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By

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I. INTRODUCTION

A. Observational Astronomy

Historically, the growth of astrophysical knowledge has been determined by the state of development of theoretical and experimental physics, supplemented to a large degree by engineering technology. In turn, much of physics owes its origin to the need to explain observed astronomical phenomena.

The basic information concerning the nature of the astronomical universe comes to us almost exclusively by means of electromagnetic radiation, connected in some way to the phenomena being observed.

Efforts to investigate these phenomena in greater detail has resulted in the development of telescopes, detectors, spectrometers and polarimeters both in the optical regions from the near infra-red to the near ultraviolet, and also in the radio region with wavelengths from a few millimeters to several meters. These are the spectral regions or "windows" for which electromagnetic radiation is not greatly disturbed in passage through the earth's atmosphere and ionosphere. Much has been learned from astronomical observations in these spectral regions concerning

[redacted]

the way in which matter and energy are distributed and interacts in the universe. The modern concepts of cosmic chemical abundance, of stellar structure and evolution, of galactic structure and dynamics, and of extra-galactic systems is the culmination of 350 years of astronomical observations from the bottom of the earth's atmospheric shell.

B. Ultraviolet Observations

The absorption of ultraviolet below 3000Å in the telluric atmosphere due to O_3, H_2O, O_2 and CO_2 is enormous (Watanabe 1958) and prevents any ground-based astronomical observations in that part of the spectrum. This has been very unfortunate for astronomy, as many fundamentally important astrophysical processes are known from theory to take place in the ultraviolet. Above the atmosphere, the short wavelength cut-off to practically all astronomical observations in the ultraviolet is provided by the absorption continua arising from the ground state of the more abundant elements that make up the cold interstellar gas, starting with hydrogen at 912Å. (Strom and Strom 1961). Thus the naturally defined region of astronomical (excluding the solar system) ultraviolet occurs between 3000Å and 912Å. In order to observe in this spectral range, one must use appropriate instrumentation at altitudes free of atmospheric extinction.

Sounding rockets and artifical earth satellites at altitudes of 150 Km or more, and solar system probes are presently being employed, while lunar stations might also be useful.

C. Galactic Composition

The spectroscopic and positional properties of observable objects in the celestial sphere have collectively permitted identification of the nature and spatial distribution of these objects. Stars of the Milky Way are members of our disk-shaped galaxy, which is a dynamically unified system of stars, gas, and dust having a diameter of about 35 Kpc, a thickness of some 4 Kpc, and a total mass of about 10^{11} solar masses, deduced from the observed kinematics. In addition to this mass, the galaxy contains electromagnetic radiation, magnetic fields, and cosmic rays.

The galactic mass is found to occur in subsystems, as evidenced by differences in spatial arrangement, dynamical properties, and physical content. Most of this mass is in the stars, the remaining 8% or less being gaseous. The coarsest examination uncovers two basic subsystems, known as the halo population II and the extreme disc population I. Objects belonging to the halo population show almost no concentration to the galactic plane, and partake in galactic orbits characterized by large eccentricities and random inclinations to the galactic plane. Thus their orbits tend to carry them close to the galactic nucleus at some time in their life. Prominent members of this population group are globular clusters, certain transitional variable stars, and extreme subdwarfs with very low metal content.

Extreme disc population I consists of interstellar gas clouds and newly formed massive and O-B stars which are confined a thin sheet in the galactic plane, having a thickness no more than about 1% of its planar dimension. The motion of these objects describe nearly circular orbits with very small inclinations. In our galaxy, members of population I trace out the well-known spiral structure.

Formation of stars in associations depends heavily on the availability of large concentrations of hydrogen in clouds and their complexes. Much of what is required may be hidden in the form of molecular hydrogen which has been precipitated by grains of dust intermingled with the gas. The rate of formation of stars in the galaxy, and their evolution is in turn directly connected to the rate of element generation by nucleo-synthesis within the stars. As stars age and become unstable, a sizeable fraction of these elements is returned to the interstellar medium, ultimately to be used in the formation of newer generations of stars. Because of the changed initial chemical composition, these evolve differently from earlier generations, (Burbidge 1962) and contribute differently to the radiation field of the galaxy.

D. Extragalactic Systems

Outside the boundaries of our Galaxy, the cosmic gas density falls to unobservable values of 10^{-29} gm cm^{-3} or less. Within some 60 Kpc we find the Large and Small Magellanic Clouds, each a galactic star system in its own right. In fact there is a collection of some 20 odd galaxies of varying types, including our Galaxy, all distributed within a sphere of some 800 Kpc radius. In this sampling, system masses range from 10^8 to $10^{11.5}$ $M_\odot$. Some systems are highly gaseous, others are practically gas-free. Some are very difficult to find, others are visible to the naked eye. This grouping of nearby extra-galactic systems is known as the Local Group.

Beyond the Local Group lies a continuum of extra-galactic systems, extending beyond the limits of observation with the largest telescopes. The spatial distribution of these galaxies is not smooth. There is a marked tendency toward clumpiness, often resulting in the clustering of many hundreds or thousands of systems at a time.

As a whole, the study of these objects is most important in elucidating the grand-scale structure of our universe - the total mass and energy content, its size and its evolution and natural geometry. At the same time, the nearer-by galaxies have been extremely valuable in building our knowledge of galactic structure and processes.

II. THE INTERSTELLAR MEDIUM

The total matter density in the neighboring part of the galaxy within several hundred parsecs of the sun (1 pc = 3×10^{18} cm) is about 10^{-23} gm-cm^{-3} as determined from the perpendicular component of stellar motions with respect to the galactic plane. (Lindblad 1959). According to star counts, only one-third to one-half of this density is attributable to stars alone. The remaining fraction being either gaseous or particulate matter, or less probably stars too faint to be observed. Hydrogen accounts for most of the mass of atomic gas and contributes less than 2% to the total galactic mass, as determined by radio observations at 21 cm. Roughly half the atomic hydrogen in the galaxy is known to be concentrated in gas clouds, about half of which lie within 100 pc of the galactic plane. These clouds, with dimensions of some 10 parsecs, help delineate the spiral structure of our galaxy. With an atomic hydrogen density of about 10 cm^{-3}, compared to about 1 cm^{-3} for the arm structures as a whole, they maintain a kinetic temperature near 100 °K.

More than 90 per cent of the interstellar hydrogen is in the ground state. Therefore in the solar neighborhood and in spiral arms where the local gas density is higher than avergage about 25% of the total matter density is attributed to observed interstellar gas. Up to the present, there is almost no observational evidence requiring more particulate ("dust") matter than a density of the order 10^{-26} gm cm^{-3} throughout the galaxy, or less than one percent of the atomic hydrogen density. Assuming all particulate matter is accounted for, and that there is no large error in the estimate of stellar density, a large fraction (about 40%) of the mass in that part of the galaxy near the sun remains unidentified. Because of the generally small abundance of elements heavier than hydrogen or helium, it is not expected that the heavy elements contribute appreciably to this fraction. It is therefore anticipated that a substantial portion of this will be found to be molecular hydrogen, which has no dipole rotation-vibration spectrum in the infra-red, and for which the electronic transitions are in the far ultraviolet.

A. Molecular Hydrogen

A most important problem of the interstellar medium is that dealing with the existence of the hydrogen molecule. At a temperature of about 100 °K, and with the ionizing and exciting radiation from stars blocked by a very small fraction of the hydrogen, atomic hydrogen is almost entirely in the ground state. Therefore, radiative association is an ineffective mechanism for the formation of molecular hydrogen, as the required energy-conserving radiative transition is forbidden. However, it has been shown (Gould and Salpeter 1963) that surface recombination should occur for atoms which have collided with dust grains in the gas clouds. These grains are presumed to consist mostly of ice and other simple dielectrics. This catalytic process is the only one thought able to produce H_2 in sufficient abundance to explain the aforementioned mass discrepancy in the galaxy.

The hydrogen molecule, being homonuclear, has no permanent dipole moment. The pure vibration - rotation spectrum is too weak to observe without great difficulties and there is no fine structure splitting of the ground state which could be detected in the radio region of the spectrum.

In the vicinity of hot stars rich in ultraviolet flux, the H_2 molecule will be excited to electronic states, Fig. 1. Ultraviolet transitions will return it to excited vibrational and rotational levels in the ground state, ultimately cascading

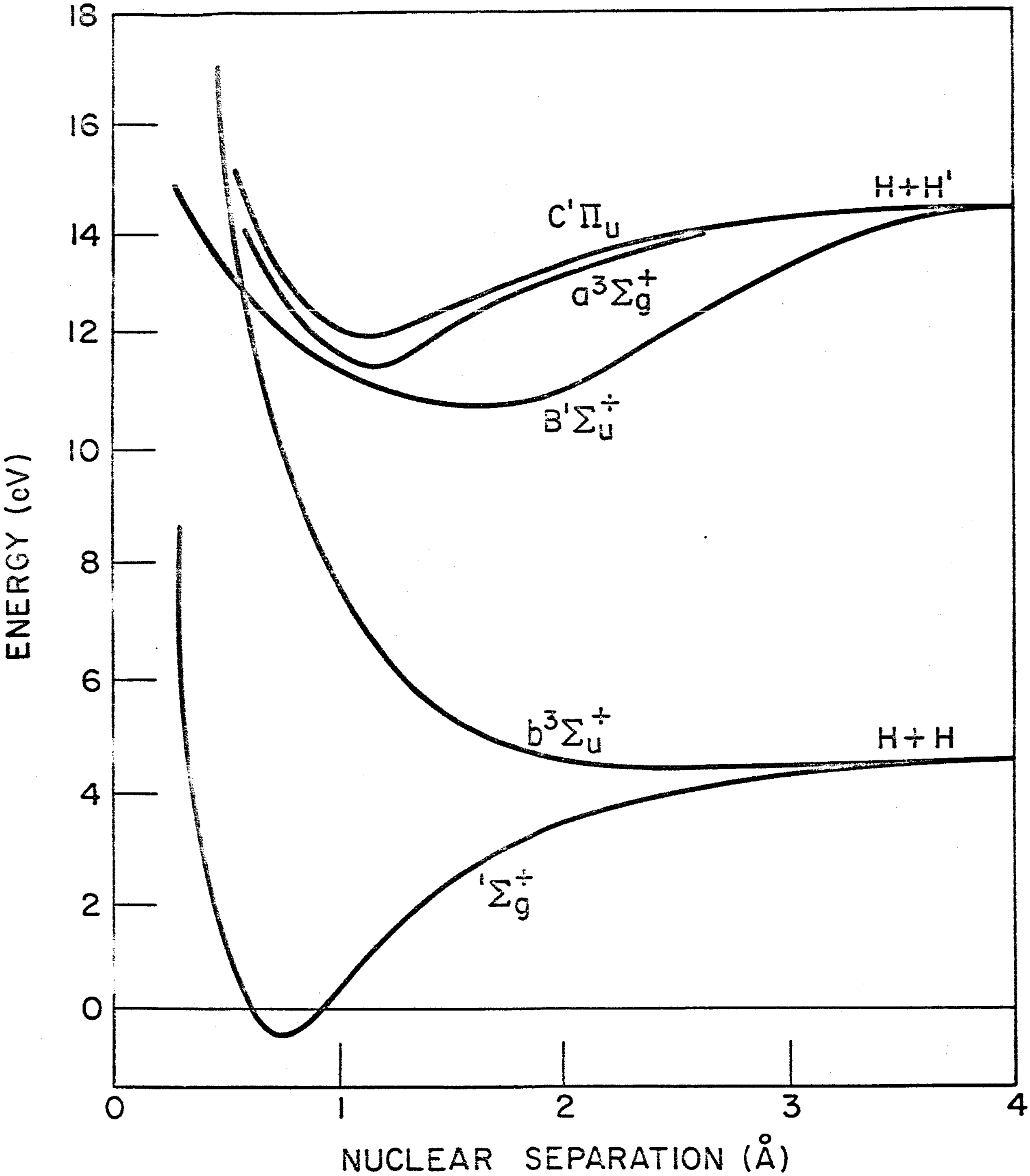

Fig. 1 - Potential Curves for some of the lower electronic states of H_2. [Adapted from J. D. Craggs and H. S. W. Massey, 1959, Encyclopedia of Physics Vol. 37/1, ed. by Flügge (Berlin: Springer-Verlag), p. 339].

to the lowest level with the emission of near or far infrared radiation. The stellar radiation used to excite the H_2 molecule from the $^1\Sigma\ g^+$ ground state is lost from the flux in the line of sight, and appears as absorption lines superimposed on the stellar spectra. The predominant lines will occur in the Lyman and Werner bands, with upper states $^1\Sigma_u^+$ and $^1\Pi u$ respectively, both series being shaded toward the red. The Lyman progression begins at 1108 Å and extends to the ultraviolet with initial separations of about 15 Å, while the Werner progression begins at 1009 Å with somewhat larger separations between the individual levels. Beyond the sixth line of the latter series, strong continuous absorption by neutral hydrogen in the galaxy sets in. Observations in these bands are also expected to be hindered by coincident atomic absorption lines arising in the atmospheres of the very stars whose continum would be used in the search for interstellar H_2.

Thus, successful observations of at least some of these absorption lines would indeed yield very significant information, for in addition to helping discover the mass makeup of the galaxy, it will at the same time bring much light to bear on the physics of the interstellar medium and its role in stellar and galactic evolution.

B. Atomic Hydrogen

Since hydrogen is by far the most abundant element, it is of special interest to inquire as to its effect to radiation in interstellar space. The atomic absorption coefficient for hydrogen in the Lyman continuum at the absorption edge is

$$\alpha_{LC} = 6.3 \times 10^{-18} \text{ cm}^2. \qquad (1)$$

Thus, for a space density n of 1 cm^{-3}, the optical depth $\tau = n\alpha x$ for a distance of only 1 pc is already greater than unity. This tremendous absorption makes astronomical ultraviolet observations impossible for a vast range below λ912Å. The Lyman Series of hydrogen will be very strongly scattered. A typical interstellar gas cloud in the galaxy would be completely opaque to this radiation (Spitzer and Zabriskie 1959), provided the scattering is non-conservative.

For even relatively nearby objects, such as the Orion nebula, Aller (1959) shows the L-α line would be totally obscured to a width of 7Å. Münch (1962) has reexamined the processes of L-α transfer in both neutral (HI) and ionized (HII) regions of hydrogen, and finds the prospects much better for a chance to observe both galactic and extragalactic sources of L-α. These findings are based on a closer consideration of the effects of non-coherency and true absorption in the process of radiation transfer through the interstellar medium. In HII regions, the 2 photon decay from the collisionally excited 2S level is the source of photon loss, while the degree of non-coherency in the scattering process determines the number of encounters within the region. In HI regions, population of the 2S level is less, but absorption by dust grains must now be taken into account. In either case, the distinct possibility exists that L-α radiation can leak out from certain configurations of sources and interstellar gas. This might, for example, allow extremely sensitive observations of interstellar hydrogen distribution above the galactic plane, and perhaps near the sun. Sample values of pertinent parameters are given in Table I for three cases discussed by Münch.

TABLE I. L-α Transfer In The Galaxy

Parameters	Dust Free Nebula, HII Region	Galactic Disc, Direction of Pole, No Dust, HI Region	Galactic Disc Strata with Dust, HI Region
Temperature, °K	1.2×10^4	1.2×10^2	1.2×10^2
N_H, cm^{-3}		1	1
N_e, cm^{-3}	10	$3 \times 10^{-4}\ N_H$	$3 \times 10^{-4}\ N_H$
λ, Probability of 2 photon conversion per encounter	$10^{-13}\ N$	$0.6 \times 10^{-13}\ N$	$0.6 \times 10^{-13}\ N$
Q, Mean Number of L-α Scatters before escape from region	$6 \times 10^{-6}\ \tau_o^2$	$6 \times 10^{-6}\ \tau_o^2$	-
τ, Central Optical Depth	10^6	2×10^8	3×10^5/PC
λQ, Exceptation of L-α Absorption in Region	6×10^{-6}	4×10^{-6}	
a, Assumed Linear Coefficient of Dust Absorption, cm^{-1}			0.9×10^{-22}
L, Mean Square Displacement before Capture			~50 PC

C. Chemical Composition and Ionization

The galactic gas stratum and clouds frequently lie in our line of sight to distant stars which have intrinsically high luminosity and an uncluttered spectral energy distribution such as occurs in O-B stars. It has been found possible to detect the presence of this gas by means of the sharp absorption lines superposed on stellar spectra. Because the gas atoms or ions are far removed from stellar surfaces, the radiation density they experience, while spectrally similar to that compound from the stars, is greatly attenuated, or diluted, by a factor of 10^{-16} or so. In addition, the gas density is extremely low, with the result that the probability an ion will be found in any other than the ground state is vanishingly small. Whenever the ionization potential is less than that of hydrogen, 13.6 e.v., ionization will occur. Hence the strength of any absorption line will depend on the abundance of the particular element and its stage of ionization. The weakest detectable lines require some 10^{11} ions per cm^2 of absorbing path.

In the photographic spectrum, all the expected lines have been identified. However, because the resonant lines of most elements and ions occur in the ultraviolet, only five elements and a few molecules have been found this way in interstellar space. Once such high resolution ultraviolet observations are attainable, it should be possible to observe perhaps three times this number, including such astrophysically important elements as C, N, O.

This new array of lines, with a wide range in optical depth of their line centers, and with new sets of elements in two states of ionization opens wonderful opportunities for exploring the interstellar medium in much greater detail. For example, more firmly established values may be found for the electron density, and finer velocity structure of the interstellar gas in the solar neighborhood may be mapped, as has been pointed out by Spitzer & Zabriskie (1959).

D. Particulate Matter

There is abundant evidence for the occurrence of interstellar matter in the form of molecular aggregates which most probably are like small grains of chemical smoke, or dust. These particles are betrayed by their ability to cause high extinction of the light from distant stars, and under appropriate conditions to be seen in their scattered light.

When large amounts of the dust are accumulated in localized regions, such as in the interstellar gas clouds, the dark clouds may show up conspicuously in photographs of the Milky Way against the bright stellar background. When illuminated by nearby bright stars, some nebulae have been seen in reflected light caused by scattering from the dust grains.

In extinction, the attenuation is very great, and increases from the infra-red to the near ultraviolet. In reflection, the albedo is high, that is, light is well conserved. These characteristics all must be explained without the introduction of much mass, in order to satisfy galactic dynamical requirements. The best solution to account for these properties is found by postulating dielectric particles, perhaps composed mostly of ice, but with some metallic impurities. There must be an appreciable range in size, but the extinction, which is caused by diffraction effects, is maximum when the wavelength is somewhere near comparable to the diameter.

An exact characterization of these grains requires many parameters, including size, size distribution, chemical composition and distribution, whereas the only measureable parameters are extinction, albedo, and polarization as a function of wavelength. Throughout the spectrum accessible from the ground, it has been possible to establish some marked differences in extinction laws for different regions of the galaxy (Hallam 1959), but the span of wavelengths is still inadequate to allow definitive grain models to be deduced. This is due to the usually smooth variation of extinction with wavelength from 1μ to 3000Å, with an absence of characteristic singularities in the dependence, and the large number of parametric variations possible within the theory.

A few rundimentary observational data in the rocket ultraviolet have recently been made available (Boggess and Borgman 1964) which are applicable. These suggest a continuing increase of extinction into the ultraviolet. Many more observations will be needed before it is clear how general this trend may be.

III. GASEOUS EMISSION NEBULAE

Among the objects showing high galactic concentration are the diffuse gaseous emission nebulae which are strong

Extreme Population I members found in spiral arm gas fields, and the planetary emission nebulae which belong to the old Disc Population II, and are highly concentrated toward the galactic center. Although their origin and development are not related, they are nevertheless similar in that they display emission lines, including forbidden transitions, characteristic of rarefied gases.

It was noted in the section treating interstellar dust that dust is sometimes evidenced by its reflection properties when it occurs in a gas cloud near a bright star. It was first pointed out by Hubble (1922) that when the associated star is of type O or B_o, abundant in ultraviolet flux, the nebular light instead of having the spectral characteristics of the star, exhibits strong emission lines of fluorescense. These diffuse emission nebulae have been very important in our understanding of the chemical makeup, densities and temperatures in the interstellar gas of the spiral arms. The Orion Nebula is a well-studied example of a diffuse nebula.

Planetary nebulae, the most familiar example of which is the "Ring" Nebula in Lyra, are usually symmetrical shells of expanding (10 to 50 Km/sec) gas surrounding a star of very high surface temperature (50,000 to 100,000 °K), with mass comparable to the sun's but smaller in diameter. The surrounding shells have a large range of sizes, perhaps from 20 000 to 200 000 astronomical units. The density of the nebula is typically 10^4 atoms per cm^3 and the electron temperature is about 10,000 °K.

The source of excitation energy in both types of nebulae is the ultraviolet flux below 912 Å from the associated stars which ionizes the abundant hydrogen and imparts its excess energy per photon to the kinetic energy of the gas. As the hydrogen is ionized, the gas becomes transparent to the remaining flux which will then be used up by ionizing all the available adjacent hydrogen, until either all the hydrogen or all the photons are depleted. Other constituents of the gas will also be ionized by the stellar flux, but their low relative abundances contribute little to the total number of free electrons. The electron density is thus equal to that of ionized hydrogen, and this strongly influences the rate of recombination. As the nebula is nearly opaque to Lyman radiation (see Section II, B.) by virtue of resonant scattering within itself, nearly every Lyman photon produced in the nebula by recombination will be multiply scattered until at last a transition to the ground state by cascade through one or more levels occurs. Then hydrogen radiation in the other series will be produced, always culminating in a Balmer transition and a Lyman-alpha photon. The main source of excitation to atoms in the ground state is by excitation through electron collision. Because of the similar dilution of both radiation and matter in the nebula with respect to that at the surface of the star, the electron temperature assumes a value near 10,000 °K. Excitation of the $n = 2$ level of hydrogen is thus infrequent, and the nebula is therefore highly transparent to hydrogen line emission in all but the Lyman series.

At the same time, the more easily excited levels of other ions are populated by electron collision, with subsequent de-excitation by radiative and non-radiative transitions. It is obvious that the non-radiative transitions will be competitive only for metastable levels requiring non-dipole transitions.

Once values are known for transition probabilities and collision cross-sections, a consistent model may be obtained, from which emission line strengths are derived. These will clearly depend on 1) the spectral distribution and amount of the stellar flux below 912 Å, 2) the distribution of matter about the star, 3) the chemical composition of the gas. Because much of the stellar ultraviolet energy is converted to Balmer radiation before it leaks out of the nebula, and into visible lines of other ions as well, much can be inferred about the ultraviolet stellar flux without directly observing it. Moreover, if the nebula is sufficiently thick, it would be impossible to observe the star itself below 912Å, which would be the usual case.

There are however, many emission lines expected in the vacuum ultraviolet between 912 Å and 3300 Å, which will greatly enhance our understanding of the nebulae. Osterbrock (1963) has made a detailed prediction of such lines for the ten most abundant elements. Besides collisionally excited lines, recombination lines are possible, and in general Osterbrock finds collisional excitation dominant for excitation potentials of roughly 10V or less. Continuous ultraviolet emission will also be stimulated, due to recaptures by He^{+}, He^{2+}, and by the two-photon mechanism (Spitzer and Greenstein 1951), which has a maximum at 2431Å. Ions which contribute to lines in the Osterbrock list are CII, III, IV; NII, III, IV, V; OLLL, IV, V; NeIII, IV; MgII; SiII, III, IV; SII, III, IV, V, VI; ArII, III, IV, V, VI; HeI, HeII.

IV. STELLAR RADIATION

A. Stellar Relationships

Stars in the galaxy exhibit a large range of characteristics for which systematic descriptions derived from observations are possible (Arp 1958). Compared to the sun, definite ranges in mass, total luminosity, surface temperature and deduced chemical composition exist as given in Table II.

TABLE II

Ranges of Stellar Characteristics

$0.01 < \frac{M}{M_{\odot}} < 65$	$10^{-6} < \frac{L}{L_{\odot}} < 10^{6}$
$2000 < T < 50{,}000\ ^{\circ}K$	$\frac{1}{400} < \frac{R}{R_{\odot}} < 300$
$0.003 < Z < 0.04$, Mass fraction of elements heavier than He.	

Basically it has been shown that given a mass and chemical composition for some minimal accumulation of matter, gravitational condensation will result in a self-luminous star with a specific luminosity (total radiative outflow), size, and surface temperature. By further considering nuclear mechanisms for energy conversion, as well as gravitational potential, a time dependent stellar model can be deduced in which major evolutionary changes in internal structure, luminosity, surface temperature, chemical composition, and dynamical stability may be followed for most of the lifetime of the star (Chandrasekhar 1938, Schwarzschild 1958, Menzel, Bhatnagan, and Sen 1963). Such excellent results have been realized by sophisticated application of these principals that the basic observational stellar parametric relationship, the Hertzsprung-Russel diagram, is now mostly comprehensible on theoretical grounds using amazingly few initial inputs. This diagram is a two-dimensional representation of observed values of spectral type and absolute (intrinsic) stellar magnitude. The spectral classification sequence corresponds to a monotonic arrangement of stellar surface temperature. It is often convenient, or necessary to replace the ordinate of spectral type with a measure of the gradient of the spectral energy distribution. This is usually a color-index, which is the difference in magnitude of the stellar continuum flux when measured through two separated band passes. Then we obtain, instead of the H-R diagram, a color-magnitude diagram, or array (Fig. 2). The distribution of stars within the diagram defines which combination of luminosity L and surface temperature T exist in nature. It has been found that these values are confined to several continuous sets which may be idealized as line functions of L and T with some dispersion.

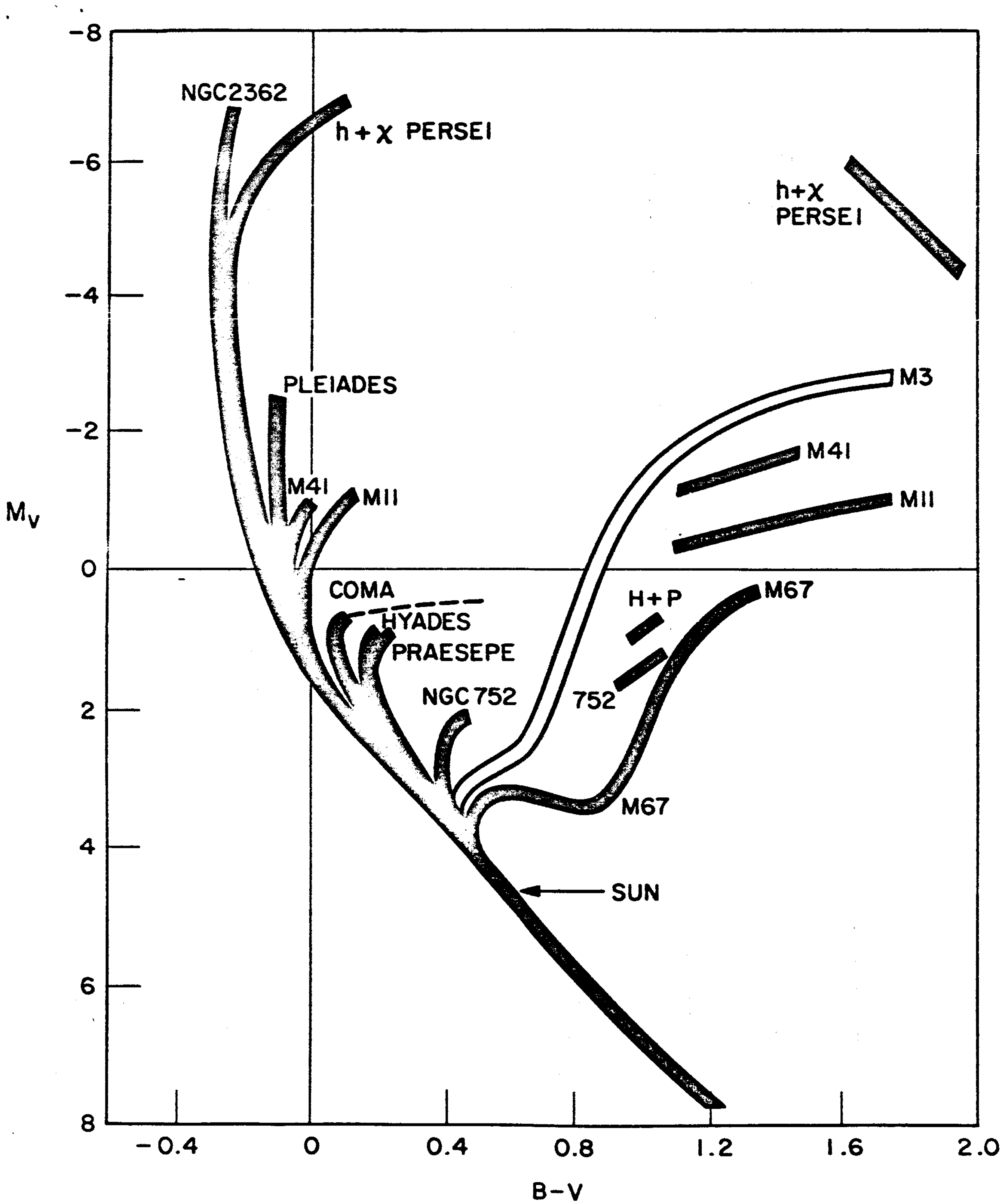

Fig. 2 - Superimposed color-magnitude diagrams for ten galactic and one globular cluster. The ordinate is absolute visual magnitude, while the abscissa is the blue-visual color index. (From A. Sandage, 1957, Ap. J. 125, 436).

The best defined of these is the main sequence, in which L is a single valued function of T which runs diagonally from low values of L and T to high values. Stars of the main sequence are found predominately as members of galactic population I. Such a sequence is derivable from theory for stars of similar chemical composition as the sun. The observed dependence of luminosity on mass for stars of the main sequence is very approximately $L \propto M^{3.8}$.

When particular systems of stars are plotted on a color-magnitude diagram, concentrations of stars are found in other parts of the diagram besides the main-sequence. Just where they fall depends on the selection of stars being investigated. Neverthless, consistent explanations can usually be derived in terms of mass of the stars and their chemical composition as a function of their age. Although most of the stars in the Milky Way belong to the main sequence, these will eventually move off to the right once they consume some critical amount of hydrogen through energy generation deep inside. This evolution largely accounts for the other branches or regions on the color-magnitude diagrams - the sub-giants, giants, super-giants, sub-dwarf and white dwarfs. These names apply to a star's luminosity for a given spectral type, compared to stars of the main sequence.

The mass of a star changes almost imperceptibly during normal evolution. Evolutionary changes in a star's outward appearance occur principally in response to fundamental changes in the site and rate of energy generation in the star's interior which result from continuing nucleo-synthesis or gravitational contraction. (Burbidge and Burbidge 1958). In a steady state transfer of energy, and with no mass loss, a change of energy generation rate shows up as an equal change in radiant flux through the stellar atmosphere. This can be accomplished either by a change in stellar radius R or of effective surface temperature Te, which follows from an application of Stefan's law:

$$L = 4\pi R^2 \sigma T_e^4 \ . \qquad (2)$$

Just how the star will adjust its radius and surface temperature depends on the equation of state of its interior matter and on its chemical composition throughout which determines the mean molecular weight and the opacity. If the interior source of energy increases, the star will expand, and while the luminosity increases to match the new energy rate, the surface temperature and pressure may drop at the same time. In an assemblage of stars of varying masses, the general course of evolution proceeds at a slower rate for the less massive stars, and the observed distribution of spectra, temperatures, and luminosities assume defineable tracks on the H-R and color-magnitude diagrams that are indicators of the age of the assembly.

The outer gaseous layers of a star rapidly become opaque, forming an effective surface to the <u>stellar atmosphere</u>. Stars of higher surface temperature are more abundant in ultraviolet flux. For stars with T_e greater than 10,000 °K, the integrated flux below

$\lambda 3000$ Å becomes very large compared to the total flux. None of this flux can be observed from the ground, and the customary procedure to obtain the total radiative flux L from ground data requires a theoretical estimate of the unseen flux derived from model atmospheres based on observations of spectra and spectral energy distribution of the stellar continuum. The additional derived flux, expressed in stellar magnitudes, is known as the bolometric correction B.C., while the luminosity, when expressed as a magnitude, is called the bolometric magnitude. In the theory of stellar interiors the bolometric magnitude, which is equivalent to the rate of energy generation, is a fundamental parameter as it is also in the theory of stellar atmospheres where it determines the radiation density. In stellar atmospheres, it is also required to know the spectral distribution of the flux. Both of these requirements can be reasonably well met by so-called wide-band photometry where the spectral resolution $5 < \frac{\lambda}{\Delta\lambda} < 20$, but care in the choice of such bandpasses is needed if they are to be fully effective in optimizing our information about stellar sources.

B. Stellar Atmospheres

A model stellar atmosphere is an attempt to represent the physical situation near the surface of a star where the character of the radiation that leaks out is determined. A successful model matches the spectral distribution of the net flux with that which is observed. When the stellar energy is transferred by radiative flow alone, hydrostatic equilibrium prevails, and thermodynamic equilibrium is very nearly achieved throughout the atmosphere between each local volume and its surroundings (local thermodynamic equilibrium). The equation of state of the gas then allows the density structure of the atmosphere to be determined, while the opacity, through the equation of transfer, permits simultaneous evaluation of the source function everywhere. The characterization of the atmosphere is therefore established by assigning values to the emergent flux from the normalized stellar hemisphere (or its equivalent, the effective temperature T_e), to the surface gravity, and to the relative numerical abundances A_i of the chemical elements.

Because of their greater abundance, hydrogen and helium are of overwhelming importance in establishing the nature of the continuous absorption which is responsible for maintaining the thermodynamic state of the atmosphere and of the radiation field. The role of the heavier elements is greatest under those conditions where they provide free electrons which are used in the formation of H^-, the most important continuous absorber for stars of spectral types K, G, and F. As the temperatures of the stellar atmospheres increase still further, atomic hydrogen becomes the most important contributor until even higher temperatures cause such preponderout ionization of hydrogen that electron scattering predominates in the outermost layers. Additional sources of continuous opacity in high temperature stars are HeI, HeII, H_2^+ and Rayliegh scattering for atomic hydrogen, all of which have certain domains of importance as functions of local temperature and pressure.

A starting approximation to the temperature dependence with depth in a model atmosphere is adjusted in the course of numerical integration until the condition of constant net flux through each layer is fulfilled for radiative transfer. Münch (1960) has conveniently listed published models of high-temperature model atmospheres through 1960, and compared them with respect to surface temperature To, surface gravity g, effective temperature Te, initial approximation to the source function, type of mean absorption coefficient $\bar{\kappa}$, and fractional variation of the flux from that corresponding to the nominal effective temperature. From this comparison, Münch concludes that enough attention has not been given to accurate numerical integration required in the determination of the models, with the result that certain otherwise unexplicable discordances occur. He cautions that a range of errors in temperature and gravity which are permissible in the representation of the continuous spectral energy distribution cannot be tolerated when the model is used to derive spectral line features.

Later models, making use of better computational aids, have largely overcome the previous defects of integration. Underhill (1963) has discussed some of the problems inherent in model atmosphere computations as well as those connected with comparisons between observation and theory. She has given values of emergent flux for eight models from B9V to O9V. Strom (Strom 1964) has reviewed in detail the problems associated with high-temperature models and presents a grid of twenty-two models bracketed by $3.0 \leq \log g \leq 4.0$, and $10{,}000^{0} \leq T_e \leq 20{,}000$ °K, which corresponds to a range of spectral types between A_o and B3. Mihalas (1965) has computed thirty-three models with a range for log g of 1 to 4.4 and for T_e from 7200 to 50,000 °K.

When opacity sources other than continuous are considered, the formulation of a model atmosphere becomes very difficult. For higher-temperature stars, the visible spectra show hydrogen lines to be the major source of additional absorption. In the ultraviolet below the Balmer limit, hydrogen lines will still play an important role. The formation of these lines takes place high in the stellar atmsophere, and the energy absorbed by them is redistributed elsewhere in the spectrum, thus modifying the spectral energy distribution to some extent. Other metallic lines are also formed in the ultraviolet. Gaustad and Spitzer (1961) have made a preliminary survey of ultraviolet lines to be expected for a B_2 star. Besides those of hydrogen, the strongest lines are due to CII, CIII, NII, NIII, ClIII, SiIII. About 25% of the stellar flux would be absorbed by all the lines from 912 to 3000 Å. The exact effect of this line blanketing on the emergent flux distribution has not been worked out in detail. Morton (1965) has found a total blanketing due to ultraviolet lines of about 30% for a B_2 star and about 20% for a B_o star, under his initial assumptions. He further found that line absorption from 950 Å to 1100 Å is sominated by lines from multiply ionized C, N, and Si rather than the Lyman lines of hydrogen alone.

C. Observations

Observations of stellar ultraviolet fluxes have not yet firmly established whether there is any major discrepancy with theory. Several years ago, large discordances were suspected, in the sense that the observed fluxes of B stars were falling well below the predicted values. It seems evident now that part of the problem was due to inaccurate models including the neglect of line blanketing, while part can be attributed to inaccuracies of calibration, the poor overlap and general paucity of data, and interstellar extinction.

Because of this state of uncertainty and non-uniformity pertaining to observed ultraviolet fluxes, it is not convenient here to treat the data as a whole, let alone examine it in detail. Seaton (1965) and Heddle (1965) have recently both given useful summaries of the observational material. Seaton points out that in the comparison of observational results, the ratio of discrete ultraviolet fluxes to visible flux constitutes a very sensitive parameter. In fact, flux ratios have always been of most immediate value in observational studies where most work is based on relative measurements, so this is not surprising. It is surprising, however, that so much emphasis has been placed on the absolute flux values, the determination of which requires meticulous care to carry out well. Not enough mention has been made in the literature about calibration techniques and associated problems, to inspire confidence in the published absolute values.

In the vacuum ultraviolet, it requires great care to even maintain relative spectral constancy of optical efficiency. Important changes in spectral response can be caused by contaminants common to laboratory and launch sites, such as oil vapors, water vapor, and salt spray. Most stellar ultraviolet measurements have been made from sounding rockets. There are periods of such flights where atmospheric absorption is still important. Data obtained during such periods should be treated very cautiously, since well determined corrections usually do not exist, and extinction can rapidly become very large.

V. EXTRA-GALACTIC ULTRAVIOLET

Extra-galactic systems provide important clues in guiding more detailed studies within our own. We may expect in the vacuum ultraviolet that this will continue to be true. It is interesting to speculate that in those galaxies, for which the red-shift is sufficient, there will be regions of L-α emission sufficiently close to the edge that some of this radiation will escape (see Sec. II, B). As this light is red shifted with respect to our galaxy, it will pass unhindered to the earth. Wereas L-α from such regions would be for the most part obscured to us within our own galaxy, we would have here an opportunity to study them in their relation to galaxy as whole. Some stellar radiation which lies below the Lyman continuum may similarly become observable, depending on the distribution of gas near these sources. Fortunately, a good number of the nearer galaxies may display sufficient red-shift to make L-α observable.

Field (1959) has discussed possibilities for the state of hydrogen and the infleunce of L-α radiation in intergalactic space. Observations of red-shifted L-α will evidently play an important role in the interpretation of the cosmological problems.

VI. INSTRUMENTATION

A. Sounding Rockets

Stellar ultraviolet rocket instruments have been flown by Boggess, Stecher, Milligan and Kupperian of the Goddard Space Flight Center; Alexander, Bowen and Heddle of University College London; Chubb, Byram, Gulledge and Packer of Naval Research Laboratory; and by Code, Bless and Houck of the University of Wisconsin. Reports by all of these groups except the latter are contained in the Proceedings of I.A.U. Symposium No. 23 (in press).

The photometric techniques use ultraviolet sensitive photomultipliers or gas-gain ion chambers as detectors, filters or gratings as spectral discriminators, and mirrors, quartz-fluorite lenses or collimating tubes as collectors. Brighter stars yield incident U.V. fluxes of the order 10^{-9} erg.cm^{-2}.sec^{-1}.Å^{-1} as seen at the earth. Without rocket stabilization only the brighter stars are observable, as the total observation time per star is very small, measured in fractions of a second. Because of the limited collecting area permitted by the size of sounding rockets, it is apparent that with unstabilized rockets only limited spectral resolution is attainable. On the other hand, large areas of sky are often swept out by the motion of the rocket during single flights. With relatively large acceptance angles of the photometers (fields are usually several degrees to a side), sky background also becomes important in setting the limiting magnitude. This problem is not alleviated by objective dispersing instruments. Fainter stars and higher spectral resolution require pointed instruments and background rejection, such as is attainable with slit spectra. Examples of rocket instrumented with sky-scanning photometers are shown in Figures 3 and 4.

Boggess has recently begun to fly ultraviolet cameras with objective gratings to obtain spectrograms of many stars at one time. These typically employ apertures of several inches with fields of some 20°, and dispersions of a few hundred Angstroms per degree. These cameras require 3-axis stabilization, which is provided by the Attitude-Controlled Aerobee Hi. Morton and Rogerson of Princeton University are also making use of this attitude-controlled rocket to obtain stellar ultraviolet spectra of selected stars with a scanning spectrophotometer.

B. Satellites

The applications of satellites to ultraviolet astronomy other than the sun is primarily being undertaken by the Orbiting Astronomical Observatory, which is an inertially stabilized satellite platform sufficiently large to carry a 36-inch diameter telescope, or several smaller telescopes. Four telescopic systems have been, or are being, designed and built for ultraviolet astronomical observations.

The first OAO will contain a system developed at the University of Wisconsin by A. Code and T. Houck of four 8-inch

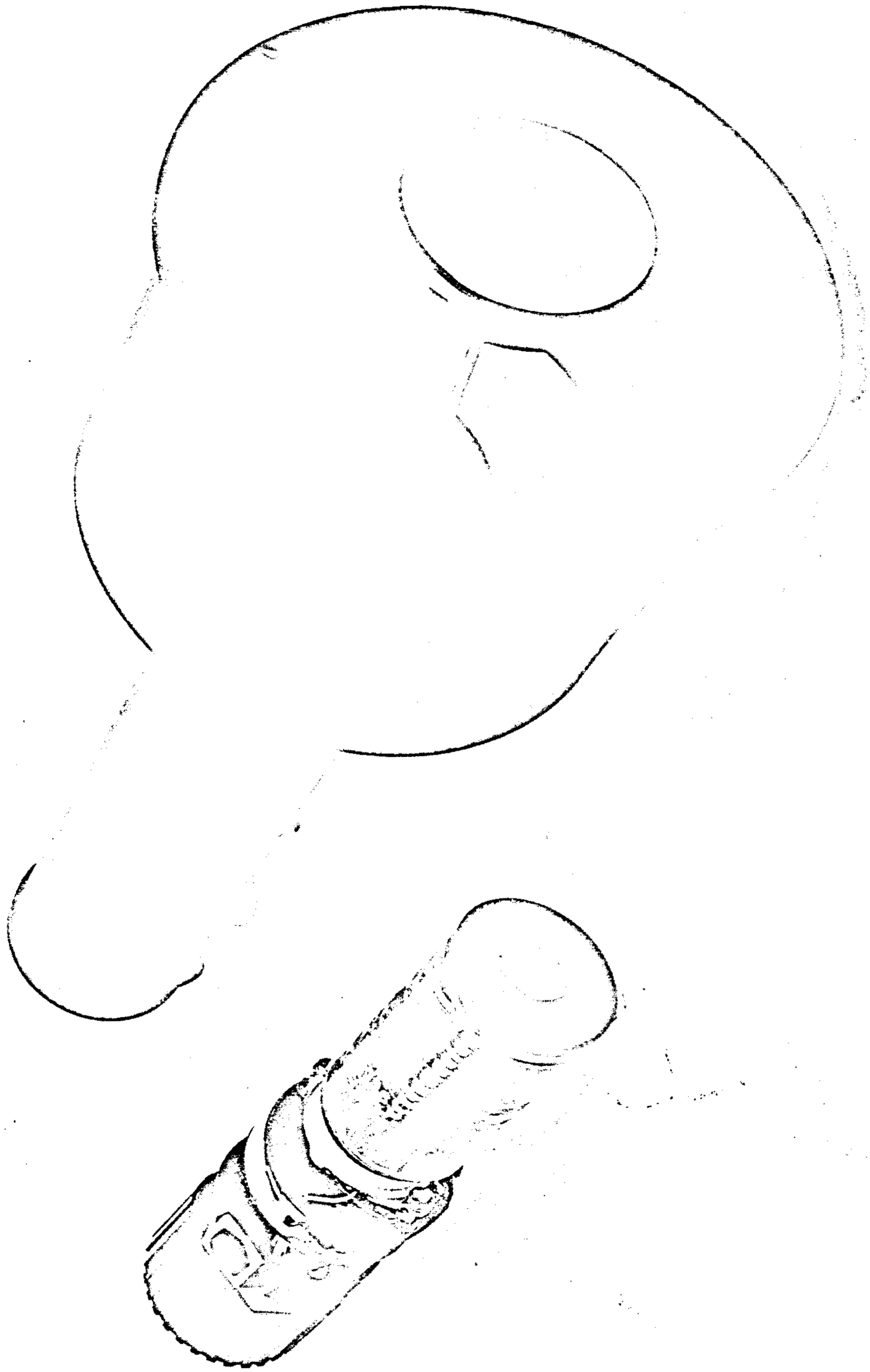

Fig. 3 - A cassegrain ultraviolet stellar filter photometer as used by Boggess in unstabilized Aerobee-Hi sounding rockets.

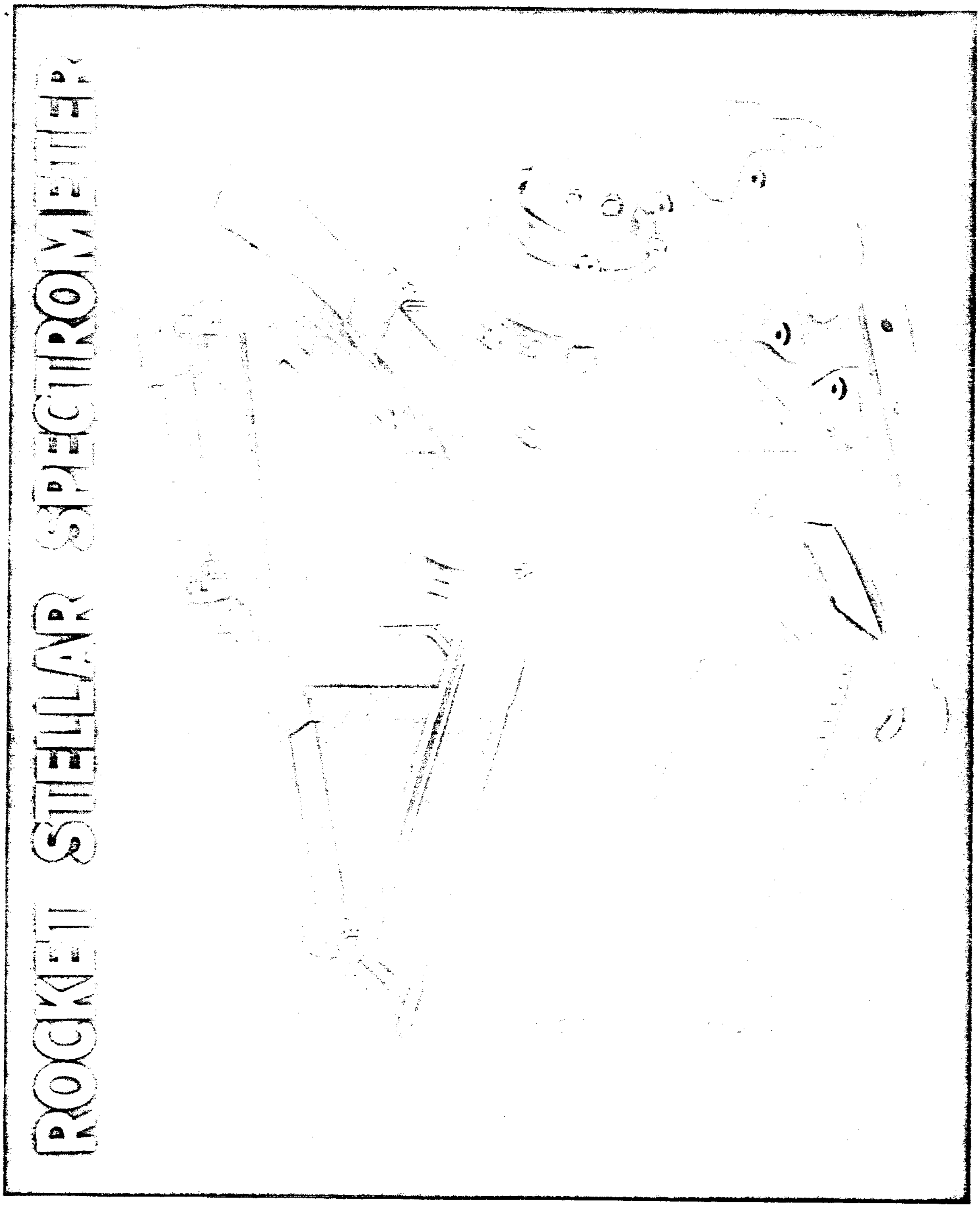

Fig. 4 - An objective grating ultraviolet stellar spectrophotometer, as used by Stecher and Milligan in unstabilized Aerobee-Hi sounding rockets. Roll of the rocket causes the spectrum to move across the exit slit.

telescopes, a single 16-inch telescope, all of which employ bandpass filters, and two objective grating spectrophotometers.

A follow-on OAO is planned to carry the Smithsonian telescope system which is a set of four 12-inch television cameras with 2.8 degree field of view, working in various ultraviolet bands to map the sky. This project is under the direction of E. Whipple and R. Davis. J. Milligan and J. Kupperian at Goddard Space Flight Center are responsible for the development of the second OAO telescope package (Fig. 5). This is a single instrument which utilizes a 36-inch aperture cassegrain telescope coupled to a high-purity rocking plane-grating spectrophotometer with multiple exit slits (Fig 5). At Princeton University, L. Spitzer, Jr. and J. B. Rogerson, Jr. are preparing a telescope-ultraviolet spectrometer system for the third OAO. This is a large aperture, high focal-ratio cassegrain feeding a concave grating spectrophotometer. All of the OAO telescope systems are reviewed in detail by Rogerson (1963). (J. B. Rogerson, Jr., <u>Space Science Reviews</u> <u>2</u> (1963) 621.

In anticipation of the long lead-time required for completion of OAO systems, Hallam (Hallam and Mangus 1964) developed an astronomical ultraviolet telescope-spectrophotometer for OSO-B2, the second of the Orbiting Solar Observatories, which is shown in Fig 6. This is a 6-inch sperture modified Gregorian telescope working into a rocking-grating spectrophotometer, and utilizes the two-axis stabilization provided by the OSO to systematically cover the sky.

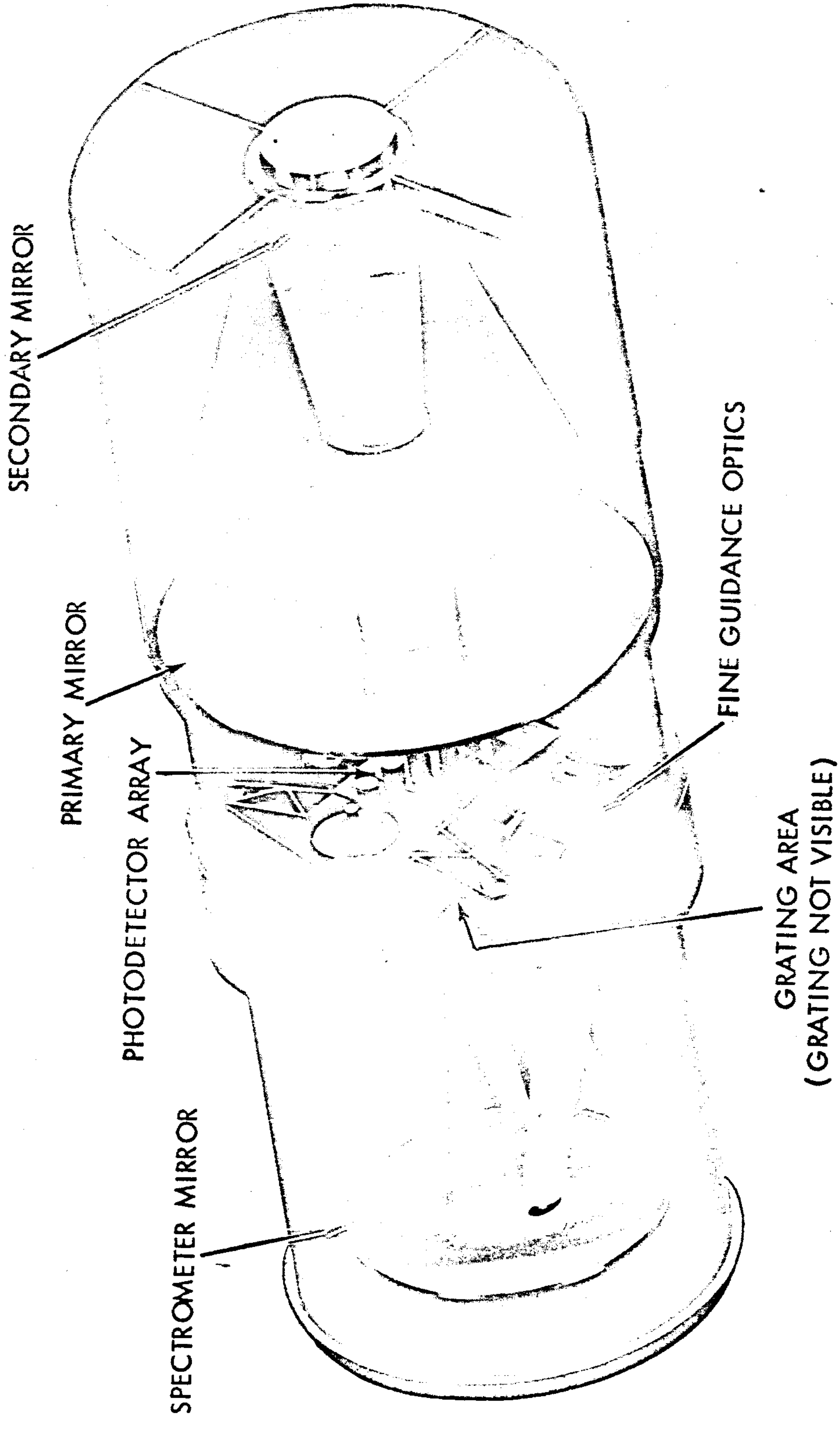

Fig. 5 - The Goddard Space Flight Center Experiment Package for an Orbiting Astronomical Observatory

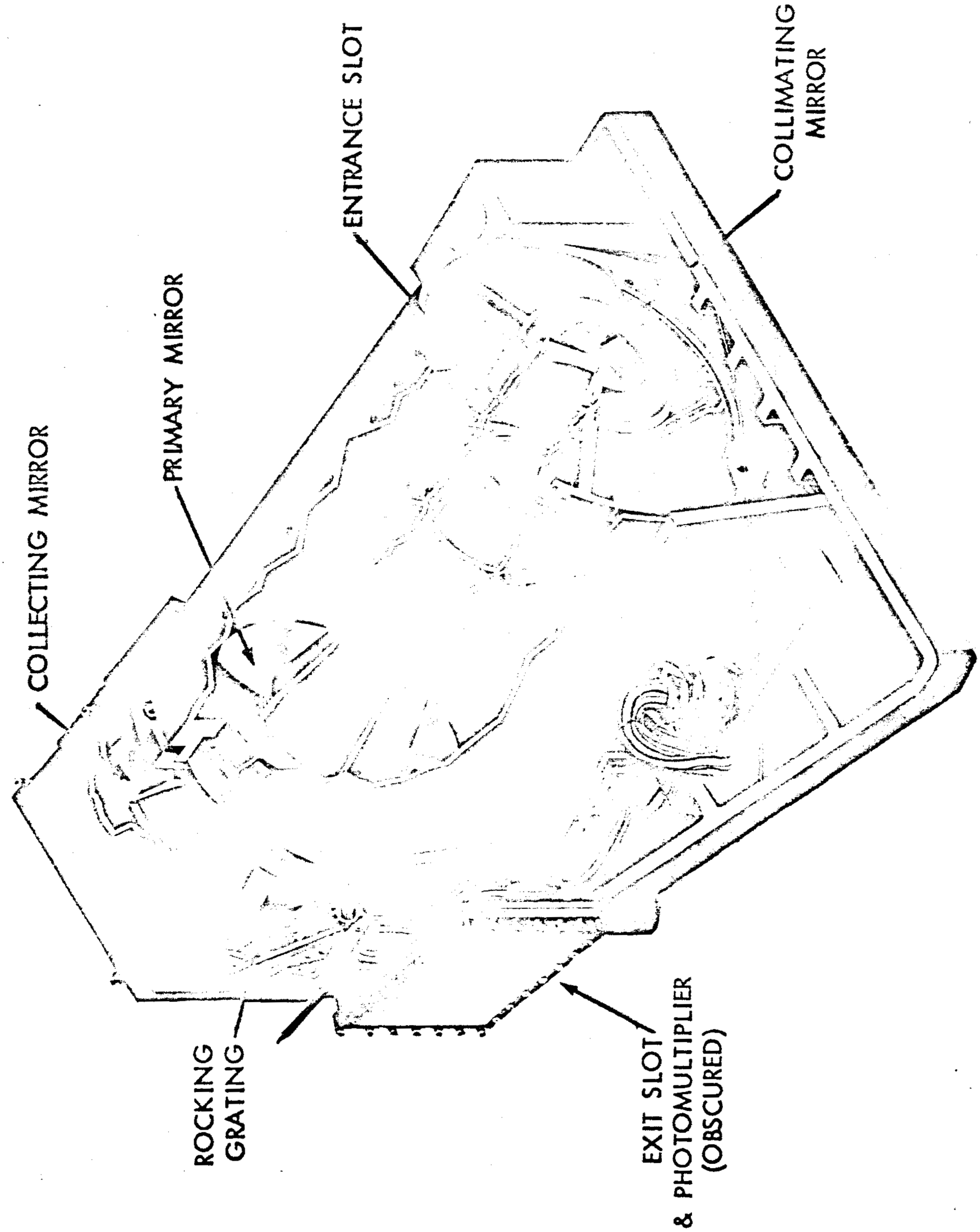

Fig. 6 - The Goddard Space Flight Center astronomical ultraviolet spectrophotometer for the Orbiting Solar Observatory.

C. Space Laboratories

There are plans by several groups to utilize the capabilities of some Gemini and Apollo missions to carry and operate ultraviolet wide angle objective prism cameras to obtain stellar spectrograms. Such programs provide a means of monitoring the conditions of data acquisition not available to unmanned satellites, and they provide photographic data retrieval, which is indeed valuable. Larger and more sophisticated forms of manned and unmanned astronomical facilities are presently under study by various groups. Certainly there will come a time when development of such facilities will be appropriate, in order to allow further advances in extra-atmospheric astronomy.

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