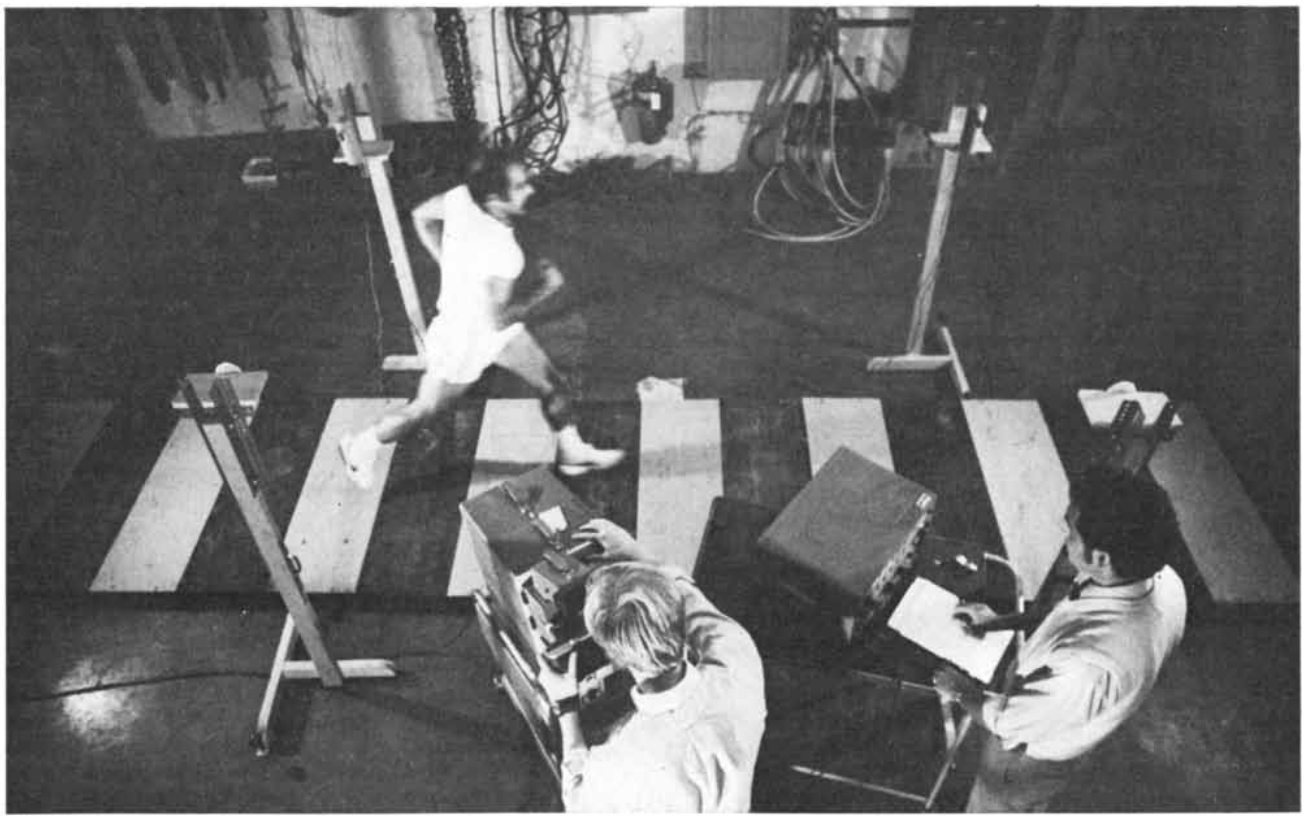
our purposes the most useful way to measure running speed is as the ratio of step length (the distance the body moves forward while one foot is on the ground) to ground-contact time (the time the foot is on the ground). On a tuned track the ground-contact time should be minimized and the step length should be maximized. In the model it is primarily the runner's mass and the motion of the damped spring that determine the body motion during the ground-contact phase and therefore the ground-contact time; it is the motion of the rack-and-pinion element that determines the leg and hip positions at the beginning and end of the ground-contact phase and therefore the step length.

Consider first the relation of track stiffness to ground-contact time. To derive an expression for ground-contact time as a function of track stiffness it is necessary to assign to a runner a spring stiffness and also to determine the extent to which the combined effects of the force-velocity relation and the velocity feedback from the reflexes act to damp his spring. We observed that once a runner's muscles have guided his foot into contact with the ground their most important role is to contract as forcefully and as soon as they can in order to reverse the downward velocity of the body. For this reason we chose to make the somewhat arbitrary assumption that the rack and pinion cannot be disturbed by external forces while the foot is on the ground, so that the ground-contact time on a hard surface depends entirely on the runner's mass and the properties of the damped spring. Hence the numerical values denoting the runner's spring stiffness and damping can be derived from the measurement of his ground-contact time when he is running on a hard surface. (The matter is complicated by the fact that a runner's spring stiffness is affected by his effort. Muscle strength varies greatly among runners, and the stronger a runner is, the more muscle fibers he can recruit in parallel and the stiffer his spring is. For this reason we chose to determine a runner's spring stiffness by measuring his ground-contact time as he was running at top speed on a hard surface.)

Once a runner's stiffness and damping constants have been determined it is a straightforward matter to calculate how his ground-contact time is changed on tracks of various stiffnesses. This result was the most important in predicting the effect of track stiffness on running speed. It can be assumed the runner is tuned to the track so that he rebounds from it in half a period of the lowest natural mode of vibration. As intuition suggests, the calculations show that the ground-contact time on soft surfaces is long. If there were no damping element in the spring of human muscle, the ground-contact time would decrease continuously from that value as track compliance decreases, reaching a minimum at the compliance of infinitely hard surfaces. In that case a running surface such as concrete would be the fastest. Our findings show, however, that the ground-contact time does not decrease over the entire range of compliances. Since the runner is a damped system, his ground-contact time reaches a minimum at an intermediate compliance; at a track stiffness between two and four times greater than the runner's the ground-contact time is shorter than it is on harder surfaces. Therefore on tracks of precisely the right stiffness enhanced speeds should be possible.

To check these results we built several test tracks, ranging from wood tracks with an adjustable compliance to pillows or large foam-rubber blocks laid end to end. Test subjects were not given any information concerning our expectations. They were simply instructed to run at top speed, first on an experimental track and then on the concrete



MODEL RESULTS WERE TESTED with runners on tracks of various degrees of stiffness. In the experimental setup shown here a force platform under one of the panels of the track (not visible) records the beginning and end of a ground-contact phase. The results are plotted on the oscilloscope shown at the bottom of the photograph. Running speed is recorded with the electronic timer at the lower right and the two pairs of timing lights arranged on each side of the track. (The lights are placed at the level of the runner's neck to avoid the triggering of false timing readings by the runner's arms and legs.) The running trials were also recorded on high-speed motion-picture film.

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RUNNING FILMS show that whether a runner is on a fairly stiff wood track (*top*) or on a soft pillow track (*bottom*) the trajectory of his head is nearly level. Therefore for the purposes of the model it can be assumed that the hip follows a level path no matter what surface runner is on. Assumption simplifies calculation of effect of track stiffness on the step length (*see bottom illustration on opposite page*).

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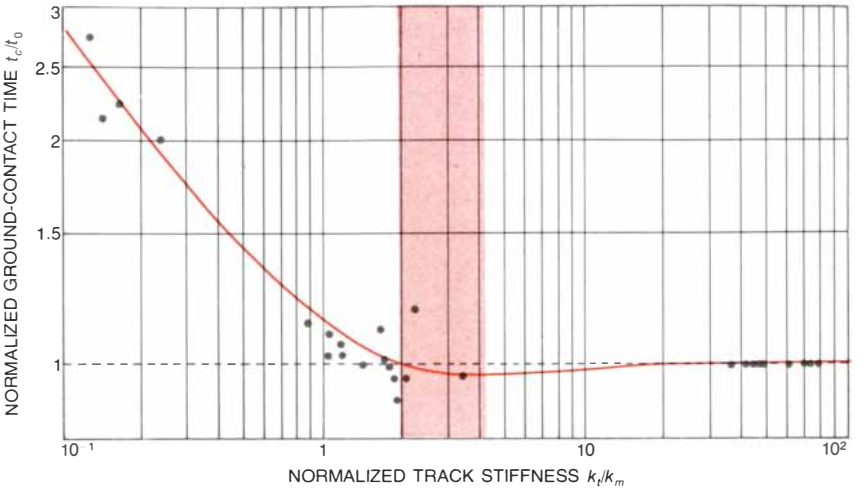
floor beside it. The trials were recorded with motion-picture cameras in order to measure the ground-contact time. Photoelectric timers and a precision force platform were also used. On all the tracks the measurements agreed well with the model predictions.

Running speed is not entirely determined by ground-contact time, however; step length is also an important factor. Remember that step length is the distance traveled while the foot is on the ground, as opposed to the distance between footprints, which is stride length. We noticed that as our subjects ran on the more compliant experimental tracks, such as the one consisting of foam-rubber blocks, their step length was greater. The explanation of this phenomenon has to do with the position of the contact leg at the beginning and the end of the contact phase. At those points the leg is fully extended, and it can be assumed there are no loads acting on the spring, that is, the geometry of the leg as it strikes the ground depends solely on the rack-and-pinion element.

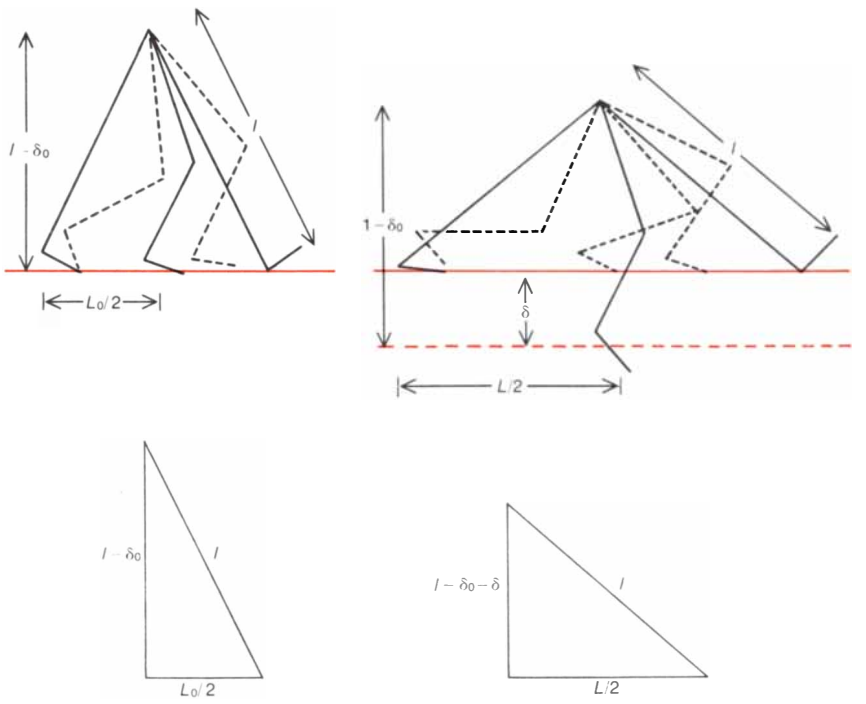
For our investigations of the rack-and-pinion motion we made another assumption based on a feature we observed in the running films. No matter how hard or soft the running surface was, the trajectory of each runner's head was nearly level, as if his postural controllers were trying to give the acceleration-sensing mechanism of the inner ear a smooth ride. In any case it is certain that at the frequency in question, with the modest value of the acceleration due to gravity and the short time between footfalls, the vertical motion of the body's center of mass cannot be great. Hence we chose to assume that the hip follows a level path whether the runner is on a hard surface or a soft one.

The step length on a track of arbitrary compliance can be calculated as follows. In each running step one of the runner's legs makes contact with the ground as the other swings over the running surface. As the swing leg moves forward it stays above the undeflected surface of the track, whether the track is hard or soft. On a hard track the contact leg also stays above the surface. On a soft track, however, the contact leg sinks below the surface. Therefore it is necessary to visualize the runner moving across a hypothetical surface a distance δ below the undeflected one, where δ is the average track deflection over a complete stride cycle. (The stride cycle includes not only the ground-contact phase but also the aerial phase; if the runner were standing motionless on the compliant track, he would be standing in a well of depth δ.)

At the beginning (and end) of the contact phase the runner's contact leg is fully extended, and we shall call the full hip-to-heel length l. At mid-stance,



GROUND-CONTACT TIME can be derived from the model as a function of track stiffness. In this graph of the function, normalized, or dimensionless, values of each parameter have been used so that theoretical results (*curve*) can be compared with experimental findings for many runners (*black dots*). Ground-contact time has been normalized by dividing the time on a compliant surface t_c by the time on a hard surface t_0; track stiffness has been normalized by dividing the track stiffness k_t by the runner's stiffness k_m. Because of the damping of human muscle ground-contact time does not decrease continuously as track stiffness increases but reaches minimum at stiffnesses between two and four times that of average athelete (*color*).



STEP LENGTH IS LONGER on a compliant surface (*right*) than on a hard one (*left*) because the bending angle of the hip joint is greater, as is shown by these schematic representations of a runner on the two surfaces. At the beginning and end of either running step the contact leg (*solid black line*) is fully extended, with length l. After heel contact (*leg position farthest to the right*) the contact leg moves back (to the left) as the swing leg moves forward. At mid-stance, when the body has traveled a distance of half a step length, the contact leg is flexed, that is, shortened by a distance of δ_0, which is taken to be independent of the track compliance. Hence on a hard surface, which has step length L_0, the distance from the hip to the track surface is $l - \delta_0$. On a compliant surface, however, the flexed contact leg sinks below the undeflected track surface (*solid color line*). It is as if the runner were moving across a hypothetical surface (*broken color line*) a distance δ below the undeflected surface, where δ depends on the compliance of the track and the mass of the runner. Therefore the distance from the hip to the undeflected surface on a compliant track is $l - \delta_0 - \delta$. The right triangles below each figure in the illustration show how these factors result in a greater step length L on a compliant surface. Since the distance δ is equal to the runner's weight divided by the track stiffness, and since L_0 and l can be measured directly, the step length on a track of arbitrary stiffness can be calculated by applying Pythagorean theorem to the two triangles (*see illustration on page 162*).

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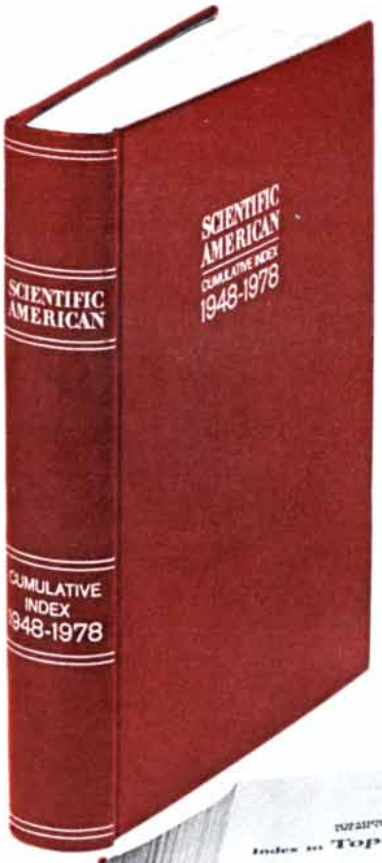
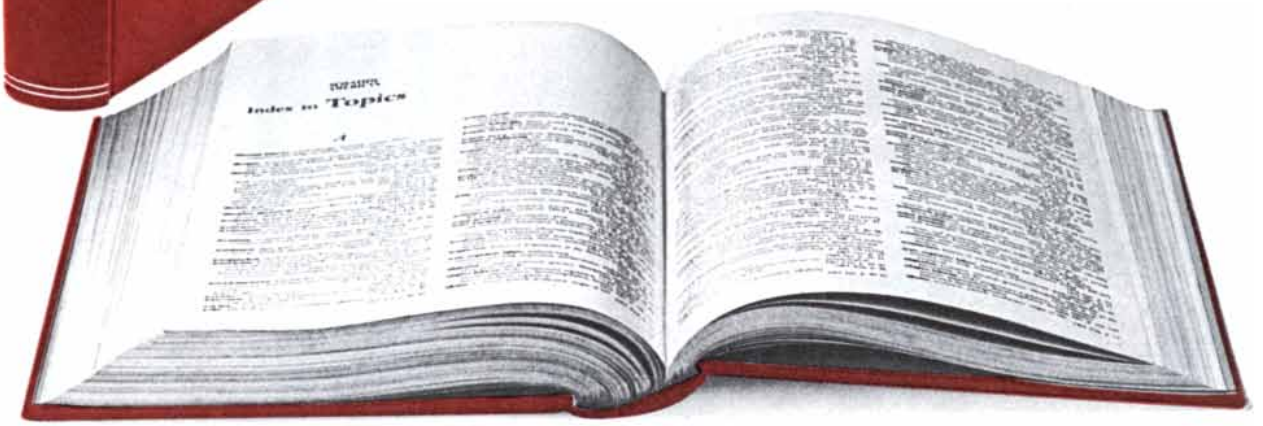
An advance announcement of the new SCIENTIFIC AMERICAN CUMULATIVE INDEX MAY 1948-JUNE 1978



This November the Editors of SCIENTIFIC AMERICAN will publish a Cumulative Index to the 362 issues of the magazine from May 1948 through June 1978. This new Index embraces all the issues published under the present editorial direction, recording 30 momentous years of intellectual history.



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Index to Topics

A rotated key word index that offers access to the subject matter of all articles and Science and the Citizen items (*see facing page*).

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The names of all persons mentioned in the articles or Science and the Citizen items and of places and institutions featured in a primary role.

Listing of Tables of Contents

A chronological listing of the contents of all 362 issues that permits ready identification, by titles and authors, of the articles cited in the two foregoing indexes.

Index to Authors

An alphabetical listing of all authors of articles.

Index to Titles

An alphabetical listing of all articles by the first key word in the title and by the other key words in the title.

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A listing of the longer book reviews in three parts: authors of books reviewed, titles of the books and reviewers.

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A listing of the puzzles, games and diversions presented in this department since its inception in January 1957, under the editorship of Martin Gardner.

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How the Index to Topics provides direct access to subject matter of 362 issues of SCIENTIFIC AMERICAN...and how to use it.

The Index to Topics is a rotated key-word index. That is: The topics cited in a given article are entered together in a cluster:

DNA, genetics, molecular structure, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

Each of these "key words" takes its turn as the first term in the cluster in its entry and re-entry down through the alphabet of the Index to Topics:

DNA, genetics, molecular structure, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

genetics, DNA, molecular structure, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

molecular structure, DNA, genetics, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

x-ray crystallography, DNA, genetics, molecular structure, DNA double helix resolved 1954 Oct. p. 54-61 [5]

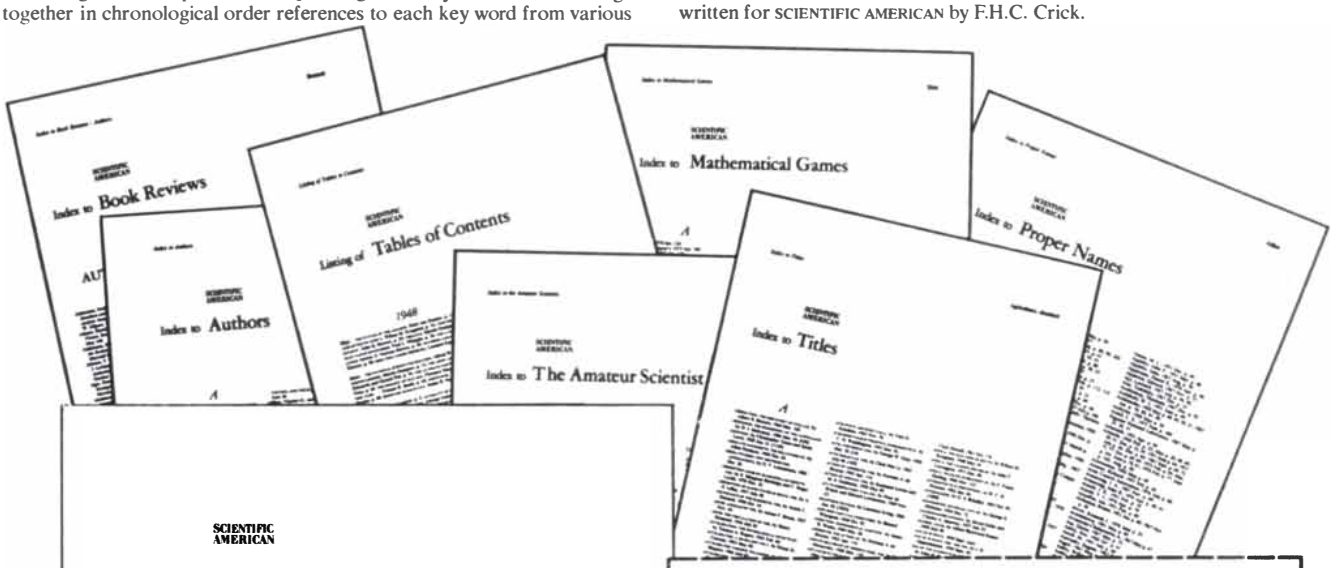
In most cases, a secondary citation, highlighting some aspect of the article, rides along with the rotating primary citations (In the example above: DNA double helix resolved). Each entry serves, therefore, as a "miniabstract" of the original. The alphabetical sequencing of the key words, in turn, brings together in chronological order references to each key word from various issues of the magazine. A portion of the grouping of clusters for "x-ray crystallography" follows:

x-ray crystallography, DNA, genetics, molecular structure, DNA double helix resolved 1954 Oct. p. 54-61 [5]
amino acids, myoglobin, proteins, 3-D structure of protein molecule 1961 Dec. p. 96-110 [121]
crystal structure, solid state, semiconductors 1962 Dec. p. 39-48 [249]
Bragg's law, crystal structure, diffraction, fourier series 1968 July p. 58-70 [325]
photoelectric effect, x-ray absorption 1976 Apr. p. 96-103

Articles are referenced by first and last page numbers. Thus, the entry for x-ray crystallography informs the reader that first appearance of the term is in the October 1954 issue, pages 54-61. Reference to the Listing of Tables of Contents discloses that the article is "The Structure of the Hereditary Material" by F.H.C. Crick.

References to about one-third of the articles close with a bracketed number. This is the offprint number and identifies articles republished as offprints. Thus, the Crick article in the example is identified as Offprint #5.

Reference to the Index to Authors will disclose, as well, all of the articles written for SCIENTIFIC AMERICAN by F.H.C. Crick.



SCIENTIFIC AMERICAN

Index to Topics

A

SCIENTIFIC AMERICAN CUMULATIVE INDEX MAY 1948-JUNE 1978

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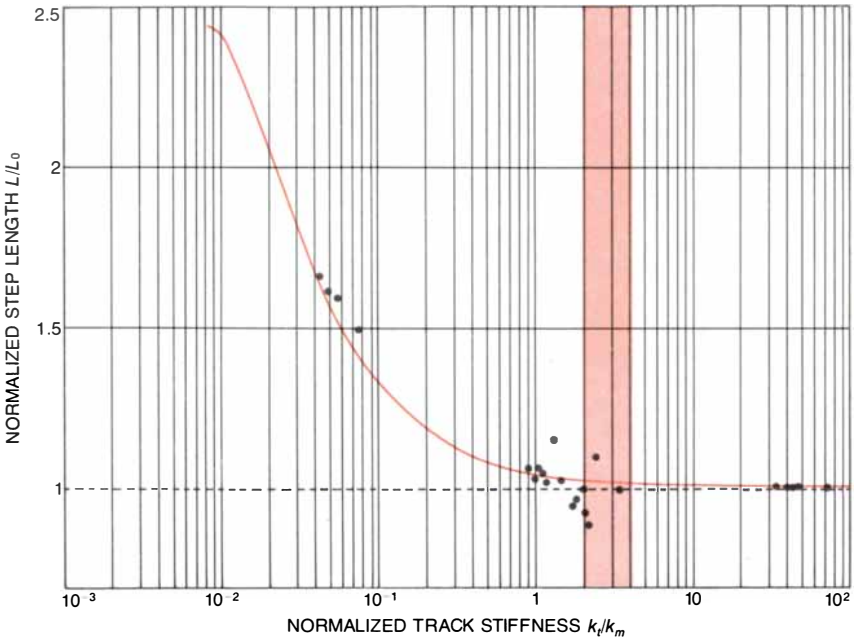

MODEL PREDICTIONS of the effect of track stiffness on step length (*curve*) are in close agreement with experimental findings (*black dots*). Step length is greatest on softer surfaces, where ground-contact time is also greatest. In the range of stiffnesses where ground-contact time is minimized and therefore optimum with respect to running speed (*color*) step length is still slightly increased over its hard-surface value. Hence in that range, and particularly in the low end of the range, running speed is enhanced. (In the graph step length has been normalized by dividing step length L on a surface of arbitrary stiffness by step length L_0 on a hard surface; track stiffness has been normalized by dividing track stiffness k_t by runner's stiffness k_m.)

when a distance of half a step has been traveled, the contact leg is flexed, shortened by, say, a length of δ_0 on a hard track, so that the distance between the hip and the hard-track surface is $l - \delta_0$. Assuming that the hip follows a level path, this situation is described by a right triangle with hypotenuse l and sides $l - \delta_0$ and $L_0/2$, where L_0 is the step length on a hard surface. On a compliant track, however, the comparable triangle has sides l, $L/2$ and $l - \delta_0 - \delta$, where L is the step length and $l - \delta_0 - \delta$ is the distance from the hip to the undeflected track surface. The average deflection δ is determined by two measurable quantities: the runner's body weight and the track stiffness. The leg length l and the step length on a hard track L_0 can be measured directly. Hence by applying the Pythagorean theorem to the two triangles it is a simple matter to calculate what a runner's step length will be on a track of arbitrary stiffness.

We found that the model predictions agreed well with our experimental measurements of step length on compliant surfaces. Just as we had calculated, the foam-rubber blocks increased a subject's step length by approximately 50 percent, partly compensating for the more than 100 percent increase in ground-contact time with the same surface. The net effect was that the runners were slowed to only about 70 percent of their hard-surface speed; if their step length had stayed constant on the foam rubber, they would have been slowed to about 50 percent of that speed.

Thus step length is most increased (a desirable effect) in the range of track compliances where ground-contact time is increased (an undesirable effect). It turns out, however, that in the range of compliances that are optimum with respect to ground-contact time, step length is still slightly increased over its hard-surface value. Therefore in this range of compliances—at a stiffness slightly more than twice the stiffness of the runner—the two factors determining running speed come together in an optimum way. Our model results showed that on tracks in this range of compliances the combined effect of decreased ground-contact time and increased step length should lead to a speed enhancement of between 2 and 3 percent.

At the end of the 1977–78 track season, the first season the track was in service, we compared the overall performance of members of the Harvard track team on the new track with their performance at the Intercollegiate Amateur Athletic Association of America championships held at Princeton University and the Heptagonal championships held at Cornell University. The Princeton and Cornell tracks are almost identical with the new Harvard track in size, but both of those tracks have a hard substructure with a synthetic top surface. (The Harvard track is also the only one of the three with banked turns. There is disagreement over the value of this feature of track design: banked turns increase the comfort and safety of running at high speeds, but they work to the disadvantage of runners moving at speeds lower than those for which the banking was designed: a fast quarter-mile.)

The analysis of the track records leaves little doubt about the effects of the tuned track. Although the two meets away from Harvard were championships, where runners are challenged to make their best showing, every Harvard runner except one ran his best time of the year on the new Harvard track. The runners' average speed advantage on the new track was 2.91 percent, which is in close agreement with the predictions derived from our model. In the preceding year the team ran an average .26 percent slower at home (on a cinder track) than they did away, and so it seems unlikely that these statistics reflect a home advantage. Moreover, similar statistics on 11 of the top runners from four other institutions show that they experienced the same kind of improvement, running an average of 2.12 percent faster on the new Harvard track than they did at the championships.

In the same season an individual Harvard runner's best time on the new track was an average of 3.87 percent faster than his best time off it and an average 2.04 percent faster than his best time of the preceding season. In terms of competition, however, the real advantage of a properly tuned track is probably not its speed enhancement; after all, the opposing teams run faster on it too. It is the comfort and safety of a tuned track that gives the home team an edge, enabling them to train much harder than they could on an ordinary track. A coach who can train ambitiously without fear of injuring his runners during practice can build a better team. Far fewer runners have been injured on the new track, although the Harvard team trained very hard last year.

In view of the discussion so far it may come as a surprise that no one expects a world record to be set on the Harvard track. That is because the International Amateur Athletic Federation does not recognize records for indoor running. Indoor tracks must usually be fitted into existing structures and so there is little standardization of design; for example, the length of such tracks and the radii of their turns vary greatly. Hence official world records can be set only on outdoor tracks.

No outdoor track of the optimum mechanical design has yet been built. If such a track is built, we predict that the world record for the mile could be improved by as much as seven seconds. The opportunity stands as a challenge.

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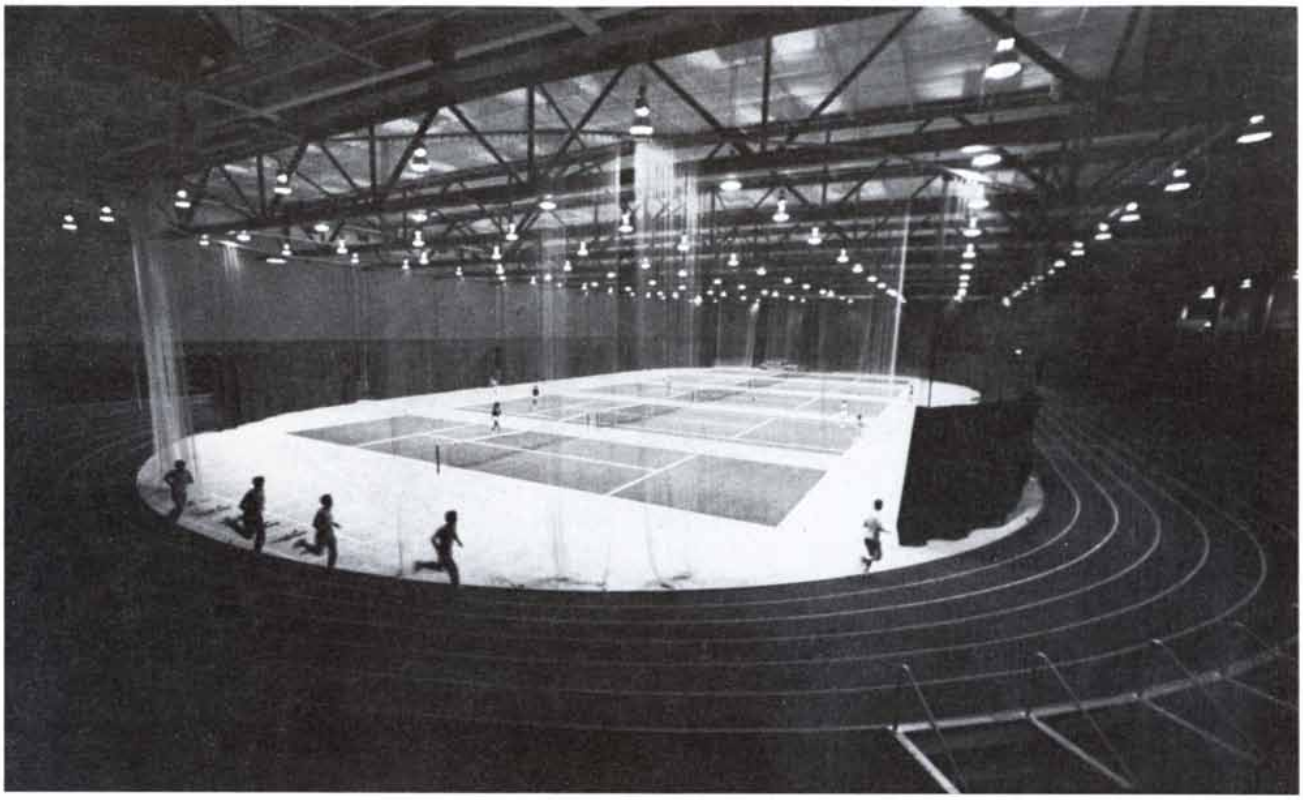

INDOOR TRACK AND TENNIS FACILITY at Harvard University opened in October of last year. Its six-lane 220-yard track features banked turns, a polyurethane top surface and a substructure made primarily of wood. The substructure is designed to convey a stiffness between two and three times the stiffness of an average athlete. Stiffness is in the low end of the range authors found to be optimum with respect to running speed. Facility was designed and built by T.A.C., Inc., and the Turner Construction Company of Boston.

		1977–78 SEASON			1976–77 SEASON		
EVENT	RUNNER	AVERAGE TIME AT HOME/ NUMBER OF MEETS	AVERAGE TIME AWAY/ NUMBER OF MEETS	SPEED ADVANTAGE AT HOME (PERCENT)	AVERAGE TIME AT HOME/ NUMBER OF MEETS	AVERAGE TIME AWAY/ NUMBER OF MEETS	SPEED ADVANTAGE AT HOME (PERCENT)
	EICHNER	9:05.56/4	9:32.5/1	4.9	9:29.0/3	9:28.0/2	−0.2
	MEYER	9:18.7/6	9:36.5/2	3.2			
TWO MILE	FITZSIMMONS				9:02.5/2	9:12.5/4	1.8
	DUNN				9:20.7/1	9:28.3/3	1.4
	SHEEHAN				9:25.2/1	9:33.4/1	1.4
	EICHNER	4:13.4/3			4:21.35/2	4:17.93/3	−1.3
ONE MILE	McNULTY	4:11.56/7	4:08.74/2	−1.1			
	CAMPBELL				4:15.0/2	4:12.5/3	−1.0
	FINN				4:26.4/1	4:24.8/3	−0.6
	CHAFEE	2:15.95/2			2:15.3/1	2:15.4/2	
1,000 YARDS	DOLSON	2:14.58/5	2:18.1/1	2.6	2:16.0/1	2:15.5/1	
	CAMPBELL				2:15.3/1	2:13.78/4	−1.1
	CHAFEE	1:54.92/6	1:56.43/2	1.3			
880 YARDS	DOLSON	1:55.14/2	1:57.33/1	1.9			
	SELLERS	1:57.94/6	2.01.1/1	2.7			
600 YARDS	SCHMIDT				1:13.8/2	1:13.4/4	−0.6
	SELLERS				1:19.3/2	1:17.4/1	−2.5
	LAMPPA	50.46/7	51.7/1	2.5			
440 YARDS	NICODEMUS	50.36/7	53.3/1	5.8			
	SCHMIDT	48.93/2	51.5/1	5.3			
				AVERAGE 2.91%			AVERAGE −0.26%

HARVARD TEAM'S TRACK RECORDS for the first season on the new track (*color*) show that the track substantially enhances running performance. Each Harvard runner's performance on the new track is compared with his performance at the Intercollegiate Athletic Association of America and the Heptagonal meets, which were run on standard tracks. The new track conveyed an average speed advantage of nearly 3 percent. Further analysis of these statistics shows the probability is about 93 percent that any given individual will run faster on the new track. Similar statistics are given for preceding year (*white*), when Harvard team's home meets were run on cinder track.

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Gaseous Nebulas

These spectacular clouds within our galaxy are sites of star formation. Radio spectroscopy indicates, among other things, that the clouds belong to much larger systems of gas and dust

by Eric J. Chaisson

Astrophysicists generally agree on the broad outlines of a theory of star formation. Briefly, a star is born as follows. In the beginning a cool, diffuse cloud of gas and dust fills a huge region of interstellar space. Within the cloud a few atoms happen to come together, at first by accident. Provided that their combined gravitational force is greater than any countervailing forces, they begin to attract other atoms in the vicinity. In time the continuing action of gravity forms a dense concentration of matter and proceeds to compress it further. Frictional heating then causes the temperature of the gravitationally compressed gas to rise. After a few million years the gas reaches a critical temperature of about 10 million degrees Kelvin, at which point hydrogen nuclei begin to fuse in the core of the nascent star. The release of enormous amounts of thermonuclear energy from the "burning" hydrogen halts the gravitational collapse of the star, which thereafter radiates energy from its surface into space in the form of electromagnetic waves, including those of visible light.

In spite of the almost universal acceptance of the foregoing scenario, it has until recently received little observational support. A few years ago a number of astronomical observatories undertook programs designed to examine regions of space thought to be conducive to star formation. Attention was directed initially toward the gaseous nebulas and later toward their surrounding interstellar environment. These visually spectacular parts of the galaxy are rich in gas and dust, and they are known to contain comparatively young stars (some no more than a few million years old). Yet places where such young stars and even more primitive protostars coexist often tend to be quite dusty and hence dark; they are hidden either partly or totally from the view of astronomers working with optical telescopes, because of the efficient scattering of light waves by the intervening dust. Fortunately radio waves penetrate such interstellar debris far more readily, making them superior to light waves for probing the interior of either partly obscured gaseous nebulas or totally obscured dark galactic clouds. I shall review here some interesting radio-wave observations made in recent years of a representative selection of gaseous nebulas and their interstellar environments. Such investigations may well furnish the key to a surer understanding of the process of star formation.

A gaseous nebula is a more or less spherical volume of plasma, or ionized gas, surrounding a very hot star or cluster of stars, each of which has an effective surface temperature in excess of 30,000 degrees K. Such blue-white stars are much hotter than our own star, the sun, which has a surface temperature of only about 6,000 degrees. Hot stars of the former type emit copious amounts of ultraviolet radiation, which is capable of interacting with the surrounding matter. Of all the photons of electromagnetic radiation emitted by such a star only an ultraviolet, or comparatively high-frequency, photon has more energy than that necessary to bind an electron to its parent nucleus. As a result the absorption of ultraviolet radiation by neutral, or un-ionized, atoms causes electrons to be stripped from their nuclei, creating a near-perfect plasma around the central star or stars. The energy released by the interaction of an ultraviolet photon and an atom is imparted as kinetic energy to the liberated electron, which is then free to wander about in the ionized gas. The behavior of these unbound electrons, called photoelectrons, is critical to the observation of the nebula. They can manifest their presence in three different ways.

First, after several hundred years of wandering, a free electron eventually comes close enough to a nucleus (usually a hydrogen nucleus, or single proton) to be recaptured, making a neutral atom again. As the process of recombination begins, the electron generally enters the bound atomic system in an upper, excited state, decaying to lower energy levels at an average rate of about one level per second, thereby reaching the ground state, or lowest energy level, rather quickly. During the successive stages of recombination photons are emitted at specific frequencies characteristic of the atom's structure. Low-level transitions (those involving the first few principal quantum states of the atom) are responsible for the familiar hydrogen and helium emission lines that appear in optical spectrograms of stellar objects. Transitions between higher adjacent energy levels of the same elements give rise to longer radio waves, which can also escape the nebula and be analyzed spectroscopically.

Second, unbound electrons often collide with atoms of trace elements, such as singly or doubly ionized oxygen or singly ionized sulfur, that have very low energy levels. (The more abundant hydrogen and helium ions do not have comparably low-lying energy levels.) This collisional process can be sufficiently violent to transfer energy from the free electron to the ion, thereby populating some ionic energy states just above the ground level. In principle collisions can also depopulate the excited levels of an ion, but in general collisions are fairly rare in the tenuous interstellar environment, and as a result once an ion has been excited collisionally to a higher level it is much more likely to relax radiatively to the ground level by emitting a low-energy photon capable of escaping the nebula. Such transitions, which are said to be forbidden because their spectral lines cannot be detected in the much denser gases encountered in terrestrial laboratories, are responsible in part for the visually spectacular colors of the gaseous nebulas; singly ionized oxygen emits forbidden lines in the violet part of the visible spectrum, doubly ionized oxygen in the green, singly ionized sulfur in the red and so on.

Finally, inelastic, or energy-transferring, collisions among the free electrons themselves can rapidly (on the order of minutes) distribute the electrons' initial-

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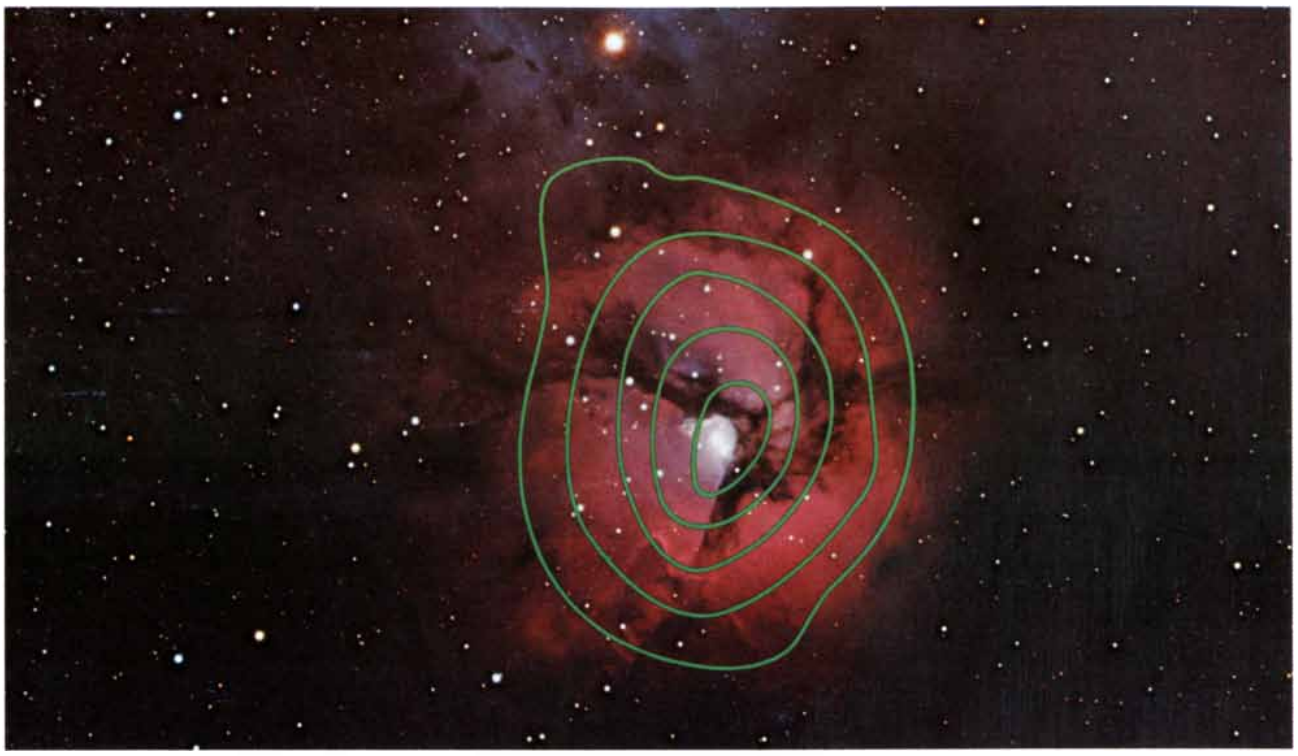
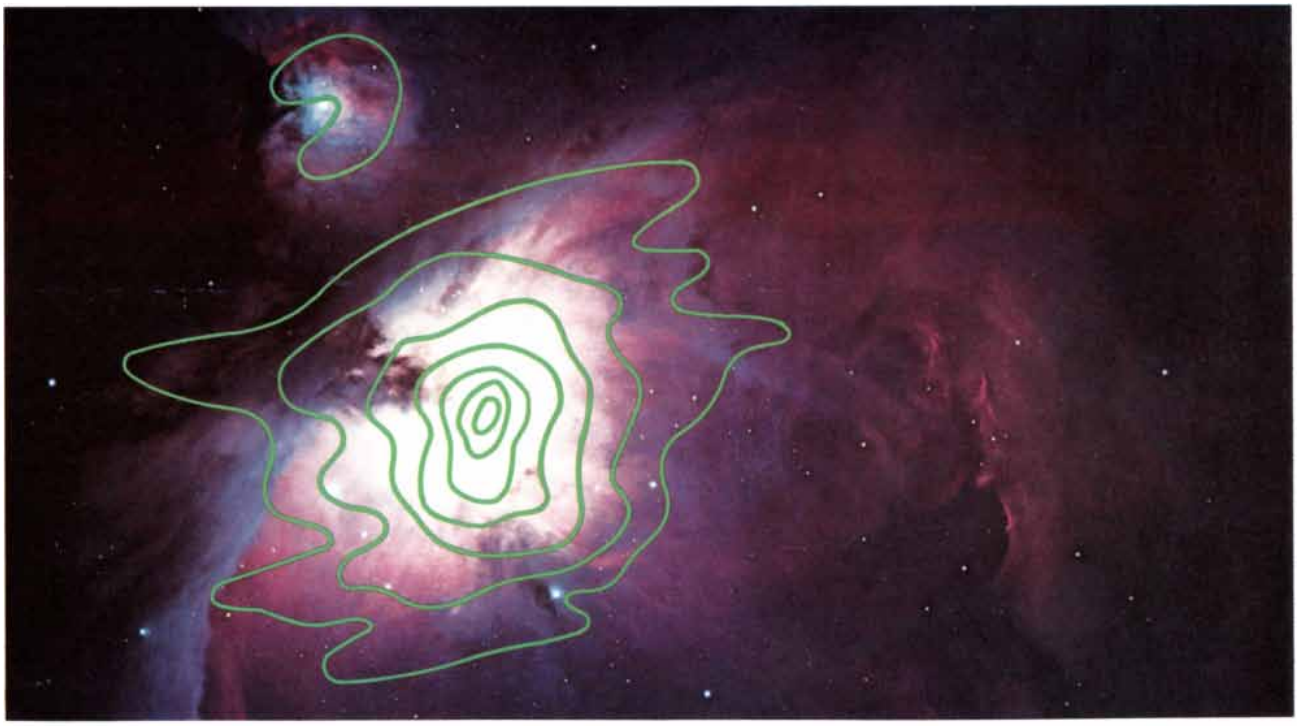


TRIFID NEBULA, designated M20 in the Messier catalogue of extended celestial objects, is represented here in two ways. The photographic image, made with the four-meter reflecting telescope at the Kitt Peak National Observatory, records the various wavelengths of visible light emitted by the nebula as a result of the recombination of free electrons with different atoms in the volume of ionized gas surrounding the central exciting star. The green contours, drawn from data obtained with the 37-meter radio antenna at the Haystack Observatory, show the distribution of radio waves emitted by the nebula at a frequency of eight gigahertz. In this case the constant-intensity contours increase uniformly inward toward the known position of the central star, coinciding closely with the shape of the visible nebula.



GREAT NEBULA IN ORION (M42) is similarly represented in both optical and radio form. In this case, however, the map of radio intensity shows that substantial parts of the nebular gas are hidden from the view of astronomers working with optical telescopes. The radio map of M42 is more detailed than the one of M20, because for this observation the Haystack antenna was operated at a frequency of 24 gigahertz, and the higher frequency yielded a better angular resolution. New stars are almost certainly being born in or near both of these representative gaseous nebulas. In all the astronomical photographs accompanying this article north is at top and east is at left.

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ly gained energy throughout the region of ionized gas, establishing a thermodynamic state, called a Maxwellian distribution, that is characterized by a mean nebular temperature of about 10,000 degrees. (This gas temperature is actually a measure of the electrons' average velocity in the nebula.) In this way the thermal structure of the nebula is generally maintained in a steady-state equilibrium between heating by photoionization and cooling by recombination and collisional processes that generate low-energy radiation capable of escaping the nebula. It is of more than passing significance that it is the trace ions (those at least 1,000 times less abundant than hydrogen and helium) that serve to control the nebula thermostatically, maintaining the nebular temperature generally between 5,000 and 15,000 degrees.

In addition to the thermal equilibrium established among the various heating and cooling mechanisms gaseous nebulas are characterized by an ionization equilibrium. Since the time it usually takes for an electron to recombine (a few hundred years) is small compared with the lifetime of a typical nebula (about 10 million years), the number of recombinations per unit of volume equals the corresponding number of ionizations. There are two distinct physical processes competing here. On the one hand, the rate at which an ultraviolet photon interacts with a nearby neutral element depends solely on the element's atomic properties and the number of sufficiently energetic photons, and it is independent of the thermodynamic properties of the gas. On the other hand, the rate of radiative recombination of an electron with an ion is a sensitive function of the temperature and density of the nebular gas.

To a first approximation, solving the equations of ionization equilibrium is remarkably simple. The solution, which specifies the ionization structure and geometry of a nebula, demands that the flux of stellar radiation become diluted at some distance from the central exciting star, partly because some ultraviolet photons are continually being used to ionize new elements (predominantly hydrogen) as the ionized zone, quickly at first and then slowly, expands into the surrounding neutral region. Some 10,000 years or less after the birth of the central exciting star or stars the size and shape of the nebula reach a virtual steady state, becoming almost completely ionized within a well-defined region and remaining almost entirely neutral beyond it. Such regions are sometimes called Strömgren spheres, after the astronomer Bengt Strömgren, who was the first to solve the equations of ionization equilibrium.

Stars of different spectral types have characteristic Strömgren radii. The calculation of the nebular radius is com-

NEBULA-RICH REGION of our galaxy is seen in the wide-angle black-and-white photograph at the right, made with a three-inch sky-patrol camera at Harvard University's southern observing station at Bloemfontein in South Africa. The view is toward the center of the galaxy, northeast of the constellation Sagittarius; the broken white line indicates the central plane

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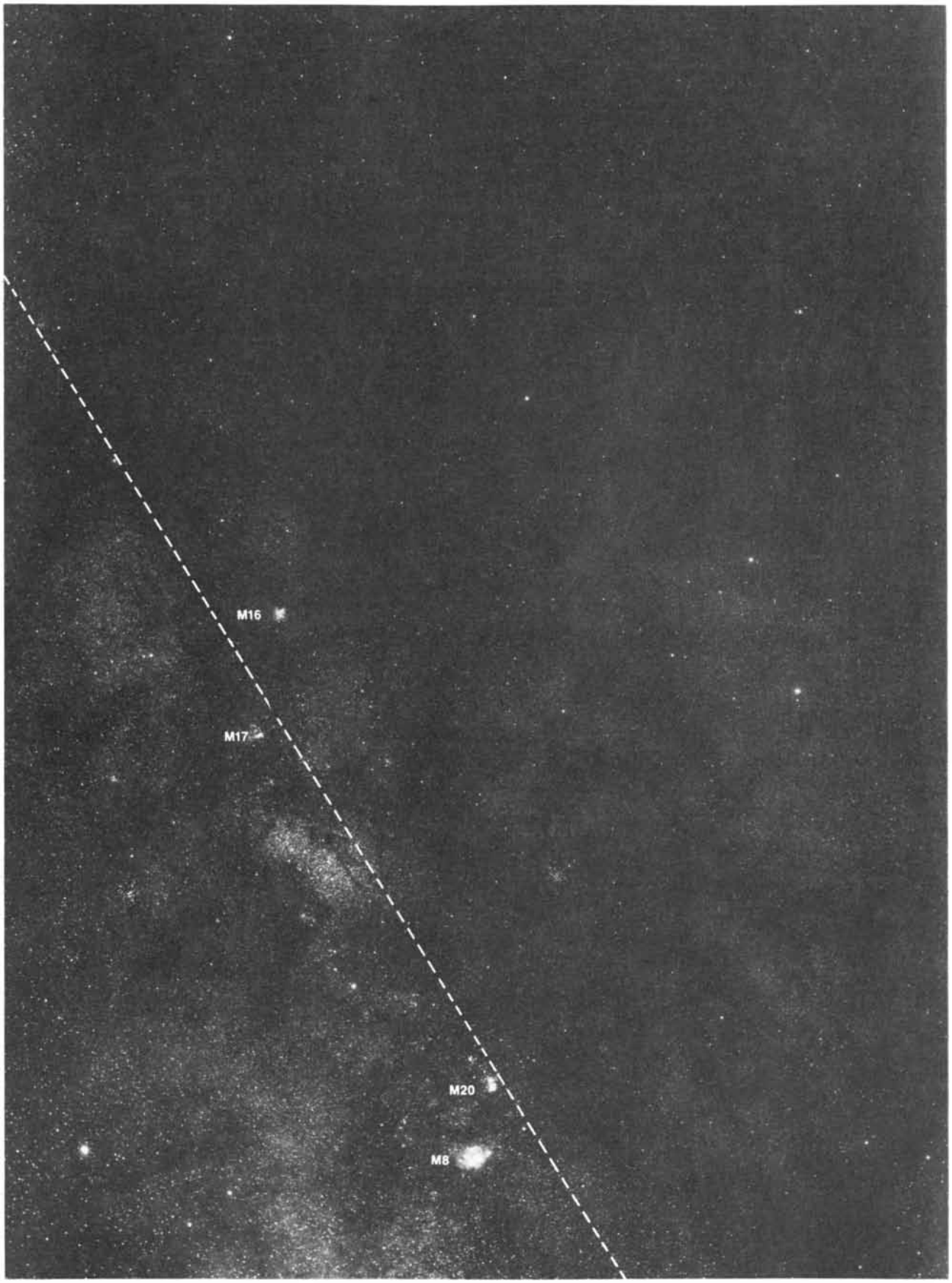

of the galaxy. The photograph extends over an extraordinarily large angular section of the sky, measuring 26 degrees in declination (vertically) and 19 degrees in right ascension (horizontally). It contains several notable nebulas, including the three shown in color at the left. Reading from top to bottom they are M16, the Eagle Nebula; M17, the Omega Nebula; M8, the Lagoon Nebula. (M20, also indicated in the wide-angle view, is reproduced in color elsewhere in this article.) Color photographs were all made with Kitt Peak four-meter telescope.

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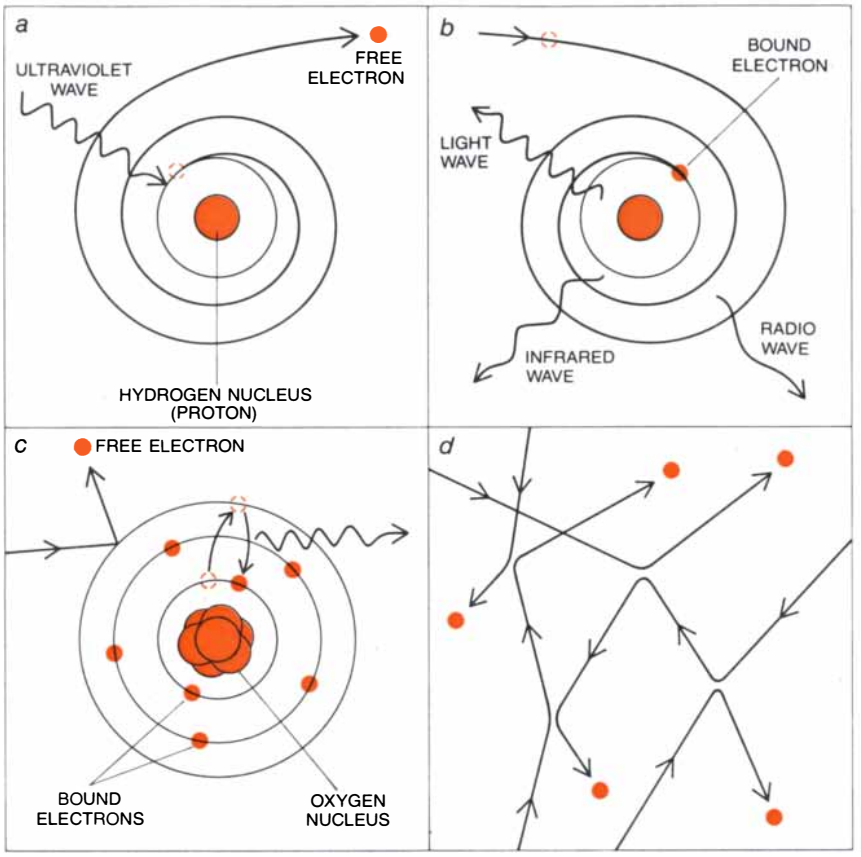
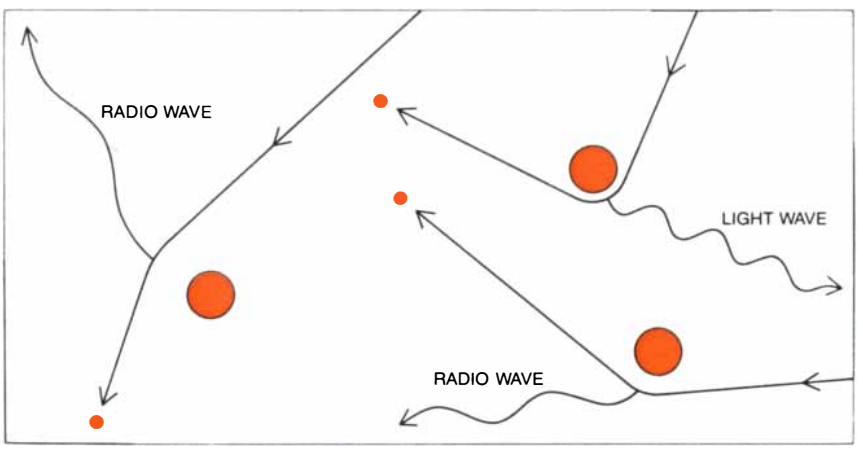


FREE ELECTRONS can interact with other particles in the ionized nebular gas in three principal ways once they have been individually liberated from the single-proton nuclei of hydrogen atoms by the action of ultraviolet radiation from a central star (*a*). First, a free electron can simply be recaptured by a proton, forming a new hydrogen atom (*b*); as the electron cascades to the lowest energy level of the atom some of the electron's kinetic energy is emitted in the form of electromagnetic radiation at characteristic wavelengths (first at low-frequency radio wavelengths, then at medium-frequency infrared wavelengths and finally at high-frequency optical wavelengths). Second, a free electron can transfer some of its kinetic energy by colliding with certain atoms such as singly ionized oxygen (*c*); the collision excites an electron within the ion to a higher energy state, from which it can then return to its normal energy state, emitting energy in the form of visible light. Third, free electrons can interact among themselves, establishing a fairly uniform nebular-gas temperature of about 10,000 degrees Kelvin (*d*).



RADIATION IS ALSO EMITTED from a gaseous nebula when free electrons pass near protons or other positively charged nuclei without combining with them. In a particularly close encounter of this type the electron loses a considerable amount of energy, emitting a photon of high-frequency optical radiation in the process. Most electrons are hardly deflected at all, however, and they emit comparatively low-frequency radio waves. The net result of a large number of such grazing encounters is a continuous spectrum of radiation, the radio-frequency portion of which is transmitted through space completely unattenuated by interstellar debris. Radiation produced by this mechanism is referred to as bremsstrahlung, or "braking radiation."

paratively insensitive to the assumed temperature of the nebula, since the ionized region is thermostatically controlled by the collision rate of the photoelectrons with the trace ions. The density of the nebula, however, can be expected to vary by more than an order of magnitude from an average value of 300 ions per cubic centimeter. For example, very diffuse nebulas (those with a density of about 10 ions per cubic centimeter) can extend some 20 light-years from a very hot star. Even larger nebulas can exist when several hot stars (or a full-fledged cluster of stars) collectively provide a large flux of ultraviolet photons.

In spite of the complete ionization of interstellar regions near hot stars, any star or cluster of stars can produce only a finite number of ultraviolet photons, and therefore it can ionize only a finite volume of matter. Of course, if there is a lack of neutral material capable of becoming ionized near a hot star, then the size of such a "density-bounded" nebula becomes limited by the amount of neutral material present, and its generally irregular shape depends on the geometrical distribution of the interstellar material in the neighborhood of the star. In recent years, however, astronomers have come to realize that most nebulas are embedded in much larger and more massive clouds of neutral atoms and molecules that envelope the "radiation-bounded" nebulas. Such nebulas often have some symmetry about their exciting sources. The equations of ionization equilibrium further specify that the thickness of the transition region between the hot, completely ionized gas within the nebula and the cold, predominantly neutral gas outside it is extremely sharp compared with the overall dimensions of the nebula. Nevertheless, it is within this transition zone, measured in light-hours rather than light-years, that the temperature and degree of ionization of the gas drop drastically, typically by several orders of magnitude.

A gaseous nebula, then, is a hot region of almost complete interior ionization separated by an exceedingly thin transition layer from a cold, predominantly neutral interstellar cloud. Information about gaseous nebulas accumulates solely by virtue of the detection of electromagnetic radiation emitted and absorbed by electrons, ions and neutral atoms. The astrophysicist categorizes these electromagnetic data according to four fundamental parameters, namely direction, frequency, intensity and polarization, in order to characterize the physical and chemical state of the gas in terms of temperature, density, composition and velocity.

To take a typical example, consider a region of space to the northeast of the constellation Sagittarius. A wide-angle photograph of this part of the sky encompasses the central plane of our galaxy [*see illustration on preceding page*].

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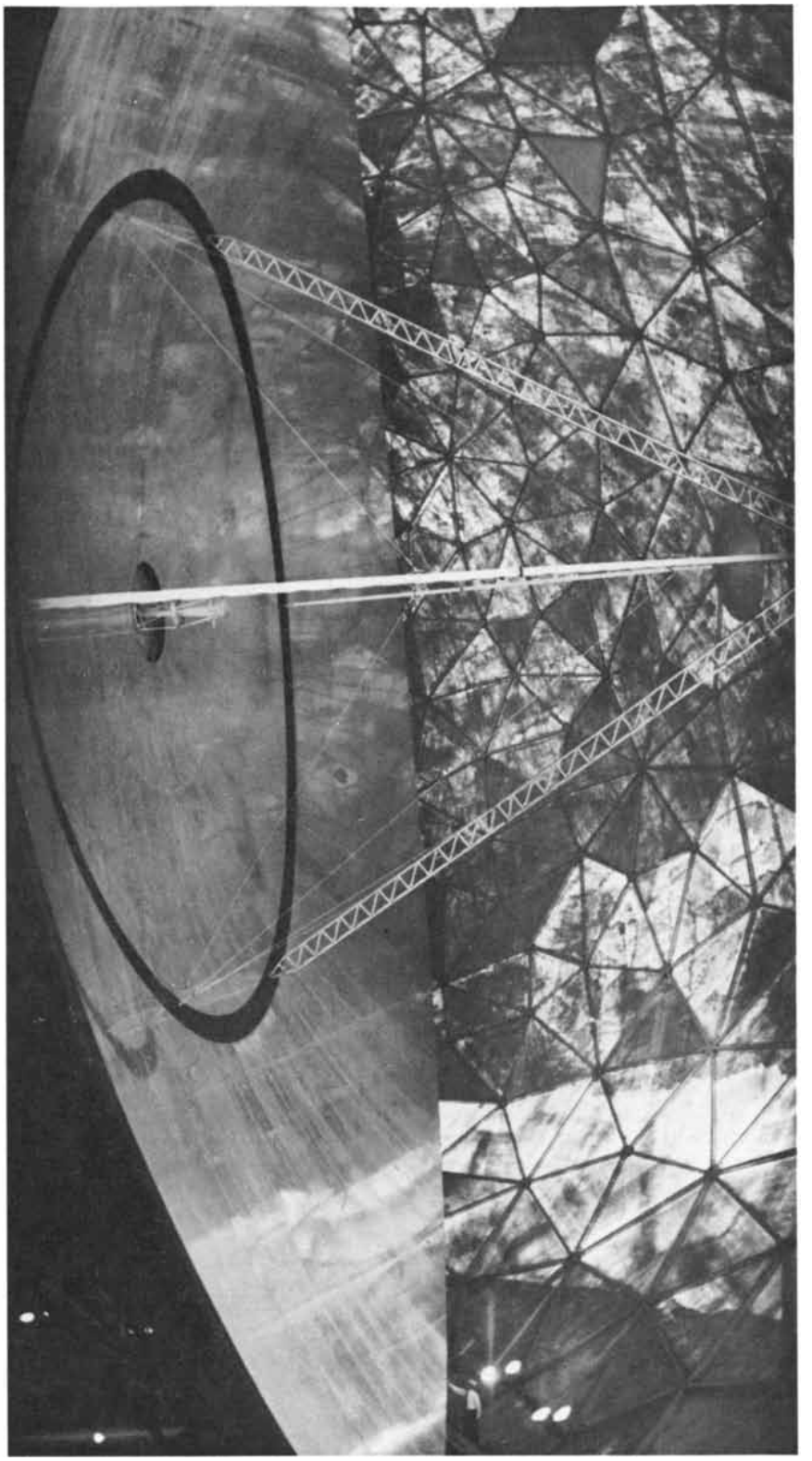
A careful examination of the black-and-white positive print reveals a mottled appearance, signifying an uneven distribution of stars. The apparent irregularity is the product of visual obscuration, blemishing an otherwise uniform distribution of stars. The obscuration is particularly evident along the galactic plane itself, where the accumulation of dust and other forms of interstellar debris is quite pronounced. Indeed, such a large degree of obscuration prevents one from seeing farther than about 10,000 light-years in this direction; accordingly there is no possibility of using optical telescopes to study the nucleus of the galaxy, which lies in the same direction some 30,000 light-years away from the solar system.

Embedded in this vast sea of interstellar gas and dust are several gaseous nebulas, four of which are shown in color in the accompanying illustrations. These are some of the visually most striking nebulas observable anywhere in the sky. Their Messier numbers (given to them by Charles Messier, the 18th-century French astronomer who first catalogued them), together with their popular names, are M8, the Lagoon Nebula; M16, the Eagle Nebula; M17, the Omega Nebula, and M20, the Trifid Nebula. A careful look at these individual nebulas shows additional obscuration, often directly across the face of the photographic image. This widespread scattering of light by interstellar dust helps to make analysis of the optical data difficult. In fact, some of the most energetic nebulas are entirely invisible, in particular those located toward the galactic center.

How then can one confidently obtain a true delineation of the gas in a nebula? For that one must rely on the fact that nebulas emit radio waves that are completely unattenuated by interstellar dust. Consider again the role of the free electrons. During the several hundred years that they wait for recombination with a nucleus unbound electrons lose some of their kinetic energy through inelastic collisions with other charged particles. In a typical electron-ion encounter the lighter electron is decelerated on entering the electrostatic field of the ion, which is usually a proton. A grazing interaction of this type does not lead to recombination, because either the approach velocity or the separation at impact is too great for capture. To conserve energy the small amount of kinetic energy lost by the electron is emitted as a comparatively low-frequency radio wave, the phenomenon known as bremsstrahlung, from the German for "braking radiation." In spite of the infrequency of individual encounters the ensemble of about 10^{58} electrons in a typical nebula is endowed with a continuous array of approach velocities and impact separations, ensur-



HAYSTACK RADIO ANTENNA is employed by the author and his colleagues at Harvard to detect radio waves from gaseous nebulas. The facility, which is managed by the Massachusetts Institute of Technology for the Northeast Radio Observatory Corporation, is on a hill in Westford, Mass. It is enclosed within a large geodesic dome to protect it against the New England winter. In this "fish eye" photograph, made from inside the dome, the 37-meter primary antenna surface is at the left. The primary surface (which is extremely smooth, approximating a mathematically perfect parabola to within half a millimeter across its entire surface) serves to focus cosmic radio waves toward a smaller secondary surface (*right*), which in turn reflects the signals back to a sensitive receiver at the center of the primary dish. The operating range of the Haystack antenna is normally between one and 25 gigahertz, although it has been used to detect higher-frequency radio signals. Man at bottom center gives an indication of scale.

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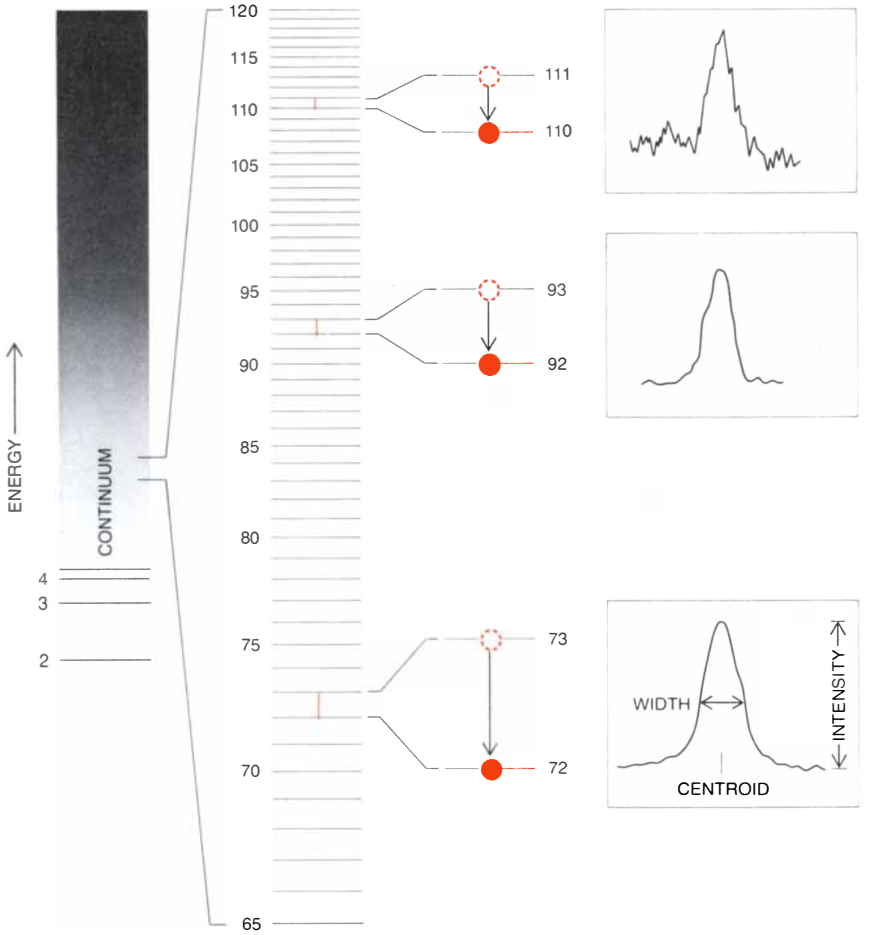
ing the continuous emission of radio waves capable of escaping the nebula.

The weak bremsstrahlung emission provides a powerful means of delineating the true distribution of nebular gas with a large radio telescope. Consider, for example, a map of the radio waves emitted from M20, the Trifid Nebula [*see top illustration on page 165*]. This radiation was sampled at the microwave frequency of eight gigahertz (eight billion cycles per second) by the Haystack antenna of the Northeast Radio Observatory Corporation, a consortium of northeastern universities. The effective angular resolution of the telescope in this case was nearly four minutes of arc. The radio map demonstrates that with the exception of the trisecting lanes of obscuring material the optical image of M20 is a reasonably good representation of the extent of the ionized gas. This, however, is a rare circumstance.

The Great Nebula in Orion (M42) provides a better example of how substantial parts of nebular gas can be visually hidden [*see bottom illustration on page 165*]. The map of radio intensity observed in the direction of M42 is more detailed because at the 24-gigahertz operating frequency of this observation the angular response was about one minute of arc. The resolution is still poor compared with that obtained with optical telescopes, but it is the best currently attainable with a large radio telescope. Two or more radio telescopes can work synchronously to form an interferometer capable of better resolution, but these arrangements are sensitive to only a small fraction of the nebular gas.

Comparatively high-resolution radio maps such as that for M42 can be used in conjunction with optical studies to make a more quantitative statement about the intervening obscuration. The radio waves, completely unattenuated by the intervening dust, can be scaled



QUANTUM-MECHANICAL PICTURE of a hydrogen atom consists of a set of discrete energy levels the atom's single electron is allowed to occupy. Electron transitions between the lowest energy levels, represented at the left, give rise to the emission of visible light. Transitions between the higher, more closely spaced energy levels, shown greatly enlarged at the middle, are accompanied by the emission of radiation at radio-wave frequencies. Three such transitions are indicated in color, along with actual tracings of their corresponding radio recombination lines (*right*), recorded from the direction of the nebula M20. The tracings for the 111-to-110 and 73-to-72 transitions were made with the aid of the 43-meter antenna of the National Radio Astronomy Observatory (NRAO). The tracing for the 93-to-92 transition was made with the Haystack antenna. Radio recombination features of this type can be fully characterized by three measurements: their intensity, their width and the frequency of their centroid.

several orders of magnitude in frequency to predict the true intensity of the optical radiation. The difference between the predicted (unattenuated) and observed (attenuated) values of the optical intensity yields a measure of the obscuration.

This procedure was recently accomplished by comparing the radio map of M42 that I made with the Haystack instrument with an optical map of M42 made by M. A. Dopita of the University of Manchester at the high-altitude Pic-du-Midi Observatory in the Pyrenees. The resulting distribution of foreground obscuration can be presented silhouetted against the glowing gas of M42 [*see bottom illustration on page 172*]. As one might expect, the dark tongue of dust to the east of the core of the nebula can be recognized as the region of heaviest obscuration.

Similar studies have shown that major parts of some nebulas, notably M17, are completely invisible. Indeed, hundreds of gaseous nebulas hidden to optical astronomers have been uncovered in recent years by radio-astronomical techniques.

In addition to providing a measure of the degree of obscuration, radio maps of continuous nebular radiation can yield a wealth of information about the thermodynamic state of the ionized gas. For example, the total intensity of the radio waves emitted obviously depends on the number of electrons encountering ions within a given volume of space. A mathematical description of the bremsstrahlung process can then be inverted to determine the electron density or the ion density, given the observed radio intensity. If the distance to the nebula is known, its physical size can be calculated from its apparent size; the mass of the nebula can then be determined from its known volume and density. Estimates of the distance, the Strömgren radius, the density and the mass for the five nebulas prominent in this article are listed in the table on page 178. The densities and masses given depend somewhat on a theoretical model, yet they satisfactorily represent the gross properties of the hundreds of nebulas distributed throughout the galaxy. By comparing the observed size of a nebula with its theoretical Strömgren radius one can even infer the spectral type of the central exciting star or stars. In this way the energetics of the nebula can be studied without ever having to see the central exciting star.

Eventually the free electrons recombine with protons and occasionally with more complex nuclei in the nebular gas. Quantum physics predicts that captured electrons can have only discrete energies, corresponding to the atomic energy levels described above. As the bound electrons seek the lowest energy level the successive downward transitions re-

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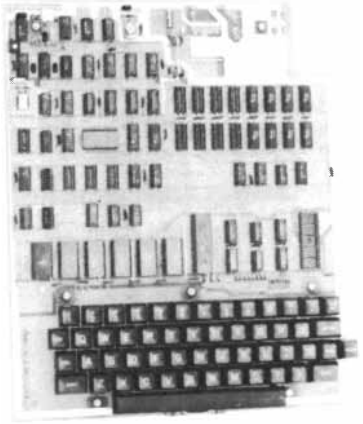

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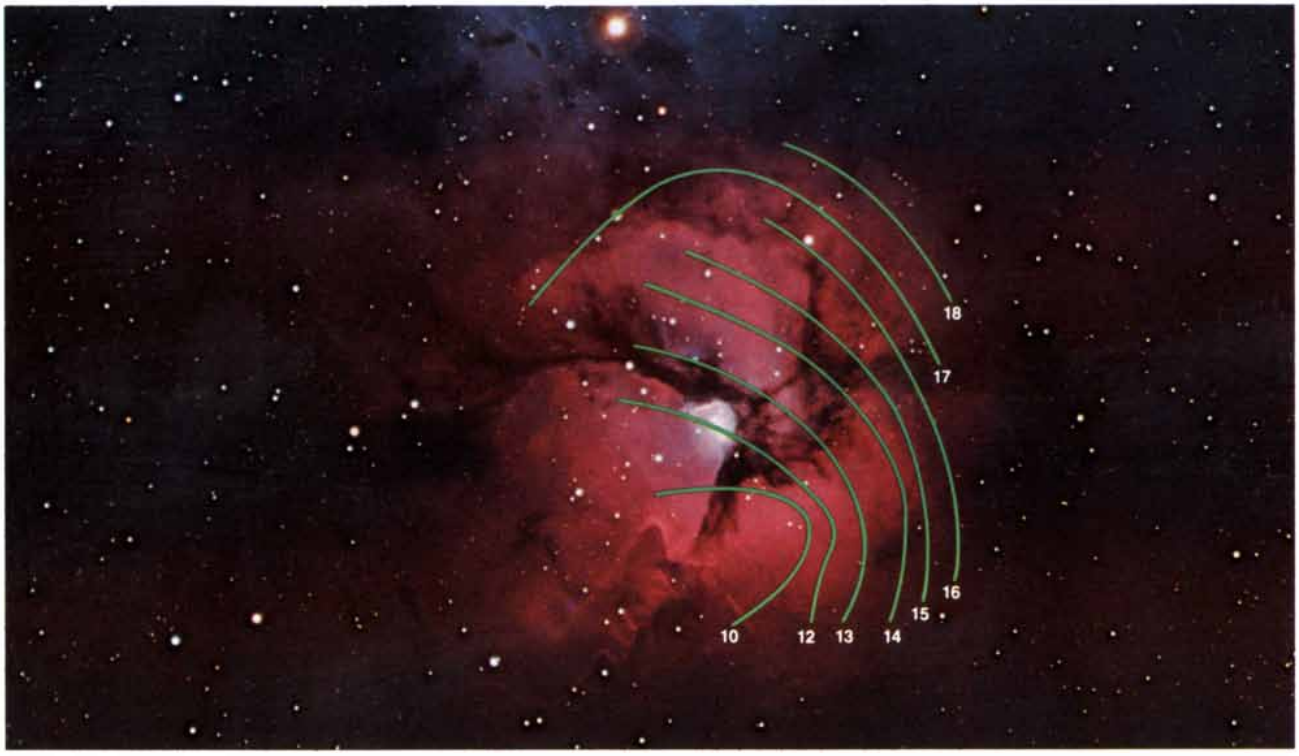
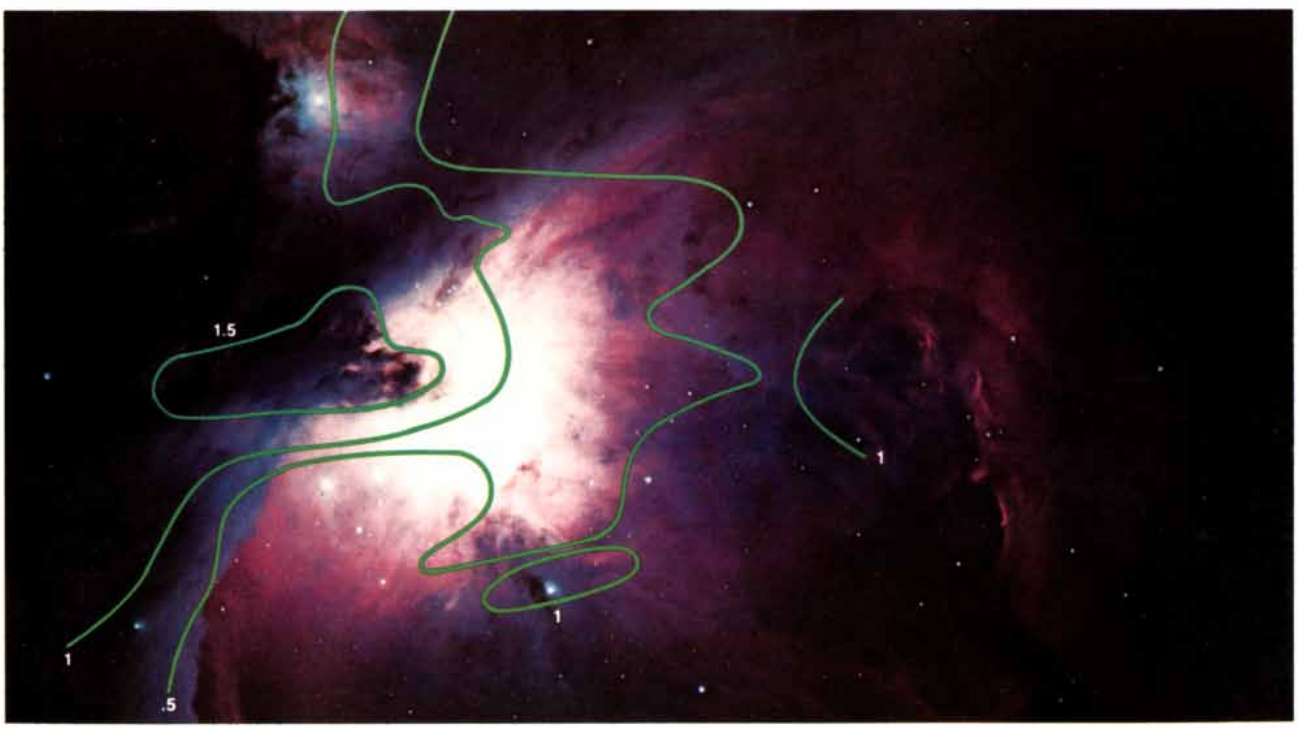


SLOW ROTATION OF NEBULA is suggested in the case of M20 by this map of the velocity distribution of the ionized gas, obtained by analyzing the centroids of a number of radio recombination lines. The contours show the varying Doppler shifts of different parts of the nebula, measured in kilometers per second with respect to a frame of reference based on a local group of stars near the sun. The resulting kinematic map, superposed on the same Kitt Peak photograph of M20 reproduced at the top of page 165, suggests that the nebula is rotating on an axis oriented 45 degrees east of north with a period of several million years. Alternative interpretations are also possible.



ATTENUATION OF LIGHT from a nebula by interstellar dust and other forms of galactic debris can be plotted in the form of a contour map. In the case of M42, shown here, the dust appears to be concentrated in the dark region to the east of the core of the nebula. Visible light from the zone within the magnitude contour marked 1.5 is diminished by about 80 percent; light from within the 1-magnitude contour is about 60 percent less than it would be in the absence of the dust, and light from within the .5-magnitude contour is about 40 percent less. It is not known whether the dust is physically mixed with the nebular gas or whether it is in the form of foreground clouds unrelated to the nebula. The striking asymmetry of the visible nebula and the nonuniform distribution of the nearby stars were the first clues that the ionized volume of the gaseous nebula is only a small part of a much larger aggregation of neutral interstellar matter.

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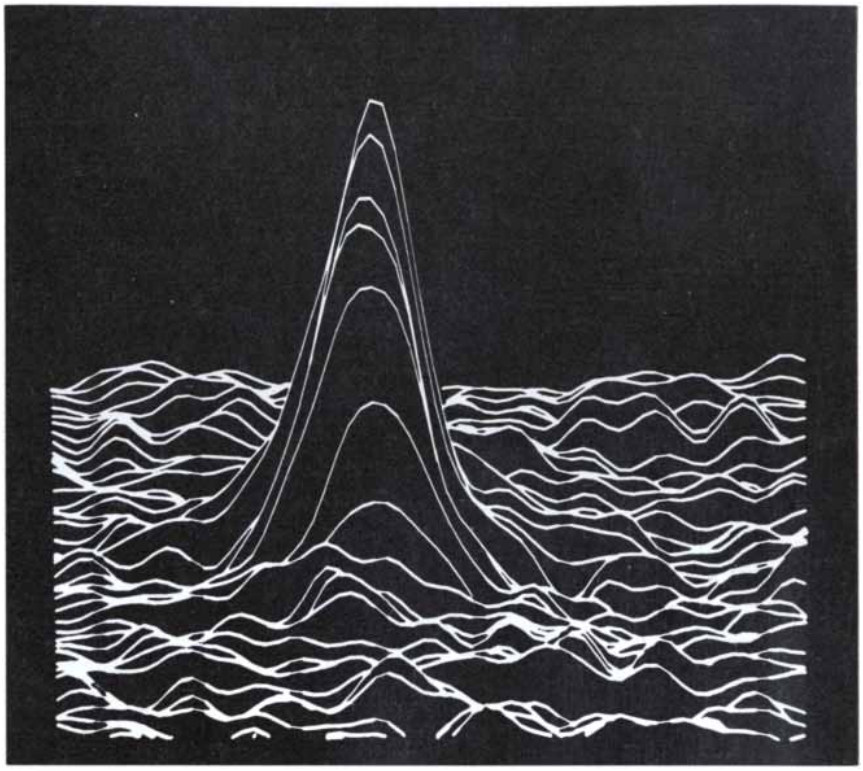
lease precise, quantized packets of radiation (photons), giving rise to clearly defined spectral lines that are superposed at precise frequencies on the spectrum of continuous radiation. The study of these spectral features enables astronomers to examine any single nebular atomic species to the exclusion of all others. Such spectroscopic analyses of nebulas continue to provide more accurate experimental data with which to build more realistic models of nebulas and of their interstellar environment.

The downward cascade of an electron within the quantized ladder of bound energy levels leads first to the emission of radio waves from levels high within the atom, then to infrared radiation and finally to visible light. The frequency of the emission shifts because the energy difference between adjacent atomic levels gets smaller with increasing distance from the central nucleus. For example, the permitted visible lines of hydrogen and helium seen with an optical spectroscope are actually recombination lines involving electron transitions between the very lowest energy levels of an atom. Their intensities are often confused by scattering, much as the continuum radiation of starlight is.

Infrared spectrometers are only now being constructed to observe lower-frequency recombination lines from electron transitions between atomic levels higher than about level five. Radio-frequency spectrometers attached to large radio telescopes, however, can easily detect very-low-frequency recombination lines from electron transitions between energy levels higher than about level 30. In fact, radio recombination lines are now routinely observed from gaseous nebulas at frequencies ranging from about 300 megahertz to 100 gigahertz. At the lowest frequencies electrons cascade between exceedingly high atomic levels, sometimes approaching level 300, enabling radio astronomers to study the largest atoms ever observed spectroscopically. These giant atoms have a diameter of about five thousandths of a millimeter and cannot be studied in terrestrial laboratories because in the comparatively dense conditions of even a laboratory "vacuum" collisions depopulate the electrons from the highly excited atomic levels before they have a chance to radiate.

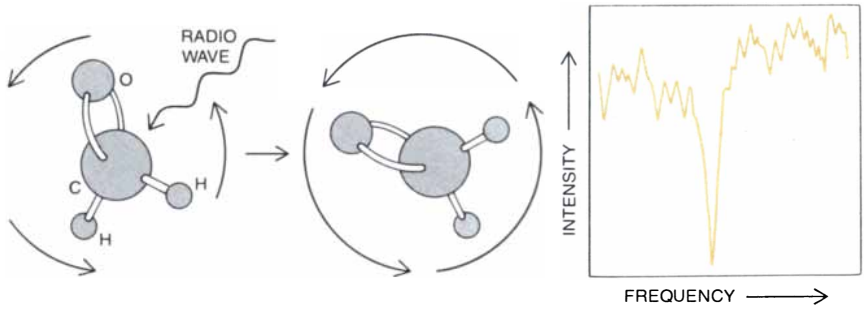
Consider the typical appearance of a radio-frequency spectral line emitted as nebular electrons cascade from level 111 to level 110 in the hydrogen atom [*see illustration on page 170*]. This observation was made toward M20 with the multichannel spectrometer attached to the 140-foot radio telescope of the National Radio Astronomy Observatory in Green Bank, W.Va. Bell-shaped lines of this type are specified mathematically by their intensity, their width and the frequency of their centroid. Of



PROFILE OF INTENSITY OF RADIO WAVES from M42 is derived from the same data as the contour map of the nebula shown in the bottom illustration on page 165. In this case, however, the radio-intensity distribution is viewed from the perspective of a 30-degree elevation. Maps of this type, displayed on a large television screen at the Haystack Observatory, emphasize the greater radio intensity at the center of the nebula and demonstrate how gaseous nebulas and other strong radio sources rise up out of the "noise" of the galactic background radiation.

course, such spectral features arise not from a single atom but from large numbers of electrons undergoing a particular transition within the nebular volume sampled by the telescope.

Spectral lines can generally yield a great deal of information about the emitting or absorbing gas, whether it is a laboratory sample or a cosmic sample. My Harvard colleagues and I at the Haystack Observatory use radio recombination lines to extract physical, chemical and kinematic information from the measurements of spectral features of different elements at a variety of different locations. For example, we have constructed a contour diagram of gas velocities across M20 [*see top illustration on opposite page*]. This map was made from observations of a radio recombination line at many locations distributed across the nebula. The central frequency of the spectral line was converted to a radial velocity on the basis of the Dopp-



FORMALDEHYDE MOLECULES in interstellar space rotate at specific quantized rates according to their energy content. Changes in the rotational configuration of such a molecule are accompanied by the emission or absorption of radio-frequency radiation, which can be detected on the earth in the form of a characteristic spectral feature such as the one shown at the right. In the pair of diagrams at the left a photon of comparatively low-frequency radio radiation emitted by a nebula is shown being absorbed by a molecule of formaldehyde (H_2CO) in a foreground cloud, causing the formaldehyde molecule to rotate faster. The particular spectral feature illustrated was recorded for M20 by the 43-meter radio antenna at the NRAO.

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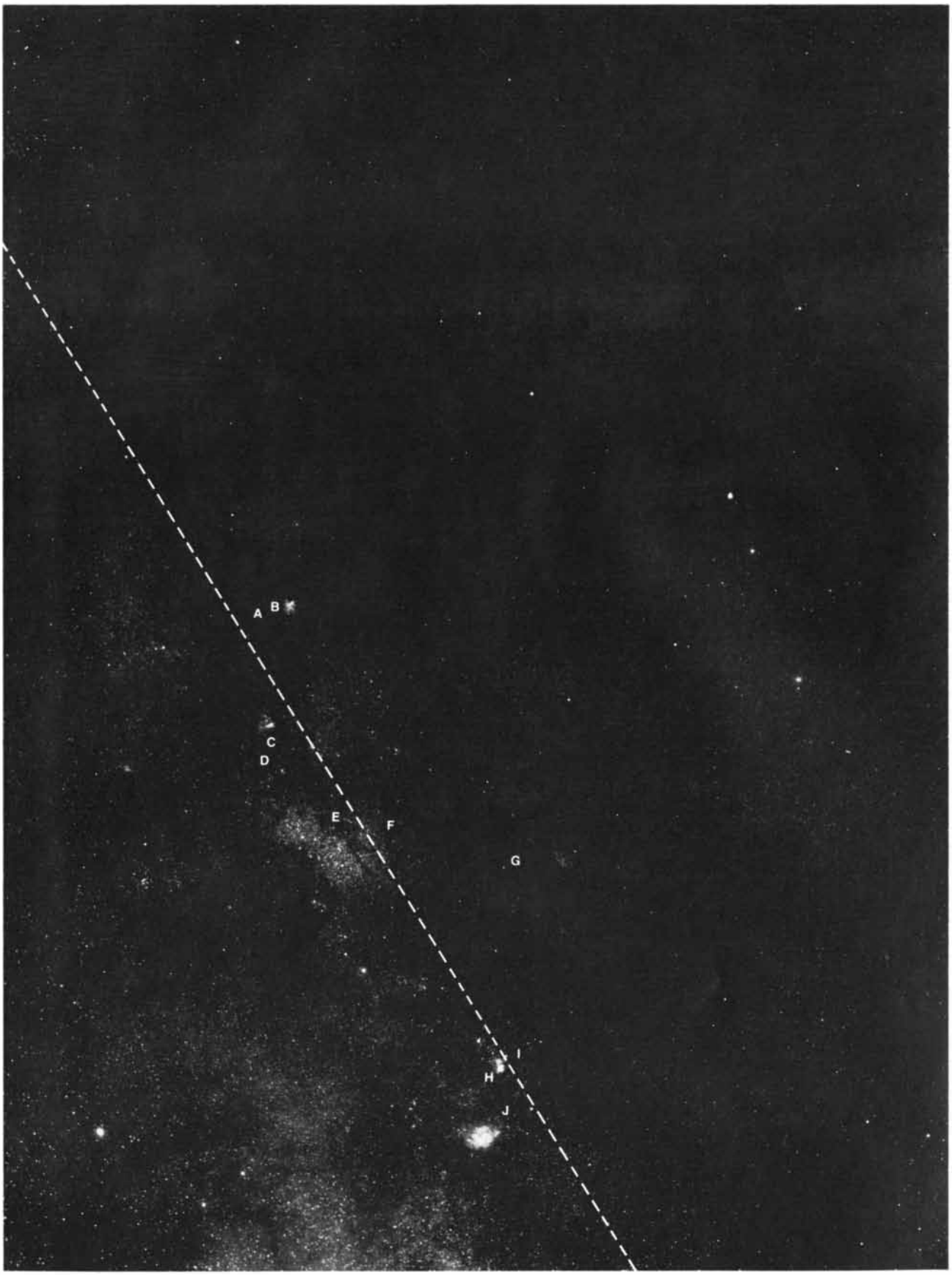

RECENT RADIO OBSERVATIONS of formaldehyde in the region of space lying in the general direction of the galactic center delineate a vast cloud of neutral molecules that apparently engulfs many nebulas, including M8, M16, M17 and M20. This wide-angle photograph is the same as the one shown on page 167. Letters give the location of measurements of formaldehyde line (*see graphs on opposite page*).

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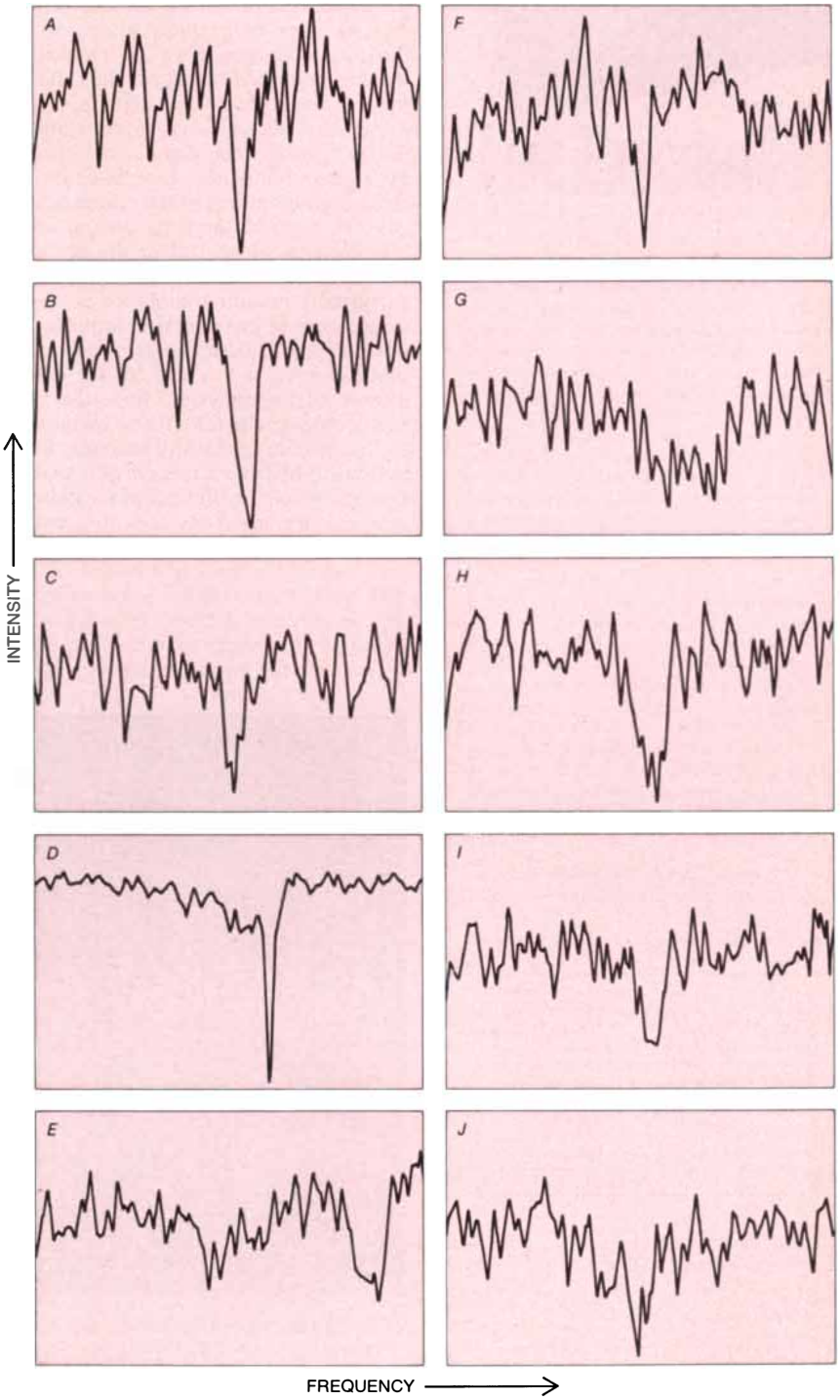
ler effect, according to which the frequency shift of radiation can be used to interpret motion of approach or recession. It should be emphasized that Doppler motion is only line-of-sight motion; transverse motion cannot be studied for distant objects.

A close examination of the gas-velocity map suggests that this nebula is rotating on an axis oriented approximately 45 degrees east of north. If that is the case, then given the distance to M20 the apparent velocity gradient implies a solid-body rotation period of a few million years. That is pretty slow; in fact, the rotation period is longer than the suspected age of a dusty young nebula such as M20. Alternative interpretations are also possible; in particular, the observations may result from the differential expansion, or shearing, of the hot nebular gas against the cold surrounding environment. Future observations, made with instruments capable of a finer angular resolution, will be needed to unravel numerous ambiguities such as this one concerning the bulk dynamics of the nebular gas.

Careful analysis of a spectral line can provide much additional information about the physical conditions within a nebula. Consider the various mechanisms that can broaden a spectral line. Heat is one obvious source of line broadening, since each of the electrons undergoing a specific downward transition has an agitated random motion; some thermal motions are receding, others are approaching, but all serve to widen a spectral line because of the Doppler effect. Nonthermal, turbulent motions of bulk nebular matter on a scale that is small compared with the angular resolution of the telescope are another source of line broadening; microturbulent cells of gas have different motions and when they are averaged over the entire nebula, can measurably broaden or distort the spectral profile. Large-scale motions of the gas, particularly rotation, could also conceivably contribute to the broadening of an observed feature, although none has yet been observed unambiguously. In addition inelastic collisions of recombining atoms with the surrounding plasma, notably with the free electrons, can appreciably broaden a spectral line, particularly if the bound electrons undergoing recombination are far removed from their parent nuclei at the moment of collision.

Fortunately the mathematics of many of these line-broadening mechanisms can be formulated precisely so that one can accurately specify the dominant physical factors giving breadth to the spectral lines associated with particular recombination events. For example, thermal Doppler motions of individual atoms are obviously a function of the temperature of the gas: the hotter the gas, the greater the microscopic atomic motion and the wider the profile of the line. Similarly, a dense gas ensures more frequent collisions and therefore a wider spectral line.

The objective in analyzing the observed spectral features is to invert one's theoretical knowledge of the individual line-broadening mechanisms, disentangle the magnitude of the various contributions and extract meaningful information about the nebula. This task has been successfully done for several nebulas by observing many recombination lines of the same element at different frequencies, and sometimes of different elements at almost the same frequency. Values for gas temperature and density found in this way agree remarkably well with those obtained from analyses of the radio-frequency continuum radiation. The values for gas turbulence are usual-



TRACINGS of the formaldehyde absorption feature at the various locations indicated by the letters on the photograph on the opposite page show that the absorption is strongest in the dustiest regions, where the conditions are best suited for the formation and protection of fragile molecules. Tracings were obtained by the author and his colleagues with the NRAO antenna.

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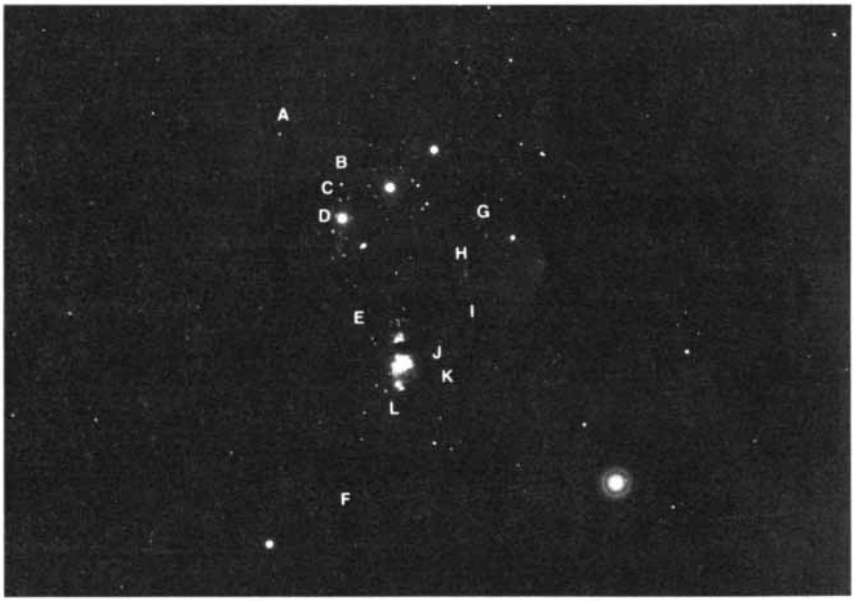
ly less than the anticipated 11-kilometer-per-second speed of sound in a tenuous gas at 10,000 degrees K. Some nebulas, however, notably those with large excitation requirements such as M17, show some evidence for supersonic turbulence, which can be regarded either as the product of nebular shock fronts or as the accumulated motion of individual subsonic cells maintained by high-velocity winds from several exciting stars.

Chemical abundances can also be determined from observations of radio recombination lines. In particular we have obtained values for the ratio of helium ions to hydrogen ions for several nebulas. The average value, about 9 percent, equals the cosmic helium-to-hydrogen abundance if, as is expected from considerations of the energetics of gaseous nebulas, there are no appreciable amounts of neutral or doubly ionized helium.

Actually helium-abundance determinations are of considerable importance not only for a better understanding of gaseous nebulas but also for the entire science of astrophysics. Since the proton-proton cycle that fuses helium in stellar interiors generally accounts for a helium-to-hydrogen ratio of less than 1 percent, given the lifetime of the galaxy, cosmologists generally seek to account for the production of another 8 or 9 percent helium in the early stages of the "big bang" that is believed to have created the universe. Objects for which the helium-to-hydrogen ratio is substantially less than the 10 percent cosmic abundance therefore present potential difficulties for many cosmological theories, since there is no way to destroy helium once it is formed. Thus measurements of the abundance of helium made with unscattered radio waves originating from a large number of galactic objects may ultimately have profound implications for an understanding of the nature of the universe itself.

In short, spectral-line intensities, widths and centroids can be mapped across nebulas. In this way angular variations in temperature, density, turbulence, composition and velocity have been documented for several nebulas in an attempt to learn more about the general properties of plasma near young stars.

The preceding discussion represents only a brief survey of a rather detailed set of physical parameters that can be extracted from spectroscopic studies of gaseous nebulas. There are, of course, a few critical assumptions inherent in the interpretation of nebular spectral lines. Nevertheless, the frontier of the subject is largely concerned with the fine measurement of spectral features of several elements in an attempt to assess the validity of these basic assumptions, and hence to accurately determine the nature of the interstellar plasma. In fact, investigators working in the field have reached the point where they quibble about whether a nebular gas temperature is 8,000 or 9,500 degrees K. and whether the gas density is 500 or 800 electrons per cubic centimeter. That is remarkable precision for galactic as-



CONSTELLATION ORION also appears to be engulfed in a vast molecular cloud, according to measurements of the characteristic formaldehyde absorption feature at various locations in this region of the sky. The photograph, which measures 13 degrees by 19 degrees, was made with a three-inch sky-patrol camera at one of Harvard's northern observing stations in Massachusetts. The Orion nebula itself (M42) is the extended spot of nebulosity surrounding the middle star of the three vertically aligned stars at the center. In classical representations of the constellation these three stars correspond to Orion's sword, which hangs from his belt, defined by the row of three brighter stars just above it. Letters refer to the tracings on the opposite page.

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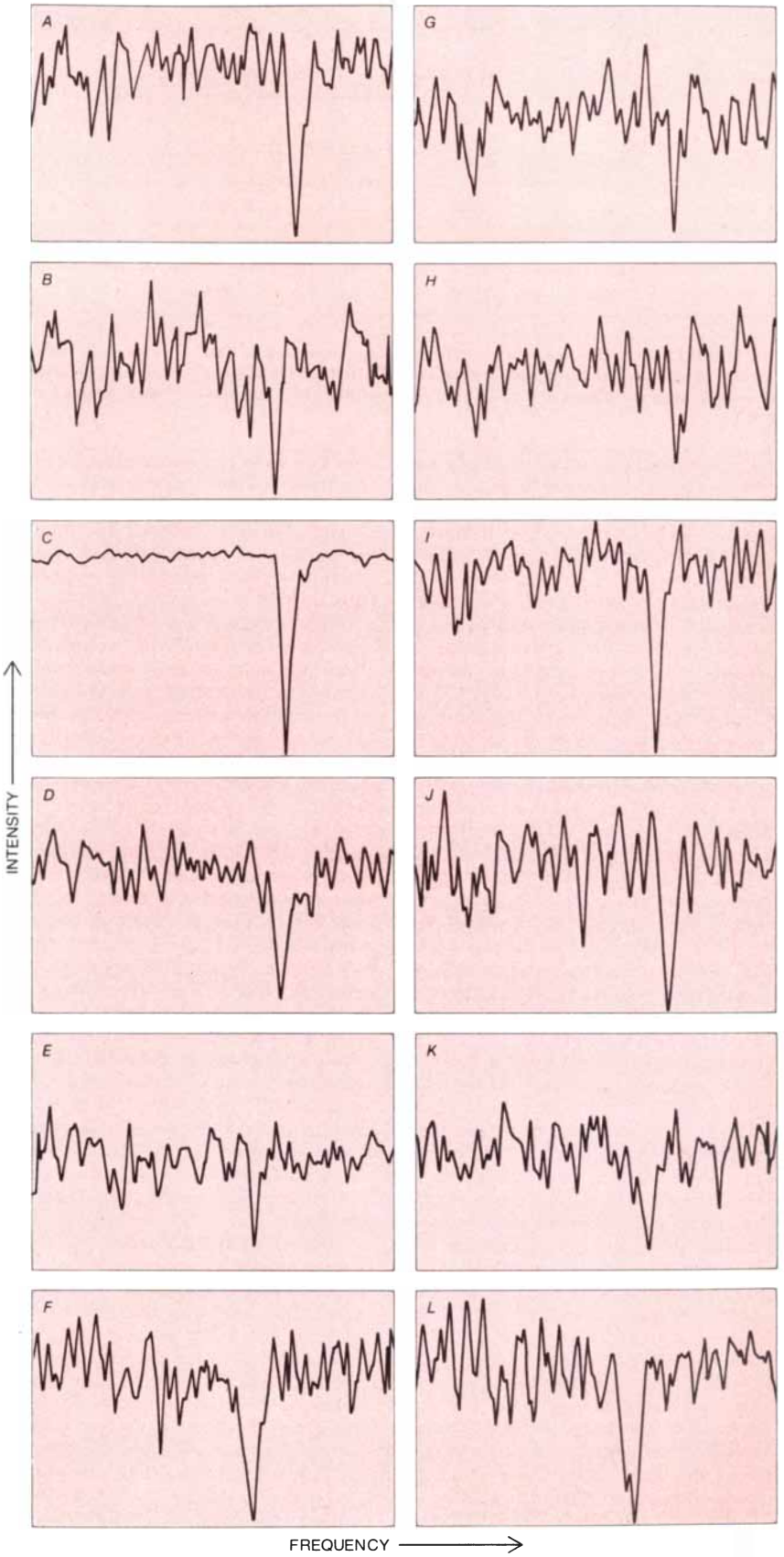
tronomy. It is in marked contrast to many areas of astrophysics for which theoretical arguments, let alone observations, can be made no more accurate than an order of magnitude. It is indeed an indication of how well radio astronomers soon hope to achieve a full understanding of matter in one of its commonest nonterrestrial forms.

To gain a complete understanding of gaseous nebulas, however, one must also examine their surrounding interstellar environment, because it is there that galactic matter condenses to form hot stars in the first place. Until recently gaseous nebulas were thought to be among the most massive objects in the galaxy. Within the past few years, however, radio astronomers have uncovered evidence for huge, dense molecular clouds that dwarf gaseous nebulas in both size and mass. Many of these molecular clouds are in the spiral arms of the galaxy, regions that are rich in gas and dust but devoid of nebulas. Several of the more prominent clouds, however, are known to be intimately associated with gaseous nebulas. In fact, it is now widely assumed that molecular clouds play an important role in the prestellar evolutionary sequence of interstellar matter. Therefore a complete understanding of gaseous nebulas necessarily includes a description of their inhomogeneous galactic environment.

There are several ways to study neutral matter near a nebula. One observational technique used to estimate obscuration along the line of sight to a nebula was noted above. Additional evidence for interstellar debris can be gleaned by visually scanning the nonuniform star field adjacent to a nebula. Numerous dark areas often obscure partly or totally an otherwise uniform distribution of background stars. For example, a zone with a low star count nearly encompasses each visual nebula illustrated here; in particular, such zones are found to the south and west of M17 and also of M20. Such inhomogeneities in the distribution of stars, including the appearance of several small blotches of complete obscuration, become even more apparent on long-exposure photographs. Another discipline where there is considerable potential for the elucidation of neutral matter near nebulas is infrared astronomy. At present infrared studies clearly imply the presence of dust, although it is not known whether the dust is mixed with the nebular gas or external to it. Actually it is still virtually impossible to determine the precise physical relation between the dusty regions of obscuring matter and the ionized regions of nebular gas.

In any case there are obvious limitations to these methods. The comparison of optical and radio radiation can be made only for those few regions where radiation can be detected visually, star



SPECTRAL FEATURES characteristic of the absorption of radio waves by interstellar formaldehyde were recorded at the 12 locations denoted by the letters in the photograph of the constellation Orion on the opposite page. All the measurements coincide with dark clouds, which serve to protect the molecules against disruption by ultraviolet radiation from the nearby stars.

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NAME OF NEBULA	MESSIER NUMBER	DISTANCE FROM EARTH (LIGHT-YEARS)	STRÖMGREN RADIUS (LIGHT-YEARS)	DENSITY (ELECTRONS PER CUBIC CENTIMETER)	MASS (MULTIPLES OF SOLAR MASS)	ELECTRON TEMPERATURE (DEGREES KELVIN)	VELOCITY OF TURBULENT GAS (KILOMETERS PER SECOND)	He^+/H^+ (PERCENT)
LAGOON	M8	3,500	4	400	60	7,500	9	9
EAGLE	M16	8,000	12	100	600	8,000	12	6
OMEGA	M17	7,000	5	800	300	8,700	17	10
TRIFID	M20	6,500	8	100	150	8,200	7	10
ORION	M42	1,500	1	2,000	10	9,000	10	9

PROPERTIES of the five representative nebulas discussed in this article are listed. The Strömgren radius, named after the astronomer Bengt Strömgren, measures the region of space within which the nebular gas is ionized by ultraviolet radiation from central star. Last column gives ratio of helium ions (He^+) to hydrogen ions (H^+) in the nebulas; average value (about 9 percent) equals cosmic He^+/H^+ ratio.

counts have only limited accuracy even for those workers eager to take on such laborious tasks and infrared astronomy so far lacks spectroscopic techniques and an adequate knowledge of the emission properties of dust particles. It appears that the observational technique currently best suited to addressing the problem of nebular environments is the radio-frequency spectroscopy of interstellar molecules.

Molecular astronomy is a new and rapidly developing interdisciplinary science. Within the past eight years more than 40 new molecular species and 100 new spectral lines have been detected by means of microwave and millimeter-wave spectroscopy. Some of these molecules, such as the hydroxyl radical (OH) and formaldehyde (H_2CO), absorb radiation from intense background radio sources. Others, such as carbon monoxide (CO), carbon monosulfide (CS), hydrogen cyanide (HCN) and methyl alcohol (CH_3OH), emit radiation of their own. Still others, such as water (H_2O) and silicon monoxide (SiO), emit intense radiation as a result of maserlike processes.

In spite of the novelty of molecular astronomy the presence of rather complex molecules in interstellar space is not very surprising. The basic physical and chemical properties of more than a million different molecules have been accumulating for years in laboratory studies, but not until recently did astrophysicists recognize that some molecules are virtually ubiquitous throughout the galaxy. Most of the chemical processes that serve to form molecules have been studied only under terrestrial conditions and hence are poorly understood in the interstellar environment, since the densities there are usually orders of magnitude less than the best vacuums achievable in terrestrial laboratories. Nevertheless, the notion that even simple molecules would be easily destroyed by interstellar radiation has now perished with the recognition that large amounts of dust not only provide suitable sites for the formation of molecules but also serve to protect molecules from the harsh radiation of interstellar space. Indeed, within the past few years it has become an observational fact that the abundance of all molecules is strongly correlated with interstellar regions of obscuration.

How can molecules be detected in the interstellar medium? One technique utilizes modifications in their electron configuration, in analogy with the electron transitions described above for atoms. These alterations, however, usually lead to high-frequency ultraviolet radiation that is scattered by interstellar debris and cannot be observed from the earth because it is completely blocked by the earth's atmosphere. Instead it is the bulk motion of the molecules themselves that generally gives rise to observable spectral lines. Molecules rotate end over end and vibrate like a coiled spring simply by virtue of their heat. They do so, however, at precise rates, according to the rules of quantum mechanics. Vibrational modes usually give rise to characteristic spectral lines in the relatively inaccessible domain of the infrared. On the other hand, a large variety of molecules, from simple diatomic inorganic molecules to complex polyatomic organic ones, rotate at specific frequencies capable of detection in the radio-frequency spectrum.

Several competing processes serve to excite molecules and thereby populate specific rotational states in much the same way that the high-level energy states of atoms are populated by radiative and collisional effects. The commonest sequence of events goes as follows. Local stellar sources of ultraviolet radiation heat the dust, which transfers energy through collisions to molecular hydrogen (H_2), the most abundant neutral molecular species, which in turn excites more complex molecules through collisions. The heat input then is primarily stellar radiation, whereas the dominant cooling mechanism is thought to result from the emission of radiation that accompanies transitions between high rotational-energy levels of carbon monoxide molecules. Dense molecular clouds, however, often become opaque to this carbon monoxide radiation, creating an imbalance in the heating-cooling competition. Lacking an effective cooling mechanism, certain parts of a cloud (the densest parts) may then begin to heat up. They are on their way to becoming stars.

The ubiquitous formaldehyde molecule serves to illustrate some of the foregoing considerations. By absorbing or emitting radiation this polyatomic molecular species can undergo a change in its rotation at the characteristic frequency (among others) of 4,830 megahertz. That frequency corresponds to a change in the molecule's rotational configuration nearly five billion times a second. Modern radio-frequency spectrometers can easily detect such radiation as an emission or absorption feature at a wavelength of about six centimeters, unscattered by interstellar debris and unattenuated by the earth's atmosphere.

Molecular lines of this type can be analyzed in much the same way that atomic lines are. Molecular-line profiles generally furnish valuable information about the temperature, the density, the composition and the motions of the molecular cloud. Furthermore, precise knowledge of the physics of the molecule under observation and of the rate of operation of the collisional scenario sketched above yields an estimate of the density of the dominant colliding species: neutral diatomic hydrogen. In this way the total density and mass of a molecular cloud can be inferred, provided that the extent of the cloud is fully delineated. In general molecular clouds are cold, dense and massive, in fact so massive that most of them dwarf their associated gaseous nebula.

In a dramatic illustration of just how large some molecular clouds can be I recently detected formaldehyde molecules at numerous locations between M16 and M8, a span of more than 11 degrees across the sky. (The full moon is

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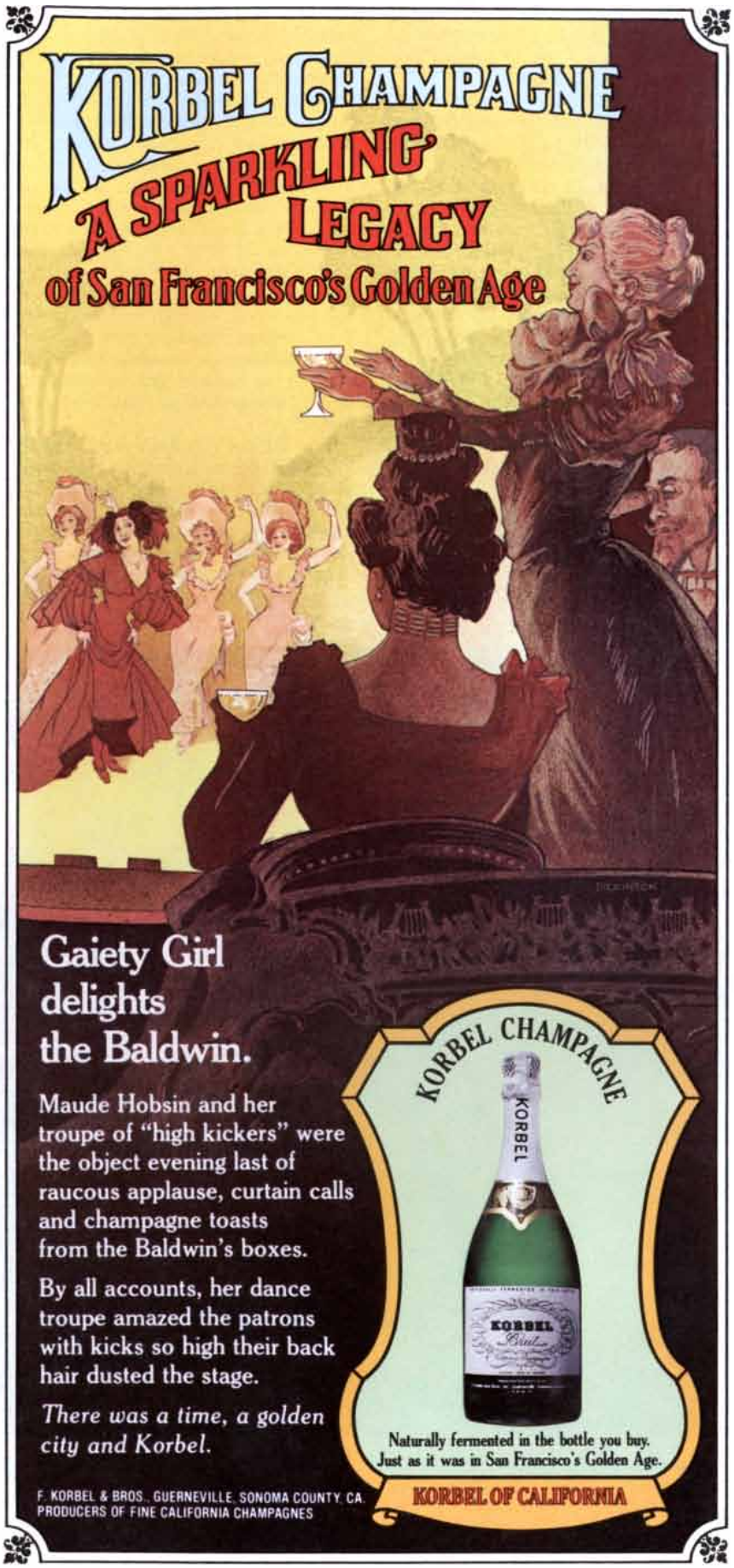
only half a degree across.) The nearly constant velocity of these features suggests that there is a giant cloud of molecular matter extending from M16 to M17, from M17 to M20 and possibly from M20 to M8. It implies that each of these nebulas arose from what was, and for the most part might still be, a single incredibly vast interstellar cloud.

At the mean distance of the nebulas (some 7,000 light-years) the cloud would have a dimension of about 1,300 light-years, at least in the plane of the sky. It is surely not a homogeneous cloud, because formaldehyde can be detected only in those places that are particularly dark and obscuring; this in itself is a remarkable demonstration of the strong correlation between the abundance of molecules and the amount of dust. The mass of this vast cloud, which is still not completely delineated, could be more than 10 million times the mass of the sun. A similarly vast molecular cloud apparently engulfs the M42 nebula and much of the constellation Orion. Our recent observations in this part of the sky show again that wherever there is a dark region there is formaldehyde, and by implication there are other molecules as well.

It is evident that our galaxy is richly populated by an assortment of molecules, mainly associated with gaseous nebulas, although some infrared objects and dark clouds devoid of nebulas harbor substantial numbers of molecules. The small kinematic (motion) differences observed in the atomic (nebular) and molecular (interstellar) velocities are not surprising, because if nebulas indeed evolve through the collapse of a molecular condensation, they will do so predominantly at the cloud's periphery, 90 percent of the mass of the uniformly dense sphere being concentrated in its outer half. Thus it seems likely that most visible nebulas, particularly those objects considered here, represent ionized foreground fragments of larger molecular clouds.

How closely do these observations match the broad scenario for star formation suggested at the beginning of this article? Consider once again the M20 complex as a representative example of a region potentially rich in newborn stars. A contour map of the concentration of formaldehyde near M20 appears to engulf this gaseous nebula from the south and west [*see illustration on next page*], mimicking the distribution of obscuration by dust. In fact, the peaks of molecular abundance coincide with a totally opaque dark blotch we have labeled M20SW. There are fewer molecules to the east and northeast of the blotch, where the density of background stars appears to be comparatively unobscured. Interestingly enough, the blue reflection nebula to the northeast of the M20 complex appears to hold enough dust to scatter starlight (much as sun-



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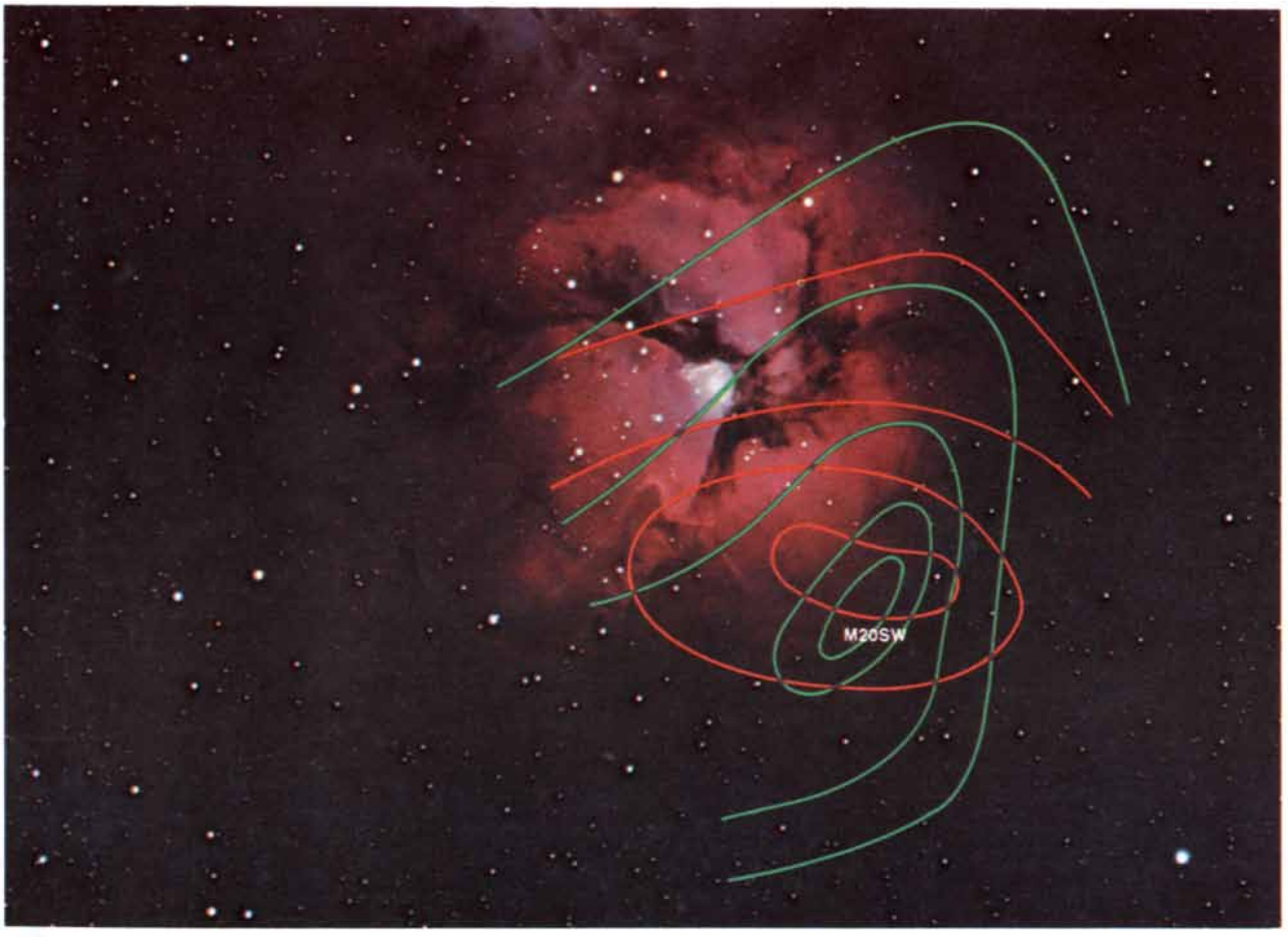
light is scattered in the earth's atmosphere to give the sky a blue tint) but not enough to protect the molecules from destruction by radiation.

The same illustration includes a map of the formaldehyde line width, which also peaks at M20SW. The common symmetry of the kinematic distribution and the molecular concentration suggests that the molecular condensation at M20SW may be in a state of gravitational collapse; at the periphery of the cloud narrower molecular features are observed because the motion of infalling material is primarily transverse to the line of sight, playing no role in the Doppler-effect broadening of the line profile. If this interpretation is correct, the M20 complex includes one of the first examples known to embody observational evidence for the interstellar evolutionary scenario I have outlined here.

A review of our findings on the M20 complex appears to provide tentative evidence for the three principal phases of star formation. In the northwest of the complex the nebular velocity of about 18 kilometers per second deduced from the analysis of radio recombination lines meshes nicely with the velocity of the adjacent molecular cloud, thereby establishing the initial or quiescent phase for which the total density is probably not very high (perhaps 100 particles per cubic centimeter). The velocity of 18 kilometers per second can be viewed as a measure of the motion of the giant interstellar cloud prior to the formation of M20's exciting star. At certain locations, for example at M20-SW, the molecular cloud has probably reached a high enough density (greater than 1,000 particles per cubic centimeter) and mass (greater than 2,000 solar masses) to initiate gravitational collapse, the intermediate phase of star formation.

The M20 nebula itself represents the final phase of star formation. The outermost contour of our eight-gigahertz radio map of the nebula shows two irregularities that could be real. The first is an outer bulge to the northeast, where photographs show some ionization and where the molecular cloud is absent or at least tenuous. The second is an inner bulge at the nebular boundary closest to M20SW. It is easy to visualize a wave of ionization created by the action of stellar ultraviolet radiation propagating into the dense molecular region near M20SW. The shock front preceding the ionization of material would certainly compress the gas and probably contribute to the enhanced density in the molecular cloud near M20SW. It is even conceivable that such a shock wave could act as a triggering mechanism for rapid star formation at that location.

Future observations of the radio waves emitted by various atomic and molecular species, particularly observations with better spatial resolution, may make possible quantitative estimates of the degree of shocklike interaction of the hot, tenuous nebular gas with the cold, dense molecular matter. It may then be possible to identify an additional phase intermediate between the collapsing phase and the nebular phase, namely a small-scale fragmentation of the cloud into individual sites of star formation.



FORMALDEHYDE IS CONCENTRATED in the vicinity of a dark region to the southwest of the center of M20, the Trifid Nebula. The green contours, which indicate an increase in radio intensity in uniform steps from the outside to the inside, show that the formaldehyde concentration reaches a peak in the zone marked M20SW. The orange contours, which also increase in uniform steps from the outside to the inside, plot the velocity distribution of the formaldehyde in terms of the Doppler broadening of the characteristic formaldehyde absorption line. Since only line-of-sight motions produce such a Doppler effect, the greater broadening of the line at M20SW implies that the cloud may be in a state of gravitational collapse at that point. The data may thus constitute evidence of the impending birth of a star.

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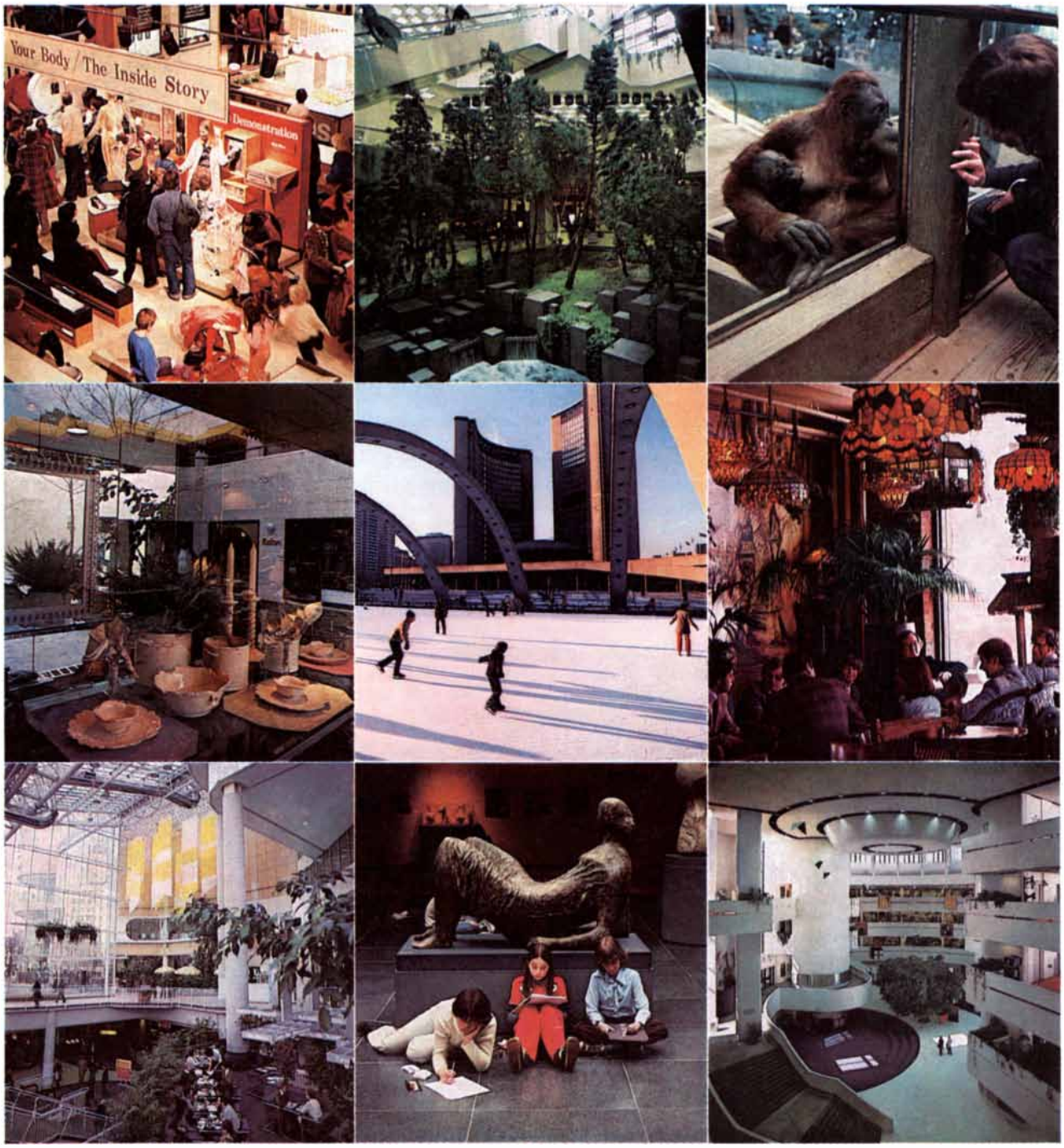

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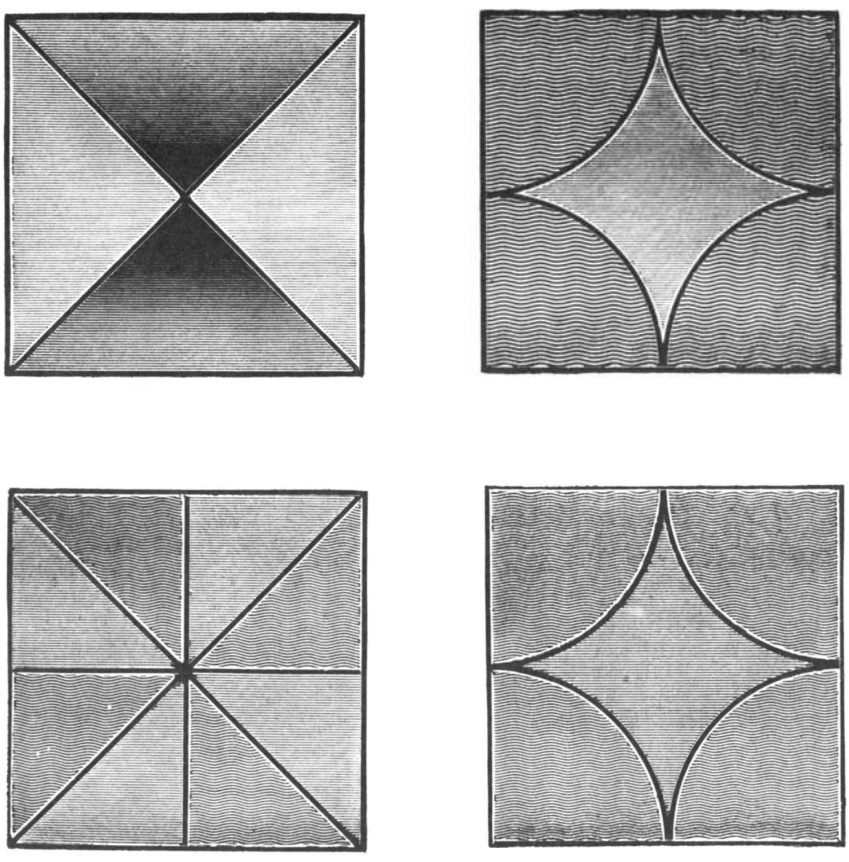
THE AMATEUR SCIENTIST

Moiré effects, the kaleidoscope and other Victorian diversions

by Jearl Walker

This month I shall discuss some classic visual toys that appeared in the 19th century. Although a few of the toys are still sold, most of them have fallen victim to newer entertainments. They are so diverting and instructive that they deserve a better fate.

One of the simplest of the visual toys involved what are now called moiré patterns, the shimmering effect one sees when certain regular patterns are laid one over the other so that in some places they are in step and in others they are out of step. A simple illustration of the effect can be seen with a haircomb. Hold the comb parallel to a mirror so that you can look through the teeth and see the image of the comb in the mirror. If the comb is the right distance from the mirror, some of the teeth in the image will coincide with the real teeth in your field of view. Other teeth will be exactly out of step with the real teeth. What you see is a periodic pattern along the comb's length. The pattern is darker where the teeth are out of step. If you move the comb parallel to the mirror, the periodic pattern of darkness (assuming the comb is dark) runs along the length of the comb in a wavelike motion.



Patterns that can give rise to moiré effects

This kind of motion was employed in illustrations published in the 19th century. A black-and-white illustration was drawn with many closely spaced parallel lines. The reader was told to place over the drawing a screen that was also covered with evenly spaced parallel lines. I am not sure what the screen was made of; it could have been glass or some kind of translucent paper. When the viewer slowly moved the screen over the drawing, the moiré pattern that developed between the screen and the drawing moved across the drawing, giving the illusion that objects in the drawing were moving.

Dover Publications has reproduced (under the title *The Magic Moving Picture Book*) a book that was originally published in London in 1898 as *The Motograph Moving Picture Book*. The transparent screen is acetate ruled with closely spaced lines. The pictures include geometric designs, a representation of an erupting volcano and a scene in which a fireman directs water at a fire. When you move the acetate over the picture of the fireman, for example, the moving moiré pattern makes the fire shimmer, the smoke rise and water on the street flow along the pavement. In other illustrations the moiré effect seems to make wheels turn and water flow past a ship.

You can easily duplicate the effect for yourself. Draw on a sheet of paper a geometric design consisting of many evenly spaced parallel lines. Then rule similar lines with comparable spacing on a sheet of transparent acetate. The acetate can be bought in an art-supply store, where you can find out what kinds of ink adhere well to acetate.

After the ink dries place the acetate on your picture and move it slowly across the picture with the lines in the acetate and the picture parallel. The pattern in the picture will wiggle and squirm. You can try several variations of the trick. Make the lines on the paper slightly more or less widely spaced than the lines on the acetate or make them wavy rather than straight. Try orienting the lines on the paper at angles different from the ones on the acetate and making composite figures consisting of areas with different orientations of lines. Finally, you can draw scenes in which only the appropriate areas show motion.

A related toy was marketed recently through "7-Eleven," the national foodstore chain, to promote a beverage. The toy, now under patent application by Magic, Magic, Magic, Unlimited, consists of two plastic cups that are nested and can be rotated individually. The outer cup is clear plastic with an area of vertical black stripes. The opaque inner cup bears two superposed drawings consisting of vertical stripes the same width as those on the outer cup.

With one orientation of the inner cup

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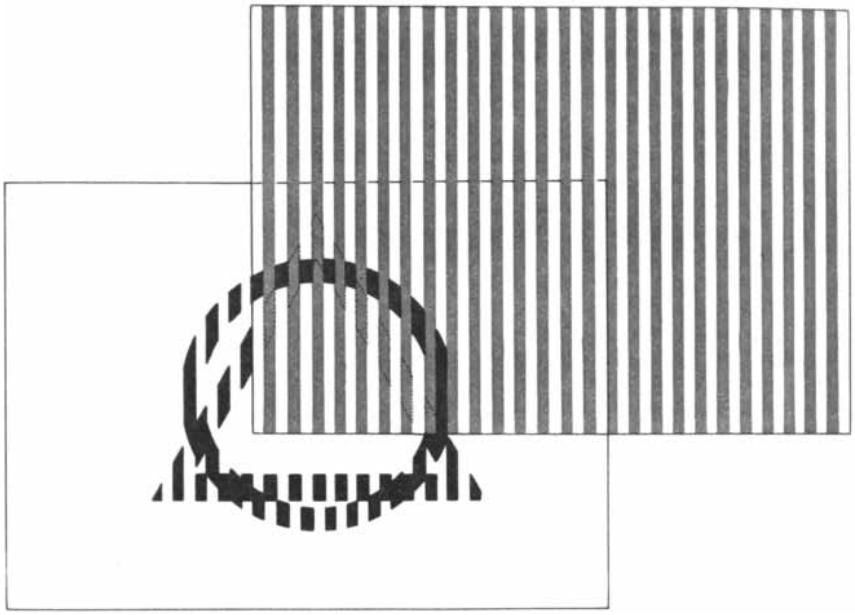
the black stripes block all the vertical segments of one of the drawings and expose all the segments of the other drawing. From a distance of a foot or so the viewer sees a nearly complete picture because the black stripes are apparently ignored and the viewer mentally completes the picture across the stripes. By rotating the inner cup the viewer can replace the exposed segments of one picture with those of the other. Slowly continuing the rotation alternates the exposure of the two pictures. On my cup a baseball player is either bending down to field a ball or is standing. When I rotate the inner cup, he appears to alternate between the two poses.

A large variety of changeable pictures were available in Victorian times. The simplest kind involved nothing more than a picture that had several slits through which segments of an alternate picture could be slipped. Motion was better suggested by the slipping slides developed for the "magic lantern," which today is called a slide projector. These consisted of a glass slide with a scene painted on it and a second slide that could be slipped in front of the first one. The second slide bore the element of the composite picture that was to be moved. When the slide was projected, the operator could slip the second slide over the first to give motion to the projection.

You can easily duplicate this system with most slide projectors. In the book *Making Victorian Kinetic Toys* Philip and Caroline Freeman Sayer suggest using the thin sheets of glass from the mounts for 35-millimeter slides. Buy a translucent paint that adheres to glass and does not degrade in the heat of a slide projector. Paint the fixed scene on one sheet of glass. You may want to trim the other sheet so that there is more room for sliding it. Attach to that sheet a convenient handle, such as a plastic toothpick, so that when both sheets have been inserted into the slide holder of the projector, you can move the second sheet by the handle.

One Victorian visual toy, the kaleidoscope, is still popular. It was invented (or at least patented) in 1816 by David Brewster, who is best remembered for his work in classical optics and particularly for the Brewster angle of the polarization of light by reflection. Although there are many variations on the kaleidoscope theme, the basic design is a tube containing two rectangular mirrors or pieces of shiny metal taped together at an angle of about 45 degrees with the taped edges running the length of the tube. At one end of the tube is a compartment containing bits of colored glass or other material. At the other end is a small hole through which the viewer peers. One can see a pie-shaped section of the bits of material at the other end and reflections of the same segment in the mirrors. When the tube is rotated, the symmetrical pattern shifts as the bits of material fall into different configurations.



Intermixed patterns

Designs for a homemade kaleidoscope are available in Carson I. A. Ritchie's excellent book *Making Scientific Toys.* Cut off the bottom of a fairly long plastic bottle with a narrow neck opening. The bottle will serve as the tube and the opening will be the aperture through which you will look. Inside the tube will be two rectangular mirrors with their edges at an angle of between 40 and 70 degrees. The bottle should be about a centimeter longer than the mirrors once they are fitted in.

Put the cutoff end of the bottle on a sheet of 1/8-inch Plexiglas, trace a circle on the Plexiglas around the circumference of the bottle and then with a jigsaw cut out the circle of Plexiglas. File the edge until the piece just fits inside the bottle.

Hinge the two mirrors together with strong reinforced tape. Put the Plexiglas piece on a table, stand the mirrors upright on it and fasten them to it by gluing some small wood blocks into the angle between them and the piece. The blocks will also fix the angle between the mirrors. Your results will be best if you have positioned the mirrors so that both edges of each touch the circumference of the circle. When the glue of the assembly has dried, push the assembly into the bottle (Plexiglas end last) as far as it will go. Now make another Plexiglas circle of the same size, but instead of leaving it transparent rub it with steel wool to make it translucent. This piece will be the end of the kaleidoscope.

To make a compartment for the bits of colored glass cut out a strip of stiff cardboard that is long enough to be fashioned into a ring to fit in the bottle between the two Plexiglas circles. The cardboard should not stick out of the end of the bottle. Glue the ring to the translucent piece of Plexiglas. Put into the ring a few bits of colored glass and slip the ring into the end of the bottle. You now have a kaleidoscope with a changeable display.

To investigate the effect of the angle between the mirrors you might prefer to work with a simpler arrangement. Hinge the two mirrors together and stand them upright on a geometric design drawn on a piece of paper. Look down into the trough formed by the mirrors to see the kaleidoscope design. How many pie-shaped sections do you see for a given angle between the mirrors? Try varying the angle from the smallest one you can achieve to one as close to 90 degrees as is possible, recording the number of images as a function of the angle. Do all the pie sections have the same angular width? In particular, is the pie section lying behind the hinge of the mirror the same size as the other sections?

One of the best kaleidoscopes I have found has a lens at the far end instead of a container. (I think the device is properly called a teleidoscope, but I am not certain.) The focal length of the lens is less than the length of the tube. When a fairly distant object is viewed with the device, the image size is reduced by the lens so that many such objects can be seen simultaneously. To me the effect is beautiful, since it is brighter and more colorful than the images in a standard

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kaleidoscope, where the bits of colored glass and the translucent backing reduce the intensity of the light. If I watch passing scenery with the device as I ride in a car, the constantly varying display is almost psychedelic.

You can make this kind of kaleidoscope out of a cheap lens, a cardboard tube and the usual two mirrors. Choose the lens and the tube so that the focal point is about halfway down the length of the tube. The opening at the viewing end of the tube should be small but should still be large enough for you to see all the image, including the reflections in the mirrors.

An enormously popular diversion in the late 19th century was viewing photographs in a stereoscope. In his book Ritchie gives plans for making replicas of the old stereoscopes. You can find old stereoscopes and stereo cards in antique shops, and you can buy replicas from Stereo Classics Studio, Inc., 145 Algonquin Parkway, Whippany, N.J. 07981. The commonest kind of stereoscope has two lenses, one for each eye, through which a viewer sees two pictures, one for each eye. The pictures are not identical but give slightly different perspectives of the same scene to match the perspectives each eye would see in the same setting. Hence when the pictures are fused by the stereoscope, they are seen in the original three dimensions.

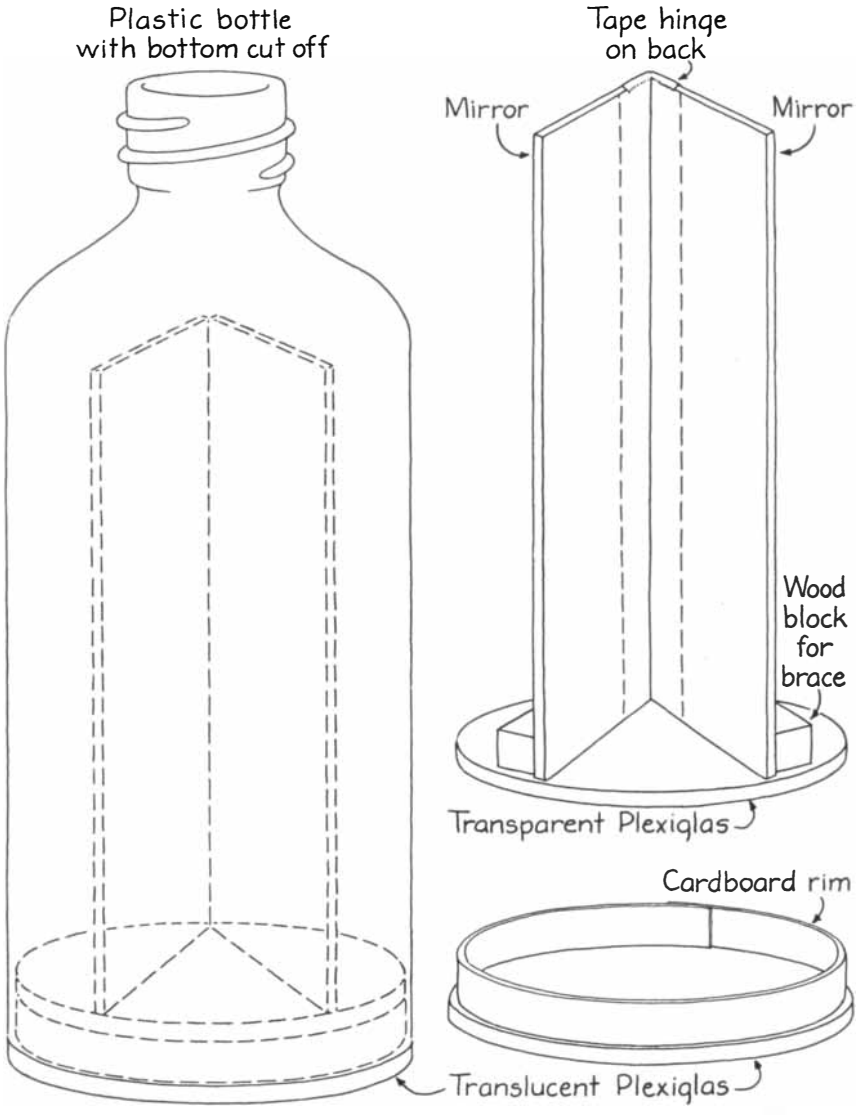
Budd Wentz describes a simple procedure for making a different type of stereoscope in his book *Ready-to-Make Photo & Scene Machines*. The viewer looks through a piece of cardboard resembling a Halloween mask. One purpose of the mask is to eliminate distractions so that the viewer can concentrate on details that help him in assigning depth to the objects in the picture.

In the center of the mask there is a length of stiff cardboard that has a flat mirror glued or taped to one side. The idea is to view one picture directly with one eye while viewing a reflection of the other picture in the mirror with the other eye. This system forces the eyes to converge, which in turn helps the viewer to assign depth to the pictures. As before, the two pictures show slightly different perspectives, but in addition one of them must be "flopped" (left and right reversed) so that it has the same orientation as the other one after reflection. If everything is done right, the viewer fuses the two images to get a single three-dimensional image. Wentz provides reproductions of some of the stereo cards that were popular with this type of device in the late 19th century and early 20th.

The standard stereoscope available in antique shops is different from Wentz's in that it has two wedge-shaped lenses to facilitate the merging of the different images seen by the viewer. Both pictures have the same orientation, since no reflection is involved. This kind of stereoscope was apparently developed in 1859 by Oliver Wendell Holmes, partly on the basis of earlier work by Brewster. Photographs were usually made with a camera that had two lenses, which were separated from each other by about the distance between the eyes of an average person. The focal lengths of the lenses in the camera and in the stereoscope were the same, so that the viewer saw the same perspective the camera did. The photographs could also be obtained with an ordinary camera by making one photograph and then moving the camera seven or eight centimeters to the side to make the other.

Thomas B. Greenslade, Jr., and Merritt W. Green III have published an account of their experiments with this type of stereoscope and their attempts at making photographs for it. You might like to follow up on some of their work either with an antique stereoscope or with a stereoscope you have made. If you make one, Ritchie suggests that you have an optician grind the lenses. His specifications for the lenses are "power approximately flat B 1/SPH + 5.50, lens cut on optical center, 8 base out E/E 47 pound blank." You might try to work with some wedge-shaped glass prisms instead.

Greenslade and Green were able to make their photographs with a Polaroid camera (Model 180) that had a lens with a focal length close to that of the antique stereoscope they had bought. In one experiment they wanted to ascertain how the lateral displacement of camera positions between successive photographs affected the quality of the three-dimensional illusion. Ideally the displacement should match the distance between the viewer's eyes, but depth appeared in the



Carson I. A. Ritchie's design for a homemade kaleidoscope

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pictures even when the camera displacement was more than or less than the ideal distance. With a large displacement, however, the objects in the photographs became "unreal" in proportion from front to rear because the larger separation gave them too much depth.

Greenslade and Green also found that stereo photographs could be made by rotating the camera through a small angle (they made it 7.7 degrees) between successive photographs. The rotation apparently altered the perspective enough for the viewer to be able to perceive depth when he made the two photographs fuse. You might want to experiment with a range of angles to see if the three-dimensional effect persists and if large angles give rise to distortions in the perceived view.

I had easy success with a Polaroid Model 104, making street-scene stereo photographs holding the camera by hand. Using a tripod to displace or rotate the camera would undoubtedly improve the quality of the pictures, but the three-dimensional illusion was readily apparent even with my casual efforts. I aligned the left side of the camera's field of view on an object and made one photograph. Then I rotated the camera five or 10 degrees to the left, aligned it so that the reference object was at the same height in the field of view and made the second photograph.

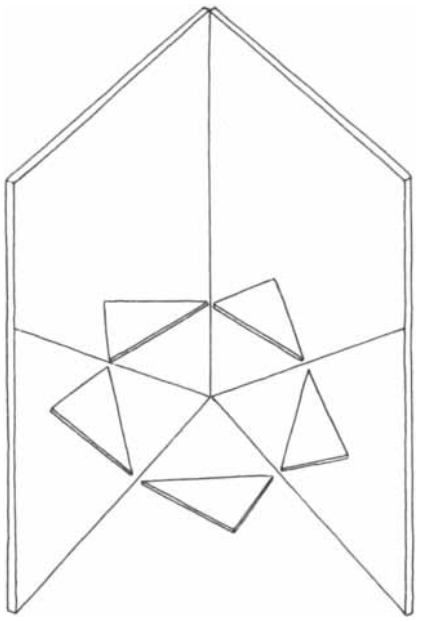
Next I trimmed the white edges off the photographs and put them in the stereoscope. As I viewed the pictures through the instrument I slid one of them across my field of view until it approached the correct position, whereupon the photographs suddenly snapped together into a single image with depth. Then I taped the pictures together and mounted them on stiff cardboard to keep them at the right spacing.

When the photographs were correctly positioned, my left eye saw more of the left side of the scene than my right eye did. This difference is automatic if you rotate or laterally displace the camera. Even if I photographed exactly the same scene without moving the camera between successive exposures, I could still get a reasonably good three-dimensional illusion by fiddling with the position of the photographs in my stereoscope. I find, however, that this does not work for everyone.

Making your own stereo cards is great fun. You could even use an old Polaroid snapshot if you have it duplicated, either by Polaroid or by making a photograph of it yourself. For new pairs of photographs the best type of scene to shoot is one with objects in both the foreground and the background.

You normally assign depth to a scene with the aid of several clues, among them the fact that you usually know the relative sizes of the objects you see and so can judge their distance partly by the relative angles they subtend in your field of view. Also of help are shadows and the converging geometry of things such as walls and roads as they are seen receding from you.

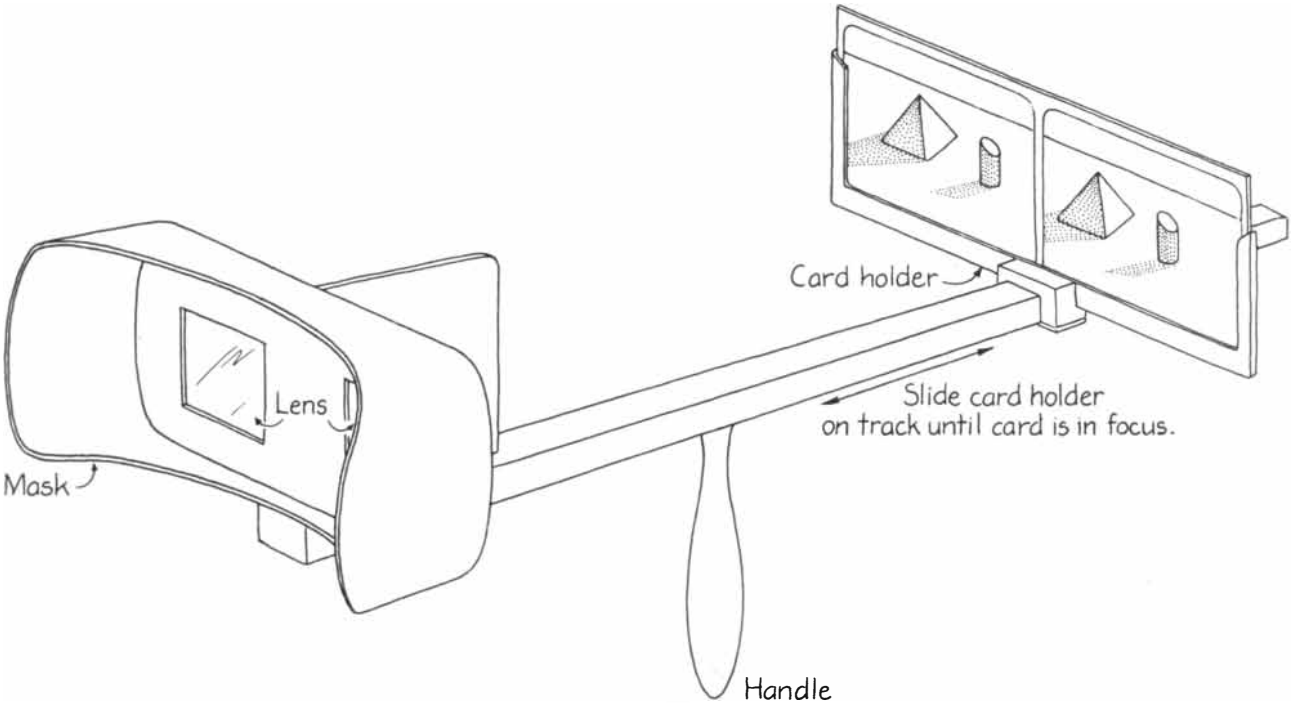
You also unconsciously sense the accommodation and convergence of your eyes as you view an object in a scene.



A multiple-reflection pattern

Accommodation reflects the amount of muscular stress that must be placed on the crystalline lens of the eye to alter its shape so that the image of the object is in focus on your retina. This clue to the depth does not depend on an interplay between the two eyes; it is monocular.

Convergence is a binocular clue, having to do with the angle between the optical axes of the eyes. The axis is an imaginary line running through the cen-



Components of a stereoscope

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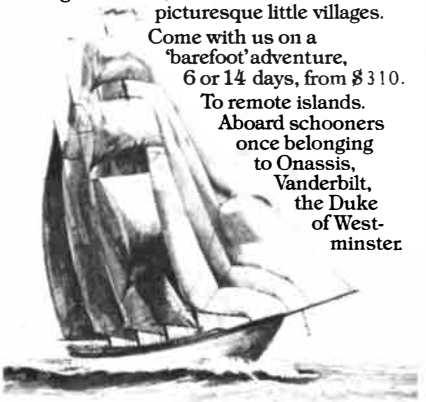

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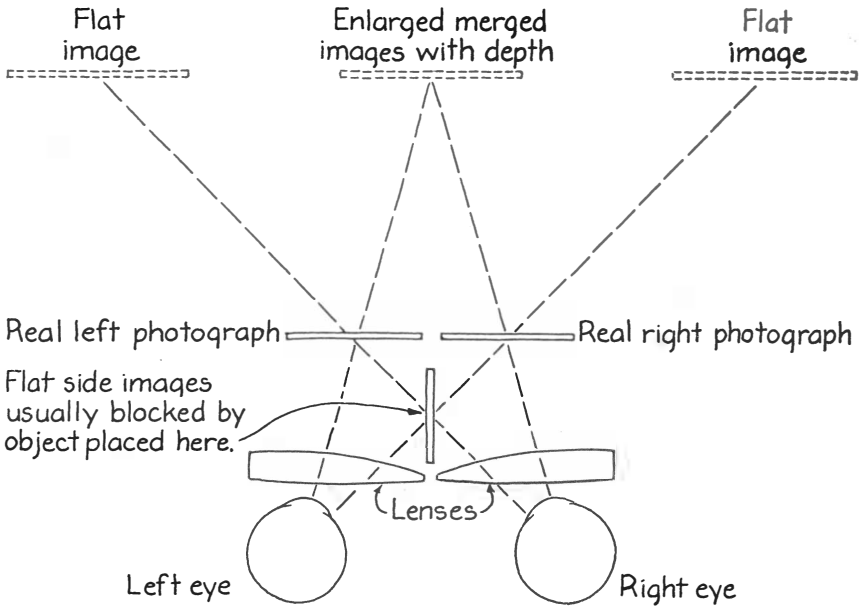

Optics of a stereoscope

ter of the lens and into the fovea, the pitlike depression on the retina where the photoreceptors are the most densely packed. Normal viewing involves moving the eyes to the left or the right until the image of the object falls on the fovea. For a distant object the optical axes from the two eyes are nearly parallel. For a nearby object they are at a significant angle. The muscle control necessary to make the optical axes converge on an object helps you to gauge the distance of the object.

Suppose you view a collection of objects that are at different distances. You will have a sense of their different depths even if you do not look at them individually because the positions of their images on the retina around the fovea will be different for the two eyes simply because of the separation of the eyes. The difference in position with respect to the fovea will be greater for a nearby object than for a distant one. Through this effect the brain can assign proper depths to the objects.

In re-creating depth from a two-dimensional photograph the problem is to trick the brain into ignoring the clues that suggest it is seeing a photograph. When you look at a photograph, both the focusing of each eye and the convergence between them tell you that you are looking at a photograph rather than a real scene. Two adjacent photographs are no better; your brain knows you are only looking at two adjacent photographs.

The stereoscope enables you to focus on the photographs while you are forcing your eyes to converge; the result is that the images occupy the same positions on the retinas they would occupy if you were viewing the real scene. This clue is so strong, at least for people who can see the three-dimensional illusion, that you are convinced there is depth in the fused pictures. The brain so wants to assign depth that the photographs in the stereoscope do not have to be exactly in their proper position. As they come close to the proper position the brain suddenly snaps their images together and immediately begins to assign depth. It apparently can do this to some degree even with photographs that are exact duplicates.

Although a stereoscope is a convenient means of getting the illusion, it is not strictly necessary. You can see depth in a stereo card alone by means of a simple trick. After focusing your eyes on an object about five feet away quickly slip a stereo card into your field of view. As you are focusing on it, try to maintain the same convergence of your eyes as you had for the object at five feet. With some practice this trick will enable you to merge two images from the stereo card into a single image having depth, just as you do with a stereoscope. I can actually create this three-dimensional illusion at will and without the trick by merely staring at a stereo card while deliberately adjusting the convergence of my eyes until the two images, one from each eye, merge.

With either the trick or the brute-force technique what you see is noticeably different from the illusion in the stereoscope. Without the instrument you see, on each side of the image with depth, an additional two-dimensional image of the scene in the stereo card. Greenslade and Green offer a demonstration to explain the two flat images. Focus your eyes on an object about five feet away, simultaneously holding two pencils vertically about 10 inches in front of your eyes and about three

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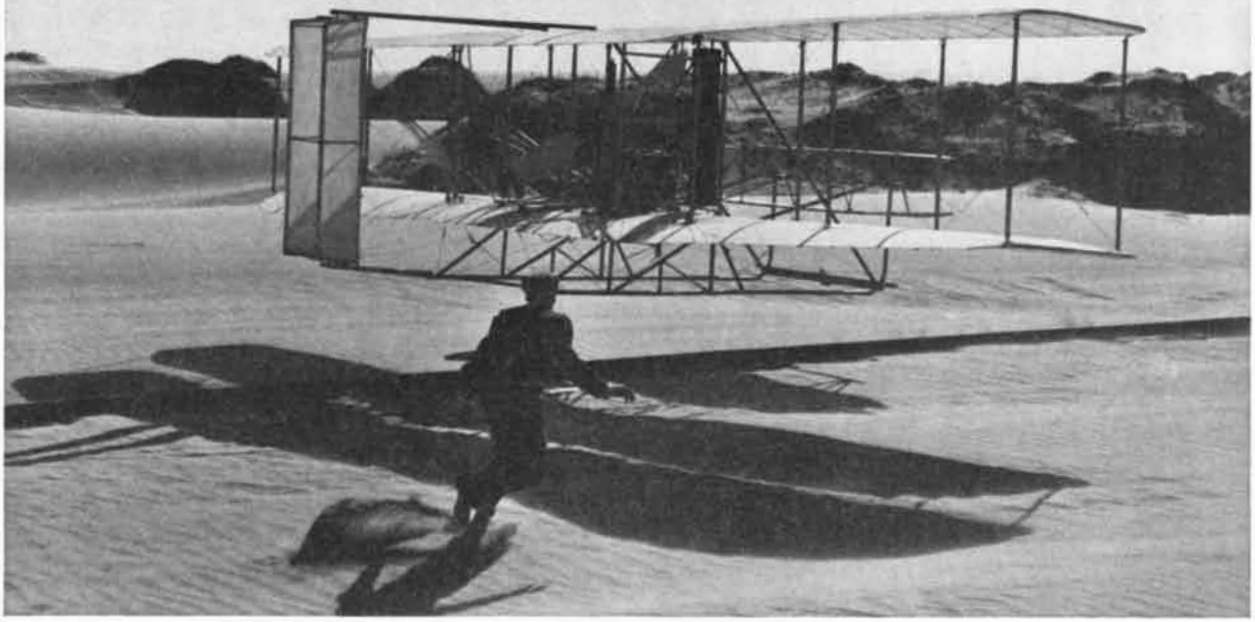

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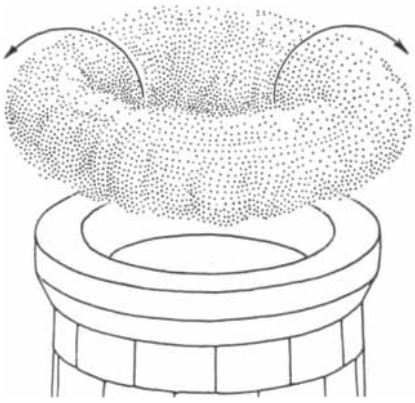


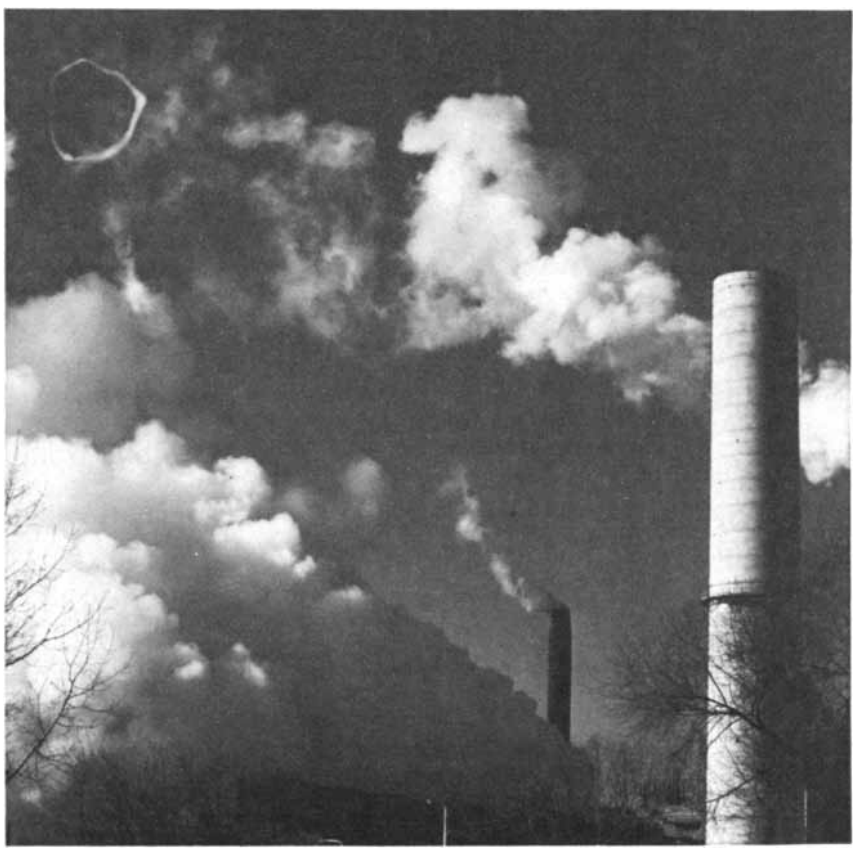
A smoke-ring vortex

inches apart. You will notice that you see not two pencil images but four, two with each eye. As you concentrate on the distant object, move the pencils closer together until the two inner images merge. It is this merging of images that forms the three-dimensional image when you view stereo cards through a stereoscope. With the pencils the two outer images are still present: the left image is the left pencil as seen by the right eye and the right image is the right pencil as seen by the left eye. In the stereoscope those two outer and distracting images are eliminated by the thin wall in the apparatus that is positioned between the eyes and perpendicular to the face.

In May I discussed the shape of smoke plumes from chimneys under various vertical temperature profiles. G. Frederick Stork of Chevy Chase, Md., has sent me a photograph of a rare occurrence: a smoke ring. Although he did not see the emergence of the ring, he and I believe it must have been blown from the chimney that appears in the foreground. As a puff of hot gas is sent through a circular opening the viscosity between the wall and the gases adjacent to the wall forces those gases to move slower than the gases in the center, causing the latter to curl around the former once they have emerged. The curling creates the ring structure. The stack must have somehow condensed water in the puff and so made the ring visible.

As many readers pointed out, I should make three corrections in my July article about chemical oscillations: (1) The oxidation of a chemical means that electrons are removed and reduction means that electrons are added, not vice versa. (2) A two-normal solution of sulfuric acid is equivalent to a one-molar solution, not the other way around. (3) In adding Tritox X-100 surfactant or "photoflo" in A. T. Winfree's oscillator use one microgram per liter.

Winfree still has samples of his chemical waves for which you can send. In-



G. Frederick Stork's photograph of a smokestack's smoke ring

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lled by Modern Photography "the best" the Questar 700 is unique in inging to the telephoto market a lens that guarantees theoretical optical rfection and flatness of field from edge to edge, with no linear distortion. ecise focusing from infinity down to 10 feet is accomplished with a single rn of the focusing ring, and at the 10-foot distance the image magnifi- tion is 1:4, an unheard-of ratio in telephoto lenses. Only Questar can eliver such performance. With its standard screw-thread T-mount adapter stem, the Questar 700 can be connected to virtually every 35 mm SLR mera. Write for our literature: Questar Corporation, Box Q700, New ope, PA 18938.

Specifications

Number of Elements	4	Angle of Acceptance	3° 25'
Focal Length	700 mm.	Length	8 inches
Aperture Range	f8	Diameter	4⅛ inches
Clear Aperture	88.9 mm.	Weight	4 pounds
Minimum Focusing Distance	10 feet	Filter Provisions	35 mm.

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formation on ordering these beautiful and inexpensive samples appears on page 156 of the July issue.

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Television broadcasting direct from satellites to schools, hospitals, hotel and motel chains, and other institutional users may be one result of a new NASA program. Hughes will develop for NASA's Goddard Space Flight Center a low-cost, mass-producible 12-GHz receiver for TV reception from broadcast satellites. Objective: a smaller, less expensive receiver to sell for under $1000. Current ground terminals are in the 4-GHz frequency range, and cost between $20,000 and $30,000. The higher frequency range has already been approved by the FCC for domestic TV satellite systems.

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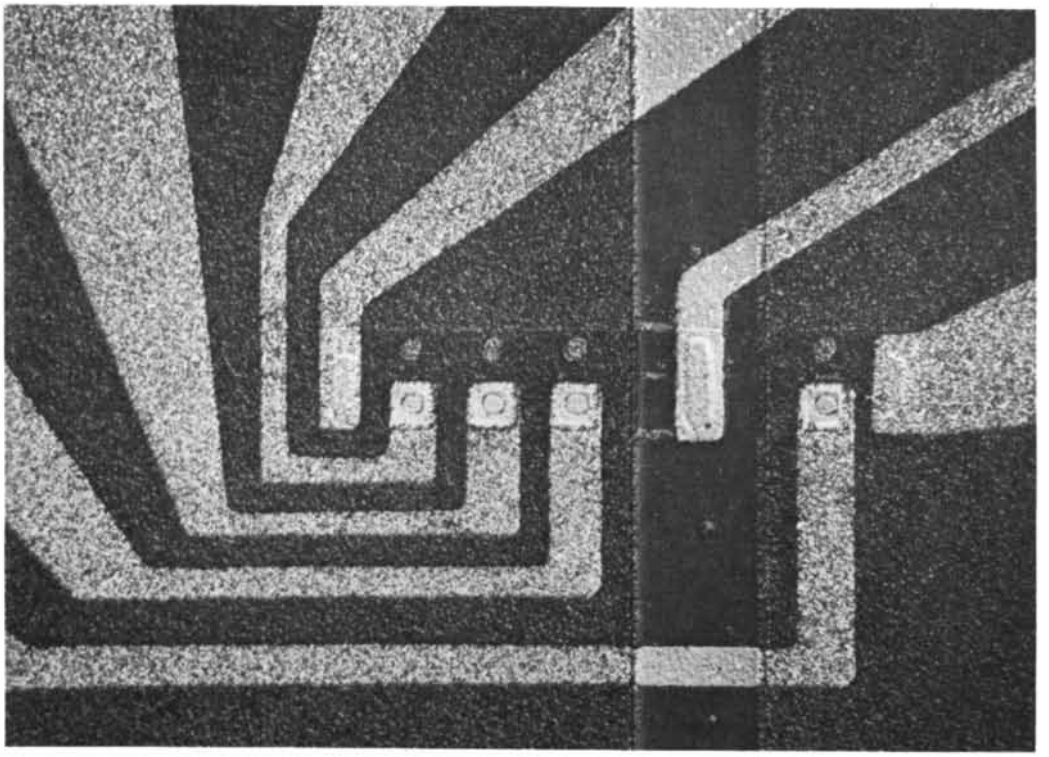

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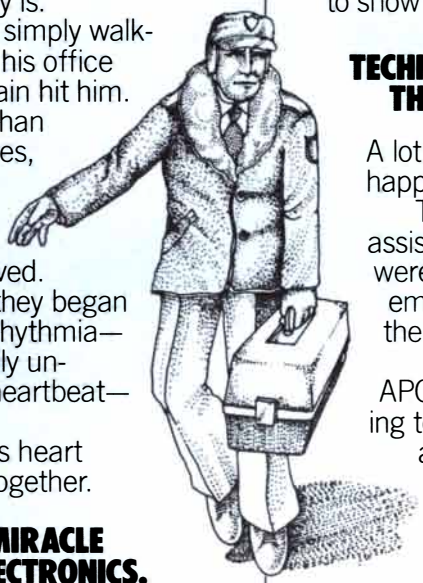

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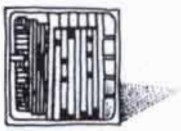

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