

INVITED DISCOURSE B

given to participants in the General Assembly at 20^h 30^m on Friday 28 August 1964 in the Auditorium Maximum of the University in Hamburg by

Professor Leo Goldberg

(Harvard and Smithsonian Observatories, Cambridge, Massachusetts)

on

SOME ASPECTS OF SPACE ASTRONOMY

INTRODUCTION

My first encounter with what has come to be known as Space Astronomy took place at the Harvard Observatory in 1937 at a colloquium by Dr M. N. Saha on 'A Stratosphere Solar Observatory,' in which he described some of the advantages that astronomy would gain if the solar spectrum could be photographed from a balloon at a height of 40 kilometers, or above what was then thought to be the altitude of the ozone layer. As Saha put it, 'the great intensity of the Balmer series and the associated continuous spectrum in the chromosphere has given rise to a large number of speculative theories.' He then went on to suggest that if only the Lyman lines could be observed, the problem of hydrogen excitation in the Sun and stars would probably be completely explained, and the problems of stellar atmospheres would be nearer solution.

It is somewhat beside the point that the actual observation of the Lyman lines has increased rather than diminished the incidence of speculative theories about the chromosphere. The main thing is that no one in Saha's audience could possibly have foreseen that 20 years later astronomers would be using not merely 'stratosphere solar observatories' but 'orbiting solar and stellar observatories,' to say nothing of probes to the Moon, to the planets, and even to the Sun.

Space Astronomy has developed so rapidly since 1946 that it is becoming increasingly difficult to decide what portion of the subject may still be called astronomy and what portion of it has become something quite different, such as particle physics, geochemistry, meteorology, or even simple exploration and adventure. Some astronomers believe in the thesis 'Once an astronomical body, always an astronomical body,' even after man has set foot on it. Now we do not shut our eyes to knowledge gained by more direct means, such as exploration, but for sheer intellectual excitement studying the Moon with the aid of returned samples simply cannot compare with the thrill of deciphering a smudge on a photographic plate. No true astronomer would ever want to go to the Moon and planets.

On the other hand, I cannot agree with those who find space astronomy unchallenging and who prefer to look at the universe through a hazy, dirty, semi-opaque atmosphere. This point of view is illustrated by a letter I received a few years ago from one of my colleagues. On learning that I was moving to Harvard to engage in work on Orbiting Solar Observatories, he wrote to express his regret that I was leaving astronomy to take up space research. He then went on to ask if that meant he would not be seeing me at the next General Assembly of the IAU.

In my talk this evening I shall take the position that observation of the universe from a distance is still astronomy, even though carried out from above the atmosphere. So defined,

space astronomy may be conducted from airplanes, balloons, rockets, and satellites. Certain activities carried out with space probes, as exemplified by photography of the front and rear sides of the Moon and observations of Venus and Mars from nearby spacecraft, are also legitimately part of astronomy.

All of these vehicles are now being used by astronomers as observational platforms. Airplanes have been used for many years to observe the corona at great distances from the Sun during total eclipses, notably by Blackwell. At recent eclipses, large jet aircraft have been fitted out as flying laboratories both in the U.S.S.R. and in the U.S.A. Although the equipment is relatively modest compared with that which can be erected on the ground, results are virtually guaranteed. It seems certain that in the future, supersonic aircraft will be used to follow the Moon's shadow along the eclipse path and thus to prolong the duration of eclipses from seconds or minutes to hours. Stratospheric balloons now transport payloads of 2.5 tons to altitudes of 80 000 feet or higher. Individual flights may last a full day or a full night, as required, and observational programs are carried out by radio command from the astronomer on the ground. The balloon has proved its worth whenever the light path must be free of dust, water vapor, or turbulent air, although its operation is far from routine, and therefore its use must be confined to carefully selected projects.

The high-altitude sounding rocket continues to serve space astronomy well. A typical scientific rocket, such as the U.S. Aerobee, may transport a payload of about 150 pounds to an altitude of about 150 miles, which is sufficient for many purposes. However, for radio astronomy observations, which must be made well outside the ionosphere, the so-called deep space rocket can attain altitudes of several thousand miles. The usefulness and scientific range of the astronomical rocket will be further enhanced when it becomes possible to point continuously at individual stars. Despite the greater sophistication of the orbiting observatories, rockets will continue to be widely used in space astronomy, both in the testing of new instruments and components, and for observations that require only short 'exposure times.'

Satellite observatories have developed rather more slowly than was expected a few years ago, although solar observations and a few radio astronomy experiments have been carried out from satellites in several countries. However, although satellite astronomy is still in its infancy, we are aware of the tremendous engineering effort which has been under way for a number of years and which should soon begin to bear fruit. In the U.S.A. alone, five Orbiting Solar Observatories are scheduled to be launched between now and the next solar maximum. Each satellite will carry 70 pounds of pointed experiments stabilized towards the Sun with an accuracy of about 1 arc minute. Plans have also been announced for an Advanced Orbiting Solar Observatory carrying 250 pounds of pointed experiments, with an angular resolving power of about 5 seconds of arc. Stellar astronomy can also look forward to the Orbiting Astronomical Observatory, with a payload of about 700 pounds. The first of three launchings is scheduled for 1965. A committee of astronomers of the U.S. National Academy of Sciences has recommended that at least one such OAO be maintained in orbit continuously for a period of about 10 years. Plans for a large astronomical satellite (LAS) are also being generated by the European Space Research Organization. The reporting of results from orbiting observatories should be a feature of the next General Assembly.

I. RECENT RESULTS

I should like this evening to review some recent results obtained by space techniques and to give an indication of what may be in store for the future. Many of these results were reported for the first time last week at the Liège symposium—after this paper was prepared. So I am obviously indebted to many of the authors for advance information.

I.1. *Solar XUV*

It is natural to begin such a review with the Sun, where major advances have been made. The first rocket ultraviolet spectra of the Sun, obtained by Tousey and associates in late 1946 and early 1947, extended to 2200 \AA and were of such low resolving power, about 1.5 \AA , that identifications were difficult. Immediately following the XIth General Assembly at Berkeley on 29 August 1961, the same spectral region was again photographed by the Naval Research Laboratory, this time with an échelle spectrograph at a resolution of about 0.03 \AA , which begins to be comparable in quality to the best spectra obtainable on the ground with tower telescopes. Even so, only about half of the lines can be identified by comparison with the ultraviolet multiplet tables and finding list.

One year later, in August 1962, the spectrum from $2000\text{--}1200\text{ \AA}$ was photographed with a resolution of 0.2 \AA and shows very clearly the transition from a Fraunhofer to an emission line spectrum and from limb darkening in photospheric radiation to limb brightening in chromospheric emission. In the region $1250\text{--}800\text{ \AA}$, the resolving power is 0.07 \AA . The improvement in resolution over previous spectra in this region is by a factor of 5 to 10.

Very beautiful photographs of extremely short wavelengths from $33\text{--}242\text{ \AA}$ have been obtained by NRL within the last year. Many strong lines between 170 \AA and 220 \AA can be attributed to iron in unknown stages of ionization, because they are also observed in high-temperature laboratory plasmas containing iron, which have been produced in the Zeta machine at Harwell and in the θ -pinch at NRL. There is a sudden decrease in the number and intensity of emission lines below 170 \AA which is real and unexplained, although exaggerated by the properties of the aluminum filter used to reduce stray light. The identified lines include the helium-like and hydrogen-like resonance lines of Carbon v and vi as well as lines of Si, Mg and Fe in very high stages of ionization.

Until now, the resolving power of far UV spectra has not been sufficient to permit registration of line profiles, except for one or two selected lines such as Lyman- α and $-\beta$. But the spectral resolution is already beginning to approach the calculated Doppler widths of certain lines of light elements, such as those of the O vi doublet at 1035 \AA . The measurement of line profiles, which is just a short step away, will be of incalculable value in studying the physics of the chromosphere and corona.

Whenever absolute intensity measurements are required, or when film cannot be recovered, as from a satellite, photo-electric recording of spectra is essential. The technique of using windowless photomultipliers with photo-cathodes of high threshold has been pioneered and developed by Hinteregger and shown to be extremely effective for satellite operation during very long periods of time by Lindsay and his group at the Goddard Space Flight Center. The spectral resolution obtained in this way by Hinteregger is almost equal to that of the best photographs, at least at very short wavelengths.

The successful launching of the first Orbiting Solar Observatory by the Goddard Space Flight Center in March 1962 showed that it is feasible to point satellite instruments at the Sun with high accuracy and to maintain in orbit equipment that will respond to radio commands from the Earth and that can store and transmit large quantities of observational data to the Earth. During the life of the satellite, many thousands of scans of the spectrum of solar radiation in the range $50\text{--}400\text{ \AA}$ were recorded, including observations of many chromospheric flares.

Until now, satellite spectra have been made only in integrated sunlight, but the lines of highly-ionized atoms are very sensitive to solar activity and therefore the integrated line intensities are often observed to vary with the period of solar rotation. The form of the variation is dependent on the ionization potential, and therefore may be used as a kind of temperature

classification to assist in line identifications. Neupert has used this idea to identify the resonance lines of Fe XIV in spectra recorded in the NASA Orbiting Solar Observatory.

During the VIth General Assembly at Stockholm in 1938, Professor Edlén showed photographs made by Tyren in his laboratory at Uppsala of the helium- and hydrogen-line spectra of oxygen and nitrogen in the wavelength region 10–30 Å. These beautiful spectra were not thought to be of direct astrophysical interest and indeed they were not even mentioned in the Draft Report of the Stockholm meeting. But, exactly 25 years later, most of the same lines were measured in the Sun by Friedman, including members of the Lyman series of N VII and O VIII and also the resonance lines of O VII and Fe XVII. No one knows what new spectra will be displayed during the XIIIth General Assembly—perhaps the Lyman series of Fe XXVI.

Some of the younger members of the IAU may wonder why astronomers did not think X-ray spectra important in 1938. For one thing, it seemed out of the question to observe them through the Earth's atmosphere. Besides, how could an atmosphere in thermodynamic equilibrium at a temperature of 6000°K emit X-rays? I still recall a certain paper in the *Astrophysical Journal* of that period which argued that the coronal lines could not be forbidden lines because their observed great widths would imply an impossibly high temperature of one million degrees.

Time-lapse photography in the monochromatic light of H α and the K-line has greatly advanced the study of solar activity in the low chromosphere. A few years ago, spectroheliograms were secured in Lyman- α and now the technique has been extended by the Naval Research Laboratory to other lines covering a wide range of ionization potential, so that solar activity may now be studied at many different heights throughout the chromosphere and inner corona. The enhancement of active regions is found to be greater in the far UV than in H α or Ca K, and is greatest in lines of Fe XV and XVI. Furthermore, the limb brightening is slight in Lyman- β and C III, λ 977, but very marked in the O VI lines, perhaps because the latter are less self-absorbed. We hope soon to obtain time-resolved spectroheliograms in some of these lines from the OSO-B satellite.

It is now well established that solar flares and X-ray emission are closely correlated. Numerous measurements of X-ray emission have been made during the past two to three years from high-altitude balloons, from sounding rockets and from satellites instrumented in the U.S.A., the U.S.S.R., and the United Kingdom. The results of these measurements may be summarized as follows. Solar flares are accompanied by bursts of high energy X-rays, particularly in the range 2–150 kilovolts. The higher frequencies are intensified during flare activity. Rapid variations of X-ray emission during the lifetime of a flare have also been reported. Sudden ionospheric disturbances on the Earth are caused primarily by X-rays of wavelength shorter than 8 Å, although the flux at longer wavelengths seems also to be correlated with solar activity and with flares. There appears to be a slowly varying component which correlates with that of the 2800 megacycle solar radiation, and in addition transient events lasting from 10 minutes to a few hours. Very rapid fluctuations are also observed in which the flux changes by a factor of two or more in time intervals less than one second. A number of attempts have been made to detect solar gamma radiation but no positive observations have as yet been made, even during flares of importance III.

1.2. Interpretations of solar XUV observations

Efforts to interpret the far ultraviolet solar spectrum, which are still in a rather primitive stage, are directed first at the basic question of identifications, second, at the structure of the corona and of the chromosphere-corona interface, and third at the determination of chemical abundances. According to a recent estimate by Tousey, the origin of more than half of the emission lines above 500 Å is known, but at shorter wavelengths most of the strongest lines are still unidentified. Attempts to derive the structure of the outer atmosphere have been hampered

by gross departures from thermodynamic equilibrium and complexities in the physical structure. In the absence of thermodynamic equilibrium, analyses of the spectrum must be based on consideration of the rates of detailed processes such as collisional and radiative excitation, ionization and recombination. Despite the fact that the cross sections in general use have very little experimental basis, they have generally been assumed to be accurate within a factor of two although their application has led to some rather curious results. First, the temperature of the corona deduced from ionization theory has been consistently lower by about 1.5 million degrees than temperatures derived from the Doppler widths of emission lines and from the electron density gradient. Second, the temperature of the corona seems to increase with increasing ionization potential. Third, the abundances of the heavy elements relative to hydrogen derived from the intensities of both far ultraviolet emissions and visible forbidden lines turn out to be an order of magnitude greater than values found from absorption line spectra of the Sun and other stars.

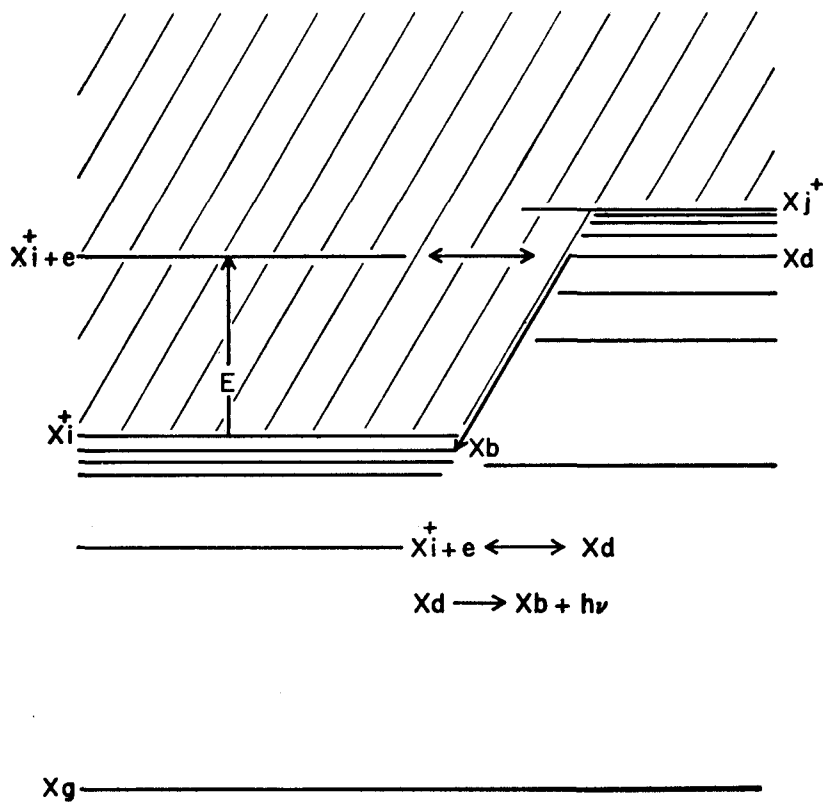


Fig. 1. Schematic energy level diagram to illustrate process of dielectronic recombination. The radiationless transition $X_i^+ + e \rightarrow X_d$ is followed by the 'stabilizing' transition $X_d \rightarrow X_b + h\nu$. X_g is the ground state of ion X , and X_i^+ and X_j^+ are the ground and excited states, respectively, of the ion X^+ .

It now appears that a rather major process has been omitted in the conventional theory of ionization equilibrium and as a result the cross sections for electron recombination have been underestimated, not by a factor of two, but by a factor of twenty or more. A few years ago

Unsöld suggested that the capture of electrons by dielectric recombination, which seems to have been first studied by Massey and Bates in 1942 in connection with the recombination of O^+ in the Earth's atmosphere, might be astrophysically important. At first the process seemed relatively trivial, but Burgess showed a few months ago that the earlier assessments were incorrect and that, under certain conditions frequently found in astrophysics, dielectronic recombination plays a dominant role in the ionization equilibrium.

The process is illustrated in Figure 1 with a schematic and idealized energy level diagram for a complex atom. On the left is the usual series of levels converging on the ground state of the next higher stage of ionization. However, if either two outer electrons or an inner shell electron are excited, there will also be one or more series converging on the first and higher excited levels of the ion, as shown to the right of the diagram. Provided that certain selection rules are fulfilled, an atom in a discrete level above the ionization limit has a high probability of auto-ionization by a radiationless transition to the ground-state of the ion, with the ejection of an electron of kinetic energy E . The lifetimes of such levels may be as short as 10^{-13} – 10^{-14} seconds. The probability of the inverse transition is also very high and dielectronic recombination is effected when capture in the doubly-excited state is followed by a so-called stabilizing transition to a level below the first ionization limit.

The point made by Burgess is that if the electron temperature is high enough so that a substantial number of free electrons have energies approximately equal to the energy of the second series limit, there will be a large number of radiationless captures in levels with high total quantum number and therefore high statistical weight. Since the rate of downward stabilizing transitions is proportional to the line strength, which in turn is proportional to the statistical weight, the addition over a large number of such levels can lead to a total capture probability one or two orders of magnitude greater than that for ordinary radiative recombination. This discovery by Burgess is fundamental and will require the re-investigation of many astrophysical problems for which the rate of capture by atoms other than hydrogen needs to be known within a factor of two. Burgess and Seaton have already recalculated the ionization equilibrium of iron in the solar corona. The higher rate of recombination raises the ionization temperature considerably, but does not completely remove the discrepancy.

1.3. *Galactic ultraviolet*

We turn now to observations of radiation from outside the solar system. The two outstanding questions discussed during the last General Assembly were 1) whether the apparent bright nebular glow around the star Spica was real and if so whether it could be explained, and 2) the extent to which the ultraviolet fluxes of O- and B-type stars departed from the theoretical calculations based on model atmospheres. As for the first question, it now appears that the earlier results were spurious, and that the intensity of the diffuse glow surrounding the star Spica is less than 1/10 of that previously reported. The question of the ultraviolet radiation field is still not resolved, but the gap between theory and observation is narrowing because more accurate measurements are giving higher fluxes and more accurate calculations predict lower fluxes than heretofore. In particular new observations of the spectra of several early-type stars by Stecher show no sign of the sharp drop in intensity below λ 2400 previously reported by Stecher and Milligan—despite the fact that the phenomenon had already received a number of theoretical explanations. As Seaton remarked at Liège, if we extrapolate the present trend, we should find that the observed fluxes will be greater than the calculated values by 1967.

1.4. *Galactic X-rays and gamma rays*

Absorption by the interstellar medium is expected to terminate observations at 912Å , and hence it seems very doubtful that very much radiation from the Galaxy will reach the Earth in the wavelength region 30Å – 912Å . At shorter wavelengths the transparency is expected

to increase very rapidly so that even the center of the Galaxy should be visible at a wavelength of 3 \AA . X-ray astronomy offers great promise for studying high energy phenomena at great distances. X-radiation from the Galaxy was first recorded by Giacconi *et al.* from the general neighborhood of the galactic center. Later, Friedman and associates at NRL observed a very strong source from the region of Scorpius and a lesser flux from the direction of the Crab Nebula. A number of other sources have been suspected but not definitely confirmed. The flux reaching the Earth from the Scorpius source is about $30\text{--}40 \text{ photons cm}^{-2} \text{ sec}^{-1}$ in the band between 3 \AA and 8 \AA . The Crab Nebula source is weaker by a factor of 10, but both fluxes are much too high to be caused, for example, by synchrotron radiation. The problem is how a source like that in Scorpius can radiate X-rays without visual or radio energy.

Very recently, the Crab Nebula has been observed by Friedman during a lunar occultation. The X-ray emission is found to originate from the nebula rather than from a point source such as a hypothetical neutron star. This does not rule out the possibility that other neutron stars may exist as supernova remnants, as first proposed by Baade and Zwicky thirty years ago, and that they may be discovered by their X-radiation. These fascinating end products of stellar evolution are composed of matter in a degenerate state at nuclear densities, and according to some recent calculations by Chiu and by Morton they would have a surface temperature of $1\text{--}10$ million degrees, a mass of about 1 sun and a radius of about 10 km. The photospheres would be only 1 cm thick. It is too early to say whether or not X-ray astronomy will follow the pattern of radio astronomy in uncovering a multiplicity of new sources. Needless to say, strong efforts should and will be made to derive information on both the angular sizes of these objects and their X-ray spectra. Chiu proposes to use a 100-inch diameter X-ray telescope and spectrograph to study these objects, of which something like 10^8 may have been left behind from supernova explosions during 10 billion years.

1.5. *Visible and infrared*

As far as the shortwave end of the spectrum is concerned, observation from space vehicles is absolutely decisive and indispensable. No radiation of wavelength shorter than about 2900 \AA can reach ground level anywhere on the Earth. The same is true for radio waves of very low frequency, although, as Reber and Ellis have shown, frequencies as low as three megacycles may leak through 'holes' in the ionosphere. At intermediate frequencies, the advantages of space astronomy are substantial, although perhaps not as decisive, because the infrared transmission of the atmosphere in some wavelength bands can be extremely high under the best conditions. However, infrared observations of even a few objects from balloons greatly enhance the ease of interpretation of ground-based observations. For example, Kuiper, and Sinton and Boyce have discovered bands of stellar water vapor in the spectrum of Mira Ceti in spite of absorption by the telluric bands at 1.3μ and 1.8μ , because the hot water bands are displaced to somewhat longer wavelengths. It must be admitted, however, that it was comforting to observe these bands above the earthly water, in spectra obtained with the Stratoscope II balloon in November 1963 by Woolf, Schwarzschild and Rose.

The infrared spectrum of Aldebaran is relatively quite free of bands, but displays an intensity peak at 1.6μ , where the absorption coefficient of the negative hydrogen ion goes through a minimum. On the other hand, the spectrum of Mira at minimum shows strong water vapor bands at 1.4μ and 1.9μ . The water vapor bands are also strong in the spectra of Betelgeuse and R Leonis. The spectrum of Jupiter shows many bands of methane and the ammonia fundamental at 3.0μ . The flight of the Stratoscope II was a beautiful example of how a space telescope can be remotely controlled from the ground and made to perform observations on a large variety of objects without advance programming.

High-resolution photography and infrared spectroscopy of the Moon and planets will be attempted from other balloons in the near future. In principle, observation of the Moon and

DD

planets from space probes or fly-bys can be made with vastly greater resolving power than is possible from a balloon or an Earth satellite. In practice, the gain in resolution is partially offset by degradation in image quality during transmission over interplanetary distances. Even so, the recent photography of the Moon from Ranger-7 showed details about 1000 times smaller than the best photographs from the ground, and we look forward now to similar attempts on Mars.

In addition to overcoming the absorption by the Earth's atmosphere, space vehicles are also being used to reduce atmospheric scintillation and sky brightness. The most recent accomplishment in this area was the white light photography of the outer solar corona from a balloon (by the High Altitude Observatory) and from a rocket (by the Naval Research Laboratory). A major instrumental advance has been the development of a coronagraph using serrated, external occulting disks which reduce stray light to about one part in 10^9 of the brightness of the solar disk. Despite some imperfections, the first results obtained from a balloon clearly show many interesting details of coronal structure and prove the soundness of the method. Newkirk's balloon photographs clearly show complex coronal streamers at both east and west limbs. Future flights of coronagraphs in satellites are designed to monitor transient events in the outer solar corona, such as the ejection of plasma clouds into the inter-planetary medium.

I.6. *Radio astronomy*

Turning now to the other end of the spectrum, we find that observations of cosmic radio noise at low frequencies are beset by many difficulties. Most of the problems are caused by the ionosphere and can be minimized in principle by going to very high altitudes. Despite the difficulties, a number of measurements of low-frequency galactic noise have been made from high altitude rockets by Michigan and Harvard, from the Canadian Alouette Satellite, and from the second United Kingdom satellite, Ariel II. The U.S.S.R.'s Electron 2 satellite also carried instrumentation for recording cosmic noise at frequencies of 0.725 and 1.525 Mc/sec.

In general, the long-wave radio radiation from the galactic plane is believed to arise from the synchrotron emission of cosmic ray electrons modified by absorption in H II regions. On this basis, the radio flux should increase with decreasing frequency until at some critical value below ten megacycles the flux passes through a maximum and then rapidly decreases with decreasing frequency. The Michigan results do, indeed, show a sharp break in the spectrum near 2.0 megacycles, and the Ariel satellite seems to give similar results. On the other hand, the Canadian measurements disagree in showing a rather flat maximum, with no positive indication that the curve turns down at low frequencies.

The Alouette satellite also recorded three type III solar noise bursts during the space of a few minutes. The calibration below 1.5 megacycles per second is not overly reliable, but there is evidence suggesting that the bursts continue right down to the sweep limit of the receiver at 0.5 megacycles per second. This would indicate the emission source reached a distance of the order of twenty solar radii from the Sun.

II. LABORATORY ASTROPHYSICS

During the last few years, the needs of both space astronomy and high temperature fusion physics have stimulated a much needed increase of activity in laboratory spectroscopy. Although the arc, the spark and the furnace are still very useful, astrophysical environments can usually be more closely simulated by the use of such devices as synchrotrons, van de Graaf generators, plasma generators, flash tubes and shock tubes. Words like the Zeta machine, theta-pinch, Scylla and the Stellarator are becoming part of the astronomer's vocabulary. Although the impetus for much of this work has come from the need to interpret satellite and rocket observations of far ultraviolet spectra, the same equipment turns out to be useful also

in the visible region of the spectrum, and so ground-based astronomy also benefits quite directly.

The tradition of laboratory astrophysics is a very old one, dating back to the experiments of Kirchoff and Bunsen with table salt in 1859. In 1904 the first report of George Ellery Hale as director of the Mount Wilson Observatory referred to a laboratory built on Mount Wilson for 'the comparative study of the radiations emitted by various substances under widely different conditions of temperature, pressure, strength of surrounding magnetic field, etc.' Early laboratory work took the form of systematic measurements of wavelengths of spectral lines, temperature classifications, measurements of the Zeeman effect, etc. Unfortunately, at about the same time that progress was beginning to be made in the quantitative analysis of stellar atmospheres, most physicists began to lose interest both in laboratory spectroscopy and in the theory of atomic spectra.

This gap could not be filled by the relatively small number of astronomers working with limited budgets, and consequently quantitative studies of astronomical spectra have been consistently and severely handicapped by a lack of basic laboratory data. When spectra are formed under conditions of local thermodynamic equilibrium, the most important need is for oscillator strengths or transition probabilities. Under conditions of non-thermodynamic equilibrium, the most extreme of which are found in the gaseous nebulae, the interstellar medium, the solar corona, etc., the problem of analysis becomes infinitely more complicated and to solve it we need the cross sections for the many types of collisional and radiative processes by which atoms exchange energy with their surroundings.

I should not give the impression that modern laboratory spectroscopy is concerned merely with relatively routine measurements. On the contrary, much of the work is quite fundamental and may provide wholly new insights into atomic and molecular structure. One very promising area for investigation is the phenomenon of autoionization, to which I have already alluded briefly in connection with dielectronic recombination, but which seems to have many other astrophysical consequences.

Shenstone in 1931 and also Majorana were the first to invoke autoionization to explain the anomalous widths of some lines and the absence of others from laboratory spectra. Transitions from the ground states of atoms to autoionizing levels usually give rise to series of lines in the vacuum ultraviolet beyond the limits of the principal series. Owing to the short lifetimes of the upper levels, the lines may be very broad and because of interactions between the discrete levels and the neighboring continuum the lines may be asymmetric. A good example of such series in He has recently been observed in the laboratory by Madden and Codling at the National Bureau of Standards in Washington. We see a series of absorption lines against a background continuum produced by a 180 MeV synchrotron. The lines arise from transitions between the ground state and three series of doubly-excited levels converging on excited levels of He⁺.

Positive astrophysical identifications of autoionized lines have thus far been limited to the strong doublet of Al I at 1900 Å, which has been observed in the rocket solar spectrum, and to a multiplet of Ca I in the solar Fraunhofer spectrum near 6350 Å, recently identified by Mitchell and Mohler and also observed in late-type stellar spectra by Griffin. The Al lines and others like it have interesting properties. First, the great width makes it easy to measure the true profile. Second, the line width arises entirely from natural broadening, and therefore the absorption coefficient is independent of depth and determined only by the *f*-value and the radiation damping constant. Third, the absorption of a photon in such a line is immediately followed by ionization, and therefore the line is formed in pure absorption even though it may originate from the ground state.

One of the best studied atoms from the standpoint of autoionization is calcium. The astrophysical importance of these studies by Kaiser, by Ditchburn and Hudson, and by Garton and

Codling seems to have been overlooked. Astronomers are not entirely at fault because it was not until about 1959 that the doubly-excited levels of neutral calcium were first observed in the laboratory. Several series of lines have been observed, originating from the ground state of Ca I and converging on the first excited level 3^2D of Ca II. Because of the fact that only the levels with $f = 1$ may combine with the ground state only a small fraction of the doubly-excited energy levels has been revealed by these studies. Levels with higher f -values can be discovered by their combinations with excited lower levels which are not populated in the furnace and similar sources but which may be observed with the aid of shock-excited absorption spectra according to techniques employed by Reeves and Parkinson at Harvard. Many such transitions will fall in the visible region of the spectrum and since the line width is proportional to λ^2 , the lines may attain widths of 200 Å or more.

Such lines make very efficient absorbers, and indeed their equivalent widths may be as much as 100 times greater than that of a normal line broadened by combined Doppler broadening and collisional damping. The overlapping of large numbers of such lines may under some conditions be a significant source of opacity in stellar atmospheres. Because they would have to arise from excited states, the appearance of such autoionized lines would be favored by relatively high temperature and high electron pressure. Thus the absorption might be enhanced in dwarfs as compared with giants. Autoionizing transitions in negative ions may be a major source of opacity in very cool stars. For example, the so-called Lindblad depression at $\lambda 4227$ which is progressively stronger with decreasing temperature in M-type dwarfs, may possibly arise from the negative ion of calcium from transitions of the type $4s^2nl \rightarrow 4s4pnl$.

In calculations of the photoionization of gases, it is usually assumed that ionization occurs as a result of transitions from discrete levels to the continuum. For Ca I, however, the experimental results of Ditchburn and Hudson show that the f -values for transitions to the autoionizing levels are about three times as large as the integrated f -value for the continuum. Hence, all calculations of absorption cross sections for elements of atomic number above 20 may have to be re-examined rather carefully.

In particular, the ionization equilibrium of the interstellar medium should be looked at anew. It is well known that the abundance ratio calcium to sodium derived from the intensities of interstellar absorption lines is smaller than that found in the stars by more than a factor of 50. The discrepancy is usually attributed to incorrect assumptions about the radiation field, which controls the proportions of Na II and Ca III. On the other hand, both Na I and Ca II may absorb far ultraviolet radiation in transitions from the ground state to autoionizing levels in their respective continua, as shown in Figure 2. The f -values for these transitions, which are estimated by Dr Charlotte Froese to lie at wavelengths of about 410 Å and 440 Å, respectively, for sodium and calcium, should be on the order of unity, whereas the integrated f -value for the entire continuum of Ca II is only about 0.01 or 0.02. Obviously, at these wavelengths, the radiation can only be effective in H II regions. It is too early to say whether the abundance anomaly can be explained in this manner, but certainly the ionization equilibrium of the interstellar medium cannot be properly discussed without taking account of autoionizing transitions. Unfortunately, these lines are difficult to observe in the laboratory.

In the interstellar medium, the problem is to explain why there is so little Ca II, but in the solar chromosphere the situation is reversed—there is too much of it extending up to heights of 10 000 km or more. Now the temperature of the chromosphere is controversial to say the least, but almost everyone agrees that at a height of 10 000 kilometers it must be at least 100 000° and therefore one would expect all of the calcium to be in the form of Ca III.

One of the more interesting features of the process of dielectronic recombination is that the rate of recombination may increase with temperature over a considerable range, as shown for example, by Burgess' results for helium. Exact calculations for Ca have not been made, but the

rate of recombination of Ca III into Ca II probably increases with increasing temperature up to 200 000° or more. Thus, although the temperature of the chromosphere increases outward, the further ionization of Ca II may be arrested.

The second and last step in the dielectronic recombination process is a transition of the form $n' l + 1, n'' l'' \rightarrow n l, n'' l''$, in which the first level is usually doubly-excited and the second

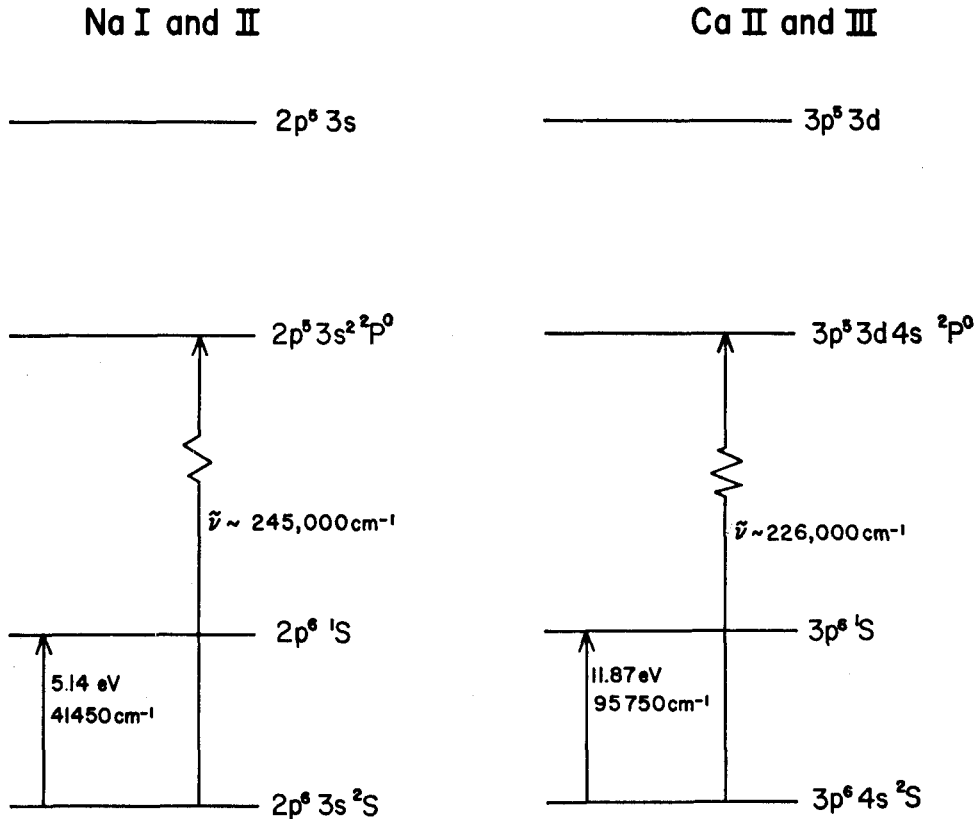


Fig. 2. Schematic energy level diagrams for Na and Ca, showing possible transitions from the ground states to autoionizing levels Na I $2p^5 3s^2 P^0$ and Ca II $3p^5 3d 4s^2 P^0$ respectively. The estimated frequencies are based on Hartree-Fock calculations by Dr Charlotte Froese.

singly-excited. The transition takes place between levels lying slightly below an excited level and the ground level, respectively, of the next higher ion. The wavelength of the transition may therefore be very nearly equal to that of the corresponding transition in the next higher stage of ionization. Thus, the integrated effect of a large number of such transitions corresponding to different values of $n'' l''$ may make an appreciable contribution to the line intensity. For example, it is suggested that all or part of the emission in the centers of the H and K lines of Ca II and Mg II are formed in this way. (see Figure 3).

Some of these ideas about the astrophysical consequences of autoionization are rather speculative, but I have presented them to emphasize how wide the gap is in our understanding of fairly fundamental properties of atomic structure. When one thinks of the almost endless

number of unexplained anomalies already observed in astrophysical spectra, one cannot avoid the conclusion that in the near future a great many astrophysical problems will be solved more readily in the laboratory than at the telescope, be it on the ground or in orbit. In this respect, we cannot rely entirely on the relatively small number of physicists who are interested in solving our problems, but must take steps to build laboratories connected with observatories in the manner once advocated by Hale at the Mount Wilson Observatory.

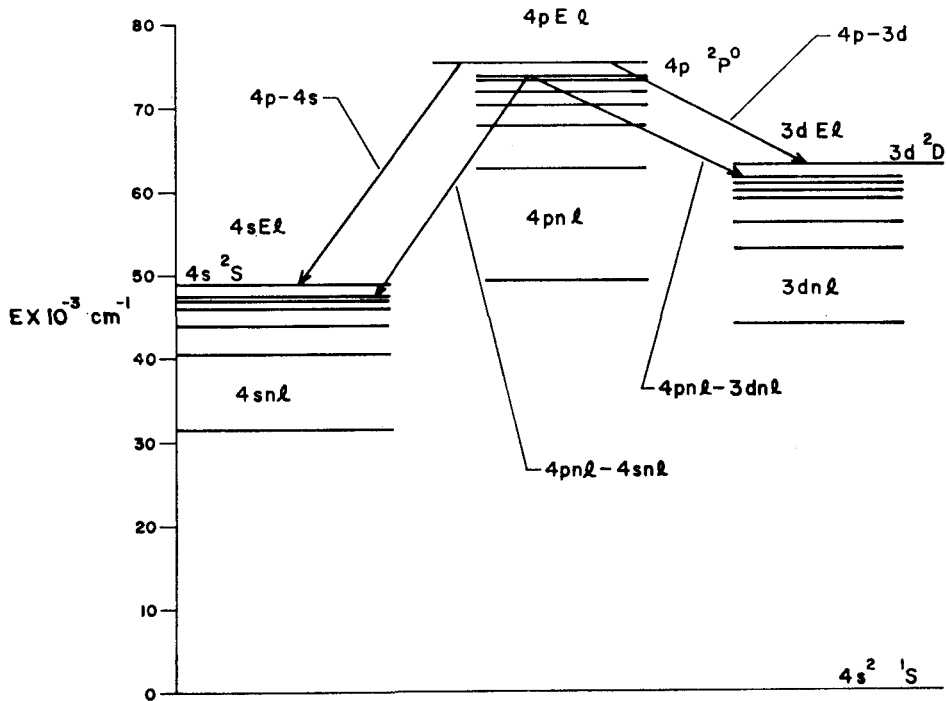


Fig. 3. Doubly-excited states of Ca I, illustrating transitions between configurations $4pnl$ and $4snl$.

III. FUTURE DEVELOPMENTS

This brief and incomplete review of space astronomy shows not only that the field is developing very rapidly, but that the second derivative of the growth curve is also positive. By the time of the next General Assembly, in 1967, several of the large orbiting observatories should be in operation and until some results have been obtained it is difficult to plan the next major step in any detail. It has been suggested that facilities like the OAO, and the Large Astronomical Satellite of ESRO, will be useful for a period of about ten years, or until 1975. Sooner or later, however, astronomers will cease to be content with a thirty-six inch aperture, and even though it is not yet clear what the size of the second generation telescope should be, ten years is not too long a time in which to carry out the necessary planning, design and construction. The best guess that can be made at the present time is that a diffraction limited reflector of about 100 inches diameter is not an unreasonable goal for 1975. One can also foresee the need for large special purpose telescopes for X-ray and solar astronomy and possibly also for astrometry.

Although it may be premature to begin work on detailed designs for such large facilities, it is not too early to begin studying the many problems that will have to be solved irrespective of the

exact size and shape of the telescope. It is not even clear at the outset whether the best location would be an orbit around the Earth or Sun or on the Moon. Both locations have their proponents. The Moon offers some advantages such as a solid foundation for stabilization, although seismic disturbances may be a problem, and a large supply of material for shielding against solar radiation. On the other hand, Spitzer, in particular, has pointed out an impressive list of disadvantages for a lunar-based observatory, such as the mirror flexure caused by lunar gravity, the large fluctuations in temperature, the possible hazards of dust on the surface, etc., whereas an Earth satellite offers zero gravity, lower cost and easier accessibility for maintenance and repair.

Another basic decision to be made concerns the choice of aperture and focal length for the main mirror. In the Russell lecture for 1964, I. S. Bowen presented the results of his analysis of the factors governing the choice of design parameters for ground-based telescopes. One hopes that a similar study may soon be made for space telescopes, unlimited by seeing and sky light. Once the size and shape of the mirror are known, a determination will have to be made whether the mirror is likely to retain its shape under gravity-free conditions or whether the final figuring would have to be done in orbit.

Whether a large telescope is emplaced on the Moon or launched into orbit, its cost will be prohibitive unless some means can be found for prolonging its life beyond the nominal value of one year that has been planned for the OAO. The cost of launching several OAO satellites is estimated at about 200 million dollars and that of the next large space telescope will be no less. Incidentally, these numbers are becoming so large that it may be necessary to adopt a new unit for money. Just as the light year replaced the kilometer or mile, I suggest that we may have to adopt the light dollar as a unit for the space budget. One light dollar is the number of ordinary dollars laid end to end that would be traversed by a ray of light in one second. Thus, the conversion factor is 2×10^9 . In these units, the cost of the OAO program is only 10 light cents and that of the manned lunar landing a mere 10 light dollars.

In all seriousness, it is clear that the key to the prolongation of telescope life as well as to a great increase in the value and versatility of a space observatory lies in the use of men (or women) for the maintenance and modification of telescopes or even possibly for their final assembly in space. By rendez-vous from the Earth or from a nearby space platform, astronaut-engineers could repair or replace worn out or defective parts, make instrumental settings, retrieve photographic plates and change auxiliary instruments.

These possibilities have been talked about for a number of years, but it is not widely appreciated how close they are coming to reality. The flights of the Vostok series of spaceships in the U.S.S.R. have shown that it will be only a very short time before two spaceships can rendez-vous in space. Such maneuvers are also planned as necessary steps in the U.S. Apollo mission to the Moon. Within the next three to four years there will be a number of Apollo flights in Earth orbits in which space for scientific experiments will be available, with the possibility that exposed photographic plates may be returned to Earth. Proposals for suitable experiments have already been invited, and although space and weight during the first flights are necessarily very limited, the future looks terribly exciting when one considers that the Saturn V launch vehicle will be capable of placing over a quarter million pounds in Earth orbit and about 90 000 pounds in lunar orbit. It is rather staggering to realize that a quarter of a million pounds is very nearly the weight of an 85-foot radio telescope. Thus there is already an enormous gap between the size and weight of astronomical equipment planned for launching during the next few years and what can be handled by rockets that will be ready at the same time or a little later. This is an opportunity that astronomy cannot afford to ignore.