Deceleration of Interstellar Hydrogen at the Heliospheric Interface

Rosine Lallement, Jean-Loup Bertaux, John T. Clarke

High-resolution spectra of nearby stars show absorption lines due to material in the local interstellar cloud. This cloud is deduced to be moving at 26 kilometers per second with respect to the sun, and in the same direction as the "interstellar wind" flowing through the solar system. Measurements by the Ulysses spacecraft show that neutral helium is drifting through the solar system at the same velocity, but neutral hydrogen appears to be moving at only 20 kilometers per second, a result confirmed by new measurements of the hydrogen emission line taken by the High-Resolution Spectrograph on the Hubble Space Telescope. These results indicate that neutral hydrogen atoms from the local interstellar cloud are preferentially decelerated at the heliospheric interface, most likely by charge-exchange with interstellar protons, while neutral helium is unaffected by the plasma. The magnitude of the observed deceleration implies an interstellar plasma density of 0.06 to 0.10 per cubic centimeter, which in turn implies that the heliospheric shock should be less than 100 astronomical units from the sun.

The generally accepted picture of the interstellar medium in the vicinity of the sun has individual diffuse clouds, with typical sizes of a few parsecs (pc), densities of 0.1 to 10 cm^{-3}, and temperatures of 5,000 to 20,000 K, with or without small cold cores, embedded in the Local Bubble, a cavity of hot and tenuous gas, about 80 pc across (*1–3*), which is thought to be a supernova remnant. The clouds are detected by means of the absorption lines they produce in the spectra of background astronomical objects, such as nearby stars. In high-resolution spectra multiple lines of the same absorbing species with different radial heliocentric velocities can often be seen, indicating the presence of more than one cloud between the sun and the observed star. In addition to the general motion associated with the galactic rotation, the stars and the interstellar clouds also have individual velocities.

The sun is known to move inside one of these clouds. There is an observed flow of hydrogen and helium atoms, at about 20 km s^{-1}, within the solar system, due to the relative motion of the sun through the surrounding medium. When they approach the sun, H and He atoms of this so-called interstellar wind resonantly scatter solar photons at wavelengths of 121.6 nm (H Ly-α) and He 58.4 nm (He) to produce the interplanetary glow, which was first mapped and understood in 1970 (*4, 5*). The measured density of the neutral H flow is 0.05 to 0.20 cm^{-3}.

Until now, it has been impossible to say which astronomically observed cloud corresponds to the solar system interstellar matter; the amount of interstellar matter involved is extremely small. In a series of recent measurements (*6*) from ground and space, however, those interstellar absorption lines due to the local cloud were identified through the reconstruction of its velocity vector by Doppler triangulation. A typical spectrum with only one absorption line, that of CaII (*7*), is shown in Fig. 1.

Doppler triangulation (*8*) is very simple. If the local interstellar cloud (LIC) moves like a solid body, Doppler shifts of its absorption lines toward any star are the projection of the LIC velocity vector onto the star direction, and the velocity vector coordinates can be deduced from the relationship between the measured shifts. However, due to the frequent presence of two or more absorption lines in the same star spectrum, a selective search for those lines (one per star) which obey such a relationship has to be done. Identification of the "local" lines and the determination of the velocity vector are done simultaneously. From all our observations, only one velocity vector emerged that gave good agreement between Doppler shifts of observed absorption lines and those calculated by projection for the whole set of stars. The derived heliocentric velocity vector V_{LIC} has the same direction (λ = 74.5°, β = −7.8° in ecliptic coordinates) as the observed solar system interstellar flow and its magnitude is 25.7 ± 0.5 km s^{-1} (*6*).

Two independent and extremely strong supporting arguments have also shown up. The first one comes from high-quality spectra of the star Capella 12.5 pc distant from Earth, taken by the Hubble Space Telescope—Goddard High-Resolution Spectrograph (HST-GHRS) (*9*). H, D, FeII, and MgII spectra exhibit only one absorption line, at a Doppler shift of 22.0 km s^{-1}. The projection of the LIC motion (*6*) onto the direction of Capella is also 22.0 km s^{-1}. The LIC, therefore, is the only cloud between the sun and Capella probed by both Capella ultraviolet (UV) lines and visible lines from surrounding stars. From the relative widths of the Capella UV lines, the temperature is 7000 ± 1000 K, and the turbulence level smaller than 1.6 km s^{-1} (*9*).

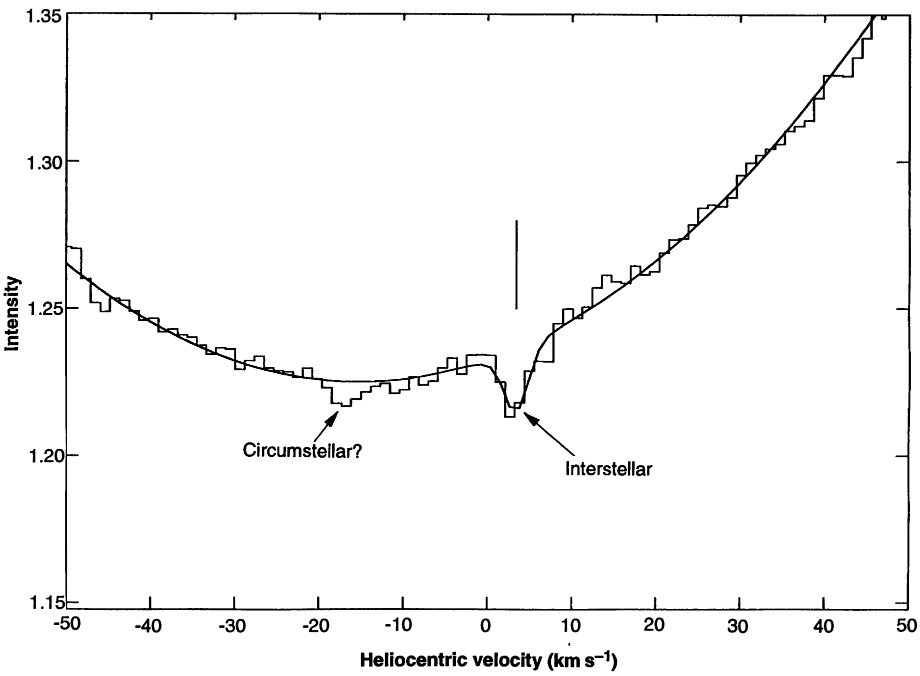

Fig. 1. An example of interstellar absorption attributed to the local cloud, detected toward the star α Lacertae located at a distance of 15 pc from the sun. The data were taken with the Aurelie spectrometer at the 1.52-m telescope of the Observatoire de Haute-Provence, France, and are centered on the line of singly ionized calcium (CaII).

R. Lallement and J.-L. Bertaux, Service d'aéronomie du CNRS BP 3, F91371 Verrières-le-buisson, France. J. T. Clarke, Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, MI 48109.

The second strong confirmation is provided by the recent results of the Neutral Gas Experiment (*10*) on board the interplanetary spacecraft Ulysses, which has measured in situ the velocity distribution of the interstellar neutral helium flow. The derived characteristics of the helium flow are a temperature of 6700 ± 1000 K and a velocity modulus of 26 ± 1 km s^{-1}, in good agreement with the properties of the LIC deduced from the CaII lines.

The identification of the local cloud has important consequences for the study of the interaction between the sun and the interstellar medium. The heliosphere, or solar wind domain, is expected to be confined by the plasma component of the local interstellar medium, the interstellar magnetic field, and the cosmic rays (*11*). The radially expanding supersonic solar wind is expected to be decelerated by a strong shock, the heliospheric shock (Fig. 2), then constrained to flow inside the heliopause, a contact discontinuity surface between the solar wind and the interstellar plasma. The interstellar plasma is itself decelerated, and flows around the heliosphere. The exact size of the heliosphere is the subject of current speculation, because the Voyager 1 and 2 and Pioneer 11 spacecraft are now leaving the solar system in the general direction of the incoming interstellar flow. They are now (January 1993) 51, 39, and 37 astronomical units (AU) from the sun, respectively, and, depending on the actual size of the heliosphere, should sooner or later detect direct or indirect signs of an approaching boundary.

Estimates of the size of the heliosphere have ranged between 50 and 500 AU, depending on assumed values of the interstellar magnetic field, the density of low-energy cosmic rays, and the interstellar plasma density (mainly characterized by the proton density n_p, which is also very poorly known), all three contributing to the confinement. Estimates of n_p (approximately equal to the electron density) range from 0.003 cm^{-3}, deduced from local interstellar medium observations of the ionization state of magnesium (*12*), up to about 0.015 cm^{-3} according to ionization calculations by integrated celestial UV radiation (*13*). With a magnetic field of 1.6 μG in a direction perpendicular to the flow (*14*) and a low-energy cosmic ray pressure of 10^{-13} dynes cm^{-2} (*11*), the above range for n_p corresponds to a distance R to the heliospheric shock in the interval 170 to 210 AU. There is, however, no real observational upper limit to the local value of n_p. The interstellar medium is inhomogeneous, and what is found when integrating over large distances may be different from the local conditions. There could also be other sources of ionizing flux (*13*).

Besides dictating the size of the heliosphere, the value of n_p has an observational implication inside the heliosphere, even though the interstellar plasma cannot itself enter it. Only neutral atoms can flow through the heliopause and enter the heliospheric cavity. Theory predicts that neutral helium interstellar atoms flow through the shocks and heliopause without being decelerated (Fig. 2), and this is indeed observed. By contrast, hydrogen atoms could be significantly coupled to the decelerated interstellar plasma through charge-exchange reactions with the protons upstream of the heliopause. H-H^+ charge-exchange is simply the capture by the proton H^+ of the electron from neutral H, with the result that a new H with the same momentum as the initial proton is produced. Through this process undecelerated interstellar neutral hydrogen atoms are replaced by new atoms moving at the smaller velocity of the plasma. Heliospheric models involving neutral gas coupled with the plasma (*15–18*) predict such a deceleration and a possible subsequent heating of the neutral H when it enters the heliosphere, with a maximum effect along the stagnation line (sun-wind axis).

We report here an observation of the neutral H velocity inside the heliosphere. Recently an HST-GHRS spectrum of the interplanetary H Ly-α emission line (Fig. 3A) has been obtained as a by-product of an observation of the planet Mars (*19*). The spectral dispersion is only 1 km s^{-1} per spectral bin, with a rectangular spectral spread of 20 km s^{-1} for emission filling the aperture, and provides a much higher signal to noise detection than previously obtained with the Orbiting Astronomical Observatory Copernicus and the International Ultraviolet Explorer satellite (*20–22*). The motion of the interplanetary flow with respect to the Earth red-shifts the weak interplanetary emission line from the huge geocoronal emission. After correction for the geocoronal contamination (*22*), the remaining interplanetary line profile is compared with a computer simulation of the emission line, assuming an initial bulk velocity of 20 km s^{-1} before close solar gravitational interaction and ionization (Fig. 3B). The model is well centered on the data, whereas a model using 26 km s^{-1} provides a poorer fit. The observed line is somewhat broader than the computed one. The temperature in the computed model is 8000 K (*19*) which is already higher than the helium and LIC temperature. We think the observed additional broadening is mainly due to Ly-α multiple scattering effects in the solar system, which are expected to be more important when looking in the downwind direction (to where the wind blows), as is the case for this spectrum. This broadening may explain the earlier IUE measurement (*23*).

This new measurement fully confirms earlier measurements (20 ± 1 km s^{-1}) of the bulk velocity of the H flow in the solar system obtained with a hydrogen cell (*24, 25*), but in a more direct way. The magnitude of the initial velocity and the question of equality or inequality of H and He velocities have been the subject of a 5-year-long debate, from which direct LIC velocity measurements and precise spectrometric observations of the neutral helium velocity were missing. The LIC detection and the Ulysses in situ results put an end to this controversy. The two high-resolution Ly-α measurements (H cell and direct GHRS spectrum) suggest that a significant fraction of the H flow, if not all of it, is decelerated by about 5 to 6 km s^{-1} at the interface along the sun-wind axis.

This measured deceleration provides important constraints on the characteristics of the plasma interface. The fraction of momentum transmitted to the interstellar neutrals by the decelerated interstellar plasma is very sensitive to the local proton density of this plasma, and then to the unknown ambient interstellar medium proton density n_p. Existing heliospheric interface models (*17, 18*) involving neutral gas coupled to interstellar protons provide estimates for the neutral hydrogen

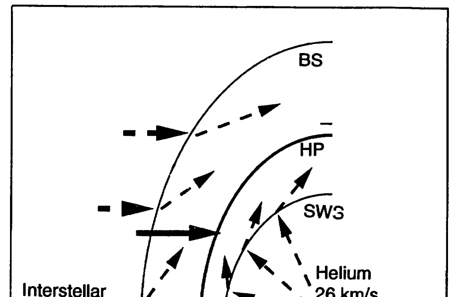

Fig. 2. Schematic view of the heliospheric interface between the solar wind and the ambient interstellar medium. SWS, solar wind shock; HP, heliopause; BS, bow shock. Plasma flows (solar wind and interstellar plasma), dashed arrows; neutral flows, solid arrows. Interstellar neutral helium is unaffected by crossing the interface. Hydrogen atoms are coupled with the decelerating interstellar plasma and are themselves decelerated in the region between HP and BS boundaries.

deceleration as a function of the plasma density, and the observed 6 km s^{-1} velocity decrease requires a plasma density n_p of 0.06 to 0.10 cm^{-3}, depending on assumptions about the type of interface and the magnetic field intensity (*26*). Compared with the neutral H density of about 0.10 cm^{-3}, such a high value of n_p implies large ionization fraction in the local medium, and has in turn important consequences for the confinement of the solar wind and the size of the heliosphere. Assuming n_p = 0.08 cm^{-3}, the equality of pressures near the heliopause (*11*) requires the distance to the solar wind shock to be of the order of 100 AU, for the magnetic field and cosmic ray pressure quoted above (*11, 14*). The distance would be smaller if the pressure is larger, and it is small enough for the Voyager 1 spacecraft to reach the shock region before 2010 and record the event if it remains in good health.

A similar distance to the shock is suggested by two different observations. One estimate derives from the detection radio waves of 2- to 3-kHz frequencies, observed by Voyager (*27*) and interpreted as radiation trapped in the heliosphere (*28*) and reflected back and forth between the solar wind inhomogeneities and the compressed plasma behind the heliopause. The frequency of this radiation increases with time in a way that is connected with the size of the heliosphere, through a sophisticated model that takes into account the large-scale inhomogeneities of the solar wind and its corotating structure. The second indication is related to Voyager measurements of the galactic cosmic rays and the anomalous cosmic-rays, energetic particles thought to originate from inflowing interstellar neutrals (He, N, Ne, O, and C), singly ionized when entering the heliosphere, convected outward by the solar wind, and accelerated to high energy at the heliospheric shock. The density of these particles increases with increasing heliocentric distance. Through models of convection and diffusion of these particles in the spiraling solar magnetic field and solar wind structures, the observed density gradients are compatible with a close shock (*29, 30*). Compared to these two methods, measurement of the deceleration of the neutral H has the advantage of using more direct observations, and being easier to interpret through models that are almost independent of solar cycle effects and the evolving pattern of large-scale structure in the solar wind.

Now that the velocity of the LIC has been identified, each absorption line can be assigned more securely to the LIC or to a different cloud, according to its observed projected velocity. In particular, very high resolution UV observations of different ionization states of the same element should provide an independent determination of the plasma density. The high value estimated from the deceleration of neutral H is at least four times larger than would be expected from standard UV fluxes. A large ionization degree is likely to occur if, for example, the sun is close to the edge of the local cloud, where soft x-ray emission from the interface with the hot gas becomes important (*13*), or if the local gas has not reached ionization equilibrium, as would be the case if there had been a supernova explosion in the sun's vicinity less than 5 million years ago. The geometry of the LIC can also be determined. Assuming a constant volume density, each column density measured from an absorption line in a stellar spectrum can be transformed into a cloud dimension in the direction of the star. From the data already collected (*6*), we know that the distance at which the interstellar gas velocity differs from the LIC velocity is much closer in the direction of motion of the sun than in the opposite direction, in agreement with the sun being at the edge of our cloud. Unlike the situation described in Fred Hoyle's story "The Black Cloud," where the sun entered a dense interstellar cloud, with catastrophic consequences on Earth, one can estimate that the sun entered the tenuous LIC about 200,000 years ago and will leave it in less than 100,000 years. It should then fairly soon enter a similar "cloudlet," the future LIC, probably after having spent some time traveling through the tenuous and hot gas of the Local Bubble.

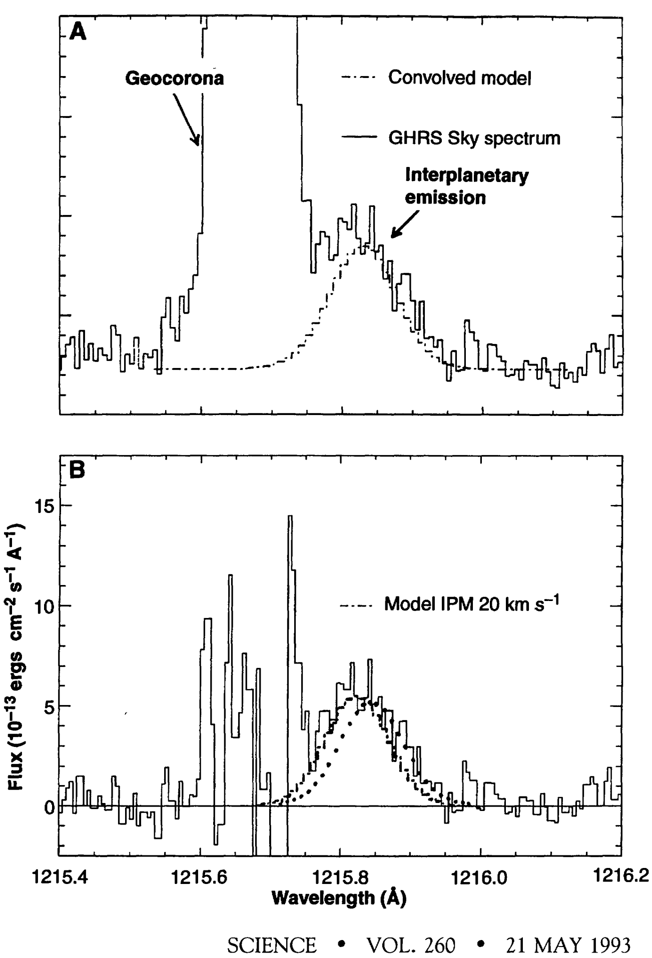

Fig. 3. (**A**) Hubble Space Telescope Goddard High-Resolution λ Spectrograph sky background spectrum at H Ly-α. The strongest emission is due to terrestrial hydrogen (the geocorona). The interplanetary/interstellar hydrogen resonance emission is shifted because of the relative motion of the inflowing gas with respect to the Earth. (**B**) After correction for the largest part of geocoronal contamination (noise from a residual geocoronal signal is visible between 121.560 and 121.575 nm), the remaining interplanetary line profile is compared with a computer simulation of the emission line, assuming an initial bulk velocity of 20 km s^{-1} (dashed line) and 26 km s^{-1} (dots).

REFERENCES AND NOTES

1. P. C. Frisch and D. G. York, *Astrophys. J.* **271**, L59 (1983).
2. D. P. Cox and R. J. Reynolds, *Annu. Rev. Astron. Astrophys.* **25**, 303 (1987).
3. S. L. Snowden, D. P. Cox, D. McCammon, W. T. Sanders, *Astrophys. J.* **354**, 211 (1990).
4. J. L. Bertaux and J. E. Blamont, *Astron. Astrophys.* **11**, 200 (1971).
5. G. E. Thomas and R. F. Krassa, *ibid.*, p. 218.
6. R. Lallement and P. Bertin, *ibid.* **266**, 479 (1992).
7. The resolution is $R = \lambda/\Delta\lambda$ = 110,000. The absolute wavelength calibration is accurate to less than 1 km s^{-1}. The profile-fitting program takes into account the measured instrumental profile, and permits determination of the intrinsic linewidth, and then the temperature of the absorbing gas, assuming negligible turbulence. Column densities are of the order of 10^{10} atoms cm^{-2} for CaII and NaI.
8. R. N. Crutcher, *Astrophys. J.* **254**, 82 (1982).
9. J. L. Linsky *et al.*, *ibid.* **402**, 694 (1993).
10. M. Witte, H. Rosenbauer, M. Banaszkiewicz, H. J. Fahr, *Adv. Space Res.*, in press.
11. W. H. Ip and W. I. Axford, *ibid.* **6**, 27 (1986).
12. P. C. Frisch, D. G. Welty, D. G. York, J. R. Fowler, *Astrophys. J.* **357**, 514 (1990).
13. R. J. Reynolds, in *Physics of the Outer Heliosphere*, S. Grzedzielski and D. E. Page, Eds, (Pergamon, Oxford, 1990), pp. 101–104.
14. P. C. Frisch, in *ibid.*, pp. 19–28.

15. M. K. Wallis, *Astron. Astrophys.* **130**, 200 (1984).
16. V. B. Baranov, M. G. Lebedev, Ju. G. Malama, *Astrophys. J.* **375**, 347 (1991).
17. Ju. G. Malama, *Astrophys. Space Sci.* **176**, 21 (1991).
18. R. Osterbart and H. J. Fahr, *Astron. Astrophys.* **264**, 260 (1992).
19. J. L. Bertaux, J. T. Clarke, M. Mumma, T. Owen, E. Quemerais, in *Science with the Hubble Space Telescope*, European Southern Observatory Conference and Workshop Proceedings No. 44 (1993), p. 459.
20. T. F. Adams and P. C. Frisch, *Astrophys. J.* **212**, 300 (1977).
21. J. T. Clarke, S. Bowyer, H. J. Fahr, G. Lay, *Astron. Astrophys.* **139**, 389 (1984).
22. The GHRS spectrum of sky 2 arc min from Mars was taken with Echelle-A grating and a 2–arc sec aperture in May 1991. The line-of-sight was 42° from the downwind direction for an integration time of 20 min. The red edge of the geocoronal line was estimated by symmetrical reflection of the blue edge. The model line profile has been convolved with a line spread function 0.008 nm wide.
23. Due to the blending with the geocorona at the IUE lower resolution, the red part of the line was preferentially fitted (*21*). The derived value of 25 km s^{-1} is consistent with the broad interplanetary line and the centering at 20 km s^{-1} as we observed here.
24. J. L. Bertaux, R. Lallement, V. G. Kurt, E. N. Mironova, *Astron. Astrophys.* **150**, 82 (1985).
25. The hydrogen absorption cell used on the Prognoz spacecraft (*24*) acts as a kind of negative spectrometer of quasi-infinite resolution, absorbing all the emission within a restricted wavelength range smaller than the Ly-α linewidth. The Doppler shift between the earth and the inflowing gas changes when viewing in different directions provides a modulation of the absorption fraction. From the observed modulation and through modeling of the flow, the initial velocity is 20 km s^{-1}.
26. The first number refers to the simple Parker type (*18*), assuming the LIC flow is submagnetosonic, and the second to the so-called two-shocks model (*16, 17*), which is relevant for a supermagnetosonic flow. In the former case, a deceleration of 2 km s^{-1} is obtained with a plasma density of 0.02 cm^{-3} (*18*). In the latter case, a deceleration of 14 km s^{-1} is obtained with a plasma density of 0.2 cm^{-3} [R. Lallement *et al.*, *Astrophys. J.* **396**, 696 (1992)]. In the two models the neutral hydrogen density is of the same order (0.1 and 0.07 cm^{-3}, respectively).
27. W. S. Kurth, D. A. Gurnett, F. L. Scarf, R. L. Poynter, *Nature* **312**, 27 (1984).
28. A. Czechowski and S. Grzedzielski, *ibid.* **344**, 640 (1990).
29. J. R. Jokipii, in *Physics of the Outer Heliosphere*, S. Grzedzielski and D. E. Page, Eds. (Pergamon, Oxford, 1990), pp. 169–178.
30. R. B. McKibben, in *ibid.*, pp. 107–118.

19 January 1993; accepted 30 March 1993

Slow Magnetic Relaxation in Iron: A Ferromagnetic Liquid

R. V. Chamberlin and M. R. Scheinfein

The remanent magnetization of single-crystal iron whiskers has been measured from 10^{-5} to 10^4 seconds after the removal of an applied field. The observed response is accurately modeled by localized magnon relaxation on a Gaussian size distribution of dynamically correlated domains, virtually identical to the distribution of excitations in glass-forming liquids. When fields of less than 1 oersted are removed, some relaxation occurs before 10^{-5} second has elapsed; but when larger fields are removed, essentially all of the response can be accounted for by magnon relaxation over the available time window. The model provides a physical picture for the mechanism and observed distribution of Landau-Lifshitz damping parameters.

The Landau-Lifshitz-Gilbert equations govern all classical ferromagnetic response mechanisms (*1–3*). Relaxation toward the local internal magnetic field (H_I) is characterized by a dimensionless Landau-Lifshitz damping parameter α, which connects the free-electron gyromagnetic ratio, $\gamma = 1.76 \times 10^7\ s^{-1}\ Oe^{-1}$, to the observed relaxation rate, $1/\tau = \alpha\gamma H_I$ (note, 1 Oe $= 10^3/4\pi$ A m^{-1}; or, in vacuum, $H = 1$ Oe produces $B = 1$ G). Experimental values of α ($\sim$0.01) are usually determined from ferromagnetic resonance linewidths in $H_I \sim 1$ kOe (*4, 5*), so that gyromagnetic precession occurs at microwave frequencies and $\tau \sim 10^{-9}$ s. Here we report magnetic relaxation measurements of single-crystal Fe whiskers in very low residual fields ($H_I < 1$ mOe), so that $\tau \sim 10^{-3}$ s is within the time window of our superconducting quantum interference device (SQUID) magnetometer. The primary response is accurately modeled by a Gaussian size distribution of localized internal degrees of freedom (localized magnons), virtually identical to the distribution of excitations in glass-forming liquids (*6, 7*). The model provides a physical picture for the mechanism and observed distribution of Landau-Lifshitz damping parameters.

Classical ferromagnetic response mechanisms include domain switching, wall motion, and magnon relaxation (*8, 9*). Domain walls usually move quite rapidly, so that an equilibrium configuration is achieved within 10^{-6} s. Most previous models for the "slow" ($t > 10^{-5}$ s) response in magnetic rocks (*10*), spin glasses (*11, 12*), and ferromagnets (*13, 14*) have considered domain switching (domain inversion by means of activation over an intermediate barrier), where large domains with large barriers relax slowly. The key distinction of our approach is that we consider the response of low-energy, internal degrees of freedom (examples include magnons, phonons, and polaritons) for which the energy-level spacing decreases with increasing domain size. Our model gives better agreement with the observed response from dozens of different materials, including magnetic relaxation in random ferromagnets, spin glasses, and oxide superconductors (*7, 15*) as well as the dielectric response or structural relaxation of liquids, glasses, polymers, and metals (*6, 7, 16*). Here we show that this model accurately describes the primary magnetic response of single-crystal Fe.

Although magnon-like internal degrees of freedom have been shown to dominate the slow relaxation of ferromagnetic EuS (*17*), the observed response was less than 2% of the initial (in-field) magnetization; most of the relaxation occurred within 10^{-5} s. Furthermore, negligible domain switching might have been anticipated because EuS has highly isotropic localized spins with poorly defined static domain structure. In contrast, single-crystal Fe whiskers have well-defined macroscopic domains; hence, switching and wall motion should appear as conspicuous jumps in the net magnetization during relaxation.

We have measured the magnetization of single-crystal Fe whiskers from 10^{-5} to 10^4 s after removing an applied field, H. For $H < 3$ Oe, only smooth relaxation is observed. Small jumps ($< \pm 2\%$) appear when $H > 3$ Oe, but they do not contribute significantly to the otherwise smooth response; essentially, all of the net change in magnetization can be accounted for by localized magnon relaxation over the range 10^{-5} to 10^{-2} s, consistent with the observed distribution and expectedly slow Landau-Lifshitz damping rates.

Single-crystal Fe whiskers are often investigated as an ultrapure form of Fe (*18*). High-quality whiskers have a square cross section with length [(100)-direction] much longer than width. Typical dimensions are 5 mm by 0.1 mm by 0.1 mm. The static magnetic domain configuration consists of aligned regions that orient in diverse directions to minimize the net dipolar energy of the sample. In zero field, a typical Fe whisker may contain four macroscopic domains: one oriented longitudinally up one side of the whisker, another oriented down the other side, and one small closure domain at each end (*19, 20*). In a small magnetic field applied along the axis of the whisker, the domain that is oriented in the direction of H grows at the expense of the oppositely oriented domain (*21, 22*). In

Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287–1504.