PI. The polarization angle χ is rotated by 90 degrees to show the plane-of-the-sky *B*-field orientation (χ_B). We measure an image plane integrated flux density of $I = 62\,\mathrm{mJy}$, integrated polarization fraction of $P = 0.6 \pm 0.1\%$, where $P = PI/I$, and *B*-field orientation of $\chi_B = (-0.7 \pm 1.4)$ degrees. The mean of the distribution of polarization fractions and *B*-field orientations is $\langle P \rangle = 0.6 \pm 0.3\%$ and $\langle \chi_B \rangle = (0.8 \pm 18.3)$ degrees, respectively. Note that the uncertainties are the dispersion of the distribution of individual measurements within the galaxy, not the accuracy in the polarization measurement (Methods).

Using the lens model derived from previous high-resolution millimetre continuum emission and optical *Hubble Space Telescope* imaging, the source plane CO(4–3) emission, tracing the cold molecular gas reservoir, has been shown to be well-modelled by a rotating disc of maximum radius 2.6 kpc, inclined by approximately 50 degrees to the line of sight, with a position angle (PA) on the sky of approximately 5 degrees East of North[4,5]. With this model as a constraint, we explore what source plane *B*-field configurations are consistent with the image plane polarization observations. The most likely source plane configuration is a large-scale ordered *B*-field orientated $\chi_\mathrm{B} = 5^{+5}_{-10}$ degrees east of north with an extent matching that of the CO emission (Figure 2). This result implies the presence of a 5 kpc-scale galactic ordered magnetic field orientated parallel to the molecular gas-rich disc. Angular variations of χ_B across the galaxy present in the image plane maps, corresponding to scales of 600 pc in the source plane, can be explained by the low signal-to-noise ratio and beam effects (Methods). This result implies that the introduction of a random *B*-field component with an angular variation of ± 5 degrees in addition to the large-scale ordered *B*-field is also consistent with the observations. We currently lack the sensitivity and resolution to map the configuration of the *B*-field strength at scales $\sim$100 pc where structure related to turbulence can start to be resolved. The observed *B*-field configuration parallel to the disc is consistent with the galactic *B* fields measured in local spiral galaxies observed at far-infrared and radio wavelengths[1,2]. Note that our far-infrared polarimetric observations trace a density-weighted average *B*-field in the cold and dense ISM, rather than a volume average *B*-field in the warm and diffuse ISM by radio polarimetric observations.

The mean and integrated polarization fractions of 9io9 are consistent with the $P \sim 0.8\%$ level measured in nearby spiral and starburst galaxies at wavelengths of 53–214 μm[2]. The observations presented here are sensitive to polarized emission beyond this range, pushing into the Rayleigh-Jeans tail of the thermal emission spectrum at $\lambda_\mathrm{rest} = 350\,\mu$m. In recent models of diffuse interstellar dust, the polarization fraction, P, is independent of wavelength across 200–2000μm, consistent with observations of Galactic dust emission[?]. Observations of local starburst galaxies show that P only varies by 0.4 per cent over the 50–150 μm range, with an increase of up to $\sim$1 per cent towards 214 μm[2]. We therefore conclude that 9io9 has a polarization level similar to local star-forming discs and starburst galaxies, with a key difference being the order-of-magnitude difference in gas mass and star-formation rate, with the disc of 9io9 being close to molecular gas dominated, contrasted with the $f_{\rm gas} \approx 10$ per cent gas fractions of local star-forming discs[9].

The large-scale ordered magnetic fields that exist in massive disc galaxies in the local Universe is thought to arise through the amplification of seed fields, and this has been predicted to occur on relatively short cosmological timescales, of order $1\,{\rm Gyr}$[10–12]. Weak seed fields (as low as $B \sim 10^{-20}\,{\rm G}$) could be formed in protogalaxies either through trapping of a cosmological field, possibly primordial in nature, or through the battery effect following the onset of star formation[13–16]. Although turbulent gas motions in discs can reduce net polarization if they impart a strong turbulent component to the *B*-field[17], recent theoretical models of the formation of galactic-scale magnetic fields invoke turbulence in the ISM as the origin of a 'small-scale' dynamo that can rapidly amplify the weak seed fields to μG levels[12,18,19]. This small-scale dynamo is mainly driven by supernova explosions with coherence lengths of order 50–100 pc, but turbulence can be injected into the ISM on multiple scales through disc instabilities and feedback effects, including stellar winds and outflows driven by radiation pressure, supernova explosions, and large scale outflows from an active galactic nucleus.

The average turbulent velocity component of the disc of 9io9, determined from kinematic modelling of the CO emission, is $\sigma_v \approx 70\,{\rm km\,s^{-1}}$ and the star-formation rate density exceeds $100\,M_\odot\,{\rm yr^{-1}\,kpc^{2}}$[5]. The high dense gas fraction of the molecular reservoir – as traced by the ratio of CO(4–3)/C I(1–0) emission – is also consistent with the injection of supersonic turbulence, which plays a key role in shaping the lognormal probability distribution function of the molecular gas density[20]. There is also tentative evidence of stellar feedback in action through the broad lines of dense gas tracers[5]. Finally, one expects a high cosmic ray flux density in the ISM of 9io9, commensurate with the high star-formation rate density, and this too could serve to amplify magnetic fields. Therefore, 9io9 likely has the conditions required to rapidly amplify any weak seed fields via the small-scale dynamo effect, with amplification occurring on scales up to and including the full star-forming disc. Assuming equipartition between the turbulent kinetic and magnetic energies, we estimate an upper-limit of the equipartition turbulent *B*-field strength of 514 μG (Methods). This is comparable to the estimated turbulent *B*-field strength of 305 ± 15 μG within the central kiloparsec of the starburst region of M82 also using FIR polarimetric observations[21]. This indicates that the starburst activity of 9io9 could be be driving the amplification of *B*-fields across the disc.

Feedback-induced turbulence is a route to accelerating the growth of the seed fields, but to produce the ordered field on the kpc-scales observed requires a mean-field dynamo[14,22]. This mean-field dynamo can be achieved through the rapid differential rotation of the gas disc, and this provides a mechanism for the ordering of an amplified *B*-field driven by star formation and stellar feedback processes. 9io9 is turbulent, intensely star-forming and rapidly rotating ($v_{\rm max} \approx 300\,{\rm km\,s^{-1}}$). This suggests that rather than an episode of violent feedback priming a large-scale but turbulent field that later evolves into an ordered field during a period of relative quiescence[19], the small-scale and mean-field dynamo mechanisms operate in tandem. We estimate that the mean-field dynamo in 9io9 has not yet had time yto maintain or amplify the *B*-field (Methods). This implies that the intense starburst is most important in amplifying the galactic field at $z = 2.6$. We postulate that this 'dual dynamo' might be the common mode by which galactic-scale ordered magnetic fields are established in young gas-rich, turbulent galaxies in the early Universe.

Coherent magnetic fields consistent with the mean-field dynamo have been observed at $z = 0.4$ via Faraday rotation of a background polarized radio source[3] (note that such observations are not possible for 9io9). Magnetic fields are already known to be present in the environment around normal galaxies at $z \approx 1$ as revealed by the association of Mg II absorption systems along quasar sightlines that exhibit Faraday rotation[23], and indirectly through the existence of radio synchrotron emission from star-forming galaxies. However, mapping the *B*-fields in individual galaxies at high redshift has so-far proven challenging. Our observations show that the polarized emission from magnetically aligned dust grains is a powerful tool to trace the *B*-fields of the cold and dense ISM in high redshift galaxies.

9io9 is a particularly luminous example of a population of dusty star-forming galaxies in the early Universe that contribute a significant portion of the cosmic infrared background (CIB). If the one per cent level of polarization detected in 9io9 is representative of the general population of dusty star-forming galaxies[24] then routine detection and mapping of magnetic fields in galaxies at high redshift is feasible (i.e., in integration times of less than 24 hr) even in unlensed systems with ALMA. This offers a new window to characterise the physical conditions of the ISM in galaxies when galaxy growth was at its maximum, and will enable a better understanding the role of magnetic fields in shaping the early stages of galaxy evolution. The strength of the galactic magnetic field in local spiral galaxies is of order $10\,\mu$G[1], and up to an order of magnitude higher in starbursts[8]. Without resolving the polarization field in 9io9 below 100 pc scales it is not possible to reliably estimate the *B*-field strength using dust polarization observations. Nevertheless, given the injection of kinetic turbulence driven by stellar feedback we estimate the strength of the *B*-field in 9io9 to be likely greater than that of local spiral galaxies, but similar to that of the central regions of nearby starburst galaxies (Methods).

Finally, these observations imply the CIB itself may be weakly polarized[24,25]. Although misalignments of galaxies along the line of sight will serve to reduce the net polarization of the CIB, if the orientation of discs that host large scale ordered *B*-fields is correlated on large scales due to tidal alignments[26], then a polarization signal could remain, and therefore fluctuations in the polarization intensity of the CIB could be used as a new probe of the physics of structure formation[25]. This has consequences for cosmological experiments that seek to derive information on primordial conditions from observations of the polarization of the cosmic microwave background (CMB), especially if a curl component is present in the CIB polarization field[25,27]. A polarized component of the CIB at millimeter wavelengths, of extragalactic origin and dominated by emission at $z \approx 2$ and with a power spectrum that is driven by large scale structure at this epoch, will be a subtle but important foreground for future precision CMB experiments to contend with.

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Figure 1: **The magnetic field orientation of the gravitationally lensed galaxy 9io9 at z=2.553.** (**a-d**), ALMA 242 GHz polarimetric observations of the Stokes I, Q, and U parameters, and the polarized intensity PI. The synthetic beam of the observations ($1.2'' \times 0.9''$, $\theta = 68$ degrees) is shown as the red ellipse, lower left. The *B*-field orientation is indicated by white lines displayed at the Nyquist sampling, with line lengths proportional to the polarization fraction. (**e-h**), Synthetic polarimetric observations using a constant *B*-field configuration in the source plane. Contours indicate signal-to-noise: for Stokes I, the contours increase as $\sigma_I \times 2^{3,4,5,\cdots}$. For Stokes Q and U, and PI, the contours start at 3σ and increase in steps of 1σ.

Figure 2: **Source plane configuration of the magnetic field and lensing model.** (**a**) Source plane intensity and field orientation. (**b**) Lensed source plane image. (**c**) Synthetic observations with the synthetic beam size ($1.2'' \times 0.9''$, $\theta = 68$ degrees) indicated by the red ellipse. The *B*-field orientation is indicated by white lines with lengths proportional to the polarization fraction. The median and root mean squared values of the polarization fraction and *B*-field orientation are indicated top right. The caustics in the source plane and image plane are shown as green and yellow lines respectively.