23. S. Persson *et al.*, *Mol. Phylogenet. Evol.* **36**, 734 (2005).
24. P. J. Adam *et al.*, *J. Biol. Chem.* **278**, 6482 (2003).
25. D. A. Thompson, R. J. Weigel, *Biochem. Biophys. Res. Commun.* **251**, 111 (1998).
26. L. Iten, S. Bryant, *Willhem Roux Arch. Dev. Biol.* **173**, 263 (1973).
27. J. D. Salley, R. A. Tassava, *J. Exp. Zool.* **215**, 183 (1981).
28. B. M. Carlson, *Principles of Regenerative Biology* (Elsevier Inc., London, 2007).
29. F. V. Mariani, G. R. Martin, *Nature* **423**, 319 (2003).
30. L. Niswander, *Nat. Rev. Genet.* **4**, 133 (2003).
31. K. Crawford, D. L. Stocum, *Development* **102**, 687 (1988).
32. L. T. Pecorino, A. Entwistle, J. P. Brockes, *Curr. Biol.* **6**, 563 (1996).
33. G. C. Fletcher *et al.*, *Br. J. Cancer* **88**, 579 (2003).
34. M. Rosel, C. Claas, S. Seiter, M. Herlevsen, M. Zoller, *Oncogene* **17**, 1989 (1998).
35. G. Lemke, *Sci. STKE* **2006**, pe11 (2006).
36. C. L. Yntema, *J. Exp. Zool.* **142**, 423 (1959).
37. C. S. Thornton, M. T. Thornton, *J. Exp. Zool.* **173**, 293 (1970).
38. R. J. Goss, *Principles of Regeneration* (Academic Press, New York, 1969).
39. M. Singer, K. Rzehak, C. S. Maier, *J. Exp. Zool.* **166**, 89 (1967).
40. We thank P. Driscoll, I. Gout, and P. Martin for their help and comments, and M. Larkum for fabrication of the electroporation electrodes. This work was supported by a Medical Research Council (UK) Research Professorship and Programme Grant to J.P.B.

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# A Bright Millisecond Radio Burst of Extragalactic Origin

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**Pulsar surveys offer a rare opportunity to monitor the radio sky for impulsive burst-like events with millisecond durations. We analyzed archival survey data and found a 30-jansky dispersed burst, less than 5 milliseconds in duration, located 3° from the Small Magellanic Cloud. The burst properties argue against a physical association with our Galaxy or the Small Magellanic Cloud. Current models for the free electron content in the universe imply that the burst is less than 1 gigaparsec distant. No further bursts were seen in 90 hours of additional observations, which implies that it was a singular event such as a supernova or coalescence of relativistic objects. Hundreds of similar events could occur every day and, if detected, could serve as cosmological probes.**

Transient radio sources are difficult to detect, but they can potentially provide insights into a wide variety of astrophysical phenomena (*1*). Of particular interest is the detection of short radio bursts, no more than a few milliseconds in duration, that may be produced by exotic events at cosmological distances, such as merging neutron stars (*2*) or evaporating black holes (*3*). Pulsar surveys are currently among the few records of the sky with good sensitivity to radio bursts, and they have the necessary temporal and spectral resolution required to unambiguously discriminate between short-duration astrophysical bursts and terrestrial interference. Indeed, they have recently been successfully mined to detect a new galactic population of transients associated with rotating neutron stars (*4*). The burst we report here, however, has a substantially higher inferred energy output than this class and has not been observed to repeat. This burst therefore represents an entirely new phenomenon.

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The burst was discovered during a search of archival data from a 1.4-GHz survey of the Magellanic Clouds (*5*) using the multibeam receiver on the 64-m Parkes Radio Telescope (*6*) in Australia. The survey consisted of 209 telescope pointings, each lasting 2.3 hours. During each pointing, the multibeam receiver collected independent signals from 13 different positions (beams) on the sky. The data from each beam were one-bit sampled every millisecond over 96 frequency channels spanning a band 288 MHz wide.

Radio signals from all celestial sources propagate through a cold ionized plasma of free electrons before reaching the telescope. The plasma, which exists within our Galaxy and in extragalactic space, has a refractive index that depends on frequency. As a result, any radio signal of astrophysical origin should exhibit a quadratic shift in its arrival time as a function of frequency, with the only unknown being the integrated column density of free electrons along the line of sight, known as the dispersion measure (DM). Full details of the data reduction procedure to account for this effect, and to search for individual dispersed bursts, are given in the supporting online material. In brief, for each beam, the effects of interstellar dispersion were minimized for 183 trial DMs in the range 0 to 500 $cm^{-3}$ pc. The data were then searched for individual pulses with signal-to-noise (S/N) ratios greater than 4 with the use of a matched filtering technique (*7*) optimized for pulse widths in the range 1 to 1000 ms. The burst was detected in data taken on 24 August 2001 with DM = 375 $cm^{-3}$ pc contemporaneously in three neighboring beams (Fig. 1) and was located ~3° south of the center of the Small Magellanic Cloud (SMC).

The pulse exhibited the characteristic quadratic delay as a function of radio frequency (Fig. 2) expected from dispersion by a cold ionized plasma along the line of sight (*8*). Also evident was a significant evolution of pulse width across the observing frequency band. The behavior we observed, where the pulse width $W$ scales with frequency $f$ as $W \propto f^{-4.8 \pm 0.4}$, is consistent with pulse-width evolution due to interstellar scattering with a Kolmogorov power law [$W \propto f^{-4}$ (*9*)]. The filter-bank system has finite frequency and time resolution, which effectively sets an upper limit to the intrinsic pulse width $W_{int}$ = 5 ms. We represent this below by the parameter $W_5 = W_{int}/5$ ms. Note that it is entirely possible that the intrinsic width could be much smaller than observed (i.e., $W_5 << 1$) and that the width we observe in Fig. 2 results from the combination of intergalactic scattering and our instrumentation.

We can estimate the flux density of the radio burst in two ways. For the strongest detection, which saturated the single-bit digitizer in the observing system, we make use of the fact that the integrating circuit that sets the mean levels and thresholds is analog. When exposed to a source of strength comparable to the system equivalent flux density, an absorption feature in the profile is induced that can be used to estimate the integrated burst energy. For a 5-ms burst, we estimated the peak flux to be 40 Jy (1 Jy ≡ $10^{-26}$ W $m^{-2}$ $Hz^{-1}$). Using the detections from the neighboring beam positions, and the measured response of the multibeam system as a function of off-axis position (*6*), we determined the peak flux density to be at least 20 Jy. We therefore adopt a burst flux of 30 ± 10 Jy, which is consistent with our measurements, for the remaining discussion. Although we have only limited information on the flux density spectrum, as seen in Fig. 2, the pulse intensity increases at the lowest frequencies of our observing band. This implies that the flux density $S$ scales with observing frequency $f$ as $S \propto f^{-4}$.

It is very difficult to attribute this burst to anything but a celestial source. The frequency dispersion and pulse-width frequency evolution argue for a cosmic origin. It is very unlikely that a swept-frequency transmitter could both mimic the cold plasma dispersion law to high accuracy (see Fig. 2) and have a scattering relation consistent with the Kolmogorov power law. Furthermore, terrestrial interference often repeats, and this was the only dispersed burst detected with S/N > 10 in the analysis of data from almost 3000 separate positions. Sources with flux densities greater than ~1 Jy are typically detected in multiple receivers of the multibeam system. Although this is true for both terrestrial and astrophysical sources, the telescope had an elevation of ~60° at the time of the observation, making it virtually impossible for ground-based transmitters to be responsible for a source that was only detected in three adjacent beams of the pointing.

We have extensively searched for subsequent radio pulses from this enigmatic source. Including the original detection, there were a total of 27 beams in the survey data that pointed within 30 arcmin of the nominal burst position. These observations, which totaled 50 hours, were carried out between 19 June and 24 July 2001 and showed no significant bursts. In April 2007 we carried out 40 hours of follow-up observations with the Parkes telescope at 1.4 GHz with similar sensitivity to the original observation. No bursts were found in a search over the DM range 0 to 500 cm$^{-3}$ pc. These dedicated follow-up observations implied that the event rate must be less than 0.025 hour$^{-1}$ for bursts with S/N > 6 (i.e., a 1.4-GHz peak flux density greater than 300 mJy). The data were also searched for periodic radio signals using standard techniques (*8*) with null results.

The galactic latitude ($b$ = −41.8°) and high DM of the burst make it highly improbable for the source to be located within our Galaxy. The most recent model of the galactic distribution of free electrons (*10*) predicts a DM contribution of only 25 cm$^{-3}$ pc for this line of sight. In fact, of more than 1700 pulsars currently known, none of the 730 with $|b|$ > 3.5° has DM > 375 cm$^{-3}$ pc. The DM is also far higher than any of the 18 known radio pulsars in the Magellanic Clouds (*5*), the largest of which is for PSR J0131-7310 in the SMC with DM = 205 cm$^{-3}$ pc. The other four known radio pulsars in the SMC have DMs of 70, 76, 105, and 125 cm$^{-3}$ pc. The high DM of PSR J0131-7310 is attributed (*5*) to its location in an H II region (Fig. 1). We have examined archival survey data to look for ionized structure such as Hα filaments or H II regions that could similarly explain the anomalously large DM of the burst. No such features are apparent. The source lies 3° south from the center of the SMC, placing it outside all known contours of radio, infrared, optical, and high-energy emission from the SMC. This and the high DM strongly suggest that the source is well beyond the SMC, which lies 61 ± 3 kpc away (*11*).

No published gamma-ray burst or supernova explosion is known at this epoch or position, and no significant gamma-ray events were detected by the Third Interplanetary Network (*12*, *13*) around the time of the radio burst. The Principal Galaxy Catalog [PGC (*14*)] was searched for potential hosts to the burst source. The nearest candidate (PGC 246336) is located 5 arcmin south of the nominal burst position, but the nondetection of the burst in the beam south of the brightest detection appears to rule out an association. If the putative host galaxy were similar in type to the Milky Way, the nondetection in the PGC (limiting B magnitude of 18) implies a rough lower limit of ~600 Mpc on the distance to the source.

We can place an upper bound on the likely distance to the burst from our DM measurement. Assuming a homogeneous intergalactic medium in which all baryons are fully ionized, the intergalactic DM is expected (*15*, *16*) to scale with redshift, $z$, as DM ~ 1200 $z$ cm$^{-3}$ pc for $z \leq 2$. Subtracting the expected contribution to the DM from our Galaxy, we infer $z$ = 0.3, which corresponds to a distance of ~1 Gpc. This is likely an upper limit, because a host galaxy and local environment could both contribute to the observed DM. Using the electron density model for our Galaxy (*10*) as a guide, we estimate that there is a 25% probability that the DM contribution from a putative host galaxy is >100 cm$^{-3}$ pc and hence $z$ < 0.2. Obviously, the more distant the source, the more powerful it becomes as a potential cosmological probe. The sole event, however, offers little hope of a definitive answer at this stage. To enable some

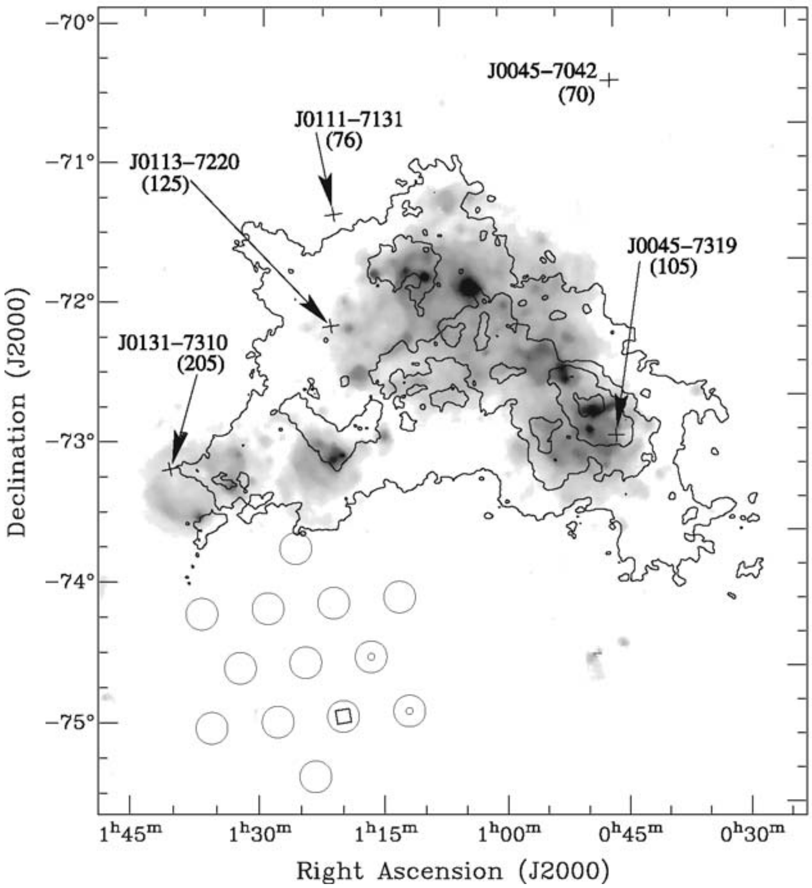


**Fig. 1.** Multiwavelength image of the field surrounding the burst. The gray scale and contours respectively show Hα and H I emission associated with the SMC (*32*, *33*). Crosses mark the positions of the five known radio pulsars in the SMC and are annotated with their names and DMs in parentheses in units of cm$^{-3}$ pc. The open circles show the positions of each of the 13 beams in the survey pointing of diameter equal to the half-power width. The strongest detection saturated the single-bit digitizers in the data acquisition system, indicating that its S/N >> 23. Its location is marked with a square at right ascension 01$^h$ 18$^m$ 06$^s$ and declination −75° 12′ 19″ (J2000 coordinates). The other two detections (with S/Ns of 14 and 21) are marked with smaller circles. The saturation makes the true position difficult to localize accurately. The positional uncertainty is nominally ±7′ on the basis of the half-power width of the multibeam system. However, the true position is probably slightly (a few arcmin) northwest of this position, given the nondetection of the burst in the other beams.

indicative calculations about potential source luminosity and event rates, we adopt a distance of 500 Mpc. This corresponds to $z \sim 0.12$ and a host galaxy DM of 200 $\mathrm{cm}^{-3}$ pc. In recognition of the considerable distance uncertainty, we parameterize this as $D_{500} = D/500$ Mpc. If this source is well beyond the local group, it would provide the first definitive limit on the ionized column density of the intracluster medium, which is currently poorly constrained (*17*).

What is the nature of the burst source? From the observed burst duration, flux density, and distance, we estimate the brightness temperature and energy released to be $\sim 10^{34} (D_{500}/W_5)^2$ K and $\sim 10^{33} W_5 D_{500}{}^2$ J, respectively. These values, and light travel-time arguments that limit the source size to <1500 km for a nonrelativistic source, imply a coherent emission process from a compact region. Relativistic sources with bulk velocity $v$ are larger by a factor of either $\Gamma$ (for a steady jet model) or $\Gamma^2$ (for an impulsive blast model), where the Lorentz factor $\Gamma = [1 - (v^2/c^2)]^{-1/2}$ and $c$ is the speed of light.

The only two currently known radio sources capable of producing such bursts are the rotating radio transients (RRATs), thought to be produced by intermittent pulsars (*4*), and giant pulses from either a millisecond pulsar or a young energetic pulsar. A typical pulse from a RRAT would only be detectable out to ~6 kpc with our observing system. Even some of the brightest giant pulses from the Crab pulsar, with peak luminosities of 4 kJy $\mathrm{kpc}^2$ (*18*), would be observable out to ~100 kpc with the same system. In addition, both the RRAT bursts and giant pulses follow power-law distributions of pulse energies. The strength of this burst, which is some two orders of magnitude above our detection threshold, should have easily led to many events at lower pulse energies, either in the original survey data or follow-up observations. Hence, it appears to represent an entirely new class of radio source.

To estimate the rate of similar events in the radio sky, we note that the survey we have analyzed was sensitive to bursts of this intensity over an area of about 5 square degrees (i.e., 1/8250 of the entire sky) at any given time over a 20-day period. Assuming the bursts to be distributed isotropically over the sky, we infer a nominal rate of 8250/20 ≈ 400 similar events per day. Given our observing system parameters, we estimate that a $10^{33}$-Jy radio burst would be detectable out to $z \sim 0.3$, or a distance of 1 Gpc. The corresponding cosmological rate for bursts of this energy is therefore ~90 $\mathrm{day}^{-1}$ $\mathrm{Gpc}^{-3}$. Although considerably uncertain, this is somewhat higher than the corresponding estimates of other astrophysical sources, such as binary neutron star inspirals [~3 $\mathrm{day}^{-1}$ $\mathrm{Gpc}^{-3}$ (*19*)] and gamma-ray bursts [~4 $\mathrm{day}^{-1}$ $\mathrm{Gpc}^{-3}$ (*20*)], but well below the rate of core-collapse supernovae [~1000 $\mathrm{day}^{-1}$ $\mathrm{Gpc}^{-3}$ (*21*)]. Although the implied rate is compatible with gamma-ray bursts, the brightness temperature and radio frequency we observed for this burst are higher than currently discussed mechanisms or limitations for the observation of prompt radio emission from these sources (*22*).

Regardless of the physical origin of this burst, we predict that existing data from other pulsar surveys with the Parkes multibeam system (*23*–*26*) should contain several similar bursts. Their discovery would permit a more reliable estimate of the overall event rate. The only other published survey for radio transients on this time scale (*27*) did not have sufficient sensitivity to detect similar events at the rate predicted here. At lower frequencies (~400 MHz) where many pulsar surveys were conducted, although the steep spectral index of the source implies an even higher flux density, the predicted scattering time (~2 s) would make the bursts difficult to detect over the radiometer noise. At frequencies near 100 MHz, where low-frequency arrays currently under construction will operate (*28*), the predicted scattering time would be on the order of several minutes, and hence would be undetectable.

Perhaps the most intriguing feature of this burst is its 30-Jy strength. Although this has allowed us to make a convincing case for its extraterrestrial nature, the fact that it is more than 100 times our detection threshold makes its uniqueness puzzling. Often, astronomical sources have a flux distribution that would naturally lead to many burst detections of lower significance; such events are not observed in our data. If, on the other hand, this burst was a rare standard candle, more distant sources would have such large DMs that they would be both red-shifted to lower radio frequencies and outside our attempted dispersion trials. If redshifts of their host galaxies are measurable, the potential of a population of radio bursts at cosmological distances to probe the ionized intergalactic medium (*29*) is very exciting, especially given the construction of wide-field instruments (*30*) in preparation for the Square Kilometre Array (*31*).

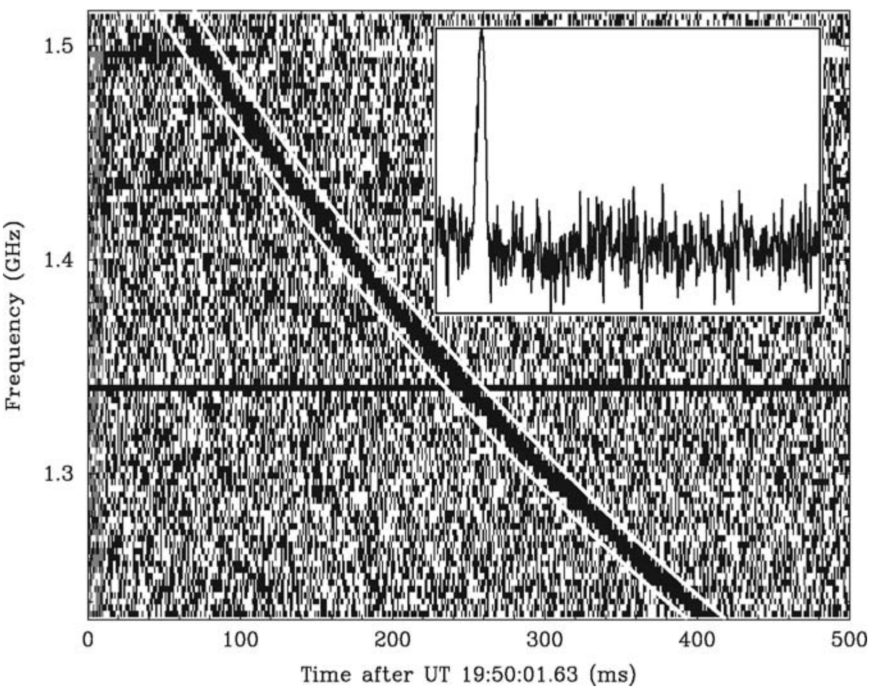


**Fig. 2.** Frequency evolution and integrated pulse shape of the radio burst. The survey data, collected on 24 August 2001, are shown here as a two-dimensional "waterfall plot" of intensity as a function of radio frequency versus time. The dispersion is clearly seen as a quadratic sweep across the frequency band, with broadening toward lower frequencies. From a measurement of the pulse delay across the receiver band, we used standard pulsar timing techniques and determined the DM to be 375 ± 1 $\mathrm{cm}^{-3}$ pc. The two white lines separated by 15 ms that bound the pulse show the expected behavior for the cold-plasma dispersion law assuming a DM of 375 $\mathrm{cm}^{-3}$ pc. The horizontal line at ~1.34 GHz is an artifact in the data caused by a malfunctioning frequency channel. This plot is for one of the offset beams in which the digitizers were not saturated. By splitting the data into four frequency subbands, we have measured both the half-power pulse width and flux density spectrum over the observing bandwidth. Accounting for pulse broadening due to known instrumental effects, we determine a frequency scaling relationship for the observed width $W = 4.6$ ms $(f/1.4\ \mathrm{GHz})^{-4.8 \pm 0.4}$, where $f$ is the observing frequency. A power-law fit to the mean flux densities obtained in each subband yields a spectral index of −4 ± 1. The inset shows the total-power signal after a dispersive delay correction assuming a DM of 375 $\mathrm{cm}^{-3}$ pc and a reference frequency of 1.5165 GHz. The time axis on the inner figure also spans the range 0 to 500 ms.

**References and Notes**

1. J. M. Cordes, T. J. W. Lazio, M. A. McLaughlin, *N. Astron. Rev.* **48**, 1459 (2004).
2. B. M. S. Hansen, M. Lyutikov, *Mon. Not. R. Astron. Soc.* **322**, 695 (2001).
3. M. J. Rees, *Nature* **266**, 333 (1977).
4. M. A. McLaughlin *et al.*, *Nature* **439**, 817 (2006).
5. R. N. Manchester, G. Fan, A. G. Lyne, V. M. Kaspi, F. Crawford, *Astrophys. J.* **649**, 235 (2006).
6. L. Staveley-Smith *et al.*, *Proc. Astron. Soc. Pac.* **13**, 243 (1996).
7. J. M. Cordes, M. A. McLaughlin, *Astrophys. J.* **596**, 1142 (2003).
8. D. R. Lorimer, M. Kramer, *Handbook of Pulsar Astronomy* (Cambridge Univ. Press, Cambridge, 2005).
9. L. C. Lee, J. R. Jokipii, *Astrophys. J.* **206**, 735 (1976).
10. J. M. Cordes, T. J. W. Lazio, http://arxiv.org/abs/astro-ph/0207156 (2002).
11. R. W. Hilditch, I. D. Howarth, T. J. Harries, *Mon. Not. R. Astron. Soc.* **357**, 304 (2005).
12. K. Hurley *et al.*, *Astrophys. J. Suppl. Ser.* **164**, 124 (2006).
13. K. Hurley, personal communication.
14. G. Paturel *et al.*, *Astron. Astrophys.* **412**, 45 (2003).
15. K. Ioka, *Astrophys. J.* **598**, L79 (2003).
16. S. Inoue, *Mon. Not. R. Astron. Soc.* **348**, 999 (2004).
17. P. R. Maloney, J. Bland-Hawthorn, *Astrophys. J.* **522**, L81 (1999).
18. J. M. Cordes, N. D. R. Bhat, T. H. Hankins, M. A. McLaughlin, J. Kern, *Astrophys. J.* **612**, 375 (2004).
19. V. Kalogera *et al.*, *Astrophys. J.* **601**, L179 (2004).
20. D. Guetta, M. Della Valle, *Astrophys. J.* **657**, L73 (2007).
21. P. Madau, M. Della Valle, N. Panagia, *Mon. Not. R. Astron. Soc.* **297**, L17 (1998).
22. J.-P. Macquart, *Astrophys. J.* **658**, L1 (2007).
23. R. N. Manchester *et al.*, *Mon. Not. R. Astron. Soc.* **328**, 17 (2001).
24. R. T. Edwards, M. Bailes, W. van Straten, M. C. Britton, *Mon. Not. R. Astron. Soc.* **326**, 358 (2001).
25. M. Burgay *et al.*, *Mon. Not. R. Astron. Soc.* **368**, 283 (2006).
26. B. A. Jacoby, M. Bailes, S. M. Ord, H. S. Knight, A. W. Hotan, *Astrophys. J.* **656**, 408 (2007).
27. S. W. Amy, M. I. Large, A. E. Vaughan, *Proc. Astron. Soc. Aust.* **8**, 172 (1989).
28. B. W. Stappers, A. G. J. van Leeuwen, M. Kramer, D. Stinebring, J. Hessels, in *Proceedings of the 363. Heraeus Seminar on Neutron Stars and Pulsars*, W. Becker, H. H. Huang, Eds. (Physikzentrum, Bad Honnef, Germany, 2006), pp. 101–103.
29. V. L. Ginzburg, *Nature* **246**, 415 (1973).
30. S. Johnston *et al.*, *ATNF SKA Memo 13* (Australia Telescope National Facility, 2007).
31. P. N. Wilkinson, K. I. Kellermann, R. D. Ekers, J. M. Cordes, T. J. W. Lazio, *N. Astron. Rev.* **48**, 1551 (2004).
32. J. E. Gaustad, P. R. McCullough, W. Rosing, D. Van Buren, *Proc. Astron. Soc. Pac.* **113**, 1326 (2001).
33. S. Stanimirović, L. Staveley-Smith, J. M. Dickey, R. J. Sault, S. L. Snowden, *Mon. Not. R. Astron. Soc.* **302**, 417 (1999).



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# Nanoscale Friction Varied by Isotopic Shifting of Surface Vibrational Frequencies


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**Friction converts kinetic energy at sliding interfaces into lattice vibrations, but the detailed mechanisms of this process remain unresolved. Atomic force microscopy measurements reveal that changing the mass of the terminating atoms on a surface, and thus their vibrational frequencies, affects nanoscale friction substantially. We compared hydrogen- and deuterium-terminated single-crystal diamond and silicon surfaces, and in all cases the hydrogenated surface exhibited higher friction. This result implies that the lower natural frequency of chemisorbed deuterium reduces the rate at which the tip's kinetic energy is dissipated. This discovery is consistent with a model describing energy transfer to adsorbates from a moving surface.**


Friction converts translational kinetic energy to vibrational energy. Hence, rubbing two bodies together produces heat. This process occurs even in the absence of wear. In contact-mode atomic force microscopy (AFM), a nanoscale tip slides along a surface, but based on theories of atomic dissipation, some of the tip's translational energy can be converted to lattice vibrations or electronic carriers (*1*–*4*). It would be technologically beneficial to control how energy is lost through each of these channels by tuning phononic or electronic properties. Recently, Park *et al*. increased nanoscale friction electronically (*5*), whereas in the present work we show that friction also depends on the vibrational properties of surfaces.

We altered surfaces by varying the mass, but not the chemistry, of the chemisorbed terminating surface atom. Leaving the surface chemistry unchanged avoids chemical effects due to different interfacial forces. Based on a model of phononic dissipation for friction (*6*), the surface monolayer acts as an energy-transfer medium, absorbing kinetic energy from the tip at rates dependent on the adsorbates' natural vibration frequencies (Fig. 1). Because lighter atoms vibrate faster, energy dissipation should be more rapid, and therefore friction should be greater than friction produced by heavier species.

The systems most likely to exhibit observable mass contrast are hydrogen (H)– and deuterium (D)–terminated surfaces, the most durable and inert of which is diamond (*7*). H- and D-terminated silicon (Si) surfaces are less stable (the surface oxidizes in air after 1 or 2 hours) (*8*), but studying Si provides an additional test and provides information on an important ma-

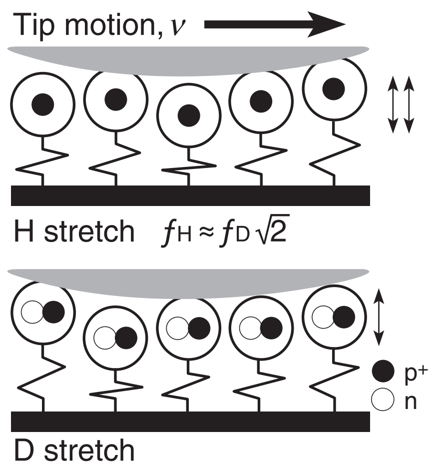


**Fig. 1.** A schematic of the frictional interface. Vibrating adsorbates collide with and dissipate kinetic energy from the moving tip at a rate that depends on the adsorbate's frequency and thus its mass; that is, at different rates for H than for D.


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