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

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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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