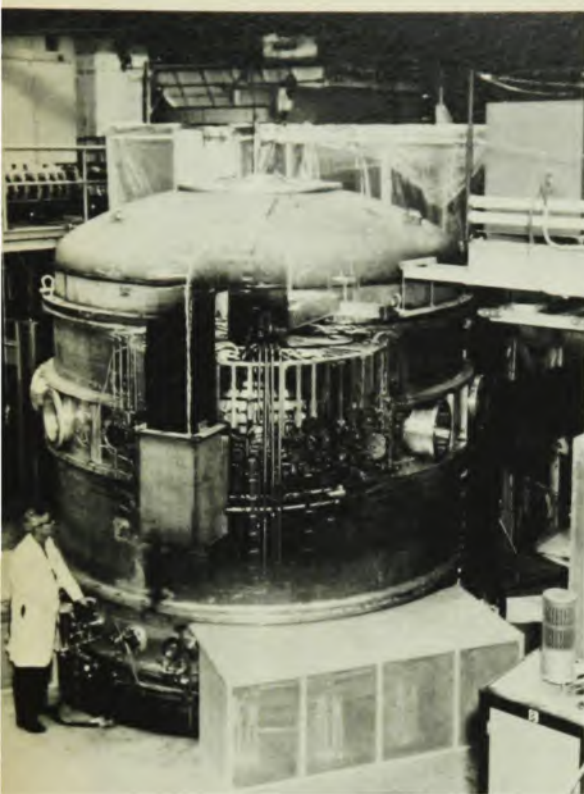




Ormak, the ohmically heated toroidal confinement device at Oak Ridge National Laboratory, is seen in this double exposure.

path of plasma ions would be about 30 or 40 times the torus circumference. In this experiment the ion collision frequency was low enough that diffusive losses from thermal conductivity were relatively unimportant and other loss mechanisms, such as charge exchange, could be studied. The Ormak geometry—a fat rather than a thin doughnut—maximized the path length of the ions with respect to the size of the so-called “banana” orbits. These banana-shaped orbits might, according to theoretical calculations for the collisionless regime, lead to trapped-particle instabilities, but no evidence of enhanced losses due to these instabilities was observed. As Herman Postma, head of the ORNL thermonuclear division, and George Kelley, director of the Ormak project, explained to us, they are still far from the Lawson criterion range, which is the $n\tau$ range for an operating reactor, but with some modifications now underway they feel able to confront some of the physics that would be important in the reactor regime.

Injection heating. The next step at Ormak is to use neutral-beam injection heating to raise the temperatures still higher—to about 1 keV—and penetrate further into the collisionless regime. Beams of very energetic neutral particles (hydrogen atoms at 12.5 keV and 25 keV) are added from the outside, and these particles transfer their energy to the plasma particles, raising the bulk temperature beyond what ohmic heating can do. Recent results at the Princeton Adiabatic Toroidal Com-

pressor showed compressive heating to be a useful booster for ohmic heating (see *PHYSICS TODAY*, January, page 17), and the Princeton group now is preparing to combine the compression and injection techniques.

Ormak is now in a shutdown period, so that the injection heaters can be added, and Postma tells us that the project should be at the data-taking

stage again by the end of the summer. He points out that injection heating will also provide a simulation of the energetic alpha particles ($4\frac{1}{2}$ MeV) produced in a self-sustaining reactor—the particles that must heat the fusion plasma by transferring their energy to it. The next set of experiments should give some answers on how well this transfer takes place. —MSR

Copernicus hydrogen data confirm theory

The Copernicus Orbiting Astronomical Observatory has found that in some stellar clouds much of the hydrogen is in the molecular state and that in others essentially none of the hydrogen is molecular. Such “all-or-nothing” behavior had been predicted by David Hollenbach, Michael Werner and Edwin Salpeter of Cornell University in a detailed calculation¹ published in 1971. The Copernicus results were reported by a Princeton group² (Lyman Spitzer, J. F. Drake, E. B. Jenkins, Donald C. Morton, John B. Rogerson and Donald G. York) in one of five papers on OAO results appearing in the 1 May issue of *Astrophysical Journal Letters*.

Theory. Usually it is atomic hydrogen that is seen in an astronomical situation because its lines are visible from the ground, either in visible light or in radio waves at 21-cm wavelength. However, several people had discussed the possibility of molecular hydrogen, including H. C. van de Hulst (Leiden Observatory), Thomas Gold (Cornell), and George Field, W. B. Somerville and Kurt Dressler (then at Princeton).

In 1967 Theodore Stecher and D. A. Williams (Goddard Space Flight Center) verified theoretically a mechanism (suggested by Philip Solomon) that destroys molecular hydrogen. Unlike the usual kind of photodissociation, in which any photon with energy greater than a certain threshold will break the molecule apart, in the new process the molecules could be disrupted only by the absorption of light in the Lyman band—the molecule would be excited to an excited level and then a certain percentage would drop down to the continuum in the vibrational level. Stecher and Williams estimated that about 10% of the line absorption would produce dissociation in this way. They pointed out that because of this dissociation the ratio of molecular to atomic hydrogen should be very small—of the order of 10^{-7} .

In their paper two years ago Hollenbach, Werner and Salpeter made a detailed calculation, asking what would happen in interstellar clouds of different thicknesses. If a cloud is not very

thick then photons with the Stecher-Williams mechanism will break up the hydrogen molecules so efficiently that only a very insignificant part of the hydrogen in such a cloud would be molecular.

However, because it is only line radiation that breaks up the molecules, some self-shielding occurs. If the cloud is thick enough, then it is the hydrogen itself that filters out these photons. The ultraviolet radiation from the star would be absorbed in the dense cloud on the outer edges, and in the center of the dense cloud there would be no ultraviolet radiation. Then the cloud would have almost all molecular hydrogen. Salpeter describes the two possibilities as “all or nothing.”

To form the molecular hydrogen, the Cornell theorists argued that two hydrogen atoms would separately hit a dust grain, wander around the surface, stick onto impurity states, meet each other and finally form a molecule. The Cornell group then computed in detail the transfer of radiation in the cloud and found the percentage of atomic and molecular hydrogen as a function of distance in the cloud. They found that for typical densities, the switch over from molecular to atomic hydrogen would be roughly where the optical depth in visible light was about half a magnitude. Salpeter told us that very qualitatively Copernicus results agree with this prediction.

Observations. In 1970 George Carruthers of the Naval Research Laboratory did a rocket measurement³ of some ultraviolet lines in two stars. There were indications of the all-or-nothing effect, one star (Xi Persei) having about 40% of the interstellar hydrogen in molecular form and the other apparently having much less or none. Andrew M. Smith (Goddard Space Flight Center) recently also found this all-or-nothing effect.

The Copernicus experiment uses an ultraviolet spectrometer to analyze the light from bright stars, down to fifth or sixth magnitude.

Reddened stars have a color excess because they are behind an obscuring cloud. This color excess is proportion-

al to the amount of obscuring material in the form of solid particles between us and the star. To quantitatively determine the color excess, the star's brightness is measured in blue light, then again in yellow light, then the ratio is taken and it is compared with what it would be for an unreddened star of the same spectral type. If the blue light is diminished with respect to the yellow, it is due to the selective extinction by small solid particles that absorb more in the blue than in the yellow.

The Princeton group observed 23 stars. Eight of them were unreddened and had an upper limit to the ratio of molecular to atomic hydrogen of 10^{-7} , in agreement with theory. The remaining 15 had different reddenings. One of them is relatively unreddened but still shows a lot of molecular hydrogen. Two of them are somewhat reddened and show only a small amount of molecular hydrogen. If a color excess of 0.10 is taken as a boundary line for color excess, then there are 11 such stars, and they show that the fraction of hydrogen atoms bound in molecular form ranges from 0.08 to 0.67. Salpeter and his collaborators had predicted that more than 10% would be in molecular form, but their calculation was for a spherical cloud. As Spitzer points out, since the ratio of molecular hydrogen is less than 10^{-7} in unreddened stars, over the large dynamic range involved the dif-

ference between 10% and 67% does not appear to be significant. In a general way the observations do agree with theory.

One well known astrophysicist commenting on the molecular-hydrogen results said that problems associated with clouds and the interstellar medium are generally very complicated and difficult. In this case the theory succeeded in predicting an effect over many orders of magnitude. "That's just spectacular," he concluded. —GBL

References

1. D. Hollenbach, M. Werner, E. Salpeter, *Ap. J.* **163**, 165 (1971).
2. L. Spitzer, J. F. Drake, E. B. Jenkins, D. C. Morton, J. B. Rogerson, D. G. York, *Ap. J. Lett.*, 1 May 1973.
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Tunable infrared sources

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A third wave, ν_P , is provided by the second dye laser. The waves ν_L , ν_S and ν_P beat together to create a polarization at

$$\nu_R = E(5s)h - \nu_P = \nu_L - \nu_S - \nu_P$$

This polarization can radiate, thus providing a tunable infrared output, because the frequency of the second laser is tunable.

As originally reported,² with the use of one vapor (potassium) alone, tunable infrared output was limited to the range about 2-4 microns. This range was determined by the fact that the first dye laser had to be simultaneously tuned to generate high-intensity Raman light and yet satisfy the phase-matching condition for the four-wave mixing process. However, by the addition of a second non-resonant alkali-metal vapor (sodium) to provide linear dispersion, the phase-matching condition can always be satisfied with the first dye laser tuned for maximum Raman-Stokes generation. In this way, by "biasing" the vapor for long-wavelength output, the IBM group generated¹ coherent infrared over the range 2-24 microns.

The two-laser method extends the tuning range of the dye laser, which was previously tunable only from the near-ultraviolet, across the visible spectrum and into the near-infrared to about 1.2 microns.

The technique produces peak powers between 0.1 and 100 milliwatts, using a 100-kW nitrogen laser pump. The infrared output is proportional to the cube of the pump power; thus a 1-MW nitrogen laser is expected to increase the infrared output by 1000.

In a related experiment, Sorokin, Wynne and Lankard have also generated laser infrared at a number of discrete wavelengths in the range 12-220 microns, forming a "picket-fence" spec-

trum. This is done by tuning the second harmonic of one dye laser to various resonance lines in potassium.

The IBM group told us that among the advantages of their scheme are the continuously tunable nature of the output (that is, it does not display mode hopping) and an absence of the need for cryogenic temperatures.

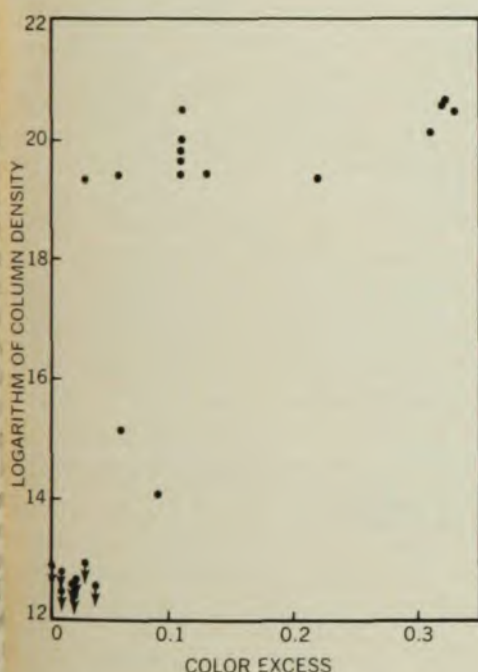
At Bell Labs Kumar Patel and his collaborators have been using two carbon-dioxide lasers to obtain step-tunable far-infrared radiation, work first discussed by them³ in 1969. Now T. J. Bridges and Van Tran Nguyen of Bell reported at the March meeting of the American Physical Society that they have used one carbon-dioxide laser to pump a spin-flip Raman laser, producing a source that is tunable from 80 to 120 microns.

In a spin-flip Raman laser, a magnetic field is applied to an indium-antimonide sample. Raman scattering occurs when the conduction electrons in the crystal flip their spins in the magnetic field, B . The frequency ω_S of the shifted light varies as $\omega_S = \omega_0 - g\mu_B B$; ω_0 is the pump frequency, μ_B is the Bohr magneton, and g is the effective gyromagnetic ratio of the electrons in indium antimonide.

When the carbon-dioxide laser pumps the spin-flip Raman laser, two frequencies come out— ω_0 and $\omega_0 - g\mu_B B$. The radiation enters a second indium-antimonide crystal and difference-frequency mixing occurs, resulting in an output of frequency $g\mu_B B$. The output is tunable because the magnetic field can be varied.

The Bell experimenters have produced output powers of about 1 microwatt with a pulse repetition frequency of about 400 times per second, an average power of 10^{-8} - 10^{-9} watts. Patel notes that this power is more than sufficient to do any kind of spectroscopy desired. The group has measured the absorption of carbon monoxide with a signal-to-noise ratio of about 10 000. There is not enough power to do further nonlinear optics, however. To do that they will need to increase the input power, since in a difference-frequency mixing experiment, the output is proportional to the product of the two input powers.

In the spectroscopic measurements the Bell group's narrowest lines are about 0.1 cm^{-1} . The line width arises because the spin-flip Raman laser is not continuously tunable; it has its own modes, which are separated by about 0.1 cm^{-1} . Patel notes that this is very close frequency spacing, at least compared to doing difference-frequency mixing between two carbon-dioxide lasers. In the present spin-flip Raman laser the crystal faces are parallel so that light bounces back and fourth, making the crystal act like the modes of a cavity. On the other hand, tilting



Copernicus results for molecular hydrogen amount in stellar clouds between Earth and 23 different stars. Column density is number of molecules in a column, 1 cm^2 in cross section, extending from Earth to the star; the color excess measures the reddening of a stellar spectrum produced by small solid particles. Points shown with downward arrows represent upper limits. Note the all-or-nothing effect.