Simultaneous Radio and Optical Polarimetry of GRB 191221B Afterglow

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Gamma-ray bursts (GRBs) are the most luminous gamma-ray transients in the universe, and are utilized as probes of early stars¹⁻³, gravitational wave counterparts⁴, and collisionless shock physics⁵. For understanding the fundamental physical quantities of GRB jets and their environments as well as their emission mechanism, coordinated multi-wavelength (semi-)simultaneous measurements are crucial as the global communities demonstrated in the past three decades. In spite of studies on polarimetry of GRBs in individual wavelengths that characterized intriguing properties of prompt emission⁶⁻¹⁴ and afterglow¹⁵⁻²³, no coordinated multi-wavelength measurements has yet been performed. Here, we report the first coordinated simultaneous polarimetry in the optical and radio bands for the afterglow associated to the typical long GRB 191221B. Our observations successfully caught the radio emission, which is not affected by synchrotron self-absorption, and show that the emission is depolarized in the radio band in comparison with the optical one. This result excludes a simple one-zone model that the polarization degree is nearly constant above the synchrotron self-absorption frequency²⁴, and has important implications for plasma-scale turbulent magnetic fields²⁵⁻²⁷ and existence of cool electrons^{24,28}. Our simultaneous polarization angle measurement supports the latter model rather than the former one. The existence of cool electrons increases the estimate of the total jet energy²⁹ by a factor of > 2 for this typical GRB. Further coordinated multi-wavelength polarimetric campaigns would improve our understanding of the total jet energies and magnetic field configurations in the emission regions of various types

of GRBs, which are required to comprehend the mass scales of their progenitor systems and the physics of collisionless shocks.

GRB 191221B was detected on 21 December 2019, 20:39:13 UT and its X-ray afterglow was rapidly identified by the Neil Gehrels Swift Observatory³⁰. The optical afterglow was discovered by the MASTER auto-detection system³¹. Optical polarization with a possible time evolution in the early afterglow phase was also detected by the Southern African Large Telescope (SALT) and Very Large Telescope (VLT)³². The redshift was measured as $z = 1.148$ based on metal absorption lines in the optical afterglow observed by VLT/X-shooter³³. The isotropic equivalent energy of $E_{\gamma, \text{iso}} = (3.6 \pm 0.4) \times 10^{53}$ erg and the rest-frame peak energy of the time-integrated spectrum $E_{\text{peak}}^{\text{src}} = 810 \pm 65$ keV were derived by the Konus-Wind observation (with the standard cosmological parameters $H_0 = 67.3$ km/s/Mpc, $\Omega_M = 0.315$, and $\Omega_\Lambda = 0.685$)³⁴. The duration of the prompt emission in the 15-350 keV band is 48.0 ± 16.0 sec³⁵. These prompt emission properties obey the empirical correlation (Extended Data Figure 1) and indicate that GRB 191221B is one of the typical long GRBs.

The first semi-simultaneous polarimetry for the afterglow between millimetre and optical bands was conducted at 2.5 days after the burst by using Atacama Large Millimetre/submillimetre Array (ALMA) and VLT (Figure 1). The VLT observation measured linear polarization degree (PD) of 1.3 ± 0.3 % with polarization angle (PA) of 61.6 ± 6.3 deg at the r -band. The PD is consistent with other optical afterglows (average of 1.6% among 84 polarimetric measurements)²⁰. The ALMA observation put the upper limit on PD of 0.6% with 3σ confidence level at 97.5 GHz.

The detection in Stokes- U maps and non-detection in Stokes- Q maps (Extended Data Figure 2) constrained the range of PA as $37.7\text{--}52.3$ deg with 1σ confidence level. This simultaneous polarimetry between optical and radio bands therefore indicates depolarization in the radio band. The significantly low upper limit is also consistent with the first detection of linear polarization in the GRB radio afterglow (i.e., 0.2% for the low-luminosity GRB 171205A)²².

The synchrotron self-absorption (SSA) effect, which suppresses polarization below the SSA frequency (ν_a), is not a reliable explanation for the observed depolarization. ALMA observations at 97.5 GHz, 145 GHz and 203 GHz (Figure 2 & Table 1) indicate that the light curve at the 97.5 GHz band exhibited a broken power-law decay with power-law indices of $\alpha = -0.33 \pm 0.06$ (before the break) and $\alpha = -2.1 \pm 0.2$ (after the break), and a break-time at 8.1 ± 0.2 days, where and hereafter we describe the temporal and spectral properties of the flux density as $F_\nu \propto t^\alpha \nu^\beta$. The multi-frequency measurements (Figure 3) showed that the spectral slope changed from positive power-law index of $\beta \sim 0.602 \pm 0.007$ at 1.5 day and $\beta \sim 0.32 \pm 0.15$ at 2.5 day to negative one ($\beta \sim -0.7$) at 9.5 and 18.4 day. These spectral slopes are in disagreement with the SSA effect which leads to $\beta = 2$ ^{36,37}.

These afterglow properties are instead reproduced by the standard model^{36,37} of optically-thin synchrotron emission from an expanding shock in a uniform density medium with an isotropic energy $E_{\text{iso}} = 1.9 \times 10^{53}$ erg, an ambient medium density $n = 8.1 \text{ cm}^{-3}$, a fraction of shocked energy transferred to non-thermal electrons $\epsilon_e = 9.4 \times 10^{-2}$, that to magnetic field $\epsilon_B = 1.3 \times 10^{-3}$, the energy spectral slope of non-thermal electrons $p = 2.5$, the jet opening half angle $\theta_j = 3.3$

deg, and the viewing angle $\theta_v = 2.5$ deg (see Methods). The energy scale is comparable to the observed γ -ray energy $E_{\gamma, \text{iso}}$, and the micro-physical parameters are also consistent with other cases³⁸. The peak frequency at ~ 300 GHz in Figure 1 is the synchrotron frequency of minimum-energy electrons ν_m . The model lines in Figure 2 are the results of our numerical calculations of synchrotron flux from the collimated shock expanding with relativistic speed by taking account of the equal observed times of photons^{26,39}. The model also explains the X-ray and optical afterglows (Extended Data Figure 3).

If the magnetic field is ordered in the emitting shocked region, the PD of synchrotron emission is $\simeq 70\%$ at $\nu > \nu_m$ while 50% at $\nu < \nu_m$, and the polarization direction is perpendicular to both the magnetic field direction and the line of sight in the comoving frame, where the electron momentum distribution is assumed to be isotropic⁴⁰. Usually, however, the magnetic field in the shocked region is tangled through its amplification process from the field of the ambient medium by some type of instability^{41,42}, and therefore, the net polarization of observed synchrotron emission is reduced, depending on the magnetic field configuration in the visible region. One may consider a simple one-zone model in which the PDs at various frequencies, i.e., $\nu > \nu_m$ and $\nu < \nu_m$, are reduced by the same factor^{24,28,43} (the grey dashed line in Figure 1 b), but this model is ruled out by the observed PD data in the radio and optical bands.

One of the most actively discussed magnetic field amplification process is Weibel instability, which occurs at relativistic collisionless shocks and generates strong magnetic fields with random directions on plasma skin depth scale^{41,43–45}. In this case the field component parallel to the shock

plane may be dominant. This anisotropy results in a sizable PD at each position of the shock, although the field is tangled on the tiny scale^{46,47}. We numerically calculated the net linear polarization in various frequencies based on the synchrotron emission model explained above (see more details in Methods). As shown in the middle panel of Figure 1, the PD at $\nu \lesssim \nu_m$ is much lower than that at $\nu > \nu_m$ since the surface brightness distribution is significantly non-uniform at the frequencies $\nu > \nu_m$ ^{26,39}. This property can be consistent with the data. This model has a clear prediction that the PA at $\nu > \nu_m$ and $\nu \lesssim \nu_m$ are the same or 90 deg different²⁶. The difference in the observed PA at the radio and optical bands (the bottom panel of Figure 1) does not support this model, although the relatively large errors of PA measurements (significance of the difference of the PAs is $\sim 90\%$) do not fully exclude it.

Another possible process of magnetic field amplification is magnetohydrodynamic instabilities at the shock. These include Richtmyer-Meshkov instability, which occurs for the case of ambient medium with inhomogeneous density^{42,48}. In this case, the magnetic field directions in the shocked region can be random mainly on hydrodynamic scales comparable to the shock width, and the internal Faraday depolarization can be significant in the radio band if the number of non-thermal electrons is a fraction $f (< 1)$ of the total shocked electrons. The fraction $1 - f$ of the total shocked electrons remain so cool that cause the Faraday depolarization on the emission from the non-thermal electrons. The true isotropic energy is E_{iso}/f and the true fraction of non-thermal electron energy is $\epsilon_e f$ in this case. We calculate the PD in the one-zone model similar to Sokoloff et al. (1998)⁴⁹, and plot the model in the middle panel of Figure 1 (see more details in Methods). For explaining the observed PDs, the Faraday rotation in the shocked region should be significant

at $\nu < 100$ GHz. This leads to an upper limit $f \lesssim 0.3$. Thus, the true isotropic energy should be larger than 6×10^{53} erg. The difference of the surface brightness distribution in optical and radio bands or the contribution from the ordered magnetic field⁴⁹ may explain the observed difference in PAs.

Our observations performed the first simultaneous polarimetry between the millimetre and optical bands for the typical long GRB 191221B. The multi-frequency observations of the afterglow were also described by the standard model. The measured radio PD was significantly lower than the optical one. The measured PAs supported the Faraday depolarization caused by cool electrons in the hydrodynamic-scale magnetic field, but does not exclude the plasma-scale magnetic field model. Our observation consolidates a new methodology for revealing the total jet energies and collisionless shock physics of various types of GRBs. If f is very small for low-luminosity GRBs and/or short GRBs, their true total jet energies are much larger than the current estimates, which may increase their neutrino production rates^{50,51} and the lower bound of total explosion energies or mass scales of progenitor systems.

Methods

Atacama Large Millimetre/submillimetre Array and Atacama Compact Array Observations

In total of six epochs (1.5, 2.5, 9.5, 18.4 and 33.4 days) of radio observations were conducted using the Atacama Large Millimetre/submillimetre Array (ALMA) and Atacama Compact Array (Table 1). Two epochs (2.5 and 9.5 days) of observations were performed with the polarization mode at 97.5 GHz (i.e. Band 3). Except the final epoch (33.4 days), multi-frequency observations

were managed with the photometry mode at 145 GHz. At the first two epochs (1.5 and 2.5 days), additional photometry at 203 GHz were also conducted. Semi-simultaneous optical polarimetry was also performed at 2.5 days after GRBs using the Very Large Telescope (VLT).

Regarding the ALMA calibrations, the bandpass and flux were calibrated using observations of J1037-2934, and J1036-3744 was used for the phase calibration. The polarization calibration was performed by observing of J1058+0133. The raw data were reduced at the East Asian ALMA Regional Center (EA-ARC) using CASA (version 5.6.1)⁵². We further performed interactive CLEAN deconvolution imaging with self-calibration. The Stokes I , Q , and U maps were CLEANed with an appropriate number of CLEAN iterations after the final round of self-calibration. The off-source rms levels in I , Q , and U are consistent with the expectations for thermal noise alone. The quantities that can be derived from the polarization maps are the polarized intensity ($\sqrt{Q^2 + U^2}$), polarization degree ($100\sqrt{Q^2 + U^2}/I$ %, PD), and polarization position angle ($1/2 \arctan(U/Q)$, PA). By applying the polarization calibration to the phase calibrator J1036-3744 and creating Stokes maps for 6, 9, and 18 epochs during the 3-hr observing period, we confirm that the stability of linear polarization degree is <0.02 %, which is consistent with the systematic linear polarization calibration uncertainty of 0.033% for compact sources. The ACA data were flagged, calibrated and imaged with standard procedures with CASA (version 5.6.1). The bandpass and flux were calibrated using observations of J1058+0133 and J1107-4449. The observations of J1018-3123 was used for the phase calibration.

Very Large Telescope Observations

Polarimetric observations were acquired using the Focal Reducer and low dispersion Spectrograph

(FORS2) mounted on the VLT. A Wollaston prism was inserted in the light path to split the image of each object in the field into two orthogonal polarization components. A mask was used to avoid overlap of the two images; we used the FORS2 R band filter. For each position angle $\phi/2$ of the half-wave plate rotator, we obtained two simultaneous images of cross-polarization at angles ϕ and $\phi + 90^\circ$. We obtained observations at position angles 0, 22.5, 45 and 67.5° of the half-wave plate. This technique allowed us to remove any differences between the two optical paths (ordinary and extraordinary ray), including the effects of seeing and airmass changes. With the same setup we also observed polarized and unpolarized standard stars to convert position angles from the telescope to the celestial reference frame, and to correct for the small instrumental polarization introduced by the telescope. Reduction, i.e. bias, flat-field correction, bad pixel masking, etc. were carried out following standard recipes. Aperture photometry was obtained for the target and several nearby sources in the field. We used custom software tools based on the python astropy library*. More details on polarimetric data analysis are reported in Covino et al. (2003)⁵³ and Wiersema et al. (2012)⁵⁴.

Extended Data Figure 3 shows the temporal evolution of polarization combined with the optical polarimetric results reported by the Buckley et al. (2021)³². There are only three epochs of observation including our measurements. Buckley et al. (2021) made two epochs of polarimetry during the optical light curve showed the wiggles variability and reported the marginal decreasing of polarization degree (by $\sim 0.3\%$) over a timescale of ~ 7 h. Regarding the second epoch, no error estimation was reported³². The 1st and 3rd epoch of measurements are consistent within the

*<http://www.astropython.org>

1-sigma errors. The weighted average of PA is 62.6 ± 5.3 deg. This could imply no temporal evolution in polarization and may suggest that a sizable fraction of the observed polarization is due to dust-induced polarization in the host galaxy. However, the sparse monitoring might miss temporal evolution of polarization, and thus an intrinsic origin is still possible. Based on the two-sample t-test by assuming no temporal evolution in optical polarization, the PA between radio and optical is different at $\sim 90\%$ confidence level. This relatively low significance does not fully rule out the plasma-scale magnetic field model.

X-ray spectrum of GRB afterglows with optical polarimetry

The signal-to-noise ratio of spectro-polarimetric data shown in Buckley et al. (2021) was insufficient for testing the semi-empirical relation between polarization and A_V , the Serkowski law⁵⁷, to fully exclude the case of dust-induced polarization. Instead of the Serkowski law, we checked the hydrogen column density of line of sight (N_H), which is one of the indicators of dust extinction of afterglows at their host galaxies. There are 8 known- z GRB afterglows including GRB 191221B available with optical polarimetry and *Swift* X-ray observations. For 6 events (GRB 080928, GRB 091018, GRB 091208B, GRB 110205A, GRB 121024A, and GRB 131030A), the optical observations reported the detection of intrinsic polarization^{17,19,20,54–56}. For GRB 190114C, Jordana-Mitjans et al. (2020)²³ reported the detection of polarization induced by the dust in the host galaxy. The X-ray data obtained by the *Swift*/XRT were collected from the UK Swift Science Data Centre^{58,59}. We rebinned the spectra so that each spectral bin contains more than five counts. Using the software XSPEC 12, we perform spectral fitting with a single power law modified with intrinsic and Galactic absorptions, the latter of which are fixed at values calculated from Willingale et al.

(2013)⁶⁰. TBabs and zTBabs that incorporate three absorption elements (i.e., gas, molecules, and grains)⁶¹ were used to describe the spectral absorptions. The derived best-fitting values are summarized in Extended Data Table 2. Using Schady et al. (2010)⁶², the measured N_H are converted to A_V . Five events including GRB 191221B exhibited the intrinsic absorption column density of 10 to the 21st power. The intrinsic absorption column density of GRB 191221B is the smallest one ($N_H = 1.6_{-0.8}^{+0.9} \times 10^{21} \text{ cm}^{-2}$). In contrast, the GRB 190114C X-ray spectrum is highly obscured with the intrinsic absorption column density of $N_H = 8.5 \times 10^{22} \text{ cm}^{-2}$ (Extended Data Figure 4). These results naturally explain the dust induced optical polarization of GRB 190114C and support the intrinsic polarization observed in other events. Hence, optical polarization of GRB 191221B could be the intrinsic origin.

Afterglow modeling

The observed radio spectra and the light curves in the radio, optical and X-ray bands are explained by the standard forward shock model^{36,37}. The temporal change of the spectral slope in the 97.5-203 GHz (Figure 3) and the breaks of the 97.5 and 145 GHz light curves (Figure 2) at $t \sim 8$ days indicate the crossing of the synchrotron frequency of minimum-energy electrons ν_m at the observed frequencies. From the observed spectral slope $\beta \sim -0.7$ at $\nu > \nu_m$, the electron energy spectral index is estimated as $p = -2\beta + 1 \sim 2.4$. Then the theoretical temporal decay indices at $\nu < \nu_m$ and at $\nu > \nu_m$ are $1/2$ and $3(1 - p)/4 \sim -1.1$, respectively, in the case in which the collimated forward shock expands in uniform density medium and its edge is not visible due to the strong relativistic beaming. After the edge becomes visible (without sideways expansion of the shock), the geometrical flux reduction $\theta_j^2/(1/\Gamma)^2 \propto t^{-3/4}$ results in the decay indices $-1/4$

206 (at $\nu < \nu_m$) and -1.8 (at $\nu > \nu_m$), which are roughly consistent with the observed ones -0.33
 207 and -2.1 , where θ_j and Γ are the opening half angle and Lorentz factor of the shock. The wind
 208 type ambient medium gives decay indices $-3/4$ (at $\nu < \nu_m$) and -2.3 (at $\nu > \nu_m$), which are
 209 too steep. We note that our assumption of no sideways expansion of shock is based on the results
 210 of high-resolution hydrodynamic simulations, which show the collimated shock after the time of
 211 $1/\Gamma \sim \theta_j$ expands sideways logarithmically, not exponentially^{63,64}.

212 We performed numerical calculations of flux from the shock with a fixed θ_j which evolves
 213 as the Blandford-McKee (BM) self-similar solution, by taking account of the equal arrival time
 214 surface of photons^{26,39}. Then we tried to fit the model flux to the observed data by adjusting the
 215 model parameters, namely the isotropic energy E_{iso} , the ambient medium density n , the fraction
 216 of shock energy carried by the electrons ϵ_e , that carried by amplified magnetic field ϵ_B , and the
 217 viewing angle θ_v , as well as θ_j , and p . We found a model which has the value of E_{iso} is similar
 218 to the prompt emission energy $E_{\gamma, \text{iso}}$ and explain the radio data with ν_m crossing of 97.5 GHz
 219 at $t \sim 4$ day. This model can also fit the data in the optical and X-ray bands (Figures 1, 2,
 220 and Extended Data Figure 3). The model parameters are $E_{\text{iso}} = 1.9 \times 10^{53}$ erg, $n = 8.1 \text{ cm}^{-3}$,
 221 $\epsilon_e = 9.4 \times 10^{-2}$, $\epsilon_B = 1.3 \times 10^{-3}$, $\theta_v = 2.5$ deg, $\theta_j = 3.3$ deg, and $p = 2.5$. These values of n ,
 222 ϵ_e , and ϵ_B are typical of GRB afterglows³⁸. The observed light curve can be well fit with different
 223 parameter values. We note that $\theta_v \neq 0$ is required to obtain non-zero linear polarization in the
 224 model of plasma-scale random magnetic field (see below).

225 It is reasonable that our model light curves do not well fit the radio data at $t \gtrsim 20$ days,
 226 because our calculations assume the BM solution for the shock evolution, which may be a good

approximation for $\Gamma \gtrsim 3$, which is valid at $t \lesssim 20$ days. The shock should have a transition from BM solution to Sedov-Taylor solution (i.e. non-relativistic self-similar solution), for which the light curve becomes shallower^{63,65,66}. As for the time $t < 0.5$ day, the observed light curves in the optical and X-ray bands are shallower than our model. The continuous energy injection to the shock by ejecta with initial slow speed or long-term central engine activity may be important at this early phase^{67,68}.

Polarization in the plasma-scale magnetic field model

The synchrotron polarization depends on the magnetic field configuration at each position in the shocked fluid. Here we focus on the turbulent magnetic field with coherence length on plasma skin depth scale, which is many orders of magnitude smaller than the shock width. Such magnetic field is created by Weibel instability at relativistic collisionless shocks^{41,43–45}, and in this case the field may be anisotropic, i.e., $\xi^2 \equiv 2\langle B_{\parallel}^2 \rangle / \langle B_{\perp}^2 \rangle \neq 1$, where $\langle B_{\parallel}^2 \rangle$ and $\langle B_{\perp}^2 \rangle$ are the averages of the powers of magnetic field components parallel and perpendicular to the shock normal, respectively. Based on this model, we can calculate the local Stokes Q and U parameters corresponding to the surface brightness of the shock by averaging the emissivity with respect to the field directions at each position, and find that the synchrotron emission at each position is polarized due to the anisotropy of the turbulent magnetic field^{25,46,47}. The polarization directions are symmetric around the line of sight, so that the net polarization degree is non-zero only when the visible region of angular size $\sim 1/\Gamma$ includes the jet edge and becomes asymmetric^{25,46,47}.

We numerically calculated the linear PDs in various frequencies based on the light curve model explained above. The parameter value $\xi^2 = 0.91$ leads to the optical PD $\simeq 1.3\%$. In the

optical band, the surface brightness has a peak at $\theta \sim 1/\Gamma$ from the line of sight, while in the radio band, the region around $\theta \sim 0$ with low local PD is also bright³⁹, so that the net radio PD is lower²⁶. As a result, the model polarization spectrum at 2.5 day (Figure 1; middle panel) is consistent with the upper limit on the radio PD. The polarization angle in the radio band is the same as that in the optical band. The difference in the observed PAs at the radio and optical bands does not support this model, although the relatively large errors of PAs measurements do not fully exclude it.

The temporal changes of optical PD and PA in this model are plotted in Extended Data Figure 3. The PD changes as the angular size of visible region $\sim 1/\Gamma$ increases. It has the maximum value when $1/\Gamma \sim \theta_j + \theta_v$. The PA experiences a sudden 90 deg change at $t \sim 0.1$ day, and it is constant before and after the time. This model can explain the observed PDs and PAs at $t \sim 2.5$ day and ~ 0.4 day. If the observed flux densities in the optical and X-ray bands which are shallower than the model at $t \lesssim 0.6$ day are caused by the continuous energy injection to the shock, as explained above, the shock deceleration and the temporal increase of $1/\Gamma$ are slower, so that the temporal increase of PD are slower, and the 90 deg change of the PA is earlier. This might roughly explain the observed PD at $t \sim 0.1$ day.

Faraday depolarization model

The low PD in the radio band could be ascribed to internal Faraday depolarization effect by cool electrons. The standard forward shock model usually assumes that all shocked electrons gain energy from shocked protons and form the power-law energy distribution $dn/d\gamma \propto \gamma^{-p}$ for $\gamma \gtrsim \gamma_m \sim \epsilon_e(m_p/m_e)\Gamma$. Plasma particle simulations showed that all the electrons gain energy from shocked protons⁶⁹, but it has not been confirmed by observations yet. Indeed, the forward

shock model in which only a fraction $f(< 1)$ of the total electrons is energized can also explain the observed afterglow light curves and spectra²⁹. In this case, the fraction $1 - f$ of the total electrons remain as cool thermal electrons with Lorentz factor $\tilde{\gamma}_m = \eta\Gamma$, where η is a factor of the order of unity if the cool electrons are just isotropized at the shock front, and the correct physical parameters are $E'_{\text{iso}} = E_{\text{iso}}/f$, $n' = n/f$, $\epsilon'_e = \epsilon_e f$, and $\epsilon'_B = \epsilon_B f$. The cool electrons cause Faraday depolarization on the synchrotron emission of the non-thermal electrons above self-absorption frequency²⁴.

We assume that the magnetic field in the shocked fluid is turbulent on hydrodynamic scale, which is comparable to the shock width. Such field can be created by magnetohydrodynamic instabilities at the shock, such as Richtmyer-Meshkov instability^{42,48}. For simplicity, we consider that the globally ordered magnetic field is negligible and that the plasma in the visible region consist of N random cells in each of which magnetic field is ordered. At the optical band, for which the Faraday effect is not significant, the net PD is $P_0 \sim \frac{(p+1)}{(p+7/3)} \frac{1}{\sqrt{N}}$, so that $N \sim 5000$ can explain the optical PD $\sim 1\%$. The Faraday rotation effect within the emission region results in the PD as⁴⁹ $P_0[(1 - e^{-S})/S]$, where $S = (\nu/\tilde{\nu}_V)^{-4}$ and $\tilde{\nu}_V$ is the frequency at which the Faraday depth is unity, $\tilde{\nu}_V \sim 200(1+z)^{-15/16}(\frac{1-f}{10f})^{1/2}\eta^{-1}\sqrt{\ln \tilde{\gamma}_m}N^{-1/12}(\frac{E_{\text{iso}}}{10^{52}\text{erg}})^{3/16}n^{9/16}(\frac{\epsilon_B}{0.01})^{1/4}(\frac{t}{1\text{day}})^{-1/16}$ GHz²⁴. The middle panel of Figure 1 shows the Faraday depolarization model for the radio and optical data, which indicates $\tilde{\nu}_V \gtrsim 100$ GHz. This leads to $f^{-1} - 1 \gtrsim 2\eta^2(\ln \tilde{\gamma}_m)^{-1}$.

1. Tanvir, N. R., Fox, D. B., Levan, A. J., et al. 2009, Nature, 461, 1254

2. Cucchiara, A., Levan, A. J., Fox, D. B., et al. 2011, The Astrophysical Journal, 736, 7

- 290 3. Totani, T., Aoki, K., Hattori, T., et al. 2014, Publications of the Astronomical Society of Japan,
291 66, 63
- 292 4. Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, The Astrophysical Journal Letters, 848,
293 L13
- 294 5. Sironi, L., Keshet, U., & Lemoine, M. 2015, SSRv, 191, 519. doi:10.1007/s11214-015-0181-8
- 295 6. Götz, D., Laurent, P., Lebrun, F., et al. 2009, The Astrophysical Journal Letters, 695, L208.
296 doi:10.1088/0004-637X/695/2/L208
- 297 7. Yonetoku, D., Murakami, T., Gunji, S., et al. 2011, The Astrophysical Journal Letters, 743,
298 L30. doi:10.1088/2041-8205/743/2/L30
- 299 8. Yonetoku, D., Murakami, T., Gunji, S., et al. 2012, The Astrophysical Journal Letters, 758, L1.
300 doi:10.1088/2041-8205/758/1/L1
- 301 9. Götz, D., Covino, S., Fernández-Soto, A., et al. 2013, Monthly Notices of the Royal Astronom-
302 ical Society, 431, 3550. doi:10.1093/mnras/stt439
- 303 10. Kopač, D., Mundell, C. G., Japelj, J., et al. 2015, The Astrophysical Journal, 813, 1.
304 doi:10.1088/0004-637X/813/1/1
- 305 11. Troja, E., Lipunov, V. M., Mundell, C. G., et al. 2017, Nature, 547, 425.
306 doi:10.1038/nature23289
- 307 12. Zhang, S.-N., Kole, M., Bao, T.-W., et al. 2019, Nature Astronomy, 3, 258.
308 doi:10.1038/s41550-018-0664-0

- 309 13. Burgess, J. M., Kole, M., Berlato, F., et al. 2019, *Astronomy and Astrophysics*, 627, A105.
310 doi:10.1051/0004-6361/201935056
- 311 14. Kole, M., De Angelis, N., Berlato, F., et al. 2020, *Astronomy and Astrophysics*, 644, A124.
312 doi:10.1051/0004-6361/202037915
- 313 15. Covino, S., Lazzati, D., Ghisellini, G., et al. 1999, *Astronomy and Astrophysics*, 348, L1
- 314 16. Greiner, J., Klose, S., Reinsch, K., et al. 2003, *Nature*, 426, 157. doi:10.1038/nature02077
- 315 17. Uehara, T., Toma, K., Kawabata, K. S., et al. 2012, *The Astrophysical Journal Letters*, 752,
316 L6. doi:10.1088/2041-8205/752/1/L6
- 317 18. Mundell, C. G., Kopač, D., Arnold, D. M., et al. 2013, *Nature*, 504, 119.
318 doi:10.1038/nature12814
- 319 19. Wiersema, K., Covino, S., Toma, K., et al. 2014, *Nature*, 509, 201. doi:10.1038/nature13237
- 320 20. Covino, S. & Gotz, D. 2016, *Astronomical and Astrophysical Transactions*, 29, 205
- 321 21. Steele, I. A., Kopač, D., Arnold, D. M., et al. 2017, *The Astrophysical Journal*, 843, 143.
322 doi:10.3847/1538-4357/aa79a2
- 323 22. Urata, Y., Toma, K., Huang, K., et al. 2019, *The Astrophysical Journal Letters*, 884, L58.
324 doi:10.3847/2041-8213/ab48f3
- 325 23. Jordana-Mitjans, N., Mundell, C. G., Kobayashi, S., et al. 2020, *The Astrophysical Journal*,
326 892, 97. doi:10.3847/1538-4357/ab7248

- 327 24. Toma, K., Ioka, K., & Nakamura, T. 2008, *The Astrophysical Journal Letters*, 673, L123.
328 doi:10.1086/528740
- 329 25. Rossi, E. M., Lazzati, D., Salmonson, J. D., & Ghisellini, G. 2004, *MNRAS*, 354, 86
- 330 26. Shimoda, J. & Toma, K. 2021, *The Astrophysical Journal*, 913, 58. doi:10.3847/1538-
331 4357/abf2c2
- 332 27. Birenbaum, G., & Bromberg, O. 2021, *MNRAS* in press. doi:10.1093/mnras/stab1936
- 333 28. Sagiv, A., Waxman E., & Loeb, A. 2004, *The Astrophysical Journal*, 615, 366
- 334 29. Eichler, D. & Waxman, E. 2005, *The Astrophysical Journal*, 627, 861. doi:10.1086/430596
- 335 30. Laha, S., Simpson, K. K., & Neil Gehrels Swift Observatory Team 2019, GRB Coordinates
336 Network, Circular Service, No. 26534, 26534
- 337 31. Lipunov, V., Gorbovskoy, E., Kornilov, V., et al. 2019, GRB Coordinates Network, Circular
338 Service, No. 26537, 26537
- 339 32. Buckley, D. A. H., Bagnulo, S., Britto, R. J., et al. 2021, *Monthly Notices of the Royal Astro-*
340 *nomical Society*. doi:10.1093/mnras/stab1791
- 341 33. Vielfaure, J.-B., Arabsalmani, M., Heintz, K. E., et al. 2019, GRB Coordinates Network,
342 Circular Service, No. 26553, 26553
- 343 34. Frederiks, D., Golenetskii, S., Aptekar, R., et al. 2019, GRB Coordinates Network, Circular
344 Service, No. 26576, 26576

- 345 35. Sakamoto, T. & Swift-BAT Team 2019, GRB Coordinates Network, Circular Service, No.
346 26562, 26562
- 347 36. Sari, R., Piran, T., & Narayan, R. 1998, The Astrophysical Journal Letters, 497, L17.
348 doi:10.1086/311269
- 349 37. Zhang, B., Mészáros, P. 2004, IJMPA, 19, 2385.
- 350 38. Panaitescu, A. & Kumar, P. 2002, The Astrophysical Journal, 571, 779. doi:10.1086/340094
- 351 39. Granot, J., Piran, T., & Sari, R. 1999, The Astrophysical Journal, 513, 679.
352 doi:10.1086/306884
- 353 40. Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York:
354 Wiley-Interscience)
- 355 41. Medvedev, M. V. & Loeb, A. 1999, The Astrophysical Journal, 526, 697. doi:10.1086/308038
- 356 42. Sironi, L. & Goodman, J. 2007, The Astrophysical Journal, 671, 1858. doi:10.1086/523636
- 357 43. Gruzinov, A., & Waxman, E. 1999, The Astrophysical Journal, 511, 852.
- 358 44. Spitkovsky, A. 2008, The Astrophysical Journal Letters, 682, L5.
- 359 45. Keshet, U., Katz, B., Spitkovsky, A., & Waxman, E. 2009, The Astrophysical Journal Letters,
360 693, L127.
- 361 46. Sari, R. 1999, The Astrophysical Journal Letters, 524, L43. doi:10.1086/312294
- 362 47. Ghisellini, G., & Lazzati, D. 1999, MNRAS, 309, L7.

- 363 48. Inoue, T., Shimoda, J., Ohira, Y., et al. 2013, *The Astrophysical Journal Letters*, 772, L20.
364 doi:10.1088/2041-8205/772/2/L20
- 365 49. Sokoloff, D. D., Bykov, A. A., Shukurov, A., et al. 1998, *Monthly Notices of the Royal Astro-*
366 *nomical Society*, 299, 189. doi:10.1046/j.1365-8711.1998.01782.x
- 367 50. Murase, K., Ioka, K., Nagataki, S., et al. 2006, *The Astrophysical Journal Letters*, 651, L5.
368 doi:10.1086/509323
- 369 51. Kimura, S. S., Murase, K., Mészáros, P., et al. 2017, *The Astrophysical Journal Letters*, 848,
370 L4. doi:10.3847/2041-8213/aa8d14
- 371 52. McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, *Astronomical Data*
372 *Analysis Software and Systems XVI*, 376, 127
- 373 53. Covino, S., Malesani, D., Ghisellini, G., et al. 2003, *Astronomy and Astrophysics*, 400, L9.
374 doi:10.1051/0004-6361:20030133
- 375 54. Wiersema, K., Curran, P. A., Krühler, T., et al. 2012, *Monthly Notices of the Royal Astronom-*
376 *ical Society*, 426, 2. doi:10.1111/j.1365-2966.2012.20943.x
- 377 55. Gorosabel, J., Duffard, R., Kubanek, P., et al. 2011, *GRB Coordinates Network, Circular*
378 *Service*, No. 11696, #1 (2011), 11696
- 379 56. King, O. G., Blinov, D., Giannios, D., et al. 2014, *Monthly Notices of the Royal Astronomical*
380 *Society*, 445, L114. doi:10.1093/mnrasl/slu149
- 381 57. Serkowski, K. 1973, *Interstellar Dust and Related Topics*, 52, 145

- 382 58. Evans, P. A., Beardmore, A. P., Page, K. L., et al. 2007, *Astronomy and Astrophysics*, 469,
383 379
- 384 59. Evans, P. A., Beardmore, A. P., Page, K. L., et al. 2009, *Monthly Notices of the Royal Astro-*
385 *nomical Society*, 397, 1177
- 386 60. Willingale, R., Starling, R. L. C., Beardmore, A. P., et al. 2013, *Monthly Notices of the Royal*
387 *Astronomical Society*, 431, 394. doi:10.1093/mnras/stt175
- 388 61. Wilms, J., Allen, A., & McCray, R. 2000, *The Astrophysical Journal*, 542, 914.
389 doi:10.1086/317016
- 390 62. Schady, P., Page, M. J., Oates, S. R., et al. 2010, *Monthly Notices of the Royal Astronomical*
391 *Society*, 401, 2773. doi:10.1111/j.1365-2966.2009.15861.x
- 392 63. Zhang, W. & MacFadyen, A. 2009, *The Astrophysical Journal*, 698, 1261. doi:10.1088/0004-
393 637X/698/2/1261
- 394 64. van Eerten, H. J. & MacFadyen, A. I. 2012, *The Astrophysical Journal*, 751, 155.
- 395 65. Dai, Z. G. & Lu, T. 1999, *The Astrophysical Journal Letters*, 519, L155. doi:10.1086/312127
- 396 66. Livio, M. & Waxman, E. 2000, *The Astrophysical Journal*, 538, 187. doi:10.1086/309120
- 397 67. Zhang, B., & Mészáros, P. 2001, *The Astrophysical Journal Letters*, 552, L35.
- 398 68. Rees, M. J., & Mészáros, P. 1998, *The Astrophysical Journal Letters*, 496, L1.

- 399 69. Sironi, L. & Spitkovsky, A. 2011, The Astrophysical Journal, 726, 75. doi:10.1088/0004-
400 637X/726/2/75
- 401 70. Amati, L., Frontera, F., Tavani, M., et al. 2002, Astronomy and Astrophysics, 390, 81.
402 doi:10.1051/0004-6361:20020722
- 403 71. Yamaoka, K., Ohno, M., Tashiro, M. S., et al. 2017, Publications of the Astronomical Society
404 of Japan, 69, R2. doi:10.1093/pasj/psx026

Figure 1: **Spectral flux distribution and polarization spectrum of GRB 191221B afterglow at 2.5 days.** a, Spectral flux distribution (red points). The black dotted line is the best fitted forward shock model. b, PDs at 97.5 GHz and optical r -band (red points), and polarization spectrum of the simple one-zone model (grey dashed line), the plasma-scale magnetic field model (purple dashed-dot line) and the cool electron model (green solid line). c, PAs at 97.5 GHz and optical r -band (red points). The observed difference of PAs with $\sim 90\%$ confidence level (i.e., 16.6 ± 9.6 deg.) supports the cool electron model. The relatively large PA measurements errors do not fully rule out the plasma-scale magnetic field model, which predicts a constant PA over the frequencies (e.g., purple dashed-dot line).

Figure 2: **Radio afterglow light curve of GRB 191221BA with the simultaneous optical polarimetric observation.** The red dashed line indicates the best fitted smoothly connected broken power-law functions of the 97.5 GHz light curve. The radio light curves and the optical photometric measurement are described by the standard forward shock synchrotron radiation model. The best fit model describes the passing of synchrotron spectral peak over the ALMA observing band around 4 days, which is consistent with observed spectrum changes between 2.5 and 9.5 days (Figure 3).

Figure 3: **Spectral flux distributions of the GRB 191221B afterglow at 1.5, 2.5, 9.5 and 18.4 days after GRB.** The photometry with high signal-to-noise characterized the spectral slope β as 0.602 ± 0.007 at 1.5 days, 0.3 ± 0.15 at 2.5 days, and -0.7 at 9.5 and 18.4 days, respectively. The changing of spectral indices from positive to negative indicated the passing of the spectral peak frequency through the radio band.

Extended Data Figure 1: $E_{\text{peak}}^{\text{src}} - E_{\gamma,\text{iso}}$ **relation**^{70,71}. GRB 191221B, marked with the red box point, obeys the relation.

Extended Data Figure 2: **Stokes *I* (a), *Q* (b), and *U* (c) maps of the GRB191221B afterglow taken on 2019 December 24 (2.5 days after the burst).** The ALMA beam size is shown in the open circles. The map null detection on the Stokes-*Q* map constrained the range of PA of 37.7-52.3 deg.

Extended Data Figure 3: **GRB 191221B afterglow light curves in X-ray, optical, and radio bands together with optical polarization variability.** a, Multi-frequency light curves. Dotted lines indicate the model light curves fitted to radio and optical data observed by ALMA and VLT. Differences in early optical afterglow and its wiggles variability may be caused by the magnitude-to-flux conversion of optical observations made by the very broad-band filter or intrinsic physics such as energy injection. b, Optical PD combined with measurements by Buckley et al. (2021)³². c, PA in the optical band combined with the measurements by Buckley et al. (2021)³². In panel b and c, measurement errors are not available for values at ~ 0.4 days³². The sparse monitoring made it hard to identify temporal evolution in the optical polarization. The purple dashed-dot lines indicate the plasma-scale turbulent magnetic fields model.

Extended Data Figure 4: **X-ray spectrum for GRB191221B (a) and GRB190114C (b) afterglows.** a, GRB191221B X-ray afterglow spectrum described by a single power law modified with intrinsic and Galactic absorptions, the latter of which is fixed at $N_H = 8.6 \times 10^{20} \text{ cm}^{-2}$. The derived best-fitting values of the intrinsic absorption column density and spectral index are $N_H = (1.6_{-0.8}^{+0.9}) \times 10^{21} \text{ cm}^{-2}$ and $\beta_X = -0.96 \pm 0.06$, respectively, with reduced $\chi^2/\text{dof}=0.88/246$. b, GRB190114C X-ray afterglow spectrum. The highly obscured spectrum with the intrinsic absorption column density of $N_H = (8.5_{-0.3}^{+0.3}) \times 10^{22} \text{ cm}^{-2}$ is reasonable for the dust induced origin of polarization observed in the optical afterglow reported by Jordana-Mitjans et al. (2020)²³.

Table 1: Polarization and Photometric Observing Log

Days	Frequency	PD	PA	I flux	Q flux	U flux
	[GHz]	[%]	[deg]	[mJy]	[mJy]	[mJy]
2.525	97.5	< 0.64	37.7–52.3	3.949 ± 0.007	0.006 (rms)	-0.023 ± 0.006
	4.77×10^5	1.3 ± 0.3	61.6 ± 6.3	0.027 ± 0.003	—	—
5.482	97.5	< 1.3	—	2.371 ± 0.090	0.007 (rms)	0.007 (rms)
1.523	97.5	—	—	4.579 ± 0.038	—	—
9.482	97.5	—	—	1.213 ± 0.016	—	—
18.449	97.5	—	—	0.464 ± 0.017	—	—
33.444	97.5	—	—	0.200 ± 0.019	—	—
1.471	145	—	—	5.823 ± 0.125	—	—
2.442	145	—	—	4.742 ± 0.099	—	—
8.444	145	—	—	1.046 ± 0.063	—	—
9.401	145	—	—	0.906 ± 0.022	—	—
18.431	145	—	—	0.352 ± 0.018	—	—
1.498	203	—	—	7.051 ± 0.589	—	—
2.505	203	—	—	4.434 ± 0.205	—	—

Table 2: X-ray spectral properties for 8 known- z GRBs with optical polarimetry

Events	Redshift	Galactic N_H	Intrinsic N_H	Spectral index (β_X)	Reduced χ^2/dof	A_V
		(10^{20} cm^{-2})	(10^{22} cm^{-2})			(mag)
GRB080928	1.692	7.16	$0.42^{+0.16}_{-0.15}$	-1.07 ± 0.07	1.12/204	0.13
GRB091018	0.971	3.07	$0.35^{+0.06}_{-0.05}$	-1.02 ± 0.05	0.98/266	0.11
GRB091208B	1.063	5.75	$1.68^{+0.29}_{-0.25}$	-1.13 ± 0.09	1.09/188	0.51
GRB110205A	2.22	1.70	$0.56^{+0.15}_{-0.14}$	-0.93 ± 0.05	0.97/264	0.17
GRB121024A	2.298	7.87	$1.37^{+0.38}_{-0.34}$	-1.00 ± 0.08	0.71/175	0.42
GRB131030A	1.293	5.62	$0.59^{+0.11}_{-0.10}$	-1.07 ± 0.06	0.97/244	0.18
GRB190114C	0.425	0.75	$8.5^{+0.3}_{-0.3}$	-1.09 ± 0.06	1.05/517	2.6
GRB191221B	1.148	8.62	$0.16^{+0.09}_{-0.08}$	-0.96 ± 0.06	0.88/246	0.05