THE SOLAR SYSTEM

By A. G. W. CAMERON

BOUNCING RADAR SIGNALS off the moon was considered quite a feat 20 years ago. Today they are being bounced off planets on the other side of the sun. This accomplishment is symbolic of the enormous expansion in our knowledge of the solar system that has taken place in the last two decades. The expansion has resulted jointly from the development of new technology and from the large investment in the space program and in geophysical and astrophysical research.

The existence of the space program has in itself given an enormous stimulus to ground-based research, largely because a few observations made in space and in the vicinity of other planets render ground-based measurements more meaningful. There is also a psychological factor involved: People are more likely to do solar-system research when it appears probable that the more important problems can be solved in a few years.

Geophysics

In recent years there has been wide study of the earth's interior and of the atmosphere that surrounds us.

Geodesy. Artificial satellites have allowed determination of much-improved spherical-harmonic coefficients for mass distribution in both the earth and moon. Although there are interesting correlations with anomalies in terrestrial heat-flow data, conclusions regarding the static strength of the lunar and terrestrial interiors and the possibility of convection in the earth's mantle are still in dispute.

Seismology. Modern computing methods applied to seismic travel times have allowed a great improvement in knowledge of the structure of the earth's interior. Observation of oscillations of the earth as a whole with new long-period seismographs give important information about the earth's core but are not quite consistent with the travel-time analyses. Experimental and theoretical studies of the properties of matter at high density have greatly strengthened inferences about the predominant iron composition of the core.

Geomagnetism. The main geomagnetic field probably arises from some little-understood "dynamo" process involving the interaction of seed magnetic fields with fluid motions in the earth's core. A highlight of the last two decades is the discovery that the main field irregularly and abruptly changes sign every few million years or so.

Geophysical fluid dynamics. Nothing very new in the way of fundamental principles has been added to the classical understanding of this subject. The modern computer, however, has greatly facilitated construction of fluid-dynamic models of geophysical fluid situations. Oceanographers, studying internal and surface wave motions on a wide range of scales, have made some progress in understanding oceanic circulation.

Meteorologists have made great progress in understanding the structure of atmospheric turbulence and have studied internal gravity waves in the atmosphere in some detail. Owing to the advances in construction of global models of atmospheric circulation and numerical weather prediction, we can, in the near future, expect fairly reliable forecasts as far as two weeks ahead. There are, however, fundamental limitations that will prevent longer range forecasts: One of the major, current problems is lack of knowledge of the physical properties of the air–sea interface.

Earth's envelope

From rocket, satellite and radar investigations we have gained new insights concerning the nature of the ionosphere and magnetosphere, and especially the effects of solar activity on these regions.

Upper atmosphere and ionosphere. Knowledge of the uppermost regions of the atmosphere has increased enormously in two decades, owing to sounding rockets, satellites and powerful radar systems (which now detect Thomson backscatter from the ionosphere). The upper atmosphere is subject to diffusive separation of gases; the gases in uppermost layers, composed of helium and hydrogen, are ionized by solar ultraviolet radiation. Both satellite-drag measurements and ionospheric measurements show that the upper atmospheric densities undergo diurnal, semiannual and annual variations. Many of these are correlated with solar activity and consequent variations of solar-ultraviolet heating, but there also appear to be density variations correlated with fluctuations in the solar wind. The mechanism of solar-wind heating of the upper atmosphere may involve hydrodynamic waves, but the details are not understood. Rocket measurements have also detected upper-atmosphere currents responsible for significant and variable contributions to the outer geomagnetic field.

The magnetosphere. One of the most significant discoveries of the last 20 years is the region of trapped ra-

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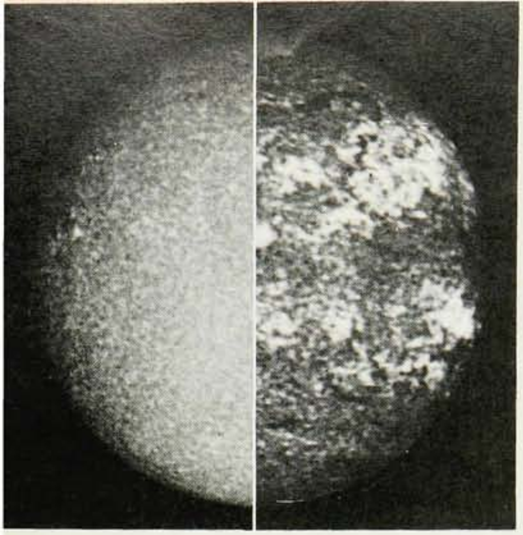

QUIET AND NOISY SUN. The spectroheliogram at left was taken in 1954, and one at right was taken in 1958.

diation above the atmosphere. Satellite measurements have now extensively mapped the magnetic-field intensity and direction, particle fluxes and spectra throughout the magnetosphere, and some insight has been gained into their time variations. There is still much dispute over the particle acceleration and injection mechanisms responsible for populating the magnetosphere. In principle the interaction of the solar wind with the magnetosphere appears to be responsible for much of the acceleration, probably through generation of hydromagnetic waves and by causing gross magnetic variations in the magnetosphere. Wave–wave and wave–particle interactions are important aspects of plasma physics that are insufficiently explored and must play an important role here. The magnetic flux through the polar caps is deformed into the geomagnetic tail. Current investigations suggest that much particle acceleration takes place in the neutral sheet where the two bundles of magnetic flux merge together; these particles appear mainly responsible for auroral phenomena as they are precipitated into the upper atmosphere.

Beyond the earth

Space probes have provided valuable information about interstellar space and the planets. We have greater understanding of the solar wind and nuclear reaction rates in the sun's interior, but theories of coronal heating and stellar evolution remain inadequate. By studying the planets we hope to gain new insight into terrestrial processes.

The interplanetary medium. In the first of our two decades it was clear that some sort of particle streams were emerging from the sun and interacting with comets to produce an ion tail separated in space from the dust tail. In the second decade satellites and space probes have given much quantitative information concerning the solar wind. The wind is now understood to be a supersonic hydrodynamic expansion of the hot solar corona. Under "quiet" conditions, at the earth's orbit there are about ten ions per cubic centimeter flowing at a bulk velocity of $\sim 5 \times 10^7$ cm/sec. Under "disturbed" conditions, there are irregularities and fluctuations in the flow arising from inhomogeneous heating of the solar corona.

The interplanetary medium is a collisionless plasma (see "Plasma Physics," page 46) in which the particles nevertheless interact by way of the magnetic field pulled out from the sun. Collisionless shock waves exist both in interplanetary space and adjacent to the magnetosphere; the inadequately understood structure of these waves presents a challenge to the plasma physicist.

Solar physics. During the last 20 years the sun has been extensively studied. Nuclear reaction rates responsible for energy generation in the deep interior have been determined experimentally and theoretically to a fair degree of precision. The opacity that affects radiative energy transport in the interior has been carefully calculated for a multitude of known processes. Nevertheless the anticipated high-energy neutrino flux predicted from solar-model calculations has not been observed. This failure now poses a serious challenge to stellar evolutionary theory.

Much work has also been done during these years on the mechanisms for heating the solar chromosphere and corona. It appears that the outer solar-convection zone can generate magnetoacoustic, Alfvén and internal gravity waves, all of which can propagate upwards and deposit energy in the outer solar atmosphere. The transmission and dissipation of these waves is rather complicated, and at the present time there is still no theory of coronal heating that would survive the test of predicting coronal conditions in another kind of star.

Plasma physicists have studied the mechanism of solar flares. Here the problem is to account for the observed rapid release of energy (presumably by magnetic field annihilation) in an extensive highly conducting plasma. No fully satisfactory theory has yet been formulated.

Planetary physics. Investigation of the other planets leads to new insight into terrestrial processes. In the last two decades there have been a considerable number of optical, radar and radio observations of several planets. Space-probe measurements in the vicinity of the moon, Venus and Mars have determined the basic atmospheric compositions and structures of Venus and Mars, and we now realize that standard techniques in terrestrial meteorology are not applicable for these atmospheres. The generalization of meteorological concepts for these planets will benefit the understanding of our own atmosphere. None of the other three bodies has a significant internal magnetic field. On the other hand, radio studies of Jupiter show that it has a strong off-center magnetic-dipole field with an accompanying magnetosphere. These facts may give clues to the geomagnetic processes operating in the earth's interior.

The lunar surface has strange backscattering photometric properties not properly understood yet. In general the moon's surface constitutes an important laboratory in which the effects of long, continued exposure of solid materials to space environment has occurred. Controversy over the probable cohesiveness of lunar surface dust has now been partially resolved by Surveyor experiments that show the cohesiveness to be important but not as great as had been feared.

The physicist's role

Let us contemplate the role of the physicist in these areas of pure research. He finds that he becomes mostly an applied physicist in that his task is to understand the basic features of the solar system in terms of known physical processes. In general he must utilize knowledge from several areas of physics to construct models of physical phenomena. He is frequently challenged by finding that current physical knowledge is inadequate to account for observed properties. Then he must become a pure physicist and conduct experimental or theoretical investigations to supply the missing knowledge. Ultimately his objective is not only to determine what the solar system is like, but how it evolved into its present state.

Probably the areas in which fresh physical insight is needed most are fluid dynamics and plasma physics. Much more detailed knowledge is needed in solid-state physics (for radiative transfer and creep in planetary interiors) and in atomic and molecular physics (for reaction rates in planetary atmospheres and for opacity studies). We expect that significant advances will be made in the next two decades.

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Useful guides to the geophysical literature can be found in the US reports to the meetings of the International Union of Geodesy and Geophysics. These have been appearing in Transactions of the American Geophysical Union. *The planetary and solar literature is periodically reviewed on a worldwide basis in the commission reports in the* Transactions of the International Astronomical Union.

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TWENTY YEARS OF PHYSICS

ASTROPHYSICS

By LODEWYK WOLTJER

RADIO SOURCES had just been discovered twenty years ago, but their nature was unknown. The 21-cm hyperfine-structure line of hydrogen had been predicted but was not yet observed. Theories of stellar and galactic evolution were primitive: The origin of the elements was a mystery, and the nature of cosmic rays was obscure.

Today studies of radio and x-ray sources and of cosmic rays have revealed an entirely new aspect of the universe, in which energetic particles and magnetic fields play a prime role. With the help of the 21-cm line, a map of our galaxy has been made. The important phases of stellar evolution are at least semiquantitatively understood, and the processes responsible for the formation of the chemical elements in stars have been outlined. Let us look at the rather coherent picture of astronomy that has emerged from developments in the last two decades.

Stellar evolution

In its simplest form the study of stellar structure is concerned with the analysis of static, spherical, masses of gas. The equilibrium of such a mass is governed by two conditions: The forces acting on any part of the star should balance, and the net outflow of heat energy from any volume should be compensated for by generation of (mainly nuclear) energy. The first condition yields a relation between the pressure gradients and the gravitational forces in the star. The second condition connects the heat flow, which depends in a complex way on the physical parameters of the gas because the heat transport is mainly radiative, with the rates of the nuclear processes in the stellar interior. Thanks to the progress in low-energy nuclear physics over the past two decades, now these rates can be accurately evaluated for given physical conditions.

With the advent of fast computers it has become possible to determine the structure of stars of different masses and composition with good accuracy. The remaining uncertainties in the models are mostly due to possible small inaccuracies in our knowledge of the opacity of stellar material. However, in real stars the effects of rotation and magnetic fields probably are more important.

Nucleogenesis. At birth, stars are composed mostly of hydrogen. The main nuclear reactions convert hydrogen into helium. Slowly, therefore, the composition of a star is changing; important modifications occur when a good fraction of all hydrogen in the core has been transmuted. In a qualitative way it is easy to see what the nature of these modifications will be.

Suppose that a star had used up all available hydrogen. It would continue to radiate because the interior is hot; hence its total energy would become progressively more negative. According to the virial theorem (applied to an ideal gas in a quasisteady state), the gravitational potential energy E_g equals minus twice the kinetic (thermal) energy E_{th}. Hence, the total energy $E = E_g + E_{th} = 1/2E_g = -E_{th}$. Strictly taken, this applies only for a static configuration, but it will be satisfied to a good approximation for most quasistatic changes (quasistatic on a free-fall time scale). We conclude that when the star loses radiant energy uncompensated for by nuclear energy, the star contracts and heats up since contraction increases $|E_g|$. But when the temperature increases, thermonuclear reactions between more complex nuclei become possible. Thus some time after hydrogen in the core has been depleted helium will begin to burn into carbon. Later still the carbon may

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