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COVER The hoatzin, *Opisthocomus hoazin*, a neotropical leaf-eating bird, is the only bird known to have ruminant-like foregut fermentation. This unexpected digestive system in a small flying endotherm provides new insights into theoretical size limitations in vertebrate herbivores and the evolution of foregut fermentation as a digestive strategy. See page 1236. [Photograph by Stuart D. Strahl, WCI–New York Zoological Society]

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The Human–Voyager 2 Collaboration

The successful Grand Tour of the outer planets by Voyager 2 represents one of humanity's great achievements. The splendid outcome* of the mission carried out in forbidding and hostile environments was due to exemplary exercise of imagination, ingenuity, careful design, and a high level of human-machine operational interaction. An essential ingredient was excellent engineering capability at the Jet Propulsion Laboratory (JPL) that had been nurtured by earlier Mariner missions to the inner planets. Vidicon TV cameras developed for those flights had proved their utility and dependability. Instruments used in science experiments had also been successfully flown. Perhaps most important was experience gained in long-distance human-computer interaction that permitted response to glitches that too often arise in electronic equipment exposed to the rigors of space.

Voyager, though light in weight, had features that facilitated coping with many contingencies. In the 1800-pound spacecraft were six computers, eleven different science instrument packages, ^{238}Pu thermoelectric generators furnishing about 400 watts of power, attitude-controlling devices, propellant for mid-course maneuvers and attitude control, two radios for sending information, and two for receiving it. Redundancy in the computers and radio receivers was later to prove crucial.

Two of the six computers were devoted to attitude control in three dimensions. Two were devoted to the scientific instrumentation. The remaining two were the brains of the vehicle. They were reprogrammable from Earth and could control the various functions of the spacecraft.

Less than 8 months after blast-off, defects that could have ruined the mission developed in the two radio receivers. One went dead. The second was found to be "tone-deaf." That is, it could not cope with the variations in frequency arising from a variable Doppler effect. In addition, the frequency that the receiver could recognize was influenced by temperature effects as small as 0.25°C. The JPL engineers diagnosed the problems and prepared computer tapes that slowly varied the sending frequency to compensate exactly for the disturbing effects. This restored good communication with Voyager. More than 11 years later, the receiver is still tone-deaf, but it can recognize the signals coming to it from Earth more than 4 light-hours away.

The Voyager 2 mission was one of the few times that a major space effort exceeded the promises made for it. JPL had only promised exploration of Jupiter and Saturn. But even before reaching Saturn the Voyager 2 team was making plans and developing capabilities for encounters with Uranus and Neptune. The images obtained from Jupiter and its satellites had been well received by the public. It was desirable to obtain good and many images of the two outer planets despite the low intensity of sunlight on them. At Neptune, light intensity is only 1/900 that at Earth. To obtain good pictures at the outer planets required a comparatively long exposure. But the attitude of the spacecraft tends to drift, leading to blurring of the image. The engineers devised and tested a way of minimizing this drift and radioed the necessary instructions to Voyager 2. Steps were taken to improve reception of image signals on Earth through expanding the array of radio dishes. A major improvement came from employing a redundant computer on the spacecraft. The memory and processor of the computer were used to compress the TV signals. A special computer code enabled Voyager 2 to send back the differences in light intensity from adjacent picture elements. This in effect enhanced the rate of communication of images by a factor of 2.5. Another improvement applicable to small satellites being passed at more than 40,000 miles per hour was to pan the camera by rotating the spacecraft while passing by. Instructions for this were communicated to the spacecraft which later implemented them at the appropriate moment.

One is left with a deep admiration for the quality of teamwork between humans and the spacecraft though they are nearly 3 billion miles apart. The humans safe on Earth have been able to use facilities of equipment and consultation to devise programming techniques that have wrung from Voyager 2 performance that was not imagined at blast-off on 20 August 1977.—PHILIP H. ABELSON

*Results from Voyager's encounter with Neptune and Triton will be published in a future issue of *Science*.