loss of dimensionality." Youth is more chaotic than old age.

Experiments on pituitary cells grown in vitro have shown that healthy cells obey the chemical orders of their natural regulators, but tumor cells have a rhythmic activity that does not respond to the regulators. Their behavior is locked into a fixed rhythm.

Even the most enthusiastic researchers in the field believe it will be a long time before the increasing understanding of the body's complicated dynamics will pay off with better diagnostics and treatment. "The gap between lab and clinic will be very great," Rapp says. But some of the possible applications are already being discussed.

The first are likely to be diagnostic. Goldberger hopes that by testing for lowered dimensions in EKGs, doctors eventually will be able to pick out those patients most at risk of a heart attack. The same type of test might be able to predict the approach of a seizure in epileptics.

Insight into the body's rhythms might also help improve the effectiveness of current treatment. Glass and Mackey in *From Clocks to Chaos: The Rhythms of Life* (reviewed on page 675) suggest that one of the reasons the survival rate for patients with chronic myelogenous leukemia is no better now than it was from 1910 to 1948 is the oscillations in the numbers of white blood cells, which doctors do not take into account in treatment. "One possible explanation is that some patients die because of the therapy much sooner than if they had been left alone, while others have their life-span increased," they write. Understanding the natural rhythms of the white blood cell control system could lead to a more effective therapy, they suggest. Eventually, doctors might use their knowledge of natural physiological rhythms in such procedures as setting a pacemaker, administering insulin, suppressing tremors, treating epileptics, or even adjusting out-of-sync circadian rhythms.

■ ROBERT POOL

ADDITIONAL READING

A. Babloyantz and A. Destexhe, "Low-Dimensional chaos in an instance of epilepsy," *Proc. Natl. Acad. Sci. U.S.A.* **83**, 3513 (1986).

A. L. Goldberger, V. Bhargava, B. J. West, A. J. Mandell, "On a mechanism of cardiac electrical stability," *Biophys. J.* **48**, 525 (1985).

A. L. Goldberger and D. R. Rigney, "On the nonlinear motions of the heart: Fractals, chaos and cardiac dynamics," to appear in *Theoretical Models for Cell-to-Cell Signalling* (Academic Press, New York, in press).

A. L. Goldberger and B. J. West, "Applications of nonlinear dynamics to clinical cardiology," *Ann. N.Y. Acad. Sci.* **504**, 195 (1987).

P. E. Rapp *et al.*, "Experimental studies of chaotic neural behavior: Cellular activity and electroencephalographic signals," *Nonlinear Oscillations in Biology and Chemistry* (Springer-Verlag, Berlin 1985).

C. A. Skarda and W. J. Freeman, "How brains make chaos in order to make sense of the world," *Behav. Brain Sci.* **10**, 161 (1987).

Collision and Cannibalism Shape the Galaxies

Collisions among galaxies are turning out to be a frequent event; they may even explain why galaxies are the way they are

LIKE CORPORATIONS caught up in a frenzy of leveraged buy outs, galaxies seem to spend their lives amidst the constant chaos of collision, disruption, merger, and outright cannibalism.

Indeed, observations increasingly suggest that the brightest and blandest galaxies, the blob-like ellipticals, are in fact the biggest cannibals of all: they are cosmic conglomerates that achieved their present bulk by the simple expedient of swallowing everything in reach. And at least a few astronomers now argue that *all* galaxies grew this way, including our own.

"[The evidence] is not nearly a proof. But it is tantalizing," says François Schweizer of the Carnegie Institution of Washington, who has done a good deal of the observational work in this area, and who recently gave an invited review talk at the meeting of the American Astronomical Society in Boston.* Sharing the podium on that occasion was Alar Toomre of the Massachusetts Institute of Technology, who was has long been a leader in the theoretical analysis of galaxy collisions.

Schweizer and Toomre noted that the basic idea of colliding galaxies is an old one. After all, the very fact that galaxies are randomly darting around at hundreds of kilometers per second means that collisions are inevitable. Moreover, astronomers have known for generations that certain close pairs of galaxies are connected by bridges and streamers of stars. Such galaxies are obviously interacting.

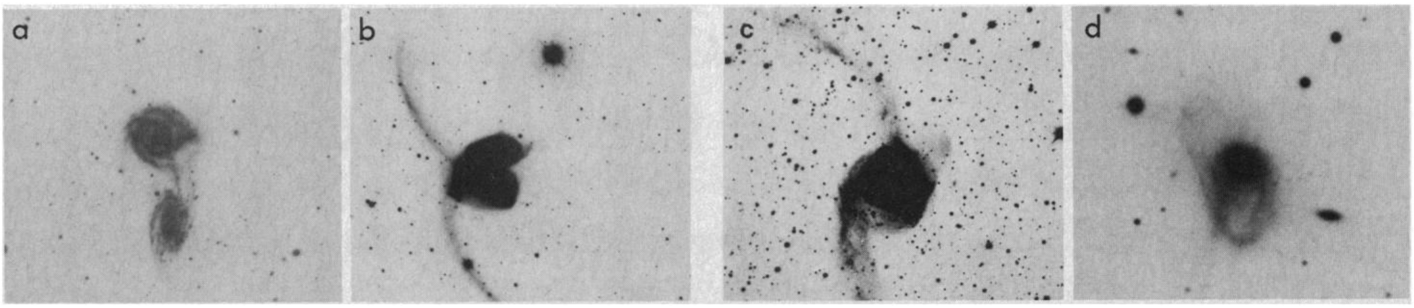
However, the full significance of collisions was not really appreciated until the early 1970s, when Alar Toomre and his brother Juri Toomre of the University of Colorado in Boulder performed a series of pioneering computer simulations of the process. By varying such details as the velocities, the masses, and the relative orientation of the colliding galaxies, the Toomre brothers found that pure gravitational interactions could produce the most amazing variety of effects—everything from simple bridges of stars, to long "rat tails" arcing off at odd angles, to circular "smoke rings" of stars orbiting over the poles of the remnant galaxy at right angles to its main rotation. Furthermore, every one of these effects had already been seen in the sky, where they had seemed so incomprehensible that astronomers began to speculate about mysterious explosions and totally new physical principles. The most famous compendium of such objects, *The Atlas of Peculiar Galaxies* compiled in the 1960s by Halton Arp of the Max Planck Institute for Astrophysics in Munich, reads in retrospect like a textbook on collision phenomena.

In the years since then the art of simulation has improved markedly, says Toomre, as better algorithms and faster computers have allowed researchers to model the colliding galaxies with more precision and realism. And in the meantime, says Schweizer, observational evidence for the ubiquity of collisions has continued to pile up.

When quasars are studied with modern imaging techniques, for example, one often finds that these brilliant energy sources are buried at the center of disturbed galaxies possessing loops and streamers exactly like those in the computer models. The presumption is that the galaxy has recently suffered a collision. And indeed, this interpretation fits in well with the prevailing theory of quasars. The idea is that a quasar's ferocious luminosity is generated by a billion-solar-mass black hole, which pulls in gas and stars from the surrounding galaxy and then converts much of their mass into radiant energy just before swallowing them. The theory presumes that the ill-fated stars and gas can somehow be nudged out of their stable orbits in the host galaxy and deflected into the black hole. And collisions, of course, are an excellent way of doing just that.

Still another piece of evidence regarding the frequency of collisions was provided in 1983 by the Infrared Astronomy Satellite (IRAS), which made the first full-scale survey of the sky at infrared wavelengths. Among the sources detected by IRAS was a large population of galaxies that appeared to be unusually bright in the infrared. Few of them had been bright enough to attract

*The 173rd meeting of the American Astronomical Society, 8 to 12 January 1989, Boston.



François Schweizer

Galaxies in collision. *In (a) a merger has just begun; in (d) another merger is almost finished. The other galaxies are in between.*

much attention in optical surveys. But when examined more closely, a great many of them proved to be involved in collisions. In each case, the shock of collision had apparently compressed the galaxies' interstellar gas into dense clouds, which had then collapsed further under the force of gravity to form new stars. This burst of infant stars, in turn, had warmed the remaining gas to produce the infrared glow.

The upshot of all this is that galactic collisions and mergers are now universally accepted among astronomers as frequent and important events. The controversies only start when one asks, How important?

At the heart of the controversy is a longstanding puzzle: why do galaxies come in two basic varieties, elliptical and spiral? Ellipticals, as the name suggests, are featureless, rather fuzzy-looking ovals that rotate slowly, if at all. Their stars tend to be old and reddish. And by no coincidence, they contain very few interstellar gas clouds; the presumption is that most of their gas condensed into stars long ago. On the other hand, ellipticals can also be incredibly bright and massive. The very biggest of them far outrank the biggest spirals.

Spirals, of course, are the showy pinwheels familiar from innumerable posters and photographs. Our own Milky Way is a typical example of one. The pinwheel part, known more formally as the disk, has a large population of mature stars like the sun, as well as a substantial quantity of interstellar gas. The gas provides the raw material for vigorous star formation. Indeed, the spiral arms trace out waves of star formation; that is why they are so bright. The disk also rotates quite rapidly on a cosmic time scale. (Our solar system takes about 200 million years to go around once.) And in most spirals the disk is very thin in comparison to its diameter, having roughly the proportions of a long-playing phonograph record.

Leaving aside a population of small irregular galaxies, whose numbers are not well known, spirals comprise about 80% of all galaxies and ellipticals about 20%. However, this may not be quite the same thing as saying that spirals outnumber the ellipticals. At the center of every spiral, looking like the yolk of a fried egg, is an oval of ancient stars known as the bulge. In some galaxies it is tiny, and in others it is huge, almost overwhelming the disk. But in all cases, the spiral bulges show a remarkable resemblance to elliptical galaxies. Indeed, one can plausibly argue that spiral bulges *are* elliptical galaxies that just happen to be sitting in the middle of a disk. The trick is to figure out why and how this came about.

The conventional wisdom on this subject is that the ellipticals formed first and that some of the smaller ellipticals later managed to pull in enough extra gas to form disks. But now, says Schweizer, one can think about turning that scenario on its head. Perhaps the spirals formed first, and then the ellipticals formed later out of the mergers.

There are several lines of argument that make this plausible, he says. For example, ellipticals are more common in dense clusters where collisions are presumably more frequent. Moreover, computer simulations show that colliding spirals will often coalesce into an elliptical-like blob. And as the Toomre brothers first pointed out in the early 1970s, one can use the observed rate of galactic collisions today to estimate the total number of collisions over the lifetime of the universe. The answer comes out to be roughly the same as the observed number of ellipticals. So if the collision remnants did not become ellipticals—where are they?

But going beyond mere plausibility, says Schweizer, a number of independent observers have recently begun to turn up more direct evidence. When long-exposure images are made of their faint outer regions, for example, many ellipticals take on a distinctly squared-off, boxy appearance. Many others reveal faint, concentric shells of stars. Both of these phenomena emerge quite naturally in computer simulations when a preexisting elliptical swallows a small companion galaxy. In just the past year, meanwhile, the central regions of many ellipticals have been found to have "decoupled cores"—massive concentrations of stars that are rotating rapidly and at an angle to the rest of the galaxy. Again, this seems to be a distinctive signature of a merger.

Observations such as these have made the case for mergers much more compelling, says Schweizer: "In the past year, acceptance of the idea has passed the 50% mark." Even so vocal a skeptic as Princeton University's James Gunn recently conceded to *Science* that, while he is still not completely convinced, "It's *possible* that you could make ellipticals from mergers."

The collision idea becomes very controversial indeed, however, when it comes to making spiral bulges. The most fundamental objection, voiced by Gunn and many others, is that spiral disks are very fragile. It is easy enough to see how the disks could have formed to begin with: in space, any large, rotating cloud of gas and dust will collapse into a disk very quickly because of internal friction and heating. This is what happened to the particles forming Saturn's rings, which is why the rings are flat. And this is presumably what happened long ago in the clouds that formed the spiral galaxies.

Once a spiral disk has formed, however, computer simulations suggest that it is very sensitive to perturbations. Absorbing even a tiny companion galaxy would cause it to swell and thicken. Such fat disks have been seen, says Gunn, but they are rare. "So we can be almost sure that mergers played no role in the formation of spiral galaxies," he says.

Yet Schweizer is not so sure. He points out that recent studies of bulges have begun to turn up exactly the kind of boxiness and shells seen in ellipticals. There is also some evidence that certain spiral bulges—our own among them—have streams of stars orbiting in the opposite direction to the disk. And there have even been some recent computer studies suggesting that interstellar gas in the disk could absorb much of the energy of a collision and thus leave the stars of the disk undisturbed. So perhaps fragility is not such a problem after all.

Again, Schweizer is the first to concede that the evidence is still a long way from proof. Nonetheless, the hypothesis that collisions are responsible for ellipticals and spiral bulges alike is clearly a provocative one. And even if it is wrong, it should still inspire some good observations.

■ M. Mitchell Waldrop