structure be stable for extended reaction times, and will it also have activity for other reactions catalyzed by supported gold nanoparticles? Clearly, these questions will inspire much research from experimentalists and theoreticians alike.

The authors characterize the active gold film as a bilayer. In the strictest sense this may be true, but it is also confusing, because the total number of gold atoms per unit area in this film is 20% less than that in the topmost atomic layer of Au(111). This implies that the nearest-neighbor coordination sphere of the surface gold atoms includes many Ti and O neighbors, and not only gold atoms. Such a scenario may explain why the reactivity of the neutral gold atoms differs from that of bulk gold. Furthermore, it even leaves room for reactants to bond directly to O or Ti atoms, so that their direct participation in the reaction cannot be fully excluded. Determining the crystal structure of the gold film would go a long way toward clarifying many of these issues, and would greatly aid future theoretical studies of the catalytic mechanism. We also look forward to the next step—determining the structure of the gold film in the presence of adsorbed reactants.

References and Notes

1. M. Haruta, *Catal. Today* **36,** 153 (1997).
2. T. Hayashi, K. Tanaka, M. Haruta, *J. Catal.* **178**, 566 (1998).
3. M. Valden, X. Lai, D. W. Goodman, *Science* **281**, 1647 (1998).
4. M. S. Chen, D. W. Goodman, *Science* **306**, 252 (2004**)**.
5. M. C. Wu, J. S. Corneille, C. A. Estrada, J. W. He, D. W. Goodman, *Chem. Phys. Lett.* **182**, 472 (1991).
6. J. Libuda *et al.*, *Surf. Sci.* **318**, 61 (1994).
7. T. Schroeder, J. B. Giorgi, M. Baumer, H. J. Freund, *Phys. Rev. B* **66**, 165422 (2002**)**.
8. J.-D. Grunwaldt, A. Baiker, *J. Phys. Chem. B* **103**, 1002 (1999).
9. M. M. H. Schubert *et al.*, *J. Catal.* **197**, 113 (2001).
10. L. M. Molina, B. Hammer, *Phys. Rev. Lett.* **90**, 206102 (2003).
11. V. Bondzie, S. C. Parker, C. T. Campbell, *Catal. Lett.* **63**, 143 (1999).
12. C. Lemire, R. Meyer, S. Shaikhutdinov, H. J. Freund, *Angew. Chem. Int. Ed.* **43**, 118 (2004).
13. N. Lopez *et al.*, *J. Catal.* **223**, 232 (2004).
14. R. Zanella *et al.*, *J. Catal.* **222**, 357 (2004).
15. G. Mills, M. S. Gordon, H. Metiu, *J. Chem. Phys.* **118**, 4198 (2003).
16. A. Sanchez *et al.*, *J. Phys. Chem. A* **103**, 9573 (1999).
17. J. Guzman, B. C. Gates, *J. Phys. Chem. B* **106**, 7659 (2002).
18. Q. Fu, H. Saltsburg, M. Flytzani-Stephanopoulos, *Science* **301**, 935 (2003).
19. J. A. Rodriguez *et al.*, *J. Am. Chem. Soc.* **124**, 5242 (2002).
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ASTRONOMY

Astronomical Masers

Mark Claussen

Maser emission from molecules such as water, hydroxyl (OH), and silicon monoxide (SiO) is an important tracer of the gas kinematics and magnetic field strength in astrophysically interesting regions. Since their discovery in 1965, these emissions have provided clues about the molecular gas in and around young stellar and protostellar objects, around stars at the end of their life, at the interface of supernova remnants and molecular clouds, and near the black holes at the centers of active galaxies. Because they are bright, they can be observed with the finest angular resolution currently possible in astronomy. They can thus be used to probe much smaller physical scales than with other astronomical methods, and to infer accurate distances to objects within and outside the Milky Way.

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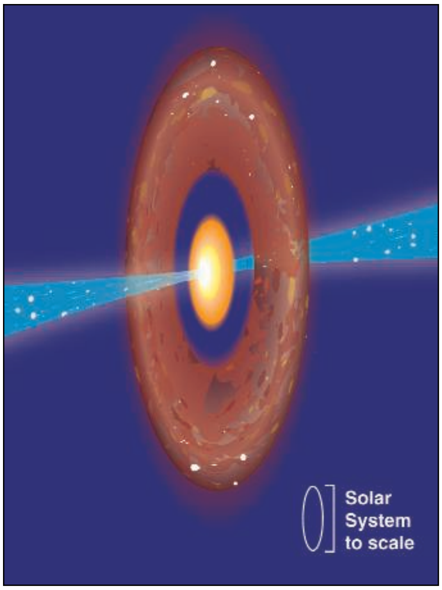
The first interstellar masers were discovered from the ground state of OH (at a wavelength near 18 cm) but were not recognized as such initially (*1*). It was only because laboratory masers had already been invented [see accompanying Perspective by Walsworth (*2*)] that the discoverers could understand the physical mechanism of the maser. Many early observations characterized the emission from OH masers as time-variable, polarized (both linearly and circularly), and having narrow line widths. These characteristics are typical of most astronomical masers.

As radio telescopes became more sensitive and able to look at a broader range of frequencies, and interferometry provided much better angular resolution, more molecular masers were discovered and their sizes were measured. Brightness temperatures (the temperature that they would have if they were emitting as thermal sources) of $>10^9$ K and sizes of <0.001 arc sec (1 arc sec = ~1/2000 of the angular diameter of the Sun as seen from Earth) were found to be typical of these natural masers. Masers have been found in transitions of OH, SiO, water, methanol, ammonia, and other molecules, and also in recombination lines of hydrogen.

The study of masers has gone hand-in-hand with the development of very long baseline interferometry (VLBI), which enables angular resolutions of 0.0001 arc sec at the highest radio frequencies. The Very Long Baseline Array (VLBA), built and operated since 1993 by the National Radio Astronomy Observatory, has provided the lion's share of recent maser observations.

Masers occur in several places in the universe: in the vicinity of newly forming stars and regions of ionized hydrogen (H II regions) (OH, water, SiO, and methanol masers); in the circumstellar shells of stars at the end of their life—that is, red giants and supergiants (OH, water, and SiO masers); in the shocked regions where supernova remnants are expanding into an adjacent molecular cloud (OH masers); and in the nuclei and jets of active galaxies (OH and water masers).

The brightest water masers seen in the direction of forming stars and H II regions in the Milky Way were used in the 1980s to measure the distances of such objects from Earth by purely geometric and kinematic methods (*3*). This and other procedures were used to model the motions of the water maser spots in a star-forming region at the center of the Milky Way, and thus make an independent measurement of the distance to the galactic center. More recently, water masers in low-mass young stellar objects have been used to trace the collimated outflows from these "protostars" at unprecedentedly small physical scales (*4*). Polarization measurements of OH masers near H II regions have allowed an estimate of the magnetic field throughout the spiral arms of the Milky Way (*5*). Water masers can also be used to trace magnetic fields through the Zeeman effect; with sufficient-



Artist's impression of masers in the outflow from a protostar.

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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.

References

1. H. Weaver, D. R. W. Williams, N. H. Dieter, T. W. Lum, *Nature* **208**, 29 (1965).
2. R. L. Walsworth, *Science* **306**, 236 (2004).
3. R. Genzel, M. J. Reid, J. M. Moran, D. Downes, *Astrophys. J.* **244**, 884 (1981).
4. M. J. Claussen, K. B. Marvel, A. Wootten, B. A. Wilking, *Astrophys. J.* **507**, L79 (1998).
5. V. L. Fish, M. J. Reid, A. L. Argon, K. M. Menten, *Astrophys. J.* **596**, 328 (2003).
6. P. J. Diamond, A. J. Kemball, *Astrophys. J.* **599**, 1372 (2003).
7. I. M. Hoffman *et al.*, *Astrophys. J.* **583**, 272 (2003).
8. M. Miyoshi *et al.*, *Nature* **373**, 127 (1995).
9. D. S. Shepherd, M. J. Claussen, S. E. Kurtz, *Science* **292**, 1513 (2001).

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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