Apollo-Soyuz Pamphlet No. 1:

The Flight

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Apollo-Soyuz Experiments In Space

This is one of a series of nine curriculum-related pamphlets for Teachers and Students of Space Science

Titles in this series of pamphlets include:

EP-133 Apollo-Soyuz Pamphlet No. 1: The Flight
EP-134 Apollo-Soyuz Pamphlet No. 2: X-Rays, Gamma-Rays
EP-135 Apollo-Soyuz Pamphlet No. 3: Sun, Stars, In Between
EP-136 Apollo-Soyuz Pamphlet No. 4: Gravitational Field
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EP-140 Apollo-Soyuz Pamphlet No. 8: Zero-G Technology
EP-141 Apollo-Soyuz Pamphlet No. 9: General Science

On The Cover

Apollo Spacecraft and Docking Module
Facing the Soyuz Spacecraft Just
Before Docking. By Artist Robert McCall, 1974

Apollo-Soyuz
Pamphlet No. 1:

The Flight

Prepared by Lou Williams Page and Thornton Page From Investigators' Reports of Experimental Results and With the Help of Advising Teachers

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Preface

The Apollo-Soyuz Test Project (ASTP), which flew in July 1975, aroused considerable public interest; first, because the space rivals of the late 1950's and 1960's were working together in a joint endeavor, and second, because their mutual efforts included developing a space rescue system. The ASTP also included significant scientific experiments, the results of which can be used in teaching biology, physics, and mathematics in schools and colleges.

This series of pamphlets discussing the Apollo-Soyuz mission and experiments is a set of curriculum supplements designed for teachers, supervisors, curriculum specialists, and textbook writers as well as for the general public. Neither textbooks nor courses of study, these pamphlets are intended to provide a rich source of ideas, examples of the scientific method, pertinent references to standard textbooks, and clear descriptions of space experiments. In a sense, they may be regarded as a pioneering form of teaching aid. Seldom has there been such a forthright effort to provide, directly to teachers, curriculum-relevant reports of current scientific research. High school teachers who reviewed the texts suggested that advanced students who are interested might be assigned to study one pamphlet and report on it to the rest of the class. After class discussion, students might be assigned (without access to the pamphlet) one or more of the ''Questions for Discussion'' for formal or informal answers, thus stressing the application of what was previously covered in the pamphlets.

The authors of these pamphlets are Dr. Lou Williams Page, a geologist, and Dr. Thornton Page, an astronomer. Both have taught science at several universities and have published 14 books on science for schools, colleges, and the general reader, including a recent one on space science.

Technical assistance to the Pages was provided by the Apollo-Soyuz Program Scientist, Dr. R. Thomas Giuli, and by Richard R. Baldwin, W. Wilson Lauderdale, and Susan N. Montgomery, members of the group at the NASA Lyndon B. Johnson Space Center in Houston which organized the scientists' participation in the ASTP and published their reports of experimental results.

Selected teachers from high schools and universities throughout the United States reviewed the pamphlets in draft form. They suggested changes in wording, the addition of a glossary of terms unfamiliar to students, and improvements in diagrams. A list of the teachers and of the scientific investigators who reviewed the texts for accuracy follows this Preface.

This set of Apollo-Soyuz pamphlets was initiated and coordinated by Dr. Frederick B. Tuttle, Director of Educational Programs, and was supported by the NASA Apollo-Soyuz Program Office, by Leland J. Casey, Aerospace Engineer for ASTP, and by William D. Nixon, Educational Programs Officer, all of NASA Headquarters in Washington, D.C.

Appreciation is expressed to the scientific investigators and teachers who reviewed the draft copies; to the NASA specialists who provided diagrams and photographs; and to J. K. Holcomb, Headquarters Director of ASTP operations, and Chester M. Lee, ASTP Program Director at Headquarters, whose interest in this educational endeavor made this publication possible.

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1 Introduction

Goals of the Apollo-Soyuz Test Project

The two launches and the docking of the Apollo-Soyuz spacecraft comprised the first manned spaceflight coordinated by two nations. The primary goal was to show that two major powers, while still competing in space, could benefit by a cooperative mission. The achievements were partly psychological, partly scientific, and partly technological. For the first time, the Russian people saw U.S. astronauts on television and Americans were able to view a Soviet launch and landing. Specialists in both space agencies recognized the value of a common docking system for possible rescue missions in space. Planners saw the value of combining the ''know-how'' of both countries for further exploration of space. People in the rest of the world, seeing the cooperation between two rival major powers, may now have more interest in space science and technology.

The joint space project was first discussed by personnel in the National Aeronautics and Space Administration (NASA) and the Soviet Academy of Sciences in October 1970. Almost 2 years later on May 24, 1972, the mission concept was finalized in Moscow when ''An Agreement Concerning Cooperation in the Exploration and Use of Outer Space'' was signed by the Chairman of the U.S.S.R. Council of Ministers Aleksey Kosygin and President Richard M. Nixon. During the next 2 years, detailed plans for all aspects of the flight, including common design elements, joint experiments, and press coverage, were negotiated. The astronauts and the cosmonauts exchanged visits, learned each other's language, and subsequently shared meals while in orbit 222 kilometers above the Earth. They are now respected friends.

As for previous spaceflights, NASA scientists and engineers planned experiments and other activities that would yield data of the greatest possible value from the overall mission investment of approximately $220 million.

Figure 2.1 Apollo-Soyuz crewmen Donald K. Slayton, Thomas P. Stafford, Vance D. Brand, Aleksey A. Leonov, and Valeriy N. Kubasov.

2 International Meeting in Space

A Astronauts and Cosmonauts

The men who made the first international docking in space, three NASA astronauts and two Soviet cosmonauts, are shown in Figure 2.1. The Apollo Commander, Tom Stafford, is a Major General in the U.S. Air Force. Before Apollo-Soyuz, he had flown on three NASA missions—Gemini VI, Gemini IX, and Apollo 10. The Soyuz Commander was Col. Aleksey Leonov. On March 18, 1965, during the Voskhod 2 mission, he had taken man's first walk in space.

For 13 years, D. K. (Deke) Slayton, the Docking Module Pilot, had been Director of Flight Crew Operations at the NASA Lyndon B. Johnson Space Center (JSC). He was excluded from spaceflight because of a heart problem which cleared up by 1972. Apollo-Soyuz was also the first space mission for Vance Brand, the Command Module Pilot. Valeriy Kubasov, the Soyuz Flight Engineer, had flown on one previous Soviet mission, Soyuz 6.

In addition to the general training for the entire mission, each astronaut had to become a specialist. For instance, before the flight, Deke Slayton learned every design detail of the Docking Module (DM) and was ready to repair or service it. All three astronauts were taught to speak Russian, and the cosmonauts learned to speak English. The rule was that the speaker must always use the listener's language. Before the flight, each astronaut studied the objectives, equipment, and procedures of the 28 scientific experiments.

During the flight, each crewman had an active and specific role in at least 10 experiments. In addition, all had programed duties in spacecraft operation, space medicine, and engineering tests. Altogether, their tasks occupied almost every minute of the flight, except for meals and rest periods.

After the flight, each astronaut was subjected to several medical examinations and took part in many conferences concerning the experiments and tests.

B Time Schedule

The Apollo-Soyuz Test Project (ASTP) mission began with the launch of the Soyuz spacecraft from the Baykonur Cosmodrome near Tyuratam in the State of Kazakh, U.S.S.R., on July 15, 1975, at 12:20 GMT. Greenwich mean time was used throughout the mission to avoid confusion between Moscow time, eastern daylight time (EDT) at the NASA John F. Kennedy Space Center (KSC) in Florida, and central daylight time (CDT) at JSC in Houston, Texas.

Another kind of time was also used in planning the flight schedule, starting at the precise launch time of Soyuz. This ground elapsed time (GET) was zero hours zero minutes (00:00) at Soyuz launch and was used for both crews' "time line," or schedule of duties. GET was used because the planners didn't know in advance what the exact GMT of the Soyuz launch would be.

Another timing difficulty occurred in matching crew activities with public activities in both the United States and the U.S.S.R. The astronauts' meals and rest periods were normally scheduled at the times that people in Houston eat and sleep. The cosmonauts' schedule was similarly linked to Moscow time. But live television broadcasts for both the United States and the U.S.S.R. required some exceptions. For instance, the dinner shared by Astronauts Stafford and Slayton and Cosmonaut Leonov on Apollo started at 5 p.m. Moscow daylight time or 14:00 GMT, which was 9 a.m. CDT in Houston.

C The Spacecraft

The Apollo and Soyuz launch configurations are shown in Figure 2.2. The two different booster rockets are standard items that have been used for many launches in the two countries. The Soyuz booster was designed by Soviet engineer Sergei Korolyov, the top man in the Soviet space program until his death in 1966. Its 20 ''engines'' use kerosene fuel burned with liquid oxygen (LOX) to give a thrust of 7×10^6 newtons (795 tons). This thrust lifted the Soyuz spacecraft to an altitude of approximately 180 kilometers. The acceleration increased during this time because of the loss of mass as fuel was burned. The booster then pitched the spacecraft over to push it horizontally into an orbit[1] around the Earth. This orbit was not exactly circular. It was slightly elliptical, varying from 186 to 222 kilometers above the Earth's surface, and was inclined 51.8° to the Equator.

The big booster was then jettisoned (detached), pushed back, and allowed to fall. Next, the smaller rocket in the Soyuz spacecraft was fired twice, each burn taking place when the spacecraft was at the highest point in its elliptical orbit—farthest from the Earth. This point is called ''apogee.'' By increasing the spacecraft speed, these ''apogee kicks'' caused it to begin traveling in a circular orbit at the former apogee altitude.

The Apollo launch was similar, except that after the Saturn IB first-stage booster started turning the Apollo vehicle, it was jettisoned before the horizontal thrust from the Saturn IVB put Apollo into a slightly elliptical orbit between 148 and 168 kilometers above the Earth. This orbit was later circularized at 167 kilometers, 55 kilometers lower than the Soyuz orbit. (The maneuvers necessary to raise the Apollo orbit for a rendezvous with Soyuz are described in Section 3.)

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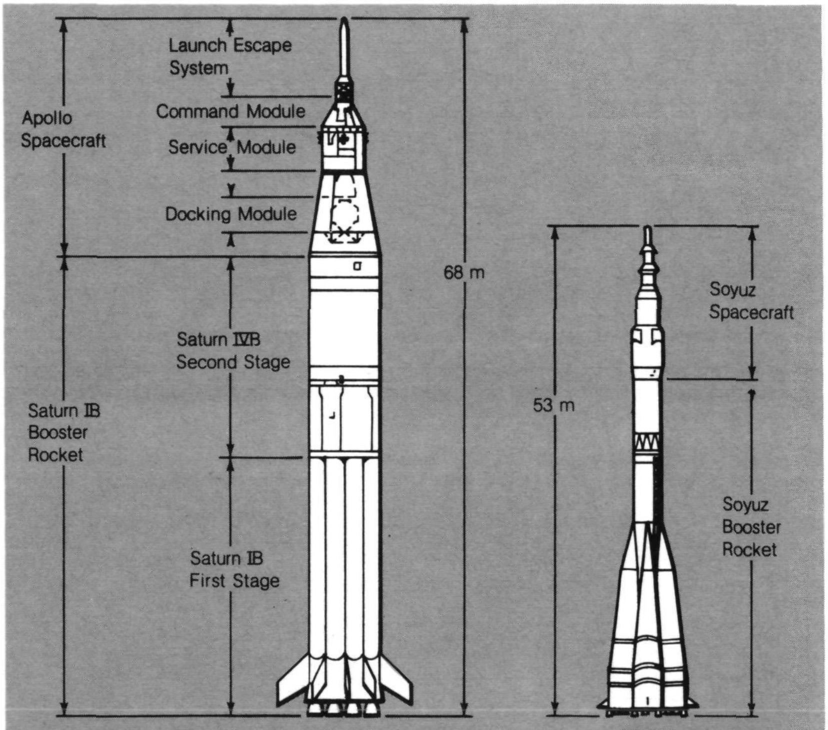
[1] Project Physics, Sec. 7.3; PSSC, Secs. 13-5 and 13-6. (Throughout this pamphlet, references will be given to key topics covered in these two standard textbooks: ''Project Physics,'' second edition, Holt, Rinehart, and Winston, 1975, and ''Physical Science Study Committee'' (PSSC), fourth edition, D. C. Heath, 1976.)

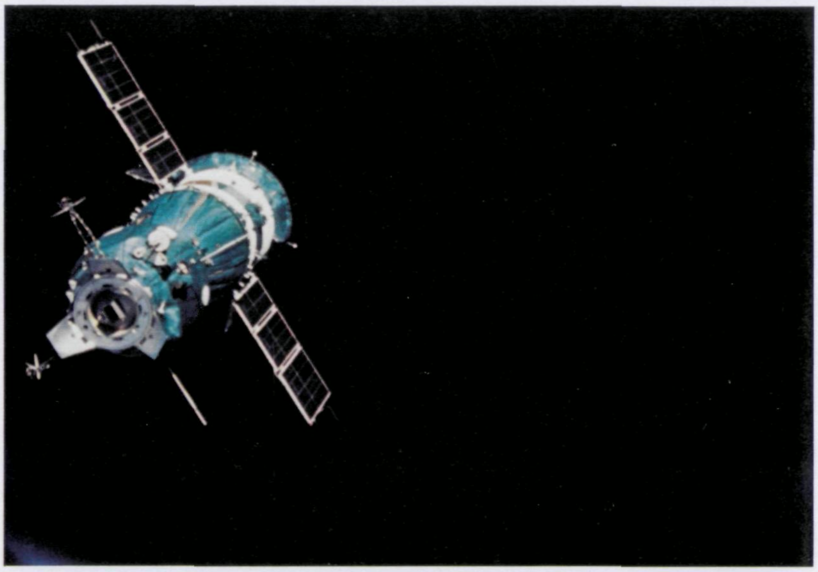
The astronauts' view of Soyuz as Apollo approached to dock, and the cosmonauts' view of Apollo, is shown in Figure 2.3. When two spacecraft dock, they must be sealed together tightly so that none of the atmosphere inside either spacecraft will leak out. In previous NASA lunar missions, an Apollo Command Module (CM) had docked with a Lunar Module (LM) designed to fit it accurately.



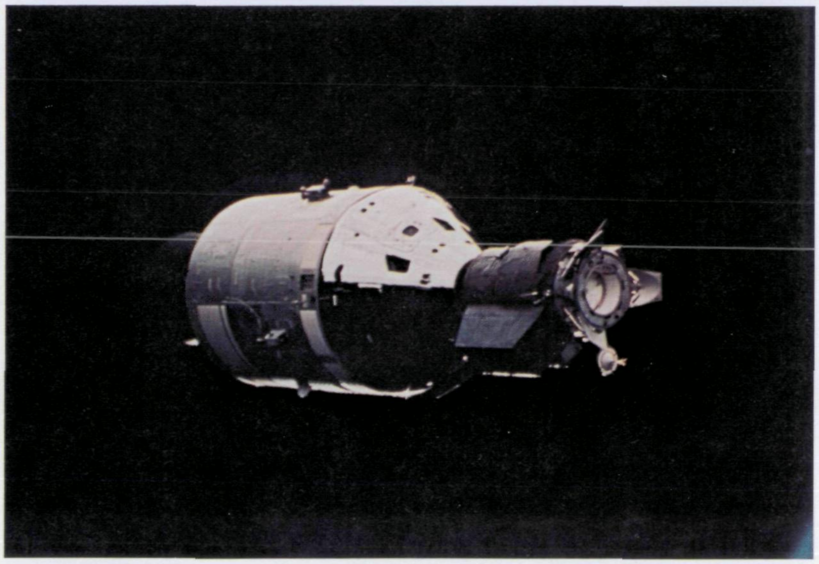
	APOLLO	SOYUZ
Spacecraft mass	14 900 kg	6750 kg
Lift-off thrust	6.67×10^6 N (Saturn IB)	7.03×10^6 N
Secondary thrust	1.0×10^6 N (Saturn IVB)	
Number of engines	8 (Saturn IB) 1 (Saturn IVB)	20 (in two stages)
Fuel	Kerosene/LOX (Saturn IB) Liquid hydrogen/LOX (Saturn IVB)	Kerosene/LOX
Launch weight	588 000 kg	300 000 kg
Firing time	2 minutes 30 seconds (Saturn IB) 7 minutes 25 seconds (Saturn IVB)	12 minutes

Apollo and Soyuz launch configurations. **Figure 2.2**

Figure 2.3 The Apollo and Soyuz spacecraft in flight.



(a) The Soyuz spacecraft as seen from Apollo.



(b) The Apollo spacecraft as seen from Soyuz (Courtesy of U.S.S.R. Academy of Sciences).

D The Docking Module

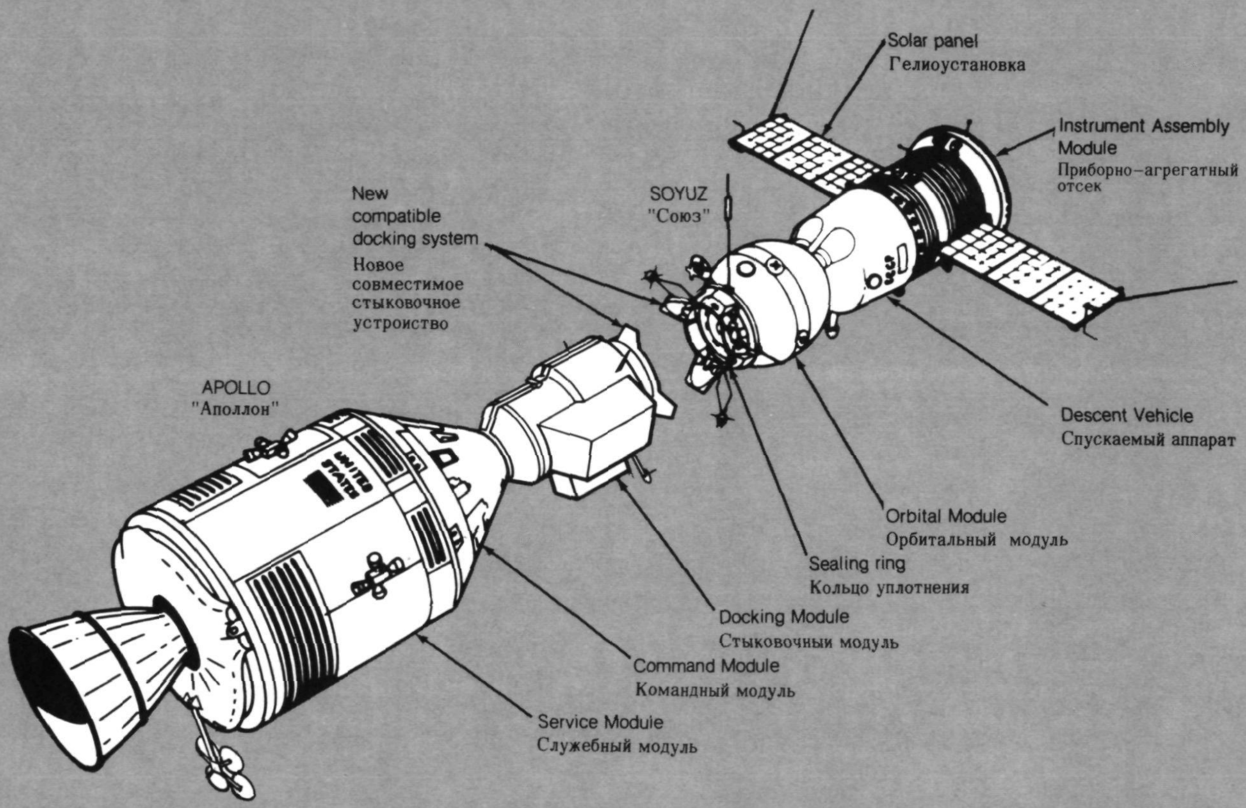
For Apollo-Soyuz, a special DM had to be designed and built with seals and latches on one end to fit the front Soyuz hatch. On the other end of the DM were seals and latches to fit the Apollo CM hatch. The DM was built by Rockwell International Space Division in Downey, California, under contract with JSC.

The DM provided space for several experiments. It also was a chamber for converting from the Apollo cabin atmosphere of pure oxygen at one-third atmospheric pressure (3.4×10^4 N/m^2) to the Soviet cabin atmosphere, which was essentially air (oxygen and nitrogen) at two-thirds atmospheric pressure (6.7×10^4 N/m^2). The Russians normally use air at 1 atmospheric pressure (1.01×10^5 N/m^2) in their spacecraft but, for the ASTP docked activities, they reduced the pressure so that the crews could go back and forth between the two spacecraft without too long a delay for changing the atmosphere in the DM. If the atmospheric pressure is reduced too quickly, as deep-sea divers well know, a man suffers pains due to bubbles of gas forming in his blood. This is called "the bends." The Soviet space program chose ordinary air at 1-atmosphere pressure as simpler and less dangerous than the lower pressure pure-oxygen atmosphere used in the Apollo spacecraft.

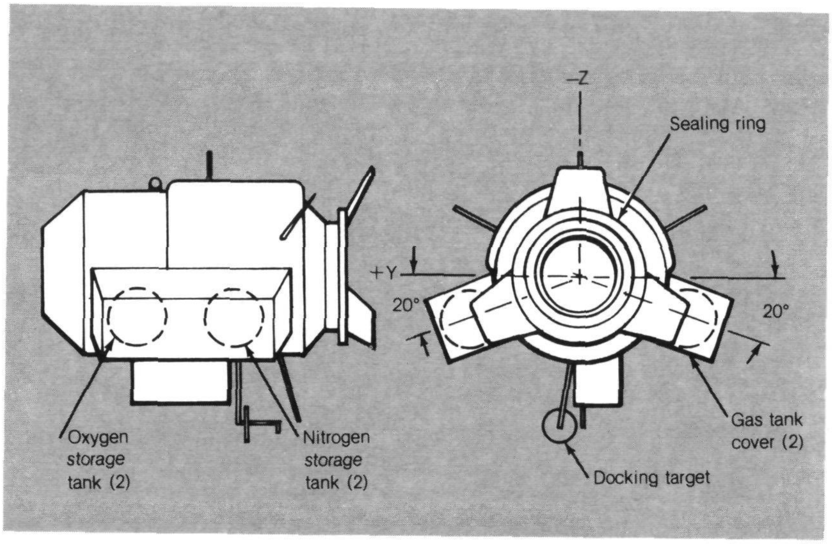
The Apollo vehicle, including the DM, was larger (12 meters long without the boosters) and more massive (14 900 kilograms) than the 6-meter, 6750-kilogram Soyuz. Figure 2.4 shows details of the two spacecraft at a larger scale than in Figure 2.2. During launch, the DM was stowed below the Service Module (SM) just as the LM was for flights to the Moon. After launch, the DM was latched onto the front of the Apollo CM, as shown in Figure 2.4. This transfer of the DM required another Apollo maneuver before docking, as described in Section 3D.

Important design differences included the fittings on each spacecraft that the DM had to match. The "compatible docking system" of the DM, shown in Figure 2.5, included three flaplike guides to center the end of the Soyuz spacecraft, a circular sealing ring to fit the sealing ring on Soyuz, and three strong latches to fit the hooks on the front of Soyuz. Figure 2.5(b) shows the sealed "hatch 3" farther into the DM. The space between hatch 3 and the front end of the DM was called the "DM tunnel." Hatch 3 was opened only after the two spacecraft were sealed together and cabin air was let into the DM tunnel to check that the docking seal was tight. Figure 2.5(b) also shows the oxygen and nitrogen tanks that could be tapped to match either the Apollo or the Soyuz cabin atmosphere. Figure 2.5(a) shows the docking target below center on the DM, where the cosmonauts could see it and roll the Soyuz to the correct angle for the latches to catch and hook.

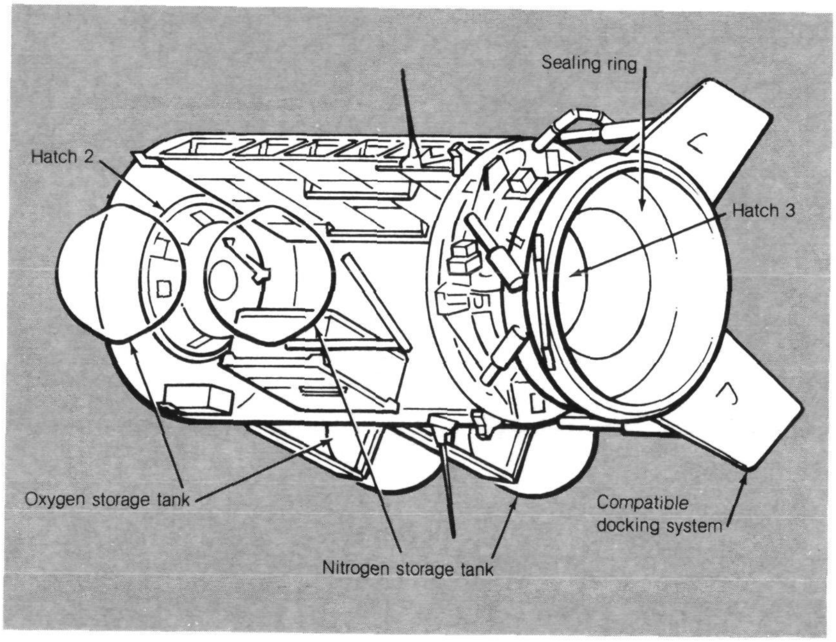
Figure 2.4 The Apollo-Soyuz rendezvous and docking configuration.



The Docking Module. **Figure 2.5**



(a) External features.



(b) Internal features.

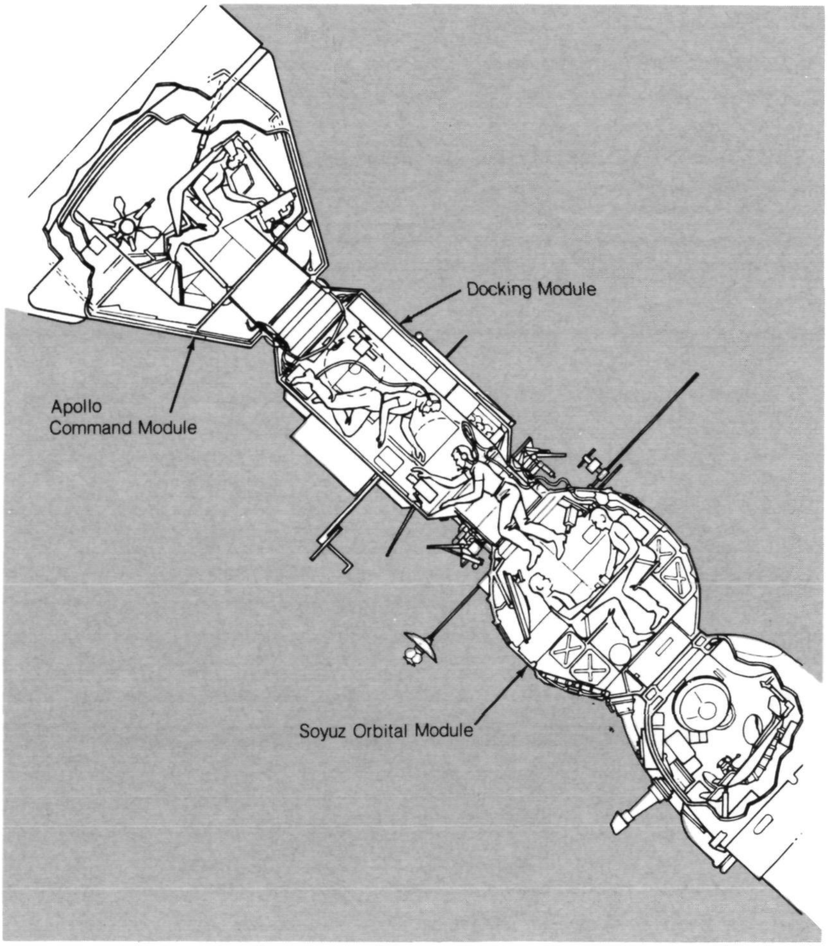
E Handshakes and Toasts in Space

Docking was completed on July 17, 1975, at 16:09 GMT. The two spacecraft were linked for 44 hours of joint operations. During this time, the crews worked on scientific experiments and engineering tests. The "first international meeting in space," shown in Figure 2.6, was between the two commanders, Stafford and Leonov, at the Soyuz hatch leading into the DM. Figure 2.7 shows how crewmen moved from one spacecraft to the other. Other astronaut-cosmonaut pairs worked in the DM, and each crewmember visited the other spacecraft for a meal. The Russians served Ukrainian borsch (beet soup), spiced veal, sausage, cake, and fruit juice. The Americans served roast beef, potato soup, rye bread and cheese, strawberries, almonds, and tea with lemon. There were no toasts in the ordinary sense because liquids do not

Figure 2.6 Apollo Commander Stafford and Soyuz Commander Leonov meet in space.

stay in a glass or cup when they are in the weightless zero-g environment in an orbiting spacecraft. The soups, juices, and tea were handed around in plastic "squeeze bags" and squirted from a nozzle into the mouth.

The experiments and some of the tests completed while the spacecraft were docked are covered in Section 4 and in other pamphlets of this series. Two of the five joint American-Soviet experiments required separation of the spacecraft and complicated maneuvering of Apollo. One of these (Experiment MA-148) produced an artificial eclipse of the Sun. The other (Experiment MA-059) involved sending a light beam from Apollo to Soyuz and reflecting it back to Apollo.



Crewmen moving between Apollo and Soyuz. **Figure 2.7**

F Questions for Discussion

(Time Zones, Emergencies)

1. The initial handshake between Stafford and Leonov was a significant event for television coverage. How does prime television time in Moscow compare with prime time in New York?

2. Why can't a satellite be launched at 45° above the horizontal to put it in orbit around the Earth without boosting it first vertically and then in a horizontal direction?

3. Why was there never an open passageway between the two docked spacecraft?

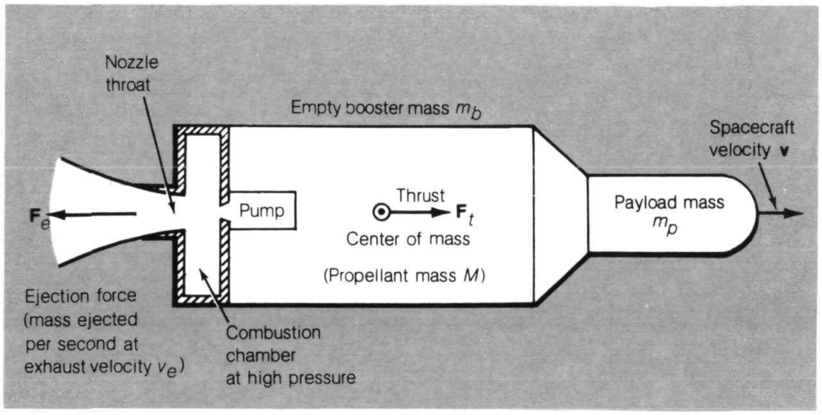
4. The hatches must be perfectly tight when two spacecraft are undocked. If there is even a small leak, the cabin atmosphere will leak to the outside vacuum and the crew would be in serious danger. What precautions would you take while undocking Apollo from Soyuz to ensure that the hatches are tightly closed?

3 Spacecraft Launch, Control, and Rendezvous

A Reaction Motors and Thrust[2]

The launch configurations included several rocket motors, thrusters, and jets, each designed to produce a force on the spacecraft—or a twist (torque) on it about some axis. Newton's Third Law of Motion[3] is the basis for all these reaction motors, as shown in Figure 3.1. This law states that for every action, there is an equal and opposite reaction. The big Saturn IB and Saturn IVB boosters and the Soyuz booster are liquid-propellant motors and provide a thrust of more than 6.67×10^6 newtons (750 tons). These boosters burn kerosene and LOX or liquid hydrogen and LOX in the combustion chamber at high pressure. The exhaust gases are forced out through the nozzle at ejection velocity $\mathbf{v}_e$. The reaction to this (rearward) ''action force'' $\mathbf{F}_e$ is the equal and opposite forward thrust $\mathbf{F}_t$.

''An impressed force,'' Newton wrote, ''is an action exerted upon a body to change its state of motion.'' His Second Law states that the force on a mass of ejected gas m_e gives that gas an acceleration $\mathbf{a}_e$; that is, $\mathbf{F}_e = m_e\mathbf{a}_e$. In simple words, the more gas ejected per second and the larger the ejection (jet) velocity $\mathbf{v}_e$, the bigger is the ejection force $\mathbf{F}_e$ and the bigger the forward thrust $\mathbf{F}_t$. (The acceleration of the gas is from zero velocity to $\mathbf{v}_e$ in a very short time and is higher for higher temperature and higher pressure in the combustion chamber.) At first, the booster thrust $\mathbf{F}_t$ (Fig. 3.1) must lift the full weight of the launch configuration. This weight is the downward force of gravity $\mathbf{F}_g$ on the mass of the booster m_b plus the huge mass of propellant M and the mass



Reaction motor: schematic diagram of a large spacecraft booster. **Figure 3.1**

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[2] Project Physics, Sec. 19; PSSC, Sec. 22-7.

[3] Project Physics, Secs. 3.9 to 3.11; PSSC, Secs. 14-5, 14-8, and 16-6.

of the payload m_p. The upward acceleration of the whole launch configuration is again given by Newton's Second Law: $\mathbf{a} = (\mathbf{F}_t - \mathbf{F}_g)/(m_b + M + m_p)$.

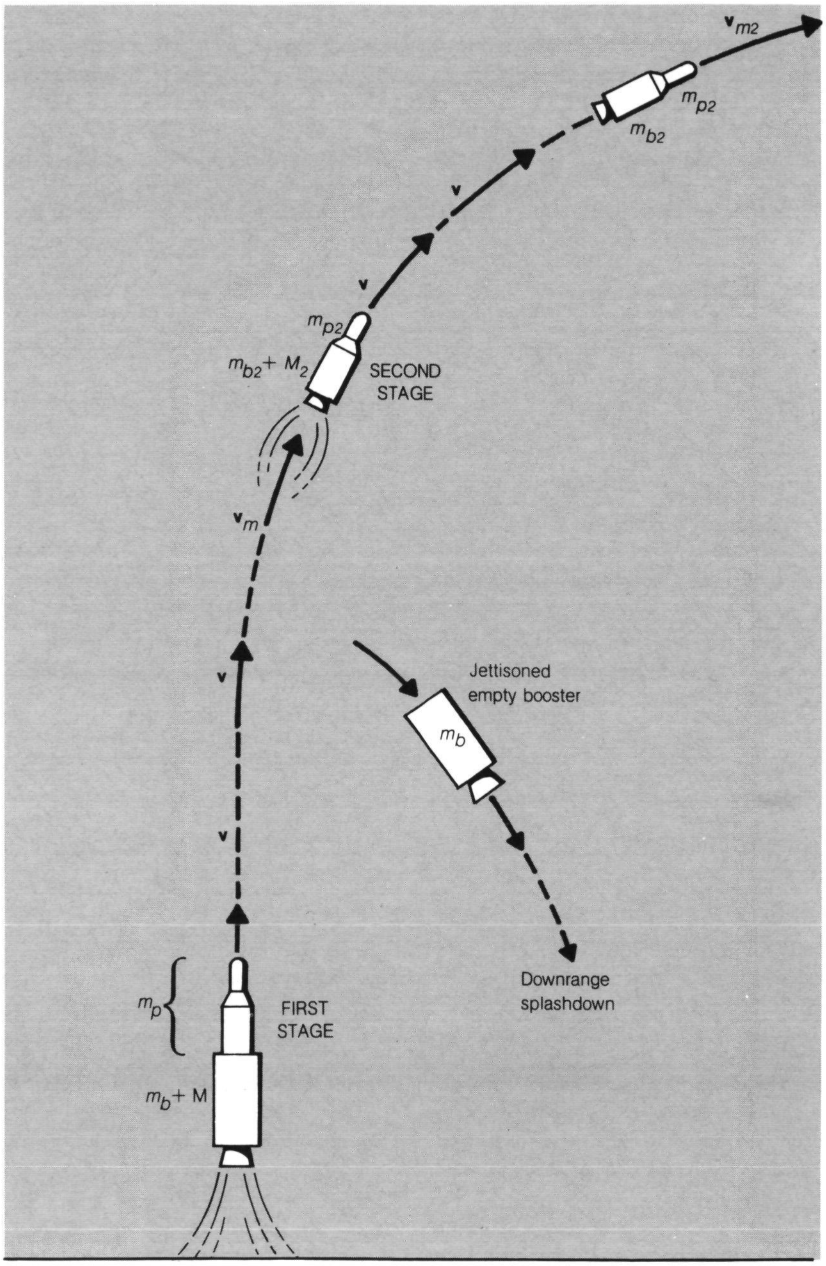
This acceleration is small at first but soon gets larger because M is reduced by the amount of propellant (kerosene, liquid hydrogen, and LOX) burned and ejected. This reduces the weight $\mathbf{F}_g$ and the mass $(m_b + M + m_p)$, so that **a** increases to a large value (27.9 m/sec²—almost 3 g's) just as all the propellant is used. Equations are given in Table 3.1 showing how you can calculate the final (maximum) velocity $\mathbf{v}_m$ from the quantities illustrated in Figure 3.1. (The effects of air resistance, which last for only a few minutes early in the flight, are not included in the equations.)

B Multistage Launch

For Soyuz, $\mathbf{v}_m$ is large enough to put the payload (spacecraft) into orbit. However, the heavier Apollo required a second-stage booster, as shown in Figure 3.2. That is, the component called payload in Figure 3.1 consists of another booster (''Saturn IVB'' in Fig. 2.2, ''second stage'' in Fig. 3.2) of mass $m_{b2} + M_2$ and a payload of mass m_{p2}. The second stage ignites at velocity $\mathbf{v}_m$ and, after jettisoning the empty first-stage Saturn IB booster, accelerates to $\mathbf{v}_{m2}$. This ''staging'' saves weight and propellant because of the jettisoned mass of the empty first-stage booster. When it is dropped, there is less mass to be accelerated by the second-stage booster. (Space Shuttle, NASA's next manned spacecraft, has two large first-stage boosters which are jettisoned like this but are provided with parachutes so that they can be recovered and used again. In fact, the Shuttle payload has wings and can be brought back to Earth and landed like an airplane.)

For missions to the Moon or to other planets, the system can be extended to third and fourth stages. The equations in Table 3.1 show that four stages will give four times the maximum velocity of one stage if each stage is designed with the same ''mass ratio'' R. This is the ratio of a fully filled stage to an empty stage or $R = (m_b + M + m_p)/(m_b + m_p)$.

For an efficient launch, engineers make R as large as possible by using very lightweight materials and thin-walled tanks in the booster (low m_b). The equations show that if R is larger than 2.72 (so that $\ln R$ is greater than 1.00), v_m is larger than the gas ejection (jet) velocity $\mathbf{v}_e$. The engineers make $\mathbf{v}_e$ large by using high combustion-chamber pressure; they get the high temperature (for the pressure) by using high-energy propellants. Early rockets used solid propellants like gunpowder with a ''specific impulse'' of 70 seconds, but liquid propellants give much more. Kerosene-LOX has a specific impulse of 265 seconds; hydrogen-LOX, 364 seconds; and hydrogen-fluorine, 373 seconds. (The specific impulse is a measure of the power of a propellant;



Schematic diagram of a multistage launch. **Figure 3.2**

Table 3.1 Formulas for Booster Launch Calculations[a]

Calculation	*Equation*
Newton's Second Law in vector notation, where Δt = time interval	$\mathbf{F} = m\mathbf{a} = m\Delta\mathbf{v}/\Delta t$
Newton's Second Law in terms of momentum, where $\boldsymbol{\Delta}\mathbf{mv}$ = change in momentum (impulse)	$\mathbf{F} = (\boldsymbol{\Delta}\mathbf{mv})/(\Delta t)$
Rearward force on ejected gas, where $\Delta m_e/\Delta t$ = mass ejected per second	$-\mathbf{F}_e = -\mathbf{v}_e(\Delta m_e/\Delta t)$
Newton's Third Law for forward thrust	$\mathbf{F}_t = -\mathbf{F}_e$
Weight of launch configuration, where $-\mathbf{g}$ = downward acceleration of gravity, 9.8 m/sec^2	$-\mathbf{F}_g = -(m_b + M + m_p)\mathbf{g}$
Initial upward acceleration of launch configuration	$\mathbf{a} = (\mathbf{F}_t - \mathbf{F}_g)/(m_b + M + m_p)$ $= \mathbf{F}_t/(m_b + M + m_p) - \mathbf{g}$
Final upward acceleration of launch configuration	$\mathbf{a}_m = (\mathbf{F}_t - \mathbf{F}_g)/(m_b + m_p)$
Final (maximum) upward velocity, where mass ratio $R = (m_b + M + m_p)/(m_b + m_p)$ and $\ln R$ = natural logarithm of R	$\mathbf{v}_m = -\mathbf{v}_e \ln R$

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[a] Project Physics, Secs. 3.9 to 3.11, 8.6 to 8.8, 9.4; PSSC, Secs. 13-8, 13-10, 14-1, 14-5, 14-8, 16-6.

Table 3.1 Concluded

Calculation	*Equation*
Maximum upward velocity for two stages, if mass ratios $R_1 = R_2 = R$	$\mathbf{v}_{m2} = -\mathbf{v}_e \ln(R_1 R_2)$ $= -2\mathbf{v}_e \ln R$
Maximum upward velocity for four stages	$\mathbf{v}_{m4} = -\mathbf{v}_e \ln(R^4) = -4\mathbf{v}_e \ln R$
In circular orbit, acceleration toward center	$\mathbf{a}_c = \Delta\mathbf{v}/\Delta t$
From Newton's Law of Gravitation	$a_c = GM_E/r^2$
From Fig. 3.3 triangles (small Δt)	$\Delta v/v_c = v_c \Delta t/r$ $\Delta v/\Delta t = v_c^2/r$ $GM_E/r^2 = v_c^2/r$
Velocity in circular orbit of radius r	$v_c = \sqrt{GM_E/r}$
Velocity of escape from distance r	$v_e = \sqrt{2GM_E/r}$

expressed in seconds, it is equal to the thrust (in pounds) divided by the amount of propellant burned (in pounds per second), in old-fashioned units of pound-force and pound-mass.)

C Earth Orbit

The first-stage launch booster propels the spacecraft almost vertically upward. A horizontal thrust is needed to put it in orbit. The booster rocket starts the turn from vertical to horizontal by deflecting its exhaust gases sidewards. This is done by vanes behind the nozzle shown in Figure 3.1, or by turning one whole reaction motor on gimbals. (In fact, vanes or a gimbaled motor are usually provided to keep the thrust force aimed through the center of mass.) In the Apollo launch (Fig. 3.2), the Saturn IB booster starts the turn just before it is jettisoned, and the second-stage Saturn IVB continues the turn to horizontal. Although there is no sudden turn to horizontal, the Saturn IVB ''inserts'' the spacecraft into the desired elliptical Earth orbit.

With all jets and the booster off, the orbiting spacecraft is now in free fall, as shown on the left side of Figure 3.3, where the spacecraft is at perigee (point nearest the Earth). The arrow $\mathbf{v}_p$ represents the horizontal velocity at that place. If there were no force on the spacecraft, it would move in a straight line along the vector $\mathbf{v}_p$. After a while, say 5 minutes, it would get to the end of the arrow. However, there *is* a force on the spacecraft toward M_E. So, in that 5 minutes, the spacecraft would fall the distance $\Delta\mathbf{r}$ toward the center of the Earth. The acceleration toward Earth is somewhat smaller than $\mathbf{g}$ (the acceleration of gravity at the Earth's surface) because the spacecraft is at the distance H_p above the Earth's surface or r_p from the Earth's center. The radius of the Earth is R_E (6378 kilometers or 3963 miles), so $r_p = H_p + R_E$.

Newton's Law of Gravitation[4] states that there is a force of attraction F_g between two masses m and M separated by distance r, and $F_g = GmM/r^2$, where G is a universal constant. In Figure 3.3, the orbit has been drawn much larger than any followed by Apollo and Soyuz. If it were drawn to scale, the orbits at $H = 170$ to 220 kilometers would be only 1 millimeter or so from the circle representing the Earth. This shows that F_g is only a little less than the force of gravity at launch on the Earth's surface. Using the mass of the spacecraft m_s and the mass of the Earth M_E, we find $F_g = Gm_sM_E/r_p{}^2$, and the acceleration of m_s toward M_E (center of Earth) is $a_p = F_g/m_s = GM_E/r_p{}^2$. But m_s is moving rapidly horizontally at velocity $\mathbf{v}_p$, and the acceleration $\mathbf{a}_p$ merely ''bends'' its path into the orbit shown in Figure 3.3. Following its motion step by step, with Newton's Second Law, we find that the orbit is an

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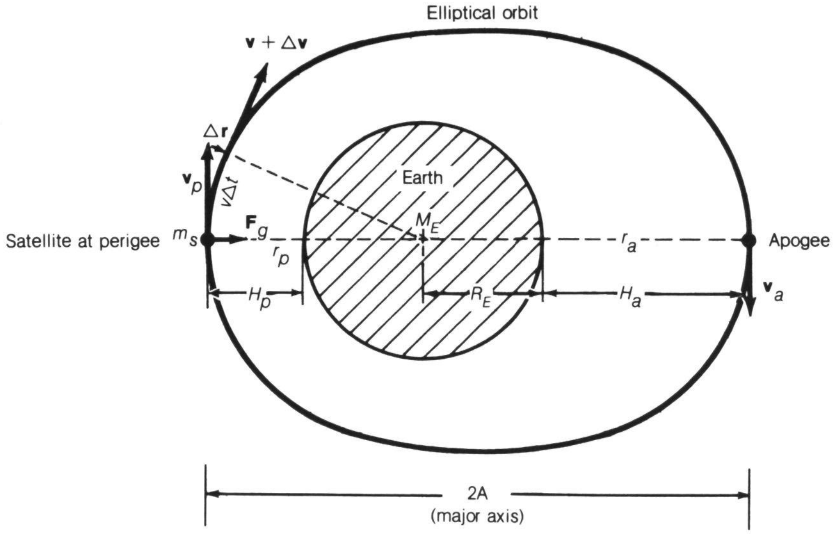
[4] Project Physics, Secs. 8.6 to 8.8; PSSC, Secs. 13-8 and 13-10.



Actual heights, km

	H_p	H_a
Soyuz initial	186	221
Apollo initial	148	168
Apollo-Soyuz docked (circular)	222	222

$r_p = R_E + H_p$

$r_a = R_E + H_a$

The orbit of a satellite around the Earth. The size of the orbit is exaggerated for clarity. **Figure 3.3**

ellipse, from perigee at height H_p, to apogee at height H_a at the opposite side (to the right in Fig. 3.3), then back to perigee. The satellite is falling toward M_E all the time, but its horizontal velocity prevents it from ever reaching Earth's surface. The space engineer refers to such an orbit by the values of H_p and H_a. For instance, Soyuz' initial orbit was 186 by 222 kilometers, meaning $H_p = 186$ kilometers and $H_a = 222$ kilometers.

Free fall means that no support is provided—or needed—for the spacecraft or any of its contents. This is the condition of zero-g or zero gravity, which results in the weightless state. Food floats off the table unless anchored, drinks float out of an open container, astronauts and cosmonauts float around their cabins, there is no convection of cabin air, and liquids do not stay at the bottom of a partly filled closed container. These phenomena must be anticipated and planned for in spaceflight.

Astronomers describe an orbit[5] by six "elements." These six numbers

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[5] Project Physics, Sec. 7.3; PSSC, Secs. 13-5 and 13-6.

define the size, shape, and orientation of the orbit and the time when the satellite passed perigee (or perilune for the Moon, perihelion for the Sun, perijove for Jupiter, etc.). The size is given by half the major axis from perigee to apogee (A in Fig. 3.3). The shape is described by the eccentricity, $e = (r_a - r_p)/2A$. The orientation is given partly by the inclination i of the orbital plane to the Earth's Equator (or to the plane of the Earth's orbit for other orbits around the Sun). Two other angles are needed to define the direction of A in space. The orbits of low Earth satellites are usually described by H_p, H_a, i, the period T (time for one revolution), and the direction to perigee. Actually, the period can be calculated from $T^2 = 8\pi^2 A^3/GM_E$ (Kepler's Third Law). For a circular orbit (eccentricity = 0, $r_p = r_a = A$), this law can easily be derived from Figure 3.3 and Newton's Laws.

D Orbit Corrections

For several reasons, a circular orbit was planned for Apollo-Soyuz. The 186- by 222-kilometer Soyuz orbit was therefore circularized by two "apogee kicks," which increased v_a by approximately 15 m/sec, leaving $H_p = H_a = 222$ kilometers. Each apogee kick was a timed burn (5.7 and 21.0 seconds) on the main thruster as the spacecraft reached apogee with correct orientation (longitudinal axis pointed along v_a by control jets).

In order to aim their thrusters (and also to aim the spacecraft for certain experiments), both Apollo and Soyuz had to be rolled about the X-axis or turned around the Y-axis or Z-axis. This was done by four sets of "RCS quad" jets on Apollo, as shown in Figure 3.4. The reaction control system (RCS) jets are centered around the Apollo center of mass. Firing two of them, as in Figure 3.4, starts a turn or roll. When Apollo reached the desired orientation, jets were fired in the opposite direction to stop the turn or roll. In this way, the Apollo main thruster was aimed correctly (to give $\mathbf{F}_t$ along $\mathbf{v}_a$ in Fig. 3.3) for apogee kicks.

The Apollo orbit was circularized from 149 by 168 kilometers to 167 kilometers and was in the same plane ($i = 51.8°$) as Soyuz on July 15 at 23:31 GMT. Approximately 2 hours earlier, the Apollo crew had separated their spacecraft (CM and SM) from the large Saturn IVB booster, turned around by using the small RCS quad jets (Fig. 3.4), and latched onto the DM in the Saturn IVB. Slowly they backed away, pulling the DM out of the Saturn IVB. Then they made a burn (0.9 m/sec) to get far away from the abandoned Saturn IVB and thus avoid a possible collision.

The trickiest maneuvering was for rendezvous, when Apollo came up from a lower orbit to join Soyuz in a 222-kilometer orbit just a few kilometers away. Before this maneuver, the "phasing" had to be right. Apollo had to be

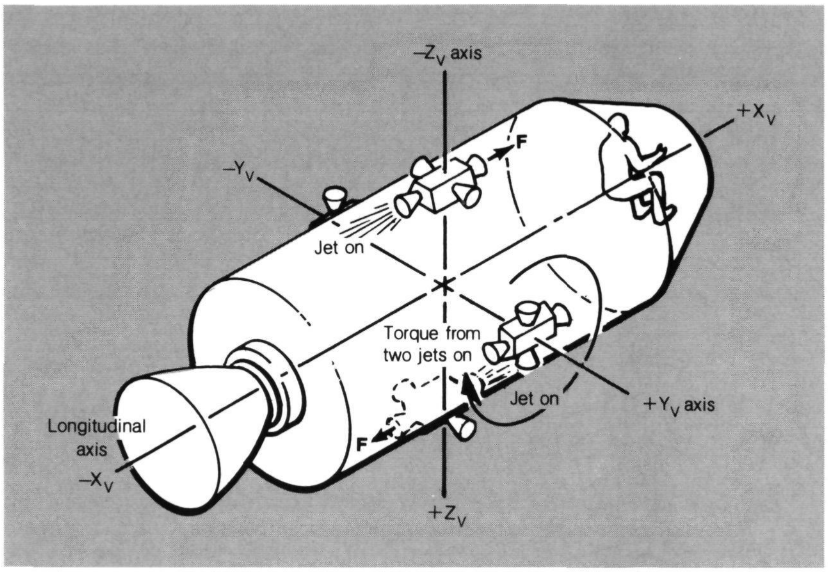


Figure 3.4

Control jets used to turn the Apollo Command and Service Module. Four RCS quads of the Reaction Control System are located around the center of mass of the Command and Service Module. The two jets that are firing, as shown schematically here, provide clockwise torque around the Y_v axis.

at the right place in its orbit, so that when it was boosted to higher orbit, it would be near Soyuz—not only in the same orbit but also at the *same place* in the orbit. Figures 3.5, 3.6, and 3.7 show the rendezvous maneuver. In Figure 3.5, the circular orbits around the Earth are shown, with Apollo moving faster in its lower orbit, then rising (with a burn) a little higher than Soyuz, and finally dropping back to the Soyuz height for the rendezvous. In more detail, Figures 3.6 and 3.7 show the height above Earth at various times after the Soyuz launch. For the first 14 hours, Soyuz oscillated between apogee (222 kilometers) and perigee (186 kilometers, increased to 191 kilometers 5 hours 32 minutes after launch). Each oscillation is one full orbit around the Earth.

Starting 7 hours 30 minutes after the Soyuz launch, Apollo reached a 148- by 168-kilometer orbit, circularized at 11:11 GET, then burned again at 13:08 GET to reach a 168- by 196-kilometer elliptical orbit. Figure 3.7 shows the last 4 hours (48:00 to 52:00 GET) in greater detail, with Soyuz circularized at 222 kilometers and Apollo briefly circularized at 205 kilometers. Apollo made a burn at 50:56 GET to spiral outward for rendezvous. This burn was timed when Apollo was somewhat ahead of Soyuz so that the upward climb slowed Apollo to approach Soyuz from the forward direction. The speed in orbit is

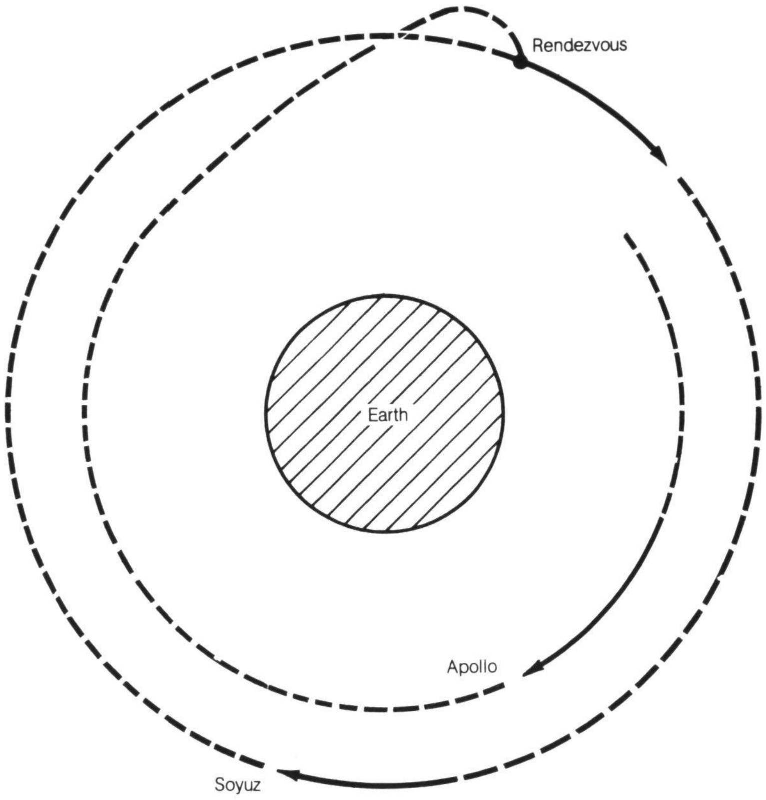
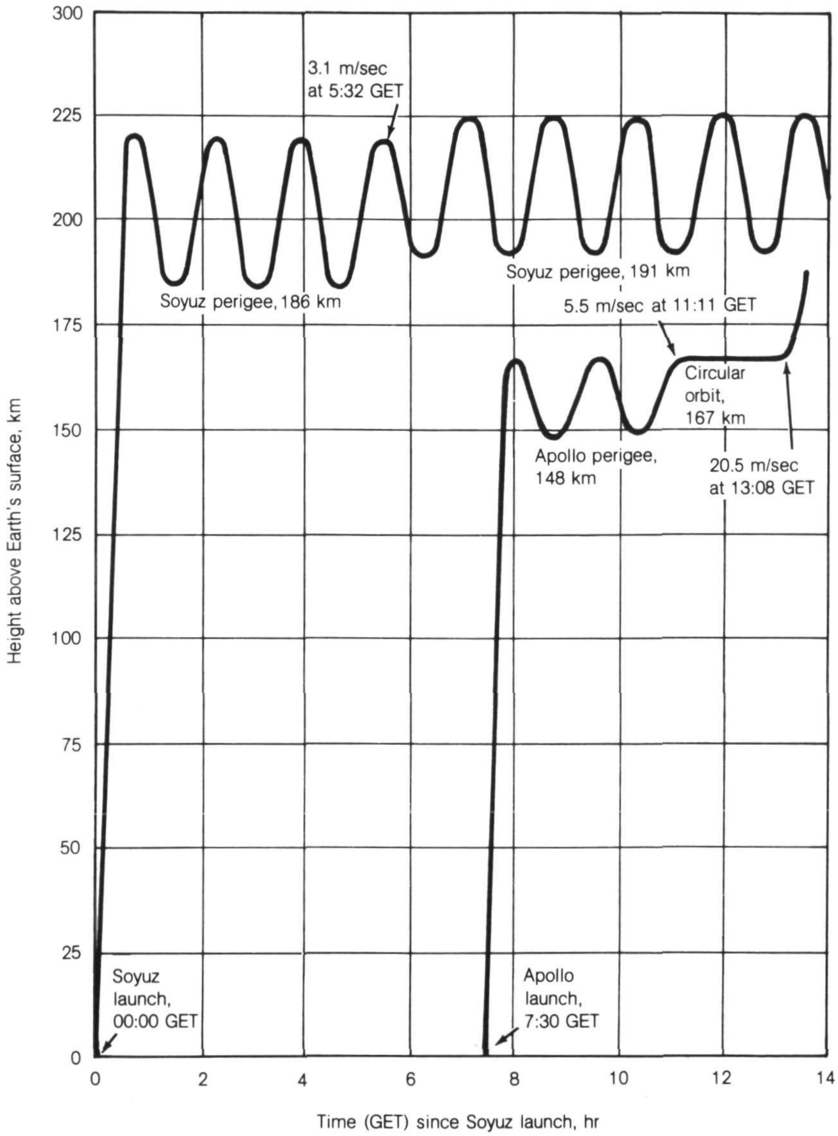


Figure 3.5 **Apollo and Soyuz orbits during the last hour before rendezvous.**

given by a formula that can be derived (Table 3.1) from Figure 3.3 and Newton's Law of Gravitation, $v = \sqrt{GM_E/r}$. Orbital speed is slower for larger r, so when Apollo was boosted higher than Soyuz, it came back at Soyuz from the front side, as shown in Figure 3.7. Soyuz just waited in circular orbit. The crews lined up the two spacecraft accurately, and the Apollo crew gently guided the DM against the front end of Soyuz (only 18 millimeters off center) on July 17 at 16:09 GMT.

Except for the final steps in docking, these orbital maneuvers were planned by large electronic computers at NASA JSC and at the Soviet Baykonur Cosmodrome. The computations are based on Newton's Laws, as in Table 3.1 and in Figure 3.3, together with small corrections for atmospheric drag (a deceleration of approximately 0.0001 m/sec^2 at the 222-kilometer altitude). A spacecraft's position in space is computed moment by moment and checked in several ways: onboard accelerometers check changes in velocity, Earth-based radars track the spacecraft, and Earth-based cameras photograph it against the background of stars. The spacecraft "attitude" (directions of X-, Y-, and



Apollo and Soyuz heights above the Earth for the first 14 hours of ground elapsed time. **Figure 3.6**

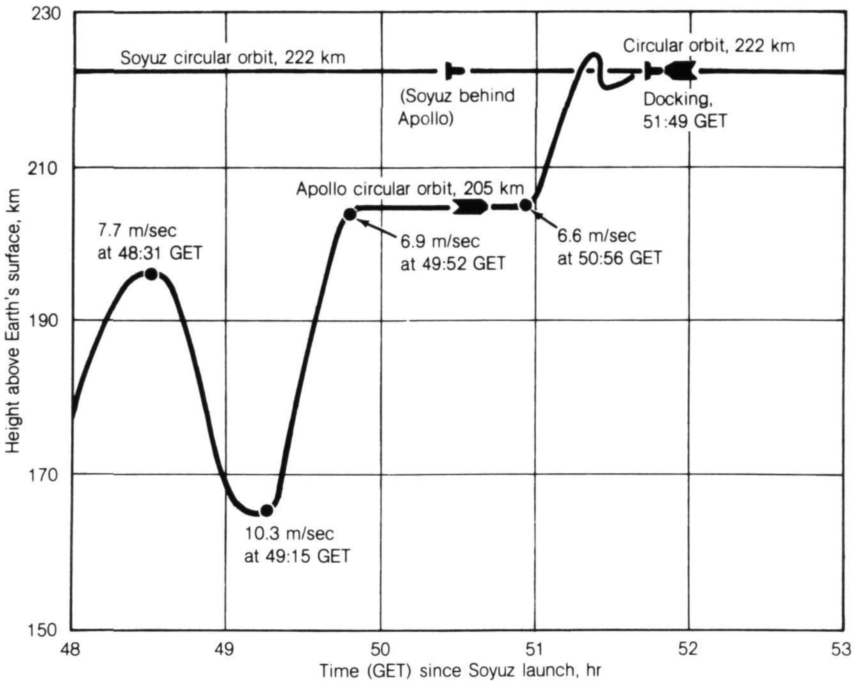


Figure 3.7 **Apollo and Soyuz heights above the Earth for the 4 hours before rendezvous.**

Z-axes in space—see Fig. 3.4) is checked and controlled from time to time. This is necessary for docking, for providing thrust in the correct direction, for "aiming" solar panels at the Sun (Soyuz used solar power, as shown in Figs. 2.3 and 2.4), and for pointing directional radio antennas correctly.

E

Attitude Control

A reference frame for attitude control is provided by small gyroscopes in the spacecraft. Three of these spinning wheels, one with its axle along the X-axis, one along the Y-axis, and one along the Z-axis, are supported by gimbals (bearings). The spinning wheels tend to keep their axles in fixed directions. There is an inevitable slow "drift" due to friction in the gimbals. If they were perfect, without drift, these gyros would measure even the slightest change in direction of the spacecraft axes. The directions are checked from time to time by astronaut sightings on the Sun and stars. The astronauts updated the onboard computer when sightings were made, so that the attitude of Apollo was known fairly accurately at any instant. (On larger spacecraft such as

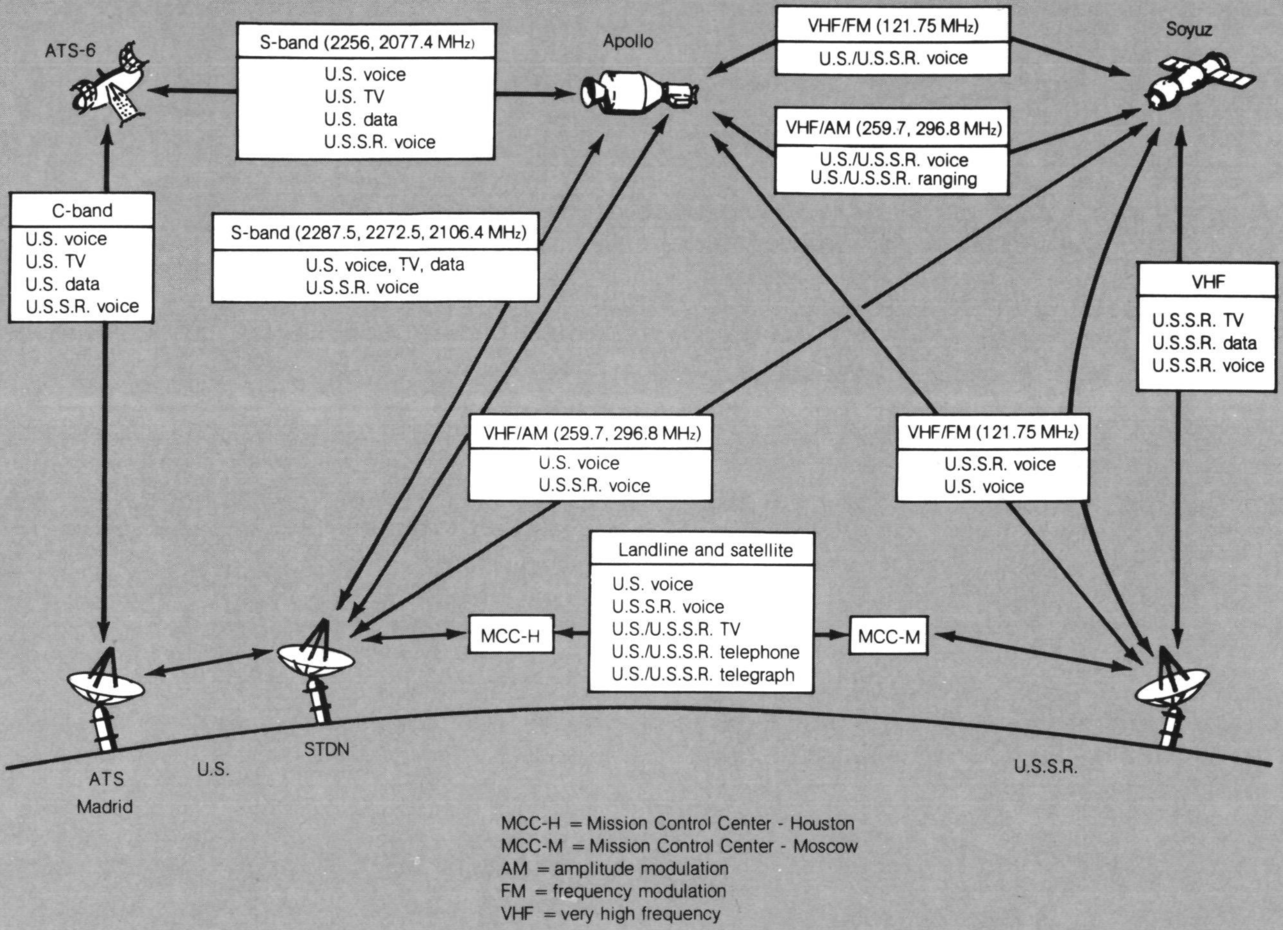
Skylab, very large stabilizing gyros were used to maintain attitude. For instance, if the spacecraft started to roll because an astronaut was moving something, the Y-axis gyro would automatically be torqued to oppose the roll.)

F Communications

The computer in the Mission Control Center at JSC in Houston kept track of these gyro readings and of the RCS quad jet torques (Fig. 3.4). Keeping track of attitude, orbital maneuvers, data from experiments, and all the other operations on Apollo-Soyuz required a worldwide communications network, as shown schematically in Figure 3.8 and discussed in Section 4D. Seventeen ground stations and two ships of the NASA Spaceflight Tracking and Data Network (STDN)—which is operated all around the world at a cost of $100 million/yr—were used for the 10 days of the Apollo-Soyuz mission. At least one of the STDN stations could "see" Apollo-Soyuz approximately 17 percent of the time; that is, the line of sight to the spacecraft was at least 5° above the horizon at the ground station so that radio communication was possible. The ATS-6 communications satellite, which was in a 24-hour geosynchronous orbit 35 900 kilometers above Lake Victoria in East Africa (42 280 kilometers from the Earth's center), could relay Apollo-Soyuz signals through the ATS ground station at Madrid, Spain, about half the time. When the crews were out of contact, they tape-recorded reports and scientific measurements, then played the tape back the next time radio contact was made.

There were nine Soviet radio receivers, seven in the U.S.S.R. and eastern Europe and two on ships at sea. Figure 3.8 shows the radio frequencies in megahertz used on each radio circuit and the landlines used between the Mission Control Centers in Houston (MCC-H) and Moscow (MCC-M). Of course, the voice circuit and radar ranging between Apollo and Soyuz were essential during docking maneuvers. Soviet ground stations also relayed Apollo voice messages to Houston and STDN relayed Soyuz voice messages to Moscow. All these communication links were heavily loaded at times, as noted in Section 4D, but they worked well.

Figure 3.8 **Apollo-Soyuz communications links.**



G Questions for Discussion

(Newton's Laws, Nuclear Power, Escape Velocity)

5. What physical laws predict that a satellite will have lower orbital velocity at apogee than at perigee (the point closest to the Earth)?

6. Explain how an orbit is circularized when the spacecraft velocity is increased at apogee (the point farthest from the Earth).

7. How would you circularize an orbit when the spacecraft is at perigee? How would the size of the resulting circular orbit compare with that resulting from an apogee kick?

8. How would you use nuclear power for rocket propulsion? What precautions would have to be taken?

9. The escape velocity from Earth is 11.2 km/sec. How much more is needed to escape from the solar system?

10. If all the fuel for the small RCS quad control jets had been used, would it have been possible for the astronauts inside Apollo to twist (roll) the spacecraft to a new attitude by pulling themselves around inside?

11. If a satellite's orbital eccentricity must be *increased*, when would you fire its thruster?

12. For which Apollo-Soyuz experiments in Table 4.1 was a circular orbit helpful? A low orbit? A high orbit?

13. Suppose that the boost had been imperfect and Apollo were in circular orbit 10 kilometers directly above Soyuz. How would you get it down close to Soyuz for rendezvous and docking?

14. Newton's Second Law states that an object doesn't change its motion unless it experiences a force. In orbiting spacecraft, why, then, does food float off a plate and liquid float out of a cup?

15. What messages on the voice circuit between Apollo and Soyuz before, during, and after docking would you consider important?

16. How does atmospheric drag affect the orbital speed of an Earth satellite?

4 Apollo-Soyuz Experiments and Tests

A Experiments Performed

In 1972, NASA invited scientists from all over the world to propose experiments for the Apollo-Soyuz mission. In all, 161 proposals were submitted to NASA Headquarters in Washington, D.C. Each proposed experiment was assigned a number: MA-001 to MA-161. Of the 161 proposals, 135 came from scientists in the United States; eight from West Germany; seven from France; four from India; three from the U.S.S.R.; and one each from Ireland, Scotland, Sweden, and Switzerland. Each proposal specified a scientific objective, described the equipment necessary, estimated the weight and volume of the equipment, and estimated the amount of astronaut or cosmonaut time required in flight. Finally, the cost of building the equipment and analyzing the experiment results was estimated. For U.S. investigations, NASA supplied the necessary funds; foreign investigators were sponsored by their respective governments.

The U.S. National Academy of Sciences reviewed most of the proposals and rated them according to scientific value. Then, on the basis of weight, cost, operating time, and complexity of spacecraft maneuvers required, the NASA Manned Space Flight Experiments Board (MSFEB) selected the 28 experiments listed in Table 4.1. The MSFEB added some engineering tests and retained many of the biomedical tests of the astronauts that had been standard on all NASA manned flights. For explanation of the terms used in Table 4.1, see the referenced pamphlet.

The experiments and three of the engineering tests are described in the other eight pamphlets in this series. They are grouped according to subject matter in physics, geology, biology, and engineering courses. Five of the experiments (MA-148, MA-059, MA-147, MA-150, and AR-002) required joint activities by astronauts and cosmonauts. The other 23 were ''NASA unilateral'' experiments—conducted by astronauts only. Of these, two German experiments (MA-107 and MA-014) were funded by the Federal Republic of Germany. Each experiment was supervised by a Principal Investigator (PI). Table 4.1 lists the scientific organization which, in most cases, provided laboratory space and expert assistance to the PI.

Table 4.1 Apollo-Soyuz Experiments and Tests

Experiment number	*Experiment name*	*Objective*	*Principal Investigator's organization*	*Reference*
MA-048	Soft X-Ray Observation	Survey the sky for soft x-ray sources and background	U.S. Naval Research Laboratory	Pamphlet II, Sec. 3
MA-151	Crystal Activation	Measure the radioactive isotopes created by cosmic rays in crystals used for gamma-ray detectors	NASA Robert H. Goddard Space Flight Center (GSFC)	Pamphlet II, Sec. 4
MA-148	Artificial Solar Eclipse (joint)	Photograph the solar corona from Soyuz while Apollo blocks out the Sun	Soviet Academy of Sciences, Moscow, and NASA JSC	Pamphlet III, Sec. 2
MA-083	Extreme Ultraviolet Survey	Survey of the sky for extreme-ultraviolet sources and background	University of California at Berkeley	Pamphlet III, Sec. 3
MA-088	Interstellar Helium Glow	Detect interstellar helium entering the solar system and measure its density and motion	University of California at Berkeley	Pamphlet III, Sec. 4
MA-089	Doppler Tracking	Measure large-scale (300-km) gravity anomalies on the Earth's surface by detecting minute changes in the 300-km separation between Apollo and DM	Smithsonian Astrophysical Observatory and Harvard University	Pamphlet IV, Sec. 4
MA-128	Geodynamics	Measure large-scale gravity anomalies by detecting small accelerations of Apollo in the 222-km orbit, using Doppler tracking from the ATS-6 geosynchronous satellite	NASA GSFC	Pamphlet IV, Sec. 5
MA-136	Earth Observations and Photography	Detect, photograph, and measure peculiar surface features (rifts, deserts, long waves in the sea)	Smithsonian Institution	Pamphlet V, Sec. 2

Table 4.1 Continued

Experiment number	*Experiment name*	*Objective*	*Principal Investigator's organization*	*Reference*
MA-007	Stratospheric Aerosol Measurement	Measure infrared sunlight intensity at spacecraft sunrise and sunset to determine the amount of aerosols from 30 to 150 km altitude, and test this technique for continuous monitoring of the atmosphere	University of Wyoming and NASA Langley Research Center	Pamphlet V, Sec. 3
MA-059	Ultraviolet Absorption (joint)	Measure the density of atomic oxygen and nitrogen at the 222-km altitude by detecting absorption of 1304 and 1200 Å (130.4 and 120.0 nm) light from a beam reflected from Soyuz back to Apollo	University of Michigan and NASA JSC	Pamphlet V, Sec. 4
MA-106	Light Flashes	Count the flashes seen by blindfolded astronauts and measure high-energy cosmic-ray intensity in the CM cabin	University of California at Berkeley	Pamphlet VI, Sec. 2
MA-107	Biostack III	Expose to cosmic rays spores, seeds, and eggs in stacks between layers of plastic and photographic film to measure high-energy cosmic-ray tracks	University of Frankfurt, West Germany	Pamphlet VI, Sec. 3
MA-147	Zone-Forming Fungi (joint)	Photograph cultures of funguslike cells and their spores before, during, and after exposure to zero-g and cosmic rays and measure the cosmic-ray intensity	Soviet Academy of Sciences, Moscow, and NASA JSC	Pamphlet VII, Sec. 3
MA-011	Electrophoresis Technology	Operate and photograph eight static electrophoresis columns in zero-g to separate live blood cells and live kidney cells for postflight examination	NASA George C. Marshall Space Flight Center (MSFC)	Pamphlet VII, Sec. 4

Table 4.1 Continued

Experiment number	*Experiment name*	*Objective*	*Principal Investigator's organization*	*Reference*
MA-014	Electrophoresis	Test in zero-g the operation of a free-flow electrophoresis tube with electric field across the flow	Max Planck Institute of Biochemistry, Munich, West Germany	Pamphlet VII, Sec. 4
AR-002	Microbial Exchange (joint)	Obtain skin-swab samples from astronauts and cosmonauts before, during, and after flight, and saliva and blood samples before and after flight for postflight analysis	NASA JSC and Institute of Biological Problems, Soviet Ministry of Health, Moscow	Pamphlet VII, Sec. 5
MA-031	Cellular Immune Response	Collect astronaut blood samples before and after flight for analysis of lymphocyte response	Baylor College of Medicine, Houston, Texas	Pamphlet VII, Sec. 6
MA-032	The Effects of Space Flight on Leukocyte Response	Collect astronaut blood samples before and after flight for analysis of leukocyte (white blood cell) response	Baylor College of Medicine, Houston, Texas	Pamphlet VII, Sec. 6
MA-161	Killifish Hatching and Orientation	Observe and photograph baby fish and fish hatched from eggs in zero-g	Baylor College of Medicine, Houston, Texas	Pamphlet VII, Sec. 2
--	Liquid Demonstrations	Operate and photograph demonstrations of chemical foams, liquid spreading, and wick action in zero-g	NASA MSFC	Pamphlet VIII, Sec. 2
MA-010	Multipurpose Electric Furnace	Design, test, and operate in zero-g an electric furnace providing temperatures up to 1423 K (1150° C; 1200° F)	Westinghouse Research Laboratories, Pittsburgh, Pa., and NASA MSFC	Pamphlet VIII, Sec. 3
MA-044	Monotectic and Syntectic Alloys	Heat to 1423 K (1150° C) and cool three small samples of aluminum-antimony and three of lead-zinc in zero-g	NASA MSFC	Pamphlet VIII, Sec. 3

Table 4.1 Concluded

Experiment number	*Experiment name*	*Objective*	*Principal Investigator's organization*	*Reference*
MA-150	Multiple Material Melting (joint)	Heat to 1423 K (1150° C) and cool small samples of aluminum-tungsten, germanium-silicon, and aluminum in zero-g	Institute for Metallurgy, Moscow, and NASA MSFC	Pamphlet VIII, Sec. 3
MA-070	Zero-g Processing of Magnets	Heat to 1348 K (1075° C) and cool small samples of bismuth-manganese and copper-cobalt-cerium alloys in zero-g	Grumman Aerospace Corporation, Bethpage, N.Y.	Pamphlet VIII, Sec. 3
MA-041	Surface-Tension-Induced Convection	Heat to 923 K (650° C) and cool three small samples of lead and lead-gold alloy in zero-g; heat three others to 723 K (450° C)	Oak Ridge National Laboratory, Oak Ridge, Tenn.	Pamphlet VIII, Sec. 3
MA-131	Halide Eutectic Growth	Heat to 1153 K (880° C) and cool a small sample of sodium chloride-lithium fluoride in zero-g	University of California at Los Angeles	Pamphlet VIII, Sec. 3
MA-060	Interface Markings in Crystals	Heat to melting, then cool in zero-g with thermal pulses every 4 seconds, three small samples of germanium doped with gallium and antimony	Massachusetts Institute of Technology, Cambridge, Mass.	Pamphlet VIII, Sec. 4
MA-085	Crystal Growth From the Vapor Phase	Heat to 877 K (604° C) three small samples of germanium compounds and alloys in zero-g, allowing crystal growth at the cool end of the ampoule	Rensselaer Polytechnic Institute, Troy, N.Y.	Pamphlet VIII, Sec. 4
MA-028	Crystal Growth	Photograph crystal growth in six tubes with reactants producing lead sulfide, calcium tartrate, and calcium carbonate as large crystals in zero-g	Rockwell International Science Center, Thousand Oaks, Calif.	Pamphlet VIII, Sec. 4

There were also six "Soviet unilateral" experiments conducted by the cosmonauts:

1. Solar Corona and Zodiacal Light. Photographs taken just before sunrise and just after sunset added to the results of MA-148, Artificial Solar Eclipse.

2. Earth's Upper Atmosphere. Photographs of the Sun and stars near the horizon show the refraction of light in the atmosphere, from which air density at high altitude (H) can be derived.

3. Earth's Horizon. Photographs of the Sun near the horizon are used to estimate aerosol density at various altitudes H. This experiment was similar to MA-007, Stratospheric Aerosol Measurements.

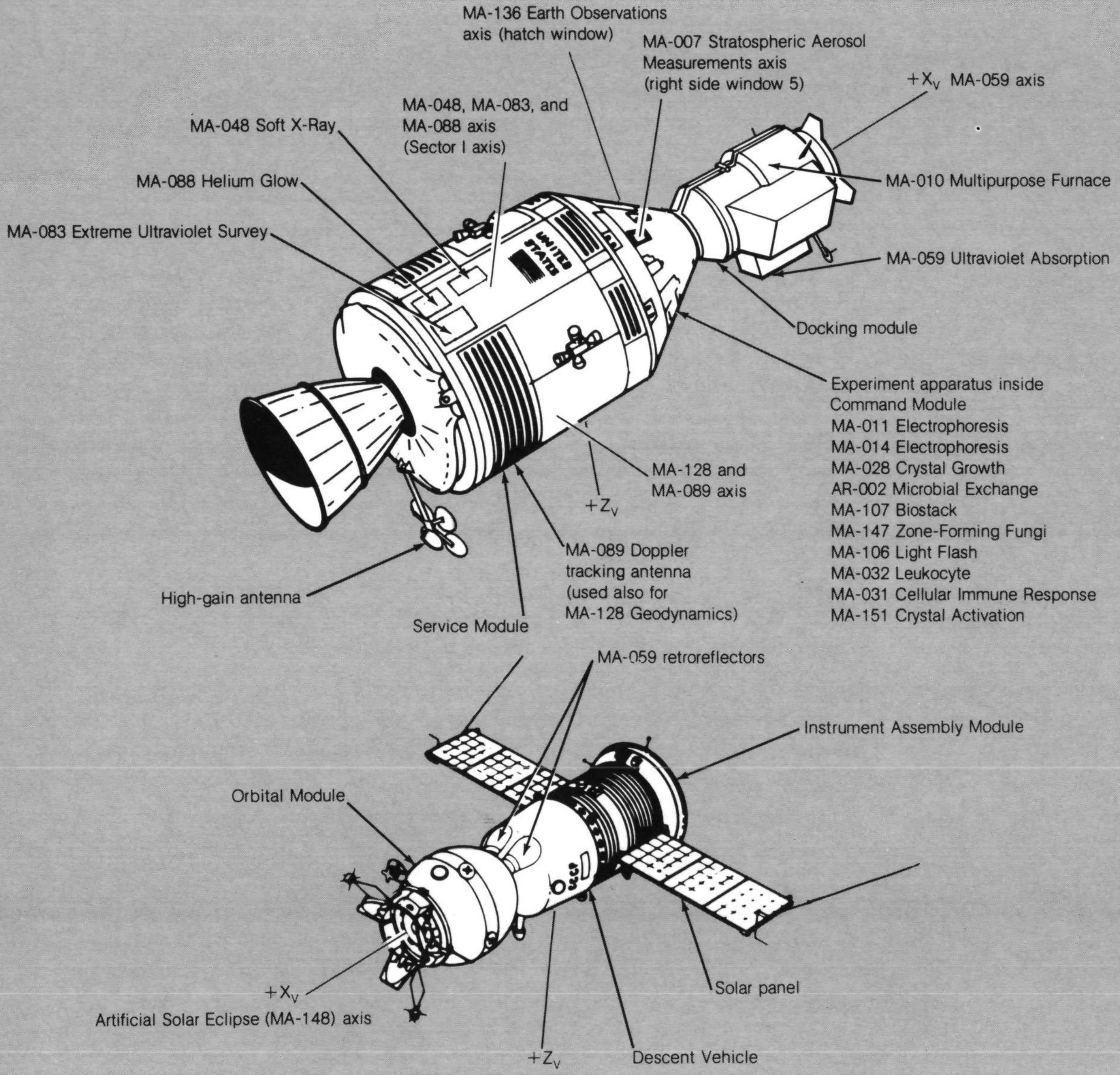
4. Bacteria Growth. This experiment was an independent study related to MA-147, Zone-Forming Fungi.

5. Fish Embryonic Development. This experiment was similar to MA-161, Killifish Hatching and Orientation.

6. Genetic Experiment. Various living cells were carried on Soyuz. Postflight examination by microscope sought to detect the effect of weightlessness on cell division.

The locations of experimental equipment on Apollo and Soyuz are shown in Figure 4.1, together with the vehicle axes, X_V, Y_V, and Z_V. Note that Soyuz photography of the Artificial Solar Eclipse (MA-148) was aimed through a window in the forward Soyuz hatch along the plus-X_V axis when Apollo had the DM aimed at Soyuz. Also, the ultraviolet-light source (MA-059) was beamed out of the DM along the Apollo plus-X_V axis and reflected from retroreflectors on the back of Soyuz (minus-X_V axis) and sidewise along its minus-Z_V axis.

Locations of the experiments on the Apollo and Soyuz spacecraft. Figure 4.1



B Major Experimental Results

Following are some of the important results of the Apollo-Soyuz experiments.

MA-048, the Soft X-Ray Observation Experiment, detected pulses from an x-ray[6] source in the Small Magellanic Cloud (SMC X-1), which showed it to be a pulsar—a rotating Neutron Star—in orbit around a hot giant star. See Pamphlet II.

MA-083, the Extreme Ultraviolet Survey, detected four very hot stars, including the white dwarf HZ 43 (corroborated by MA-048) with a temperature of 110 000 to 150 000 K. See Pamphlet III.

MA-136, the Earth Observations and Photography Experiment, showed that the Red Sea Rift extends along three fault lines north of Beirut, Lebanon, and implies a counterclockwise rotation of the Arabian plate in its continental drift. This experiment also detected waves of salinity in the ocean off the western coast of Spain. See Pamphlet V.

MA-007, the Stratospheric Aerosol Measurement Experiment, showed that routine monitoring of atmospheric aerosols is possible from long-term satellites, and found the aerosol density in the Northern Hemisphere to be 1.5 times that in the Southern Hemisphere. See Pamphlet V.

MA-059, the Ultraviolet Absorption Experiment, detected 1.2 billion oxygen atoms/cm^3 and 8.6 million nitrogen atoms/cm^3 at the 222-kilometer altitude. See Pamphlet V.

MA-011, the Electrophoresis Technology Experiment, showed that the static column worked well in zero-g and may be an effective way to enhance the production of urokinase, an enzyme useful in treating victims of strokes. See Pamphlet VII.

MA-060, Interface Markings in Germanium Crystals, showed that crystallization in space proceeds at an increasing speed as liquids cool to form solids. See Pamphlet VIII.

MA-085, Crystal Growth From the Vapor Phase, showed that large and perfect crystals can be grown much faster in zero-g than on Earth. See Pamphlet VIII.

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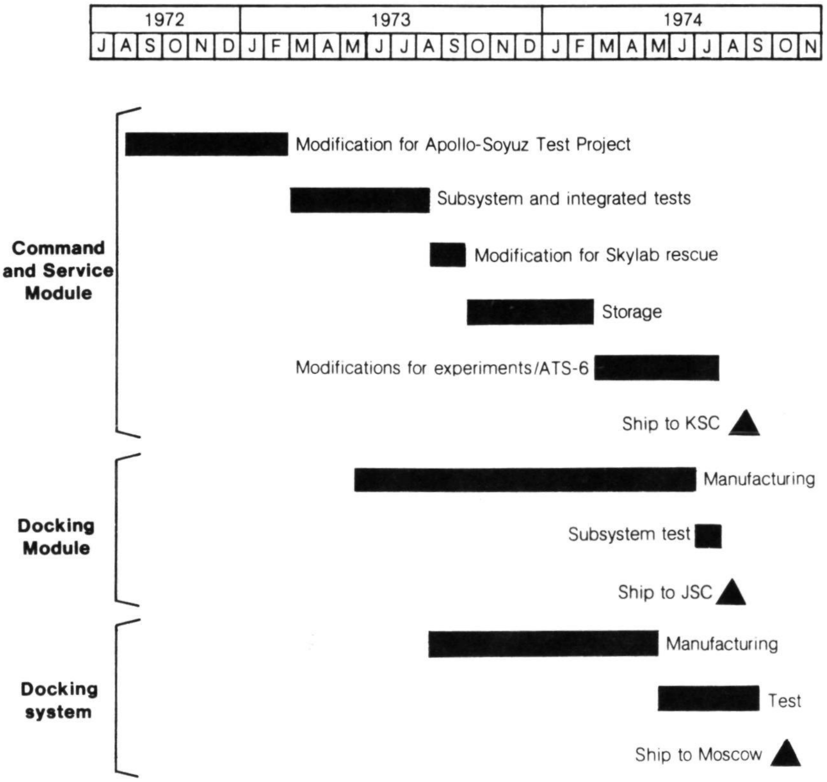
[6] Project Physics, Sec. 18.6; PSSC, Sec. 23-9.

C

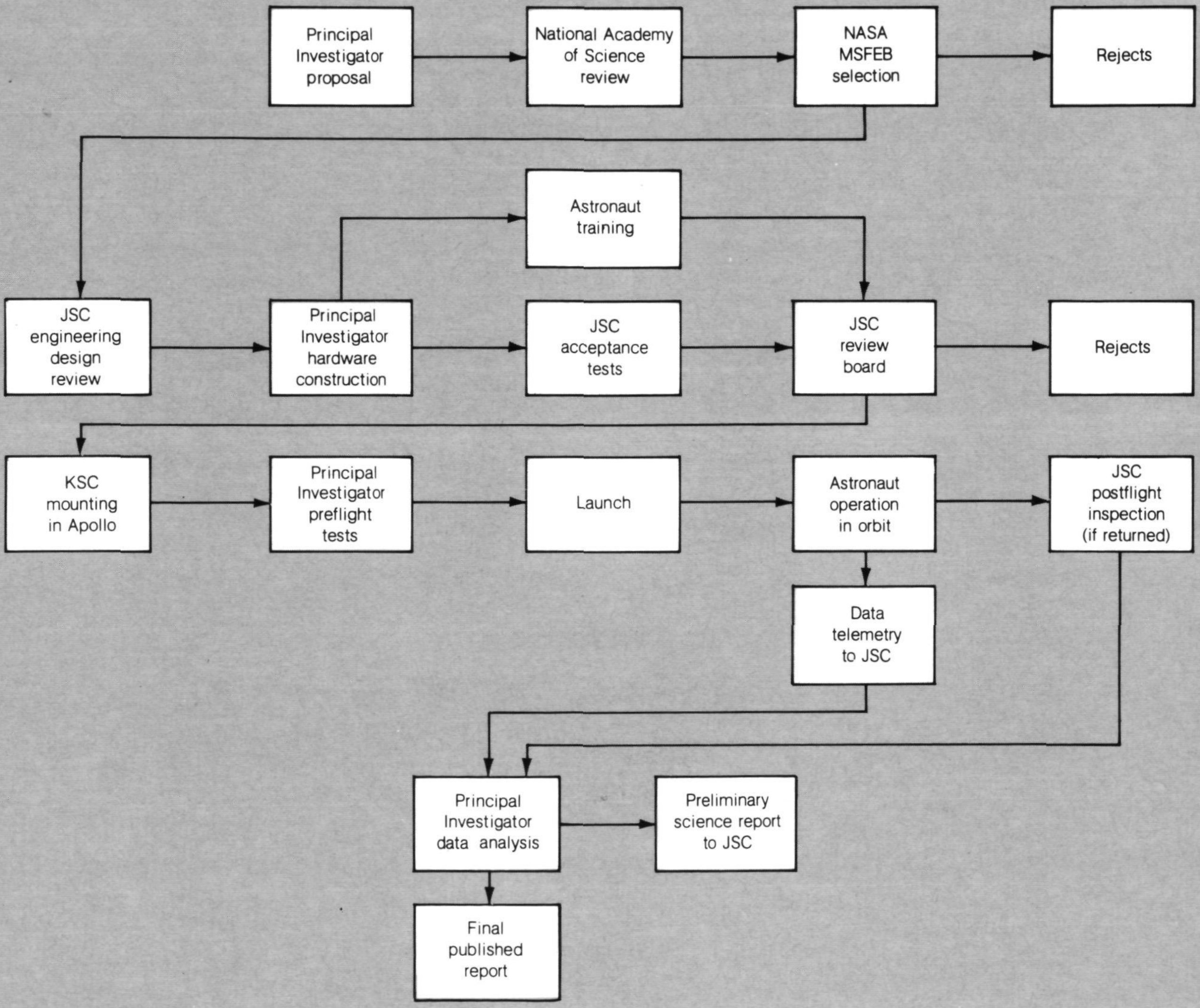
Organization of Flight Experiments

Study of the data obtained from some of the Apollo-Soyuz experiments will continue at least until 1977—5 years after the scientists made their proposals in 1972. This is not surprising. Important measurements are worth 3 years of preparation and 2 years of study. Figure 4.2 shows why it took this long to prepare for the flight. The modification of the Apollo CM and SM and the construction of the DM took approximately 2 years. During this time, the proposals and preparations for the experiments were reviewed, selected, approved, designed, reviewed, built, and tested, as shown in Figure 4.3. This careful preflight work makes sense. On a $220-million mission, you don't want to put an experiment in orbit only to find that it doesn't work. The individuals and groups responsible for the experiments on the Apollo-Soyuz mission are shown on the organization diagram in Figure 4.4.

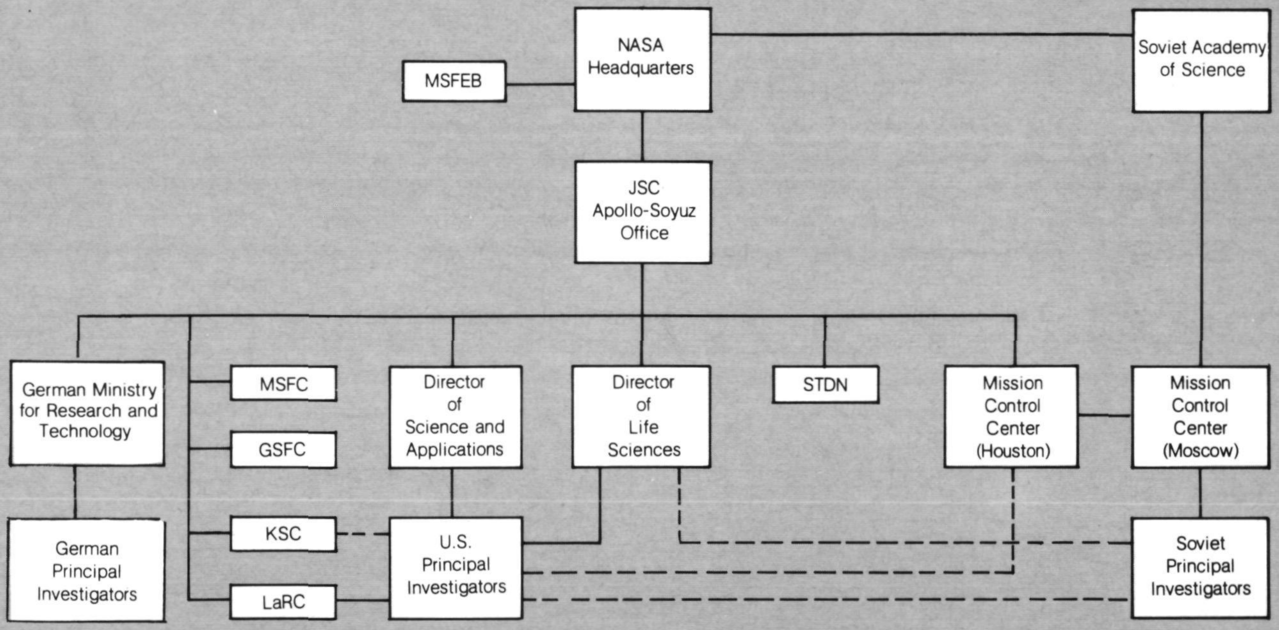


Schedule of Apollo modification and Docking Module construction. **Figure 4.2**

Figure 4.3 F low diagram of experiments from proposal to final published report.



Organizational diagram of NASA space science experiments. The Principal Investigators (bottom boxes) proposed the experiments and are responsible for reporting the results. **Figure 4.4**



D Schedule and Telemetry

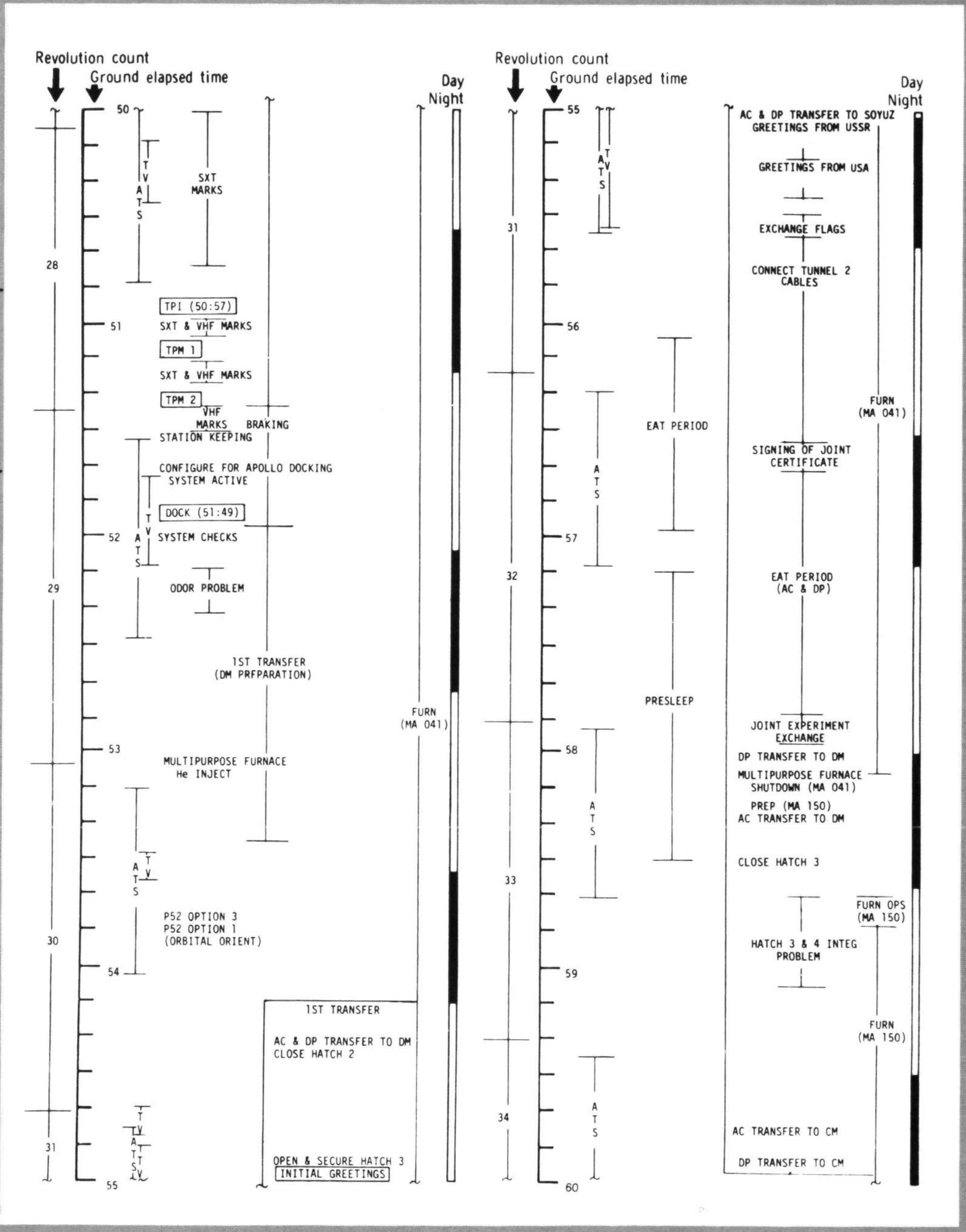
As on the previous Apollo missions, two other organizational schemes were important. These were the astronauts' "time line" and the communications schedule. Both were "time limited." There was so much for the astronauts to do that almost every minute of their working day was scheduled. Spacecraft maneuvers or "housekeeping," skin swabs, light flashes, Earth observations, all sorts of photography, starting the multipurpose furnace, crawling into the DM to shake hands, eating a Russian meal, turning off the furnace, and counting the hatched killifish were only a few of their activities. Figure 4.5 is a sample of 10 hours of the flight plan, where all these activities are fitted together. When there was a change in the flight plan because something went wrong (such as the breakdown in the MA-048 Soft X-Ray Observation Experiment) or because something was added, the astronauts got an evening message from MCC-Houston, giving detailed changes in the next day's activities. Mostly, the time line followed the flight plan, which the astronauts had rehearsed many times before launch.

Sometimes the communication links (Fig. 3.8) were heavily loaded. When Apollo was out of contact with the STDN radio receivers and the ATS-6 radio-relay satellite, spacecraft and experiment data were recorded on tape and played back when STDN receivers next came in view.

An elaborate communications plan was prepared before the Apollo-Soyuz mission. Almost every needed message was foreseen, and voice-radio, telephone, teletype, and facsimile circuits were set up to handle them. Between Moscow and Houston, there were 13 voice circuits as well as two teletype circuits and television. If the Apollo astronauts or Soyuz cosmonauts could be heard only in Moscow, their messages were instantly transmitted to Houston, and vice versa. Experiment data, telemetered in digital form, went from ground receivers through the NASA Robert H. Goddard Space Flight Center (GSFC), near Washington, D.C., to Houston through circuits capable of carrying 100 000 bits/sec. The communications plan was so well thought out that none of these circuits were overloaded—that is, no message had to wait for a free circuit.

It is remarkable that the Apollo-Soyuz mission was completed with so few problems. Near the very end, as Astronauts Stafford, Brand, and Slayton went through 3-g deceleration in reentering the Earth's atmosphere, dangerous gases were sucked into the Apollo cabin. Nitrogen tetroxide, used in the attitude-control jets, came into the spacecraft through a valve used to make the cabin atmosphere equal to that outside the spacecraft. The crew failed to set an automatic system to prevent the gas from entering the cabin, and, as a result, their lungs were burned before they reached the open air. Extensive medical testing after splashdown and a period of rest showed that their injuries were not serious.

Sample flight plan schedule from 50:00 to 60:00 GET, including docking and crew transfers. **Figure 4.5**



Predocking operations

Computer operations

AC	Apollo Commander (Stafford)
DP	DM Pilot (Slayton)
CP	CM Pilot (Brand)
ATS	ATS-6; see Figure 3.8
SXT	sextant

E Questions for Discussion

(Engineering, Emergency)

17. How can you explain the greater density of atmospheric aerosols in the Northern Hemisphere of the Earth than in the Southern Hemisphere?

18. What manufacturing industries might benefit by operating in a space station at zero-g?

19. How can NASA reduce the preparation time for space experiments?

20. If the astronauts and cosmonauts had not learned each others' language, how would you have rerouted communications between Apollo and Soyuz?

Appendix A

Discussion Topics (Answers to Questions)

1. (Sec. 2F) Moscow is at 38° E longitude, New York at 74° W longitude. The time difference, at 15° longitude/hr, is 7.5 hours; Moscow time is later than New York's. (The standard time zones are 7 hours apart.) Assuming that most Russians want to watch television at 7 p.m., prime time in Moscow would be at noon eastern standard time in New York (1 p.m. EDT). The handshake actually took place at 9:20 p.m. Moscow standard time, 10:20 p.m. Moscow daylight time, or 3:20 p.m. EDT.

2. (Sec. 2F) A 45° launch, unless it exceeded the escape velocity of 11.2 km/sec, would give an elliptical orbit around the Earth's center that would come closer than R_E to the center (Fig. 3.3). Thus, the spacecraft would crash into the Earth's surface.

3. (Sec. 2F) It was necessary to keep the Soyuz oxygen-nitrogen cabin atmosphere at two-thirds normal Earth-surface pressure and to keep the Apollo pure-oxygen cabin atmosphere at one-third atmospheric pressure. The DM atmosphere alternated between the two. If there had been an open passageway, neither Soyuz nor Apollo could have maintained the proper pressure and oxygen content for astronauts and cosmonauts to breathe naturally. Actually, higher pressure would have opened leaks in the CM, and higher oxygen content would have been a serious fire hazard in Soyuz.

4. (Sec. 2F) After the hatches are closed, open a valve releasing air from the DM tunnel, then close it. If the vacuum in the space between Soyuz and the DM remains hard, no air is leaking through the hatch or valves in Soyuz or Apollo.

5. (Sec. 3G) Two physical laws are involved: the *conservation of energy* and the *conservation of angular momentum*. If no energy is lost to atmospheric drag, the sum of a satellite's kinetic and potential energy is a constant. At *perigee*, where the satellite is closest to the Earth, it has *low potential energy* and high kinetic energy ($\frac{1}{2}m_s v_p^2$) or *high orbital velocity* $\mathbf{v}_p$. At *apogee* (farthest from Earth), it has *high potential energy* and low kinetic energy or *low orbital velocity* $\mathbf{v}_a$.

Kepler's Second Law of Planetary Motion is somewhat simpler; it states that a line from the Sun to a planet (or from the Earth's center to a satellite) sweeps out equal areas in equal times, anywhere in the orbit. This is required to conserve angular momentum $m_s v_\perp r$, where $v_\perp$ is the cross velocity perpendicular to r and is equal to $\mathbf{v}_p$ at perigee and to $\mathbf{v}_a$ at apogee. At perigee, the satellite has smallest r and largest $\mathbf{v}$; at apogee, it has largest r and smallest $\mathbf{v}$.

6. (Sec. 3G) At apogee, the orbital velocity $\mathbf{v}_a$ and the kinetic energy $E_a = \frac{1}{2} m_S v_a^2$ are lower than for a circular orbit at that distance r_a from the Earth's center (Fig. 3.3). An "apogee kick" increases $\mathbf{v}_a$. With the correct burn time, it can increase $\mathbf{v}_a$ to $\mathbf{v}_c$, the circular velocity. Then the spacecraft has higher kinetic energy and is in a higher energy orbit.

7. (Sec. 3G) At perigee, the orbital velocity $\mathbf{v}_p$ and the kinetic energy $E_p = \frac{1}{2} m_S v_p^2$ are higher than for a circular orbit at that distance r_p from the Earth's center (Fig. 3.3). By firing the thruster to *reduce* $\mathbf{v}_p$ to the smaller circular velocity at r_p, the orbit can be circularized. It is smaller than the circular orbit in Question 6, but note that the circular velocity and kinetic energy are *larger* because $v_c = \sqrt{GM_E/r}$.

8. (Sec. 3G) Controlled nuclear fission might be used to heat water, as in Earth-based nuclear power plants. Nuclear-fission energy would then be substituted for the fuel's chemical energy for heating the exhaust gases, but water (or other propellant material) must still be carried, and nuclear-powered rockets designed so far have serious weight disadvantages. Precautions are needed to shield the crew and the instruments in the payload from nuclear radiation and to avoid contamination of the Earth's atmosphere (or that of other planets) with radioactive exhaust gases.

9. (Sec. 3G) The mass of the Sun is 2×10^{30} kilograms or 330 000 times the mass of the Earth, and our distance from the Sun is about 150 million kilometers, 23 500 times the Earth's radius. The velocity of escape from the solar system at the Earth's location is the velocity of escape from the Sun at that location, $v_S = \sqrt{2GM_S/r_S}$. This velocity is $\sqrt{300\,000/23\,500} = 3.74$ times the velocity of escape from the Earth, or 41.9 km/sec.

10. (Sec. 3G) If there were convenient handholds like ladder rungs around the inside circumference of the DM, an astronaut could turn himself around the longitudinal axis (Fig. 3.4) and make the Apollo spacecraft roll in the opposite direction. (Refer to conservation of angular momentum.) When he stops, the spacecraft roll stops. The angle through which the spacecraft turned is a small fraction of the opposite angle turned by the astronaut. It depends on the mass and size of the astronaut (90 kilograms, 2 meters) and the spacecraft (13 450 kilograms, about 4 meters in diameter).

11. (Sec. 3G) Make "perigee kicks" to increase $\mathbf{v}_p$ (Fig. 3.3).

12. (Sec. 3G) Apollo-Soyuz was in a low (222 kilometer) circular orbit. Almost all the experiments in Table 4.1 were affected by the height H. In an elliptical orbit, where the height would change by a large amount, six experiments would have been affected; that is, their measurements would have been less accurate or more difficult to interpret. The following experiments benefited from a near-circular orbit:

MA-059, Ultraviolet Absorption, because the oxygen and nitrogen densities would vary if H varied

MA-089, Doppler Tracking, and MA-128, Geodynamics, because they could detect *gravity anomalies of the same size* all around the Earth at constant H

MA-136, Earth Observations and Photography, because the *mapping scale* (size of a 1-kilometer feature on photographs) is always the same at constant H

MA-088, Interstellar Helium Glow, because the *spacecraft speed* (*and its Doppler effect*) is constant at constant H

The low orbit benefited MA-089, Doppler Tracking, and MA-128, Geodynamics, because they could detect *smaller gravity anomalies* from low H.

The following experiments would have benefited from a *higher orbit*:

MA-136, Earth Observations and Photography because the *spacecraft speed would have been slower*, and larger areas of the Earth's surface could have been seen at one time

MA-148, Artificial Solar Eclipse, because the *sky background* of scattered sunlight would have been less

MA-083, Extreme Ultraviolet (EUV) Survey, and MA-088, Interstellar Helium Glow, because EUV absorption in the Earth's atmosphere would have been smaller and EUV background from the geocorona (cloud of hydrogen and helium around the Earth) would have been smaller

MA-011 and MA-014, the Electrophoresis experiments, and all the electric-furnace experiments (MA-010, MA-044, MA-150, MA-070, MA-041, MA-131, MA-060, MA-085, MA-028) because Apollo-Soyuz at $H = 222$ kilometers was not exactly at zero-g. (Atmospheric drag caused a deceleration of 0.0001 m/sec^2, or 0.00001 g.) At higher H, *atmospheric drag* is closer to zero, and weightlessness is nearly perfect.

13. (Sec. 3G) Because orbital velocity v is proportional to $1/\sqrt{r}$, the higher Apollo would lag behind Soyuz, even if you provide a thrust directly toward Soyuz. A thrust backward, *reducing* Apollo's v, will drop Apollo below Soyuz to smaller r and higher v. In this elliptical orbit, Apollo would catch up to Soyuz after one orbit, about 90 minutes later.

14. (Sec. 3G) The ''floating'' is generally the remainder of previous motion. If food were carefully placed at rest on a table top, it would remain at rest there. However, the very small force of an air current would start it moving.

15. (Sec. 3G)

Apollo: ''Soyuz, are you aligned, ready for docking?'' (In Russian)

Soyuz: ''Give me another 2 minutes.''

Apollo: ''Docking latches engaged and tightened.'' (In Russian)

Apollo: ''Docking Module atmosphere is now okay for you.'' (In Russian)

Soyuz: ''No air leak detected between Soyuz and DM.''

Apollo: ''Confirm. Hatch 3 is open.'' (In Russian)

16. (Sec. 3G) Atmospheric drag reduces the *height* of a satellite orbit and hence *increases* its orbital speed. This continues for any low satellite or jettisoned booster until it burns up at $H = 30$ to 40 kilometers ($v_c = \sqrt{GM_E/r}$).

17. (Sec. 4E) Probably a volcano erupted in the Northern Hemisphere. Industrial wastes (smoke) and aircraft pollution seldom get very far above the troposphere. Meteor dust is equal in both hemispheres. Stratospheric aerosols settle downward but are known to remain for years after a large volcanic explosion. See Pamphlet V.

18. (Sec. 4E) Industries that (1) produce large, perfect crystals for optical and electronic instruments; (2) cast perfect spheres of metal and glass; (3) manufacture very strong fiber-linked composites or accurate fiber-optics; (4) use rapid chemical processing and produce biological materials like vaccines; (5) produce high-uniformity alloys—all would benefit by operating at zero-g.

19. (Sec. 4E) Use a spacecraft able to carry a larger payload, so that experiments need not be designed and constructed in miniature and can be mounted in a simple manner. (NASA plans to fly a large reusable spacecraft called the Space Shuttle in the 1980's. With more frequent flights, experiments will not need to be reviewed and tested so many times for reliability.) See Figure 4.3.

20. (Sec. 4E) From Soyuz to an interpreter in MCC and back to Apollo; from Apollo to an interpreter in MCC and back to Soyuz. For brief messages, this would introduce a delay of about 1 minute. (During the actual mission, interpreters at both MCC-H and MCC-M monitored the voice communications for possible misunderstandings.)

Appendix B

SI Units
Powers of 10
Symbols

International System (SI) Units

Names, symbols, and conversion factors of SI units used in these pamphlets:

Quantity	Name of unit	Symbol	Conversion factor
Distance	meter	m	1 km = 0.621 mile 1 m = 3.28 ft 1 cm = 0.394 in. 1 mm = 0.039 in. 1 μm = 3.9×10^{-5} in. = 10^4 Å 1 nm = 10 Å
Mass	kilogram	kg	1 tonne = 1.102 tons 1 kg = 2.20 lb 1 gm = 0.0022 lb = 0.035 oz 1 mg = 2.20×10^{-6} lb = 3.5×10^{-5} oz
Time	second	sec	1 yr = 3.156×10^7 sec 1 day = 8.64×10^4 sec 1 hr = 3600 sec
Temperature	kelvin	K	273 K = 0° C = 32° F 373 K = 100° C = 212° F
Area	square meter	m^2	1 m^2 = 10^4 cm^2 = 10.8 ft^2
Volume	cubic meter	m^3	1 m^3 = 10^6 cm^3 = 35 ft^3
Frequency	hertz	Hz	1 Hz = 1 cycle/sec 1 kHz = 1000 cycles/sec 1 MHz = 10^6 cycles/sec
Density	kilogram per cubic meter	kg/m^3	1 kg/m^3 = 0.001 gm/cm^3 1 gm/cm^3 = density of water
Speed, velocity	meter per second	m/sec	1 m/sec = 3.28 ft/sec 1 km/sec = 2240 mi/hr
Force	newton	N	1 N = 10^5 dynes = 0.224 lbf

Quantity	Name of unit	Symbol	Conversion factor
Pressure	newton per square meter	N/m^2	$1\ N/m^2 = 1.45 \times 10^{-4}\ lb/in^2$
Energy	joule	J	$1\ J = 0.239$ calorie
Photon energy	electronvolt	eV	$1\ eV = 1.60 \times 10^{-19}\ J$; $1\ J = 10^7$ erg
Power	watt	W	$1\ W = 1\ J/sec$
Atomic mass	atomic mass unit	amu	$1\ amu = 1.66 \times 10^{-27}\ kg$

Customary Units Used With the SI Units

Quantity	Name of unit	Symbol	Conversion factor
Wavelength of light	angstrom	Å	$1\ Å = 0.1\ nm = 10^{-10}\ m$
Acceleration of gravity	g	g	$1\ g = 9.8\ m/sec^2$

Unit Prefixes

Prefix	Abbreviation	Factor by which unit is multiplied
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

Powers of 10

Increasing	Decreasing
$10^2 = 100$	$10^{-2} = 1/100 = 0.01$
$10^3 = 1\ 000$	$10^{-3} = 1/1000 = 0.001$
$10^4 = 10\ 000$, etc.	$10^{-4} = 1/10\ 000 = 0.000\ 1$, etc.
Examples:	Example:
$2 \times 10^6 = 2\ 000\ 000$	$5.67 \times 10^{-5} = 0.000\ 056\ 7$
$2 \times 10^{30} =$ 2 followed by 30 zeros	

List of Symbols in this Pamphlet

A	half the major axis (long dimension) of an elliptical orbit
$\mathbf{a}$	acceleration, with subscript c for circular orbit, subscript e for ejected gas, and subscript m for maximum
E	kinetic energy
e	eccentricity of an elliptical orbit
$\mathbf{F}$	force, with subscript e for ejection, subscript g for gravity or gravitation, and subscript t for thrust
G	Newton's constant of gravitation
$\mathbf{g}$	acceleration of gravity
H	height (altitude) of a spacecraft above the Earth's surface, with subscript a for apogee and subscript p for perigee
i	inclination of a satellite orbit to the Earth's Equator
ln	natural logarithm, 2.3 times the ordinary logarithm to base 10
M	mass of propellant, or large mass, with subscript E for Earth and subscript S for Sun
m	small mass, with subscript b for booster, subscript e for ejected gas, subscript p for payload, subscript s for spacecraft, and prefix Δ meaning "change in" (m also stands for meter, a unit of distance)
R	mass ratio (launch mass/mass after the propellant is gone)
R_E	radius of the Earth
r	radius of orbit; i.e., distance of a satellite from the Earth's center, with subscript a for apogee, subscript p for perigee, subscript S for Sun-Earth distance, and prefix Δ meaning "change in"
T	period of a satellite orbit
t	time, with prefix Δ meaning "change in"
$\mathbf{v}$	velocity, with subscript a for apogee, subscript c for circular orbit, subscript e for ejection, subscript m for maximum, subscript p for perigee or payload, subscript r for escape from Earth, subscript S for escape from the Sun, and prefix Δ meaning "change in"

Appendix C

Glossary

References to sections, Appendix A (answers to questions), figures, and tables are included in the entries. Those in *italic* type are the most helpful.

accelerometer instrument used to measure spacecraft acceleration by a spring balance. (Sec. 3D)

aerosol very small particles of dust, or droplets of liquid, suspended in the Earth's atmosphere. (Secs. 4A, 4B; App. A, no. 17)

apogee the point farthest from Earth in an elliptical Earth orbit. To enlarge or circularize the orbit, a spacecraft's thruster is turned on at apogee to give the craft an "*apogee kick.*" (Secs. 2C, 3D; App. A, nos. 5, 6; *Fig. 3.3*)

Apollo spacecraft a three-man spacecraft launched by Saturn boosters, originally designed for trips to the Moon. (Sec. 2C; Figs. 2.2 to 2.4, 4.1)

atmosphere a term with three different meanings. (1) The *Earth's* atmosphere is 80-percent nitrogen and 20-percent oxygen. The density and pressure decrease with altitude and are barely detectable at 200 kilometers (see *drag*). (2) *Cabin* atmosphere in Soyuz was normally ordinary air at sea-level pressure. In Apollo, the cabin atmosphere was almost pure oxygen at one-third that pressure. (Secs. 2D, 2F; App. A, no. 3) (3) Atmosphere is also a common *unit* of gas pressure equal to 1.01×10^5 N/m^2.

ATS-6 communications satellite a satellite in geosynchronous (24-hour period) orbit, 35 900 kilometers above Lake Victoria in East Africa, used to rebroadcast radio signals to and from the control station in Madrid, Spain. (Secs. *3F*, 4D; Figs. *3.8*, 4.5)

attitude the direction toward which a spacecraft is pointing, usually defined by the directions of its X-, Y-, and Z-axes relative to the stars. (Secs. 3D, 3E)

booster rocket the large reaction motor used to launch a spacecraft. (Sec. 3; Figs. 2.2, *3.1*, 3.2)

circuit communications link between manned spacecraft and ground stations. Some circuits are reserved for voice, television, data telemetry, or computer. (Secs. 3F, *4D*; Fig. 3.8)

circularize to change an elliptical orbit into a circular one, usually by "apogee kicks." (Secs. 2C, *3D*; App. A, nos. 6, 7; Figs. 3.6, 3.7)

Command Module (CM) a component of the Apollo spacecraft, attached to the Service Module (SM) until reentry into the Earth's atmosphere, when the SM is jettisoned. (Sec. 2C; Figs. 2.2, 4.1, 4.2)

communications sending and receiving messages by radio, television, teletype, or telephone line, centered at the Mission Control Center during a space mission. (Secs. *3F*, 4D; App. A, no. 20; Fig. 3.8)

docking sealing two spacecraft together in orbit with latches and sealing rings so that two hatches can be opened between them without losing cabin atmosphere. The *docking target* (Fig. 2.5) is used by the crews to align the spacecraft so that latches fit into hooks. (Secs. 2D, 2E, *3D*; App. A, no. 15; Figs. 2.4, 2.5, 3.7, 4.5)

Docking Module (DM) a special component added to the Apollo spacecraft so that it could be docked with Soyuz. (Secs. *2D*, 3D, 4C; App. A, nos. 3, 4, 15; Figs. 2.2, *2.4*, *2.5*, 4.1, 4.2)

drag atmospheric resistance to the orbital motion of a spacecraft. The effect of drag is to lower the orbit. Above 200 kilometers, the altitude decreases very slowly. Below 150 kilometers, the orbit ''decays'' rapidly. (*Sec. 3D*; App. A, no. 16)

Earth third planet, averaging 149 598 000 kilometers from the Sun, very nearly a sphere of 6378-kilometer radius, 6×10^{24}-kilogram mass. The Earth is accompanied by the Moon, about one-fourth its size. The Earth-Moon distance is 384 405 kilometers. (Sec. 3C; Fig. 3.3)

eccentricity (e) a measure of the ovalness of an orbit. When $e = 0$, the orbit is a circle; when $e = 0.9$, it is a long, thin ellipse. (Sec. 3C) See Project Physics, Sec. 7.3; PSSC, Sec. 15-5.

eclipse covering a bright object with a dark one. In a normal solar eclipse, the Sun is covered by the Moon. Apollo covered the Sun for Soyuz.

ellipse a smooth, oval curve accurately fitted by the orbit of a satellite around a much larger mass. (Secs. 2C, 3C; *Fig. 3.3*)

energy the capability of doing work. Kinetic energy is the energy of motion and is equal to $\frac{1}{2}mv^2$. Potential energy depends on position and is larger the farther mass m is from Earth. (App. A, nos. 5 to 8)

escape velocity the speed necessary to escape from Earth's gravity. It is smaller the farther a spacecraft is from Earth. (App. A, no. 9; Table 3.1)

force (F) a push or pull on a mass m that produces an acceleration $\mathbf{a}$; $\mathbf{F} = m\mathbf{a}$. (Sec. 3A; Fig. 3.1; Table 3.1)

free fall when a spacecraft is moving solely under the force of gravity (no drag, no thrust). (Sec. 3C)

geosynchronous orbit an orbit that is synchronized with the Earth's rotation. A satellite 35 900 kilometers above the Equator with a period of 24 hours would be in a geosynchronous orbit; it would always be above the same point on Earth. (Sec. 3F)

gravity anomaly a region where gravity is lower or higher than expected if the Earth's crust is considered to have uniform density.

Greenwich mean time (**GMT**) the time of an event, from 0 at midnight to 12 hours at noon to 24 hours at midnight, as measured at 0° longitude (Greenwich, near London, England). (Sec. 2B)

ground elapsed time (**GET**) the time since launch (Soyuz launch on the Apollo-Soyuz mission). (Sec. 2B; Figs. 3.6, 3.7, 4.5)

GSFC the NASA Robert H. Goddard Space Flight Center at Greenbelt, Maryland.

hatch a door in the pressure hull of a spacecraft. The hatch is sealed tightly to prevent the cabin atmosphere from escaping to the outside vacuum. (Sec. 2D; App. A, no. 4; Fig. 2.5)

jettison to discard. When the fuel in a booster rocket is used up, the now-useless booster is disconnected from the spacecraft and jettisoned (allowed to fall back to Earth). (Secs. *2C*, 3B, 3C; Fig. 3.2)

JSC the NASA Lyndon B. Johnson Space Center in Houston, Texas.

Kepler's Third Law the law which states that T^2 is proportional to A^3, where T is the period and A measures the orbit size (Fig. 3.3). Based on early observations of planets,the law also applies to satellites of the Earth and is explained by Newton's Laws. (Sec. 3C)

KSC the NASA John F. Kennedy Space Center at Cape Canaveral, Florida.

launch configuration the combination of boosters, spacecraft, and launch escape system that must be lifted off the ground at launch. (Secs. 2C, 3A; *Fig. 2.2*; Table 3.1)

LOX liquid oxygen at temperature 90 K or $-183°$ C, used with kerosene fuel as a propellant in booster rockets. (Secs. 2C, 3A)

Magellanic Cloud nearby galaxy outside the Milky Way Galaxy. See Pamphlet II. (Sec. 4B)

Mission Control Center (**MCC**) the operational headquarters of a space mission. For Apollo-Soyuz, there were two: MCC-H in Houston and MCC-M in Moscow. (Sec. 3F; Figs. 3.8, 4.4)

momentum mass times velocity, referring to motion in a straight line. *Angular momentum* refers to rotation and to motion around orbits. It is mass times cross-velocity times distance from the axis of rotation or center of orbit. Both are conserved. (App. A, no. 5; Table 3.1) See Project Physics, Sec. 9.4; PSSC, Sec. 14-1.

MSFC The NASA George C. Marshall Space Flight Center in Huntsville, Alabama.

MSFEB The NASA Manned Space Flight Experiment Board, which decided which proposed experiments would be conducted on Apollo-Soyuz. (*Sec. 4A*; Figs. 4.3, 4.4)

multistage launch a launch that uses several stages to boost the payload into orbit. After the first-stage booster uses its fuel, it is jettisoned and the secondary booster is fired. When the second-stage fuel is gone, that booster is jettisoned, and so on. Such multistage launching allows very high payload velocities. (Sec. 3B; Fig. 3.2)

Neutron Star a very high density star made of neutrons, not atoms. See Pamphlet II. (Sec. 4B)

Newton's Laws the three laws of motion and the law of gravitation, published in 1687, explaining almost all the motions of planets and satellites with high accuracy. (Secs. 3A to 3D; Table 3.1) See Project Physics, Secs. 3.9 to 3.11, 8.6, 8.8; PSSC, Secs. 13-8, 13-10, 14-5, 14-8, 16-6.

nuclear power power derived from nuclear reactions between neutrons and atoms of uranium, thorium, or plutonium, which undergo fission (splitting). Such power might be used for reaction motors. The fission products are highly radioactive. (App. A, no. 8)

orbit the path followed by a planet around the Sun or by a satellite around the Earth, usually an ellipse. (Secs. 2C, *3C*, 3D; App. A, nos. 5 to 7, 12, 13; Figs. 3.3, 3.5) See Project Physics, Sec. 7.3; PSSC, Secs. 13-5, 13-6.

payload the components to be put into orbit on a single-stage launch, such as that of Soyuz. On a multistage launch, the second stage is payload for the first; the third stage is payload for the second; and so on. (Sec. 3B; Fig. 3.1)

perigee the point closest to Earth on an elliptical orbit around the Earth. (Secs. 3C, 3D; App. A, nos. 5, 7, 11; Figs. *3.3*, 3.6)

period (T) the time taken by a satellite to travel once around its orbit.

Principal Investigator (PI) the individual responsible for conducting a space experiment and reporting the results. (Figs. 4.3, 4.4)

propellant both the fuel (kerosene) and the oxidizer (LOX) for a reaction motor. The propellant is ejected at high velocity $\mathbf{v}_e$ to provide forward thrust. (Secs. 3A, *3B*; App. A, no. 8; Fig. 3.1)

pulsar a pulsating, condensed star of a type first detected by regular 1-second pulses of radio waves. (Sec. 4B)

RCS quad jets small jets used to roll or rotate the Apollo spacecraft. (Sec. 3D; *Fig. 3.4*)

reaction the equal but opposite push on your hand when you push something (Newton's Third Law). *Reaction motors* push gas out the rear nozzle to get the reaction as a forward thrust. (Sec. 3A; *Fig. 3.1*)

rendezvous the close approach of two spacecraft in the same orbit so that docking can take place. (Sec. 3D; Figs. 3.5, *3.7*)

Saturn IB, Saturn IVB boosters (first stage and second stage) for the Apollo spacecraft. (Secs. 2C, 3A, 3D; Fig. 2.2)

sealing rings mechanical devices designed to fit tightly when two spacecraft are docked so that cabin atmosphere will not leak out. (Sec. 2D; Figs. 2.4, 2.5)

Service Module (SM) the large part of the Apollo spacecraft that contains the main thruster, tanks, radio equipment, and other support equipment. It is attached to the CM until just before the CM reenters the Earth's atmosphere. (Figs. 2.2, 4.1)

solar panel a winglike set of cells that convert sunlight to electric power, used on Soyuz and many NASA spacecraft but not on Apollo. (Sec. 3D; Fig. 2.4)

Soyuz the Soviet two-man spacecraft. (Secs. 2C, 2D, 3B; Figs. 2.2 to 2.4, 4.1)

specific impulse a measure of the power of a propellant. (Sec. 3B)

stage one part of the launch sequence; see *multistage launch*. (Sec. 3B; Fig. 3.2; Table 3.1)

STDN the NASA Spaceflight Tracking and Data Network. (Secs. *3F*, 4D; Fig. 4.4)

telemetry the automatic transmission of data to ground receivers. (Sec. 4D; Fig. 4.3)

thrust the forward force $\mathbf{F}_t$ provided by a reaction motor. (Secs. 2C, 3A, 3C; App. A, no. 13; Fig. 3.1)

time line the planned schedule for astronauts on a space mission. (Secs. 2B, 4D; Fig. 4.5)

time zone a region using the same time of day. There are 24 time zones around the world, each about 15° wide in longitude. In the United States, they are called eastern, central, mountain, and Pacific standard time, each 1 hour different from the zone on either side. (Sec. 2B; App. A, no. 1)

torque a twist provided by two offset forces on a body. (Sec. 3A; *Fig. 3.4*)

vector a directed quantity, like velocity, force, acceleration. Vector symbols (**v**, **F**, **a**) are given in **boldface** type. (Fig. 3.3; Table 3.1)

velocity (v) change of position per unit time, in meters per second. (Secs. 3A to 3D; App. A, nos. 5, 6, 13; Fig. 3.3; Table 3.1)

weight ($\mathbf{F_g}$) the downward force on a mass at the Earth's surface. The force on 1 kilogram is 9.8 newtons. (Sec. 3A; Table 3.1)

weightlessness the condition of free fall or zero-g, in which objects in a spacecraft are weightless. (Secs. 2E, *3C*)

$\mathbf{X_V}$, $\mathbf{Y_V}$, $\mathbf{Z_V}$ spacecraft (vehicle) axes, with X_V directed forward (away from the thruster nozzle), Y_V to one side, and Z_V "up." (Sec. 3E; Figs. *3.4*, 4.1)

zero-g the condition of free fall and weightlessness. (Secs. 2E, *3C*; App. A, no. 18)

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Appendix D

Further Reading

ABC's of Space by Isaac Asimov, Walker and Co. (New York), 1969—an illustrated glossary of spaceflight terms.

Apollo Expeditions to the Moon, Edgar Cortright, ed., NASA SP-350, 1976—well-illustrated descriptions of the Saturn boosters, the Apollo spacecraft, mission control, and astronaut training.

Apollo-Soyuz Test Project Preliminary Science Report, NASA TM X-58173, 1976—advanced-level accounts of experimental results.

Astronauts and Cosmonauts: Biographical and Statistical Data (Available from the U.S. Government Printing Office, Washington, D.C. 20402), 1976—describes the men who have gone on space missions.

Carrying the Fire by Michael Collins, Farrar, Strauss, & Giroux, Inc. (New York), 1974—a beautifully written account of astronaut training and the flight of Apollo 11.

The Kremlin and the Cosmos by Nicholas Damiloff, Alfred A. Knopf (New York), 1972—an interesting history of space exploration by the U.S.S.R.

The Language of Space: A Dictionary of Astronautics by Reginald Turnill, John Day Co., Inc. (New York), 1971—a well-written glossary of 1100 terms, with a section on "the next 20 years in space."

Learning About Space, British Department of Education and Science, 1970—excellent explanations of spaceflight.

Living in Space (Available from the U.S. Government Printing Office, Washington, D.C. 20402), 1976—a popular account of astronaut living conditions.

Living in Space: The Astronaut and His Environment by Mitchell R. Sharp, Doubleday and Co., Inc. (New York), 1969—well-illustrated survey of space biology; describes radiation and weightlessness.

Rendezvous in Space: Apollo-Soyuz by F. Dennis Williams (Available without charge from NASA Educational Programs Division, Washington, D.C. 20546), 1975—a popular account of the Apollo-Soyuz mission.

Robot Explorers by Kenneth Gatland, Macmillan Publishing Co., Inc. (New York), 1972—well-illustrated survey of spaceflight to 1972.

Soviets in Space by Peter L. Smolders, Taplinger Publishing Co., Inc. (New York), 1974—a well-illustrated history of Soviet spaceflight.

Space Science and Astronomy: Escape from Earth, Thornton Page and Lou Williams Page, eds., Macmillan Publishing Co., Inc. (New York), 1976—contains articles by experts on almost every phase of space exploration.

Suiting Up for Space by Lloyd Mallan, John Day Co., Inc. (New York), 1971—describes the development of space suits since 1940.

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