Research in Progress

Far Out

FROM 300 MILES above the earth, outside the distorting and obstructing atmosphere, the Space Telescope will consider the universe from a new point of view. Its 94-inch primary mirror and six accompanying instruments will be able to respond to the entire optical spectrum from far ultraviolet to far infrared; its maximum resolution will be improved by a factor of ten over observations from earth; and it will be able to see seven times farther from the solar system.

Of these instruments, the most versatile and the one that will collect the greatest number of bits of information is the wide-field/planetary camera. James Westphal, professor of planetary science, is principal investigator for the camera and head of the investigation definition team chosen in 1977 to develop the instrument — to decide what it's to do and how it's to do it.

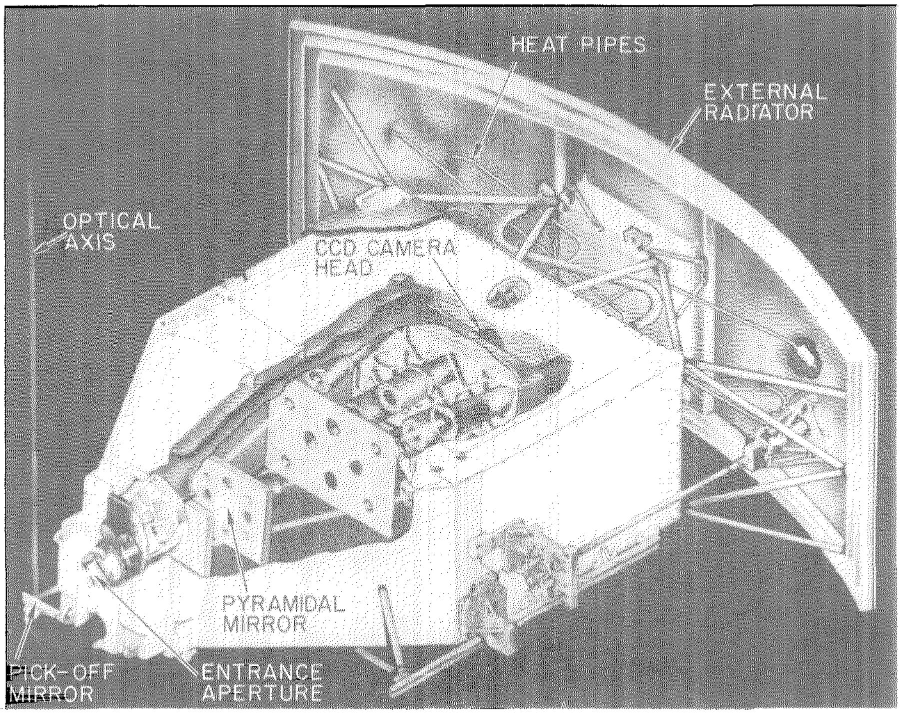
The camera is being built at JPL. Almost all the individual parts have been constructed, and the instrument is currently being assembled. After testing, calibrating, and operating with the other instruments, it will be installed in the Space Telescope and, after more testing, launched in the spring of 1985. The telescope is expected to remain in orbit at least 15 years, and probably much longer, with periodic service calls by astronauts and occasional trips home for major maintenance.

Out in space the wide-field/planetary camera, which is actually two instruments in one, will be located on the side of the telescope that will usually be turned away from the sun. Incoming light will be "folded" from the primary mirror to the secondary mirror and then back to a "pick-off" mirror, which deflects the beam into the wide-field/planetary camera. From there the beam goes through a shutter and one of 48 color filters. The beam will then be split by a four-sided pyramid mirror into the four quadrants of the wide-field position. Or the pyramid mirror can be rotated 45° to switch the four beams to the planetary mode.

With the two modes to choose from, the best tradeoff between field coverage and spatial resolution can be selected for each target, whether a large piece of the sky or a planet. That tradeoff is a factor of 2½ in resolution between the sensors of the wide-field mode, whose individual picture elements subtend an angle of 0.1 arc-second, and those of the planetary mode, which at 0.043 arc-second utilize almost all of the optical capability of the Space Telescope. Even though the planetary camera sacrifices a larger picture (it covers one-fifth as much sky as the wide-field camera) for its better resolution, it can still get all of Jupiter in on one shot — in a view similar to that from Voyager five days away.

For sensors the wide-field/planetary camera does not use photographic film but is equipped with charge-coupled devices (CCDs), tiny silicon chips that are the most sensitive and efficient detectors known. This camera's CCDs are about one-half inch square and ten microns thick and have 800 individual picture elements (pixels) on a side — 640,000 pixels for each of the eight CCDs (four for each mode). Each of the pixels is almost completely independent of all the others and can record and store, depending on the wavelength, up to 70 percent of the photons that strike it during exposure. This photon pattern is translated into a pattern of electrons and holes with a 1:1 correspondence to the photons. A numerical value can be generated proportional to the electrons, and these can be read out, pixel by pixel, back on earth. All 640,000 signals from one chip can be read out in 16 seconds, or a little over a minute for the four quadrants of the image, which can be recombined if the researchers wish.

Westphal's research team, along with the other groups developing instruments,



Incoming light is deflected by the pick-off mirror into the wide-field/planetary camera and through one of 48 filters mounted on rotating wheels. Then the pyramidal mirror splits the beam and directs it into either the four charge-coupled devices of the wide-field camera or the four CCDs of the higher resolution planetary mode. A cooling system (not visible) to reduce thermal noise in the CCDs necessitates the heat pipes and the external radiator, which forms part of the outside surface of the Space Telescope satellite.

will get first crack at observing time — more than a month's worth — as a benefit for their years of dedication to the project. The 11 members of the team have research interests that mirror the whole range of the camera's versatility; Westphal himself is interested in planets, Jupiter and Venus in particular, as well as distant galaxies. Of the other local team members, Jerome Kristian, staff member at Mount Wilson and Las Campanas Observatories, will also study distant galaxies, while Edward Danielson, member of the Caltech professional staff, will look at Jupiter and Saturn.

Other targets in our solar system for the camera's overall science program include Uranus and Neptune, which will be visible at ten times the resolution of observations from earth. Such objects as comets and the newly discovered satellite of Pluto can be studied in detail. The instrument will also search for planetary systems around nearby stars. Such a system could be identified by perturbations in a star's path.

Nearby galaxies will be visible with almost the same resolution as our own, and extremely distant quasars and radio galaxies as yet unseen from earth will also be studied. And the camera's broad wavelength response will enable it to see galaxies with different redshifts farther back in time than any now discernible and investigate such cosmological questions as the expanding universe concept itself.

The Space Telescope is a NASA project under the direction of the Marshal Space Flight Center in Huntsville, Alabama. The scientific data will be coordinated by the Space Telescope Science Institute being established at Johns Hopkins University and operated by the Associated Universities for Research in Astronomy, of which Caltech is a member. ☐ *–JD*

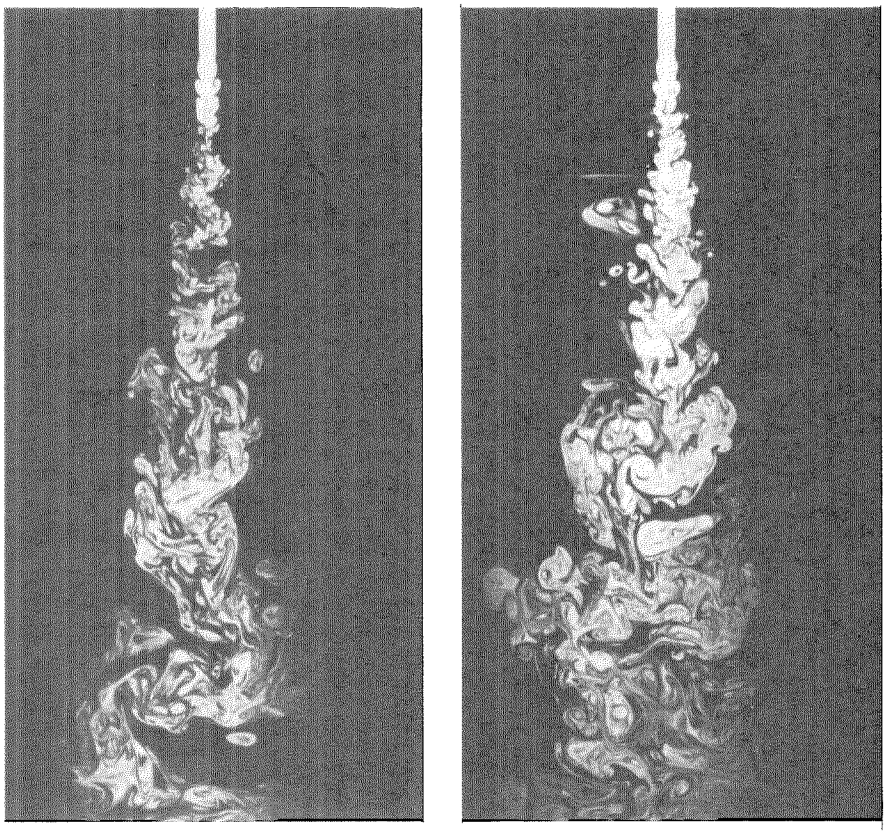
Inside Turbulence

THE STRUCTURE of turbulent flow has quite literally come to light in Caltech laboratories over the past decade. New techniques for making such flows visible have, in addition to producing pretty pictures, also overturned many of the long-held traditional views about turbulence as a more or less random behavior of fluids.

Paul Dimotakis, associate professor of aeronautics and applied physics, compares this juncture in the evolution of our understanding of turbulence with the transition, a little while ago, in our perception of the world, which was based on the ancient models of the universe constructed from Ptolemy's geocentric theory. Eventually the realization dawned that there was no way to keep adjusting the Ptolemaic model by adding more and more epicycles to fit the "predictions" with the observations. The trouble, of course, was that it was wrong in concept.

A similar conceptual revolution may be in progress today in fluid mechanics. The textbook definition of turbulence, on which almost all present engineering practices are based, assigns responsibility for turbulent entrainment and mixing to a gradient diffusion process. This is presumed analogous to the mechanism of molecular diffusion, the result of the random motion of molecules, with no particular organization, and describable only in statistical terms. In the conventional description of turbulence, it has also been assumed that there exists a relatively simple interface that separates the turbulent region from the non-turbulent region, so that a point is either inside or outside the turbulence; entrainment was understood as the "turbulent diffusion" of the non-turbulent fluid across this interface.

Work at the aeronautics department at Caltech suggests that the conventional view of turbulence is largely incorrect in concept and should be replaced by a picture in which turbulent transport is associated with coherent flow structures whose

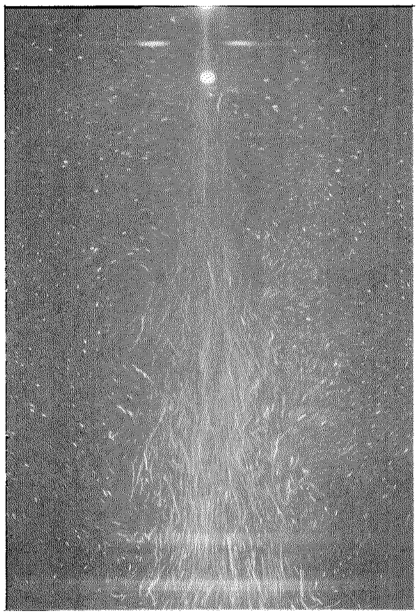


These photographs of laser induced fluorescence record the concentration of jet fluid in the plane of symmetry of a turbulent jet. The zig-zag pattern with the large regions of clear entrained fluid, which is particularly evident in the picture on the left, provides evidence for a large-scale vortical structure that in this case is probably helical. The small scales and complicated intertwining of the entrained fluid in both pictures casts doubt on the validity of a single interface between the turbulent and non-turbulent regions.

behavior can be described kinematically and thus can ultimately be predicted by solving appropriate equations of motion.

In the early 1970s, Garry Brown and Anatol Roshko, both professors of aeronautics, discovered the presence of an organized structure in shadowgraph pictures of turbulent shear flows, which are formed whenever two streams of different velocities meet. The structure was in the form of vortical "roller bearings" between the two streams. This was a complete surprise, because the experiments involved high-speed turbulent flow that should have been "disorganized," as proper turbulence is expected to behave. Subsequent experiments performed by Dimotakis and Brown confirmed the persistence of these organized structures to even higher velocities. Was it possible, however, that the shear layer was a special case, not typical of turbulent flow?

About five years ago Dimotakis and his students developed a technique using lasers to slice through the turbulence permitting a view of the interior of the turbulent region. The technique, called laser induced fluorescence, utilizes special dyes that can be selectively excited by a laser to emit light. Using appropriate optics to turn the laser beam into very thin sheets of a few hundred microns, one can monitor in this manner the instantaneous concentration of the fluid that has been labeled by the dye, in the plane illuminated by the thin laser sheet. It is also significant that dyes are available whose fluorescence properties depend on their local chemical environment. This allows monitoring the processes of entrainment and mixing down to the molecular scale, by comparing measurements in chemically reacting and non-reacting flows. Although variations of this technique have been used elsewhere, the resolution achieved in Dimotakis's experiments is considerably higher than elsewhere, allowing measurements down to the smallest length and time scales expected in the turbulent flow.



The conditions in this particle streak record of a turbulent jet flow field are identical to those in the photograph at left. Vortical structures can be seen at the edges of the jet, as well as high entrainment velocities far from the outskirts of turbulence.

The power of this new diagnostic technique was turned on to investigate the flow of a turbulent jet, surely a case of bona-fide turbulence. What the fluorescent dye revealed was that, just as in the shear layer, entrainment and mixing were not a matter of "turbulent diffusion." In the case of the jet, the structure of the flow turned out to be topologically richer than that of the shear layer, but the basic mechanisms appeared to be much the same. Large-scale vortical patterns became apparent, which in this case resembled ring vortices or helical structures, dominating the dynamics of the flow and gulping in the reservoir fluid. Reynolds number (the measure of the relative importance of inertial forces to viscous forces) also appeared to make no significant difference, with the slower moving, more viscous flow behaving in a manner similar to those with a high Reynolds number.

Dimotakis can perform various tricks with this technique, illuminating different aspects of the turbulent jet. He can arrange the chemistry of the dyes, for example, so that the fluorescence will turn on (or even change color) only when every part of the jet fluid has mixed with at least a certain amount of reservoir fluid. Conversely, the fluorescence can be turned off when the jet has mixed to a certain ratio with the reservoir.

The picture that emerges from these experiments on chemically reacting turbulent jets, conducted with Gene Broadwell, senior research associate in aeronautics, reveals a jet composed of large-scale vortical structures proceeding downstream and interacting with their upstream and downstream neighbors in almost discrete steps. It would appear that each structure passes mixed fluid on to the next downstream structure, which mixes it in turn with the fresh reservoir fluid it is entraining, and so on. This mixing mechanism is so efficient that at each step the chemical composition is very nearly the result of homogenizing the original jet fluid with all the entrained fluid up to that point.

A parallel set of experiments, in which the turbulent flow is made visible by recording time exposures of laser light scattered by small, neutrally bouyant particles in water, support the preceding conclusions. On time-exposure photographs, the particles leave streaks of light whose length and magnitude are a good indication of the local velocities of the flow. These photographs show clearly that portions of the non-turbulent reservoir fluid are set in motion and are committed to enter the "turbulence" long before they come in contact with the turbulent region, suggesting that the entrainment velocity is induced by the vorticity at some distance from the turbulence. The traditionally accepted simple interface between turbulent and non-turbulent is not apparent in these experiments.

Both the particle streak and fluorescent laser sheet pictures give a view of turbulence in which only two spatial coordinates are recorded. Even though it is possible to trade one space dimension for time using electronically scanned linear arrays of photodetectors in place of photographic film, actually all the complexities of four dimensions (three space coordinates versus time) are involved in dealing with turbulence. Efforts currently under way to analyze motion picture data would introduce time to two spatial coordinates, and other parallel efforts would also sweep the illuminated plane in the third spatial dimension synchronously with a high framing rate motion picture camera, to get at the fourth dimension. Dimotakis says that it is difficult to speculate at this time what the outcome of these experiments will be, as there are many unanswered questions at present regarding exactly how these vortices are connected to each other, or how they switch from one configuration to another. This makes the current efforts all the more exciting as they are designed to answer many of these questions.

The results of this work, and parallel efforts in other research groups in engineering, could prove to be quite important. Understanding turbulent entrainment and mixing processes could have a significant impact on such things as combustion efficiency, methods of building power plants and jet engines, and controlling pollutants. ☐ *–JD*