Fast radio bursts (FRBs) are millisecond-duration pulses of radio emission originating from extragalactic distances. Radio dispersion is imparted on each burst by intervening plasma, mostly located in the intergalactic medium. In this work, we observe the burst FRB 20220610A and localize it to a morphologically complex host galaxy system at redshift $1.016 \pm 0.002$. The burst redshift and dispersion measure are consistent with passage through a substantial column of plasma in the intergalactic medium and extend the relationship between those quantities measured at lower redshift. The burst shows evidence for passage through additional turbulent magnetized plasma, potentially associated with the host galaxy. We use the burst energy of $2 \times 10^{42}$ erg to revise the empirical maximum energy of an FRB.

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the spectrum characteristic of many lower-DM, high-Galactic latitude ASKAP-detected FRBs (7).

The 2-s dispersive sweep of the burst across the instrument bandwidth and the 2.4-s latency in the detection system resulted in only the lowest 88 MHz of the burst being captured in the 31-s-duration voltage buffer. This was sufficient to localize the burst to a precision of 0.5 arc sec. We used the voltage data to reconstruct the high time resolution and polarimetric properties of the burst (11). After correcting for dispersive smearing, the burst shows an exponentially decreasing tail (Fig. 1D), which is consistent with scatter broadening as a result of turbulence in intervening plasma (12). We measure the pulse broadening time to be 0.011 ± 0.002 ms at a reference frequency of 1447.5 MHz, assuming a ν−4 frequency dependence (where ν is the frequency).

Ordered magnetic fields in astrophysical plasmas add additional, polarization-dependent dispersion. This manifests as wavelength-dependent variation in the linear polarization position angle, referred to as Faraday rotation (13). FRB 20220610A exhibits Faraday rotation, with a rotation measure (RM) of 215 ± 2 rad m−2. After correcting for this Faraday rotation, we calculate that the burst had an intrinsic linear polarization fraction of 96 ± 1%. The high fractional linear polarization allows us to place a 67% upper limit on the Faraday dispersion (δRM < 0.6 rad m−2) induced by fluctuations in the RM in intervening turbulent plasma. Higher levels of Faraday dispersion have been detected for other FRBs (14). The burst also shows lower fractional circular polarization of 10 ± 1%. Although instrumental artifacts can induce spurious circular polarization, we do not see any correlation between the Stokes polarization parameters U and V in the spectrum, which would be expected for an instrumental effect (11). The FRB was located ~4 arc min from the beam center, which makes off-axis leakage effects unlikely (15). Circular polarization has been observed in some FRBs and could either be intrinsic to the burst (16) or result from propagation through relativistic plasma in the immediate source environment (17).

### Table 1. Properties of FRB 20220610A and its host galaxy

| Property                                             | Value                                      |
|------------------------------------------------------|--------------------------------------------|
| DM                                                   | 1458.15 ± 0.15 pc cm−3                    |
| Topocentric arrival time at 1104 MHz (UTC)           | 2022-06-10 22:26:44.313                    |
| Fluence                                              | 45 ± 5 Jy ms                               |
| Right ascension (J2000 equinox)                      | 23°24′17.569 ± 0°0.040                     |
| Declination (J2000 equinox)                         | −33°30′49.37 ± 0°0.50                      |
| Galactic longitude                                   | 8.83954°                                  |
| Galactic latitude                                    | −70.18569°                                |
| Incoherent detection S/N (1104–1140 MHz)             | 29.8                                      |
| Image S/N (1104–1152 MHz)                           | 81                                         |
| RM                                                   | 215 ± 2 rad m−2                            |

#### Measured burst properties

| Property                                             | Value                                      |
|------------------------------------------------------|--------------------------------------------|
| Fluence                                              | 45 ± 5 Jy ms                               |
| Right ascension (J2000 equinox)                      | 23°24′17.569 ± 0°0.040                     |
| Declination (J2000 equinox)                         | −33°30′49.37 ± 0°0.50                      |
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| Incoherent detection S/N (1104–1140 MHz)             | 29.8                                      |
| Image S/N (1104–1152 MHz)                           | 81                                         |
| RM                                                   | 215 ± 2 rad m−2                            |

#### Inferred burst properties

| Property                                             | Value                                      |
|------------------------------------------------------|--------------------------------------------|
| Intrinsic width (FWHM)                               | 0.41 ± 0.01 ms                             |
| Implied FRB isotropic energy density                 | 6 × 1032 erg Hz−1                         |
| Milky Way disk DM contribution                       | 31 pc cm−3                                 |

#### Measured host galaxy properties

| Property                                             | Value                                      |
|------------------------------------------------------|--------------------------------------------|
| Redshift                                             | 1.016 ± 0.002                              |
| Photometry:                                          |                                            |
| Band (central wavelength, Å)                         | 4700                                      |
| g (4700)                                             | 24.15 ± 0.07                              |
| V (5510)                                             | 23.89 ± 0.13                              |
| R (6580)                                             | 23.78 ± 0.06                              |
| I (8060)                                             | 22.17 ± 0.07                              |
| z (9620)                                             | 21.95 ± 0.12                              |
| J (12,200)                                           | 21.97 ± 0.07                              |
| Ks (21,460)                                          | 22.08 ± 0.12                              |

#### Inferred host galaxy properties

| Property                                             | Value                                      |
|------------------------------------------------------|--------------------------------------------|
| Mass-weighted age                                     | 1.02 ± 0.02                               |
| log(stellar mass)                                    | 10.1 ± 0.07                               |
| log(total mass)                                       | 9.9 ± 0.07                                |
| 100 Myr SFR                                          | 10.1 ± 0.07                               |
| log(Z/Z⊙)                                            | −0.11 ± 0.12                              |

We performed follow-up ground-based optical and infrared observations with the Very Large Telescope (VLT) and the W. M. Keck Observatory to identify and characterize the host galaxy of FRB 20220610A (11). The images (Fig. 2, A to C) show an object at the FRB location that has an extended, multicomponent morphology. We label the optical source that overlaps the radio position of the FRB as component (a) and two adjacent sources as components (b) and (c) (Fig. 2A). We use a Bayesian method to assess the chance of coincidence between a radio transient and optical galaxies (18), finding >99.99% confidence that the FRB is associated with component (a).

We performed broad-band optical and infrared spectroscopy of components (a), (b), and (c) (Fig. 2, D and E) (11). We identify two emission lines in the spectra as the [O II] 3726 and 3729 Å doublet, which is most prominent in the spectrum of component (b) (fig. S2). We measure the redshift of each component from this doublet, finding that they are all consistent with z = 1.016 ± 0.002.

We use the photometry and a stellar population model to estimate the total mass of the three components combined as 1010 solar masses, with a star formation rate of ~0.42 solar masses per year (17). These values, in addition to the estimated host metallicity and star formation history, are consistent with those of nearby FRB hosts (19, 20), but the source morphology is markedly different. Observed and estimated properties of the host galaxy are also listed in Table 1.

The presence of two bright components (a) and (c) separated by 2.0 arc sec (which corresponds to a distance of 16 kpc at that redshift), and the diffuse feature (b) between them, is consistent with two galaxies interacting or merging or with a compact galaxy group. It is also possible that the morphology is due to

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internal structure within a single galaxy; at these redshifts, about half of all galaxies have clumpy morphologies (21). We regard the latter possibility as unlikely because of the large spatial separation between the components. Only component (a) is detected in the near-infrared (Ks-band) image (Fig. 2C), which indicates that it hosts an older stellar population compared with the other components. Component (a) is also displaced from the centroid of the total optical light in the g- and R-bands, contrary to what would be expected if it was the nuclear bulge of a single galaxy.

Extending the Macquart relation
We used the measured properties of FRB 20220610A to investigate the Macquart relation out to z ~ 1, by comparing the observed DM with predictions based on previous measurements of the relation at z ≤ 0.522. Figure 3 shows the relationship between DM and redshift for the FRBs detected by ASKAP (4). We restrict our analysis to the ASKAP sample to reduce the effect of selection effects, which depend on the observing system. We do not refit the Macquart relation because doing so in an unbiased way would require a reanalysis of the entire updated FRB sample from ASKAP.

After subtracting a model Milky Way foreground contribution to the observed DM (H), we estimate the non-Galactic DM of FRB 20220610A to be =1376 pc cm$^{-3}$, indicating a high column density of ionized gas between the FRB and Earth. This is higher than the DM expected from the Macquart relation, by ~650 pc cm$^{-3}$, which is a 2.4σ excess (H). If the excess is real and originates from the host galaxy, the implied electron column density is 1300 ± 320 pc cm$^{-3}$ in the host rest frame (H), with the uncertainty reflecting the intrinsic variation in the contribution from the intergalactic medium.

Interpretation of the DM
We use the scatter broadening and Faraday rotation of FRB 20220610A to investigate the properties of plasma at z = 1. A dispersion excess could potentially arise from any combination of gas in the immediate vicinity of the source, the interstellar medium of the host galaxy, or foreground gas along the line of sight—any of which could host turbulent...
measurements are smaller than the symbol sizes. (this work). White contours enclose 50% (dotted), 90% (dash-dot), and 99% (dashed) of the probability. The energy density of assuming a maximum detection probability, redshifts. The color scale indication of a model for traction of a model for extragalactic DM after sub-

FRBs at the host galaxy such as in the interstellar medium of the host galaxy rather than in the circumburst media hypothesized for other sources (11). Models of galaxy interstellar media imply that the DM of a typical spiral galaxy is unlikely to exceed a few hundred parsecs per cubic centimeter except in edge-on systems (22, 23). Higher DM values can plausibly be produced by high-density clumps of gas within the host galaxy, particularly at $z \sim 1$, where galaxies have a substantially higher fraction of their baryons in gas (rather than stars) than at $z \sim 0$ (24). Alternatively, the dispersion could originate from structure in the foreground intergalactic medium or from additional ionized material associated with the possible galaxy merger between components (a), (b), and (c) discussed above.

Our DM analysis confirms inferences from other techniques (25) that the gas of the intergalactic medium is highly ionized. The detection of an FRB at $z > 1$ allows us to study the ionized plasma toward, around, and within the host galaxy. We expect a sight line to $z = 1$ to intersect the halos of several galaxies similar in mass and size to the Milky Way (26), which has previously been used to investigate foreground galaxy properties using FRBs (27).

Interpretation of the burst energy

The measured bandwidth-averaged fluence of FRB 20220610A is $45 \pm 5$ Jy ms (where Jy is the Jansky, equal to $10^{-26}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$), which implies an isotropic-equivalent spectral energy density of $(6.4 \pm 0.7) \times 10^{32}$ erg Hz$^{-1}$ and a burst energy of $(6.4 \pm 0.7) \times 10^{41}$ erg (11). We derived the burst energy by assuming an intrinsic 1-GHz bandwidth and did not apply a redshift-dependent correction to the burst spectral energy distribution (a K-correction) (11). This value exceeds, by a factor of 3.5, the characteristic maximum energy $E_{\text{max}}$ derived by previous FRB population models (11, 28). It is unknown whether FRBs are emitted isotropically or only over a limited beaming angle, which would affect the inferred energetics and could vary between FRB sources (or between repeated FRBs from single sources). Assuming isotropic emission, we added FRB 20220610A to a previous sample of FRBs (28) and refitted the FRB burst energy distribution. We find that the best-fitting maximum energy $E_{\text{max}}$ increases by a factor of 2.7 to $10^{41.7} \pm 0.2$ erg (equivalently, the maximum energy becomes $\log_{10} E_{\text{max}} = 32.7 \pm 0.2$). In Fig. 4, we compare FRB 20220610A to the fluence of the brightest radio pulse observed from a galactic magnetized plasma. For FRB 20220610A, there is an absence of strong ($\geq 10^{14}$ rad m$^{-2}$) Faraday rotation or detectable depolarization; this is unlike the repeating FRB 20190520B, which also showed excess dispersion (6, 14). We suggest that the excess dispersion for FRB 20220610A originates in a less magneto-ionically active plasma compared with that of FRB 20190520B, such as in the interstellar medium of the host galaxy rather than in the circumburst media.
magnetar—which is a factor of $10^5$ less luminous than the burst observed from FRB 20220610A—and the wider sample of FRBs.

If a K-correction is applied, assuming a spectral index for FRB emission similar to that of the burst population found by ASKAP (11, 29), we find that the burst energy integrated over the instrument bandwidth is $\sim 2 \times 10^{42}$ erg, which is higher than most localized FRBs (Fig. 4). This constrains emission models of FRBs because the electric field strength at the source can be estimated independently of the beaming angle. The calculation assumes no amplification by gravitational or plasma lensing (see supplementary text). In one class of models, FRB emission is produced near the surface of a neutron star. From the luminosity of the burst, $\sim 3 \times 10^{46}$ erg s$^{-1}$ in the host galaxy’s rest frame, we infer an electric field strength of $4.2 \times 10^{12}$ (7/10 km)$^{-1}$ V m$^{-1}$ for a linearly polarized wave, where $r$ (10 km) is the curvature radius of the neutron star’s magnetic field. At a neutron star surface, this value is a few percent of the Schwinger critical field strength, at which an electric field aligned parallel to the local magnetic field would be screened by electron-positron pair production (30). This would suppress the FRB rate above the Schwinger luminosity of $\sim 2 \times 10^{47}$ erg s$^{-1}$ (30). In another class of models, FRBs are produced in a shock driven by relativistic ejecta, associated with the flare of a highly luminous FRB. This emission mechanism. V.A.M. developed the observatory control interpretation of the host galaxy properties. C.W.J. and W.L. conducted the FRB localization and high time resolution processing. R.D.E. developed the FRB search and localization systems with contributions from S.B. and R.M.S. A.T.D., M.G., K.G., and D.R.S. performed the FRB searches, and measured and interpreted the burst emission mechanism. V.A.M. developed the observatory control systems that enabled FRB searches and calibration observations. H.Q. and M.W.S. measured the burst temporal properties. S.D.R., K.W.B., A.T.D., C.W.J., and W.L. interpreted the burst energetics and implications for the FRB emission mechanism. V.A.M. developed the observatory control systems that enabled FRB searches and calibration observations. H.Q. and M.W.S. measured the burst temporal properties. S.D.R., K.W.B., A.T.D., C.W.J., and W.L. interpreted the burst energetics and implications for the FRB emission mechanism. V.A.M. developed the observatory control systems that enabled FRB searches and calibration observations. H.Q. and M.W.S. measured the burst temporal properties. S.D.R., K.W.B., A.T.D., C.W.J., and W.L. interpreted the burst energetics and implications for the FRB emission mechanism.

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SUPPLEMENTARY MATERIALS

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Materials and Methods

Figs. S1 to S8

Tables S1 and S2

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