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AMPTE: NOTES ON THE INITIAL OBSERVATIONS

On August 16, 1984, the three spacecraft comprising the space experiment called AMPTE—Active Magnetospheric Particle Tracer Explorers—were launched successfully from Cape Canaveral. (For a detailed account, see the *Johns Hopkins APL Technical Digest*, Vol. 5, No. 4 (1984).) The AMPTE spacecraft were provided by West Germany, the United States, and Great Britain. The project has three principal goals: (a) to study the entry into the earth's magnetosphere of ionized particles from the solar wind and of metal ion vapors ejected by the West German spacecraft, and to investigate the transport and acceleration processes that produce high-energy particles in the earth's radiation belts; (b) to study the interaction between the artificially injected plasma and the natural flowing space plasmas; and (c) to establish the composition, charge state, and energy spectrum of the magnetosphere's natural particle populations.

The West German spacecraft, the Ion Release Module (IRM), has the job of releasing canisters of barium and lithium (neither of which is known to occur naturally in space in appreciable quantities), which become the ions to be studied. The British spacecraft, the United Kingdom Subsatellite, monitors the releases in close proximity to the IRM. The U.S. spacecraft, the Charge Composition Explorer (CCE), positioned thousands of miles closer to earth (31,000 miles apogee, compared to 71,000 miles for the IRM during the initial release), carries instruments to detect any trace of the ion releases. The National Aeronautics and Space Administration sponsored the U.S. portion of AMPTE, and APL designed and built the CCE.

The first ion release occurred on September 11, 1984, when the IRM discharged two canisters of lithium into the solar wind after waiting several days for an intense magnetic storm to abate. A second lithium release followed on September 20. Both discharges were successful and produced interesting local plasma phenomena as seen by instruments on the IRM and UKS. However, the CCE, stationed in the magnetosphere 40,000 miles away, was unable to detect any ionized lithium particles from the IRM. The third planned discharge occurred on December 27, 1984, and consisted of a two-canister barium injection that produced an artificial comet visible from some parts of the western United States and the adjoining Pacific Ocean. (Barium ionizes more rapidly than lithium

and thus remains more concentrated, making possible a visible comet-like structure.) This release was also delayed because a cloud cover over the West Coast prevented the extensive visual monitoring of the comet that had been planned for December 25. The next lithium and barium injections, this time into the magnetotail instead of the solar wind, are scheduled for late March and April 1985, while a second artificial comet release is now anticipated for mid-July.

In addition to being the first *active* experiment in near-earth space, the AMPTE spacecraft are unique in that data to be transmitted to earth are displayed almost immediately, and the project participants are able to observe the space environment around the spacecraft in real time.

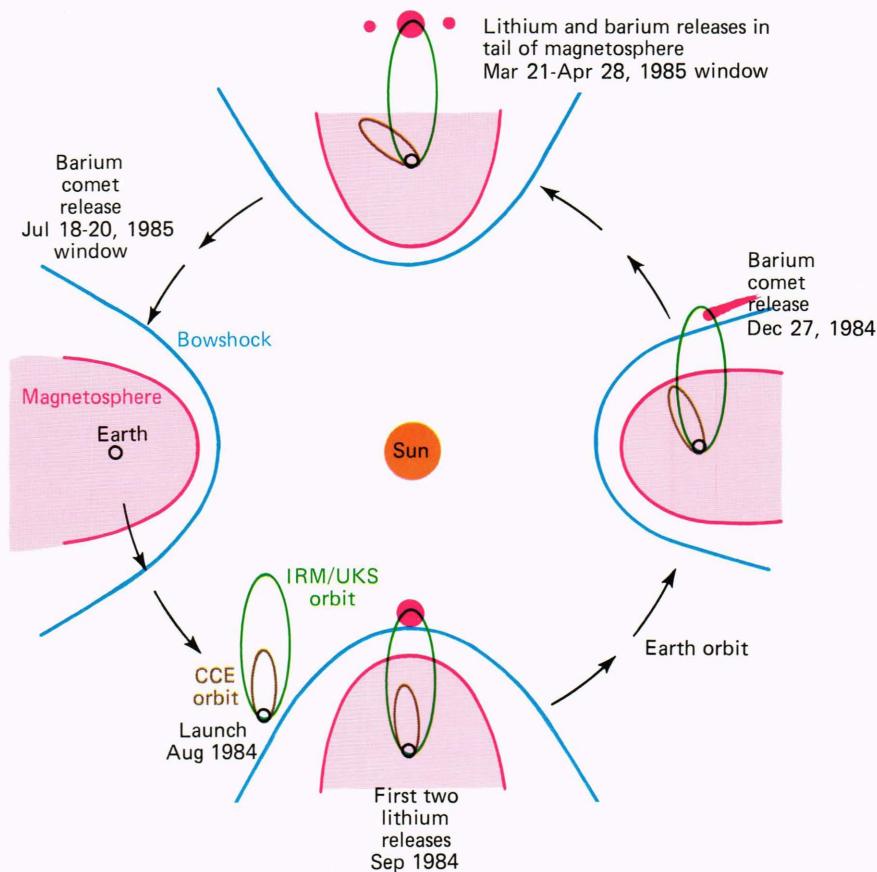
Approximately three weeks after the artificial comet release, at about the halfway point of the planned injections, we interviewed Stamatios Krimigis of APL on the results of AMPTE thus far. Tom Krimigis is the principal American investigator for AMPTE and co-originator of the entire project, along with Gerhard Haerendel of the Max Planck Institute for Extraterrestrial Physics in Germany.

MEASUREMENTS OF NATURAL RADIATION

As Krimigis noted: "Every time you launch a spacecraft with new tools—new instrumentation—you make discoveries. The Charge Composition Explorer spacecraft was no exception." He continued:

"The work of AMPTE can generally be divided into two categories: the active experiment, and measurements of the natural radiation environment.

"One of the outstanding problems for magnetospheric physics over the past 20-odd years has been to measure the composition of the varying currents which envelop the earth during so-called magnetic storms. Such events start with a big perturbation on the sun that propagates to the earth. Considerable magnetic activity follows, including changes in the surface magnetic field and heating of the upper atmosphere. We knew that during magnetic storms a current forms around the earth like a ring, at an altitude between two and five earth radii (roughly between 8,000 and 22,000 miles). The particle energies that contribute to it are in the range of 20,000 to 600,000 elec-



A mission summary diagram of AMPTE, not to scale, shows the two spacecraft orbits in relation to the sun, the earth, and the earth's magnetosphere at the time of the AMPTE chemical releases. The brown orbits are those of the U.S. CCE; the green orbits are those of the German IRM and the British UKS traveling in tandem. The large red balls are lithium releases, the smaller ones barium. The flow of solar gases distorts the earth's magnetic field into a large bullet-shaped volume known as the earth's magnetosphere. The magnetosphere is preceded by the bow shock, formed at the point where the supersonic solar wind is first perturbed by the presence of the earth in its path. The initial lithium releases of October 1984 occurred between the sun and the bow shock. The barium artificial comet in December took place beyond the dawn flank of the magnetosphere. The planned March-April 1985 releases of lithium and barium will occur in the tail of the magnetosphere, while a second artificial comet release in mid-July is expected to be placed in the dusk flank of the magnetosphere.

tronvolts. Up to this time, the instrumentation did not exist to determine what kinds of particles they were—hydrogen, helium, or oxygen. There is an immense amount of literature speculating on the nature of ring current composition. The American spacecraft on AMPTE, the Charge Composition Explorer, contains instrumentation, which, for the first time, makes all these measurements possible.

“We had the opportunity with AMPTE to study an intense magnetic storm which occurred on the 4th of September 1984. In this particular magnetic storm, we found that protons dominated, with some oxygen ions also present. We know that protons can come either from the solar wind or from the earth's ionosphere. However, the oxygen that we observed was mainly singly ionized, which means it came straight from the earth's ionosphere. Thus, we have been able with this one magnetic storm to answer questions asked by the space science community for some 25 years. Whether the results from this magnetic storm are indicative of what happens in every storm, of course, we don't know. It may be that the next one we analyze will turn out to have oxygen or even helium as the major contributor, but at this point we have seen that the protons really dominate. We are now in the process of submitting papers to *Geophysical Research Letters*, describing several aspects of these observations.

“Another thing that we have found regarding the natural composition of the radiation belts is that, in addition to the protons, helium, carbon, nitrogen, and

oxygen that were expected, there are also such elements as neon, silicon, even iron that are present within the earth's magnetosphere. These are elements which had not been known to be up there before—nobody had ever detected them. We have yet to analyze them in detail and decide their significance on questions about the origin of the radiation belts, but it is a significant discovery.

LITHIUM RELEASES INTO THE SOLAR WIND

“We observed a wonderful set of phenomena from the in situ plasma measurements following the lithium releases of September 11th and 20th. First, we observed the creation of a magnetic “cavity” in the solar wind. This was a first-ever occurrence. We also observed heating of the electrons and acceleration of the ions, and then a number of plasma wave emissions as the solar wind was perturbed by the injected lithium. These are in the process of being analyzed, with 13 papers to be submitted to the *Journal of Geophysical Research*.

“Regarding the entry of lithium into the magnetosphere, the Charge Composition Explorer did not observe lithium in any of the energy ranges of its instruments. We were only able to obtain and state upper limits to the fluxes that may have entered the magnetosphere, which were much below the expected amounts. The absence of lithium is very troubling to the theory of solar wind plasma entry into the magne-

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tosphere that has been developed over the past 20 years. The models that were used to predict what would happen after the AMPTE lithium releases suggested that there would be substantial fluxes inside the magnetosphere. The fact that these were not observed indicates some unknown processes that have not yet been taken into account by anybody's models. It is true that, when we made the releases on December 27, the interplanetary magnetic field was not in the optimum configuration. Potentially, that is a significant input into the theoretical discussion. I think that the full impact of the lithium releases is going to be felt over the next months and years as we try to understand what happened and will result in modifying the theoretical models developed over the past 25 years.

“Although some people may view the lack of lithium entering into the magnetosphere as a disappointment, it is only a disappointment if you have a particular model in mind. As we had pointed out repeatedly both in our initial proposal and in subsequent discussions and presentations to the scientific community, the presence or absence of lithium inside the magnetosphere is a significant piece of information which, either way, is going to affect our thinking.

“We have two more lithium releases planned. They are scheduled to be made in the magnetotail. I expect some surprises from these and possibly a payoff substantially larger than from the releases into the solar wind.

THE BARIUM ARTIFICIAL COMET

“For a number of reasons, we released only two of the planned four barium canisters to make the artificial comet. First, there were the poor weather conditions and the amount of observing we would be able to do from the ground. Second, the solar wind pressure was considerably higher than normal at this time, so that we ended up making a release in the solar wind rather than in the magnetosheath as we had planned. Because of this, the geometrical arrangement of the West German and British spacecraft was not optimal. We thought that, rather than release the entire amount of barium, we ought to release only two canisters. This leaves us the opportunity later on in July to make a second release, in the magnetosheath under better weather conditions. Unfortunately, the United Kingdom Subsatellite recently stopped transmitting data, partly due to a power system failure.

“In any case, the comet release was executed, and it was in our judgment spectacularly successful. With

half the amount of barium, it was of course less bright than originally predicted. We obtained very good pictures from both the Boeing 707 aircraft operated by the Argentine Research Council out of Tahiti and from the Convair 990 aircraft, operated by NASA from Ames, Calif. We also obtained ground pictures from Boulder during the first few minutes of the release. We have yet to analyze the data to draw any sort of solid scientific conclusions.

“The first impressions of the comet are that the tail was more filamentary than one might have anticipated. It consisted essentially of plasma blobs that were breaking off from the main body of the comet. The comet created a magnetic cavity in the solar wind that collapsed suddenly about 270 seconds after release, much sooner than expected. We had expected a much denser and more visible comet tail than we observed, even adjusting for half the originally planned release. One of the British observers on the Convair 990 reported very faint remnants of barium extending over a distance of something like 100,000 miles from the point of release. We were not prepared to observe anything that long in one shot, with the current viewing range of our instruments.

“Another important thing: After the comet release, the West German and British spacecraft provided some very nice in situ data. We saw the interplanetary magnetic field increase by about a factor of 15. We had predicted and expected an increase, but not to that extent. What happens is, when you actually release the cold plasma, it momentarily stops the solar wind—the solar wind has to flow around it—and the magnetic field piles up in front of this obstacle just as the pressure builds up as water in a river flows around a big rock.”

Krimigis concluded:

“I think there should be no mistaking the importance of the AMPTE project, even thus far. It has pioneered a new experimental technique which has not been used before. I certainly am convinced, and I think many of my colleagues are, that this is only the beginning for active experiments in space. Ten or fifteen years from now, this kind of experimentation will be routine. An official from NASA headquarters asked me the other day, ‘How come we’re not talking about an AMPTE II?’ I said that we need first to do some chewing and digesting of data from AMPTE. But I think it is testimony to the scientific success of the program that people are already marveling at the results when the work of the project has just barely begun.”

ON THE FAINT TRAIL OF THE CHRISTMAS COMET*

They'd put up with nature's whims long enough. This time the scientists would do it *their* way. For two decades they had patiently been observing the vast stream of charged particles spewed by the sun into space. This hot "solar wind" produced brilliant auroras over the Earth's poles, disrupted radio signals, even seemed to cause rainstorms. But how it did all this was mostly a mystery. As the solar wind bombarded their planet with 50 trillion watts of electrical energy, scientists could only watch powerlessly from below.

But now they were finally going to do something about the weather in space. Their contribution, however brief and isolated, promised to be spectacular: history's first artificial comet (*Science* 84, December). On Christmas morning a satellite would release a cloud of barium gas that would glow yellow, green, blue and purple. The solar wind would blow it into a shimmering tail appearing 10 times as long as the moon's diameter. Instead of passively observing, scientists would actively experiment. They would study nature at their convenience.

It was a fine plan. Nature, unfortunately, did not go along with it.

At 3:15 Christmas morning, Gerhard Haerendel stood at Kitt Peak observatory observing the clouds in the Arizona sky. Haerendel, a physicist at Germany's Max Planck Institute, had been planning this comet for 12 years. It was due to appear in two hours—behind the clouds.

"It's not really important if I see the comet," said Haerendel, speaking to a motley and bleary-eyed group of nonscientists gathered atop Kitt Peak. The Christmas comet had attracted two dozen journalists and a 10-year-old named Lorraine Miller, a fifth-grader at Sunrise Elementary School in Tucson who was planning (with help from her father) to photograph the comet for a regional science fair. "If the pictures come through, I think I've got a good chance of winning," she said. "No one else is doing it, and they like originality."

Haerendel gave her and the reporters some background. This collision between the solar wind and the barium cloud was a collision of two plasmas—two gases containing charged particles. Flowing plasmas make up 99.9 percent of the universe, and they frequently collide. "The gas of a hot star, in our case the sun, is impinging on the cold barium cloud. We are simulating what happens around a body like a comet or a planet or an interstellar cloud. We are simulating an astrophysical situation."

"Why, Dr. Haerendel?" cried a television reporter.

"Why? Because we are astrophysicists. That's our research."

"Can we learn anything about this in the end—say, more about our weather?"

"We will not learn anything about our weather. Okay? Don't have any hopes," said Haerendel good-naturedly. He did allow, though, that the comet might help researchers trying to harness energy from nuclear fusion by using magnetic fields to contain hot plasmas. "We're injecting a plasma that will be contained by the interplanetary magnetic field, but not for long. The plasma will try all its tricks to get out, and we're studying these tricks. We're measuring them at our leisure in space. We have the cleanest possible experiment you can imagine, without any of the impurities, walls, or restrictions of a laboratory. So it's a beautiful experiment, but the immediate return for mankind is low."

A phone rang, and Haerendel dashed to his desk inside a trailer, where six phones linked him to the rest of the international team. The news had been bleak all night. The scientists had chosen to create the comet 70,000 miles above the Pacific Ocean—over a point near Peru's coast—so they could see it from observatories at Kitt Peak and Hawaii's Mauna Kea, mountains renowned for clear skies. Tonight both were covered with clouds. At San Francisco a freak winter fog had suddenly rolled in and grounded a NASA observation plane. Scientists on a plane near Tahiti had a clear view, but Haerendel needed at least one other observing station to be able to pinpoint the comet's movement. At 5:00 A.M., eight minutes before the spacecraft was programmed to release the barium, New Mexico's White Sands Missile Range was the last hope.

"It's really clear?" Haerendel asked the American scientists at White Sands. "You checked everything, you can see the Andromeda Nebula and things like that?" Holding a phone to each ear, he sounded remarkably composed for a man being filmed by seven television cameras in a cramped trailer as he pondered a satellite 70,000 miles overhead—and the possibility of wasting about \$15 million if his team didn't photograph the comet. He gently persuaded White Sands to put a more experienced astronomer on the line. "Do you have cirrus?" Haerendel asked quietly. It seemed there were a few faint, high clouds. "*Absagen*," said Haerendel as he turned to another phone, and back in Germany a signal was radioed out to space. The comet was canceled with three minutes to spare.

Two days later they tried again, their last chance of the year. Not until July would the satellite again be in the proper position for the barium cloud to glow in the sun's light yet also be visible from the dark side of Earth. Kitt Peak and Hawaii were still clouded in, but the skies at White Sands were a little clearer, and this time both airplanes got off the ground. The NASA plane was cruising 37,000 feet above the California coast when the word came over the intercom at 4:22 A.M. Pacific Time. "We have release, but only two cannisters." Haerendel had hedged his bets. Instead

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of releasing all four cannisters of barium from the German satellite, he was saving two for another comet in July, when more ground observatories might be clear.

For 10 minutes, as planned, the two cannisters tumbled in space. Thomas Hallinan, a physicist at the University of Alaska, trained a video camera out a special optical window on the NASA plane. Compared to ordinary TV cameras, his equipment was a million times more sensitive to faint light. Its image showed up on a monitor where stars appeared as black points on a white background. At precisely 4:32, when the cannisters exploded 2.5 pounds of barium into space, a black dot appeared at the center of the screen, and cries rang out in the cabin. "There it is! That's it! Right where it's supposed to be!"

All very dramatic—if you were watching the screen. Those looking out the plane's window saw nothing the first few seconds. Then a faint speck of light appeared. To the naked eye it looked like a tiny, dim star (perhaps fourth magnitude). Through binoculars it appeared a gray, round blob that grew fainter as it expanded. It disappeared within about a minute. There were no colors, no tail, none of the skyshow that had been predicted.

It persisted only on the scientists' screens. David Rees, a physicist at University College in London, had equipment on the plane that gathered and counted individual photons of light. Two minutes after the comet's creation, Rees' computer screen showed the first signs of a tail. "He's got himself a comet," yelled Bob Cameron of NASA, the mission director on the plane. The solar wind, having quickly stripped electrons from the barium atoms, was breaking up the cloud, pushing the charged barium particles downstream. Hallinan and Rees fiddled with their equipment. They planned to track the comet for at least 30 minutes, maybe an hour.

But less than six minutes after it appeared, the comet's head and tail abruptly vanished from the screens. Some scattered, faint bits of barium lingered a few

minutes and then also disappeared. Hallinan and Rees scanned the sky, turned knobs, ordered the plane to change course, but to no avail. "I'm discouraged," Hallinan said to Rees, wondering if they had botched the experiment by losing track of the comet. But NASA's Cameron consoled them with another explanation.

"The solar wind took that comet and blew it to hell in a hurry."

And that, more or less, was the theory offered by Haerendel after gathering reports from ground stations, airplanes, and satellites. Using only half the barium, he said, naturally produced a dimmer, shorter-lived comet. But more crucial was the weather in space, which proved to be just as uncooperative as the weather on Earth. The scientists released the comet in a region of space where the solar wind is relatively mild most of the time, blowing some 400,000 miles per hour. But when the comet was released, the region was buffeted by solar winds of more than a million miles per hour.

Haerendel and his colleagues sounded gleeful as they headed back to their offices. True, the comet had fizzled early, but they had a full record of its demise. "There seemed to be a traumatic end to the comet, and that's going to be very exciting to analyze in the next few months," Rees said. "It might be related to the kinds of catastrophic releases of energy we see in solar flares and in the centers of galaxies."

Hallinan was philosophical. "Science is never any fun if everything goes as predicted. Otherwise there's no point in doing experiments."

He was probably right about the joys of the unexpected, but there were those who disagreed. Anyone, for instance, who had gotten up at 4:00 A.M. only to see a spectacle even more anticlimatic [*sic*] than Kohoutek. And Lorraine Miller, the fifth-grader who never did get her pictures. While the researchers pondered their data, she remained without a project for the science fair. "I think I might just skip it this year," she said.