ly bright water masers, line-of-sight magnetic fields have been measured in forming low-mass stars.

Masers from different molecules in the circumstellar shells of red giant and supergiant stars probe different regions of the shells. OH masers are found far out in the shell, whereas water masers are found at intermediate radii and SiO masers within the innermost few stellar radii. The latter are likely to be in the "acceleration zone," where gas and dust are accelerated away from the star by radiation pressure coming from the star. Repeated VLBI observations over the light cycle of such variable stars have allowed astronomers to make "movies" of the motions of the SiO masers. A particularly striking movie (*6*) of the red giant star TX Camelopardalis shows that the maser motion appears to pulsate, in line with what stellar astronomers expect the AGB star's atmosphere itself to do. A detailed look at the movie, however, shows some surprises: The masers also perform nonradial motions, and some maser spots move inward when most other masers in the ring are moving away from the star.

In the past decade, OH masers in supernova remnants have received renewed attention. These masers were first discovered in 1966 but were largely forgotten until recent Very Large Array (VLA) observations stimulated new studies. Very recent VLBI observations of these OH masers, together with modeling studies of their excitation, have shown that they trace transverse shocks as the supernova remnant runs into the adjacent molecular cloud (*7*). The magnetic fields on small (a few hundred astronomical units) scales can be traced in these interaction regions and have been found to be rather strong (~0.001 to 0.002 G, up to 10 times the strength found in the surrounding interstellar medium).

Water masers have also been detected and mapped in the nuclei of active galaxies, which are thought to harbor a black hole in their centers. These intrinsically bright masers are thought to lie in the accretion disk of matter that is rotating around and falling into the black hole. In one galaxy, NGC 4258, mapping the velocities of the masers indicated a nearly perfect Keplerian rotation of the disk (*8*). This observation allowed a highly accurate calculation of the central mass within the disk of 4×10^7 solar masses, strongly suggesting the presence of a black hole. Further analysis, assuming a disk model, yields the distance to the masers based only on simple geometric considerations. Thus, the distance to NGC 4258 has been measured to better than 5%, providing an independent estimate of the distance scale of the universe and therefore of the Hubble constant (the ratio of velocity to distance in the expansion of the universe).

With the construction and routine operation of the VLBA, observations of masers have become easier and more accurate. The resulting improved observations of maser emission, with much better positional accuracies, will allow astronomers to measure distances to many weaker masers and their associated astronomical objects out to more than 10 kiloparsecs from the Sun. Because distance measurements are both fundamental and difficult to make (especially for objects farther than a few parsecs from the Sun), these results will be a dramatic step forward in understanding many aspects of stars and stellar evolution in the Milky Way. In addition, the use of masers to trace the outflow and perhaps accretion and associated magnetic fields during the formation of Sun-like stars will yield important clues to stellar and planetary system formation.

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APPLIED PHYSICS

The Maser at 50

Ronald L. Walsworth

In 1954, Gordon, Zeiger, and Townes (*1*) developed the ammonia maser (see the figure, top), the first device to demonstrate "microwave amplification by stimulated emission of radiation" from atoms or molecules. The maser and its younger optical cousin, the laser, remain prototypical examples of the powerful technologies inspired by quantum mechanics and 20th-century physics. Today, masers are extending the reach of quantum mechanics to revolutionary new methods of computation and communication and are probing theories that seek to unify quantum mechanics with general relativity—the other major part of 20th-century physics.

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Masers produce coherent, monochromatic electromagnetic radiation at a characteristic frequency and wavelength. All share a few general features:

1) A "population inversion"—that is, a larger population in the higher energy of two selected quantum states of an ensemble of atoms, molecules, or ions—is created in the maser medium. Through stimulated emission, the population inversion amplifies electromagnetic fields that are resonant with the transition frequency between the two quantum states.

2) A surrounding electromagnetic resonator is tuned to the maser medium's transition frequency. The resonator typically has low electromagnetic loss at its resonant frequency, and thereby enhances the ability of electromagnetic fields to induce stimulated emission by the maser.

3) Some fraction of the radiated electromagnetic field is released from the resonator to provide the output signal.

4) In many masers, a steady, continuous output is desired. Such "active oscillation" has two requirements: There must be a continuous means of creating a population inversion, and the time for self-induced maser action (the radiation damping time) must be shorter than the decay time for the radiating electromagnetic moment of the maser medium (that is, the decay time for a coherent superposition of the two quantum states).

These conditions are met in a wide variety of systems. Indeed, the definition of a maser has expanded since 1954 to include the entire audio-to-microwave range of the electromagnetic spectrum, corresponding to wavelengths of millimeters to kilometers.

To operate at these long wavelengths, masers usually exploit magnetic dipole transitions (such as hyperfine or Zeeman transitions) in atoms, molecules, and other media. Because magnetic dipoles interact weakly with each other, with electromagnetic fields, and with environmental perturbations, masers typically provide weak but spectrally pure and temporally stable signals. [An important exception to this weak signal behavior is the electron cyclotron maser, which can be used to create very high power signals—up to hundreds of thousands of watts—in the millimeter wavelength regime (*2*).] When placed in a very cold environment, masers can also

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amplify applied resonant signals with very little added noise beyond the small effects of spontaneous emission and remnant thermal (blackbody) radiation.

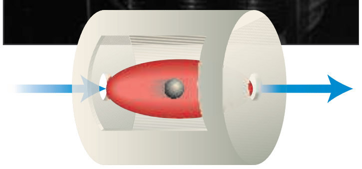
The widely used ruby and hydrogen masers are two devices that illustrate the properties and applications of masers over the past 50 years.

The ruby maser (*8*) uses electron spin (Zeeman) levels of Cr^{3+} ions embedded in ruby crystals. A population inversion is created between two Zeeman levels, typically by applying strong microwave pump fields to saturate the population difference between the lower energy maser level and one or more levels of greater energy than the higher energy maser level. Because electron Zeeman levels are used, the maser transition frequency can be tuned over many tens of gigahertz through application of an appropriate magnetic field. The ruby maser generally operates near liquid helium temperature (4.2 K) and below the active oscillation threshold [see requirement 4) above]. It can provide a tunable, low-noise microwave amplifier with a gain of ~40 dB, very low noise temperature (~4 K), and moderately broad bandwidth (~100 MHz). Ruby masers have been widely used as amplifiers in radio astronomy antennas and related applications, such as the detection of weak signals sent back to Earth by distant space probes.

The hydrogen maser, first demonstrated by Ramsey and colleagues in 1960 (*3*), was later developed by several groups into a high-stability active oscillator of outstanding robustness and reliability. It uses the hyperfine transition of ground state atomic hydrogen (the "21-cm line" of radio astronomy) to produce 1.42-GHz radiation. Atomic beams are used to create a steady flow of population-inverted hydrogen atoms into a storage bulb inside a microwave cavity that is resonant with the desired hyperfine transition. The inside wall of the bulb is coated with Teflon, which interacts weakly with hydrogen atoms. During the time of their stimulated emission, the atoms make thousands of bulb crossings, thereby averaging out inhomogeneities and enabling a narrow spectral width of ~1 Hz in the hyperfine transition.

The hydrogen maser produces a microwave output signal that is highly stable for seconds to hours. Hydrogen masers are large devices (the size of a small refrigerator), but can operate with minimal maintenance for many years in typical room conditions. They serve as "workhorse" high-stability oscillators for ensembles of atomic clocks in standards laboratories, tests of relativity and fundamental physical laws, very long baseline interferometry for radio astronomy, measurements of continental drift, and—together with the ruby maser amplifier—navigation and tracking of spacecraft in NASA's Deep Space Network of radio antennae in Australia, California, and Spain.

In recent decades, a novel form of maser—the Rydberg maser—has been developed and used in careful studies of the quantum mechanics of interacting atoms and photons (*4*). Unlike most masers, the Rydberg maser uses strongly interacting electric dipole transitions between two metastable states (typically separated by tens of gigahertz) in "Rydberg atoms," in which a single electron is in a highly excited electronic quantum state far from the atomic core. A population inversion is created by sending a beam of Rydberg atoms in the higher energy metastable level through a resonant cavity that is made of superconducting metal and maintained at very low temperatures. The combination of a strongly interacting electric dipole transition and a cavity that ensures very low losses enables active maser oscillation with very few atoms in the cavity.



Masers then and now. (Top) Inventors Charles Townes (left) and James Gordon pose with the first maser, which used large ensembles of ammonia molecules. **(Bottom)** The Rydberg maser can sustain active maser oscillation with, on average, 1 or less atoms streaming through the resonant cavity at any given time.

With recent advances in Rydberg maser technology, the average number of atoms in the microwave cavity can be 1 or less while maintaining active maser oscillation (see the figure, bottom). This "one-atom maser" is a powerful tool in the field of cavity quantum electrodynamics—for example, in the preparation of pure-photon-number states (that is, states containing a specific number of photons) (*5*). The one-atom maser is currently being applied to the study of new techniques and protocols for manipulating quantum information, such as controllably creating quantum correlations among chains of atoms. Such "entangled" states might be used in future quantum computers.

In recent years, masers have also been used in sensitive searches for new phenomena suggested by leading theories of quantum gravity, such as string theory and loop quantum gravity. These theories suggest that quantum fields may have "frozen out" soon after the Big Bang and still permeate the universe. These "background" fields can give an orientation and velocity dependence to the properties of matter and light, and as such would constitute a violation of Lorentz symmetry (*6*). Sensitive measurements could reveal a faint echo of quantum gravity through a temporal modulation of basic physical properties—such as the speed of light, the mass difference of particles and their antiparticles, and the Zeeman splitting of atomic spin energy levels—when the orientation and velocity of the laboratory are changed relative to the background quantum fields.

One of the most sensitive searches for such effects has been performed at audio frequencies with colocated noble gas Zeeman masers (*7*). Population inversions on the nuclear spin transitions of ^{3}He and ^{129}Xe atoms are created in a separate chamber by spin-exchange collisions with optically pumped Rb vapor, followed by diffusion of the state-selected ^{3}He and ^{129}Xe atoms into the maser chamber. The use of two colocated species largely eliminates the confounding effects of magnetic fields. Also, noble gases interact very weakly during collisions with walls or other atoms; thus, noble gas masers can have narrow spectral widths of ~10^{-3} Hz. They have been used to probe for sidereal modulations of the ^{3}He and ^{129}Xe Zeeman splitting down to ~5×10^{-8} Hz, with no such effect yet observed. This sensitive measurement sets a limit of less than 10^{-31} GeV on the magnitude of the coupling of the neutron to background quantum fields—about 50 orders of magnitude below the Planck scale (the energy scale of ~10^{19} GeV at which quantum gravity effects are expected to become dominant).

Ongoing efforts to improve the sensitivity of masers and related devices may soon enable an improvement of several more orders of magnitude in tests of Lorentz symmetry. These advances may provide severe constraints for string and other theories of quantum gravity, and may even usher in an era of quantum gravity as a laboratory science.

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