

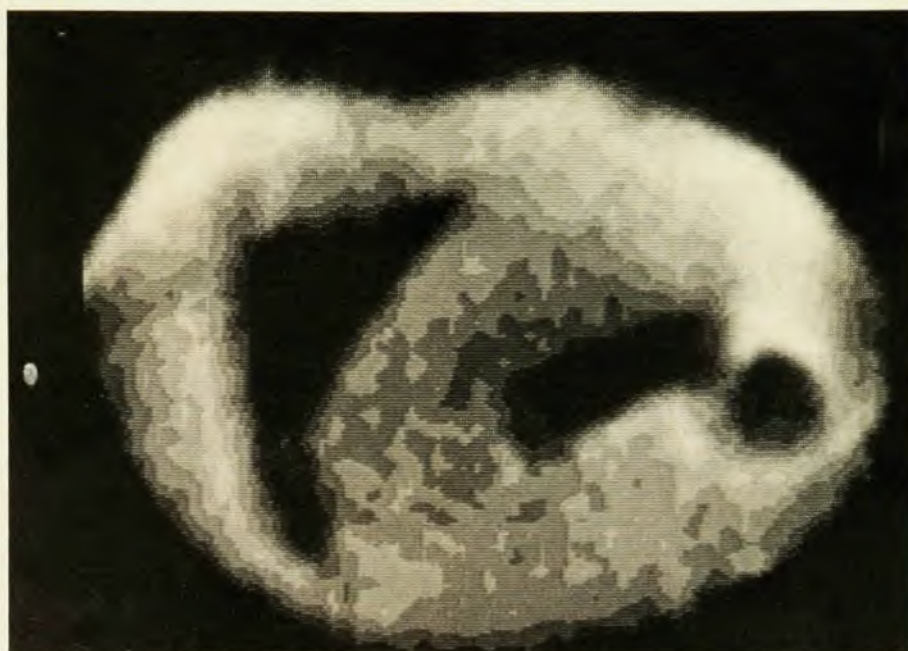
search & discovery

NMR imaging technique provides high resolution

A new tool is being developed for producing two- and three-dimensional images of the distribution of material within an arbitrary object. Christened "zeugmatography" by Paul Lauterbur, one of the leaders in the field, the nuclear-magnetic-resonance technique generally involves applying an inhomogeneous magnetic field to spread out the nmr signal in space. Ultimately, one can then deduce the spatial distribution of material, either by mathematical or analog manipulations.

Spatially controlled nmr techniques may prove useful in a variety of medical applications. For example, such techniques may be an alternative to computerized tomography for three-dimensional images. Or, they may be applied to studying flow in the cardiovascular system.

In 1976 Peter Mansfield and A. A. Maudsley (University of Nottingham) obtained¹ an nmr image of Maudsley's finger. More recently, Waldo Hinshaw, P. A. Bottomley and G. N. Holland (University of Nottingham) produced² a thin-section nmr image of Bottomley's wrist. And Raymond Damadian, M. Goldsmith and L. Minskoff (State University of New York, Brooklyn) have published³ a cross-sectional image through the experimenter's chest.



Nuclear-magnetic-resonance image of a slice of a calf heart 18-mm thick. This image was produced by Paul Lauterbur and his collaborators (State University of New York, Stony Brook) from 65 different field-gradient orientations. The experiment was done at a frequency of 4 MHz.

Nuclear magnetic resonance involves the observation of transitions between nuclear-spin Zeeman levels in sets of nuclei with magnetic-dipole moments. The

separation of energy levels and thus the resonant frequency is proportional to the product of the strength of the nuclear

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Laser heterodyne spectroscopy measures planetary winds

A new technique involving quantum electronics and lasers is being used for high-resolution astronomical observations. The technique—infrared heterodyne spectroscopy—has detected wind patterns on Venus to roughly 5 meters/sec (almost as good as the police do with radar detection of speeders). In addition, the technique has been used to detect such things as nonthermal emission from planets and the distribution of various gases in Earth's atmosphere.

Berkeley-Toronto work. Laser heterodyne spectroscopy for infrared astronomy has been pioneered by Charles Townes and his collaborators at the University of California at Berkeley (PHYSICS TODAY, July 1971, page 17). Just as in radio as-

tronomy, one collects a signal from outer space and mixes it with the sine-wave signal from a local oscillator on the ground, whose frequency is roughly the same. The nonlinear element mixes the two signals, producing the sum and difference frequencies and other side bands, which are then amplified. In radio astronomy, the local oscillator is commonly an electronic device such as a klystron.

For infrared observations, Townes explained, the Berkeley group uses a carbon-dioxide laser as a local oscillator. To be useful as a local oscillator, the laser must have frequency and amplitude stability and a simple beam pattern such as a Gaussian. Mixing is done in a solid-state diode, such as the mercury cadmium

telluride devices made by David Spears (Lincoln Lab). This is followed by an rf filter bank with 40 channels, 5 MHz each. Because the local oscillator has essentially zero frequency width, the time response of the detector determines the bandwidth of the detected radiation. Thus, the spectrometer has the effect of taking the 10-micron (3×10^7 MHz) radiation from the astronomical source and converting it to a difference-frequency range of 100–1500 MHz, retaining the information on intensity as a function of frequency. The spectrometer is capable of very high resolution because the bandwidth of the rf filter elements may be made arbitrarily small. The resolving power of the system $\lambda/\Delta\lambda$ is 10^6 – 10^7 , comparable to the highest

resolving power used in radio astronomy, Townes noted, and high enough to give the structure of any astronomical lines.

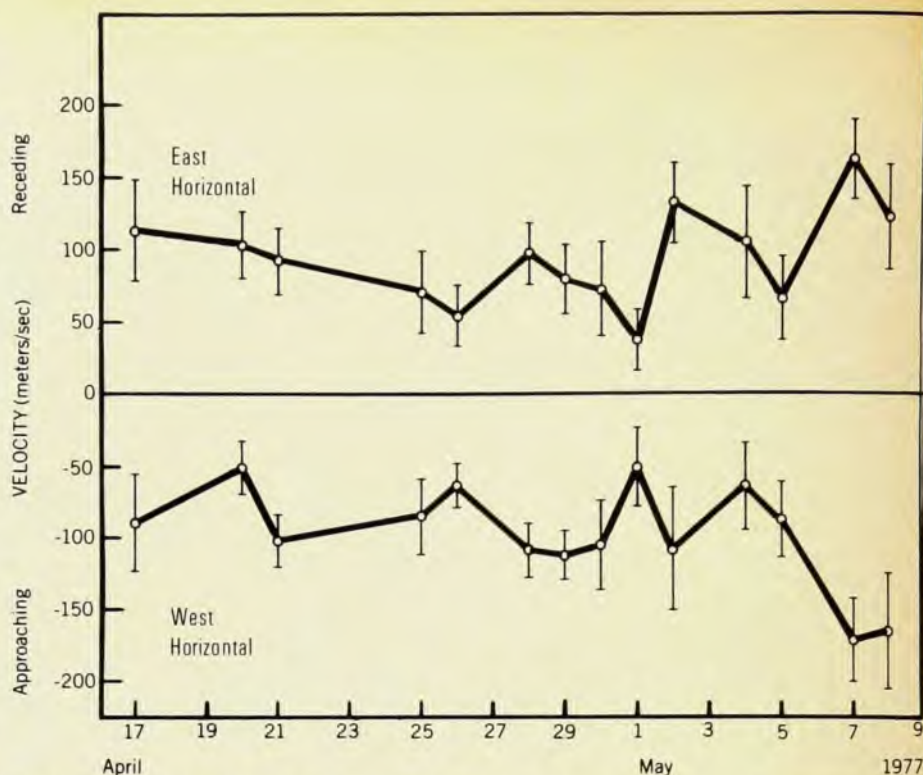
During a recent visit to Berkeley, Townes and A. L. Betz explained to us how they, M. A. Johnson and E. C. Sutton of Berkeley and R. A. McLaren and C. W. McAlary of the University of Toronto are studying the atmospheres of planets. The laser frequency must closely match that of the spectral line in the atmosphere. Michael Mumma and his collaborators at the Goddard Space Flight Center, Greenbelt, Maryland, have done this¹ with a tunable diode laser as local oscillator. But at present, the Berkeley-Toronto group believes that they can get better detection sensitivities and stability from fixed-frequency molecular gas lasers. Fortunately, the atmospheres of Mars and Venus are predominantly carbon dioxide and, the group notes, the most technically suitable local oscillator is the carbon-dioxide laser.

Other advantages to observing the CO₂ bands near 1000 cm⁻¹ are that the Earth's atmosphere is relatively transparent at these frequencies and that the thermal continuum signals from both Mars and Venus are strong enough to allow good absorption-line spectroscopy. At higher frequencies the blackbody radiation drops off rapidly and the fundamental quantum noise associated with heterodyne detection increases, thus limiting the signal-to-noise ratio.

In 1975 the group found² nonthermal emission from the mesospheres of both Mars and Venus. They measured the shapes (Gaussian) of the spectral lines to obtain the kinetic energy of the molecules. On Venus this gave temperatures of 200 K near the subsolar region and 185 K at the terminator, both at altitudes of 115 km (in the mesosphere). The CO₂ radiation was greater than an order of magnitude more intense than expected from these kinetic temperatures. Townes and his collaborators believe this nonthermal emission shows that, in the upper atmospheres of Venus and Mars, there is optical pumping by the Sun. Townes told us this pumping may produce a population inversion in some cases, but "I wouldn't call it marked amplification." There have been speculations that on some planets there may be laser action in the upper atmosphere. If so, new planets might be detectable by their nonthermal emissions. "For the moment, it's just an amusing idea."

In some ways more remarkable, the group has also measured³ wind velocities on Mars and Venus to a statistical accuracy of better than a few meters/sec; however, systematic effects limit the total accuracy to about 6 meters/sec. Because the relative velocities of Earth and the planet are known, one can simply determine the offset caused by the Doppler shift to get the wind velocity.

On Venus, the group resolved about



Stratospheric wind velocities measured at the eastern and western equatorial limbs of Venus by detection of the 11-micron absorption line of C¹³O₂. The velocities indicate an average 90-meter/sec retrograde rotation of the atmosphere at an altitude near 75 km. Error bars show ± 1 standard deviation in the daily observations. Figure from A. L. Betz, Berkeley.

10% of the planet, observing six hours per day, looking at nonthermal emission from C¹²O₂ to study the mesosphere and the weaker lines in absorption of C¹³O₂ to study the stratosphere. They find that in the mesosphere the atmosphere is accelerated symmetrically away from the Sun and flows toward the dark side of the planet. The explanation, the group feels, is just solar heating producing an expansion. The wind speed across the terminator at the equator is 130 m/sec.

In the lower altitudes of the stratosphere, the flow is more puzzling. The pattern is a slowly varying wind of 70–130 m/sec in the retrograde direction (opposite to other planets), but much faster than the 2 m/sec rotation of Venus as a whole. These results extend earlier spectroscopic detection of stratospheric circulation and cloud motion seen from the Mariner 10 spacecraft.

Townes notes that radio astronomers would find planetary wind measurements much more difficult than infrared observations because CO₂ has no radio spectrum and it would be difficult to localize the radio beams. With ir heterodyne spectroscopy, the needed angular and spectral resolution are easily obtained. Radio astronomy has shown a weak carbon-monoxide line on Venus, but Townes does not believe it will prove as useful for wind measurements as the carbon-dioxide lines.

Betz told us that because the meteorology of Venus is relatively simple, it is an ideal laboratory to gain understanding

of Earth's meteorology.

In another application of ir heterodyne detection, Townes and his collaborators are using heterodyne receivers with two 30-inch telescopes separated by 5.5 m to act as a stellar interferometer. They have measured the sizes and radiation intensities of warm dust shells around a number of stars.

At Goddard Space Flight Center, Mumma and his collaborators are also using a carbon-dioxide laser as a local oscillator, a mercury-telluride photo-mixer and a larger filter bank, with 64 channels, 40 with 5-MHz width and 24 with 50-MHz width. In their 1975 observations with a semiconductor diode laser, the group used lead selenide operating at 8.5 microns, tunable about 0.02 microns on either side. By varying the elemental composition, one can change the tuning range. Since then, Mumma said, appropriate diode lasers have not been available commercially. He noted that material improvements enable devices available at present to be tuned over a range of ± 0.5 microns.

The Goddard group has detected thermal emission from the Moon and Mars (with the semiconductor diode laser) and very recently, using a CO₂ local oscillator, they have seen nonthermal carbon-dioxide lines on Mars and Venus. Mumma told us some of the Venus data show evidence of structure within the nonthermal peak, unlike the Berkeley result. However, he says the region studied by Goddard is different than that

of the Berkeley-Toronto experimenters.

In the laboratory, the Goddard group made precise measurements (1 part in 10^7) of ammonia lines near 10 microns. Using those positions, they searched for the ammonia aurora on Jupiter, expected to be present because of the planet's strong magnetic field and trapped charged-particle belts. The group believes⁴ they observed the aurora on four or five different occasions, some of which were associated with a solar storm five days earlier (the correct transit time for protons to travel from the Sun to Jupiter).

The group has also used their heterodyne spectrometer to study molecules in Earth's atmosphere—ozone, carbon dioxide and Freon-12. They have been able to determine density as a function of altitude along one line-of-sight. NASA plans to use a similar instrument on the Space Shuttle; with such a device one could make measurements of global distributions.

Townes and Mumma both believe that infrared heterodyne spectroscopy will prove useful outside the Solar system. One can look for narrow atomic and molecular spectral lines in stellar atmospheres and molecular clouds. However, Townes concedes that some people are dubious about such observations because there may not be enough narrow lines to make this approach widely profitable.

—GBL

References

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NMR imaging technique

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magnetic moment and the strength of the applied magnetic field at the nucleus.

A variety of approaches to nmr imaging are being pursued. The term "zeugmatography" is used to describe those techniques that take advantage of the fact that because the applied magnetic field is a function of the spatial coordinates, the resonant frequency is also a function of the spatial coordinates. Thus, by applying an inhomogeneous magnetic field, one obtains a frequency distribution that is also a spatial distribution. The technique allows one to control arbitrarily the spatial resolution of detection without

being limited by such factors as the dimensions of the rf coils. It is this control over resolution that makes zeugmatography especially appealing for imaging.

In 1950 Erwin Hahn, who was studying spin echoes, demonstrated that one could measure diffusion rates of atoms or molecules in liquids by applying a known field gradient. This work was extended by Herman Carr (then Edward Purcell's student at Harvard). Meanwhile in 1951 R. Gabillard in Paris showed that by applying a magnetic-field gradient across an object, the nmr spectrum gave a profile of the density of nuclei in the direction of the gradient (a one-dimensional projection).

Over the years, other groups have taken advantage of inhomogeneous magnetic fields for specialized applications. For example, in 1972 Douglas Osheroff, Wilfred Gully, Robert Richardson and David Lee at Cornell, in their studies identifying the new superfluid phases of liquid He³, used a magnetic-field gradient to distinguish between matter at the top and bottom of the sample.

In the 1950's, several groups used nmr to measure the amount of a substance external to the coil. Their interest was in oil-well logging. In this approach, the nmr device is introduced into a bore hole and a dc current is applied in the coil, causing protons in the nearby oil to polarize. When the magnet is switched off, the magnetized protons precess in Earth's magnetic field.

In 1971 Damadian showed⁴ that the water proton spin-lattice relaxation time was longer in tissue samples from certain malignant tumors than in normal tissue. At that time he proposed that nmr might be useful in studying a living human being. The following year he filed a patent (granted in 1974) that described positioning two rf coils (one to drive and one to pick up signals) to scan selected portions of the body. The position would be defined by the intersection of the axes of the two coils.

Zeugmatography. Inspired by the observation of differing relaxation times, Lauterbur, who is at the State University of New York at Stony Brook, thought that if one could obtain complete spatial information from nmr in an inhomogeneous sample, one would have a new diagnostic tool, particularly for cancer. In 1973 he published⁴ such a proposal.

Also in 1973 Mansfield and Peter Grannell (Nottingham) had independently proposed⁵ that one could use magnetic-field gradients in an nmr experiment to analyze the structure of periodic objects such as crystals and certain biological systems.

In the simplest imaging approach, one can apply a linear magnetic-field gradient to obtain a one-dimensional image. One can repeat the experiment with many differently oriented one-dimensional gradients. Then, using a computer to do

a mathematical image reconstruction very similar to that used in x-ray computer tomography (PHYSICS TODAY, December 1977, page 32), one can obtain a two-dimensional picture, resembling a conventional diagnostic x-ray image. Lauterbur and his collaborators have taken many of these two-dimensional pictures, done additional mathematical reconstructions, and obtained a three-dimensional array of intensities.

In 1974 Hinshaw and his collaborators at the University of Nottingham developed⁶ the so-called "sensitive-point" technique, in which three orthogonal magnetic-field gradients are modulated simultaneously. By modulating one magnetic-field gradient, one can produce a null plane (no alternating field present). A second modulated gradient is added perpendicular to the first one, producing a null plane perpendicular to the first. So one obtains a null line. Then a third gradient is added, perpendicular to the first two, and the intersection of the three null planes is a null point. The alternating gradients modulate the signal everywhere except in the null point. By varying the current in the gradient coils and by observing only the static signal, Hinshaw's group could move the sensitive point around in any pattern they chose, successively detecting the signal from different points within the object.

Recently Hinshaw, Bottomley and Holland extended this sensitive-point, analog, technique, to a multiple sensitive-point technique that employs a computer. The group applied two uniform orthogonal field gradients with differing time dependence to the wrist. The null planes of the two gradients intersect, producing a line where the field is static. This line is the region of interest, to which the spectrometer is sensitive. A third, static gradient is applied along this sensitive line. The group takes the Fourier transform of the resulting nmr signal to obtain the distribution of the sample along the line. The distribution is displayed as beam intensity along a corresponding line on an oscilloscope. Scanning the sensitive line slowly through the sample while simultaneously moving the display line yields a two-dimensional image on the oscilloscope screen.

Fourier-transform zeugmatography is being done by Richard Ernst, A. Kumar and D. Welti at ETH in Zurich.⁷ In this approach, one uses pulsed nmr to generate free-induction decay, a transient response to an rf pulse. One applies a linear magnetic-field gradient in the x direction for a short time and a linear magnetic-field gradient in the y direction for a different time. Then the two signals are Fourier transformed. The experiment is then repeated, but the first gradient is applied for a slightly different time interval. And so on. Then one does a Fourier transform perpendicular to the first, in which the second time variable is