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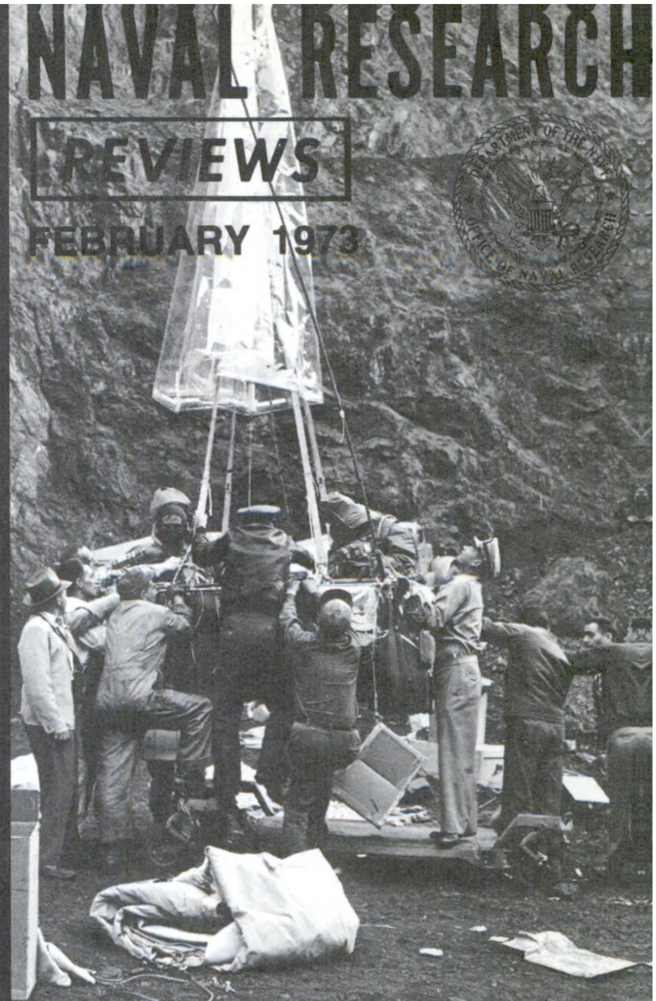

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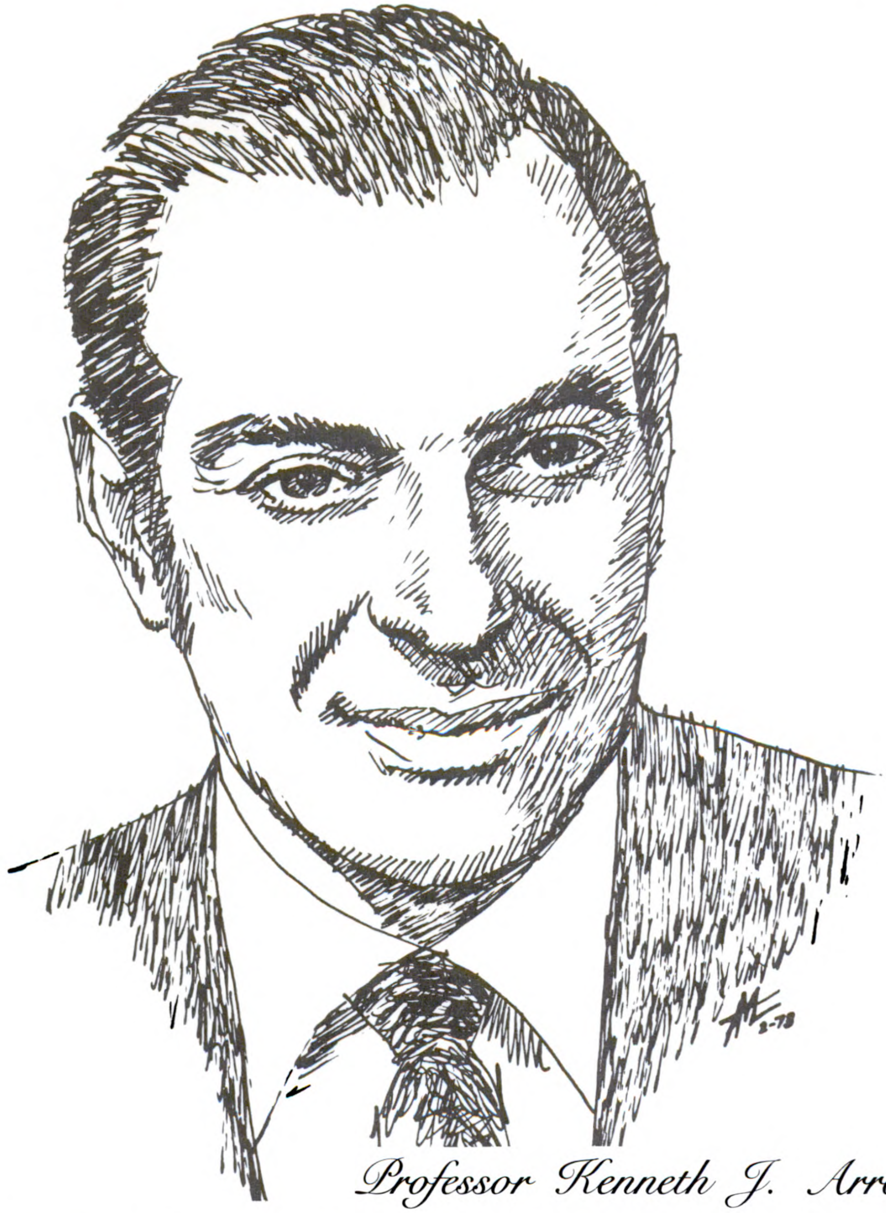

Professor Kenneth J. Arrow

Professor Kenneth J. Arrow, principal investigator of an ONR contract with Harvard for research on efficient decision methods and, shared with Sir John R. Hicks of Oxford the Nobel Memorial Prize for economics this year. Most of Professor Arrow's contributions are on the application of sophisticated mathematics to economics and management science. Some topics discussed in his books and articles are: sequential decision problems, welfare economics, inventory policy, equilibrium theory, optimal allocation of resources, optimal economic growth, and linear and non-linear programming. His work will help government and industry reach a better understanding of the effects of economic and organizational policy decisions. In his work as consultant to the Stanford Research Institute he supports research on an ONR sponsored research project concerning the introduction of an all volunteer force.

In 1968, after 20 years at Stanford University, Arrow assumed his present position as professor of economics at Harvard.

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Twenty-Five Years of SKYHOOK

CDR Ed Melton*
Office of Naval Research

On October 1, 1972 a 33.1 million cubic feet (MCF) thin-walled plastic ballon lifted off the launch pad at Cape Girardeau, Missouri, marking the 25th anniversary of ONR's Project SKYHOOK. Dr. Jonathan Ormes, a research scientist from Goddard Space Flight Center, was a most interested participant. His scientific experiment, weighing over 3000 pounds and designed to measure high energy cosmic rays, was on its way to an altitude in excess of 130,000 feet and an "on-station" time in excess of 25 hours. His payload would be recovered shortly after touchdown some 25 miles east of Nashville, Tennessee.

Historical Background

In 1946 it was realized that a stable platform from which high-altitude scientific observations could be made was needed to gather information of value for space flights of the future. The initial project, HELIOS, required the construction of plastic balloons that would make possible flight to the stratosphere in a manned gondola equipped with scientific instruments. A cluster of plastic balloons, approximating a fraction of the total mass of a rubberized balloon, was to be used to achieve an altitude in excess of 100,000 feet.

Insufficient advance in the technology of plastic balloon manufacture dictated postponement of early manned ballon flights. HELIOS studies, however, did confirm the feasibility of using plastic balloons to take scientific instruments to high altitude for periods of up to a day or more. Accordingly, the Office of Naval Research began Project SKYHOOK and the first flight of a SKYHOOK balloon occurred on September 25, 1947. Built by General Mills, Inc. and launched at St. Cloud, Minnesota, this 30,000 cubic feet volume vehicle carried a payload of 63 pounds to 100,000 feet before descending at Eau Claire, Wisconsin (Figure 1).

Since that time more than 3000 such flights flown under ONR sponsorship have been made from locations throughout the world including the high seas.

In 1948, the first shipboard SKYHOOK launch took place from the USS NORTON SOUND. Several hundred shipboard launchings have occurred since that time (Figure 2). Project ROCKOON, which featured small Deacon rockets lifted to about 70,000 feet and released from a SKYHOOK balloon, was held in Artic waters during 1952.

*CDR Melton is Project Officer for Operation SKYHOOK, Office of Naval Research. His primary field of interest is Meteorology. Recent tours of duty were as Staff Meteorologist to Commander First Fleet and as Forecaster for Carrier Division Four and *USS Independence* CVA 62.

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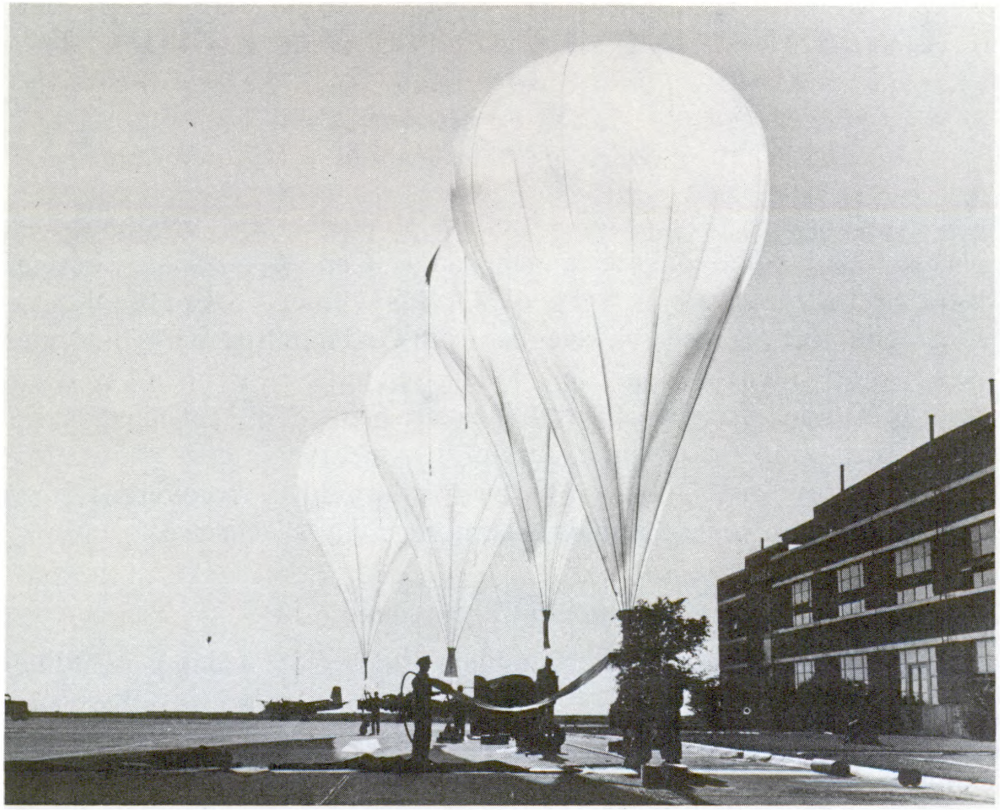

Figure 1 — Four plastic SKYHOOK balloons, constructed by General Mills, Inc. for the Office of Naval Research, are prepared for an early morning launching. The Skyhooks are only partially inflated because the gas expands as the balloons rise to the upper atmosphere.

On May 18, 1954, SUPER SKYHOOK, the largest plastic balloon (three million cubic feet) built up to that time, was launched from the University of Minnesota airport by General Mills, Inc., for the U.S. Navy. It soared to a float altitude of 117,000 feet carrying a 400 pound scientific payload designed to gather cosmic ray information. In less than seven years balloon sizes had increased by nearly two orders of magnitude (Figure 3)!

Altitude records were also being set as plastic balloon usage surged. On September 7, 1956, the University of Minnesota launched a giant unmanned Mylar plastic balloon developed by G. T. Schjeldahl Company to set an altitude record of 145,000 feet.

Project STRATOSCOPE I marked the tenth anniversary of SKYHOOK. On September 25, 1957, a giant solar telescope was carried to an altitude of 81,000 feet obtaining some of the sharpest photographs ever taken of the sun (Figure 4).

U.S. Air Force projects such as MANHIGH and FARSIDE began utilizing the balloon techniques developed for SKYHOOK and other

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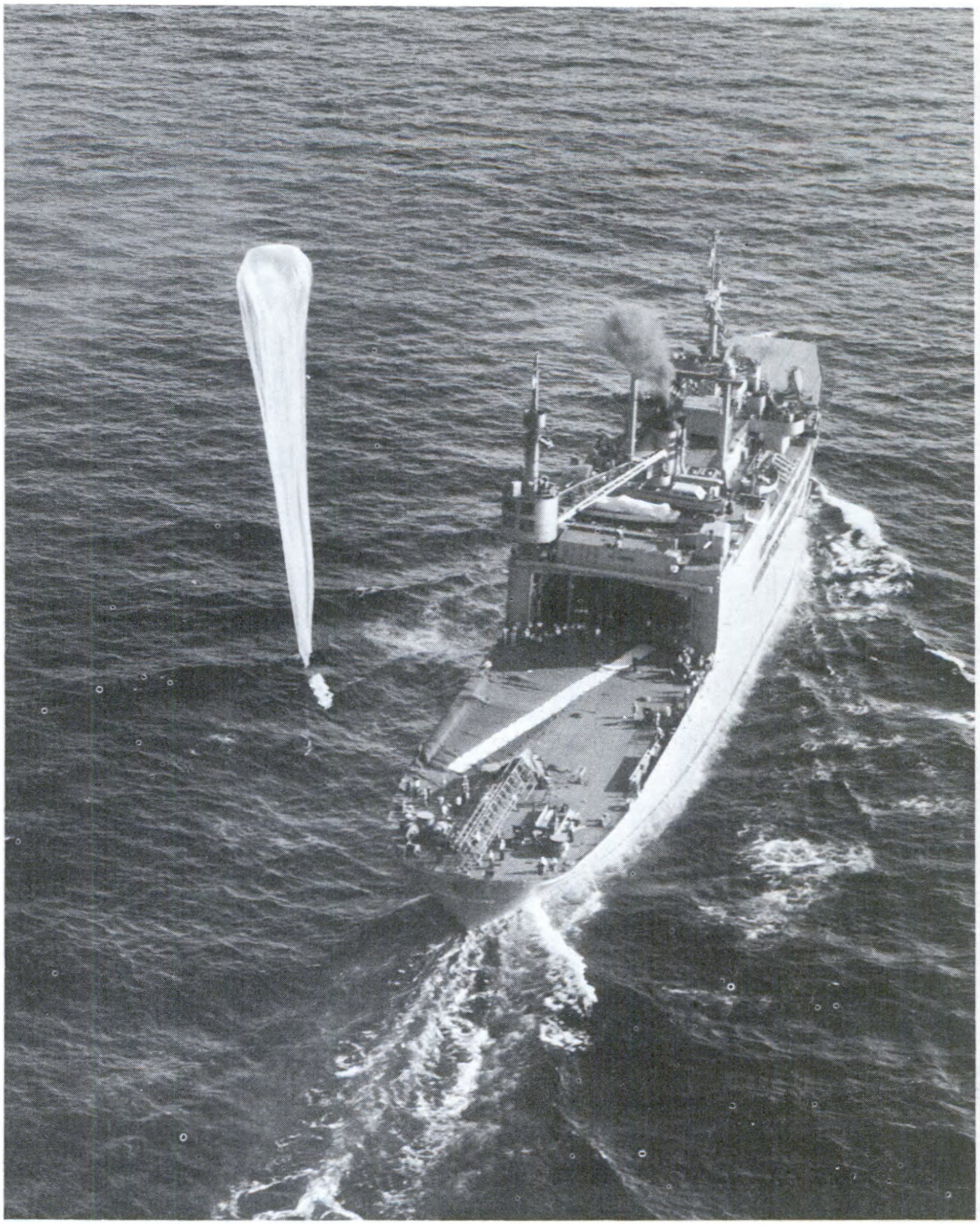

Figure 2 – SKYHOOK balloon 93 leaving the deck of the USS NORTON SOUND

ONR balloon projects. It was now time for ONR to reactivate its manned balloon program which had remained dormant for several years.

The STRATOLAB program was initiated in 1954 when the gondola shell, originally designed by Jean Piccard and built for Project HELIOS, arrived at Minneapolis to be fitted out and tested. The purpose of STRATOLAB was to provide a research platform from which important operational and physiological space barrier problems could be studied. Operational altitudes from 60,000 feet to 100,000 feet were

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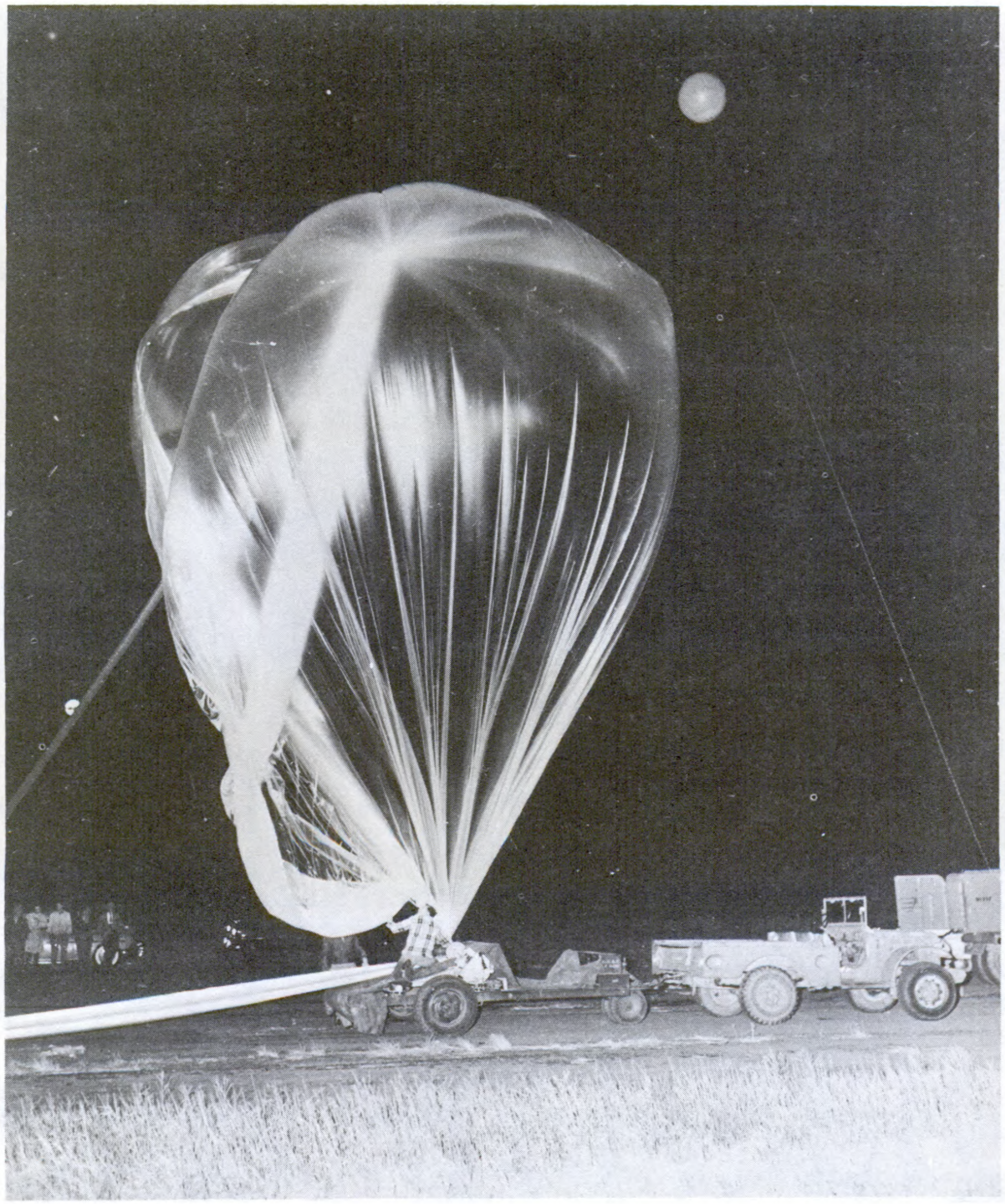

Figure 3 — One of the stages in the inflation and launching of the SUPER SKYHOOK in 1954

considered particularly significant in that future military aircraft operations were forecast to operate in that zone.

The gondola, soon to be used for stratospheric flights, was designed to be pressurized with cabin altitude remaining near sea level irrespective of altitude attained in flight. Winzen Research, Inc. and General Mills, Inc. combined talents to provide adequate climate, sensing, flight control, safety and communications equipment for the gondola.

STRATOLAB HIGH I, launched by General Mills on November 8, 1956, reached an altitude of 76,000 feet. Chief pilot of this and sub-

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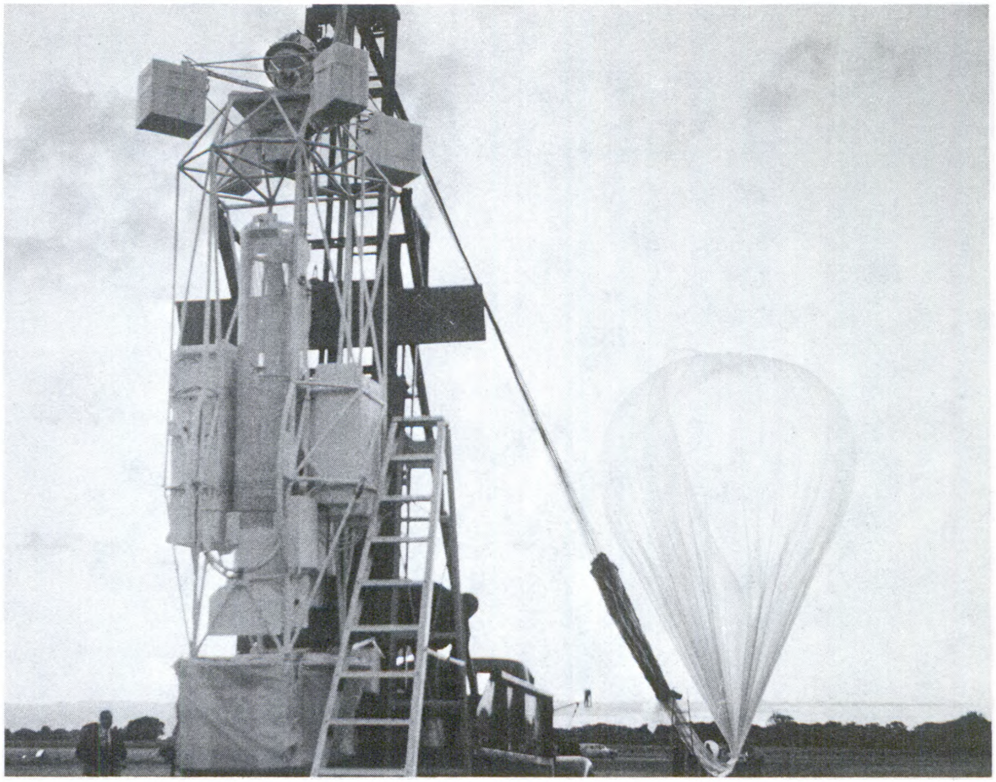

Figure 4 – During the SKYHOOK I flights over 400 photographs of sum spots were taken which did lead to a better understanding of the motions observed in the strong magnetic fields of the sum spots. The 12-inch telescope-camera was equipped with a closed circuit television camera and a remote control mechanism that enabled the research team to guide the camera and at the same time to see on the TV screen the area under observation.

sequent STRATOLAB flights was CDR Malcolm D. Ross, USNR (Ret). The late LCDR M. Lee Lewis, USN (Ret) was copilot for the first three flights. On STRATOLAB I, the 21 year old altitude record of Explorer II was broken, ushering in an era of almost routine Navy and Air Force high altitude manned plastic balloon flights. STRATOLABS II, III and IV were responsible for two major accomplishments – the first national television broadcast from outer space and the discovery of water vapor in close proximity to the planet Venus (Figure 5). The final flight in the series was STRATOLAB V which was highlighted by several ballooning "firsts." Leaving from the flight deck of the aircraft carrier, USS ANTIETAM, in 1961, STRATOLAB V became the first manned balloon flight to be so launched. Soaring to an unbroken world record height of 113,000 feet in an open gondola, the two pilots conducted the first actual environmental tests of the Navy-developed space suit. This space suit became the forerunner of the apparel used in the National Aeronautics and Space Administration's Mercury program.

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Figure 5 – Left to right LCDR Lee M. Lewis, Mr. John Strong, and LCDR Malcom D. Ross prepare to enter the gondola for a test of the equipment for Project STRATO-LAB IV

Manned flights held great public interest from 1955 through 1961 and somewhat overshadowed another program, SKYHOOK Churchill, which began within this period (1959). Taking its name from the geographical location, Fort Churchill, Manitoba, Canada, SKYHOOK CHURCHILL was inagurated utilizing eight contractor personnel, six balloons and one aircraft (for recovery of scientific payloads). Dr. James A. Earl of the University of Maryland conducted the first scientific investigations here. This past summer marked the 14th consecutive year of operations at Fort Churchill. Although the number of Churchill flights has declined from a high of nearly 40 in the mid-sixties, balloon volume and payload weight have been increasing at an incredible rate thereby dictating a steady level of operations (Figures 6-10).

Other geographical areas in which SKYHOOK flights have taken place range from the Antartic to T-3, the Artic ice island, and include Peru, Panama, Australia, Iceland and of course, numerous sites within the North American Continent.

Accordingly SKYHOOK CIAP (Climatic Inpact Assessment Program), a program to monitor stratospheric constituents on a global basis, was initiated in December, 1971. Working in close coordination with the Department of Transportation, ONR contractors accelerated

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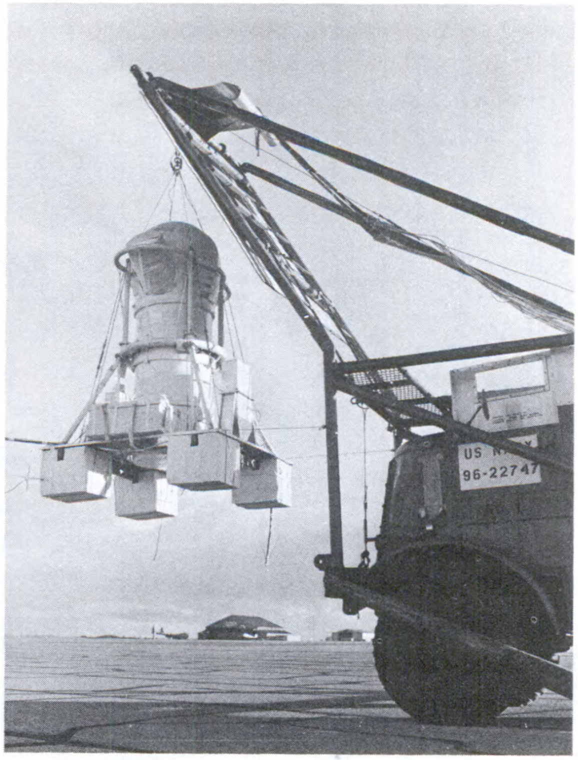

Figure 6 – Typical scientific experiment during SKYHOOK CHURCHILL operation, 1972 showing experimental equipment for the balloon hanging from launch truck.

Figure 7 – Inflation of the balloon bubble with helium gas

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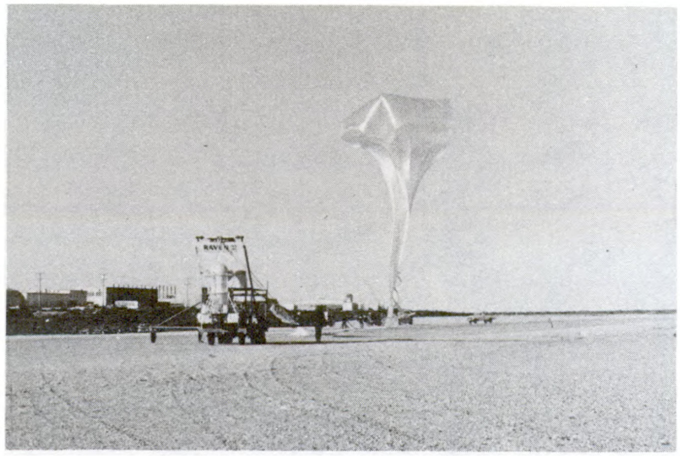

Figure 8 — Immediately after balloon bubble was released from anchor vehicle

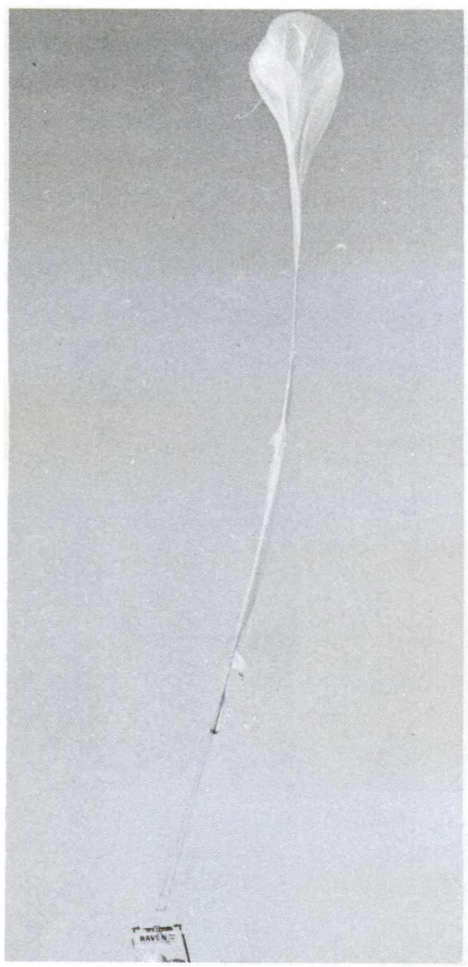

Figure 9 — Balloon erect over launch vehicle immediately before picking up the experiment weight

Figure 10 — Balloon ascending

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on-going programs to obtain a data base of ozone, water vapor and particulate matter in the stratosphere.*

Balloons for Science

Balloons were used to lift scientific experiments to the edge of space a full thirteen years before the first successful U.S. scientific satellite was placed into orbit. As approximately 99 percent of our earth's atmospheric mass is below 20 miles, scientific experiments conducted at or above this level avoid most of the atmospheric "noise" and other effects encountered at lower levels. Hence, the quality of *in-situ* and remote measurements obtained is much improved over earlier data gathering experiments utilizing less efficient, lower altitude platforms. The high altitude balloon when compared with a rocketsonde for example, provides for a longer experiment exposure and a much wider choice of geographical locations from which to launch.

Balloon reliability has increased markedly over the past 25 years. One of the pioneers in balloon design and manufacture, Otto C. Winzen, President of Winzen Research, summed up the hazards facing thin-walled plastic balloons thusly:

"Consider the traumatic flight experience a balloon has to survive: First the stresses of inflation and launching, then ascent at 200-400 meters per minute, crossing jet streams with velocities up to 250 kilometers per hour and temperatures occasionally down to −86° C. finally reaching down to 0.1 percent of an atmosphere exposing the balloon to the virtually unabated force of solar and cosmic radiation. The flight reliability of over 96 percent which has been achieved is nothing short of remarkable."

Cross agency interest in SKYHOOK remains at a high level. NASA, which provides a significant input of funds to the program, sees an increase in balloon research interest over the next few years in spite of overall budget reduction. According to their program engineer for sounding rockets and balloons, Ernest Ott, "The guys who would formerly fly experiments on satellites now can't get a place." For many of these scientists, says Ott, balloons have presented the only alternative for continuing their scientific investigation.

1972 Flight Operations

The ONR 1972 SKYHOOK Program was truly global in scope. Operations were conducted from 16 geographical locations and resulted in 63 successful flights. Major experiments were flown by the Universities of California (Riverside and Berkeley), Case Western

*To date, 34 data producing flights have been conducted by the University of Wyoming and the University of Melbourne.

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Reserve, Chicago, Louisiana State, Maryland, Melbourne (Australia) Minnesota, MIT, New Hampshire, Washington (St. Louis), and Wyoming. "Hitch-hike" or smaller, tag-along experiments were flown by the Universities of Calgary (Canada) Rice, St. Paul and Tokyo (Japan). Government agencies also participated with Goddard Space Flight Center and the Naval Research Laboratory flying large scientific packages. The Atomic Energy Commission rounded out the participation, flying a small experiment from Cape Girardeau, Missouri in late September.

Highlights

With coordination and support from the ONR and NASA, the Australian Balloon Flight Crew successfully launched and recovered the world's largest balloon from Alice Springs, Australia, on April 5, 1972. Carrying MIT's Dr. Walter Lewin's x-ray experiment to an altitude of 148,000 feet, the 46.1 MCF plastic vehicle stayed aloft for over 26 hours. To comprehend the size of this giant aerostat one need only to visualize sixteen twelve story buildings (30,000 square feet) fitting inside (Figures 11 and 12).

In early summer SKYHOOK CHURCHILL marked its 14th Anniversary with 13 successful major balloon flights. This was the seventh

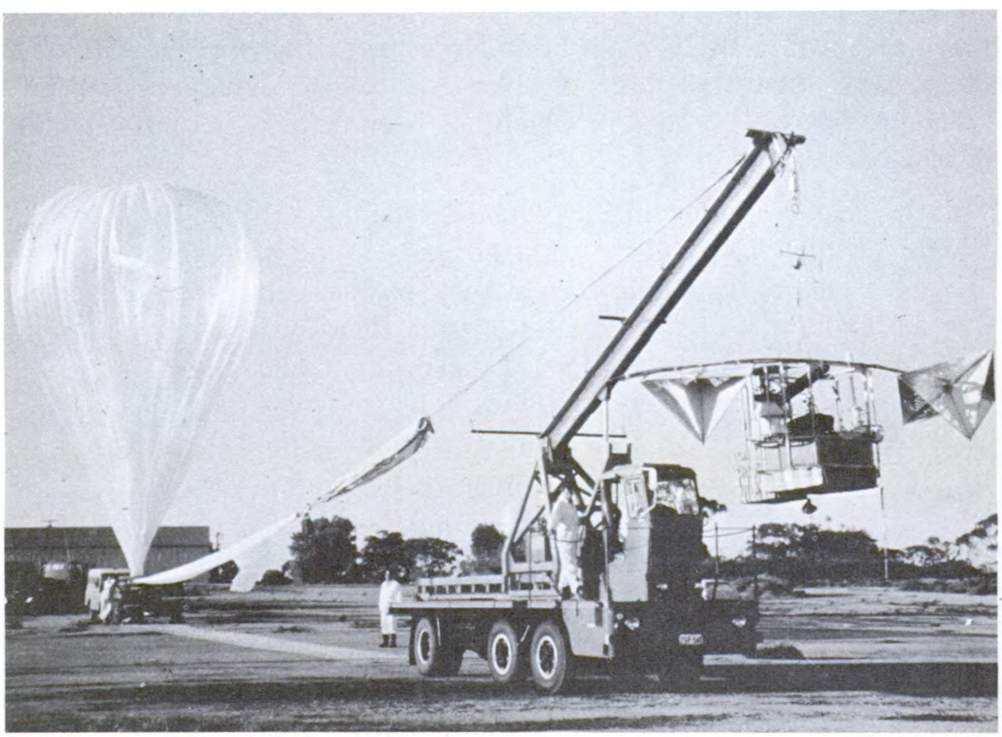

Figure 11 – Scientific equipment being launched at the Balloon Launch Station, Mildura, New South Wales, Australia on April 5, 1972

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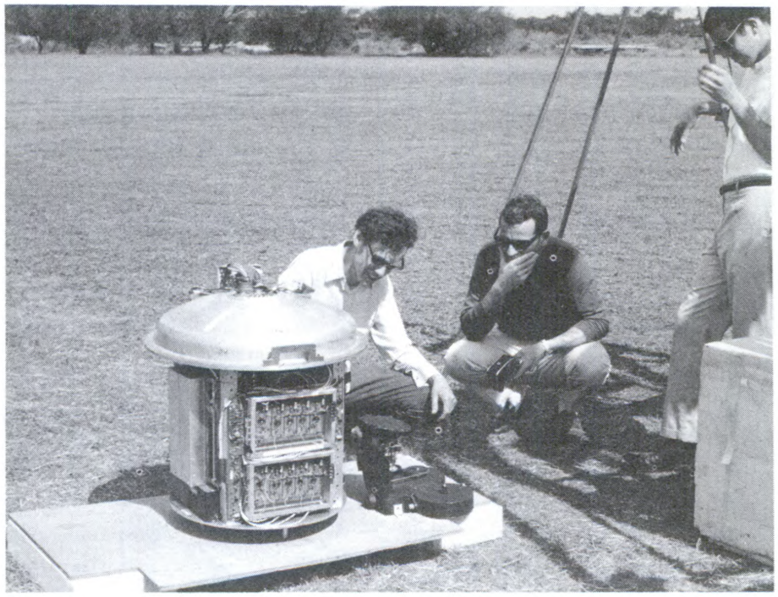

Figure 12 – Dr. Walter Lewin of MIT examines his x-ray telescope during the Australian Balloon Flight

consecutive season without payload loss. One launch abort occurred when a sudden wind shift prevented the launch truck from positioning the payload undernearth the balloon. Although slightly damaged in this evolution, the experiment was repaired and flown successfully four days later. Despite two weeks of unfavorable flying weather all scheduled scientific investigations were completed in less than one month. The flawless performance of the Winzen Research balloons and the "team" effort displayed by the flight services contractor, Raven Industries, contributed greatly to the success of SKYHOOK CHURCHILL 1972.

SKYHOOK Cape Girardeau (Missouri) was highlighted by Dr. Ormes' success mentioned previously. Of the six flights scheduled, all were successes from a scientific data gathering viewpoint. Average flight duration exceeded 19 hours and payload weights ranged from 1000 to nearly 4000 pounds, a significant increase over experiment weights at Fort Churchill. Once again the combination of Winzen balloons and Raven flight operations proved equal to the task. An otherwise perfect operation was manned when the payload of Dr. Stephen White (Univeristy of California at Riverside) free-fell and was destroyed. As data was telemetered the flight was a scientific success. Parachute malfunction has been initially assessed as the cause of this regrettable accident.

On balance SKYHOOK 1972 was a huge success. Larger balloons, heavier payloads and longer duration flights were the routine, not the exception. The next plateau of 50 million cubic feet balloons flying at altitudes in excess of 170,000 feet is at hand. ONR SKYHOOK will play a significant role in achieving this goal.

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Hydromechanics of Micro-Organism Propulsion

T. Y. Wu*
California Institute of Technology

The Navy has a continuing operational requirement for improving the efficiency and noise characteristics of propulsion systems for its ships, submarines and underwater weapons. The results of this research on cavity flows and fish propulsion should lead to criteria which will enable improved design procedures for propellers for high speed propulsion and which should permit consideration of possible new means of quiet propulsion. Theoretical and experimental investigations are being carried out in several areas of naval hydrodynamics with emphasis on real fluid effects on cavity flows, wake flows, propellers, and the fluid mechanics of swimming propulsion.

The Microscopic Biosphere

Many micro-organisms have the ability to swim or to propel themselves. Such ability, in fact, is vital for survival, and out of their survival emerges the equilibrium of life in the microscopic biosphere, in which the myriad species of protozoa, spermatozoa, bacteria, *etc*. form a necessary base for the living world to build on.

The high performance of some most impressive species is seldom fully apppreciated until one takes a good look at the live performance through a microscope. In fact, if one magnifies their scale to our common daily experience by referring to the speed of locomotion in terms of body length per unit time (as is usually done by the biologists), one would observe some exceedingly impressive records. The following Table 1 presents an estimated speed of locomotion of several organisms. In comparison with the upper limit of about 9-10 for a wide variety of fast fishes, about 6-7 for cetaceans (porpoises in fast swimming), and only slightly above 1 for human athletes in swimming, the cell motility records have given not only a remarkable impression to observers but also a strong stimulus to scientists for seeking explanation as to how the micro-organisms can be so successful in their locomotion.

Micro-organism locomotion is manifested by a variety of mechanisms. The major types are known as (i) flagellated propulsion, (ii) ciliated propulsion, (iii) variations of the first two mechanisms, (iv) all of which

*Professor Wu's association with ONR goes back more than 12 years. Through his prolific and outstanding research he is an international authority in the field of fluid mechanics. He is professor of Engineering at California Institute of Technology.

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TABLE 1

	Beat Frequency f = beats/s	Length L (μ)	Propulsion Velocity U (μ/s)	U/L ($/s$)	Propulsion Reynolds No. $U\ell/\nu$	Reference
Sea urchin sperm	30-40	40	800-1,000	20-25	$3.2 - 4 \times 10^{-2}$	Gray (1955)
Bull sperm	9.1	(60) est.	(400-500) est.	7-9	$2.4 - 3 \times 10^{-2}$	Gray (1958)
Peranema flagella	5-6	80-100	c. 200			Lowndes (1941)
Euglena flagella	12.7	128	813	6	10^{-1}	Lowndes (1941)
Stentor membranelle	27.7	30	730-920	25-31	$2.1 - 2.8 \times 10^{-2}$	Sleigh (1960)
Opalina cilia	1-4	10-20	20-100	2-5	$0.2 - 2 \times 10^{-3}$	Sleigh (1960)
Mytilus abfrontal cilia	2-3	100	500	5	5×10^{-2}	Gray (1930)
Mytilus lateral cilia	16	10-20	(160-320) est.	8-32	$1.6 - 6.4 \times 10^{-3}$	Gray (1930)
Grantia flagellum	5-20	30	25-500	1-17	$0.8 - 15 \times 10^{-3}$	Bidder (1927)
Paramecium cillium	28	12	350	30	4.2×10^{-3}	Sleigh (unpublished)
Tetrahymena	20	50	450	9	2.2×10^{-2}	Winet (1969)
Vibrio comma		1-5	200	40-200	10^{-3}	Thimann (1963)

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may be mediated by extraneous physical effects (*e.g.* to produce geotaxis, phototaxis, rheo-taxis, *etc.*). Actually, so easily observed are these characteristics that they are adopted as a basis for taxonomy; thus come the terms flagellates, ciliates, spirochetes, *etc.* From the hydromechanical point of view, important flow quantities associated with the propulsive movement are the forces and the moments of force exerted on the fluid by the cell. This facet of investigation is significant since it is necessary to establish first the fundamental explanation whether a proposed mechanism will be possible or not, at least on the basis of the hydromechanical principles.

A closely related consideration is to determine the mechanical power required for maintaining the cell movement, the energy dissipated in the flow motion, and the energy balance of the mechanical system. Such studies are of significance for several reasons. First, such information can supply the necessary data for the biochemists and the physiologists to study the chemical and mechano-chemical energy distribution in the system that is responsible for flagellar or ciliary movement. Second, from the point of view of optimization and control theory, it is of great interest to examine if there is generally an optimum movement, under some prescribed conditions, which, for given propulsive thrust, will require the minimum power. This category of control problems that arise from studies of propulsion of aquatic animals emerges as a very new field in which much is to be gained by learning. The development in this area may also cast some light on the evolutionary thesis: whether more than a billion years of continuous competition between various species of animals must necessarily have eliminated the less efficient (or less effective by some measure) species in favor of those having the ability of utilizing the optimal movements.

For these reasons a group of researchers in the Engineering and Applied Science Division of the California Institute of Technology have engaged themselves in a research program, under a joint sponsorship of the Office of Naval Research and the National Science Foundation, which is devoted to a broad and thorough study of this general subject. A close communication and collaboration with biology colleagues and interested scientists at Caltech and elsewhere has always been a strong goal. In this program both theoretical and experimental approaches to these problems have been utilized for:

1. biophysical observation and physiological analysis of swimming cells,
2. mathematical analysis of several major theoretical models of cell swimming, and
3. mechanical modelling of various different mechanisms.

While this research program also includes a wide scope of hydromechanics of swimming and flying of large animals (designated by large

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values of their characteristic Reynolds number) the present article, however, will report on the research activities on micro-organism locomotion. In our research activity many mutual impacts have already been felt regarding conceptual development and methodology between the small and large values of the Reynolds number scale. Significant developments of one are undoubtedly beneficial to the other since the hydromechanical principles underlying the two cases are very closely related.

Flagellar Movement

Flagellates usually locomote by means of undulatory movement of a single flagellum (some species may have many and some have non-undulating flagella) which is a very elongated motile organelle. The undulatory movement can be classified into the following categories (see Jahn & Votta, 1972).

(A) Planar waves—in which the flagellum assumes the form of a travelling wave (see Figure 1) either from base (that is, the intersection of the flagellum with the cell "head") to tip, the flagellum being either posterior (*Ceratium*) or anterior (*Ochromonas, Prymnesium*), or from tip to base.

(B) Helical waves—a type of motion in which a simple or somewhat more complex helical wave is propagated along the flagellum, usually from base to tip (*Trichomonas, Trachelomonas*).

(C) Three-dimensional wave—as some variations of the above simpler types, the helical waves may become so irregular as to appear interrupted (*Euglena*), or in form of a spiral (*Peranema*), or in a whiplike action.

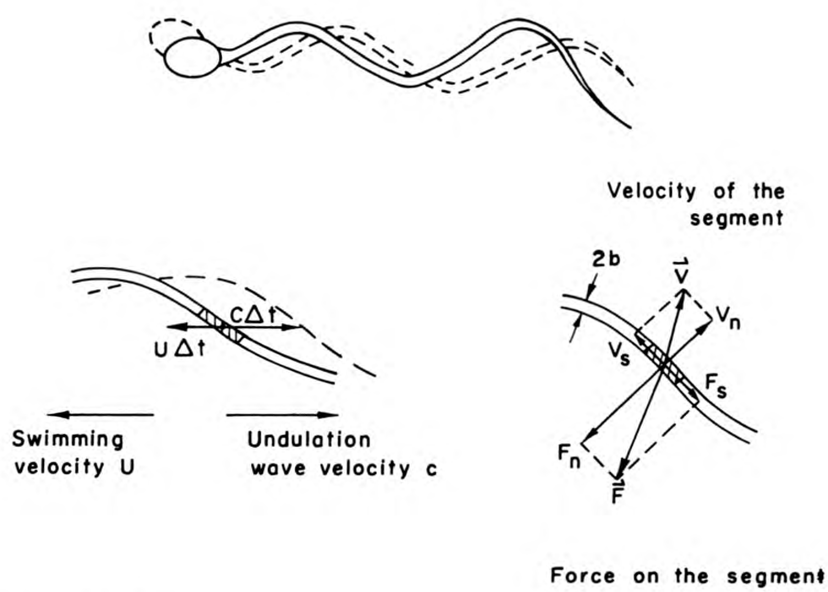

Figure 1 — Planar wave motion of a sperm and the force balance diagram

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In these movements the typical order-of-magnitude values may be given as follows: beat frequency, $f = 1 - 100$ Hz; amplitude of flagellar wave, $h = 1 - 10\mu m$; length of flagellum, $\ell = 10 - 100\mu m$; diameter of flagellum, $2b = 0.1\mu m$. On physical grounds, the characteristic Reynolds number most relevant to the analysis of locomotion should have the velocity based on $V = fh$ of the cross-flow, and the length based on b rather than the flagellum length ℓ since the latter is evidently less critical. On this basis the Reynolds number lies in the range 10^{-3} to 10^{-6}, which is about two orders smaller than the forward motion Reynolds number quoted earlier in Table 1. In this range the inertia of the surrounding liquid becomes insignificant as compared with the viscous effects and hence can be neglected. Such a simplification, when applied to elongated bodies, lead to the so-called resistive theory (Lighthill 1969). This is based on the assumption that the force between a small section of the body and the surrounding fluid is resistive and viscous in origin, depending primarily on the instantaneous values of the velocity of that body section relative to the surrounding fluid.

The resistive theory of propulsion was first considered by Taylor for an undulating sheet (1951) and undulating cylinder (1952), who showed that theoretically such systems can indeed generate propulsion even on the basis of small amplitude approximation. Motions of finite amplitude was later considered by Hancock (1953), whose analysis led Gray and Hancock (1955) to propose the following simple and powerful formulas. The resistive forces $\Delta\vec{F}_n$ and $\Delta\vec{F}_s$ acting on a segment of the cylinder having a longitudinal arc length Δs which moves with component velocities $\vec{V}_n$ and $\vec{V}_s$, respectively, are (see Figure 1)

$$\Delta\vec{F}_n = -C_n\vec{V}_n\Delta s \qquad \Delta\vec{F}_s = -C_s\vec{V}_s\Delta s,$$

where C_n and C_s are appropriate force coefficients, and

$$C_n = 2C_s, \qquad C_n = 4\pi\mu/[\ell n(2\ell/b) - 0.5]$$

μ being the viscosity coefficient, ℓ the length and b the radius of the flagellum.

This resistive theory has been widely adopted in theoretical calculations for propulsion velocity and power dissipation. Although reports on favorable agreement between such theoretical predictions and the experimental results have been known (Holwill and Miles 1971), there are, however, also reports not so satisfactory as was made by Rikmenspoel (1962), who observed that the predictions by the resistive theory are sometimes an order of magnitude higher than the experimental results.

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It has also been found experimentally at Caltech that error of this resistive theory depends on the type of movement, as evidenced by the results obtained with mechanical models.

This resistive theory has been extended by Chwang and Wu (1971) to include the helical wave movement of flagella (see Figure 2) by introducing, in addition to the forces, the moment of force (or torque) acting on a flagellum segment, of length ds, which rotates about the central axis of the segment with angular velocity $\vec{\Omega}$, as

$$d\vec{M} = -C_m\vec{\Omega}ds, \qquad C_m = 4\pi\mu b^2.$$

In self propulsion the resultant torque on the flagellum is counterbalanced by the viscous torque on the cell "head" which rotates in reaction to the flagella helical movement. Based on this theoretical calculation, two equations expressing the equilibrium of rectilinear and angular momenta determine the unknown propulsion velocity U and the angular velocity Ω of the body about the axis of propulsion. Interestingly, the theory predicts an optimum "head" size to be in the range of 15-40 times the flagellar radius, whereabouts the helical movement with $kh = 1$ (k being the helical wave number, h the amplitude) appears to have the most desirable performance. That the hydromechanical efficiency has a broad maximum in the range about $kh = 1$ has also been noted by Holwill and Burge (1963). In contrast, the optimum ratio of cell "head" radius to its flagellar radius becomes as low as 2-4 when the flagellum performs a

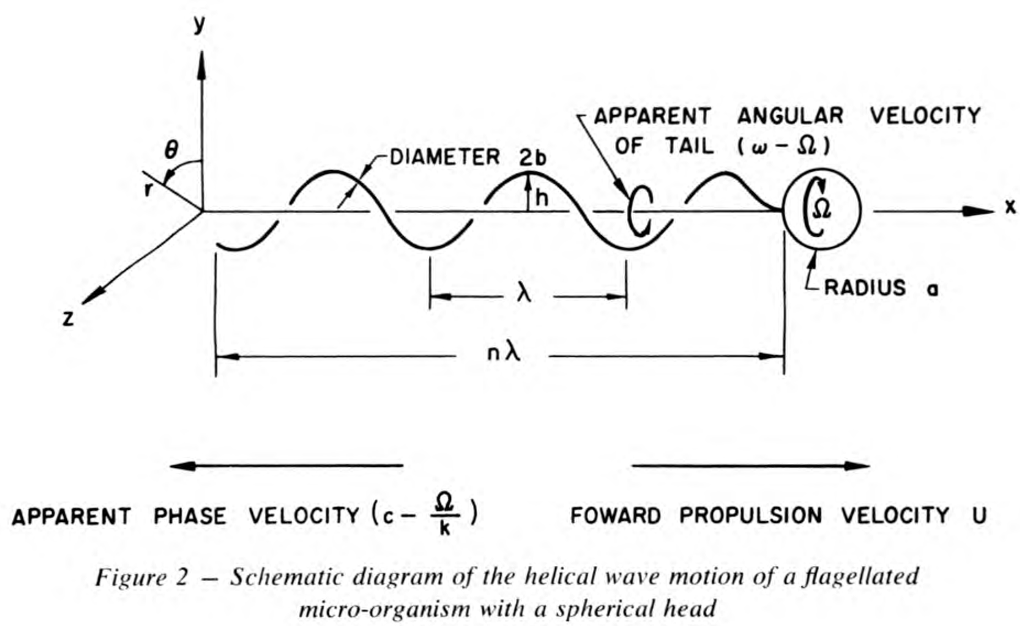

Figure 2 – Schematic diagram of the helical wave motion of a flagellated micro-organism with a spherical head

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planar wave. This finding is also in good qualitative agreement with observations on several spermatozoa which, it is quite definitely known, employ planar waves in their flagellar movements.

The spirochete paradox. Our study of the helical flagellar waves clearly suggests that too small a cell head appears to be as detrimental to propulsion as having too large a head, since our hydromechanical analysis indicates that some viscous resistance on the cell head is necessary to balance the torque experienced by the flagellum in order that the helical wave can be manifested. In the light of this understanding, a perplexing question, of long standing, about the spirochete movement then seems to have little hope for resolution, since the spirochetes and sporozoan trophozoites do not have an inert (in swimming function) head, yet, as is commonly accepted, whey swim by propagating (generally not very regular) helical waves along their entire body which behaves like a flagellum. In simple language, the question is "How can a spirochete drive itself forward if it moves like a rigid screw?" (The so-called "spirochete paradox" may be ascribed to a seemingly negative answer to the above question.) Some spirochetes are nonetheless good swimmers, apparently not being hampered by not having a cell head. One species, *Vibrio comma* (responsible for cholera) has been reported to reach a swimming speed of 100-150 body lengths per second (see Table 1).

A theoretical explanation has been proposed by Chwang, Winet and Wu (1972) that the spirochete movement, as in the version commonly accepted, is possible if the body surface has a self-rotation about the propulsion axis, with an angular velocity (Ω) which may be different from that (say ω) of the body central axis rotating about the same axis of propulsion (see Figure 3). With the extra degree of freedom, both the rectilinear and angular momenta of motion can be kept in equilibrium.

The spirillar movement. As a variation of the three-dimensional flagellar movement, spirilla propel themselves by means of a spiralling motion of a number of flagella at one or both ends of the body which has a permanent helical shape (see Figure 4). During locomotion, both the anterior and posterier flagella rotate in one and the same direction, while the rigid helical body rotates in the opposite direction and less rapidly. In the forward propulsion that results from the rotation of the helical body, the anterior and posterior flagella are bent somewhat backwards to appear rotating in two conical surfaces of revolution, swinging back from the direction of locomotion (see Figure 4), in a way much resembling a set of whirling propeller blades which are free to feather. When both polar flagella change their direction of rotation, the rigid helical body likewise reverses its rotation, and the entire organism accordingly reverses its direction of propulsion. Spirilla are noted for

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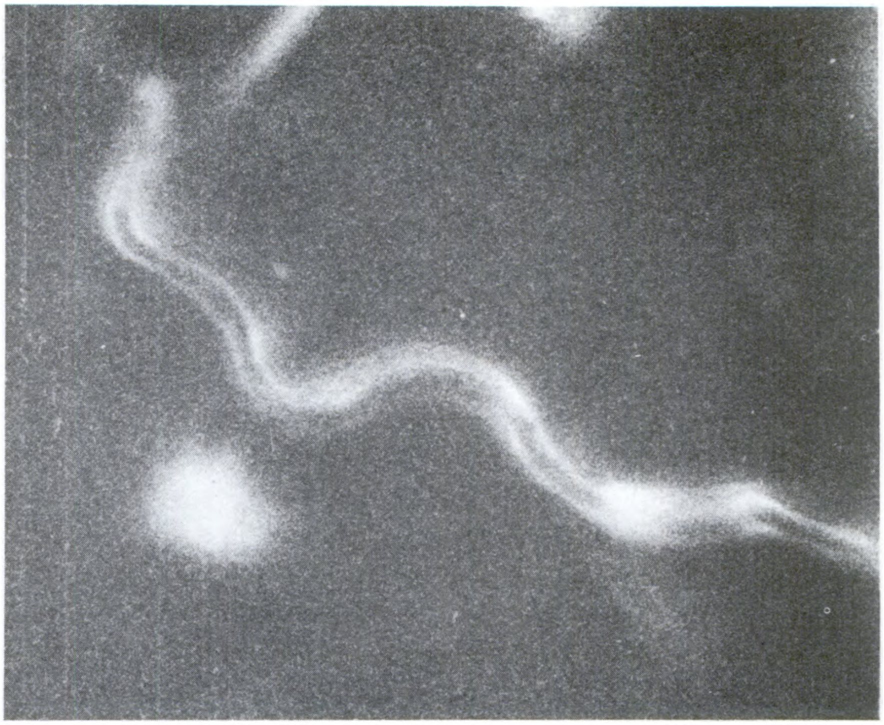

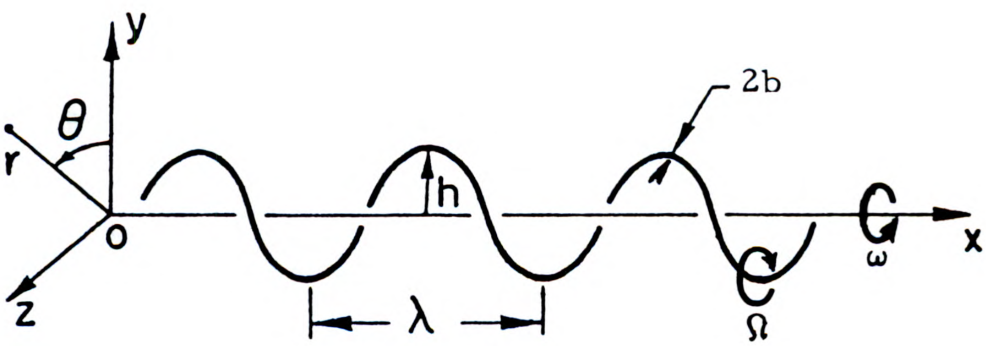

Figure 3 — Spirochetal movement

their relatively rapid locomotion in aqueous solutions by means of these helical movements. The resistive theory has been applied successfully by Chwang, Wu and Winet (1972) to provide a theoretical explanation for the mechanism of spirillum locomotion.

Improved hydromechanical analysis. A major effort is being made by Dr. Allen Chwang, Dr. John Blake and others at Caltech to improve the

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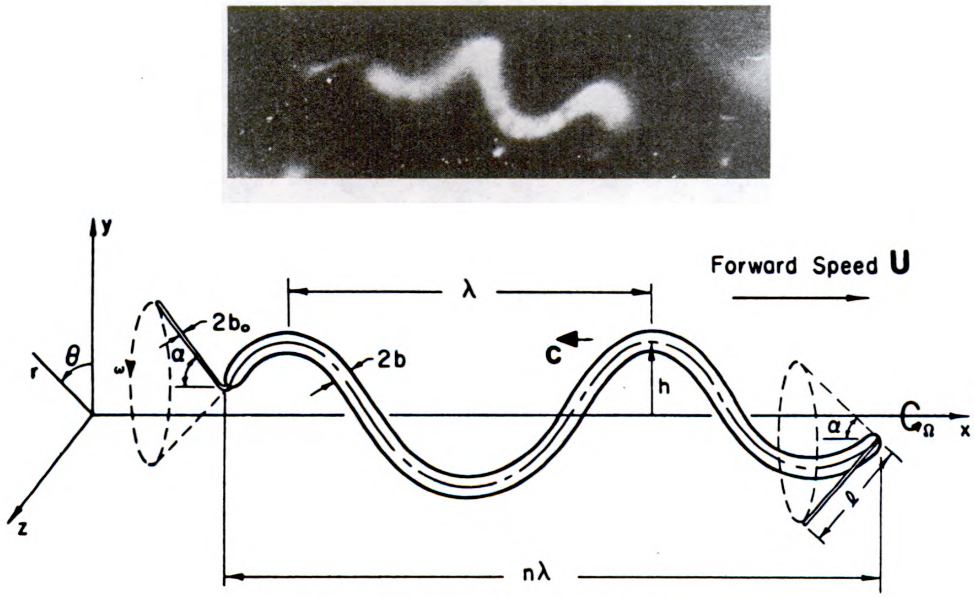

Figure 4 — Locomotion of Spirilla

accuracy of the force coefficients C_n and C_s (as mentioned before). The new approach followed here is to employ a distribution of flow singularities, such as the Stokeslet, doublet, stresslet, rotlet, and whatever may be necessary to represent the cell movement. It is expected that this new approach will be more accurate, and will enable much of the existing restrictions (such as small amplitudes, neglect of the effect of longitudinal curvature of flagella) to be relaxed.

Ciliary Movement

The ciliates are a class of protozoa which have a large number of hair-like organelles, called cilia, attached to the cell surface with a fairly even distribution, though a more refined row or column structure is also observed. They propel themselves by a periodic beating motion of cilia that can take a number of different formations for different ciliates. In the over-all picture of a majority of ciliates, cilia beat in rows, with the wave phase varying slightly from row to row, giving the general appearance in close resemblance to a wheat field in a breeze. Such metachronal (meaning not in exact synchronism) ciliary waves usually propagate backwards, somewhat obliquely, over the cell surface. Because of the obliqueness of the wave propagation a propulsive torque is generated, resulting in a gyration of the organism. In fact, virtually all ciliates swim along a helical path and gyrate; the radius of the helix, however, is generally very small.

The periodic motion of each individual cilium consists of two parts, a fast 'power stroke' and a slower 'recovery stroke' in each cycle. During the power stroke the cilium extends outward rigidly in pushing the fluid

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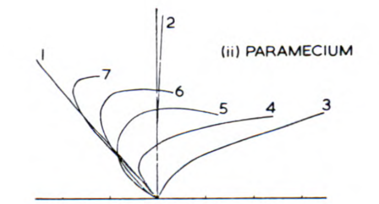
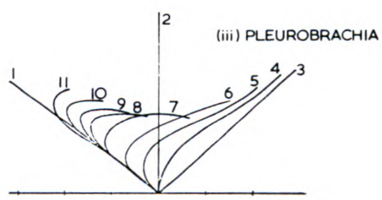
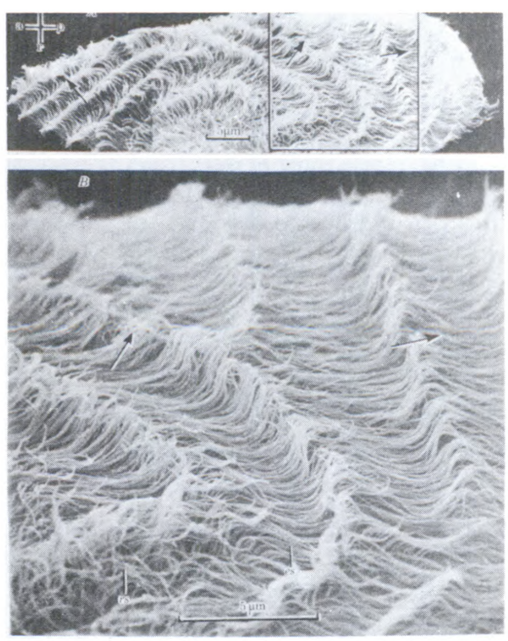
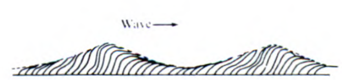
backwards, in an oar-like manner, whereas in the recovery stroke it flexes near the base and 'unfolds' into the starting position for the power stroke of the next cycle (see Figure 5). The metachronal wave is called symplectic or antiplectic when the wave propagates in the same or opposite direction of the power stroke. Waves are also found to travel transverse to the direction of the power stroke; they are called dexioplectic (right-going) or laeoplectic (left-going). These different directional waves naturally depend on the form of the power and recovery strokes (see Figure 6). There are also cases in which helical waves travel in each individual cilium (in swimming paramecium for instance, wave travels from base to tip).

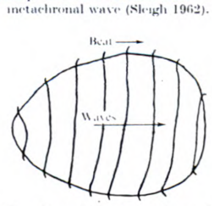








- - - -, envelope over metachronal wave of *Opalina*; →, direction of metachronal wave (Sleigh 1962).



View from above of *Opalina* to show symplectic metachronal wave patterns (Sleigh 1962).

Figure 5 – Head of individual cilia and metachronal wave

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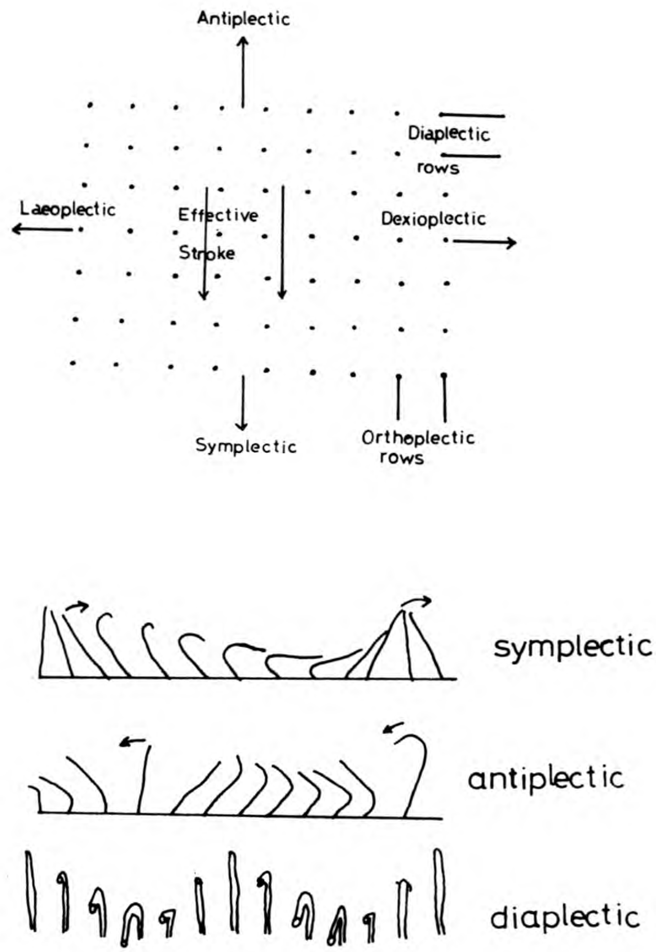

Figure 6 — Various types of metachronal wave patterns

The great complexity of ciliary movement has made rigorous analysis very difficult. Several theoretical models, however, have been adopted to investigate the hydromechanics of ciliary propulsion. One of the earliest is the 'envelope model' by which the concerted action of the cilia ensemble on the fluid is replaced by the waving movement of a 'sheet' enveloping the tips of all the cilia. It has been noted that the envelope model is especially appropriate for symplectic metachronal waves since in this case the cilia remain close to each other throughout the cycle so as to give the biologists the impression that the flow appeared to be due to the wave action as a whole (Sleigh 1962). Moreover, the mean flow across the envelope in symplectic type of motion appears to be insignificant and considerably smaller than in other types of metachronal waves. The observation further enhances the impermeable envelope as a realistic model.

The envelope model has been applied by Blake (1971a,b,1972a) to investigate the symplectic metachrony of *Opalina,* a flat, disk-like ciliate

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about 200 μm long and about 20 μm thick. The Stokes-flow approximation was employed in Blake's analysis, with the assumption of no velocity slip at the envelope, both accounts being in accord with the envelope model idea. The organism was predicted by this theory to attain a velocity of about 100 $\mu m/s$, which is close to that actually observed.

The symplectic metachronal motion has been investigated independently also by Brennen (1971) based on the envelope model. The Navier-Stokes equations are expanded for waves of small amplitude traveling along an infinite plane or an axisymmetric sheet. The boundary conditions are expressed in terms of the Lagrangian form which can be adapted to treat both the direct or inverse problems with a good versatility. The boundary configuration and movement considered by Brennen is quite general, including the problem of transverse metachronal wave first treated by Taylor (1951) and the problem of a longitudinal wave traveling along an infinite flat sheet discussed by Tuck (1968) as two extreme limits. Between these two limits the movement of the envelope sheet has both transverse and longitudinal components, like those described by Blake. From the numerical results Brennen found a certain optimum behavior of the solution that relates the wave and body configurations.

In contrast to the symplectic mode, it has been observed that in antiplectic metachronism the effective portion of the power stroke is delivered more individually by each cilium rather than the team-work like performance in the symplectic waves. It seems also true that appreciable fluid is alternately sucked in and squeezed out of the ciliary layer as the antiplectic waves travel by. These features make the envelope model seem rather inapplicable for this case. In order to calculate the antiplectic (as well as other types of) propulsion, Blake (1972b) used an alternative model which is conceptually associated with the flagellar movement. In this model Blake took two important boundary effects into account, one being that due to the proximity of the cell surface to which the cilia are attached, and the other being that due to the rest of the cilia in the whole array. With each cilium represented by a distribution of Stokeslets along its centerline, we see immediately that the effect of the cell surface and the proximity of neighboring cilia involve long-range forces (with the resulting flow velocity decaying in proportion to the inverse of distance from the force), and that the net effect, given by an integral equation, had to be resolved numerically. In comparison with this comprehensive method of analysis it remains to be seen if the envelope method can be extended to calculate all types of ciliary motions by a sophisticated modification of the boundary conditions. Investigation along this line is being pursued by Caltech.

Geotaxis and Bioconvection

Some swimming organisms (especially ciliates and flagellates) are negatively geotaxis, *i.e.* they create, by a physical process, subsurface

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(underneath the top surface) swarms of cells in cultures (such as those of *Euglena, Paramecium, Tetrahymena*). Figure 7 shows the cells of a *Tetrahymena* culture having accumulated in the subsurface layer by negative geotaxis. Under centrifugation such orientation is intensified with increasing angular velocity until the cell's propulsive thrust is overcome by the centrifugal force.

In the past surface forces of traction delivered by cilia have been ignored as irrelevant factors in geotaxis in favor of gravity alone. A new explanation for geotaxis has been proposed by Winet & Jahn (1972), who attribute the phenomenon of geotaxis to the combined effects of both the propulsive surface force and the gravity acting on the cell volume. We realize it is essential to include the surface force in the geotaxis consideration of organisms of such minute size, since the ratio of surface force to body force, their specific strength being held fixed, increases with decreasing body size (for nearly spherical or ellipsoidal

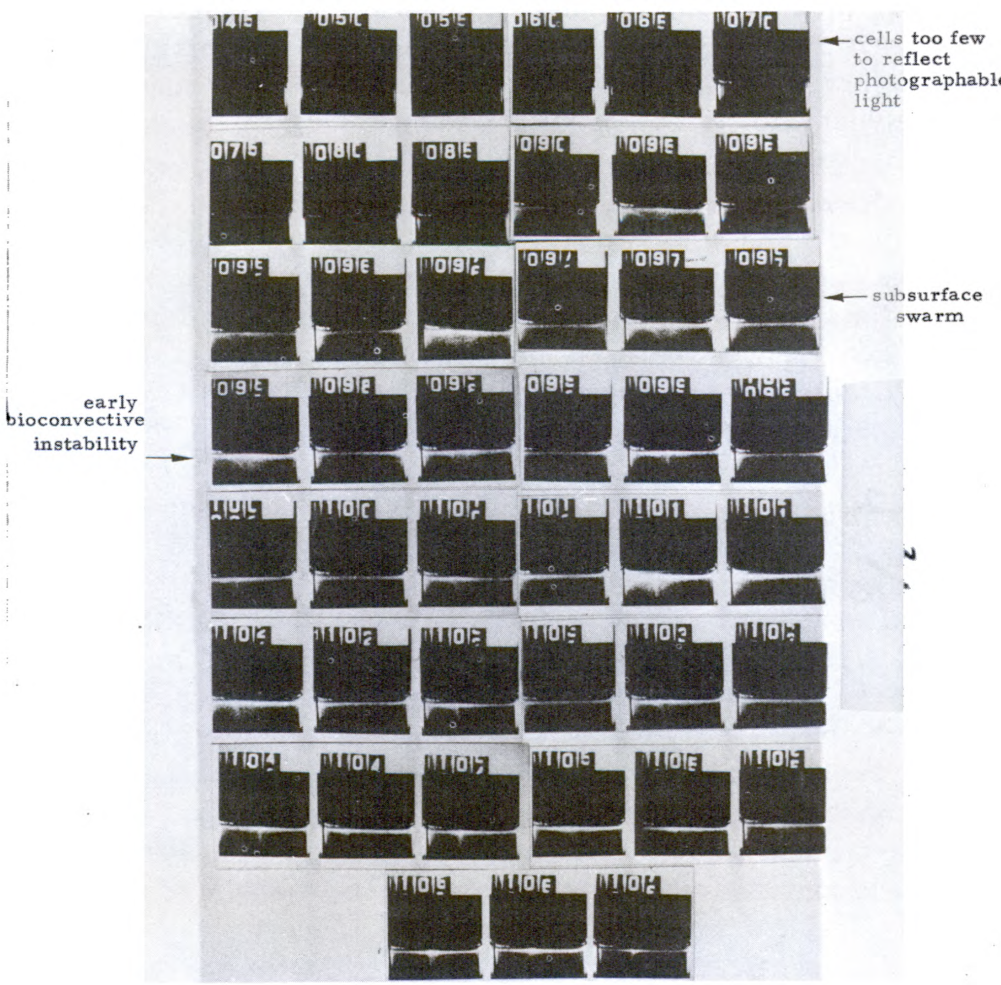

Figure 7 – Development of subsurface swarm at successive ages of culture

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forms). By this consideration, the geotaxis is negative or positive according as the center of surface thrust precedes or falls behind the center of gravity.

After the subsurface swarming is established by geotaxis in a cell culture, convections develop by which the cells are carried to the interior of the liquid medium in the formation of vertical columns of cells. This stage of the motion bears resemblance to the salt finger intrusion arising from an instability of a stratified fluid. Once the vertical columns of cells are set on, they continue to form recirculating streams in bioconvection 'cells' which is quite similar in form to the Benard cells caused by an instability of thermal convection. Figure 8 shows the side views of vertical columns and a top view of the polygonal shaped bioconvection cells.

The phenomenon of the development of vertical columns has been investigated recently by Professor M. S. Plesset, C. G. Whipple and Dr. Winet (1972). They ascribe this phenomenon to the Rayleigh-Taylor instability due to a density gradient in the culture. This model for bioconvection predicts that, given a two-layered fluid system, (a heavier fluid A over a lighter one B), a minimum perturbation wavelength can be found beyond which any small-amplitude disturbance with grow indefinitely, only to be checked by dissipation and other finite-amplitude effects.

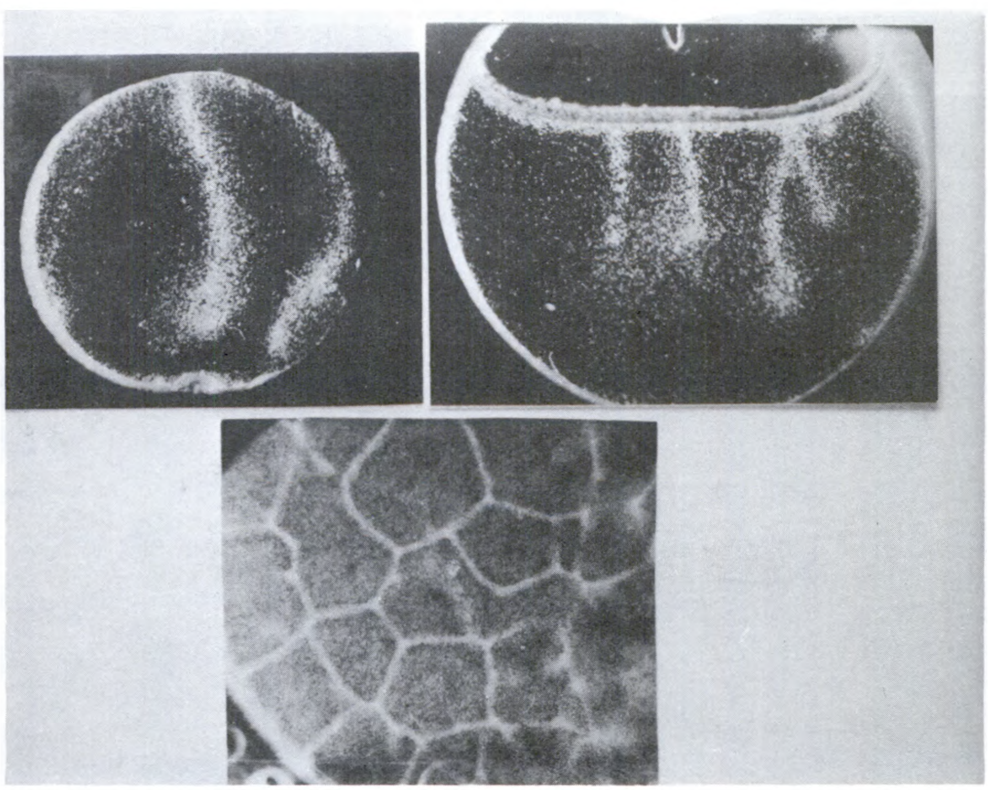

Figure 8 – Vertical column and top view of bio-convection cells

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Data Aquisition and Reduction

One of the fundamental problems in the experimental investigation of the hydromechanical aspects of micro-organism locomotion is the effective aquisition and manipulation of experimental data. For example, to accurately describe the time history of a flagellar movement, thousands of data points must be taken. In order to facilitate the aquisition of data, an image processing system is being developed. This system has affectionately come to be known as the 'bugwatcher.'

The bugwatcher consists of a television camera, a video processor, and a magnetic tape unit. The television camera is directed toward the object or event of interest (*e.g.*, at a projected motion picture frame, still picture, live event through microscope, *etc.*). The video processor digitizes the T.V. image into an X-Y array of discrete points, and stores the location of those points at which the light intensity crosses a preset threshold intensity. In this way the coordinates of the outline of a dark object on a light background (or visa versa) are instantaneously identified. These coordinates are then permanently recorded on magnetic tape.

The data on the magnetic tape can then be displayed by computer plots. Figure 9a, b, or undergo further computer programming. Such

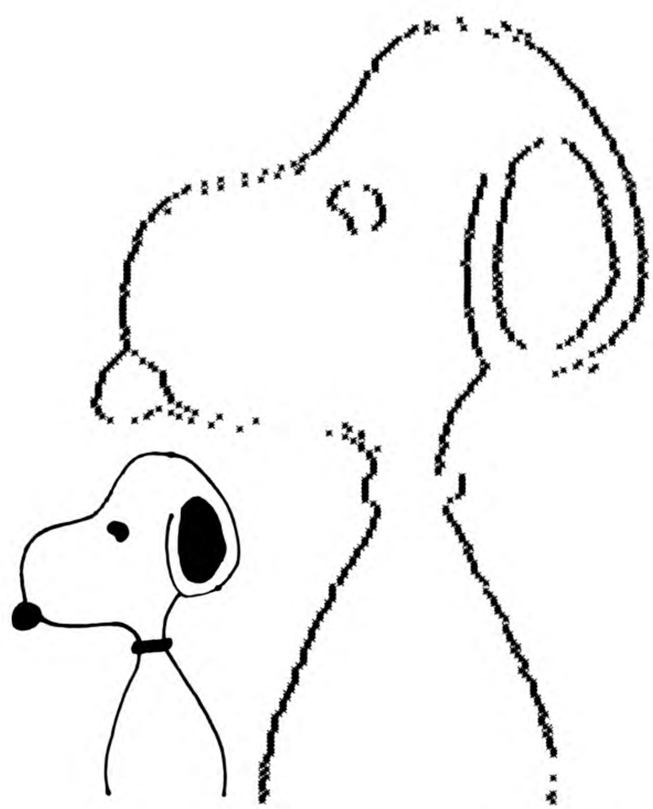

Figure 9A – Observed image (left) and computer plot after being digitized by bugwatcher (right)

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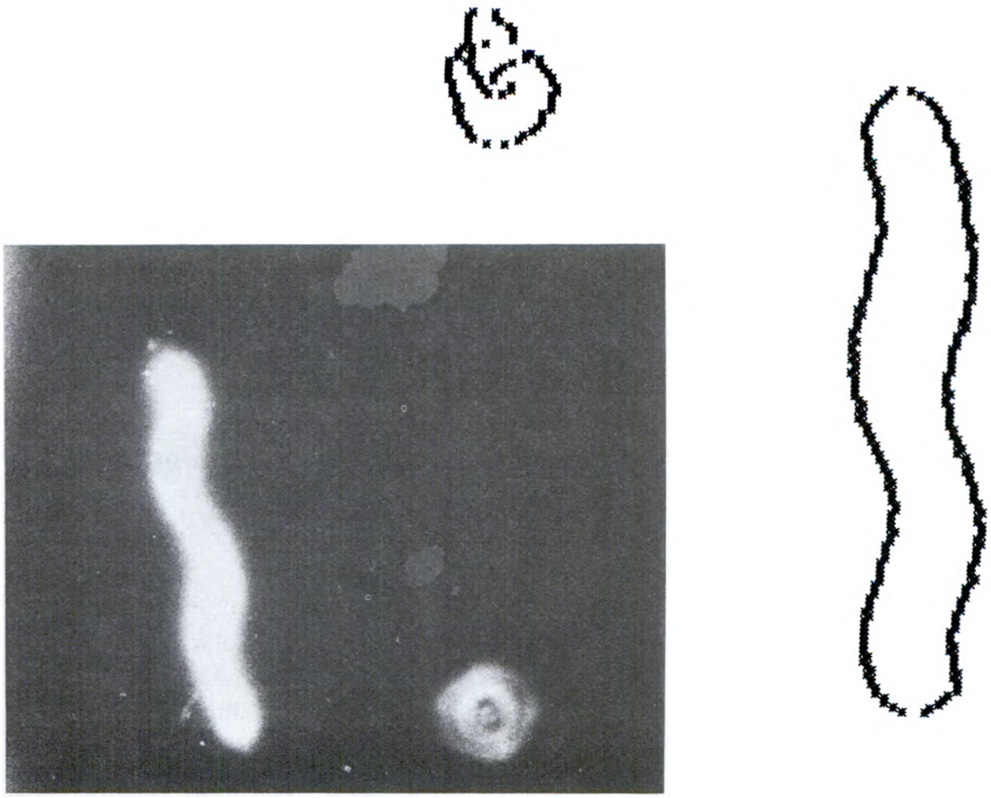

Figure 9B — Photograph of swimming spirilla (left) and computer plot of photograph at left after being processed by the bugwatcher (right)

quantities as position, body centroids, as well as exact body shapes are readily available from the stored data. By storing many sequenced data blocks, as in a motion picture film, such important quantities as velocity and acceleration may be obtained. Thus with the aid of the bugwatcher and subsequent analysis of the data, we hope to gain a more detailed description of the flows around micro-organism.

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Influence of Solar Magnetic Fields on the Weather

The investigation of geomagnetic disturbances by Professor John Wilcox at Stanford University has shown that a rotating solar magnetic field that is extended past the earth by the solar wind plasma appears to influence the stratospheric circulation pattern. The relevant component of the solar magnetic field is similar to a quadrupole with its axis parallel to the solar equatorial plane. As the sun rotates the quadrupole rotates with it so that during each 27-day rotation period the polarity as observed from the earth changes four times. Each of these four changes in the polarity of the solar magnetic field is transported out into interplanetary space by solar magnetic field lines frozen into the expanding solar wind plasma.

As observed by a spacecraft magnetometer near the earth, this rotating quadrupole magnetic pattern appears in the form of about seven consecutive days with field polarity directed away from the sun, a very narrow boundary, seven consecutive days of field directed toward the sun, another very narrow boundary followed by another away interval and toward interval to complete the 27-day pattern.

On the average, the area in the northern hemisphere covered by low pressure troughs as measured at a height of about 30,000 feet seems to be influenced by this solar quadrupole magnetic pattern. About 1-1/2 days before a magnetic polarity change is swept by the earth, the average area of these low pressure troughs begins to decrease, and reaches a minimum approximately one day after the polarity change has passed the earth. During the following 1-1/2 days the trough area returns to its normal value. Since these low ressure troughs tend to be associated with rain and storms, one may describe the effect schematically by saying that on the average the northern hemisphere weather is about ten percent better than normal during the day following the passage of solar magnetic boundary past the earth.

The physical mechanism causing this effect is not yet understood. However, the fact that the effect is reproducible, well-defined, and has an amplitude of ten percent when averaged over the entire northern hemisphere (north of 20° N) suggests the possibility that further investigations may define a physical mechanism. The solar quadrupole magnetic pattern causing the weather effect is stable during at least a few years and quite possibly during several consecutive 11-year sunspot cycles; thus this effect may be useful in weather forecasting.

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The University and Defense Research *

James Case†
University of California
Santa, Barbara, California

I think that a homily on the topic of throwing out the baby with the bath water is in order in anticipation of what is likely to develop from publishing the list of recent recipients of Department of Defense research funds in the NEXUS (the daily newspaper of the University of California, Santa Barbara).

Currently, the list indicates that I receive a yearly contract from the Office of Naval Research (ONR). The funds support a long continuing project under the general title of "The Physiology of Luminescent Signal Systems." This is a significant fraction, about half, of my total research support, and I am very glad to have it. How do I justify this, using military money in an academic environment? Let me do so by discussing, first, what I know the most about in regard to the defense research effort, the work supported by ONR. Then I would like to dwell a little on two ideas, namely that it is actually a good idea to keep the Defense Department "honest" by having as many relatively uncommitted civilians as possible involved in its research, and that there is a legitimate defense research effort that good scientists really should do, and which is "worthy" of the Halls of Academe.

The Office of Naval Research could well have been a model for the big and generally acclaimed federal scientific research programs such as those mounted by the National Science Foundation (NSF) and The National Institutes of Health (NIH). I understand that immediately after World War II virtually the only federal agency putting significant amounts of money into fundamental research was ONR. George Wald, for example, had ONR support in those days for research that undoubtedly contributed to his Nobel Prize for research in vision. Thus ONR has a long and distinguished history for research support in the area of pure science, irrespective of whatever purely military research it contracted for, and dating back to before NSF and NIH became significant contributors to research funding.

My own connection with ONR is through its Division of Oceanic Biology. My understanding is that the Division task is to support research in those areas of the marine sciences that are likely to contribute to the understanding of the sea. Much of the work that is supported is

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* Reprinted from UCSB *Daily NEXUS*, "Low Profile," November 9, 1972.
†James Case is professor of zoology at UCSB.

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undoubtedly of no immediate military significance. Much of it is probably of as much value in the civilian sphere as in the military. For example, the Division has supported research on ship fouling organisms which impede civilian as well as military ships with notable impartiality. It has spent money on studies of the senses and behavior of sharks with the end in view of ultimately finding effective ways to protect people in the water from shark attack. Lessons thus learned are of equal value to a Navy pilot down at sea and victims of a civil marine accident.

Specifics

Regarding my own ONR supported research I can state that I have never been asked to undertake work of any specified type, military or otherwise, by ONR. That is not the way it works. What really happens is that I think about research that I want to do in my area of interest. Any aspect of this that involves the ocean, I make up into an annual proposal which I submit to ONR. The agency takes it or leaves it, relying in part on the advice of a panel of scientists. Then, when the work is done, my students and I publish it in any journal we can, without screening or prior clearance from ONR. There is, in short, no significant difference evident to me between how my ONR contract operates and, for example, how my National Science Foundation grant works.

What is done with the money ONR lays on me? First of all, the University gets its cut, overhead used for general support of the campus-wide research effort. The remainder, as the title of my contract indicates, is used by me and my students to study bioluminescent animals in the sea. We work on behavior, what luminescent deep sea animals do with the light they produce; and we work on biochemistry and physiology, how light is produced and controlled. Pure science, this, as far as I am concerned. If the Navy wouldn't support it, I would send very nearly the same research application off to NSF or NIH with reasonable hope of approval.

Why does ONR support such work with your dollars? I think it is because ONR quite rightly believes that the Navy ought to know everything that there is to know about the ocean. Much of what it learns will undoubtedly never have any direct military value, but the Navy comprehends, just as does any civilian research agency, that practical science gets very weak very fast without a pure science input.

But what is the sense of having a military agency support pure research? Why isn't it only done by a purely civilian agency? I think that it is extremely important that research is not totally categorized in this manner. Indeed, it seems to me most unfortunate for the country that military research agencies have been sharply limited in the amount of pure research that they can support. As a result of this trend, I see the possibility of development of an extremely bad situation. I see a future

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with purely military research establishments working in secret only on the hardware of war.

This is bad for two reasons: (1) Civilian scientists are not going to know what is going on. As a consequence, the country as a whole is not going to know whether what is being done in such establishments is good or bad, economic or wasteful, necessary or not. (2) The chances are that sequestered military research of this sort will in fact be bad and wasteful simply because of the input from pure science that will be lacking. Thus, there is, I believe, a legitimate argument that a nation that wishes to utilize its military research establishment as wisely as possible will want its civilian scientists involved as much as possible and in ways in which they are not beholden to the military for their total research support and even their jobs.

Finally, let me say something about another aspect of contracts like mine that might not readily occur to students. This is the fact that the money thus obtained is in large part disbursed to students as salaries for work as research assistants, thus providing them both income and training in science. In addition, equipment that otherwise might be unavailable to the campus is purchased. Very often such equipment is used in training graduate students and may even be used by undergraduates.

Title to equipment purchased under military contracts is often assigned to the University once the contract terminates and thus continues to serve useful purposes for many years in research and teaching. And certainly it must not be forgotten that these funds, to the extent that they foster good research, contribute in a general but critically important way to the teaching function of the University. I think that there is no truer dictum as far as the science departments of the University are concerned than the statement that good researchers are the best teachers. These men have to be in institutions that do not interfere with their legitimate sources of research funds.

Thus we return to babies and bath water. I think that it is very bad business for a university community to categorically cut itself off from research funds simply because they come from one agency or another. It is better to ask in each instance what the money shall be used for. In short, as long as the Department of Defense has money to spend on pure research, let us take advantage of it.

Certainly, I agree that some research projects are undesirable and inappropriate to an academic situation. But generally these can be turned away not merely because of the agency proffering the award, but on the grounds that the project has no academic merit, as is quite often the case in directly military related studies. And I would also agree that a university is the antithesis in spirit of classified research, which should be conducted in a university only under conditions of clear national necessity.

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On the Naval Research Reserve

Program for NRRC 4-7

Naval Reserve Research Company 4-7 of Columbus, Ohio, is moving into a new year with a new project-oriented program for the entire unit. The company has recently completed a project that occupied its drills over the last several years; a study of submarine tactics. This was conducted with the assistance of COMSUBDEVGRUP TWO and resulted in a tactical note jointly promulgated by COMSUBLANTFLT and COMSUBPACFLT. The work was funded in part by ONR and the unit recently received a commendation from the COMMANDANT, Fourth Naval District for its achievement.

The study blended the skills and experience of members of the company with submarine backgrounds, together with a diversity of applicable experience from other members. Prominent among the submariners were CDR C. R. McLean and CDR E. C. McCabe. The leading non-submariner was CAPT Daniel Howland; in civilian life, Professor of Management Science and head of the Adaptive Systems Group at Ohio State University.

The new project is a two phased approach to the study of naval planning. All members are enrolling as a group in a Naval War College Correspondence Course, NAVAL OPERATIONS 19-2. Solutions will be developed in two ways. First, solutions will be derived using the Naval Planning procedures as presented in the course material. These will be solved individually and submitted by each member. Second, the concepts of Adaptive Systems Analysis developed in the submarine work will also be applied to the solution of operational problems, and submitted as a group effort for comparison purposes.

The Commanding Officer of the Company is LCDR Raymond Mesloh, assisted by his Executive Officer, LCDR Joel P. Citron. Drills are held at Battelle Memorial Institute, Columbus, Ohio. Interested and qualified applicants in the area are invited to inquire about affiliation.

NRRC 3-9 Views Demonstration of "The OPTACON"

Members of Naval Reserve Research Company 3-9, Brookhaven National Laboratory, Upton, New York honored their former Group Commander, CAPT B. Osthues, USNR, for his years of outstanding service to the unit at the drill meeting, 6 December 1972. Also in attendance at the meeting was CAPT Eleanor F. Kehoe, USNR, Training Officer, Research Reserve and wives and friends of the members.

The speaker for the drill meeting was Mr. John Courtney who described and demonstrated "The OPTACON," a remarkable new instrument that makes it possible for a blind person to read ordinary

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printed matter. Mr. Courtney, who is blind, is employed as an engineer at Brookhaven National Laboratory.

Three students, selected by the three services as the top winners at last year's International Science and Engineering Fair, attended the Nobel Prize ceremony in Stockholm on December 10 as their award. Here they are conversing with Dr. Rodney Porter of Great Britain, co-winner of the Nobel Prize in Medicine or Physiology. At left is Miss Cindy Lindsay of Los Alamos, New Mexico, sponsored by the Navy, followed by Van Wedeen of Brooklyn, New York, and Harold Loveridge of Lafayette, Indiana, sponsored by the Air Force and Army. In the background is Mrs. Dorothy Robinson of the Office of Naval Research who served as official escort. ONR established the program and coordinated arrangements for the three services.

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IN THIS ISSUE

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From top left to bottom right: (1) The STRATOSCOPE instrument package is being attached to balloon. The instrument package of this 1957 launch contained a powerful astronomical telescope to photograph the sun. (2) In 1958 a Navy pilot and astronomer were carried 40,000 to conduct experiments. Here the men are seated in the gondola with its plastic greenhouse ready for launch. (3) A 10 million cu. ft. Winzer research balloon being inflated in 1969 aboard the USS Valley Forge. *(4) Preparations for the first balloon test of the 1961 STRATOLAB experiment.*

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