Apollo-Soyuz
Pamphlet No. 3:

Sun, Stars, In Between

(NASA-EP-135) APOLLO-SOYUZ PAMPHLET NO. 3: SUN, STARS, IN BETWEEN (National Aeronautics and Space Administration) 64 p MF A01; SOD HC set of 9 volumes CSCL 22A
N78-27149
Unclas
G3/12 24991

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:

On The Cover

The Sun, the Solar Corona, and the Zodiacal Light as seen from Soyuz

Apollo-Soyuz Pamphlet No. 3:

Sun, Stars, In Between

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

NASA
National Aeronautics and Space Administration

Washington, D.C. 20546
October 1977

For sale by the Superintendent of Documents,
U.S. Government Printing Office, Washington, D.C. 20402
(9-Part Set; Sold in Sets Only)
Stock Number 033–800–00688–8

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.

Teachers And Scientific Investigators Who Reviewed the Text

Harold L. Adair, Oak Ridge National Laboratory, Oak Ridge, Tenn.
Lynette Aey, Norwich Free Academy, Norwich, Conn.
J. Vernon Bailey, NASA Lyndon B. Johnson Space Center, Houston, Tex.
Stuart Bowyer, University of California at Berkeley, Berkeley, Calif.
Bill Wesley Brown, California State University at Chico, Chico, Calif.
Ronald J. Bruno, Creighton Preparatory School, Omaha, Nebr.
T. F. Budinger, University of California at Berkeley, Berkeley, Calif.
Robert F. Collins, Western States Chiropractic College, Portland, Oreg.
B. Sue Criswell, Baylor College of Medicine, Houston, Tex.
T. M. Donahue, University of Michigan, Ann Arbor, Mich.
David W. Eckert, Greater Latrobe Senior High School, Latrobe, Pa.
Lyle N. Edge, Blanco High School, Blanco, Tex.
Victor B. Eichler, Wichita State University, Wichita, Kans.
Farouk El-Baz, Smithsonian Institution, Washington, D.C.
D. Jerome Fisher, Emeritus, University of Chicago, Phoenix, Ariz.
R. T. Giuli, NASA Lyndon B. Johnson Space Center, Houston, Tex.
M. D. Grossi, Smithsonian Astrophysical Observatory, Cambridge, Mass.
Wendy Hindin, North Shore Hebrew Academy, Great Neck, N.Y.
Tim C. Ingoldsby, Westside High School, Omaha, Nebr.
Robert H. Johns, Academy of the New Church, Bryn Athyn, Pa.
D. J. Larson, Jr., Grumman Aerospace, Bethpage, N.Y.
M. D. Lind, Rockwell International Science Center, Thousand Oaks, Calif.
R. N. Little, University of Texas, Austin, Tex.
Sarah Manly, Wade Hampton High School, Greenville, S.C.
Katherine Mays, Bay City Independent School District, Bay City, Tex.
Jane M. Oppenheimer, Bryn Mawr College, Bryn Mawr, Pa.
T. J. Pepin, University of Wyoming, Laramie, Wyo.
H. W. Scheld, NASA Lyndon B. Johnson Space Center, Houston, Tex.
Seth Shulman, Naval Research Laboratory, Washington, D.C.
James W. Skehan, Boston College, Weston, Mass.
B. T. Slater, Jr., Texas Education Agency, Austin, Tex.
Robert S. Snyder, NASA George C. Marshall Space Flight Center, Huntsville, Ala.
Jacqueline D. Spears, Port Jefferson High School, Port Jefferson Station, N.Y.
Robert L. Stewart, Monticello High School, Monticello, N.Y.
Aletha Stone, Fulmore Junior High School, Austin, Tex.
G. R. Taylor, NASA Lyndon B. Johnson Space Center, Houston, Tex.
Jacob I. Trombka, NASA Robert H. Goddard Space Flight Center, Greenbelt, Md.
F. O. Vonbun, NASA Robert H. Goddard Space Flight Center, Greenbelt, Md.
Douglas Winkler, Wade Hampton High School, Greenville, S.C.

Page Intentionally Left Blank

Contents

Tables and Figures

1 Introduction

After 4 years of preparation by the U.S. National Aeronautics and Space Administration (NASA) and the U.S.S.R. Academy of Sciences, the Apollo and Soyuz spacecraft were launched on July 15, 1975. Two days later at 16:09 Greenwich mean time on July 17, after Apollo maneuvered into the same orbit as Soyuz, the two spacecraft were docked. The astronauts and cosmonauts then met for the first international handshake in space, and each crew entertained the other crew (one at a time) at a meal of typical American or Russian food. These activities and the physics of reaction motors, orbits around the Earth, and weightlessness (zero-g) are described more fully in Pamphlet I, "The Spacecraft, Their Orbits, and Docking" (EP-133).

Thirty-four experiments were performed while Apollo and Soyuz were in orbit: 23 by astronauts, 6 by cosmonauts, and 5 jointly. These experiments in space were selected from 161 proposals from scientists in nine different countries. They are listed by number in Pamphlet I, and groups of two or more are described in detail in Pamphlets II through IX (EP-134 through EP-141, respectively). Each experiment was directed by a Principal Investigator, assisted by several Co-Investigators, and the detailed scientific results have been published by NASA in two reports: the Apollo-Soyuz Test Project Preliminary Science Report (NASA TM X-58173) and the Apollo-Soyuz Test Project Summary Science Report (NASA SP-412). The simplified accounts given in these pamphlets have been reviewed by the Principal Investigators or one of the Co-Investigators.

Low-density gas in the space between the stars has interested ground-based astronomers for many years. From spacecraft and rockets above the Earth's atmosphere, it is possible to make much better observations of gas near the Sun because there is little or no scattered sunlight from the atmosphere and all the extreme ultraviolet (light of very short wavelength) can be measured. (Such light is absorbed by the atmosphere before it reaches telescopes on Earth.) Three experiments on Apollo-Soyuz exploited these advantages of space astronomy.

The Artificial Solar Eclipse (Experiment MA-148) was a joint experiment that involved both astronauts and cosmonauts. The Principal Investigator was G. M. Nikolskiy of the U.S.S.R. Academy of Sciences; he was assisted by two other Russians and three Americans. While the Apollo spacecraft backed off from the Soyuz vehicle (in line with the Sun) and then moved back toward Soyuz, the cosmonauts photographed the solar corona. These photographs were later studied and measured by the Principal Investigator in Moscow.

The Extreme Ultraviolet (EUV) Survey (Experiment MA-083) counted high-energy ultraviolet photons coming toward the Earth from various parts of the sky. The Principal Investigator for this experiment was Stuart Bowyer of the University of California at Berkeley, who collaborated with many other scientists at that university and elsewhere. They used a special EUV telescope and discovered several interesting EUV sources.

The Interstellar Helium Glow (Experiment MA-088) used similar detectors and was also supervised by Stuart Bowyer. This experiment detected helium gas from interstellar space flowing through the solar system.

The theme of this pamphlet is the study of *low-density gas in space:* the gas at very high temperature in the solar corona, the "atmosphere" surrounding the Apollo spacecraft, the outer layers of gas in superhot stars, and the interstellar helium. The following three sections begin with background information on the Sun, the stars, and the interstellar medium. Each section describes one experiment and its findings.

2 Layers in the Sun

The Sun is a 1 390 000-kilometer ball of gas, mostly hydrogen and helium. Its mass of 2×10^{30} kilograms dominates the planets, the comets, the dust, and the gas in the solar system. The Sun rotates about once a month in the same direction as all the planets move in their orbits—eastward; that is, it rotates counterclockwise as viewed from the north.

At the Sun's "surface" (the edge that you can see through dark glass[1]), the temperature is about 5800 K (Fig. 2.1). Astronomers call that surface, which is 695 000 kilometers from the center of the Sun, the photosphere. As you can see during a total solar eclipse, the photosphere is not really the edge of the Sun. Below the photosphere, the Sun's gas is opaque to visible light, which causes the photosphere to look as though it had a sharp edge. Above the photosphere, transparent gases glow red for several thousand kilometers. Above that is the solar corona, which glows greenish white to at least 1 000 000 kilometers above the photosphere. The brightness of the corona is about one-millionth the brightness of the photosphere. The corona is swamped by haze and blue-sky light except during a total solar eclipse, when the Moon covers the Sun for a minute or so. (Both the Moon and the Sun are about 0.5° across as seen from Earth.) Most of what we know about the solar corona came from observations during total solar eclipses, which are visible from small regions of the Earth's surface about twice a year.

A Core of the Sun: Nuclear Reactions

The Sun is the brightest object in the sky—about 10^{10} times brighter than the brightest star and about a million times brighter than the full Moon. Where does all its radiant energy come from? It is easy to show that chemical reactions such as burning cannot provide the vast amount of power radiated by the Sun. Astronomers have carefully measured the solar energy passing through each square meter perpendicular to the Earth-Sun line each second in all wavelengths from ultraviolet through visible and infrared rays, making corrections for absorption by the Earth's atmosphere (see Pamphlet II). They multiplied the measured energy per square meter per second by the number of square meters in a sphere the size of the Earth's orbit around the Sun to get the total solar power output—the huge value of 3.83×10^{26} watts (Fig. 2.2). Even if the Sun were composed entirely of hydrogen (H) and oxygen (O), the chemical reaction $2H + O \rightarrow H_2O$ would burn out in a mere 4000 years. Geologists have evidence that the Sun has been shining at about the same brightness for at least 4.5 billion years.

---

[1]Never look directly at the Sun with the naked eye. Direct sunlight can damage your eyes.

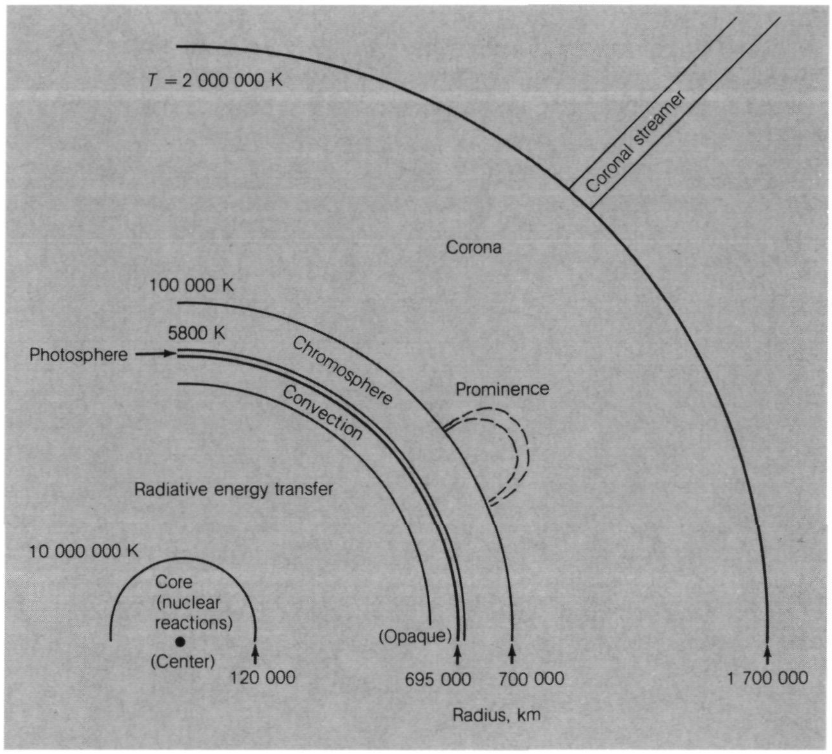


Figure 2.1 **Schematic diagram of the layers in the Sun.**

In 1904, Einstein derived from his Special Relativity Theory the formula $E = mc^2$, which shows that mass m is equivalent[2] to a very large amount of energy E (c is the velocity of light, 3×10^8 m/sec). Physicists speculated that mass was being converted to energy inside the Sun, but it wasn't until 1938 that nuclear reactions were measured in the laboratory and found to be capable of doing this mass-energy conversion under the high temperatures (10 000 000 K) and pressures known to exist in the Sun's core. Other stars are similar to the Sun, although much farther away, and these nuclear reactions also explain their power output.

[2]See Project Physics, Secs. 20.1, 24.1 to 24.4, 24.9. (Throughout this pamphlet, references will be given to key topics covered in these standard textbooks: "Project Physics," second edition, Holt, Rinehart and Winston, 1975, and "Physical Science Study Committee" (PSSC), fourth edition, D. C. Heath, 1976.)

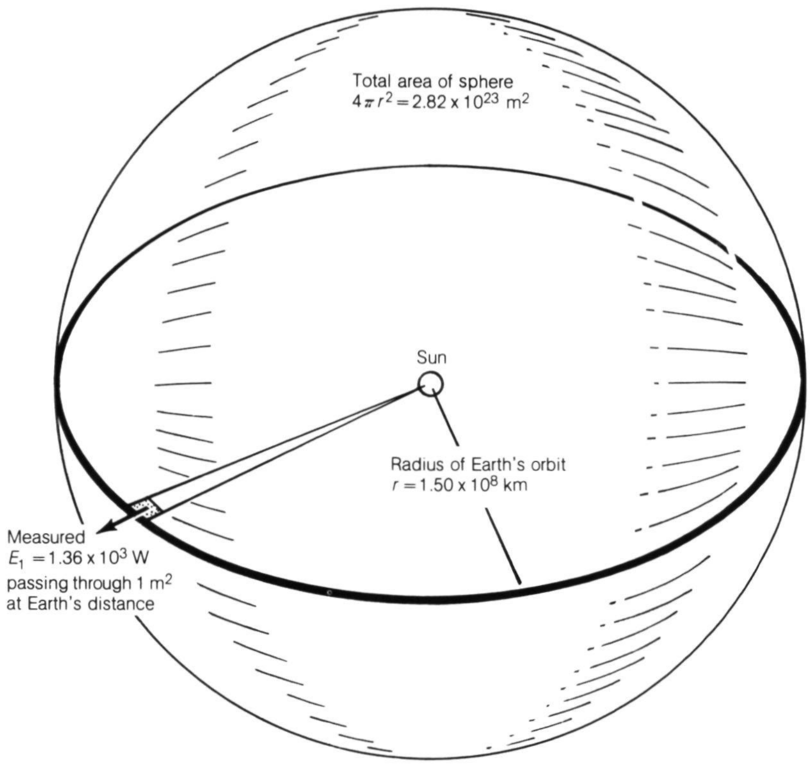


Figure 2.2

Determination of the total power output of the Sun: $E_t = 4\pi r^2 E_1 = 3.83 \times 10^{33}$ ergs/sec $= 3.83 \times 10^{26}$ watts in all directions.

The loss of mass (0.71 percent) occurs when four protons (hydrogen nuclei) of 1.0081 atomic mass units each are compressed to form an alpha particle (helium nucleus) of 4.0039 atomic mass units. This does not happen all at once but rather in a series of nuclear reactions that involve other atomic nuclei. The products of some of these reactions last for only a very short time. They can proceed only if the temperature is extremely high so that all the particles have high velocities and high-energy impacts. The pressure also must be high enough to provide many impacts on each nucleus per second.

Astronomers can compute the temperature, the pressure, and the density at various depths inside the Sun (or inside any star of given size and surface temperature), using basically the gas law and Newton's Law of Gravitation.

The *gas law*[3] states that pressure is proportional to density times temperature. *Newton's Law of Gravitation* states that the deeper layers of the Sun are pulling outer layers down, so that the gas pressure on a centimeter of gas deep in the Sun is the weight of the 1-square-centimeter column of gas above it (out to the surface of the Sun).

These calculations are complex. With the help of high-speed electronic computers, astronomers can estimate the pressure, density, and temperature at any depth in the Sun. This enables them to estimate at what depths in the Sun the nuclear reactions will ''go'' and also to calculate the energy released per second at the greater depths. They find that most of the nuclear energy comes from a central core, about one-sixth the radius of the Sun, where approximately 6×10^{11} kilograms of protons are converted to helium nuclei every second. The density in this 240 000-kilometer-diameter core is 100 to 150 times the density of water (100 to 150 gm/cm^3); therefore, it contains about 8×10^{29} kilograms, or 40 percent of the Sun's mass. Its temperature is between 10 000 000 and 15 000 000 K.

B The Photosphere: Surface Temperature and Brightness

Calculations of conditions inside the Sun depend on the surface temperature, which is measured by applying the Planck Radiation Law to the spectrum of sunlight. This law (Table 2.1) is a formula relating the intensity I of light from a hot, opaque surface to the wavelength λ of the light and the temperature T of the surface. From the complex Planck formula, two simpler formulas can be derived. The first tells about the *color* of a hot surface. It states that the wavelength of maximum intensity λ_m is inversely proportional to the temperature T. The Sun is yellow, with λ_m equal to 5000 angstroms (500 nanometers) and the ''color temperature'' T_c equal to $2.9 \times 10^7/5000$, or 5800 K. If its surface temperature were higher, λ_m would be smaller and the Sun's color bluer. If the Sun were cooler, λ_m would be larger and the Sun's color redder (Fig. 2.3). In this way, astronomers get the surface temperature of stars: red stars with a surface temperature of about 3000 K and blue stars with a surface temperature of 30 000 K or more. These temperatures can also be estimated from absorption lines[4] in the star's spectrum. Of course, the *internal* temperatures of the Sun and all the other stars are much higher (they have to be about 10 000 000 K for the nuclear reactions to occur).

---

[3]Project Physics, Sec. 11.5; PSSC, Secs. 17-1 to 17-5.

[4]Project Physics, Sec. 19.1.

Laws of Radiation **Table 2.1**
(See Fig. 2.3)

Law	*Formula*
Planck Law: the intensity I_λ at wavelength λ	$I_\lambda = \frac{4\pi hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$ where T = surface temperature in kelvin h = the Planck constant, 6.62×10^{-34} J sec k = the Boltzmann constant, 1.38×10^{-23} J/K c = the velocity of light, 3×10^8 m/sec
Color law: wavelength of maximum intensity λ_m, in angstroms	$\lambda_m = 28\,970\,000/T$
Brightness law: total energy E_t (in joules) radiated from 1 square meter each second	$E_t = \sigma T^4$ where σ = the Stefan-Boltzmann constant, 5.67×10^{-8} W/m² K⁴

The other formula derived from the Planck law tells about *brightness*. It states that the total energy E_t radiated from a surface in all wavelengths of light (ultraviolet, visible, infrared, and radio) is proportional to T^4. The data in Figure 2.2 show that each square meter of the Sun's photosphere (695 000-kilometer radius) radiates 6.3×10^7 watts. From the brightness formula (Table 2.1), we find the brightness temperature T_B to be 5800 K.

Below the photosphere, the temperature increases toward the center of the Sun. There are at least two layers we can discuss (Fig. 2.1). In the *radiative transfer* layer, the energy is carried outward by photons of light that are absorbed in the opaque gas, then reemitted, then absorbed after traveling a few millimeters, and so on. There are also one or two *convective* layers where the energy is carried outward by rising hot gas (as cooler gas falls). Such convection currents are not simple. The Sun's rotation, the strong magnetic fields near the equator, and temporary hotspots complicate the layers.

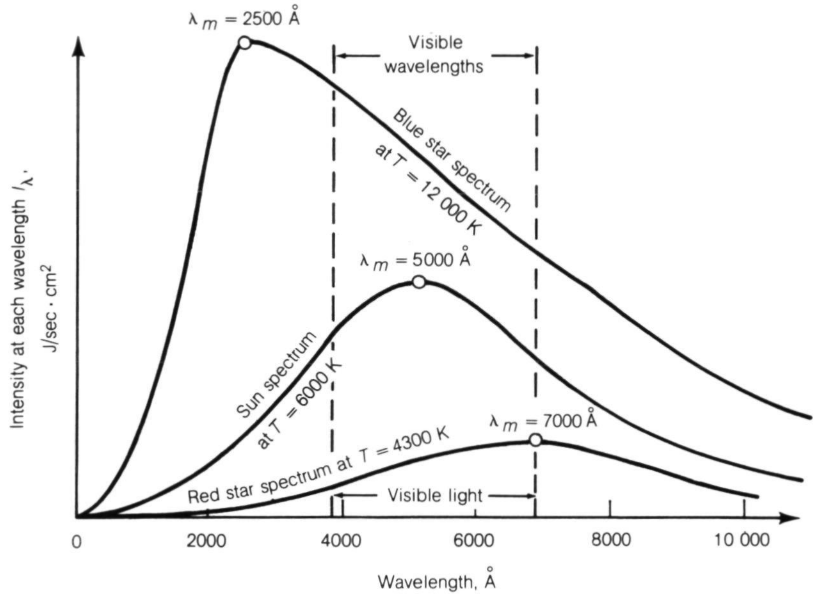


Figure 2.3 **Planck Law of Radiation from an opaque surface. The areas under the curves give the total energy output in joules per second from each square meter: $E_t = 5.67 \times 10^{-8}$ W/m² K⁴.**

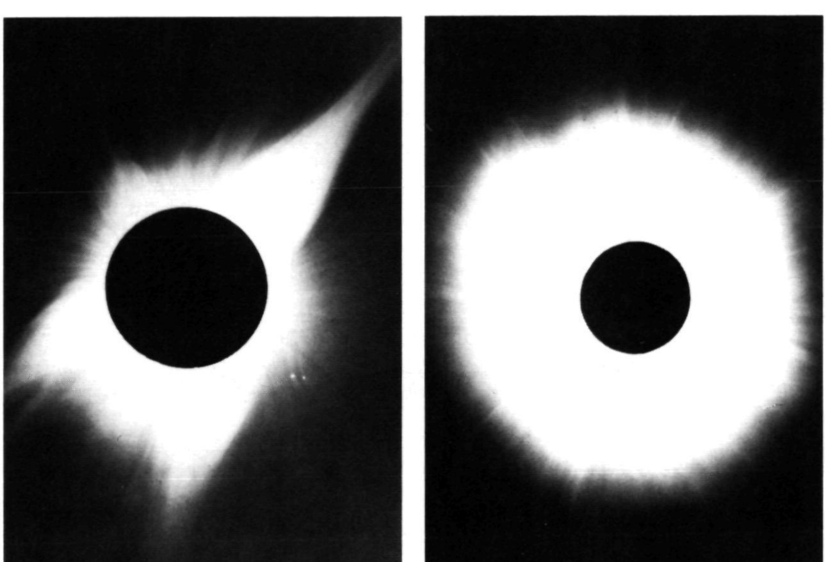
C Layers Above the Photosphere: Chromosphere and Corona

Gases above the Sun's photosphere are transparent, but they glow because of their high temperature. The red glow of the chromosphere (color sphere) can be seen for a few seconds just after the Moon covers the Sun in a total eclipse. The layer is only about 3000 kilometers thick, and the lower part is at a somewhat lower temperature than the photosphere. The red glow is mainly due to the emission of hydrogen at the 6563-angstrom (656.3-nanometer) wavelength. Astronomers can photograph the chromosphere without an eclipse, using the emission-line wavelengths only. Their photographs show huge flamelike "prominences" pushed out of the chromosphere by the pressure of sunlight. The gas density in the chromosphere is about 10^{-5} kg/m^3 (10^{-8} times the density of water), and the temperature increases from 4500 K near the bottom of the chromosphere to 100 000 K near the top (Fig. 2.1).

This increase in temperature with height continues through the greenish corona to reach several million kelvin. At first, it was puzzling to astronomers to find that the temperature of these very low density gases increases with height and gets so high that x-rays are emitted (wavelengths less than 100 angstroms, or 10 nanometers). It is now thought that sound waves carry energy up from below the photosphere to heat the corona. The intense light rays pass through the transparent corona without heating it.

Two photographs of the solar corona during a total eclipse are shown in Figure 2.4. The shape of the corona can vary widely, depending on the number of sunspots at the time of the eclipse. The corona often has long streamers and rays that are thought to match the magnetic field of the Sun. The outer edge of the corona is not as sharply defined as it appears to be in the photographs; that is, a longer exposure will show more of the "outer corona." Previous space experiments on Skylab and Apollo missions showed that the outer corona merges into the "zodiacal light," a faint band that extends all around the sky (Fig. 2.5). The zodiacal light near the Sun is part of the solar corona. Farther away, it is visible sunlight reflected from dust in the solar system—dust that is in orbit near the common plane of the planets' orbits called the zodiac (the "ecliptic" in Fig. 2.5).

The solar corona photographed during a total eclipse (Yerkes Observatory photographs). **Figure 2.4**



(a) At sunspot minimum. **(b) At sunspot maximum.**

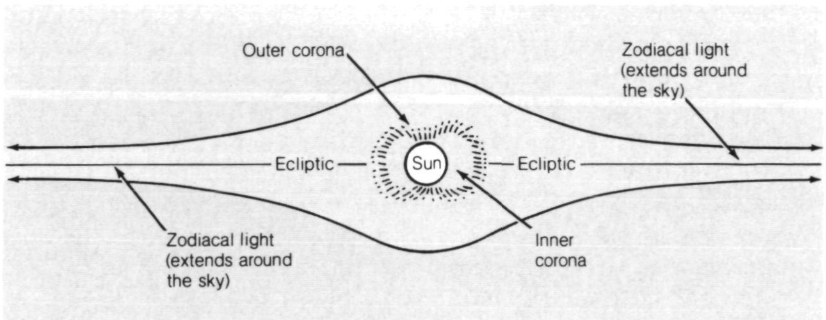


Figure 2.5 **Schematic diagram of the inner corona, the outer corona, and the zodiacal light. (Except for the Sun's photosphere, there are no sharp edges to any of these regions.)**

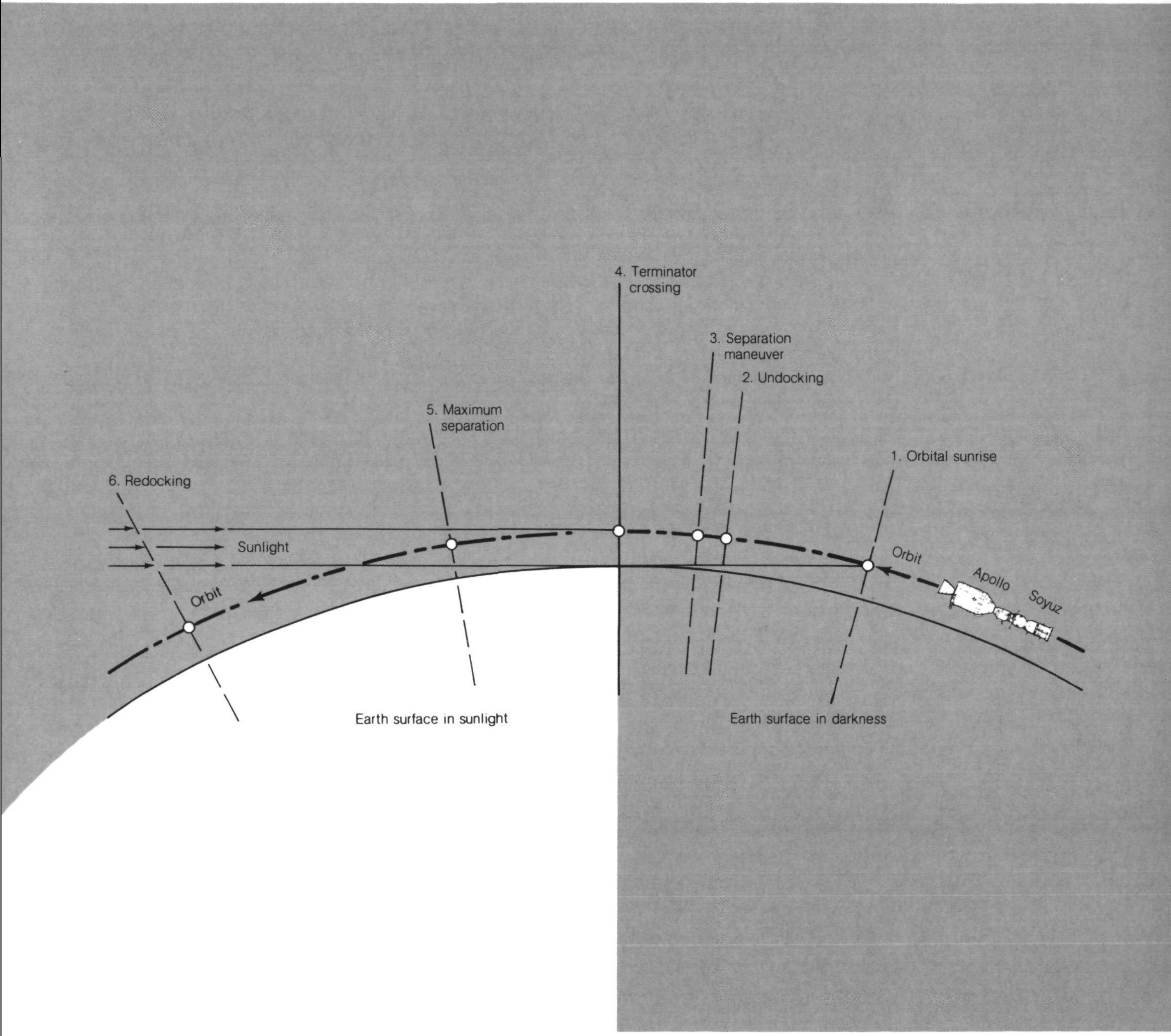
D The Artificial Solar Eclipse, Joint Experiment MA-148

The primary objective of the Artificial Solar Eclipse Experiment was to photograph the outer corona and measure its brightness in white light at wavelengths from 4000 to 7500 angstroms (400 to 750 nanometers). The Apollo spacecraft was used to eclipse the Sun for Soyuz. A secondary objective was to check the gas and particles around Apollo. Such a "contaminating atmosphere," which leaks off every spacecraft, would show up well on photographs of Apollo with the bright Sun (and corona) behind it. Of course, the Apollo atmosphere would interfere with measurements of the corona on the photographs taken from Soyuz—at least of the inner corona, close to the rim of Apollo.

The plan for separating Apollo and Soyuz just after sunrise and keeping Apollo between Soyuz and the Sun for 8 minutes is shown in Figure 2.6. The astronauts could look back at Soyuz and make sure that the round Apollo shadow covered Soyuz. The cosmonauts photographed through a window on the hatch that led into the Docking Module (see Pamphlet I) when the two spacecraft were docked. Before undocking, the astronauts attached a "light baffle" to the outside of that window. This baffle shielded the window from "earthlight" (sunlight reflected from the Earth's surface).

After the docking latches were opened, the Apollo Reaction Control System (RCS, see Pamphlet I) jets were fired for 7 seconds to give Apollo a 1-m/sec velocity away from Soyuz toward the Sun. After coasting for about 3.5 minutes to a distance of 225 meters from Soyuz, Apollo fired the RCS jets in the other direction to stop Apollo's coast and start it returning to Soyuz.

Orbit and separation of Apollo and Soyuz for the Artificial Solar Eclipse, Experiment MA-148. **Figure 2.6**

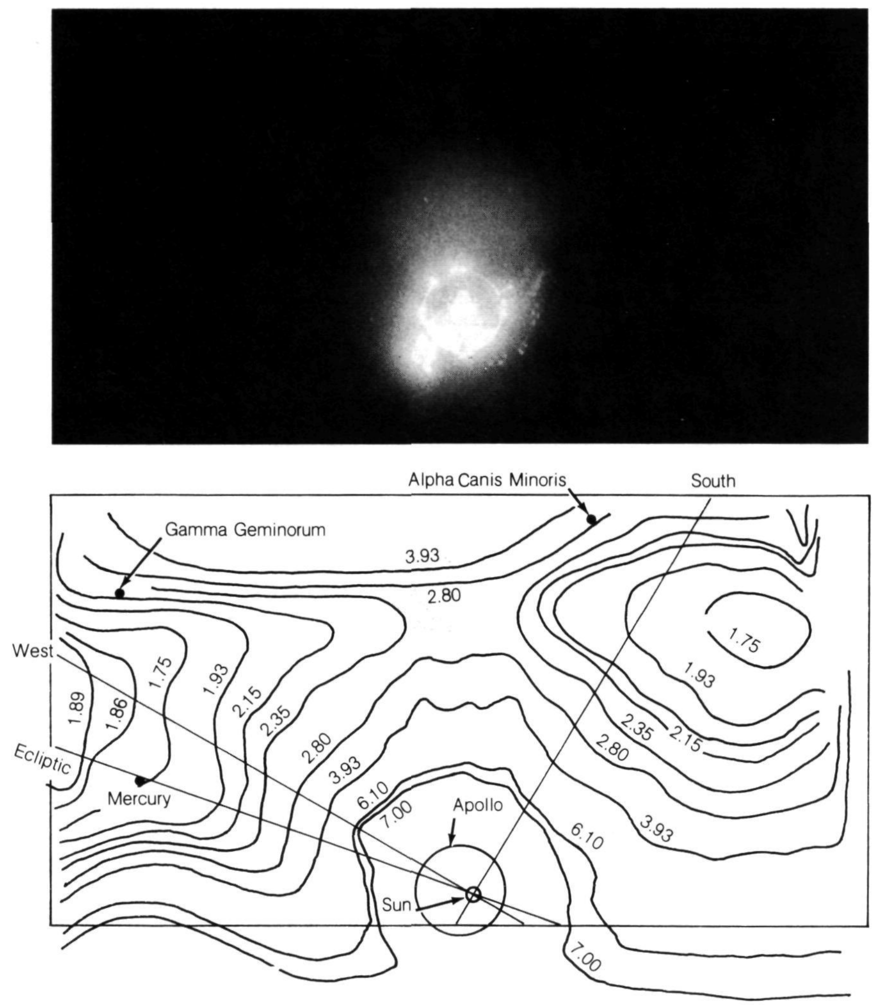


They redocked about 4 minutes later. At maximum separation (225 meters), Apollo looked twice as large as the Sun as viewed from Soyuz. It covered the Sun completely. However, there was a bright rim around Apollo that was caused by diffraction of the strong sunlight at Apollo's edges. Also, during one interval of 142 seconds, earthshine was strongly reflected off the Apollo underside and spoiled 24 of the Soyuz photographs.

The Soyuz camera was automatic. It had an f/2.8 lens with a 90-millimeter focal length and gave photographs 50 millimeters square on special high-speed Kodak film. The camera took a repeated sequence of six exposures from 1/6- to 11-seconds' duration; nine such sequences (54 photographs) were obtained before and after the four sequences spoiled by earthshine. The wide range of exposures was used because no one was sure in advance what exposure time would be best. The outer corona appeared on 19 photographs. The film was calibrated with 12 exposures to light of known brightness in a Moscow laboratory and then developed. The density of the developed film (see Glossary) was measured on the corona photographs and on the laboratory photographs. Then the corona brightness (intensity) was plotted.

The photographs show Apollo with its bright rim, the corona, the planet Mercury, and two bright stars identified as Gamma Geminorum and Alpha Canis Minoris. The positions of the stars relative to the Sun at the time the photographs were taken are known; thus, the Russian scientists could plot the Sun (behind Apollo) on each photograph and relate the measured corona intensity to places on diagrams like the one shown in Figure 2.7. The temperatures of the two stars are known from earlier observations; therefore, the intensity of their images on the Soyuz film was used to calibrate the measured corona intensity (to ± 15 percent).

There were two other problems with the photographs: (1) light from inside the Soyuz cabin was reflected from the window just in front of the camera, and (2) the camera-lens efficiency decreased from the center to the edge of each photograph. The Russian scientists took care of the first problem by measuring the reflected Soyuz cabin light in one of the first photographs taken when the nearby Apollo completely shadowed the window from outside. Then they subtracted this cabin-light intensity from the measured corona intensities. The measured intensities also had to be corrected near the edges of each photograph because of the reduced lens efficiency there.



Corona photograph and contour plot. Each line on the contour plot shows the position of one brightness level. The photograph was a 0.33-second exposure when Soyuz was 55 meters from Apollo.

Figure 2.7

E Results of the Artificial Solar Eclipse Experiment

Eight of the MA-148 photographs were accurately measured. Six of these show the outer corona and two show the effect of firing the Apollo RCS jets. Each of these photographs was scanned with a microdensitometer, a machine that measures film density in each 0.1- by 0.1-millimeter square over the entire 50- by 50-millimeter photograph ($500 \times 500 = 250\,000$ measurements on each photograph). These densities were then converted to intensities by computer.

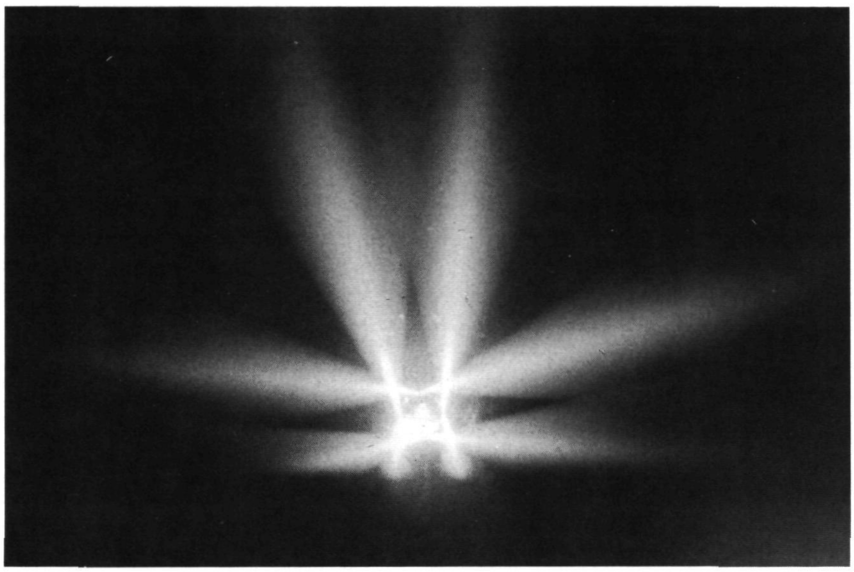
The resulting corona intensities (and the Soyuz cabin light and Apollo foreground contamination) are shown on the photograph and the contour plot in Figure 2.7. Each line on the contour plot runs through measured points of the same intensity on the photograph, and the contour line is labeled with the intensity value in units of 10^{-10} of the Sun's surface intensity in white light. The highest contour (near the circle representing Apollo) is 7 units, and the lowest (at left) is 1.75 units. The image of Mercury (left center), the star Gamma Geminorum (upper left), and the star Alpha Canis Minoris (top) are much brighter. Three straight lines through the Sun's image (off center behind Apollo) show the southerly direction toward upper right, the westerly direction toward upper left, and the ecliptic *e* running through Mercury toward the left. The straight border along the bottom of the contour plot in Figure 2.7 is the edge of the light baffle outside the Soyuz window, and all intensities below it should be zero. The Soyuz cabin light has not yet been subtracted, nor has the correction for lens efficiency been made.

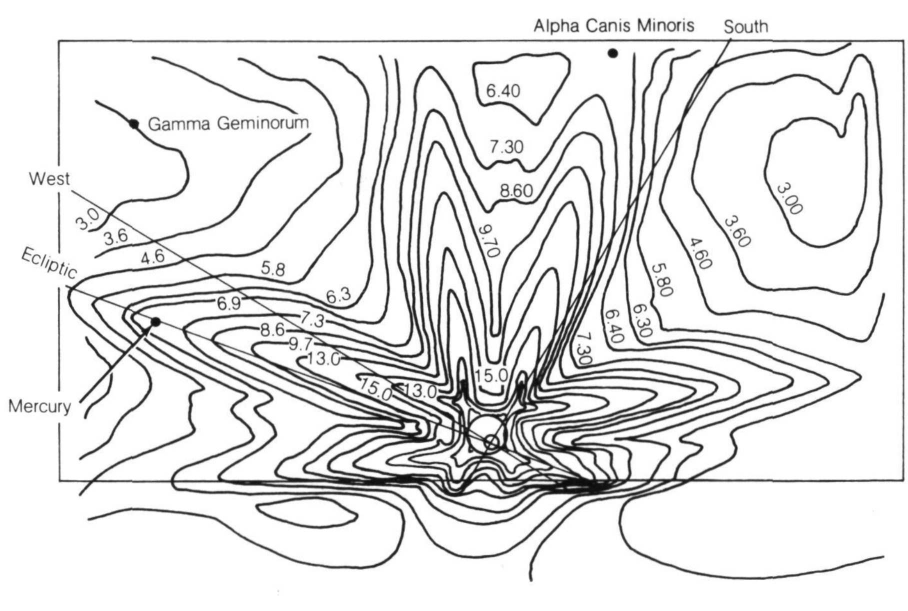
A similar contour plot and a photograph taken when the Apollo RCS jets were firing is shown in Figure 2.8. The propellant gas and particles in the jet exhaust scatter sunlight from four long plumes. The Russian Principal Investigator, G. M. Nikolskiy, notes that his experiment is "an effective way to study contaminants produced by RCS jet engines."

From Figure 2.7 and three others like it (with the RCS jets off), the Russian scientists subtracted the Soyuz cabin light and obtained intensities in the outer corona and zodiacal light from 2° to 12° from the Sun along the ecliptic. Figure 2.9 shows the measured intensities from 2° to 17° (solid line), the Soyuz cabin light (dotted line), and the corrected corona intensities (dashed line). The formula for corona intensity I_C that fits their measurements is

$$\frac{I_C}{I_\odot} = \frac{4 \times 10^{-7}}{(R/R_\odot)^{2.5}}$$

where $R_\odot$ is the radius of the Sun and $I_\odot$ is the surface brightness of the Sun.





Corona photograph and contour plot when the Apollo RCS quad jets were on. The photograph was a 0.33-second exposure when Soyuz was 109 meters from Apollo. **Figure 2.8**

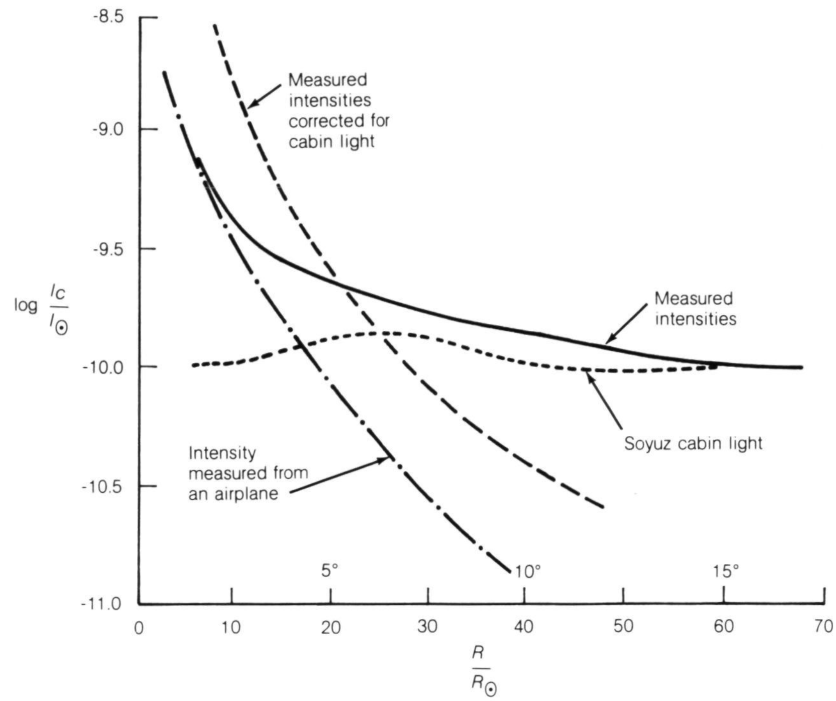


Figure 2.9 **Correction of corona intensities along the ecliptic measured in the MA-148 Experiment.**

The dot-dash line shows measurements that were made from an airplane in 1954. These measurements are three times fainter than the MA-148 results. It seems that the outer corona is much brighter than previously thought, although no explanation has been given by solar physicists.

F Questions for Discussion

(Brightness, Sun's Core, Surface Temperature, Spectra, Corona)

1. The Sun is 10^{10} times brighter than the brightest star in the sky. If stars were other suns with the same power output and size as our Sun, how far from Earth would they be?

2. If 6×10^{11} kilograms of protons are converted to helium nuclei in the Sun's core each second, how long will it be before all the protons in the core are used up? What will happen then?

3. Blue giant stars have surface temperatures as high as 30 000 K. If they are the same size as our Sun, how much more energy are they radiating per second?

4. Just before and just after totality in a solar eclipse, the chromosphere shows briefly at one edge of the Moon. What kind of spectrum does it show?

5. Flares are violent eruptions in the photosphere and chromosphere. They fire charged particles out of the Sun at high velocity. Would you expect a flare to have any effect on the corona above it?

6. During the Skylab missions, x-ray photographs were taken of the Sun from orbit. How large does the Sun look in such x-ray photographs?

7. What was the expected advantage of photographing the corona from Soyuz compared with photographing it from the ground during a total eclipse? What disadvantages were discovered?

8. How would you prevent cabin light from being reflected off the window into the camera, as occurred on Soyuz?

9. What can be learned about the Sun's corona from the corrected measurements of its brightness compared with earlier measurements from an airplane (Fig. 2.9)?

3 Stars and Gas Clouds in the Milky Way

A Stellar Spectra

Astronomers photograph the stars. They also measure stellar *spectra* by spreading a star's light out into its different colors using a prism or diffraction grating. At wavelengths longer than visible red light, there are invisible infrared "heat waves" and radio waves. At wavelengths shorter than visible light, there are ultraviolet rays, x-rays, and gamma rays (see Pamphlet II). Figure 3.1 shows the complete electromagnetic spectrum and the parts that get through the Earth's atmosphere. Note the three scales: wavelength λ in angstroms and meters, frequency f in hertz, and photon energy E in electron-volts. It is useful to remember that $f = c/\lambda$ and $E = hf$ (where c is the velocity of light and h is the Planck constant) and that $E = 12\ 345/\lambda$ in angstroms. (See Pamphlet II.)

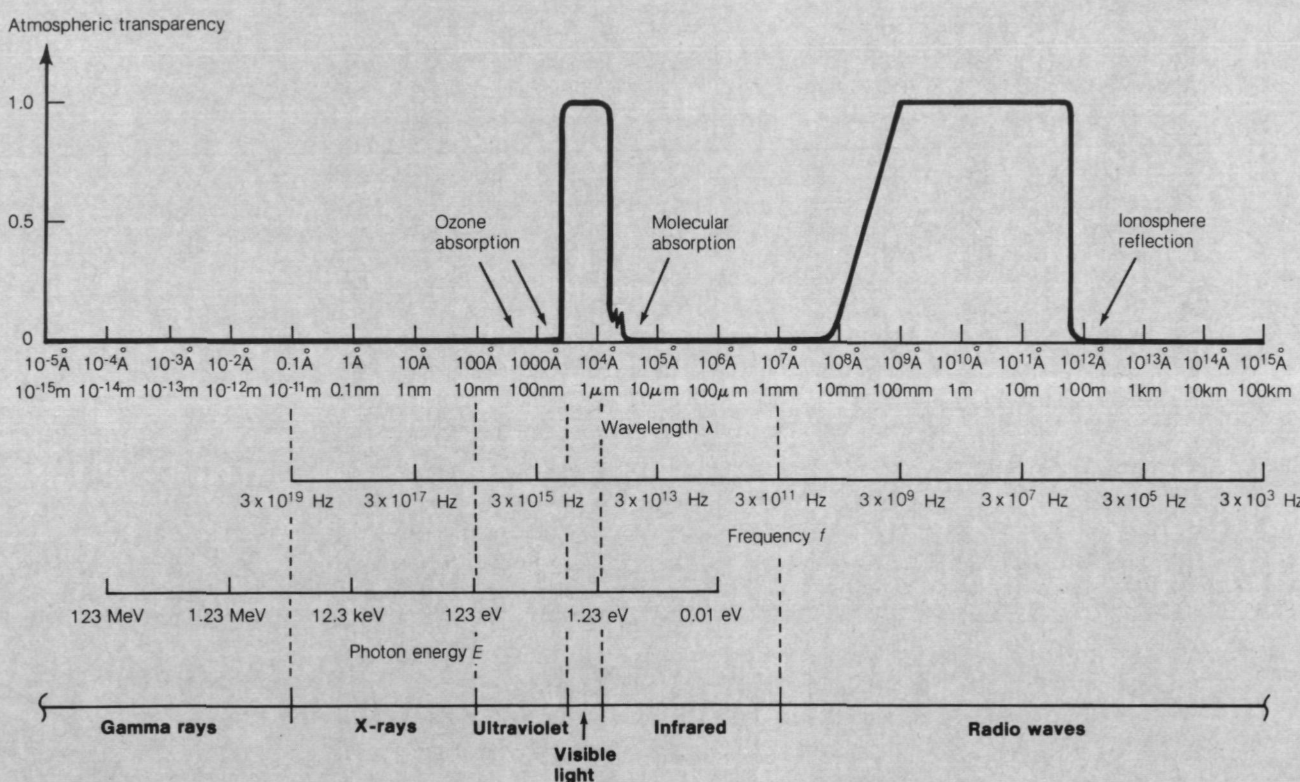
The spectrum of a star tells much about its temperature (Fig. 2.3), its material composition, its motion, and even its size. Until about 1945, astronomers could observe only that part of the spectrum that gets through the atmosphere—visible light and a little more on each side (ultraviolet and infrared). In the 1950's, radio telescopes extended the observed spectrum over most of the region shown in Figure 3.1 where the atmosphere is transparent. Now, in the Space Age, we can observe the entire spectrum with instruments on rockets and spacecraft above the atmosphere. In addition to the general changes of intensity with wavelength I_λ that indicate a star's surface temperature, the spectrum shows *absorption lines*—gaps where a gas has absorbed specific wavelengths. Each atom and each ion has a pattern of such lines; therefore, you can tell what elements are in the atmosphere of a star by measuring the lines in the spectrum. You can also estimate the temperature by noting the elements that are ionized. For example, lines due to ionized helium (He^+) show that the temperature is about 20 000 K.

If the star is receding from Earth at some speed v, the pattern of absorption lines is shifted from the normal wavelength λ to a slightly larger value $\lambda + \Delta\lambda$. The "red shift" is $\Delta\lambda = \lambda v/c$. This "Doppler shift" goes the other way (blue shift) for approaching stars (see Pamphlet IV).

A luminous cloud of gas between the stars is called a nebula. Its spectrum shows emission lines (rather than absorption lines) at the same wavelengths that are characteristic of each atom (usually hydrogen, oxygen, or nitrogen). The emission energy comes from nearby stars whose ultraviolet light is absorbed by the gas atoms, then reemitted.

About 50 years ago, astronomers discovered nonluminous gas between the stars that gives "interstellar absorption lines." These are lines due to calcium ions (Ca^+) and sodium atoms (Na) which have different Doppler shifts from other lines in the same spectrum. Such "different" lines are caused by the gas in interstellar space between us and the star. It soon became clear that

Figure 3.1 The electromagnetic spectrum and what gets through the Earth's atmosphere.



space between the stars is *not* empty. Radio telescopes detected an abundance of hydrogen, and about 30 different molecules have now been detected in interstellar space. The strongest hydrogen absorption line, at a wavelength of 1216 angstroms (121.6 nanometers), is found in the spectrum of every star observed above the Earth's atmosphere. It is due to hydrogen along the line of sight between us and the star.

B The Milky Way Galaxy

The Milky Way is a hazy band stretching all the way around the sky where the stars are much more numerous than in other parts of the sky. This band is our "inside view" of the Milky Way Galaxy. It shows us that the Galaxy is a huge disk filled with stars, gas, and dust (Fig. 3.2). The Sun and the Earth are located about two-thirds of the distance from the center to the edge of the disk. When we look along the plane of this disk, we see the band of stars that we call the Milky Way.

There are more than 100 billion stars in the Milky Way Galaxy and an almost equal mass of interstellar gas and dust. Astronomers have learned this from counting the stars on photographs and by measuring the rotation of the Galaxy. They find that the Sun and other nearby stars are moving at about 250 km/sec in enormous orbits around the center of the Galaxy, which is 30 000 light-years (2.8×10^{17} kilometers) away in the direction of the constellation Sagittarius (see Pamphlet II). (Sagittarius is a group of bright stars that look as though they are close together in space; actually, they are spread out along the arrow in Figure 3.2.) From the size and period of these orbits, one can calculate that the mass of material (stars, gas, and dust) inside the Sun's orbit is about 4×10^{41} kilograms or 2×10^{11} solar masses. (By Newton's Laws, this is the mass needed to pull the Sun around such a large orbit.) This picture is confirmed by other galaxies, much farther away, which also have spiral arms, nebulae, and dust clouds in orbit around a nucleus.

The interstellar gas is not uniform; it is more dense in some places than in others. There are also clouds of dust, which obviously obscure the visible light from more distant stars and nebulae (see Pamphlet II). This has led astronomers to a theory of star formation. Stars are being formed right now in our Milky Way Galaxy and in other galaxies. A cloud of gas and dust gets concentrated by chance in interstellar space. Then gravitational force pulls this cloud together and increases the concentration of matter. As the material falls into the center, the kinetic energy of impacts among the particles heats the material. When the star gets to be about the size of our Sun, the central temperature reaches approximately 10 000 000 K, and nuclear reactions begin.

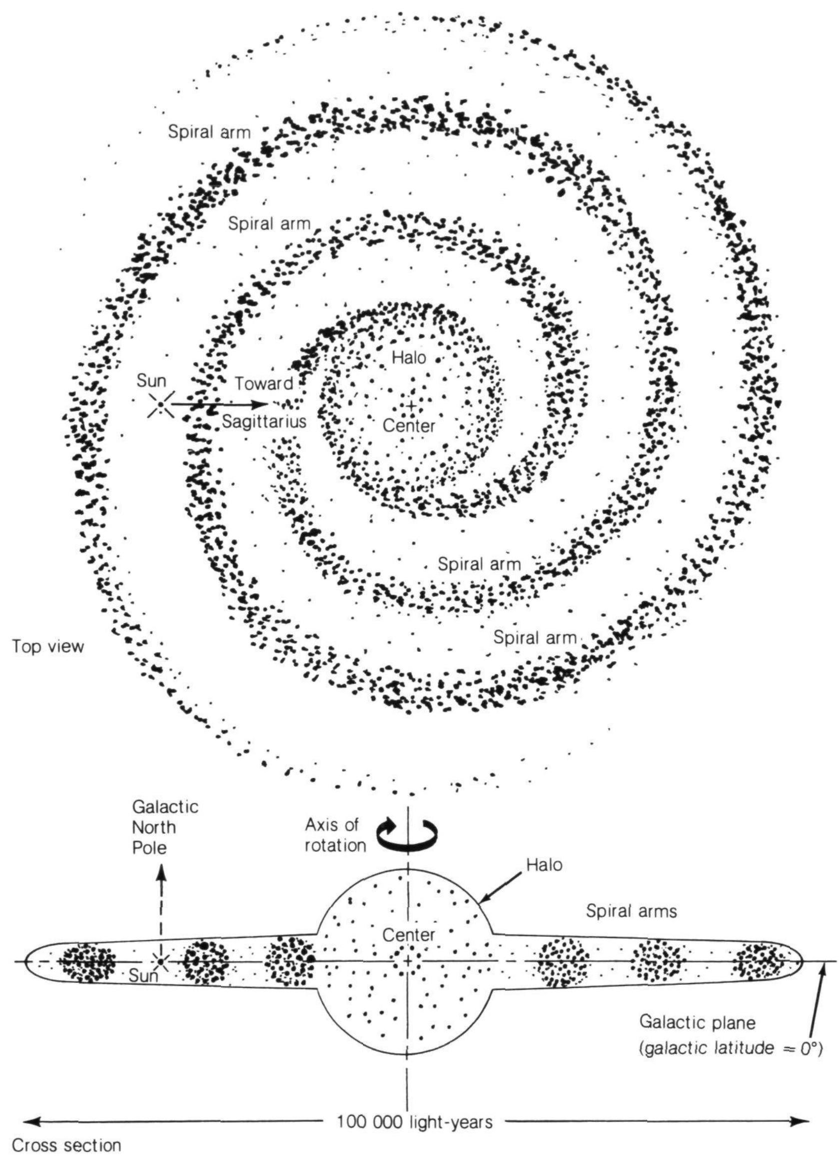


Figure 3.2 **Top view and cross section of the Milky Way Galaxy, a gigantic rotating disk of stars, gas, and dust, about 100 000 light-years in diameter and 5000 light-years thick, with a bulge or halo around the center of mass.**

C Stellar Evolution

The beginning of nuclear reactions in its core is just the first step in the life of a star. After it settles down to "burning" hydrogen (converting protons to helium nuclei), it has a long life without much change. The length of this life depends on the mass of the star. A giant star 10 or 20 times more massive than the Sun "burns" its hydrogen more rapidly and lasts a shorter time—perhaps only 100 million years. A star the size of our Sun should last 10 billion years or more, and a smaller star should last even longer.

As the hydrogen is burned up, the star's core becomes a "dead" mass of helium, and the burning hydrogen is in a shell around this dead mass of helium, which grows ever larger. In a giant star, there is finally a collapse, then a huge "supernova explosion," which blows most of the star's mass out into an expanding nebula called a "supernova remnant" (see Pamphlet II). The core remains as a compact, high-density *Neutron Star*. Before and during the explosion, a new set of nuclear reactions begins, "burning" the helium "ashes" of the earlier hydrogen burning.

If the original star was smaller—more like our Sun in mass—it may go through a pulsating stage of expansion and contraction or explode less violently. A less violent explosion leaves a *White Dwarf* star, which is compact but less dense than a Neutron Star. The White Dwarf is initially hot and cools very slowly for many billions of years. Many White Dwarfs and a few Neutron Stars have been observed by astronomers, and there are probably many more as yet undiscovered because they are so faint. Gravitational force slowly takes over as such stars cool.

How does a star die? The end of a star's life is not fully understood; however, it is theorized that, as a White Dwarf or a Neutron Star cools, gravitational force begins to take over. With no gas pressure to keep them "puffed up," gravitational force squeezes such stars into *Black Holes* with space so curved around them that neither particles nor light can get in or out (see Pamphlet II).

D The Extreme Ultraviolet Survey, Experiment MA-083

By 1974, gamma-ray, x-ray, and far-ultraviolet observations had been made from rockets and spacecraft above the Earth's atmosphere. Some of these are described in Pamphlet II. The extreme ultraviolet (EUV) rays are between x-rays and far-ultraviolet rays at wavelengths from 10 to 1000 angstroms (1 to 100 nanometers) (Fig. 3.1). Astronomers had little hope of detecting EUV

Figure 3.3 **Front view of the EUV telescope after assembly at the University of California at Berkeley (University of California photograph).**

from stars because interstellar hydrogen strongly absorbs all wavelengths from 912 down to about 20 angstroms (91.2 to 2 nanometers). (The abundant hydrogen atom absorbs these wavelengths when it is ionized.) However, there was evidence of gaps in the hydrogen clouds or of very low hydrogen density in some directions where EUV photons might get through to Earth. The EUV measurements would fill in the complete electromagnetic spectrum and might lead to discoveries of some superhot stars.

The need was to build a very sensitive EUV telescope that could detect faint EUV radiation from hot stars that were shrouded by interstellar hydrogen. Stuart Bowyer, the Principal Investigator at the University of California at Berkeley, planned the use of the EUV telescope shown in Figure 3.3. Because EUV photons behave like x-rays, the telescope could not be a lens or a concave mirror as in an optical telescope. Instead, it was a series of four ring mirrors shaped so that a beam of incoming EUV photons would be reflected to a common focus. The aperture (front opening) was 94 centimeters (about 3 feet) in diameter, and the effective area was about 10 square centimeters (because of reflection and filter transmission losses). Each ring was coated with a thin layer of gold to increase the reflection of EUV photons at high angles of incidence.

Figures 3.4 and 3.5 show how the telescope focused EUV photons through a filter onto a channeltron detector using a special semiconductor ceramic as a photocathode. The EUV photons released photoelectrons from the photocathode, and each electron was sucked into the channeltron tube by about 100 volts. The inside surface of the curved channeltron tube was coated with a material that released two or more electrons whenever an electron hit it. Therefore, about 10^8 electrons came out of the positively charged (3000 volt) end for each photoelectron that entered. This short pulse was amplified and counted. After 0.1 second, the number of counts was telemetered to the Mission Control Center (MCC) at the NASA Lyndon B. Johnson Space Center (JSC) in Houston, where it was recorded on magnetic tape together with the time.

The telescope-channeltron combination had a field of view of 2.5° in the sky; that is, it counted EUV photons from all sources in a 2.5° circle. The telescope was mounted in the side of the Apollo Service Module and could be aimed at any selected point in the sky by rolling and turning the spacecraft (see Pamphlet I). The pointing direction was radioed to JSC so that the scientists could tell where the EUV telescope was pointed every second that it was in use.

To get an EUV spectrum, five filters were used. These filters were located on a wheel in front of the detector (Fig. 3.5). Each filter was a thin film of material that let through only a selected band of wavelengths or photons of selected energies, as shown in Table 3.1.

A sixth "opaque" filter was used to check the background count, the false counts due to defects in the detector and electronics. These false counts amounted to 0.6 count/sec, which was later subtracted from the other EUV photon counts recorded at JSC. The astronauts pointed the EUV telescope by rolling and turning Apollo, then they switched the telescope on. The filter wheel automatically placed each filter in front of the detector for 0.6 second, then moved to the next filter. Radio signals to JSC indicated which filter was in place. The EUV telescope was pointed at a star for a few minutes, then pointed 3° off the star for another few minutes to get the sky background. If the star was emitting EUV photons, they were measured by determining the difference between the star and the background, as shown in Figures 3.6 and 3.7.

The sensitivity of each filter-telescope combination was known from preflight laboratory tests. The count rate for a star thus could be converted to the number of EUV photons arriving each second. This calculation was done separately for each filter, so we know the number of 9-electronvolt photons arriving each second, the number of 21-electronvolt photons, 46-electronvolt photons, and so on up through the values listed in Table 3.1. These numbers make up the *EUV spectrum* of each star observed.

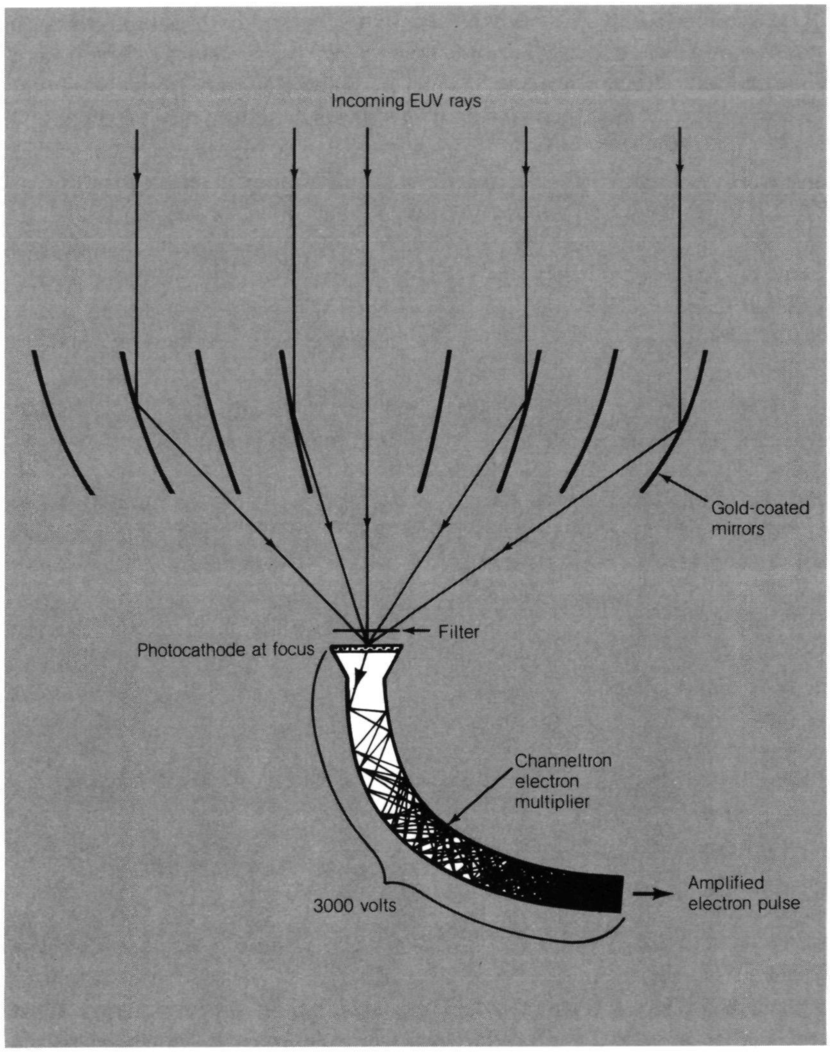


Figure 3.4 **Schematic diagram of EUV telescope focusing by the glancing-incidence mirrors. The channeltron detector is also shown.**

The EUV telescope was pointed at 30 different stars, 8 of them more than once, and at many parts of the sky background for a total operating time of 40 hours. Positive results were obtained on four of the stars, and the EUV background was measured over about one-third of the sky.

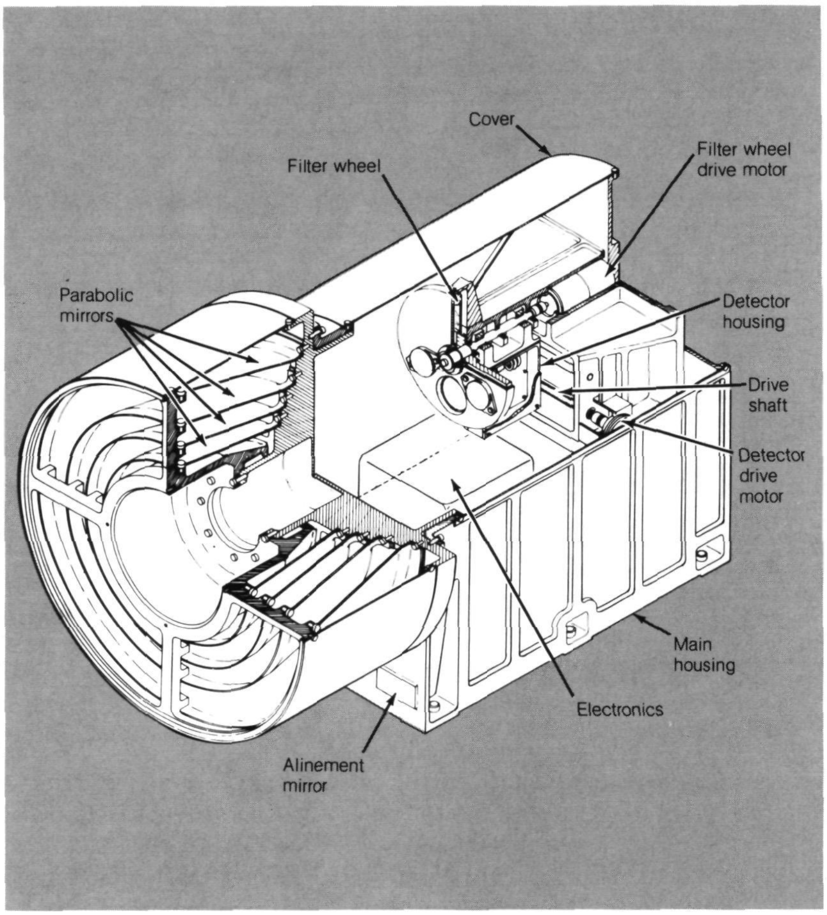


Diagram of the MA-083 EUV telescope. **Figure 3.5**

E Results of the EUV Survey Experiment

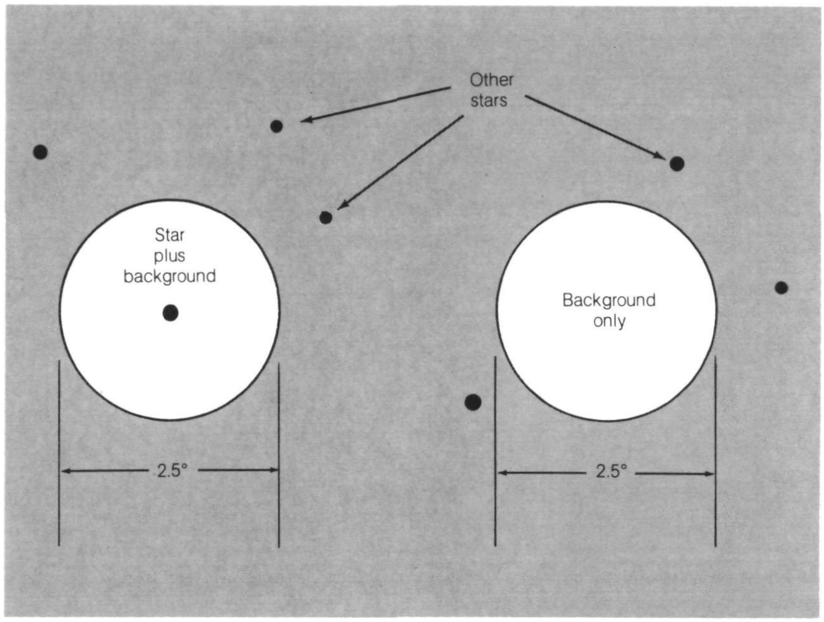
The spectrum of a star in the constellation Coma Berenices called HZ 43 is shown in Figure 3.8. (It is number 43 in a list of White Dwarf stars published by Milton Humason and Fritz Zwicky in 1950.) The peak intensity is at a photon energy of 46 electronvolts or a wavelength λ_m of 270 angstroms (27 nanometers), approximately. Using the color formula in Table 2.1, we can estimate the surface temperature as $T = 28\ 970\ 000/270 = 107\ 000$ K.

Table 3.1 MA-083 EUV Filters

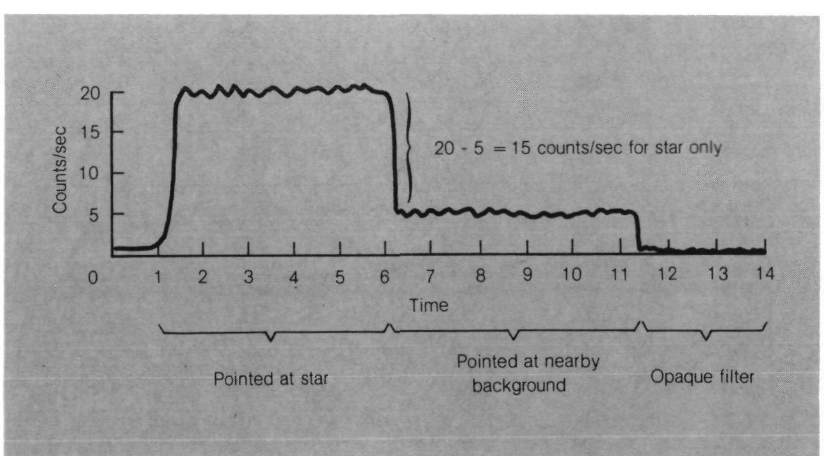
Filter material	*Wavelengths admitted, Å (nm)*	*Average photon energy, eV*
Parylene N	55 to 150 (5.5 to 15.0)	142
Beryllium/Parylene	114 to 150 (11.4 to 15.0)	100
Aluminum plus carbon	170 to 620 (17.0 to 62.0)	46
Tin	500 to 780 (50.0 to 78.0)	21
Barium fluoride	1350 to 1540 (135.0 to 154.0)	9
Opaque	None	0

This is a very high temperature for the photosphere of a star. Other astronomers measured the distance to HZ 43 as 200 light-years and showed that it is a White Dwarf star of about 5000-kilometer radius (1/140th the size of the Sun). The MA-083 Experiment EUV measurements show that it is the hottest White Dwarf known. (Measurements of the visual spectrum from ground-based observatories could not show this because the spectrum of a 100 000 K star is almost the same as the spectrum of a 50 000 K star in the interval from 3000 to 10 000 angstroms (300 to 1000 nanometers) measured from the Earth's surface. See Figs. 2.3 and 3.1.)

Three other stars were detected by the EUV telescope. In each of these four cases, there is, by chance, very little interstellar hydrogen along the line of sight. We happen to see these four stars through gaps in the interstellar hydrogen clouds. In fact, the combination of visual observations, EUV observations, and x-ray observations (Pamphlet II) gives an estimate of the number of hydrogen atoms along the line of sight—approximately 0.02 atom/cm^3 for HZ 43. Another White Dwarf, Feige 24 in the constellation Cetus, was found to be almost as hot as HZ 43; the hydrogen density in its direction is approximately 0.01 atom/cm^3.



EUV telescope pointings for a star observation. The telescope beam is 2.5° in diameter. There may be faint stars in the background of each pointing. **Figure 3.6**



Typical EUV count rates through one filter. **Figure 3.7**

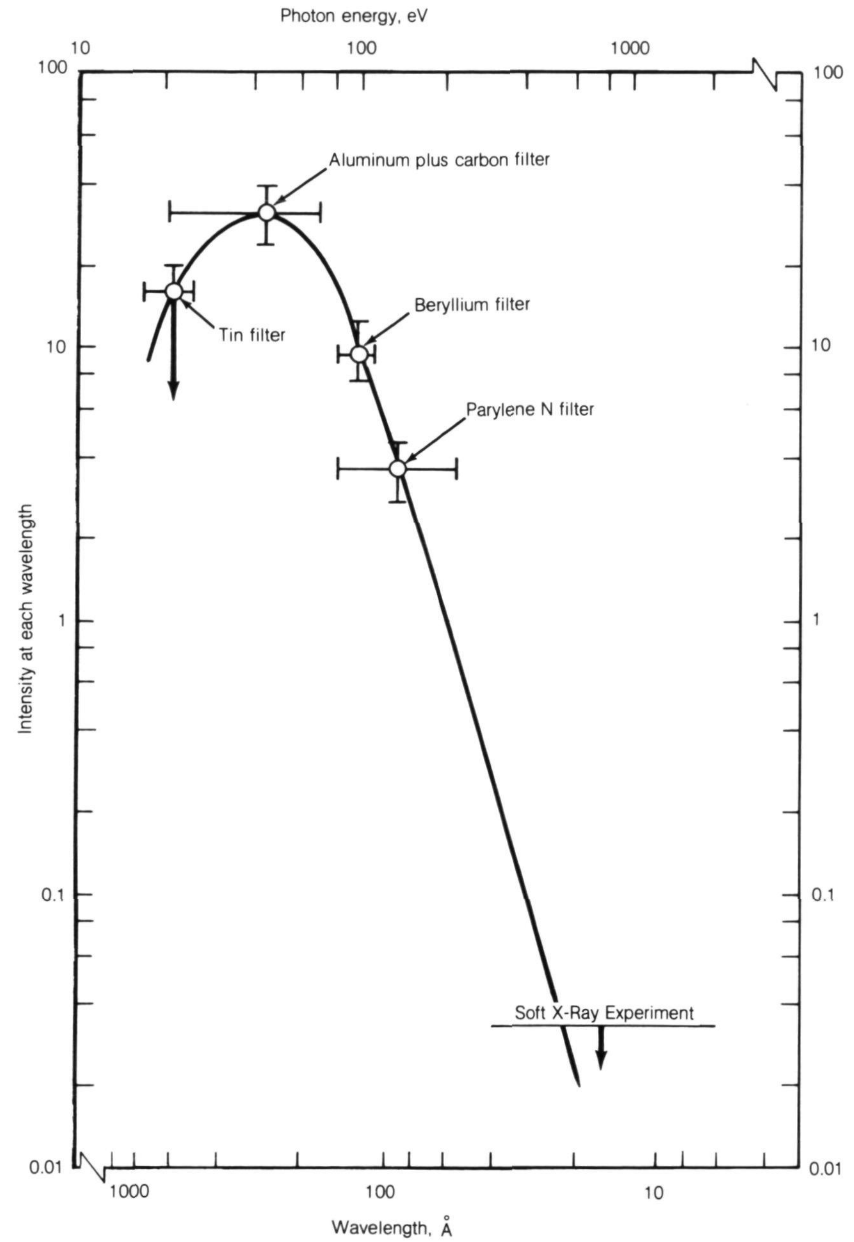


Figure 3.8 **EUV spectrum of HZ 43, a White Dwarf star in the constellation Coma Berenices.**

The third star detected was Proxima Centauri, the closest known star to the Sun, 4 light-years away. Proxima, in the constellation Centaurus, is very faint and cool (3000 K), so it is surprising that it emits 142-electronvolt photons of wavelengths from 55 to 150 angstroms (5.5 to 15 nanometers), the most sensitive EUV filter-detector combination. The star was not detected during a second pointing, which indicates that the EUV photons are emitted by Proxima in bursts or "flares." Visible-light flares from Proxima, lasting less than an hour, had previously been observed by ground-based astronomers. The flares are thought to be due to some kind of explosion, possibly caused by nuclear reactions in a small region of the star's photosphere. Such explosions more than double the star's visual brightness for a short time, and the EUV measurements showed that temperatures in the Proxima flare were about 20 times the star's surface temperature.

Another explosion was observed in a star called SS Cygni. The EUV telescope was pointed at that star in the constellation Cygnus after other astronomers telephoned the MA-083 scientists at JSC to say that SS Cygni had suddenly increased to 40 times its normal brightness on July 17, 1975. (They were monitoring SS Cygni because it is a "recurrent nova," exploding like this at unpredictable times.) Extreme-ultraviolet photons (142 electronvolts) were detected on July 20, but they could barely be detected 15 hours later and could not be detected at all on the third look 22 hours later. When all the visual observations of SS Cygni are collected and analyzed, it may be possible to combine them with the EUV intensities to plot the history of a nova explosion.

The EUV telescope was pointed at 26 other stars. Most of them were White Dwarfs not very far away, and all of them were expected to emit EUV light. None of these stars were detected. From the known sensitivity of the EUV filter-detector combinations, this means that fewer than 50 EUV photons from those stars enter a 1-square-meter aperture each second. This information is useful: it sets limits on the temperatures of the stars and on the hydrogen density along the line of sight.

The EUV sky-background measurements for each of the observed stars also give useful information. These measurements average about 2 counts/sec and are approximately the same over one-third of the sky. No one yet knows where these EUV photons are coming from. They must originate nearby, because interstellar hydrogen absorbs EUV photons so effectively.

F Questions for Discussion

(Spectra, Ionization, Temperature)

10. If you plot the *number of photons* at each energy (or wavelength) instead of the intensity in Figure 2.3, how would the curves be changed?

11. The Sun's spectrum shows many absorption lines of iron (Fe) and the iron ion Fe^+. The Fe atom is ionized to Fe^+ by 7.83 electronvolts; that is, collisions of 7.83-electronvolt energy knock one electron from the Fe atom. The Fe^+ ion has a different set of absorption lines. Explain how Fe and Fe^+ lines look in the spectra of stars cooler than the Sun.

12. In a double star, one star orbits around another—first approaching us, then receding. Suppose that such a pair of stars is on the other side of an interstellar gas cloud. Both stars and the cloud contain sodium. Describe how the sodium absorption lines in the spectrum of one of the stars change during its orbit.

13. Hydrogen atoms are ionized by 13.53 electronvolts. A 13.53-electronvolt photon (wavelength of 912 angstroms, or 91.2 nanometers) separates the electron from the proton in a hydrogen atom. What does a 14-electronvolt photon (wavelength of 880 angstroms, or 88 nanometers) do to a hydrogen atom?

14. If a galaxy (like the Milky Way Galaxy in Figure 3.2) were *not* rotating, what differences would you expect?

15. As hydrogen "burns" to helium in the core of a star, what happens to the density there?

16. Which is probably older, a cool or a hot White Dwarf star?

17. How could the EUV telescope detect separately two stars less than 2.5° apart?

18. If interstellar hydrogen were affecting the EUV spectrum of HZ 43 in Figure 3.8, would the actual temperature of that star be higher or lower than 107 000 K?

19. How do astronomers estimate the radius of a White Dwarf like HZ 43? (Hint: The brightness formula (Table 2.1) gives the energy radiated per square meter of surface area.)

4 How Much Helium in Space?

A The Discovery of Helium; Its Spectrum

The element helium, an inert gas, was discovered in the Sun about 100 years ago. (Its name is derived from Helios, the Greek word for Sun.) The discovery was made from the absorption lines of helium in the Sun's spectrum. These lines did not match the wavelengths of hydrogen, carbon, oxygen, iron, and other elements measured in the laboratory. In 1895, helium gas was identified in natural gas on Earth.

Helium absorbs and emits several lines at visual wavelengths. However, its strongest line, the most sensitive detector of helium, is at 584 angstroms (58.4 nanometers) in the EUV. The helium ion He^{+} has a different set of lines, with the strongest at 304 angstroms (30.4 nanometers), also in the EUV. If you want to detect helium or ionized helium in space, look for these two lines. That is what was done in the Helium-Glow Experiment (MA-088) on the Apollo-Soyuz mission.

B Formation of the Elements

Why is the amount of helium in space important? The answer to this question comes from a theory of how the 92 chemical elements we know were formed during the 15-billion-year history of the universe. One idea is that the universe started as pure hydrogen and that helium (and all the other elements) were formed by nuclear reactions in the cores of stars (Sec. 3C). A more recent theory states that there was 25-percent helium at the beginning, when the "Big Bang" explosion caused all the matter to fly outward and form the galaxies (and later the stars in those galaxies) that we see today. Measuring today's ratio of helium to hydrogen in interstellar space may help to decide which of these two theories about how the universe started is correct.

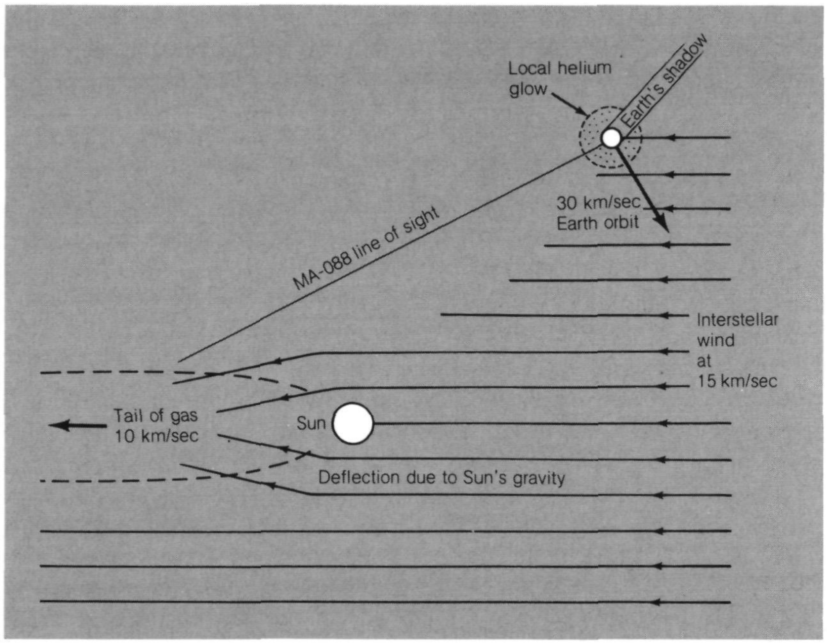
A fraction of the original hydrogen present in the universe condensed into stars. In these stars, just as in the Sun, hydrogen was converted to helium. In the case of larger stars, nuclear reactions led to the formation of elements even heavier than helium, such as carbon, nitrogen, oxygen, and iron. Eventually, the stars blew up in supernova explosions. These explosions released the heavy elements formed in the core to interstellar space as gases. These gases then mixed with the original hydrogen (or hydrogen and helium) to form a second generation of stars. These new stars then continued the manufacture of new elements. There may have been three or four such generations. It is thus of interest to determine the proportion of heavier elements present in the universe and to match these proportions to those predicted by theory.

Astronomers estimate the relative amounts of elements in stars from the strengths of their absorption lines in the spectrum of each star. In every case, hydrogen is most abundant. The Earth lost most of its atmospheric hydrogen during its early stages, but geologists can estimate what fraction of the Earth's mass is oxygen, silicon, magnesium, iron, nickel, and so on. All these observations have been combined into a single table of the abundances of elements, from hydrogen (atomic number 1) to uranium (atomic number 92). However, helium is probably more abundant in the cores of stars than on their surfaces. Thus, the place to get the correct helium/hydrogen abundance of the original universe is in interstellar space.

C Interstellar Gas Moving Through the Solar System

Because the Sun is moving at about 15 km/sec through the interstellar gas, there is an "interstellar wind" blowing into the solar system at 15 km/sec from the forward direction (the direction of the constellation Cygnus). Some of the Sun's light is absorbed and reemitted by this gas in emission lines of wavelengths of 304 angstroms (30.4 nanometers) for helium ions and 584 angstroms (58.4 nanometers) for helium. These wavelengths are changed by the Doppler shift—a blue shift if we look into the wind or a red shift if we look downwind (see Pamphlet IV). The shift is $\Delta\lambda = \lambda v/c$ = 584 (15/300 000) angstroms = 0.03 angstrom (0.003 nanometer) for the 584-angstrom line of helium. The 30-km/sec velocity of the Earth in its orbit around the Sun can change this Doppler shift, but Figure 4.1 shows that the Earth was moving across the line of sight in July 1975, giving no additional Doppler shift. The MA-088 scientists used the 0.03-angstrom red shift to separate *interstellar* helium glow from a *local* glow of helium in the outer part of the Earth's atmosphere which was also stimulated by sunlight. (The local helium glow had been photographed by a far-ultraviolet telescope on the Moon during the Apollo 16 mission in 1972. It extends more than 5000 kilometers above the Earth's surface.)

The expected direction of the interstellar wind, the positions of the Earth, and the Earth's orbital velocity around the Sun on July 20, 1975, when the MA-088 measurements were made are shown in Figure 4.1. Downwind from the Sun, there should be a concentration of the interstellar gas due to the Sun's gravitational attraction as the gas sweeps by. This "tail" was viewed from Apollo-Soyuz through the local Earth glow. The interstellar glow was red-shifted 0.03 angstrom, whereas the local Earth glow had no blue shift or red shift (because Apollo-Soyuz was moving horizontally, neither toward the



MA-088 view of red-shifted helium glow downwind from the Sun. **Figure 4.1**

local helium nor away from it). The MA-088 scientists canceled the local glow by placing in front of the MA-088 detector a 10-centimeter-long tube of helium gas that absorbed all the local helium glow but allowed the red-shifted interstellar helium glow from the Sun's tail to enter.

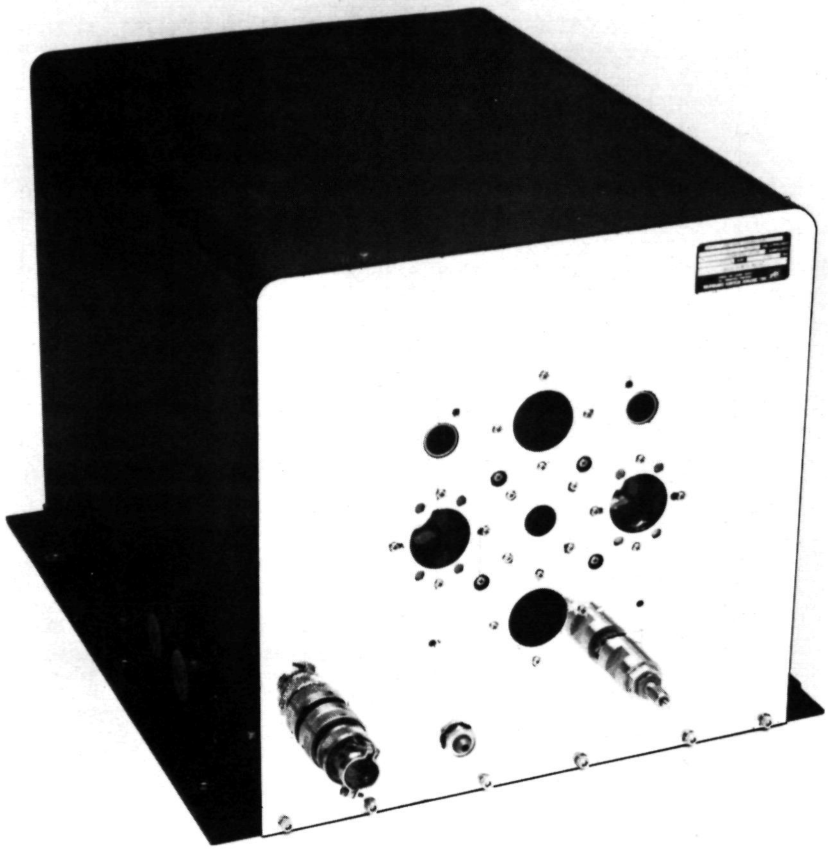
D The MA-088 Helium-Glow Experiment

The helium-glow detector was similar to the one used for the MA-083 EUV telescope. There were four channeltrons with ceramic semiconductor photocathodes. Two of them were located behind helium gas in tubes 10 centimeters long at a pressure of 0.013 N/cm^2 and a temperature of 300 K. The ends of the tubes were sealed with thin (300-nanometer) metal foil (tin and aluminum) which served as filters that were transparent to wavelengths between 530 and 640 angstroms (53 and 64 nanometers). Two other detectors were located behind aluminum-foil filters covered with thin layers of carbon. These filters transmitted 170 to 450 angstroms (17 to 45 nanometers), including the 304-angstrom line of helium ions.

Figure 4.2 shows the MA-088 Experiment detector, a 35-centimeter cube that weighed 23 kilograms. The detector was mounted on the side of the Apollo Service Module (see Pamphlet I) near the EUV telescope and the MA-048 Soft X-Ray Experiment telescope (see Pamphlet II). The four large holes (3.5-centimeter diameter) are openings for the four helium-glow detectors. The hole size, and the shields inside, limited the view of each detector to a 15° circle in the sky. All four detectors were pointed in the same direction. The two detectors without helium cells recorded the 304-angstrom wavelength, both local and interstellar ionized helium glow. The two detectors behind the helium cells recorded only the interstellar 584-angstrom helium glow when the cells were filled with helium. The two cells were alternately filled for 5 seconds and then evacuated for 5 seconds. One cell was full while the other was empty. The automatic filling was monitored by a pressure gage, and records of the pressure and the temperature of the helium gas in both cells were transmitted to JSC. When the cell was empty, the detector recorded both local and interstellar helium glow at the 584-angstrom wavelength. When the cell was full, it recorded only the interstellar helium glow.

The electronics used to read the EUV counts from each detector every 0.1 second are shown in Figure 4.3. The top two detectors without a helium absorption cell are the 304-angstrom helium detectors. The schematic "collimator" limits the view to 15°. The channeltron has 3000 volts from the high-voltage power supply (HVPS) on the output end, and this leads the 100-million-electron pulses to an amplifier and counting circuit. The "counts" accumulated each 0.1 second were compressed in analog form to reduce telemetry to JSC through the NASA Spacecraft Tracking and Data Network (STDN) of radio stations. The lower two detectors "looked out" through helium absorption cells, and the gas filling-evacuating equipment is shown schematically. Otherwise, the counting and telemetry is the same as for the top two detectors.

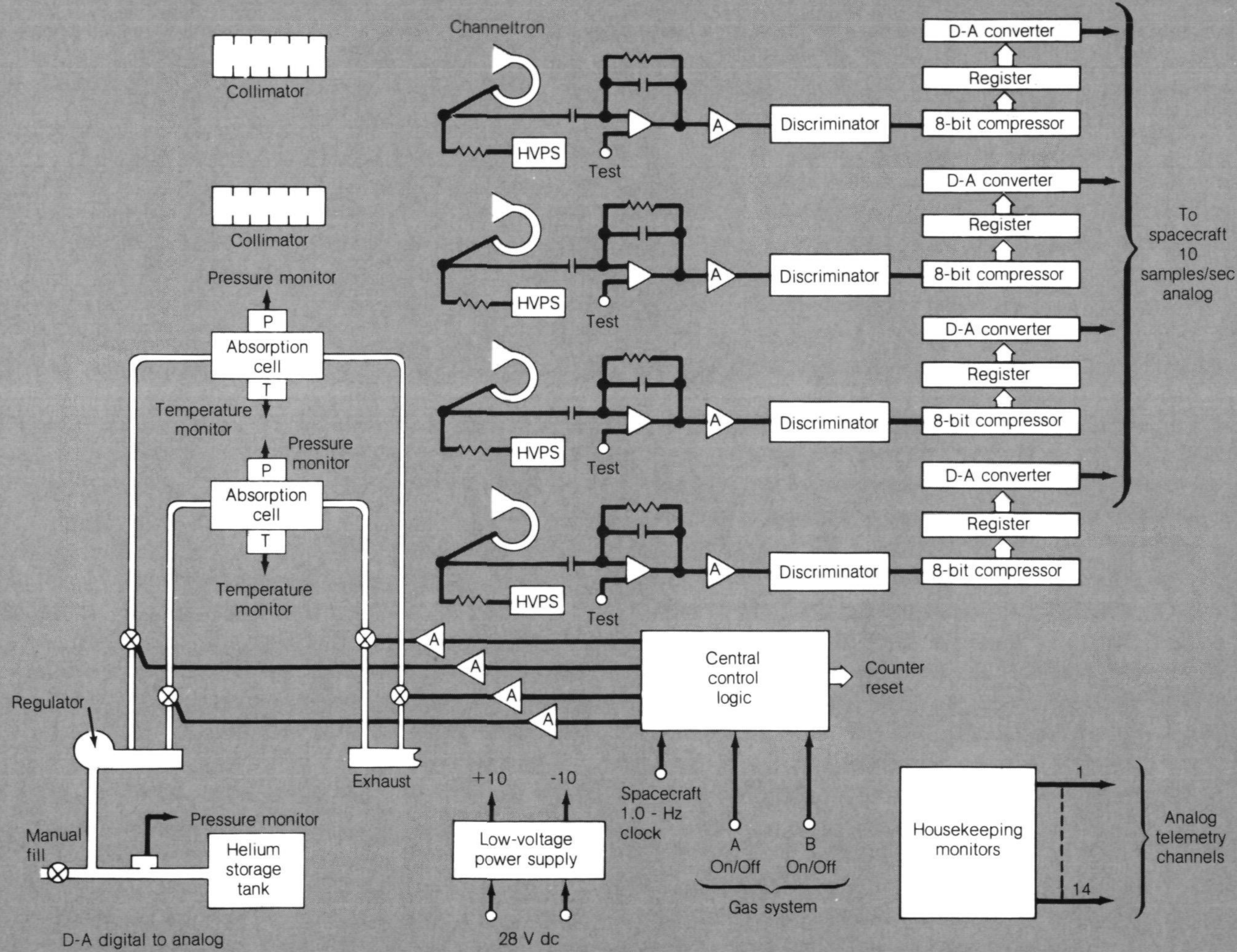
Telemetry received at JSC consisted of the following data for each 0.1 second of time that the MA-088 Experiment was in operation: the number of counts recorded in each of the four detectors, the helium pressure in each of the two absorption cells, the helium temperature in each of the two absorption cells, and "housekeeping" pressures and voltages. All these data had to be correlated with records of the spacecraft attitude; that is, with the direction in which the helium-glow detectors were pointing, second by second. The MA-088 Experiment was on for all the MA-083 EUV Survey (Sec. 3) and



The helium-glow detector. The four large holes are the viewports for the four photometers. **Figure 4.2**

MA-048 Soft X-Ray (Pamphlet II) pointings. Slow rolls of the Apollo spacecraft were made so that the MA-088 helium-glow detectors swept around the entire sky and collected counts from almost all parts of the sky. The "tail of interstellar wind" behind the Sun (Fig. 4.1) was scanned several times. The direction of the Earth's shadow was also scanned because local helium glow is small there.

Figure 4.3 Schematic diagram of the MA-088 electronics system.



E Results of the Helium-Glow Experiment

The MA-088 Experiment was operated on Apollo-Soyuz for a total of 10 hours, which includes most of the time allocated for the MA-048 (Soft X-Ray) and MA-083 (EUV Survey) Experiments. The counts were recorded every 0.1 second; therefore, 360 000 readings were received from each of the four detectors. The readings for each sky position were averaged, and corrections were made for atmospheric absorption with a large computer. The pointing direction was computed for each reading so that intensities could be plotted on a map of the sky. Basically, there are three maps: (1) the sum of local and Doppler-shifted helium 584-angstrom glow, (2) the Doppler-shifted 584-angstrom glow from interstellar helium only, and (3) the sum of local and Doppler-shifted helium 304-angstrom glow. A fourth map was made by subtracting map (2) from map (1) to get the local helium 584-angstrom glow only. This fourth map fits the idea of the "geocorona," a glowing sphere of hydrogen and helium around the Earth, about 100 000 kilometers in diameter and with a "dimple" where the Earth's shadow is (opposite the Sun) (Fig. 4.1). The MA-088 measurements show that the local geocorona glow accounts for about 30 percent of the helium 584-angstrom intensity in the nighttime sky.

Although there are some narrow gaps, MA-088 observations cover the entire sky and show 10 to 50 counts/sec in the 584-angstrom readings. Map (2) of the Doppler-shifted 584-angstrom glow shows "patterns" around the sky that agree roughly with Figure 4.1, although the Sun's tail was not clearly detected. The *temperature* of the interstellar gas should affect these patterns: the higher the temperature, the more fuzzy the patterns should be. There are no sudden changes in the 584-angstrom intensity where the gas is at high temperature, because random thermal motions of helium atoms are added to the interstellar-wind velocity and "fuzz" the expected gas motions and Doppler shifts. By detailed study of the fuzziness, the scientists hope to get the temperature of the gas as well as the amount of helium.

The helium 304-angstrom map (3) shows the glow of the local geocorona well; it also shows the "tunnel" through it along the Earth's shadow (Fig. 4.1). The scientists are studying the sharpness of this tunnel to find out whether it is an actual tunnel or just a dimple. They want to see whether there is any helium 304-angstrom light coming in from outside the geocorona. This is not easy because the tunnel edges are fuzzy; nevertheless, the investigators are continuing their studies of the MA-088 helium-glow measurements.

F Questions for Discussion

(Abundances of Elements, Doppler Shifts)

20. If you go back in time to when the first stars were being formed in our Milky Way Galaxy, would you find any carbon, nitrogen, or oxygen in those stars? If one of the stars had planets, could life have evolved on any of these planets?

21. It is stated in Section 4B that "the Earth lost most of its atmospheric hydrogen during its early stages." What major reservoir of hydrogen do we still have on Earth?

22. How do astronomers know that the Sun is moving at about 15 km/sec through the interstellar gas?

23. The Earth goes around the Sun in 12 months. If Apollo-Soyuz had wanted to get the *maximum* Doppler shift between the local helium glow and the interstellar helium glow, in what month should the MA-088 measurements have been made? (See Fig. 4.1.)

24. The Apollo-Soyuz spacecraft orbited the Earth once every 93 minutes at an altitude of 222 kilometers. The radius of the Earth is 6378 kilometers. What would be the Doppler shift of the 584-angstrom helium line viewed straight ahead or straight back along Apollo's orbit?

25. What angles to the MA-088 line of sight (Fig. 4.1) would you need to know to compute the Doppler shift of the 584-angstrom-wavelength interstellar wind? Of the local helium glow?

Appendix A

Discussion Topics (Answers to Questions)

1. (Sec. 2F) The observed brightness b of a distant light source is proportional to its luminosity (power output) L divided by the square of its distance (L/r^2). If L is the same for the star and the Sun (which is not always the case), $b_{Sun}/b_{star} = r^2_{star}/r^2_{Sun} = 10^{10}$. Therefore, the distance $r_{star} = 10^5\ r_{Sun}$ for the brightest star. Fainter stars are more distant.

2. (Sec. 2F) The core of the Sun contains about 8×10^{29} kilograms of matter. If it was originally all hydrogen and if 6×10^{11} kilograms of hydrogen are converted to helium every second, it would take $8 \times 10^{29}/6 \times 10^{11} = 1.3 \times 10^{18}$ seconds, or 4.2×10^{10} years, to use up all the hydrogen. Before these 42 billion years had passed, the shrinking core would change the Sun's structure. The Sun is estimated to be 5 billion years old now.

3. (Sec. 2F) The brightness formula in Table 2.1 shows that each square meter radiates power proportional to T^4. The Sun has a surface temperature of about 6000 K. A star of the same size (same surface area) at 30 000 K would radiate $(30\,000/6000)^4 = 5^4$ or 625 times as much power as the Sun, most of it in much shorter (ultraviolet) wavelengths. (Actually, hot blue stars are generally much larger than the Sun.)

4. (Sec. 2F) The brief spectrum of the chromosphere just before and just after totality is called the "flash spectrum." It consists almost entirely of emission lines because the chromosphere is a transparent hot gas.

5. (Sec. 2F) The charged particles (ions) from a flare follow the magnetic-field lines as they move away from the Sun. Along this flightpath, the ions collide with other ions and atoms in the corona, and the collisions "excite" these particles to emit light. The flare particles thus make long, bright streamers in the corona. Some streamers can be seen in Figure 2.4.

6. (Sec. 2F) Because the Sun's corona is so hot, it emits x-rays. Therefore, the x-ray photographs show the Sun to be as large as the corona, about three times larger (1.5° across or 4 million kilometers in diameter) than the visible Sun.

7. (Sec. 2F) The advantage was that the sky background from 222 kilometers above the Earth's surface is greatly reduced because there are no clouds or haze. Thus, the faint inner corona is not swamped with other light. The major disadvantage was the contamination around Apollo. Other disadvantages that could have been avoided were the cabin light reflected off the Soyuz window and the inferior lens used in the Soviet camera.

8. (Sec. 2F) A cone of black paper or cloth that fitted tightly against the window could have been used to prevent cabin light from reflecting off the window and into the camera.

9. (Sec. 2F) There is probably more material in the outer corona than previously thought. This material may be dust or very low density gas.

10. (Sec. 3F) Photon energy $E = hf = hc/\lambda$ is larger for short-wavelength photons than for long-wavelength photons. The curves in Figure 2.3 thus would be lower at the left (short λ) and higher at the right (long λ). Actually, the *interval* $\Delta E = (hc/\lambda^2)\,\Delta\lambda$ affects this answer. The intensity I_λ is the energy arriving each second in waves of length λ to $\lambda + \Delta\lambda$. The photon count N_E is the number of photons arriving each second with energies between E and $E + \Delta E$.

11. (Sec. 3F) The Fe lines would be stronger and the Fe^+ lines weaker than in the Sun's spectrum. At lower temperature, there are fewer collisions of energy greater than 7.83 electronvolts because the energy of particle motion $E = \frac{1}{2} mv^2 = kT$, where k is the Boltzmann constant (see Table 2.1).

12. (Sec. 3F) Sodium in the interstellar gas cloud absorbs light at 5890 angstroms (589 nanometers) plus a constant Doppler shift $\Delta\lambda = 5890\, v_i/c$, where v_i is the gas-cloud recession (or approach) velocity and c is the velocity of light. As the star approaches us, its sodium line would have a blue shift: $\Delta\lambda = -5890\, v_s/c$, where v_s is the star's orbital velocity. When the star stops approaching, $\Delta\lambda = 0$; when it is receding, $\Delta\lambda = 5890\, v_s/c$. The star's absorption line thus shifts back and forth, while the line of the interstellar gas cloud remains at a fixed wavelength.

13. (Sec. 3F) When a hydrogen atom absorbs 880 angstroms, which represents a photon of higher energy than needed to ionize it, the electron is shot off with kinetic energy equal to the excess: $14.0 - 13.5 = 0.5$ electronvolt.

14. (Sec. 3F) A nonrotating galaxy should be spherical with no spiral arms. Stars would be orbiting in all different directions around the center of mass, and interstellar gas would fall into that center. Such galaxies are observed far from us and are called EO galaxies.

15. (Sec. 3F) After the core temperature settles down in equilibrium with radiation, the density rises because alpha particles (He^{++}) are about four times the mass of protons (H^+), and the same number are packed into a cubic centimeter.

16. (Sec. 3F) The cool White Dwarf is probably older. White Dwarfs all start at about the same temperature and cool very slowly.

17. (Sec. 3F) By sweeping across the two stars slowly, the EUV telescope (MA-083) would first count photons from the first star, then from the two together, and then from the second star alone. From the times when the count rate increased and decreased, one could tell approximately when the edge of the EUV telescope field of view crossed each star.

18. (Sec. 3F) The interstellar hydrogen would be absorbing more of the HZ 43 intensity on the left side of Figure 3.8 (longer wavelengths) than on the right side (shorter wavelengths). Therefore, the unaffected spectrum would peak farther to the left (longer wavelength) and the temperature $T = 28\ 900\ 000/\lambda_m$ would be *lower*.

19. (Sec. 3F) The size of HZ 43 can be estimated from the brightness formula in Table 2.1; that is, $E_t = \sigma T^4$ joules per second radiated at all wavelengths from 1 square meter of its surface. If the distance r to HZ 43 can be estimated, the measured intensity I (energy received in all wavelengths arriving on 1 square meter) can be multiplied by $4\pi r^2$ to get the total energy radiated. This is the area of the star's surface times E_t. So, $4\pi r^2 I = 4\pi R^2 \sigma T^4$ and $R = \sqrt{I/\sigma}\ (r/T^2)$, where R is the star's radius.

20. (Sec. 4F) The first stars in the Milky Way Galaxy are thought to have formed from pure hydrogen or from hydrogen with a low percentage of helium. There were no heavier elements such as carbon, nitrogen, and oxygen. Without heavier elements, solid planets probably couldn't form, and without carbon, nitrogen, and oxygen, no living organisms could have evolved.

21. (Sec. 4F) Water is the largest reservoir of hydrogen on Earth. There is a small amount of hydrogen gas high in the atmosphere and more in oil and hydrocarbon gas deposits underground. Another large reservoir is water that is chemically locked in the rocks deep under the Earth's surface.

22. (Sec. 4F) The spectra of many stars, all around the sky, show the absorption lines of the interstellar gas, primarily ionized calcium (Ca^+) and sodium (Na). Doppler shifts show an average blue shift in one half of the sky and an average red shift in the other half. Averages for various directions in these halves of the sky and for nearby stars only show the maximum

Doppler shifts from local interstellar wind coming from the direction of the constellation Cygnus (right ascension 21^h, declination +40°; see Pamphlet II).

23. (Sec. 4F) When the Earth's orbital velocity is almost directly into the interstellar wind, the relative velocity of wind past the Earth is highest. In Figure 4.1, the Earth's orbital velocity (a vector) is about 60° below the upwind direction (toward the right). Because that vector turns 360° in 12 months, or 30° per month, it would have been as nearly upwind as possible two months earlier; that is, in May 1975. (Note: The vectors are not in one plane.)

24. (Sec. 4F) The distance around the Apollo-Soyuz orbit is $2\pi r$, where $r = 6378 + 222 = 6600$ kilometers. Thus, the spacecraft's orbital speed $v = 2\pi r/T = 2\pi(6600)/93(60) = 41\ 470$ kilometers/5580 seconds = 7.43 km/sec relative to Earth. Viewed straight ahead, the 584-angstrom line from the local helium glow (fixed relative to Earth) would be blue shifted by $584(v/c) = 584(7.43/300\ 000) = 0.014$ angstrom. Straight back, it would be red shifted by the same amount.

25. (Sec. 4F) The Doppler shift is proportional to the component of the relative vector velocity along the line of sight. The Earth has one small component of its 30-km/sec orbital velocity, and the interstellar wind in the "solar tail" has another large component. In each case, the component along the line of sight is $v \cos \theta$, where θ is the angle between the vector $\mathbf{v}$ and the line of sight. So θ_1 and θ_2 are needed, where θ_1 is the angle between the Earth's orbital velocity and the line of sight and θ_2 is the angle between the solar-tail velocity and the line of sight. The orbital velocity v_S of the Apollo-Soyuz spacecraft around the Earth adds a third, very small, component $v_S \cos \theta_3$, where θ_3 is the angle between v_S and the line of sight.

The local helium glow is at rest relative to the Earth. The component of v_S along the line of sight $v_S \cos \theta_3$ is also needed to get the Doppler shift of the local helium glow.

Appendix B

SI Units
Powers of 10

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	

Appendix C

Glossary

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

absorption line a gap or dip in a spectrum, caused by the absorption of specific wavelengths by a gas between the light source and the observer. (Secs. 2B, *3A*, 3F, 4A, 4B; App. A, nos. 11, 12, 22) See Project Physics, Sec. 19.1.

angstrom (Å) a unit of wavelength used by physicists for more than 80 years; 1 angstrom $= 10^{-10}$ meter or 0.1 nanometer. (Sec. 3A)

Apollo spacecraft a three-man spacecraft originally designed for trips to the Moon. It consisted of a Command Module (CM) attached to a Service Module (SM). For the Apollo-Soyuz mission, a Docking Module (DM) was attached to the CM.

background a uniform intensity over a large region of the sky. (Secs. 3D, 3E; App. A, no. 7; Figs. 3.6, 3.7) "Instrumental background" (Sec. 3D) is the count rate due to instrument defects when no photons are entering the detector.

"Big-Bang" cosmology the theory of the origin of the universe which states that the universe was created about 15 billion years ago when a giant explosion emitted high-frequency radiation and pushed matter apart. That matter is now condensed into stars in galaxies which are receding from the Earth. The more distant ones are receding faster because they started faster in the Big Bang. (Sec. 4B)

channeltron a curved vacuum tube that gives a 100-million-electron output pulse for each electron input. (Secs. 3D, 4D; Figs. 3.4, 4.3)

constellation a group of stars, such as the Big Dipper, that defines an area (generally 10° or 20° across) in the sky. Most of the constellations were named by the Greeks (Gemini, Cygnus, Sagittarius). (Secs. 3B, 3E, 4C; App. A, no. 22)

corona (solar) a vast, low-density cloud of gases surrounding the Sun. Its temperature increases outward to more than 1 000 000 K. (Secs. 2, *2C*, 2D, 2E; App. A, nos. 5 to 7, 9; Figs. *2.1*, 2.4, 2.5, 2.7, 2.9)

count one pulse of current or voltage from a detector, indicating the passage of a photon or cosmic ray through the detector. (Secs. 3D, 4D, 4E; App. A, no. 17)

count rate the number of counts per second; it measures the intensity of the source. (Secs. *3D*, 3E, 4E; App. A, nos. 10, 17; Fig. 3.7)

density (photographic) the blackening of an exposed, developed photographic film negative, measured (with a densitometer) as the fraction of a light beam absorbed by the darkened film. (Secs. 2D, 2E) The positive print from a negative reverses black to white. Density also means mass per unit volume of a material. (Secs. 2C, 3E; App. A, no. 15)

diffraction the bending of waves (including light waves) around an obstacle. (Sec. 2D)

Doppler shift the change of frequency and wavelength in the spectrum of a source approaching an observer (blue shift) or receding from him (red shift). (Secs. *3A,* 4C, 4E; App. A, nos. 12, 22, 24, 25; Fig. 4.1) See Pamphlet IV.

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. (Secs. 2, 2C to 2F; Figs. 2.4, 2.6)

ecliptic the line in the sky along which the Sun appears to move eastward 360° in a year. This line represents the plane of the Earth's orbit. The other planets, whose orbital planes are near that of the Earth, are always seen near the ecliptic in the sky. (Secs. 2C, 2E; Fig. 2.5)

electromagnetic waves include x-rays, light waves, and radio waves, which carry energy at a velocity c of 3×10^8 m/sec. The *electromagnetic spectrum* is the sequence of wavelengths from very short gamma rays to very long radio waves. (Sec. 3D; Fig. *3.1*)

electronvolt (eV) a unit of photon energy equal to the kinetic energy of an electron accelerated from rest by 1 volt: 1000 electronvolts = 1 kiloelectronvolt; 1000 kiloelectronvolts = 1 megaelectronvolt.

emission line a small band of wavelengths emitted by a low-density gas when it glows. The pattern of several emission lines is characteristic of the gas and is the same as the absorption lines absorbed by that gas from light passing through it. (Secs. 2C, 3A, 4A, 4C; App. A, no. 4)

energy the capacity for doing work. (Sec. 2C) Nuclear energy is released by nuclear reactions. (Sec. 2A) Kinetic energy is the energy of motion of a mass. (Sec. 3B; App. A, nos. 11, 13) Energy is also radiated in the form of photons moving at velocity c. (Secs. 2A, 2B, 3A, 3E; App. A, nos. 10, 13, 19; Figs. 2.3, 3.8; Tables 2.1, 3.1) Each photon has energy $E = hf = hc/\lambda$, where h is the Planck constant, f is the frequency, c is the velocity, and λ is the wavelength of light or x-rays. The energy arriving per second from a distant light source on a unit area is the *intensity I*.

equilibrium a state of balance, when no change takes place. Inside the Sun, radiation and temperature are in equilibrium because the energy entering a small volume of gas is equal to the energy leaving, and the temperature remains constant. (App. A, no. 15)

extreme ultraviolet (EUV) wavelengths between 100 and 1000 angstroms (10 and 100 nanometers); the short-wave end of the ultraviolet part of the electromagnetic spectrum shown in Figure 3.1. (Secs. 1, *3D,* 3E, 4A, 4C, 4D; App. A, no. 17; Figs. 3.3 to 3.7, *3.8;* Table 3.1)

filter a thin slab of selective material in front of a detector. The filter lets through only a selected color or group of wavelengths or group of photon energies. (Secs. 3D, 3E, 4D; Figs. 3.4, 3.5, 3.7, 3.8; Table 3.1)

gravitation the force of attraction between two masses, given by Newton's Law. (Secs. 2A, 3B, 3C, 4C; Fig. 4.1) See Project Physics, Secs. 8.6 to 8.8; PSSC, Secs. 13-8, 13-10.

intensity *(I)* the energy from a distant source arriving per second on a unit area. I_λ refers to energy of specific *wavelengths* (λ to $\lambda + \Delta\lambda$). A plot of I_λ versus λ shows the *spectrum*. (Secs. 2B, 2D, 2E, 3A, 3E, 4E; App. A, nos. 10, 18, 19; Figs. 2.3, 2.7 to 2.9, 3.8; Table *2.1*)

interstellar gas and dust material in the space between stars. Low-density hydrogen and other gases are detected from their absorption and emission of specific wavelengths of light and radio waves. Fine dust particles scatter light like smog does. (Secs. 1, *3A, 3B,* 3D, 3E, 4B to 4E; App. A, nos. *12,* 14, 18, *22;* Fig. 4.1)

ion an atom with one or more electrons removed or, more rarely, added. (Atoms are ionized by heat or light, x-rays and gamma rays, and cosmic rays or other moving particles.) (Secs. 3A, 3D, 3F, 4A, 4D; App. A, nos. 5, 11, 13, 22)

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

kelvin (K) a temperature scale starting at absolute zero (no heat motion). 273 K = 0° C = 32° F, the freezing point of water; 373 K = 100° C = 212° F, the boiling point of water on Earth.

light-year the distance light travels (at 3×10^8 m/sec) in 1 year (3.15×10^7 seconds). One light-year equals 9.46×10^{12} kilometers, about 63 000 times the distance from Sun to Earth.

MA-048 the Soft X-Ray Experiment on the Apollo-Soyuz mission. (Sec. 4D) See Pamphlet II.

MA-083 the EUV Survey Experiment. (Secs. 1, *3D,* 3E, 4D; App. A, no. 17; Figs. 3.3, 3.4, *3.5;* Table 3.1)

MA-088 the Helium-Glow Experiment. (Secs. 1, 4A, 4C, *4D,* 4E; Figs. *4.1,* 4.2, 4.3)

MA-148 the Artificial Solar Eclipse Joint Experiment. (Secs. 1, *2D,* 2E; Fig. 2.6)

magnetic field the strength of the magnetic force on a unit magnetic pole in a region of space affected by other magnets or electric currents. (Secs. 2B, 2C; App. A, no. 5)

Milky Way a band of stars, visible only on a clear, dark night, stretching completely around the sky. (Sec. 3B) Using the distances of the stars, astronomers can plot the Milky Way Galaxy, a disk-shaped group of more than 100 billion stars, including our Sun. (Sec. 3B; App. A, no. 20; Fig.

3.2) There are other galaxies outside the Milky Way Galaxy. (Secs. 3B, 4B; App. A, no. 14)

nebula a glowing cloud of low-density gas near one or more stars. (Secs. *3A*, 3B, 3C)

neutron an atomic particle with a mass slightly larger than that of a proton (hydrogen ion) but no charge. A *Neutron Star* is made almost entirely of neutrons; see *stars*. (Sec. 3C)

Newton's Laws the three laws of motion and the law of gravitation, published in 1687 ($F = ma$, $F_g = GmM/r^2$); see *gravitation*. (Secs. 2A, 3B) See Pamphlet I.

nova an exploding star. (Secs. *3C*, 3E) A *supernova* is the much larger explosion of a giant star after its hydrogen is mostly converted to helium (Secs. 3C, 4B). A large fraction of the mass is blown outward to form a nebula (supernova remnant). (Sec. 3C)

nuclear reaction changes in the nucleus of an atom when a proton or neutron is fired into it, or when an electron, proton, neutron, or He^{++} ion is fired out. (Secs. *2A*, 2B, 3B, 3C, 3E, 4B; App. A, no. 2; Fig. 2.1)

photon a quantum of light—the smallest separable amount of energy in a beam of light. Photon energy is proportional to frequency. High-energy photons are counted individually by detectors; see *energy, count*. (Secs. 2B, 3A, 3D, 3E; App. A, nos. 10, 13; Fig. 3.8; Table 3.1)

photosphere the visible edge of the Sun, radius 695 000 kilometers. (Secs. *2*, 2B, 2F; Fig. 2.1) Other stars have a similar surface. (Sec. 3E)

Planck Law the formula for intensity I_λ radiated in various wavelengths λ by an opaque surface at temperature T. This formula includes the *Planck constant h* (Sec. 3A), which relates frequency f with photon energy E. (Secs. *2B*, 3A; Fig. 2.3; Table 2.1)

power output the energy radiated per second from the Sun, a star, or other source. The brightness that we see is the power output divided by the square of the source distance, minus the absorption by interstellar smog. (Sec. *2A;* App. A, nos. 1, 3; Fig. *2.2*)

Principal Investigator the individual responsible for a space experiment and for reporting the results.

proton a positively charged particle, the nucleus of the hydrogen atom. Ionized hydrogen is made up of separated protons and electrons. (Secs. 2A, 3C; App. A, no. 15)

radio telescope a large dish that focuses radio waves from a distant source onto a sensitive radio receiver. (Sec. 3A)

RCS quad jets small jets used to roll or rotate the Apollo spacecraft. (Secs. 2D, 2E; Fig. 2.8) See Pamphlet I.

Service Module (SM) the large part of the Apollo spacecraft that contains support equipment; it is attached to the Command Module (CM) until just before the CM reenters the Earth's atmosphere.

Soyuz the Soviet two-man spacecraft. See Pamphlet I.

spectrum the sequence of electromagnetic waves from small wavelengths (gamma rays) to large (radio waves). Visual spectra run from 4000 to 7000 angstroms (400 to 700 nanometers), EUV spectra from 100 to 1000 angstroms (10 to 100 nanometers). See *electromagnetic waves, EUV*. (Secs. 2B, *3A*, 3D, 3E, 4A, 4B; App. A, nos. 4, 11, 18, 22; Figs. *3.1*, 3.8)

star a very hot ball of gas with an energy source near the center. (Secs. 2A, 2B, 2D to 2F, *3A*, 3B, *3C*, 3D, 3E, 4B; App. A, nos. 1, 3, 14, 16, 17, 19, 20, 22; Figs. 3.6, 3.7) Normal stars are like the Sun, about 10^6 kilometers in diameter. Blue stars (Secs. 2B, 2F; App. A, no. 3; Fig. 2.3) are much hotter than the Sun. Giant stars (Secs. 2F, 3C) are 200 times larger and White Dwarfs (Secs. *3C, 3E;* App. A, no. 16; Fig. 3.8) are 100 times smaller than the Sun. Neutron Stars and Black Holes (Sec. 3C) are even smaller. Many stars are double (Sec. 3F; App. A, no. 12)—that is, two stars orbiting around each other.

sunspots dark regions on the Sun's photosphere, some as large as 50 000 kilometers across. They often appear in pairs and groups, always in a belt about 30° on either side of the Sun's equator. There is a maximum number every 11 years. (Sec. 2C; Fig. 2.4)

temperature ***(T)*** a measure of the average kinetic energy of particles (atoms or molecules) in a gas. See *kelvin*. (Secs. 2A, *2B*, 2C, 3A, 3B, 3E, 4E; App. A, nos. 11, 15, 18; Figs. 2.1, 2.3; Table 2.1)

ultraviolet (UV) invisible light of wavelengths less than 4000 angstroms (400 nanometers), shorter than those of visible light. See *EUV*. (Secs. 3A, 3D; App. A, no. 3; Fig. *3.1)*

wavelength (λ) the distance from the crest of one wave to the crest of the next, usually measured in angstroms. EUV wavelengths are from 100 to 1000 angstroms (10 to 100 nanometers). (Secs. 2B, *3A*, 3E, 4A; App. A, nos. 10, 12, 18, 19; Figs. 2.3, *3.1*, 3.8; Tables 2.1, 3.1)

White Dwarf a compact star of high density, about the size of the Earth. More than 100 White Dwarfs have been observed. (Secs. *3C, 3E;* App. A, no. 16; Fig. 3.8)

x-rays electromagnetic radiation of very short wavelength (about 0.1 to 100 angstroms, or 0.01 to 10 nanometers) and high photon energy (about 100 electronvolts to 100 kiloelectronvolts), measured in several hundred astronomical sources. (Secs. 2C, 2F, 3A, 3D, 3E; App. A, no. 6; Figs. *3.1*, 3.8) See Pamphlet II.

Appendix D

Further Reading

The Amazing Universe by Herbert Friedman, National Geographic Society (Washington, D.C.), 1975—a clear and beautifully illustrated survey of recent research in astronomy.

Astronomy Made Simple by Meir H. Degani, Doubleday & Co., Inc. (New York), 1963—an easy-to-read description of astronomical objects.

Astronomy One by J. Allen Hynek and Necia H. Apfel, W. A. Benjamin, Inc., (Menlo Park, Calif.), 1972—a pleasant introduction to the architecture of the universe; for the serious student.

Atoms and Astronomy by Paul Blanchard (Available from the U.S. Government Printing Office, Washington, D.C. 20402), 1976—atomic spectra explained in simple terms and used to analyze the spectra of stars.

The Birth and Death of the Sun by George Gamow, Viking Press, Inc. (New York), 1952—an explanation in simple terms of how stars shine and where they come from, by the master of science writing.

Chemistry Between the Stars by Richard H. Gammon (Available from U.S. Government Printing Office, Washington, D.C. 20402), 1976—a basic discussion of gas clouds between the stars and their composition and physical conditions.

Conceptual Physics by P. Hewitt, second edition, Little, Brown and Co. (New York), 1974—see chapters 24 and 25 on stellar evolution.

The Evolution of Stars, Thornton Page and Lou Williams Page, eds., Macmillan Publishing Co., Inc. (New York), 1968—how stars form, age, and die.

Extragalactic Astronomy: The Universe Beyond our Galaxy by Kenneth Charles Jacobs (Available from U.S. Government Printing Office, Washington, D.C. 20402), 1976—includes a simple description of our own Milky Way Galaxy and discussions of other galaxies, Doppler shift, cosmology, and related topics.

Investigating the Earth (Earth Sciences Curriculum Project), Houghton Mifflin Co. (Boston), 1973—see Unit Five, "Exploring the Universe."

The Origin of the Solar System, Thornton Page and Lou Williams Page, eds., Macmillan Publishing Co., Inc. (New York), 1966—see Chapter 2, "The Sun, Source of Energy and Control," and Chapter 3, "The Outer Layers of the Sun."

Rendezvous in Space: Apollo-Soyuz by F. Dennis Williams (Available without charge from NASA Educational Programs Division/FE, Washington, D.C. 20546), 1975—a popular account of the Apollo-Soyuz Test Project, including the U.S.-U.S.S.R. agreements.

A Star Called the Sun by George Gamow, Viking Press, Inc. (New York), 1965—a masterpiece on the layers in the Sun.

Starlight: What It Tells About the Stars, Thornton Page and Lou Williams Page, eds., Macmillan Publishing Co., Inc. (New York), 1967—see Chapter 3, ''Stellar Spectra: The Analysis of Starlight.''

Stars and Clouds of the Milky Way, Thornton Page and Lou Williams Page, eds., Macmillan Publishing Co., Inc. (New York), 1968—describes the structure and motion of our Galaxy.

The Supernova: A Stellar Spectacle by W. C. Straka (Available from U.S. Government Printing Office, Washington, D.C. 20402), 1976—a well-illustrated and dramatic account of how some stars blow up, leaving a halo of gaseous remnants in the space around them.

☆U.S. GOVERNMENT PRINTING OFFICE: 1977 0--243-575

EP-135

National Aeronautics and
Space Administration