Galileo. That's "just a little disappointing," says Chapman. "Gaspra is still interesting, but it's harder to observe."

Even if it were easier to study, Gaspra might not be the best test case for resolving the great asteroid debate, for it's an odd sort of S asteroid. Gaspra's spectral characteristics show it to be composed of metal and the minerals olivine and pyroxene, as all S-types are, but it is so rich in olivine that it borders on being unclassifiable, according to Chapman. Even though Chapman thinks the S class in general is primordial, he suspects this peculiar specimen could turn out to be altered.

On top of the limitations of the target, there is Galileo's own handicap: its jammed main communications antenna (*Science*, 23 August, p. 846). Luckily, the failure of the large antenna won't hamper the recovery of data. Encounter observations will be stored on-board until Galileo makes its final swing by Earth in December 1992, when the data can be dumped at close range through a smaller antenna. But the main antenna would have transmitted the "navigation" images—photographs taken well before the flyby to help controllers aim the camera once Galileo was within range. In the absence of the main antenna, these navigation images have to trickle to Earth through the backup antenna. So, instead of a final navigation image made 24 hours before the flyby, controllers have to rely on one taken a week ahead, making the targeting of Galileo's camera during the actual flyby a cruder business.

To compensate, controllers will direct the camera to plaster the sky with 51 overlapping images. That, they figure, will give them a 95% chance of catching Gaspra in one of them. But allowing time for all that photography means it will have to start earlier in the flyby than had been planned. At that greater distance, Gaspra will be about 20% smaller than in the images that would have been possible with better camera targeting.

But even though asteroid researchers mourn the encounter that might have been, they're not giving up on the possibility of some unexpected insight. Firsts in planetary exploration are renowned for producing surprises. Perhaps Gaspra will be clearly recognizable as half metal and half rock, or marked by an impact with streaks of metal frozen in mid-splatter—a giveaway that it is altered. But even without a sudden payoff, researchers are eager to see what Galileo can turn up. "Amphitrite would have been a larger, perhaps more spectacular object," says astronomer Richard Binzel of the Massachusetts Institute of Technology. "But I wouldn't discount these small objects. They may be incredibly interesting." ■ Richard A. Kerr

Concocting a Cosmic Recipe for Matter

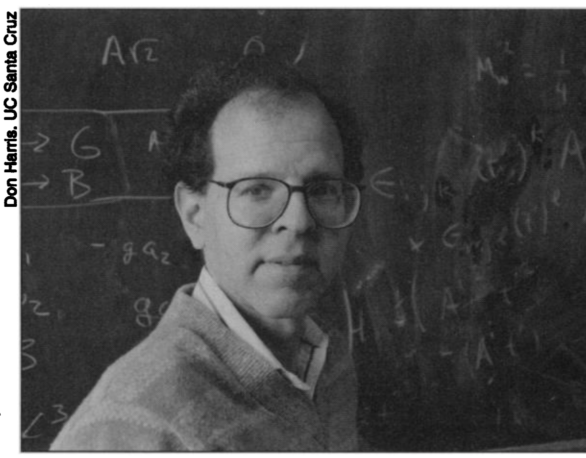
Taking their cues from accepted physics, two groups of researchers try to solve the mystery of the non-empty universe

Why is there matter? It may sound like a question from a Philosophy 101 final, but physicists have been scratching their heads over that one for the three decades since the emergence of the Big Bang account of the universe's birth. The Big Bang elegantly explained a host of puzzles, but it created a new one: According to existing physics, it should have spawned matter and antimatter in exactly equal quantities. But since matter and antimatter always annihilate each other on contact, a balanced soup would have quickly blasted itself into pure energy, leaving an empty universe and no intelligent creatures to ponder the issue. And yet here we humans are, able to contemplate the conundrum precisely because somewhere along the way matter got slightly ahead of antimatter. But how?

Now some of that excess matter—in the form of separate groups of physicists at the University of California, Santa Cruz, and the University of Minnesota—has taken a stab at explaining its own existence. If the new scenario independently developed by these groups stands up, physicists and cosmologists will breathe a sigh of relief. Their inability to nail down the source of the excess matter has left an embarrassing gap in our view of cosmology—a gap that researchers have often tried to fill by enlisting such highly speculative models as grand unified theories, which provide a single description of all of the forces of nature except gravity. In contrast, Santa Cruz physicist Michael Dine, Minnesota physicist Larry McLerran, and their colleagues would fill the Great Cosmology Gap with less exotic ingredients than grand unified theories. McLerran and Dine would be satisfied by mere inflationary cosmology, a few extensions of conventional particle physics, and a well-established (though admittedly obscure) quantum-mechanical effect that enables matter and antimatter to change places.

And that's the beauty of the Dine-McLerran model. "The exciting thing is that these scenarios are dependent on physics that should be accessible at the Super Conducting Supercollider (SSC)"—or at least so says Peter Arnold, a physicist at Argonne National Laboratory who is acquainted with the new notions.

But what exactly are these notions? The essentials of the problem were first laid out in 1967 by Soviet physicist Andrei Sakharov. He noted that skewing the universe toward matter required two things: some means of



Don Harris, UC Santa Cruz

Taking matter in hand. *Michael Dine.*

converting matter to antimatter and vice versa (known as "baryon-number-conservation violation") and some matter-antimatter asymmetry that would make this process favor the direction of matter (known as "charge-parity symmetry violation"). But having proposed these conditions, Sakharov conceded there were few clues as to how they might have been met.

One type of charge-parity (CP) violation had already been observed 3 years earlier. Princeton physicists Val Fitch and James Cronin had noticed a tiny quirk in the decay of the particle called the kaon (see *Science*, 4 October, p. 36)—a quirk that would have tilted the scales in favor of matter over antimatter. Nevertheless, the quirk was too weak by at least ten orders of magnitude to meet Sakharov's conditions.

Meanwhile, grand unified theories provided baryon-number violating processes, but such theories could only be tested at hopelessly unattainable energies. The rock-solid standard model, which provides our current view of particle physics, seemed to slam the door on baryon-number violation.

But then came Gerard 't Hooft, a Dutch

physicist who had played a major role in completing the standard model, and who in 1975 wedged that door open just a crack. 'T Hooft discovered that the standard model predicted that matter should be able to "tunnel" into antimatter, and vice versa, in much the same way as an electron can quantum-mechanically tunnel from one side of a barrier to the other. This at least provided a mechanism for antimatter, say, to switch its stripes, becoming matter—though it said nothing about why the reverse wouldn't happen at the same rate. But once again, the so-called 't Hooft effect was almost inconceivably small, allowing no more than about one particle in 10^{120} to make the switch—which explains why the effect has never been observed. Sakharov's conditions required an astronomically larger rate of switching—about one in a billion.

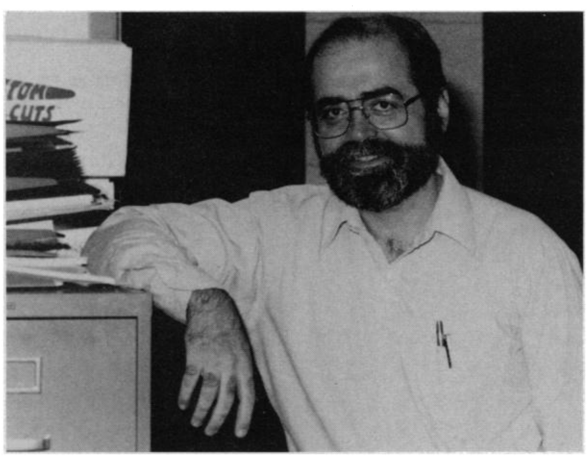
That seemed out of the question until 1985, when Soviet physicist Mikhail Shaposhnikov and his collaborators argued that the 't Hooft effect might supply the requisite baryon-number violation after all. In spite of its rarity at familiar energies, the Soviet scientists conjectured that at the very high energies that prevailed in the early universe the effect would be vastly amplified.

Still, the claim didn't impress the physics establishment, which found the Soviet group's back-of-the-envelope projections about the 't Hooft effect unconvincing. "We just didn't believe their explanation of how the baryon-number violation could get so large," recalls Dine. Which is where things stood until 2 years ago, when Dine sat down to lunch with Leonard Susskind, a theorist at Stanford University.

"I was interested in the problem and told him I had decided the Russian group couldn't be right about the baryon violation being strong enough to produce the matter asymmetry," Dine recalls. "Lenny said, 'Why not?' I gave him my reasons, and as I heard myself talking I realized I didn't have a good argument against it. I went back and thought about it some more, and pretty soon I was convinced they had been right." About the same time, McLerran started to follow the same train of thought, and soon he and Dine were leading separate groups to come up with a more solid estimate of the high-energy 't Hooft effect.

That still left the groups in need of a source of CP violation. But by this time, physicists had come to be on friendly terms with a handful of "extensions" to the standard model that attempt to answer questions the standard model leaves hanging—such as why known particles present such a baffling, and apparently arbitrary, array of masses. These extensions, which sport names such as "technicolor" and "supersymmetry," also call for CP violation that is more than a billion times stronger than the standard model can provide, satisfying the second part of Sakharov's conditions. So far, these extensions exist only in the minds of theorists, but many physicists think evidence favoring one or another may show up in the first rush of experiments at the SSC, if not sooner. "Like most physicists, I'm very optimistic we'll soon know which extension is right," says Dine.

With one of Sakharov's two elements—baryon-number violation—in hand and the other—adequate CP-symmetry violation—a good bet for the near future, Dine and McLerran went on to build complete scenarios for the origin of the matter asymmetry. Both scenarios, published separately this year in *Physics Letters B*, rely on a version of the inflationary model of cosmology, in which the newborn universe goes through an episode of sudden inflation and then experiences a "phase transition" analogous to the boiling of a liquid. As steam appears as bubbles in water, a new phase of the universe emerged as expanding bubbles. Outside the bubbles was a hot soup of massless particles in which the direction of time was ill-defined, while inside the bubbles were matter and time much as we know them.



Parallel results. *Larry McLerran.*

The challenge was to find a point in this bubbling universe in which both the amplified 't Hooft effect and the outsized CP violation were holding sway. Inside the bubbles wouldn't do, because the energy there was too low to enlarge the 't Hooft effect. Outside the bubbles wouldn't work either, because the flukey nature of time there enabled CP violation to work in both directions, canceling out any matter-antimatter imbalance. The only place where CP violation and the 't Hooft effect would have overlapped was in the walls of the bubbles. Eureka, went the thinking: All the matter in our universe is simply a relic of processes in those short-lived bubble walls. "It's a very clever mechanism," comments Edward Kolb, head of the astrophysics group at Fermilab. "I'm not sure there aren't other scenarios that might also work, but this is certainly one of the most plausible."

Based on the CP violation predicted by a particular extension to the standard model, Dine's and McLerran's groups calculated the amount of excess matter their scenarios can generate. They found that the results jibed with estimates of the matter-antimatter imbalance that must have prevailed in the early universe. "The beauty of this process is that it's only turned on for a brief time," says Dine. "It produces the right amount of excess matter and then turns off when it reaches the inside of the bubble."

No surprise, few physicists are ready to declare the case closed. After all, half of each scenario—the CP-violation part—relies on highly speculative physics. Though the models work with all of the proposed standard model extensions, Argonne's Arnold isn't entirely reassured. "It's fair to say that whatever the true mechanism [of CP violation] is, it probably has qualities in common with these extensions," he says, "but one could easily imagine a scenario in which they would be wrong."

The verdict on a source of CP violation may not be long in coming, with the next generation of accelerators due to begin colliding particles by the end of the decade. And McLerran and some other physicists (though not Dine) also voice the hope that SSC energies will be enough to uncover evidence of the turbocharged 't Hooft effect. "It would be a dramatic event, almost like a bomb going off in the detector," asserts McLerran. "Not in the sense of doing damage, of course. But [normal interactions] produce a few particles, while this would produce hundreds."

Of course, even if individual ingredients of the matter-asymmetry recipe are confirmed, physicists aren't ever likely to see the whole scenario in action. The creation of matter took place at energies beyond those of any conceivable particle accelerator, in an era no telescope can plumb. "One of the big disappointments of this theory is that you can't look through a telescope and prove it happened this way," sighs Dine. But it's a thrill, he says, "just being able to relate this sort of cosmological puzzle to real laboratory questions." ■ DAVID H. FREEDMAN

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