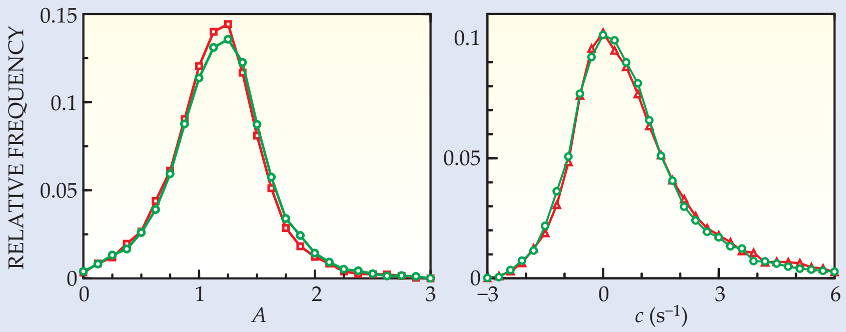

Figure 3. Separately fitting each of the Maryland team's 39 000 reconnection events with the free parameters of equation 2 yields the distributions shown here. The distribution for the dimensionless amplitude parameter *A* peaks near 1 as expected. But its width bespeaks considerable fluctuation from event to event. The width for the correction parameter *c* suggests that much of that fluctuation is due to spectator vortex lines near the reconnection site. The forward (green) and reverse (red) event distributions, as defined in the text, are almost identical, which argues for time-reversal invariance in the dynamics of reconnection. (Adapted from ref. 1.)

before t_0, and "reverse" events based on post-t_0 frames. The separate curves in figure 3 for the two classes show essentially no distinction. This apparent time-reversal symmetry implies that—unlike magnetic reconnections—the reconnection of quantized vortex lines in superfluids generates little or no energy dissipation. The widely used Gross–Pitaevskii theoretical approximation of vortex reconnection in Bose fluids is explicitly time-reversal invariant.

How then can dissipationless reconnection contribute to the relaxation of turbulence in He II? In the two-component superfluid, a quantized vortex line can dissipate energy by friction as it moves through the normal component. But without reconnection, turbulence would produce a tangle of vortex lines so dense that no line could move. Feynman pointed out that reconnection would free up the tangle. In fact, he noted, vortex *loops* created in double-reconnection events could travel with particular ease.

At lower temperatures, other dissipation mechanisms must become important as the normal component dwindles. It's thought that the twang of reconnection excites the vortex lines to helical wave motion whose highest-frequency components would dissipate energy by generating phonons in the superfluid even in the absence of a normal component.

"We haven't tested how dissipation occurs near absolute zero," says Fisher. "But what we have found, by looking for the first time with resolution good enough to see quantized vortices in action, is that superfluid turbulence is a new beast, quite different from the classical turbulence it appears to resemble at lower resolution." In turbulent classical liquids, the distribution of velocities is essentially Gaussian. But for superfluids, the quantum theory predicts a much larger high-velocity population generated by reconnection.

Sure enough, Lathrop and company find that the velocity distribution—for all tracer particles, whether or not they're involved in reconnections—has the $1/v^3$ high-velocity tail implied by the reconnection dynamics.

Bertram Schwarzschild

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Laboratory experiment shows that noise can be lessened for LISA

With a proposed spaceborne interferometer that dwarfs the Moon's orbit, researchers hope to detect gravitational waves. To do that, they need to eliminate the noise from laser frequency fluctuations.

Just as Maxwell's equations imply that an accelerating charge produces electromagnetic radiation, Einstein's theory of general relativity predicts that an accelerating mass produces gravitational radiation. As a gravitational wave propagates at the speed of light, it stretches space in one direction and compresses it in another. But because gravity is so weak, those distortions are minuscule, and extraordinary sensitivity is required to detect them.

The Laser Interferometer Space Antenna (LISA) is a proposed mission to look for gravitational waves through their effect on the distances between three spacecraft. The spacecraft would form, in essence, a Michelson interferometer 5 million kilometers on a side—more than 10 times the distance from Earth to the Moon. Researchers hope to be able to measure oscillations as small as 10 picometers in the interferometer's arm lengths.

Many technical challenges stand in LISA's way. One of the biggest has involved laser phase noise: Even with the laser frequencies stabilized as much as possible, they still exhibit fluctuations that are a billion times larger than the signal. In 1999 John Armstrong, Frank Estabrook, and Massimo Tinto of NASA's Jet Propulsion Laboratory (JPL) presented the theory for a method, called time-delay interferometry (TDI), of eliminating that noise through signal processing.[1] Now, a team of JPL experimentalists led by William Klipstein has shown in a laboratory demonstration that TDI can indeed reduce LISA's noise to the necessary extent.[2]

LISA and LIGO

Indirect evidence for gravitational waves is strong. Pulsars orbiting companion stars lose energy at exactly the rate predicted by general relativity. Researchers looking to detect gravitational radiation are less interested in proving the waves' existence than in the information they can provide: about merging black holes, core-collapse supernovae, galaxy formation—and the first 380 000 years after the Big Bang, a period when the universe was opaque and from which no electromagnetic information survives.

Different sources produce gravitational radiation of different frequencies. Ground-based interferometers, such as the Laser Interferometer Gravitational-Wave Observatory (LIGO), can be sensitive to frequencies from tens to thousands of hertz. (See the article by Barry Barish and Rainer Weiss in PHYSICS TODAY, October 1999, page 44.) At lower frequencies, LIGO is limited by seismic noise and by its relatively short (4-km) arms. Free of those limitations, LISA could detect frequencies from hertz down to millihertz.

LIGO doesn't have a problem with laser phase noise because, as is typical for a Michelson interferometer, its arms are of equal length. The light returning from one arm contains exactly the same phase fluctuations as the light returning from the other, since it was produced by the same laser at the same time, so the fluctuations cancel. For LISA to benefit from the same level of noise cancellation, its arms would have to differ by no more than 3 m. But with each spacecraft in its own orbit about the Sun, its arms will naturally vary by 75 000 km. So the TDI plan is to reduce noise by adding and subtracting signals recorded at different times.

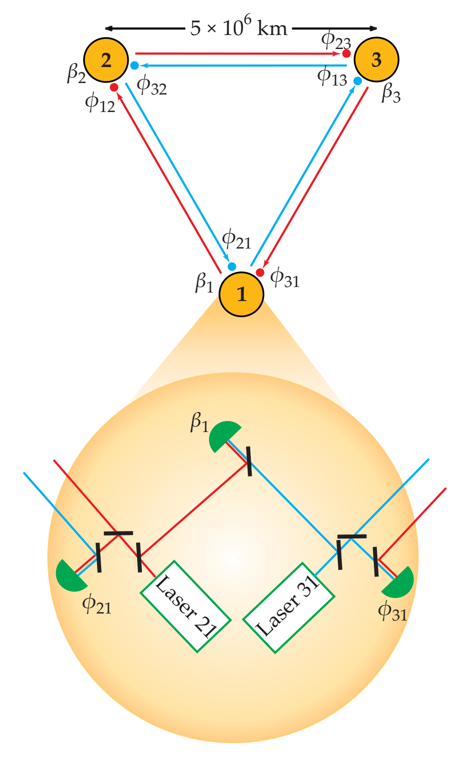

Figure 1. LISA laser links. Three spacecraft form a triangle 5 million km on a side. Laser beams (red and blue) pass in each direction between each pair of spacecraft. (Adapted from ref. 2.) Three phase measurements (green semicircles) are recorded as a function of time on each spacecraft: one between the spacecraft's two outgoing lasers ($\beta_1(t)$) and two between pairs of incoming and outgoing lasers ($\phi_{21}(t)$ and $\phi_{31}(t)$). From the nine measured phases, researchers can derive a signal equivalent to that of an equal-arm Michelson interferometer centered on any of the spacecraft.

Arms control

If LISA were an equal-arm Michelson interferometer centered on spacecraft 1, the light returning from spacecraft 2 would be combined with the light returning from spacecraft 3, and the relative phase would be observed as constructive or destructive interference. Under TDI, the light returning from each of two unequal arms is instead combined with a portion of the outgoing beam, and the resulting phases are recorded as $\phi_{21}(t)$ and $\phi_{31}(t)$. If there were no phase noise, $\phi_{21}(t) - \phi_{31}(t)$ would be the Michelson interferometer signal. In the presence of noise, $\phi_{21}(t)$ contains the laser fluctuations produced at time t and time $t - t_{21}$ (where t_{21} is the time light takes to make the roundtrip between spacecraft 1 and 2), and $\phi_{31}(t)$ contains the fluctuations from times t and $t - t_{31}$. To get rid of the noise, one subtracts the phase for each arm offset by the other arm's roundtrip time: $\phi_{21}(t) - \phi_{21}(t - t_{31}) - \phi_{31}(t) + \phi_{31}(t - t_{21})$. Both time-offset phases introduce the noise from time $t - t_{21} - t_{31}$, so those noise contributions cancel, as do all the others.

Actually, the LISA design (shown schematically in figure 1) has separate lasers directed at spacecraft 2 and 3. But with their relative phase measured and recorded (as $\beta_1(t)$), the same information is available as if one laser were used for both arms. And two more lasers are at the far ends of the arms—the spacecraft are so far apart that using mirrors to reflect the light back would leave no measurable intensity at the end of the roundtrip—and their phases relative to the incoming beams are recorded also. With a final pair of lasers making the link between spacecraft 2 and 3, researchers can derive three different TDI Michelson interferometer signals, as well as other useful combinations.

For data recorded on different spacecraft to be combined, each craft must have its own clock, and the clocks must be synchronized. But clocks light enough for spaceflight are not nearly accurate enough for LISA's needs. Instead, the plan is to remove noise due to clock error in a further signal-processing step. Each laser beam is encoded with its local clock's signal, so the interspacecraft phases (ϕ_{12}, ϕ_{21}, and so on) contain information about the relative clock noise, which can then be removed.

Testing TDI

The JPL demonstration was designed as a system-level test of both the TDI technique and the high-precision phase meter the group had developed.[3] In an effort to distill TDI's essential features, the researchers simplified their system in many ways compared with the planned LISA configuration. They used two laboratory benches—each representing a spacecraft—instead of three; two laser beams in each direction passed between the benches. They ignored, for the time being, the complication of the ever-changing Doppler shift between the spacecraft. And they did nothing to simulate light's 17-second travel time between the LISA spacecraft: The only time delay in their time-delay interferometry was a few hundred nanoseconds, mostly due to the electronics. "But," notes the group's Brent Ware, "the mathematics is the same." Separately, Guido Mueller and colleagues at the University of Florida have also developed a laboratory LISA simulator, and they do include the long time delay. They capture each laser beam en route and generate an identical beam 17 s later.[4]

To capture the properties of LISA in a lab environment that lacked picometer-level stability, and to help prevent noise sources from canceling accidentally, the JPL researchers looked at a combination of signals corresponding to a Sagnac interferometer, which measures the phase difference between light beams propagating clockwise and counterclockwise around a loop, not a Michelson interferometer. Figure 2 shows the recorded noise spectra, the fluctuations in phase measurements on the time scales of the waves LISA could detect. The red curve at the top, the raw laser phase noise, shows what they're up against. The black dotted line eight or nine orders of magnitude below shows LISA's required sensitivity.

The black solid curve represents the linear combination of signals designed to cancel all the laser phase fluctuations. The remaining noise is due to clock error, which must be canceled in two steps: one that accounts for the linear offset between the clock signals and a second that corrects for random clock fluctuations. The blue curve shows the first step, and the green curve, just below the LISA requirement, shows the second. The purple curve, mostly obscured by the green one, shows the JPL

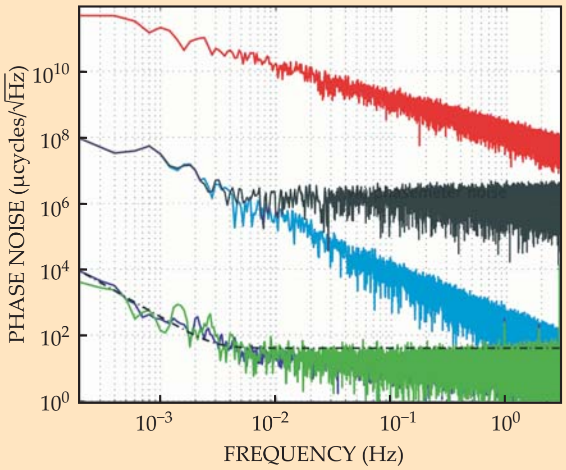

Figure 2. Noise spectral densities measured in a LISA laboratory test. Shown are the levels of phase fluctuation in the raw laser signal (red) and in linear combinations of signals designed to cancel first the phase fluctuations (black), then the clock drift (blue), and finally the clock fluctuations (green). The processed signal not only satisfies LISA's sensitivity requirements (black dashed line) but also coincides with the noise limit of the laboratory system (purple curve, mostly obscured). (Adapted from ref. 2.)

system's limitation, the noise measured in a different test run during which the clocks and lasers were all phase-locked. The researchers are working on improving that limit so they can better understand TDI's potential.

There is much more work to do before LISA is ready. And the mission's future depends heavily on the outcome of the National Academy of Sciences' Astronomy and Astrophysics Decadal Survey, a ranking of funding priorities for the next 10 years, expected to be announced later this summer. If LISA ranks highly, the spacecraft could be launched by 2021; if not, the mission could be delayed indefinitely. But, says Ware, work on TDI will pay off eventually. "Whether LISA comes out on top or not, someone will eventually build a gravitational wave detector in space. And it will look like LISA."

Johanna Miller

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Watching a Bose–Einstein condensate crystallize

If the interaction between ultracold atoms and photons in an optical cavity is strong enough, it gives rise to an intriguing quantum phase transition.

In 1954 Robert Dicke predicted a remarkable phenomenon. Imagine a dense cloud of two-level atoms in an excited state that can radiatively decay. Because each atom typically decays independently of its neighbors, the cloud is a collection of incoherent emitters. But, he argued, if the atoms interact coherently, through the same optical field into which they emit their photons, they would spontaneously and collectively radiate coherent and highly polarized light—an effect Dicke named superradiance.[1]

Nearly a half-century later, Bose–Einstein condensates began emerging as a new tool for exploring many-body physics. Thanks to the BEC's long coherence times, its collective motion induced by an optical field can be monitored with exquisite precision. In 1999 Wolfgang Ketterle, David Pritchard, and their MIT colleagues asked whether the motion of the atoms in a BEC can alter their interactions with an optical field. After shining laser light on a cigar-shaped condensate, the group observed dramatic superradiant bursts of scattered photons. In their scheme, a two-photon scattering process replaced what Dicke imagined as radiative decay.[2] (See PHYSICS TODAY, September 1999, page 17.)

The MIT group also observed the organization of atoms into narrow momentum distributions. Photon scattering imparts a recoil momentum to atoms. But because the velocity of light is so much faster than the atomic recoil velocity—about ten orders of magnitude faster—the recoiling atoms in the experiment remained within the BEC long after their emitted photons had left and thus could affect subsequent scattering events. The upshot: Recoiling atoms interfered with condensate atoms at rest to form, in effect, a matter-wave grating that enhanced the directional scattering. Photons flew off in one direction and recoiling blobs of the BEC lumbered off in another.

In that experiment, the superradiance remained limited to transient bursts. By subtly altering Dicke's Hamiltonian, however, theorists realized as early as 1973 that a steady-state superradiant phase was also possible, even at zero temperature. Their analysis of the system's minimum energy found that an interacting collection of atoms and photons could exhibit a second-order phase transition—crossing from a phase whose ground state contains no superradiant photons to one whose ground state does, provided the interaction is strong enough.

Now, by confining a BEC of some 10^5 rubidium atoms in a highly reflective optical cavity and illuminating it with laser light, Tilman Esslinger and colleagues at ETH Zürich have observed the long-predicted phase transition.[3] The role of the cavity, which repeatedly reflects superradiant light through the BEC, is crucial. The cold atoms and photons influence each other through the coherent exchange of momentum à la cavity quantum electrodynamics. BEC atoms interfere to form a dynamic refractive index that diffracts the light waves. And the light waves, in turn, interfere to form an optical lattice that guides the motion of BEC atoms, as shown in figure 1. As University of Auckland theorist Howard Carmichael puts it, "The light fields tell the atoms how to move, and the atoms tell the light fields how to couple to each other."

The phase transition is then manifest as a sudden shift in the BEC's density distribution, which changes from having the character of a homogeneous superfluid to one whose long-range order is characteristic of a self-organized, crystalline state.

Light–atom crystal

The achievement builds on earlier experimental work by MIT's Vladan Vuletić[4] and confirms predictions made